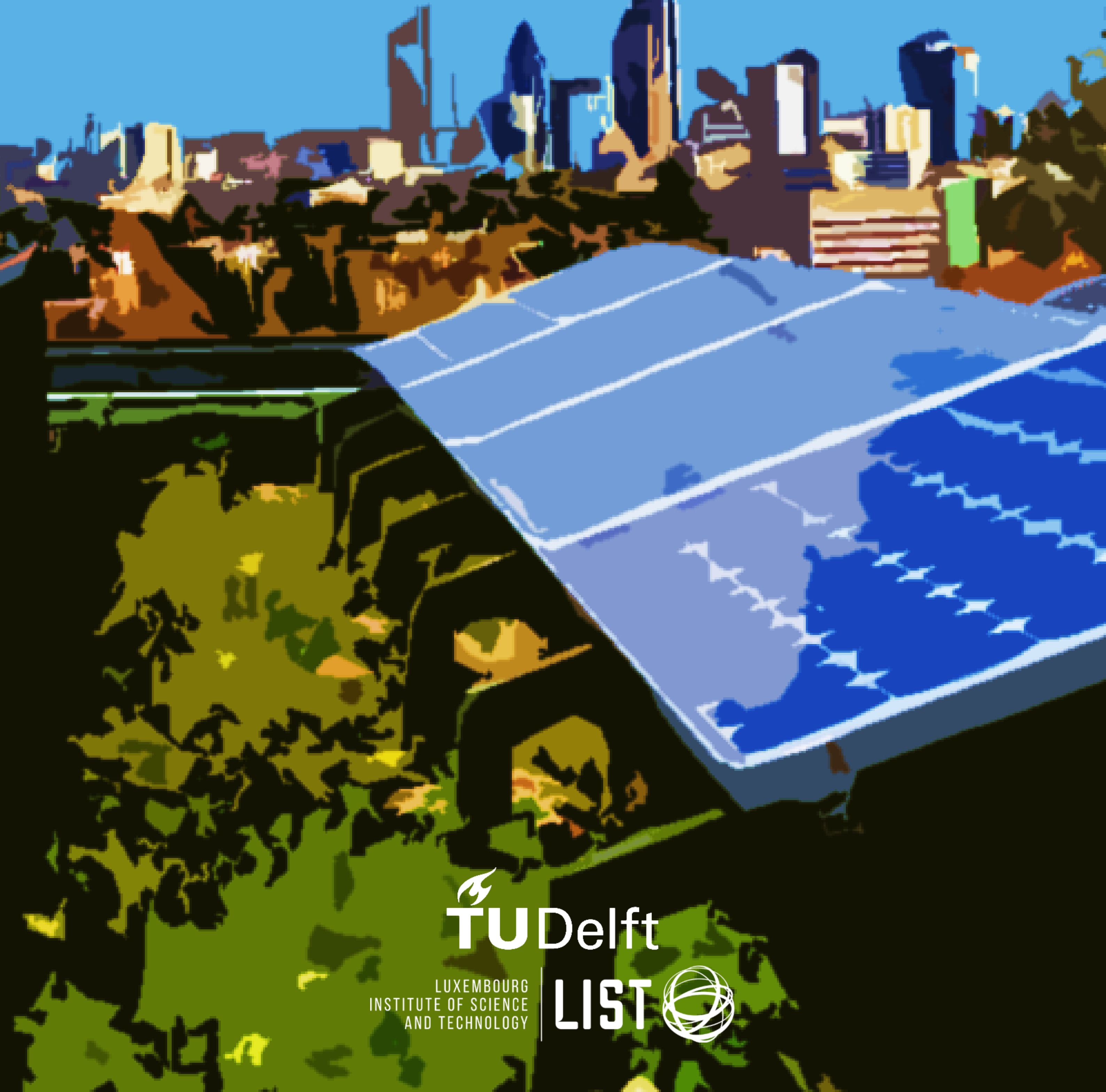
Green Roofs and Renewable Energy Communities for the European Green Deal

Legal Profiles and Probabilistic Cost-Benefit Analysis

Francesco Cruz Torres



TU Delft

LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY | LIST

Green Roofs and Renewable Energy Communities for the European Green Deal

Legal Profiles and Probabilistic Cost-Benefit Analysis

Master thesis submitted to Delft University of Technology
in partial fulfilment of the requirements for the degree of

Master of Science

in Engineering and Policy Analysis

Faculty of Technology, Policy and Management

by

Francesco Cruz Torres

Student number: 4999959

To be defended in public on August 23, 2021

Graduation committee

Chairperson	: Dr. Ir. J.H. Kwakkel, Policy Analysis
First Supervisor	: Dr. S.T.H. Storm, Economics of Technology and Innovation
External Supervisor	: Dr. Javier Babí Almenar, Luxembourg Institute of Science and Technology
External Supervisor	: Dr. Benedetto Rugani, Luxembourg Institute of Science and Technology

Preface

This thesis marks the end of a uniquely rewarding learning experience I had at Delft University of Technology. The memory of my last year of high school, in which I pondered on the reason for enrolling at university, lies vivid in my mind. A long reflection. Then the passion, the ambition, the reason.

"To till and keep" the environment (Gen 2:15).

For this reason, I enrolled at university completing a B.Sc. in Energy Engineering. I learnt how humans till, cultivate, plough, work the natural environment. I discovered how we extract resources, and most notably energy, in its various forms, from the natural environment. So little I knew, instead, about how I could keep, care, oversee, preserve it.

That is why I came to the Netherlands, where the Technology, Policy and Management department of TU Delft carefully thought about how to combine engineering with policy analysis. Here I learnt how a policymaker could write more informed and effective laws, striking a balance between the utilization of natural resources and their preservation.

In this thesis, I attempt to provide European policymakers with recommendations on how to best transpose the recent recast of the European Union's Renewable Energy Directive. I analyzed a possible specification of the Directive's renewable energy communities, namely photovoltaic-green roof energy communities. I analyzed their legal characteristics, the main institutional and technical components, their technical costs and benefits, and I studied their economic feasibility. I was caught by this specific type of energy community, perhaps, for *that* same reason. It could help its members to till and keep the natural environment. On the one hand, it "extracts" energy resources from the environment, but, on the other, it also brings interesting environmental benefits.

I would like to thank my graduation committee for the time, expertise, and experience each one of the members lent me throughout this research. In particular, I would like to thank my supervisors from LIST for the various discussions and reflections that went beyond what is written in this document and allowed me to continue learning and ponder on human development. I would also like to thank them for the genuine relationship we were able to build throughout the time of this project. A particular thanks goes also to my supervisors from TU Delft, for their kind availability, as well as for their thorough comments and detailed suggestions, which were provided with a constructive spirit.

A deep thanks is directed to my family, which remained united in difficulties, and which taught me to work with care, commitment, and perseverance.

Francesco Cruz Torres

Delft, August 2021

Executive Summary

Europe is currently experiencing an exceptionally rapid loss of biodiversity, an increasing frequency and intensity of extreme climate events, as well as persistently low air quality levels. The new growth strategy of the European Union, the European Green Deal (EGD), refers to tackling these climate and environmental-related challenges as the defining task of this generation.

The set of EGD policy objectives is far-reaching, and it includes the supply of clean, affordable, and secure energy, the preservation and restoration of biodiversity, climate neutrality, and a pollution-free environment. While a concerted effort from both European energy and environmental policies is needed, specific actions within energy policies addressing typical environmental objectives are still missing. Thus, a large potential for energy policies to further contribute to addressing biodiversity, health, and climate adaptation and mitigation objectives remains untapped.

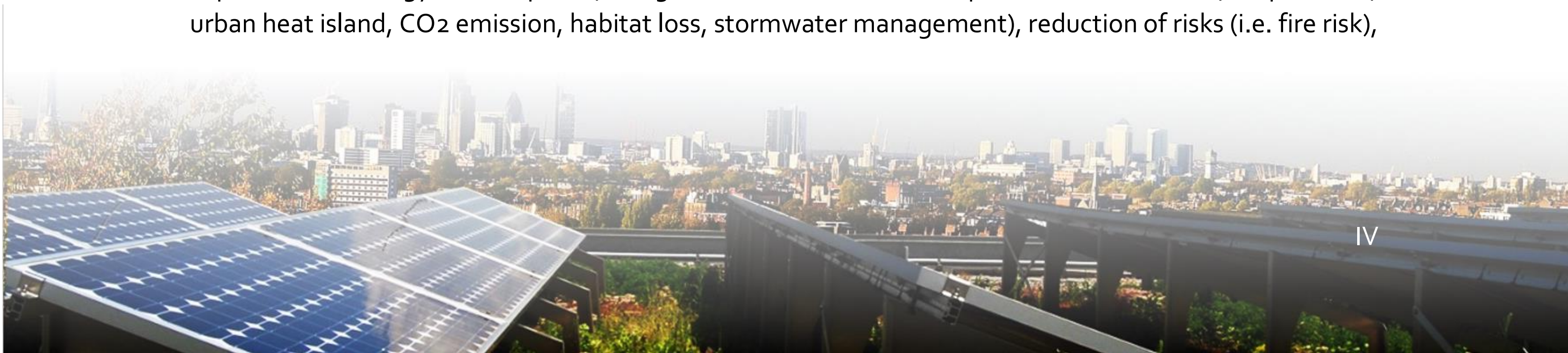
This thesis considers that the latest EU Renewable Energy Directive (RED II) provides an opportunity to contribute to addressing the above environmental objectives besides the energy ones. RED II legally defines for the first time renewable energy communities (RECs) and is currently being transposed across the EU. This dissertation proposes photovoltaic-green roof energy communities (PGECs) as a new form of RECs capable to address a wider range of EGD environmental objectives, rather than purely energy ones. PGECs are based on the integration of an energy technology, photovoltaic panels, with a nature-based solution, namely green roofs.

This work recognizes the potentiality of such communities to address policy goals while acknowledging the significant investment costs they entail. For this reason, the research question of this thesis is:

Under what conditions does the combination of photovoltaic panels and green roofs, as part of Renewable Energy Communities, meet the European Green Deal's objectives in an economically convenient manner?

Upon selecting a suitable case-study in Esch-sur-Alzette (Luxembourg), a review of all the relevant EU policy documents and two national legislative transpositions was carried out. In addition, interviews to government officials and an industry expert complemented the analysis. In order to be entitled to receive support schemes tailored to PGECs, these communities must be formed as renewable energy communities and comply with all RECs' legally defining characteristics. Thus, participation to PGECs need to be voluntary, but only open to natural persons, small and medium-sized enterprises and authorities located near the photovoltaic-green roofs. PGECs must be effectively controlled by members or shareholders in the proximity of the community installations, while remaining autonomous from individual members or external parties. The community's primary aim is to provide environmental, economic, or social benefits to its members or to the area where it is located rather than financial profits. To this end, PGECs activities include energy generation, sharing, and sale, but by no means these activities can be the professional or commercial activity of private members.

As a result of a systematic literature review, six costs and 15 benefits stemming from the whole lifecycle of photovoltaic-green roofs were identified as a consistent group of items. These costs correspond to implementation or management actions (i.e. installation, maintenance, replacement, disposal of green roofs and photovoltaic panels) or impacts derived from them (i.e. and air pollutant and CO_2 emissions generated due to the production of these technologies). The benefits correspond to a reduction of expenses (i.e. energy consumption), mitigation of environmental impacts (i.e. urban noise, air pollution, urban heat island, CO2 emission, habitat loss, stormwater management), reduction of risks (i.e. fire risk),



and enhancement of building characteristics (i.e. longevity of the roof, aesthetics, sound insulation, energy generation from photovoltaic panels).

Such a wide range of benefits were found to contribute addressing five main policy objectives of the European Green Deal. Importantly, in all such cases photovoltaic panels and green roofs reinforced the effect of one another, increasing the magnitude of the benefit that each technology alone can bring. Photovoltaic-green roofs provide renewable and more affordable energy to the members or shareholders, while contributing to the European energy security. This technology helps restoring and preserving biodiversity in urban areas, while also enhancing the air quality and, to an extent, stormwater runoff quality of such areas. Photovoltaic-green roofs contribute to the European climate neutrality objective by reducing CO_2 in the atmosphere through multiple mechanisms, and they represent a climate adaptation measure reducing the urban heat island effect. The adoption of such a technology, lastly, increases the roof's insulation of buildings where they are installed, contributing to the EGD policy objective of building and renovating in an energy efficient way. Such results underscore how photovoltaic-green roofs can be a particularly valuable lever for EU as well as national policymakers in addressing the European Green Deal objectives.

A probabilistic social cost-benefit analysis was tailored to the Luxembourgish case-study and was simulated 100.000 times using the Exploratory Modelling and Analysis workbench. The simulation activity aimed at identifying the range of net present values that can be expected by considering the differing costs and benefits valuations of photovoltaic-green roofs produced by the relevant literature. Next, the application of Scenario Discovery allowed to identify three conditions enabling the economic convenience of photovoltaic-green roofs. These are an installation cost below 57 €/m^2 (compared to the installation of a conventional black roof), an aesthetics' increase benefit above 130 €/m^2/year, and a social discount rate below 6.4%. Meeting such requirements would enable the economic convenience of photovoltaic-green roofs from a societal point of view. Instead, from the viewpoint of investors, a monetary incentive of at least 15 €/m^2 of green roof would be needed to make this technology economically convenient. When this economic condition is met photovoltaic-green roofs would be implemented, thus unlocking their benefits addressing five EGD objectives.

Photovoltaic-green roofs represent a technology at the edge of two main policy fields: energy and environmental policy. The analysis of PGECs carried out shows how environmental policy objectives can be achieved with energy policy levers, such as the support schemes for RECs. This analysis showcases that the design of renewable energy communities and of relative supporting schemes, should not be based only on energy market considerations. Rather, the transposition of the RED II Directive in Member States should foresee environmental or green technologies as one of the specificities of renewable energy communities. In this regard, support schemes for RECs should be designed to account for such a specificity.

In terms of the Luxembourgish case-study, resources to determine the economic convenience of photovoltaic-green roofs should be focused on the valuation of aesthetics' increase first. This benefit was found to be the most critical one in enabling the economic convenience of such a technology. The often-limited resources for monetary valuation could in this way be used in an efficient and effective way.

The research question of this thesis was addressed considering both a policymaking and an academic perspective. In this thesis, not only the relevance of PGECs to the EGD objectives was highlighted, but a more consistent set of costs and benefits was proposed to overcome the common incomparability and inconsistency of cost-benefit analyses carried out to date. Therefore, this thesis conducted an all-inclusive probabilistic cost-benefit analysis, considering multiple values and evaluation methods. This ensured that some benefits were not neglected or overlooked.

Abstract

In the face of environmental challenges of unprecedented scale and urgency, the European Commission enacted in 2019 a new comprehensive growth strategy with the aim of reaching net zero greenhouse gas emissions in 2050. Named as the European Green Deal, this strategy includes energy, biodiversity, pollution, and climate adaptation targets, and envisages that all EU actions and policies will contribute to its objectives. However, to date, specific actions addressing biodiversity, climate adaptation, and health issues from within the energy sector are still missing or lagging behind. This research proposes a new form of Renewable Energy Community (REC), which combines the use of solar photovoltaic panels with green, namely vegetated, roofs to address multiple Green Deal's objectives. First, this form of REC was grounded in the current European legislation so to ensure its eligibility for the support schemes that Member States are currently required to devise. Next, the costs and benefits of this REC were determined with value transfer for a case study in Esch-sur-Alzette (Luxembourg) and a probabilistic cost-benefit analysis (CBA) was conducted. By applying Scenario Discovery, the CBA was simulated under different combinations of input parameters and rather than only providing multiple net present values (NPVs), the ranges of input values resulting in desirable NPVs were determined. As a result, the conditions under which the photovoltaic-green roof energy community becomes economically convenient were determined, providing guidance to national policymakers designing RECs' incentive schemes at present.

Table of Contents

List of Figures

List of Tables

1

Introduction

1.1 Problem Introduction

Europe is currently facing environmental challenges of unprecedented scale and urgency (European Environment Agency, 2019b). In particular, the exceptionally rapid rate of biodiversity loss, climate change impacts, and environmental risks to human health have been identified as persistent problems affecting the European Union (EU) (European Environment Agency, 2019b).

In the attempt to address these challenges, the EU set in 2019 a comprehensive new growth strategy, aiming "*to transform the EU into a fair and prosperous society (…) where there are no net emissions of greenhouse gases in 2050*" (European Commission, 2019, p. 2). Named as the European Green Deal (EGD), such a strategy seeks to make energy and environmental policies, among others, advance towards specific objectives. Four important objectives set out in the EGD are the: (1) provision of clean and affordable energy, (2) restoration and preservation of ecosystems and biodiversity, (3) zero pollution ambition, and (4) 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 as 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). Specific actions addressing biodiversity, and health issues (e.g. stemming from air and water pollution) are still lacking in EU energy policies (European Commission, 2012), while the planning and implementation of climate adaptation solutions remains slow (European Commission, 2021), despite the energy sector's needs (European Environment Agency, 2019a). Thus, not only energy and environmental policy objectives appeared in need of more coordination, but the need for actions, within the energy sector, addressing biodiversity, health, and climate change adaptation has also been stressed.

To overcome this limitation, nature-based solutions (NBS) offer an attractive opportunity for mainstreaming environmental targets into sectors where they are not traditionally explicitly considered (Nesshöver et al., 2017). As an umbrella concept, NBS 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). NBS have been regarded within the EU Biodiversity Strategy as a measure that should be systematically integrated in urban planning and design of buildings (European Commission, 2020). Similarly, the EU Climate Adaptation Strategy asserts that NBS would contribute to multiple Green Deal objectives, including the strengthening of climate change adaptation efforts (European Commission, 2021).

Within NBS, green roofs, in particular, have been described as an attractive tool to address a wide range of environmental EGD objectives. Green roofs enhance biodiversity and curtail habitat fragmentation, contribute to climate change adaptation (e.g., mitigate urban heat island effect, increase stormwater storage during extreme storm events), and improve urban air quality (Berardi et al., 2014; European Commission, 2020, 2021).

Despite their additional benefits, green roofs have not been widely implemented in combination with energy technologies yet (Sattler et al., 2020; Shafique et al., 2020). For example, green roofs and solar photovoltaic (PV) panels can provide an increased energy production compared to PV panels alone (Nash et al., 2016). Nevertheless, the latest *Clean Energy for All Europeans package* of energy directives provides an untapped potential for embedding green roofs into a new form of shared energy generation. The revised Renewable Energy Directive (RED II) introduces the new legal entity of Renewable Energy Communities (RECs) in the European energy market (Directive 2018/2001 recast), appearing particularly prone to address the wider EGD objectives. Indeed, a REC's primary purpose 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*" (Art. 2 (18)).

According to the RED II, a REC owns and develops the renewable energy projects shared by the members, such as power generating installations, but it can also own and maintain members' green roofs, especially since this aligns with the REC's purpose. In urban areas, where space for power generation technologies is limited, rooftop PV panels represent a preferred technology (Sattler et al., 2020). As a consequence, the benefits of combining PV panels with green roofs could be unlocked at an urban level for all citizens engaging in a photovoltaic-green roof energy community. Most importantly, EU Member States are explicitly required to devise support schemes for RECs, which shall take into account the communities' "*specificities*" (Directive 2018/2001 recast, art. 22 para. 7). Green roofs and PV panels may well represent such a specificity, in this way benefitting from reduced financial upfront costs, which have been a major issue for the widespread implementation of green roofs hitherto (Liberalesso et al., 2020).

To date, a great number of European countries have not yet fully transposed the European legislation, nor the RECs' definition and their relative support schemes (Hinsch et al., 2021; Lowitzsch et al., 2020). This leaves an important policy window open, in which national governments are still defining the legal entity of RECs and the measures to incentivize their adoption, and hence in which recommendations become pivotal (Lowitzsch et al., 2020).

Harnessing this open policy window, this study analyzes a particular form of RECs, i.e., photovoltaic-green roof energy communities (PGECs,) which include the combination of PV panels with green roofs as a REC specificity. Such PGEC does not only contribute to the energy policies' objectives to provide clean and affordable energy (European Commission & DG Energy, 2019), but also to other four EGD goals: biodiversity enhancement, reduction of air and water pollution, climate adaptation, as well as energy efficiency in buildings.

In the next section of the present chapter the state of the art on RECs as well as on the combination of green roofs with PV panels is presented. Section 1.3 outlines the research approach, the research question, and addresses the link of this study with the M.Sc. in Engineering and Policy Analysis. Lastly, the methods used to address the research question, and the research flow diagram are presented in section 1.4.

1.2 State-of-the-Art

In order to understand the features of RECs, first the key concept of energy community is explored through a review of the literature and current legislation in section 2.1. The specific form of photovoltaic-green roof energy community is subsequently introduced in section 2.2, while section 2.3 finally determines a suitable methodology to study the economic convenience of PGECs.

1.2.1 Renewable Energy Communities

Historically the European energy sector was dominated by state-owned vertically integrated energy utilities responsible for the generation, transmission, distribution and sale of energy to end users (Prosser, 2005; Ventosa et al., 2013). While this market design was mainstream, power generation required large scale installations, which were prohibitive for end users, as they entailed high capital investments and the availability of large areas. Currently, the minimum size of power generation technologies significantly decreased, allowing also consumers to start producing and storing electricity (Ruin & Sideén, 2020).

In this context, various countries around the world experienced a growing number of collective energy initiatives involving citizens and other market actors in the small-scale generation of electricity and/or heat (Lowitzsch, 2019). According to Caramizaru & Uihlein (2020), the broad term of *community energy* can be used to refer to the range of actions by which a community of citizens participates – at various degrees – to the energy system. While these authors do not define an energy system, it can be understood as the set of generation, transformation, transport, and distribution processes of energy sources (ENI, 2020), or sometimes only as the set of generation processes (Jones et al., 2011). In general, the spread of community energy around some countries in the world shows that citizens have started to operate and manage the production and distribution of energy (Schoor et al., 2016).

In the EU, community energy has lacked a clear status in legislations until very recently, consequently, this gave rise to a plethora of community energy variations (Caramizaru & Uihlein, 2020). As of 2019, two major definitions exist for energy communities:

- The Citizen Energy Community (CEC), set out by the revised Internal Electricity Market Directive (IEMD) (Directive 2019/944); and
- The Renewable Energy Community (REC), set out by the revised Renewable Energy Directive (RED II) (Directive 2018/2001 recast).

Both types of legal entities share the same primary purpose of providing "*environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits*". Nevertheless, while CECs' membership is open to voluntary participation to all types of entities, regardless of their location, RECs can be composed by local members only. Additionally, a defining trait of CECs is that they may engage in a wider set of energy activities, ranging from power generation (including from but not limited to renewable sources) and consumption, to charging services for electric vehicles or energy distribution across the network. Instead, RECs are not defined by certain activities they perform, but rather by their purpose and other types of membership and control criteria. They are *entitled* to produce, consume, store, and sell renewable energy, as well as to share it within the REC. This means that RECs' energy-related activities are restricted to clear boundaries, but other activities, such as owning green roofs, are permitted as well, without jeopardizing the definition of the community as a REC.

A key feature of the RED II, is its requirement that EU Member States provide RECs with an enabling framework promoting and facilitating their development (Art 22. Para. 4). Inter alia, the framework will have to support public authorities (e.g., municipalities) in enabling and setting up RECs, while it will also have to ensure RECs appropriate tools to facilitate access to finance and information.

Thus, RECs are in a privileged position with respect to support schemes and incentives, compared to other forms of energy communities. Additionally, RECs seem to be potentially suitable for the ownership and development of green roofs as well as solar PV panels. Nevertheless, knowledge on how a PGEC, as a form of REC, would fit within the current EU legislation, and thus would fully benefit from the support schemes contemplated by the EU legislator, is still missing to date.

1.2.2 Photovoltaic-Green Roof Energy Communities

Given the specific purpose of the RED II to foster acceptance of renewable sources among Europeans and support their deployment (Lowitzsch et al., 2020), RECs' energy production is constrained to renewable energy sources alone.

The potential for RECs is high, since estimates suggest that by 2050 about half of EU households are expected to be producing renewable energy (European Commission & DG Energy, 2019; Kampman et al., 2016). In particular, among renewable energy sources, solar energy appears prominent. The European Commission & DG Energy (2019) calculate that by 2030 energy communities could own 21% of the installed solar capacity and 17% of wind capacity in the EU.

While wind capacity usually requires larger areas, solar panels are suitable for rooftops of farms, public buildings, and households alike (Caramizaru & Uihlein, 2020). This is particularly important when considering that urbanization is another key trend within the Energy Transition (UN-Habitat, 2016). As most citizens are concentrated in urban areas, a form of REC may benefit from being tailored to the urban landscape (Ramirez Camargo & Stoeglehner, 2018). To date, solutions in urban environments focus on solar photovoltaic, combined heat and power, and sometimes small size wind power generation (Bracco et al., 2018). Among these sources, however, solar PV has shown remarkable synergies when combined with a green roof (Shafique et al., 2020; Chemisana & Lamnatou, 2014). As the surface of PV modules heats up with the incoming solar radiation that it constantly receives, PV modules' efficiency is negatively affected. The presence of a green roof in the proximity of the PV modules, however, dampens this effect through evaporative cooling of the air surrounding the modules' surface (Hui & Chan, 2011). The resulting effect is an increase of electricity generation (Osma-Pinto & Ordóñez-Plata, 2019; Lamnatou & Chemisana, 2015; Hui & Chan, 2011), up to 6% (Kohler & Wiartalla, 2007), but estimates vary in the literature depending on the green roof type and climatic conditions, among other factors (Shafique et al., 2020).

The installation of a green roof has also demonstrated an overall increase in energy efficiency of the building where it is installed (Chemisana & Lamnatou, 2014; Hui & Chan, 2011; Lamnatou & Chemisana, 2015), resulting in a lower energy bill for consumers and a lower energy demand in general. Given that fossil fuels cover more than 70% of the European energy mix (Eurostat, 2020), the lower energy demand also means lower carbon dioxide (CO_2) emissions. Other benefits of green roofs include CO2 absorption (Lamnatou & Chemisana, 2014), and the uptake of air pollutants, improving the street canyons' air quality (Baik et al., 2012).

At the same time, the proximity of PV modules to the vegetation of a green roof, suggested an increase in habitat niches (Nash et al., 2016). Specifically, according to international technical guidelines, the particular class of green roofs suitable for the combination with PV panels, hereafter termed as PV-green roofs, is represented by *extensive green roofs* (FLL, 2018).

As briefly mentioned in the Problem Introduction, literature shows that there is a growing recognition of the mutual benefits of photovoltaic-green roofs (Nash et al., 2016; Shafique et al., 2020). Nevertheless, as Cristiano et al., (2021) noted, most of the times scholars focus on one sector alone when investigating green roof technologies. Accordingly, an overview of monetary and non-monetary costs and benefits of PV-green roofs becomes needed.

Such an integrated review would not only prove beneficial for scholars, but for policymakers as well. In fact, PV-green roofs' benefits are related to four EGD objectives: the provision of clean and affordable energy, the restoration and preservation of ecosystems and biodiversity, the reduction of air and water pollution, and the adaptation to climate change. This is an important consideration given the lack of specific actions in energy policies addressing biodiversity and health issues (European Commission, 2012), and the slow implementation of climate change adaptation solutions (European Commission, 2021).

Therefore, the benefits brought by photovoltaic-green roof energy communities, could be explicitly linked to the wider European Green Deal's objectives. A discussion of the link between this policy solution and the comprehensive European policy objectives, recently promulgated in the Green Deal strategy, is currently missing in the literature. Caramizaru & Uihlein (2020) explicitly note that more research is needed to clarify RECs' potential benefits for supporting EU's climate and energy goals. In this direction, determining how PGEC's benefits address the Green Deal's objectives, would not only contribute to bridging this literature gap, but it would also be helpful to national legislators. As anticipated in the introduction, the current period of transposition of the RED II into national laws, provides a policy window in which governments are still determining national definitions for RECs, as well as the relative incentive schemes (Lowitzsch et al., 2020).

1.2.3 The Economic Convenience of PGECs: A Probabilistic Social Cost-Benefit Analysis

A sensible planning of PGECs requires addressing their economic convenience. On one hand, green roofs are characterized by relatively high installation and maintenance costs, which private building owners may not be willing to bear (Berto et al., 2020; Shin & Kim, 2019). On the other hand, solar PV panels, on the other hand, while still subject to significant installation costs (Reindl & Palm, 2021; Xue et al., 2021), enable the consumption of the electricity generated on one's premises, thus reducing overall costs in the long-term (Manohar et al., 2015).

Multiple studies have addressed the economic feasibility of green roofs through the use of cost-benefit analysis (CBA), considering both financial, and socio-environmental costs and benefits (Teotónio et al., 2018; Mahmoud et al., 2017; Claus & Rousseau, 2012). Nevertheless, an all-inclusive CBA specifically focusing on PV-green roofs, including the costs and reciprocal benefits of both engineering solutions, is still missing in the literature.

Arguing that the limited development of green roofs to date is due to the lack of a full understanding of green roofs' economic value, Teotónio et al., (2018) proposed to distinguish between financial, economic and socio-environmental costs and benefits. The financial level includes installation and maintenance costs, as well as energy efficiency benefits and discounts on fire insurance. The economic level comprises property and aesthetic values increase, while the socio-environmental level adds benefits such as flood risk reduction, air and water pollution reduction, biodiversity preservation and CO_2 emission reduction (Teotónio et al., 2018). Parties affected by socio-environmental costs and benefits are not only the building owners or the PGEC community members, but these extend to a larger area outside of the PGEC boundaries. Indeed, flood risk reduction can benefit the entire urban settlement (Nordman et al., 2018), while CO_2 emission reduction benefits society as a whole (Ahmed Ali et al., 2020). For these reasons a social cost-benefit analysis and thus a social discount rate need to be considered when conducting a comprehensive CBA that includes all financial, economic, and socio-environmental effects.

For PV-green roofs, financial, economic, and socio-environmental costs and benefits are relevant as well. Additionally, the incentive schemes for PGECs also need to be considered. Not only they are legally required by the RED II, but the use of public incentives for PGECs is consistent with mainstream economic theory, given the public nature of many of the benefits brought by PV-green roofs (Harris & Roach, 2018).

1.3 Research Approach and Research Question

Following the state-of-the-art on RECs, PV panels, green roofs, and on the methods to evaluate their economic convenience, this section links the main gaps found in the literature to this study's research objective and approach (section 1.3.1). Next, the research question is made explicit (section 1.3.2), and finally, the match of this study with the M.Sc. in Engineering and Policy Analysis is ultimately addressed (section 1.3.3).

1.3.1 Research approach

From an overview of the state of the art on RECs, three main gaps in the literature were identified:

First, no analysis has hitherto focused on how PGECs' definition would fit within the current EU relevant legislation. Specifically, despite the recognized need of incentive schemes for PV-green roofs' (Shafique et al., 2020) as well as green roofs' implementation (Liberalesso et al., 2020; Burszta-Adamiak & Fiałkiewicz, 2019; Claus & Rousseau, 2012), an analysis of how PGECs would fully benefit from the RECs' support schemes is still missing.

Second, a more integrated assessment of green roof technologies, considering multiple sectors and benefits is needed (Cristiano et al., 2021). Additionally, the link between PGECs' financial, economic, and socio-environmental benefits, on the one hand, and the European Green Deal's objectives on the other, has not been studied yet. Such an evaluation would address the need anticipated by Caramizaru & Uihlein (2020) to further clarify how RECs' benefits could support EU climate and energy goals. It would also attend to the lack for or slow implementation of specific actions addressing biodiversity, health and climate adaptation within the energy policy domain (European Commission, 2012; European Environment Agency, 2019a; European Commission, 2021).

Lastly, while multiple analyses suggested the use of CBA for both green roofs and solar PV panels (Teotónio et al., 2018; Mahmoud et al., 2017; Vaishnav et al., 2017; Claus & Rousseau, 2012), no studies have been found that attempted an economic evaluation of PV-green roofs.

By addressing these identified knowledge gaps, the present research aims at determining the extent to which a specific form of RECs, namely PGECs, can address the European Green Deal's objectives in an economically convenient manner. To do so, two methodological approaches are anticipated in this research. The first approach, qualitative in nature, will locate PGECs within the EU policy framework related to RECs, and determine the link between PGECs' benefits and the European Green Deal's objectives. The second, more quantitative in nature, will address the economic convenience of PGECs, through the application of a Social Cost-Benefit Analysis (SCBA) to a specific case study. For this purpose, the Quartier Alzette in Esch-sur-Alzette (Luxembourg), was identified as a suitable location. Historically hosting a steel mill, the area comprises 850.000 m^2, and is planned to become a new urban district envisaging a significant integration with the environment (AGORA, 2019). This second part of the research relies on a case study approach since no "one size fits all" solution is possible for RECs (Lowitzsch et al., 2020), given the geographic and cultural diversity in the planning and implementation of RECs in Europe.

One limitation of the research approach lies in the determination of PV-green roofs' costs and benefits. In fact, some benefits exhibit uncertainty, either for political reasons (e.g., availability of public incentives), or for technical ones. As an example, Shafique et al., (2020) found that the percentage of PV power output enhancement due to the proximity to a green roof can vary from 0.5% to 6%. Thus, despite their wide use for green roofs, SCBAs might be easily questioned for their chosen input values.

To overcome such a limitation, this study performs a probabilistic SCBA, a methodology acknowledging that input variables can take a range of values as opposed to being fixed to a single one (Nassar & Al-Mohaisen, 2006). The CBA is treated as a model, whereby input parameters are uncertain and deliver a variety of model outcomes (i.e., net present values), rather than being deterministic. With the aid of a simulation approach, the desired values for input parameters, are elicited by selecting only the subset of input values resulting in a desired model outcome (i.e., a positive net present value). Lastly, the desired level of subsidy is determined by simulating a probabilistic private CBA, in which only costs and benefits directly perceived by PV-green roof buyers are included. In this way whether there is a need for a subsidy incentivizing private buyers will be determined, as well as its magnitude.

1.3.2 Research question

The proposed research will thus address the following question:

> *Under what conditions does the combination of photovoltaic panels and green roofs, as part of Renewable Energy Communities, meet the European Green Deal's objectives in an economically convenient manner?*

Such a research question can be further decomposed into the following sub research questions:

1. How would photovoltaic-green roof energy communities (PGECs) fit in the EU definition and regulation of Renewable Energy Communities?
2. What are the financial, economic, and socio-environmental costs and benefits associated with the installation and operation of PV-green roofs, as a part of a PGEC?
3. How would PGECs address the wider objectives of the European Green Deal?
4. What conditions enable photovoltaic-green roof energy communities to be economically convenient?

Sub research question (SRQ) 1 focuses on the definition of RECs adopted by the European Union. This sub research question aims at establishing the system boundaries, with respect to legislation, for the implementation of PGECs.

SRQ 2 aims at eliciting all the financial, economic, and socio-environmental costs and benefits of PV-green roofs. To this end, the components of a PGEC and its technical specifications are determined first. Subsequently, an overview of the cost and benefits are gathered from the literature published to date.

Thanks to the overview of costs and benefits obtained, SRQ 3 considers how PGECs address the EGD strategy objectives.

Lastly, SRQ 4 deals with the case-study. It focuses on the area of Quartier Alzette (Luxembourg) for the implementation of a PGEC and thus it selects from the overview of costs and benefits obtained to answer SRQ2 those that are relevant for this location. Such costs and benefits will be then aggregated by means of a probabilistic SCBA, and Scenario Discovery will allow to find the desired technical parameters' values to deliver an economically convenient solution from a societal point of view. The costs and benefits will also be aggregated by means of a probabilistic private CBA, and the incentive level needed to deliver economically convenient PV-green roofs from the technologies owners' point of view will be determined.

1.3.3 Link between the research and the M.Sc. in Engineering and Policy Analysis

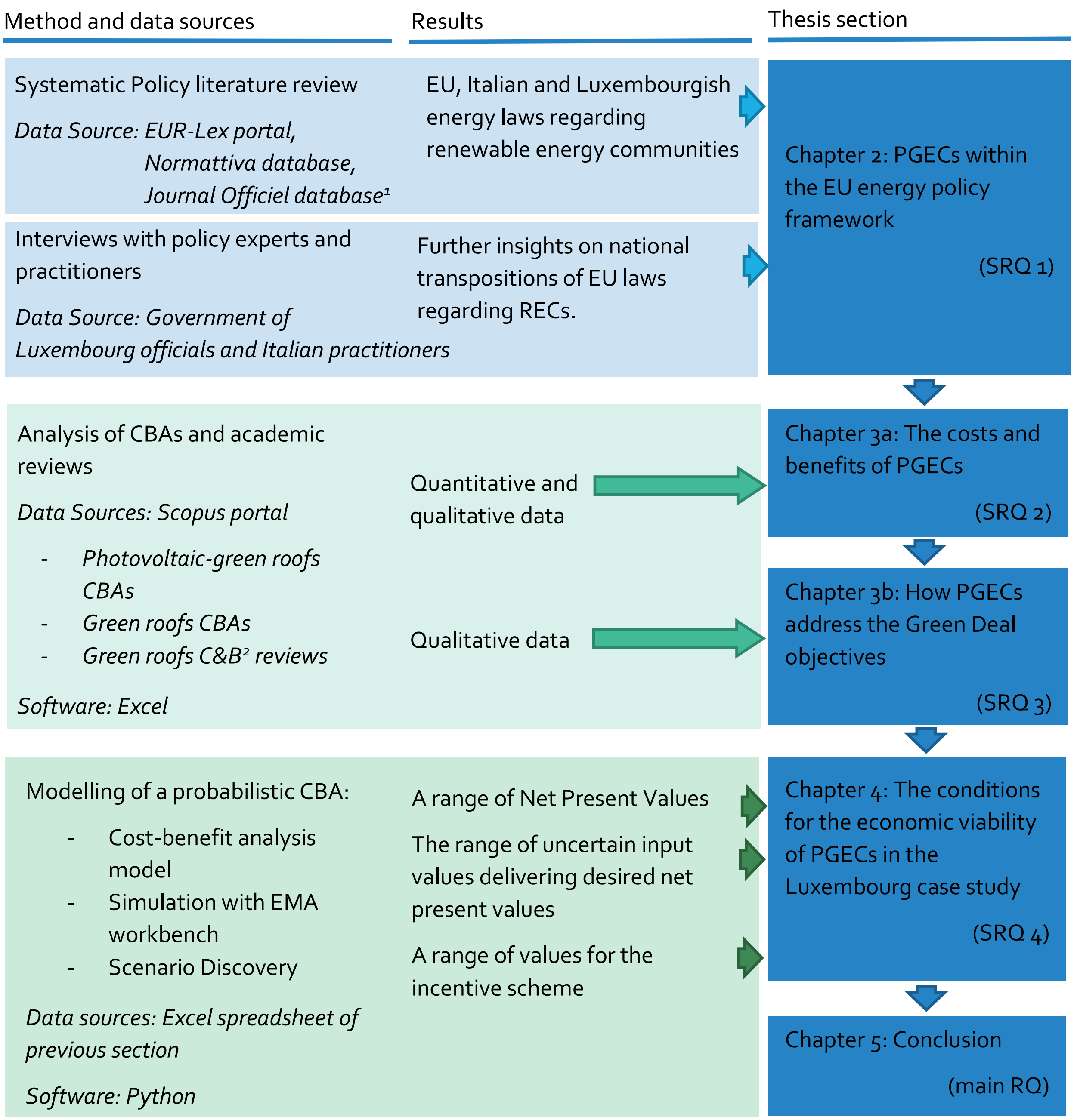
The research is rooted within the "*Grand Challenge*" of the energy transition. Motivated by environmental degradation patterns identified by the European Environment Agency (2019b), it studies how PGECs can contribute to addressing such issues from within the energy sector and policy framework.

Importantly, RECs represent a policy action since their legal existence and support is mandated by EU energy policies. Thus, by focusing on PGECs, this study focuses on a specific form of EU policy action, and evaluates it with a cost-benefit analysis, a notable tool for policy analysis (Harris & Roach, 2018). In addition, given that RECs still need to be defined in various EU Member States, the results of this study are expected to be highly relevant in the short term to national policymakers.

PGECs, their costs and benefits, the relative incentive schemes and the overall economic convenience are examined here with a systems and multi-actor perspective. All of such PGEC's elements are analyzed within the CBA's system boundaries, and a part of the CBA is devoted to how various actors reap the PGEC's benefits or bear its costs. Additionally, simulation of the CBA through the Exploratory Modelling and Analysis (EMA) workbench and Scenario Discovery will confer a further analytical and quantitative character to the work.

1.4 Research Methods

This last section presents the methods used to address each of the sub research questions of this study. To better visualize how the use of methods enables addressing the SRQs a *research flow diagram* is provided in Figure 1.1.



(1) Additionally, national legislations for Luxembourg and Italy will be complemented by national and EU reports;
(2) C&B: costs and benefits.

Figure 1.1. Research flow diagram.

In order to address SRQ 1, the relevant EU Directives for RECs were reviewed. These were found through a systematic review of policy documents, using the EUR-Lex official gateway of EU Law. This portal provides comprehensive access to all EU legal documents and it is updated on a daily basis (Publications Office of the European Union, 2021). By such policy literature review, the definition of RECs adopted by the European Union was determined and the system boundaries, with respect to legislation, for the implementation of PGECs were delineated.

As transpositions of EU directives may further specify the original provisions in the EU law, the current legislations of two EU Member States, Italy and Luxembourg, were also systematically reviewed. In this case, after the fit of PGECs within the EU legislative framework was clarified, the national transpositions of those EU laws that are relevant to PGECs were reviewed. To do this the *Normattiva* official database for the Italian legislation and the *Journal officiel du Grand-Duché de Luxembourg* for the Luxembourgish legislation were used. The choice of the Italian case relies on the fact that Italy has been one of the first EU Member States responding to the RED II with ad hoc national legislation. Additionally, according to a recent analysis, it was found to be the country making the most progress in transposing and implementing the EU legislation (Hinsch et al., 2021). The legislation of Luxembourg is reviewed for two reasons. First, the applied case study is based in such a country, which necessarily requires a review of the national legislative framework. Moreover, Luxembourg is currently defining its decarbonization strategy, meaning that policy implications stemming from the study of PGECs can be particularly valuable to national policymakers.

To gain further insight into the national transpositions of EU law, interviews with five Luxembourgish government officials and one Italian industry expert on RECs implementation were carried out. These interviews aimed at explaining potential contrasts with EU laws and eliciting insights from policy and industry experts regarding potential barriers to be faced by PGECs at a national level.

SRQ 2 requires the knowledge of PGECs' components, which will be identified and presented considering both the institutional and physical layer of PGECs. Next, to address the SRQ, costs and benefits of PV-green roofs will be identified. While these are both monetary and non-monetary, to evaluate the economic feasibility of PGECs in the last SRQ, a monetary quantification is required. For this reason, a systematic review of cost-benefit analyses of green roofs and PV panels available on the Scopus portal was carried out. Due to the little investigation of PV-green roofs to date, the review analyzed CBAs of green roofs first, which in some cases also include PV panels as an additional component. Benefits related to the coupling with PV panels were then complemented with the most recent review article on the physical benefits of green roofs and PV panels (Manso et al., 2021). For consistency with the previous data, these benefits were monetized as well.

From the selected articles, all the financial, economic, and socio-environmental costs and benefits described were recorded in an Excel spreadsheet. These items were recorded as a monetary value, and, when available, also as a physical value.

The overview obtained through SRQ 2 serves addressing both SRQ 3 and SRQ 4. Indeed, SRQ 3 concentrates on how the benefits brought by PGECs meet the European Green Deal's objectives, and it draws on the state-of-the-art scientific knowledge regarding PGECs' technical components.

The monetary data elicited from the literature were used to answer SRQ 4. In this case, only the costs and benefits relevant for Luxembourg's socio-environmental characteristics were considered, so to enable value transferability of costs and benefits to the analyzed case-study. To answer the SRQ, monetary values were aggregated by means of a probabilistic CBA relative the case study at hand. The CBA consists of one main equation expressing the net present value (NPV) of the PV-green roofs as a function of their monetized cost and benefit variables and of the discount rate.

Whenever provided by the articles, the monetized costs and benefits were directly used as input variables to the CBA, and if absent, a monetary value was estimated by applying existing equations from the literature. As a result, the main NPV equation was complemented with additional ones explicitly defining the (ranges of) cost and benefit variables. The resulting set of equations forms the probabilistic CBA model.

Costs and benefits provided by the literature in the form of ranges were used as uncertain input variables (i.e., *uncertainties*). The probabilistic CBA will essentially be treated as a model and simulated under different *experiments*, namely for different combinations of uncertainty and lever values. Such combinations will be sampled from the devised uncertainty and lever space with the help of the EMA workbench (Kwakkel et al., 2013). Lastly, Scenario Discovery (Lempert et al., 2003; Friedman & Fisher, 1999) will be applied. Namely, among all the model runs, only the ones resulting in a desired outcome (i.e., a positive NPV) will be selected, automatically identifying the corresponding region in the uncertainty and lever space delivering such desired outcomes. This will determine the conditions, namely the ranges of values for the uncertainties and the lever, which most likely result in an economically convenient PV-green roof, thereby addressing SRQ 4 and the main research question.

2

Photovoltaic-Green roof Energy Communities within the European Energy Policy Framework

Chapter 1 introduced the legal entity of PGECs, it has outlined the current research gaps on PGECs and the approach proposed to address them. This chapter establishes the system boundaries, with respect to legislation, for the implementation of PGECs in the European Union. First, it delineates the characteristics of European energy policy (section 2.1), and second it focuses on current policies relevant to PGECs (section 2.2).

2.1 European Energy Policy

2.1.1 Energy Policy

Energy policy can be related to any organization, both public and private (Islam & Hasanuzzaman, 2020; Warf, 2010). This thesis focuses however on energy policy related to government *measures* (Bregha, 2006), *interventions* (Prontera, 2009), or *commitments* (McGowan, 1996), concerned with the production, transportation, consumption and -more in general- use of energy. Considering that binding legislation is one of the instruments through which governments can reach their policy goals, energy policy can also be referred to as actual *rules* concerned with the energy sector (Tosun, 2017).

2.1.2 Three Main Phases of European Energy Policy

Energy policy in the European union[1] has taken different forms depending on the historical phase of the EU itself. Originally energy issues were dealt with provisions of the Community treaty law. Later, as the EU policymaking bodies acquired more legislative power in the sector, European energy policy also took the form of directives and regulations either published separately or in subsequent energy packages.

Three main phases of European energy policy can be distinguished. The first stretches from the 1950s until the late 1980s, the second from the late 1980s until the mid-2000s, and lastly, the third takes place from the mid-2000s onwards (Biesenbender, 2015). A brief reflection on each one of them shows the long-term motives of EU energy policy, and it enables an understanding of the current implementation practices.

2.1.2.1 First phase: from the 1950s until the late 1980s

The first phase starts with the foundation of the European Coal and Steel Community (ECSC) in 1951, soon after the end of the second world war. This foundation, together with that of the European Atomic Energy Community (EURATOM) in 1957 show that energy issues had an important role already in the first steps of the European integration process. Similarly, more technical initiatives such as the foundation of the Union for the Coordination of Production and Transmission of Electricity in 1951 mirrored the energy cooperation efforts of the political treaties.

In this first phase, the focus was the enhancement and control of coal supply and the improvement of nuclear supply (Eikeland, 2004). Security of supply remained at the top of the EU energy agenda in the following years, as well. In fact, the closure of the Suez Canal in 1967, the two oil crises in the 1970s, and the publication of the report *Limits To Growth* in 1972 fueled the perception that security of supply was endangered. These events, when considered together with earlier world war II's motives for reconstruction show an energy policy primarily reacting to, or driven by, events (cf. Buchan, 2017) .

2.1.2.2 Second phase: from the late 1980s until the mid-2000s

The second phase began with the Single European Act (SEA) of 1987 (late 1980s – mid 2000s), whereby the free movement of persons, goods, (physical and financial) capital, and services, enabled EU policymakers to frame energy issues as a liberalization and competition issue (SEA 1987; Herweg, 2015). Already in 1988, the European Commission issued a working paper arguing that the legal instruments attaining a European internal energy market were no different than those allowing the realization of Europe without frontiers (CEC, 1988). The barriers to trade in the energy sector were well-known, as Member States had predominantly favored state-owned monopolistic energy companies to secure domestic energy supply (see, for instance, Correljé et al., 2003; Foreman-Peck & Millward, 1994). Nevertheless from this period onwards, the European Commission framed energy as a good, thus, entitled to free trade within the EU (CEC, 1985; Herweg, 2015).

During this second phase, EU energy policy still relied on treaty law, such as the SEA, but started to significantly take the form of directives and regulations. In fact, EU Member States vetoed the inclusion of an energy chapter in the Treaty of Maastricht in 1992, as they primarily wanted to secure their autonomy in energy policy and protect the state-owned structure of the sector (Dutton, 2015). The European Commission's framing of energy policy as market-oriented proposals liberalizing the sector was thus advanced through a different avenue: that of directives and regulations.

Two main events helped the European Commission in gathering enough support in the European Parliament to approve energy laws. First, the end of the two oil crises brought about a period of

---

[1] In this chapter the term European Union will be used to refer to the community of European nation-states which was first represented by the European Coal and Steel Community, then by the European Economic Community, and later by the European Union. Similarly, the term European Commission will also be used for its earlier equivalent: The Commission of European Communities.

stabilization of supply-demand balances in the global energy market, as well as a decrease in oil prices (Ciambra & Solorio, 2015), which favored the discussion about a common European energy policy and market. Second, a so-called "liberal wave", associated to the ideas promoted by the governments of the late Ronald Reagan and Margaret Thatcher (de Vries et al., 2019) affected the global economy (Padgett, 2003). Accordingly, economic reform based on public choice and monetarist theories was sought by bringing market-driven competition into formerly state-dominated industries in a number of Anglo Saxon countries (de Vries et al., 2019). In Europe this meant that the United Kingdom underwent a radical change in its energy sector, mostly characterized by the privatization of oil, gas, coal and nuclear power industries (Matláry, 1997), which brought this country to favor the EU Commission's proposals. The United Kingdom acted both as promoter-by-example and as a source of practical recommendations on how to realize a single European market (J. Johnson, 2012).

As a result, a first package of directives was passed by the European Parliament in 1996-1998, consisting of the Electricity Directive 96/92/EC and the Gas Directive 98/30/EC. This was followed by a second larger package consisting of two new directives and a regulation: the Electricity Directive 2003/54/EC, the Electricity Regulation EC No. 1228/2003, and the Gas Directive 2003/55/EC, which were passed by the European Parliament in 2003 and repealed the previous ones. Despite fierce opposition by continental EU Member States, these packages of directives and regulations initiated the liberalization of the electricity and gas markets in the EU (Dutton, 2015; Tosun et al., 2015).

2.1.2.3 Third phase: from mid-2000s onwards

The Treaty of Lisbon in 2007 marked the beginning of the third phase of EU energy policy. This treaty provided a more specific frame for policy activities and a broad mandate within which EU policymakers could enact comprehensive sectoral regulation (Biesenbender, 2015). In this period, the progressively increasing attention to environmental issues already noticeable in the previous phase of energy policy, became central (Ciambra & Solorio, 2015). The Environmental Policy Integration principle was included into treaty law already in the SEA of 1987 (Art. 130r), and the Emission Trading Directive 2003/87/EC was adopted covering 45% of total EU emissions. Nevertheless, with the Treaty of Lisbon, the promotion of energy efficiency and saving, and the development of renewable energy became explicit policy goals for the energy sector (Art. 176 A). These two goals were now placed at the same level as the ones of market liberalization and integration, and security of supply.

Additionally, primarily due to the efforts of the UK's EU presidency in 2005 (Solorio & Morata, 2012), the development of the internal energy market started to include measures against climate change (Pollak & Slominski, 2011). In fact, the Treaty of Lisbon already incorporates them (Art 174).

During the third phase, European energy policy did not take the form of treaty law only, but it also consisted of two new energy packages. These are the third energy package issued in 2009, and the Clean Energy for All Europeans Package issued in 2018-2019.

The former, under the name of "climate and energy package" consisted of three regulations and two directives: the ACER Regulation No. 713/2009, the Electricity Regulation No. 714/2009, the Gas Regulation No. 715/2009, the Electricity Directive 2009/72/EC, and Gas Directive 2009/73/EC, which repealed the previous ones. This package further advanced the competition and privatization in the energy sector (cf. Eikeland, 2011; Pollak & Slominski, 2011). It also set three environmental targets to be met by 2020: the 20% reduction in greenhouse gas emissions (compared to 1990 levels), 20% of EU energy to be produced from renewables and 20% improvement in energy efficiency.

Finally, the latter package is the largest and is composed by four directives and four regulations: the Energy Performance in Buildings Directive 2018/844; the Renewable Energy Directive 2018/2001; the Energy Efficiency Directive 2018/2002; the Governance of the Energy Union Directive 2018/1999; the Electricity Regulation 2019/943; the Electricity Directive 2019/944; the Risk Preparedness Regulation

2019/941; the ACER Regulation 2019/942.They amend the previous Electricity Regulation and ACER Regulation while the previous Electricity Directive remained in force until the end of 2020. The third package's legal acts concerning natural gas, instead, still remain applicable. This last energy package further emphasized the transition from fossil fuels towards renewable energy sources and the delivery of the EU's Paris Agreement commitments to reduce greenhouse gas emissions (European Commission & DG Energy, 2019). It also further limited public intervention in the electricity market (Nouicer & Meeus, 2019).

2.2 Photovoltaic-Green roof Energy Communities within the European energy policy

This section focuses on the current European policies concerned with PGECs. Due to the supranational nature of the EU, such policies are both legal acts enacted by EU institutions and national transpositions in each EU Member State. The methods used to identify all relevant legal acts regarding RECs are described in section 2.2.1, while the results are presented in section 2.2.2.

2.2.1 Methods: a Systematic Policy Literature Review

To identify all the binding legal acts concerned with renewable energy communities a two-phase systematic policy literature review was carried out. In the first phase EU-level legislation concerned with RECs was reviewed using the EUR-Lex official gateway of EU law. This portal provides access to all European legal documents and it is updated daily (Publications Office of the European Union, 2021), providing a way to identify the most recent legal documents without overlooking parts of the EU legislation. In the second phase two national legislations defining renewable energy communities were reviewed: that of Italy and that of Luxembourg. As mentioned in section 1.4, the Italian case was reviewed since Italy provided one of the earliest national transpositions of EU law, and since recent analyses showed that such legislation has possibly made the greatest progress in the transposition of EU law (Hinsch et al., 2021). The Luxembourgish case was reviewed to inform the quantitative case-study of this research. An overview of the systematic policy literature review is presented in Figure 2.1.

The first phase of the review consists of four steps. First, all binding legal acts ("LEGISLATION") and consolidated texts ("CONSLEG") containing the phrase "energy community" or variations of it (e.g., singular and plural) in their title ("TI") or text ("TE"), were identified. However, documents only referring to the European atomic energy community or the Energy Community Contracting Parties were excluded, because of their non-relevance for decentralized renewable energy generation. Second, from all the legal acts found, only binding legal acts and consolidated texts were kept. These are regulations, directives, decisions, and the relative consolidated texts, issued by any competent EU body. Third, legal documents no longer in force were excluded, providing a total of 49 binding legal acts currently in force. In the fourth step the content of the documents was screened searching for the keyword *"energy communit*"* and verifying its relevance to the context of distributed renewable energy generation.

The last step provided four binding legal acts currently in force and relevant to renewable energy communities:

- The Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast);
- The Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action;
- The Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU;

- The Regulation (EU) 2019/942 of the European Parliament and of the Council of 5 June 2019 establishing a European Union Agency for the Cooperation of Energy Regulators.

Each of the four documents was 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 attributes specified by the laws. Next, a comparison of all the models identified was carried out to determine which legal model suits best photovoltaic-green roof energy communities.

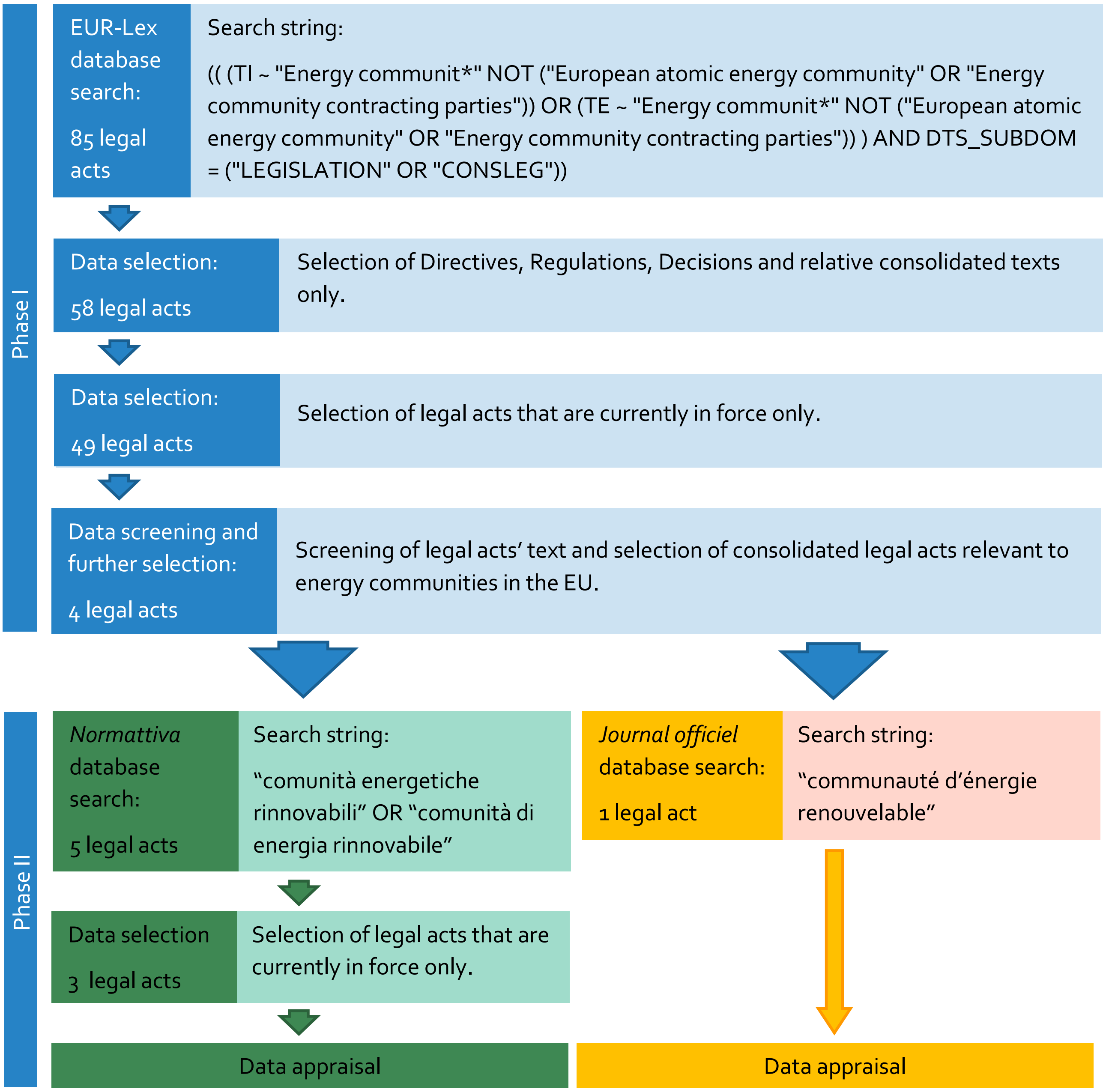


Figure 2.1. Two-phase systematic literature review of legal acts concerning renewable energy communities. The first phase concerns EU-level legislation and is represented in blue, while the second phase concerns the Italian and Luxembourgish legislations.

In the second phase of the review, the official databases of Italian and Luxembourgish laws were surveyed: the *Normattiva Database* and the *Journal officiel du Grand-Duché de Luxembourg*, respectively. The Normattiva Database was searched with the keyword "comunità energetiche rinnovabili" (i.e., renewable energy communities), resulting in 5 legal acts: of which only 3 are currently in force. Then, the *Journal* *officiel* was searched with the keyword "communauté d'énergie renouvelable", resulting in only one law still to be approved (Figure 2.1).

Finally, to gain further insight into the national transpositions of EU law, interviews with five Luxembourgish government officials and one Italian industry expert on the implementation of RECs were carried out. Such interviews aimed at explaining potential contrasts with EU laws and eliciting the opinion of policy and industry experts on potential barriers to be faced by PGECs. The complete list of questions and transcripts of the interviews carried out are available in Appendix A.

2.2.2 Results

2.2.2.1 European Union-level legislation

The review of the four EU legal acts found from the first phase of the review shows the existence of four different decentralized generation models: Renewable Energy Communities, Renewable Self-Consumers, Jointly Acting Renewable Self-Consumers, and Citizen Energy Communities. An overview of all decentralized energy generation models as specified in the EU energy policy framework is presented in Table 2.1. The overview compares the models' attributes across all the six dimensions identified: eligibility, conditions on members / shareholders, purpose, governance, activities, conditions on activities, and benefits.

A description of the attributes of each model devised in the EU legislation and a clarification of the terms used is provided in the following sub-sections.

Table 2.1. Overview of energy community initiatives specified in EU policies. Defining attributes are displayed in blue, non-defining but characteristic attributes in grey.

	Renewable energy community (REC)	***Citizen energy community (CEC)***	***Renewable self-consumer (RSC)***	***Jointly acting renewable self-consumers (JRSC)***
Eligibility	Natural persons, SMEs, or local authorities	All categories of entities	Final customer	≥ 2 RSCs
Conditions on members /shareholders (m/s)	• Open and voluntary participation • Be located in projects' proximity • For private undertakings: participation ≠ primary commercial or professional activity	Open and voluntary participation	Operate within RSC'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 m/s in projects' proximity • REC is autonomous • Projects owned and developed by REC	• CEC 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 RSC'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 m/s • Sharing within the CEC • Ownership / establishment / purchase / lease of distribution networks	• Generation, storage, consumption, and sale • Sharing	Joint RSC actions
Conditions on activities	-	-	For non-household RSCs: activities ≠ RSCs' 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	

Renewable energy communities

Directive 2018/2001 recast (henceforth referred to as RED II) **defines** in art. 2(16) *Renewable Energy Communities* as *a legal entity:*

- *(a) which, in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity;*
- *(b) the shareholders or members of which are natural persons, small and medium-sized enterprises (SMEs) or local authorities, including municipalities;*
- *(c) the primary purpose of which 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*

As described in the Directive, RECs can take a variety of forms depending on the legal entities offered by each Member State's law (e.g., potentially: joint stock company, limited liability company, or cooperative). Of course, the legal entities chosen at the national scale need to be compatible with the REC's defining features set out in the RED II.

The defining features of a REC concern four specific dimensions:

1. **Eligibility**: eligible members or shareholders are natural persons, SMEs, or local authorities;
2. **Conditions on membership**: participation is open and voluntary; members are located in the proximity of renewable energy projects;
3. **Primary 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;
4. **Governance**: a REC is effectively controlled by the shareholders or members located in the proximity of the projects; the REC is autonomous. Namely, the majority of voting rights must be held by members or shareholders based in the proximity of the installations.

Two attributes require further explanation: proximity and autonomy. First, the proximity criterion is not further defined by the RED II, meaning that Member States can further specify by themselves the maximum geographical extension of a REC. Second, an interpretation of the autonomy criterion implies that no single shareholders or member owns a controlling stake, namely, more than a third of the REC's shares (Lowitzsch et al., 2020). Nevertheless, other interpretations by Member States could also be possible (Hannoset et al., 2019).

Additional **characterizing but non-defining attributes** of a REC concern (Art. 18, Art. 22):

1. **Conditions on membership**: for private undertakings the participation must not constitute the primary commercial or professional activity;
2. **Governance**: renewable energy projects are owned and developed by the REC;
3. **Activities**: a REC is entitled to produce, consume and sell renewable energy, as well as share renewable energy that is produced by the production units owned by the REC;
4. **Benefits**:
    a. Member States shall provide an *enabling framework* promoting and facilitating the development of RECs. This means among others, ensuring tools facilitating RECs' access to finance and information, the accessibility by all consumers including low-income or vulnerable households, and providing regulatory and capacity-building support to public authorities in both setting up and participating in RECs.
    b. Additionally, members states shall take into account the specificities of RECs when designing *support schemes* in order to allow them to compete for support on an equal footing with other market participants.

Furthermore, Regulation 2018/1999 on the Governance of the Energy Union and Climate Action (2018) requires each Member State to submit every two years an integrated national energy and climate report to the European Commission (Art. 17). In this report, a summary of policies promoting the development of RECs and self-consumption must be included (Art. 20b 7).

Renewable self-consumers and jointly acting renewable self-consumers

The RED II (2018) also defines two other subjects: *renewable self-consumers* and *jointly acting renewable self-consumers* (Art. 2(14) and Art.21). The former is a final costumer operating within its premises and confined boundaries, generating renewable energy for its own consumption, storing, selling it, and with the possibility to share it with other same subjects. Nevertheless, for a non-household renewable self-consumer, energy generation, storage and sale cannot constitute its primary or professional activity.

The latter are a group of at least two renewable self-consumers located in the same building or multi-apartment block who perform joint generation, storage and/or sale of the renewable energy generated.

According to the REC II, Member States shall ensure certain benefits also for *renewable self-consumers* and *jointly acting renewable self-consumers*. Both subjects are in fact entitled to receive remuneration for electricity fed into the grid, taking into account its long-term value to the grid, the environment and society. Additionally, Member States shall provide an enabling framework promoting and facilitating the development of renewables self-consumption. This includes measures facilitating access to finance, removal of unjustified regulatory barriers to self-consumption, and incentives to building owners to create opportunities for renewables self-consumption.

Similar to the provisions set out for RECs, the Regulation 2018/1999 on the Governance of the Energy Union and Climate Action (2018) requires Member States to provide a summary of policies promoting renewable self-consumption.

Citizen energy communities

Directive 2019/944 (2019) **defines** in art. 2(11) *Citizen Energy Communities* (CECs) as a *legal entity that*:

- *(a) is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises;*
- *(b) has for its primary purpose to provide environmental, economic or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits;*
- *(c) may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services.*

Thus, as for renewable energy communities, CECs can take a variety of forms depending on the legal entities offered by each Member State's law, provided that they are compatible with the CEC definition.

The defining features of a CEC concern four specific dimensions:

1. **Conditions on membership**: participation is open and voluntary;
2. **Primary 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;
3. **Governance**: a CEC is effectively controlled by shareholders or members that are natural persons, local authorities, or small enterprises;
4. **Activities**: a CEC may engage in energy generation, distribution, supply, consumption, aggregation, storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders;

Contrary to the provisions set out concerning RECs, citizen energy communities' activities are not restricted to renewable energies only

Additional **characterizing but non-defining attributes** of a CEC concern:

1. **Eligibility**: all categories of entities (recital 44);
2. **Governance**: the decision-making powers within a CEC must be limited to members or shareholders not engaged in in large-scale commercial activity and for which the energy sector does not constitute a primary area of economic activity (recital 44);
3. **Activities**: a CEC is entitled to share its own electricity produced with other CECs; additionally, it is entitled to own, establish, purchase or lease distribution networks as well as to manage them (Art. 16);
4. **Benefits**: removal of unjustified obstacles and restrictions on the development of CECs (indirectly inferred from Art. 59).

Moreover, the progress made regarding the elimination of regulatory barriers for new market entrants, such as energy communities, must be monitored by the Agency for the Cooperation of Energy Regulators (Art.15) (Regulation (EU) 2019/942 of the European Parliament and of the Council of 5 June 2019 Establishing a European Union Agency for the Cooperation of Energy Regulators, 2019).

2.2.2.2 Proposal of PGECs as Renewable Energy Communities

By comparing the four legal models devised by EU policymakers, Renewable Energy Communities seem to be the most suitable legal model for Photovoltaic-Green Roof Energy Communities for two main reasons. The first reason concerns the primary purpose of RECs, while the second concerns the benefits entailed by the legal model of RECs.

First, the recast of the Renewable Energy Directive (RED II) establishes a **primary purpose** for renewable energy communities that captures the potential community benefits provided by PV green roofs. Not only do green roofs provide a variety of socio-environmental benefits, such as lower energy bills due to higher building efficiency, and higher clean energy generation due to the improved performance of PV modules (section 1.2.2). But these benefits are brought to the community's members or shareholders in the proximity of the roofs. In fact, the increased clean energy generation positively affects all community members while the improved building efficiency concerns all buildings' residents.

Additionally, a considerable array of other socio-environmental benefits concerns an even wider group of citizens: all those in the proximity of the roofs, including but not limited to the community members or shareholders. These are for instance the improved management of stormwater runoff, the urban heat island effect reduction, the increase in habitat niches and reduction of habitat fragmentation, the uptake of gaseous pollutants, as well as the absorption of CO_2.

Next to RECs' primary purpose, also the other defining attributes of these communities do not show any incompatibility with the specification of a REC into a photovoltaic-green roof energy community.

As for the non-defining attributes of RECs, PGECs well suit this legal model for the framing of the **benefits** that RECs are entitled to receive according to the legislation. In fact, 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). Moreover, regulatory and capacity-building support has to be granted to public authorities, e.g., municipalities, in participating and setting up RECs. This can be particularly beneficial for PGECs, since local authorities have demonstrated to address various communities' difficulties, especially when participating as members in energy communities (Meister et al., 2020). Among other forms, support from local authorities includes the provision of additional space for installations, and faster approval and planning procedures (Meister et al., 2020).

Most importantly, the RED II establishes that support schemes for the promotion of renewable energy communities shall take into account specificities of RECs. This means that the combination of photovoltaic panels with green roofs may well represent such a specificity. Simultaneously, such support schemes for PGECs would help reduce upfront financial costs of both green roofs and photovoltaic installations, which currently represent major issues for the adoption of both these technologies (Liberalesso et al., 2020; Vaishnav et al., 2017).

Identifying the suitable EU legal model for PGECs is a first step in determining how these communities fit in the EU legislation. Nevertheless, the legal model of *renewable energy community* as defined by the RED II will have to be transposed by each Member State, and it may be further specified according to its needs. For this reason, a selection of national transpositions of the EU Directive defining RECs was carried out and it is presented in the following section.

2.2.2.3 Italian and Luxembourgish national transpositions

The second phase of the systematic policy literature review focused on the Italian and Luxembourgish transpositions.

As a result of review, the Italian laws concerned with renewable energy communities are:

- *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.*
- *Legge 17 Luglio 2020, n. 77 recante misure urgenti in materia di salute, sostegno al lavoro e all'economia, nonche' di politiche sociali connesse all'emergenza epidemiologica da COVID-19.*
- *Legge 28 Febbraio 2020, n.8 recante disposizioni urgenti in materia di proroga di termini legislativi, di organizzazione delle pubbliche amministrazioni, nonche' di innovazione tecnologica.*

While the Luxembourgish law explicitly concerned with renewable energy communities is the Loi du 3 février 2021 modifiant la loi modifiée du 1er août 2007 relative à l'organisation du marché de l'électricité.

Both the Italian and Luxembourgish laws adopt the exact same **primary purpose** for RECs, as defined by the RED II (art. 42*bis*(3), Legge 28 Febbraio 2020; art. 8*quater*(3), Loi du 3 février 2021).

The REC **activities** specified by the Luxembourgish law is also exactly the same as the one stipulated in the EU law (art. 8*quater*(1)). Nevertheless, aside from electricity sharing, production, and consumption (art. 42*bis*(4)), the Italian legislation does not define other REC activities, probably due to the fact that it is still only a partial transposition for a first "experimentation" phase (RSE, 2020).

As far as the participation to RECs is concerned, **eligibility** and other **conditions on members or shareholders** in each country reflect the RED II provisions only to some extent. As in the RED II, both in Italy and Luxembourg eligible members or shareholders are natural persons, SMEs, or local authorities, whereby the participation is voluntary (art. 42bis(3), Legge 28 Febbraio 2020; art. 1(6) and 8*quater*(2), Loi du 3 février 2021). The Italian law allows participation provided that it does not constitute primary commercial and industrial activity for the participant. Conversely, the Luxembourgish law does not pose any such constrain. According to the Luxembourgish government officials interviewed, however, commercial or professional activities will be further restricted in the future versions of the law, so to match more closely RED II's requirements.

Moreover, the proximity condition was specified in both countries in the same way. Power generation installations and withdrawal points of the community need be connected to the low voltage electricity grid, through the same Medium-Voltage / Low-Voltage transformer substation in Italy, or either High-Voltage / Low-Voltage or Medium-Voltage / Low-Voltage one in Luxembourg (art. 42bis(3), Legge 28 Febbraio 2020; art. 1(6), Loi du 3 février 2021).

As for the **governance** of RECs, both legislations entitle the community to own the power generating installations, but they provide for the possibility to authorize a third party (not member of the REC) to develop and execute the electricity sharing model within the community, under the provisions decided by the REC participants in a private contract) (art. 42bis(5), Legge 28 Febbraio 2020; art. 8*quater*(5,6,10), Loi du 3 février 2021). In general, the Luxembourgish law requires members to conclude an agreement with the network operator specifying members, installations, the energy sharing key (art. 8*quater*(9), Loi du 3 février 2021). According to the interviewed officials this agreement gives members the freedom to determine the governance of the community in the way they prefer. In Italy, in contrast, RECs will take the form of predefined legal entities, such as limited liability companies, joint stock companies, or cooperatives, as defined by art.3 of the Decreto Legislativo 175/2016. In both countries, however, no further specification is made regarding the notion of *autonomy* or *effective control* of the REC.

Lastly, **benefits** granted to RECs vary between the two countries. The Italian legislation promotes RECs with two incentives: one of 110€/MWh (MiSE incentive) for 20 years to be summed with one about 8 €/MWh (ARERA incentive) on the electricity shared within the community (art. 42bis(7), Legge 28 Febbraio 2020; art. 3(1) Decreto MiSE 16 Settembre 2020; RSE, 2020). Additionally, the electricity can be sold at the hourly zonal price, which is estimated to be around 50 €/MWh (RSE, 2020). Aside from monetary incentives, an enabling framework facilitating access to all regulatory support schemes is foreseen (Art. 5h, Legge 22 Aprile 2021). The Luxembourgish law on the other hand does not provide for specific benefits for the promotion of RECs to date. According to the 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 & Rossetto, 2020) In this respect, it is worth considering that even during the interview carried out with the Italian industry expert, the need for incentives was highly stressed. Nevertheless, the position maintained by the Government of Luxembourg may be justified by the particularly high gross domestic product of this country. Government officials suggest, in addition, that the removal of any regulatory barrier and facilitation of access to information will be provided for in the future to self-consumers, including RECs. Instead, the Luxembourgish law stipulates the introduction of an electricity tax on electricity consumption to be paid by end users. An exception is granted for electricity that is produced and consumed from installations whose nominal capacity is less than or equal to 100 kW or if the self-consumed electricity is lower than 1000 MWh (Art. 30, Loi du 3 février 2021).

2.3 Discussion

2.3.1 On the Origin and Characteristics of Renewable Energy Communities in the European Legislation

The analysis of the historical development of European energy legislation shows that the legal concept of RECs is not the outcome of a recent directive only. Rather it results from two long-term motives of EU energy policy that intersected in a concrete instrument. On the one hand the motive of liberalization and introduction of privatization in the European energy markets, and on the other hand the motive of environmental protection as well as climate change mitigation and adaptation. In fact, mostly geared towards private entities, RECs aim to provide environmental, economic, or social community benefits.

From a political point of view, RECs may be viewed as a peculiar policy instrument further privatizing the European energy markets. The peculiarity lies in that RECs may not face the same hostility of Member States that characterized previous attempts of the European Commission to bring liberalization and privatization in the sector, noticeable in cases like the treaty of Maastricht. Indeed, the development of RECs occurs parallelly to the privatization of large state-owned firms, and it further privatizes the sector primarily involving citizens, in the guise of various end-users, rather than national governments.

Additionally, RECs may unlock financial capital and geographical locations that national governments could benefit from, in the view of an increased energy demand and ambitious climate targets.

From a strategic standpoint it is interesting to observe that, deliberately or not, the European Commission may have advanced the liberalization of the sector with a "pincer movement". The setting of climate targets in the last energy package requires indeed substantive investments in and space for new renewable energy installations, which not all national governments readily have. Decentralized generation in all its forms (i.e., RECs, CECs, RSCs, JRSCs, and PGECs), may provide national governments with a tool to overcome such public shortcomings. If promoted in Member States, decentralized generation would contribute to the attainment of national climate targets, though further advancing the privatization of the sector and bolstering it with citizens' support.

In essence, PGECs, as part of decentralized renewable energy generation, would not only contribute to environmental targets, but also to the privatization of the sector: decentralized privatization.

2.3.2 Possible Opportunities and Risks for Renewable Energy Communities in Luxembourg

The Luxembourgish Loi du 3 février (2021) contains an assumption by the Government of Luxembourg that no incentive schemes should be needed for RECs within the country. While this stance is not explicitly stated in the law, it is implied by the law's text which does not foresee any monetary incentive for RECs, contrary to RED II provisions, and it is underscored by the interviews carried out, which explicitly confirmed this stance. It is deemed that such assumption may entail important risks. In fact, Luxembourg is experiencing a significantly higher population growth compared to the rest of the EU. An annual population growth above 1.8% has been consistently observed since 2010, compared to a growth rate that never exceeded 0.25% in the EU within the same years (World Bank, 2021b). Since people from both the EU and other countries make up the majority of this population increase (OECD, 2020), a diverse socio-economical fabric may be expected. As a result, there could be areas where multiple households could not join RECs due to affordability issues. If this situation regularly occurred in different areas of the country, the underlying environmental and social objectives of RECs could be hampered. The often-cited citizen participation, joint action as well as social cohesion (e.g., Caramizaru & Uihlein, 2020) may not necessarily be obtained. Similarly, the spread of renewable energy technologies may also be curbed.

An interesting opportunity within the Luxembourgish Loi du 3 février (2021) is foreseen with regard to its interpretation of the proximity criterion in art. 1(6), which allowed power generation installations and withdrawal points of the community to be connected to either the same High-Voltage / Low-Voltage or Medium-Voltage / Low-Voltage transformers. This interpretation of the proximity criterion would allow RECs to easily extend out of cities and include inhabitants of rural areas, or industrial parks as well. In these cases, larger power generation installations could be included in RECs, and the larger roofs of industrial parks or warehouses could be used for both PV modules and larger green roofs. In rural areas, it is also possible that the PV-green roofs combination could give way to other technology combinations more suited to this environment, such as *agrivoltaics*, whereby PV modules are incorporated into agricultural fields (Dinesh & Pearce, 2016).

2.4 Conclusion

The aim of this chapter was to address the first sub-research question:

How would photovoltaic-green roof energy communities fit in the EU definition and regulation of Renewable Energy Communities?

The systematic review conducted showed that four decentralized generation models exist within the EU-level legislation. These are Renewable Energy Communities, Renewable Self-Consumers, Jointly Acting Renewable Self-Consumers, and Citizen Energy Communities.

RECs appear the most suitable legal model for Photovoltaic-Green Roof Energy Communities for a number or reasons. First, the primary purpose of RECs captures the potential socio-environmental community benefits provided by PV-green roofs. Not only PGECs' benefits would be brought to members but some benefits (e.g., improvement in stormwater runoff management, urban heat island effect reduction) would also be reaped by the local area where communities operate. Second, the support schemes that RECs are entitled to receive, including financial incentives, would help reduce PGECs' upfront costs. In particular, the combination of photovoltaic panels and green roofs may be recognized as a "specificity" that support schemes shall take into account. Additionally, facilitated access to training and information, as well as support from local authorities would boost PGECs' development.

RECs must be "effectively controlled" by members or shareholders in the proximity of the collectively owned power-generating installations, and the community needs to be "autonomous". To this end both the Italian and the Luxembourgish laws specified the proximity of members as their connection to the same medium (or high) to low voltage grid transformer. Nevertheless, the notions of effective control and autonomy were not further specified. As Lowitzsch et al. (2020) interpreted them, the former could be seen as the ownership of the majority of the shares, while the latter that no single shareholder more than a third of the shares, namely a controlling stake. Thus, in practice, while in Italy RECs will rely on predefined legal entities, such as *joint stock companies* or *cooperatives*, RECs in Luxembourg will be bound to a general agreement they will conclude with the network operator.

Importantly, while RECs are entitled to an enabling framework facilitating access to finance, information, and support by public authorities, as well as training, such a framework has been transposed only partially. Italian laws provide for a facilitation to regulatory support schemes, while Luxembourgish laws do not mention the framework. Conversely, a monetary support scheme was developed by the Italian legislation based on the electricity shared within the community, and the one sold to the grid operator. In Luxembourg, however, only the exemption to a future electricity tax has been specified for energy produced and consumed on one's premises. While Luxembourg features an overall lack of monetary support measures to RECs, interviews with government officials suggest that upfront financial costs should not be a limitation to RECs' development in the country; instead, a future enabling framework, focusing on access to information, and removal of regulatory barriers will be provided for in the future.

3

Photovoltaic-Green roof Energy Communities for the European Green Deal

Chapter 2 determined the most suitable legal model for the implementation of PGECs across the European Union. The characteristics of such an EU-wide legal model were also further specified in the Luxembourgish and Italian policy framework. This chapter elicits costs and benefits of PGECs and shows how PGECs address the policy objectives of the European Green Deal. First, the components of a PGEC are clarified in section 3.1. Next, in section 3.2, costs and benefits of PV-green roofs are elicited from the state-of-the-art literature at a world level and connected to the European Green Deal's objectives, highlighting how PGECs address a wide variety of such goals.

3.1 Components of a Photovoltaic-Green Roof Energy Community

In analogy to the decomposition of electricity and gas markets by de Vries et al., (2019), photovoltaic-green roof energy communities can be viewed as consisting of two layers: an institutional and a physical layer.

3.1.1 The Institutional Layer

The Institutional layer includes the actors, namely the members or shareholders of the PGEC, as well as the institutions, namely formal or informal rules that structure such actors' social interaction among themselves and with external actors (Hodgson, 2006).

In general formal institutions can always be formulated with five components delineating an *institutional statement* (Crawford & Ostrom, 1995):

1. *Attributes* (A): the properties identifying the group of actors to which the institution applies. In the case of PGECs these are the types of relations with or belonging to the community, and they identify the members or shareholders of the community, as well as other energy market parties.

2. *Deontic* (D): the right, obligation, or prohibition that applies to the actors under consideration. These are expressed by the three modal verbs "may", "must", or "must not", respectively.
3. *Aim* (I): the action being allowed, prohibited, or to be obligatorily performed.
4. *Condition* (C): the conditions identifying all the situations in which the institution applies.
5. *Or else* (O): the sanctions to be imposed by a competent authority on actors not complying with the institution.

3.1.1.1 Formal institutions

At an EU-wide level, the formal institution defining the PGEC can be formulated with the following institutional statement:

> *Natural persons, small and medium-sized enterprises, or local authorities (A) must (D)*
>
> - *provide environmental, economic or social community benefits for the PGEC's shareholders or members or for the local areas where the PGEC operates, rather than financial profits,*
> - *participate voluntarily and allow open and voluntary participation to the PGEC,*
> - *be situated locally with respect to the PGEC,*
> - *ensure that the REC is effectively controlled by shareholders or members located in the proximity of projects,*
> - *ensure that the PGEC is autonomous from individual members and other market actors cooperating through other means with the PGEC (I),*
>
> *if they want to form a PGEC (C), or else the National Energy Regulator shall not grant the legal status of renewable energy community to the PGEC they wish to form (O).*

The statement is grounded in the Directive 2018/2001 recast legally defining Renewable Energy Communities' attributes (section 2.2.2.1) and outlining the position of PGEC members or shareholders vis-à-vis other energy market actors in the EU.

Additionally:

> *Private undertakings (A) must not (D) participate in a PGEC being it their primary commercial or professional activity (D) if they want to be members or shareholders of PGEC (C), or else the National Energy Regulator will open a law infringement procedure against them (O).*

Considering that PGECs adopt the legal model of renewable energy communities, the following institutional statement formulates the rights of PGECs at an EU-level:

> *EU Member States (A) must (D)*
>
> - *ensure the availability of tools to facilitate access to finance and information to develop PGECs, as it is the case for any other renewable energy community,*
> - *ensure PGECs accessibility to all eligible actors, including low-income or vulnerable households,*
> - *ensure public authorities are provided with regulatory and capacity-building support to both set up and participate in PGECs, as well as any other REC,*
> - *take into account the specificities of the PGECs, when designing support schemes for renewable energy communities, in order to allow them to compete for support on an equal footing with other energy market participants (I)*
>
> *or else the European Commission may initiate an infringement proceeding against the country and bring it before the Court of Justice of the EU (O).*

This institutional statement is grounded in art.22 of the Directive 2018/2001 recast and art. 288, 258, and 260 of the Treaty on the Functioning of the European Union (2016).

In the Luxembourgish case, the formal institution defining the PGEC consists of the statute listing the members, photovoltaic installations, and the energy sharing key in force within the community (art. 8*quater*(9), Loi du 3 février 2021). Formally this can be formulated as:

> Eligible members of a PGEC (A) must (D) list their names and addresses, the co-owned photovoltaic installations, and the electricity sharing key applied to the electricity shared within the community, in a contract with the transmission system operator to be updated every time the members, the installations, or the electricity sharing key change (I), if they want to form a PGEC (C) or else the transmission system operator will not apply renewable energy community market conditions to the PGEC they wish to form (O).

3.1.1.2 Informal institutions

Contrary to formal institutions, informal ones do not require any authority enforcing a penalty in case of violation of the institution (Crawford & Ostrom, 1995). Accordingly, these institutions are only composed by attribute, deontic, aim, and condition (i.e., social norms) or by attribute, aim, and condition (i.e., common routines). Informal institutions are shaped by practice (Lane, 2001) implying that many of these institutions are yet to emerge with the spread of PGECs.

Based on the interviews carried out with the Luxembourgish national ministry, expected informal institutions are:

> *Municipalities in Luxembourg (A) may (D) provide PGECs with municipality buildings for installing PV-green roofs (I), if they want to form a PGEC (C).*
>
> *Members or shareholders of PGECs in Luxembourg (A) are not stopped by upfront financial costs of photovoltaic panels (I) if they want to form a PGEC (C).*

Importantly, the last informal institution provided is only applicable to the case of Luxembourg and may be due to the high Gross Domestic Product of this country. In fact, the upfront costs being a curbing element for PV and green roofs adoption is widely recognized in the literature (Berto et al., 2020; Clark et al., 2008; Feng & Hewage, 2018; Shin & Kim, 2019).

3.1.2 The Physical Layer

The physical layer of a PGEC is represented by PV-green roofs. These represent the "renewable energy projects" mentioned in the recast of the Renewable Energy Directive (2018), which are owned by the PGEC legal entity. Such roofs can be installed on all the available and suitable roof surfaces of the community, at the discretion of the PGEC members or shareholders.

Figure 3.1. Exemplars of photovoltaic-green roofs (Shafique et al., 2020; Velazquez, 2019).

A PV-green roof consists of a green (i.e., vegetated) roof on which arrays of photovoltaic panels are installed (Figure 3.1). A green roof can be defined as a rooftop covered with a growing medium intentionally vegetated and/or spontaneously colonized (Swiss Association of Engineers and Architects, 2013). Photovoltaic panels (or solar photovoltaic panels) are solid-state semiconductors converting sunlight (i.e., electromagnetic radiation) into electrical energy (Sarbu & Sebarchievici, 2017). PV panels are grouped together in PV arrays, while each panel consists of PV cells. The energy conversion occurs in each PV cell, which harnesses the sunlight's photons and releases electrons through the photoelectric effect. Freed electrons, thus, generate a current which is then used as electrical energy (Sarbu & Sebarchievici, 2017). It is important distinguishing solar PV panels from solar thermal panels, which are not part of PV-green roofs. Solar thermal panels, sometimes called solar panels, are collectors converting sunlight into thermal energy (i.e., heat). In this case the energy conversion takes place in a heat transfer fluid which is directly heated by the sunlight's electromagnetic waves. The heated fluid is then used for heating purposes (Bhatia, 2014).

While multiple categories of green roofs exist, only some are suitable for the integration with arrays of photovoltaic panels.

3.1.2.1 Suitable categories of green roofs

Based on the plants used and the depth of the growing medium, green roofs can be classified into intensive, semi-intensive (or simple intensive), and extensive (Catalano et al., 2018; FLL, 2018):

- **Intensive green roofs** are characterized by a 15-200 cm thick growing medium, on which trees, shrubs, tall and short herbaceous plants, liverworts, hornworts and mosses can grow. This is the category of green roofs hosting the widest variety of plant species, which coud make them comparable to ground-based parks and gardens with respect to the recreational function. Nevertheless, intensive green roofs require intensive maintenance (i.e., pruning, weeding, and regular water and nutrient supply) and a building structure able to support high loads. According to Manso et al., (2021) this category represents the most expensive one, with an average installation cost of 362 €/m^2.
- **Semi-intensive green roofs** are characterized by a 12-100 cm thick growing medium, on which shrubs, tall and short herbaceous plants, liverworts, hornworts and mosses can grow. The plant variety is limited, and so are the maintenance needs. As a result the average installation cost amounts to 130 €/m^2 (Manso et al., 2021).
- **Extensive green roofs** are characterized by a 6-20 cm thick growing medium hosting herbaceous plants, liverworts, hornworts, and mosses. In many cases herbaceous plants in extensive green roofs are formed mainly by succulents such as Sedum (spp.) because they are largely self-sustaining and subject to reshuffle, leading to the lower maintenance needs. According to the literature, the average installation cost for extensive roofs is 99 €/m^2 (Manso et al., 2021).

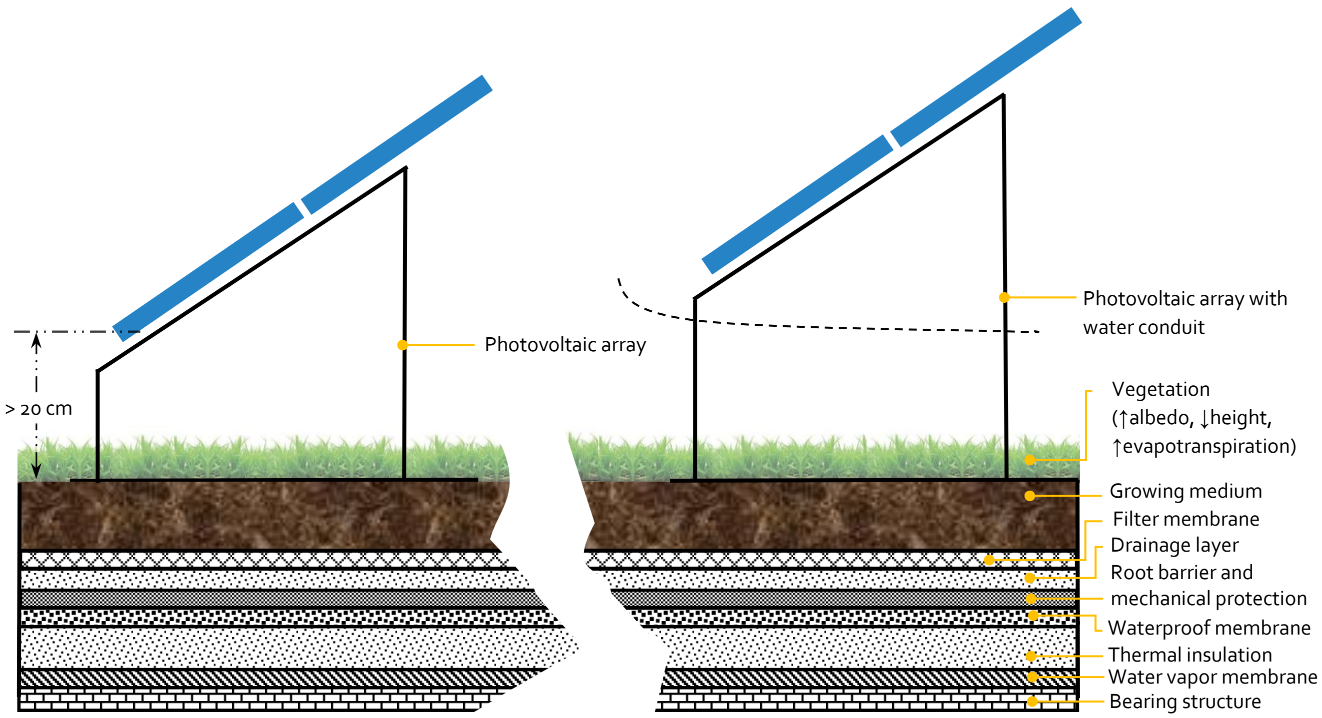


Figure 3.2. Section of photovoltaic-green roof whereby an extensive green roof is combined with arrays of photovoltaic panels. Two examples of alternative PV arrays are provided: (a) without and (b) with the water conduit redirecting rainwater to the vegetation shaded by modules. In both cases desirable roof slopes range between 2% and 8.8% without requiring adaptations in roof layers. Shaded lines represent surfaces pitted with holes.

To ensure optimal power generation PV modules should not be shaded by the vegetation, suggesting that only low-growing extensive greening should be used for PV-green roofs. Specifically, according to the Landscape Development and Landscaping Research Society (2018), a minimum distance of 20 cm should be kept between the growing medium and the lower edge of the modules. As a result, extensive and semi-intensive green roofs using low-growing plant species represent the only categories suitable for PV-green roofs. An illustration of a PV-green roof based on extensive greening is provided in Figure 3.2.

As Cook and Larsen (2021) noted, numerous co-benefits are attributed to green roofs, however green roofs are rarely designed to achieve such co-benefits. For this reason, once the suitable green roof categories are identified, it is important to identify the vegetation and structural design characteristics that enable PV-green roofs to achieve optimal co-benefits.

3.1.2.2 Vegetation and roof layers

In order to obtain a high PV panel's output increase, not only does the vegetation need to remain low, but it also needs to have a high albedo and provide significant evapotranspiration (Cook & Larsen, 2021; Lamnatou & Chemisana, 2015). Albedo consists of the fraction of incoming solar radiation that is reflected by the vegetation layer, while evapotranspiration is the rate of water evaporating from soil and transpiring from plants. A high albedo enables PV cells to receive a higher amount of solar energy to convert into electricity (holding PV efficiency unchanged), while evapotranspiration reduces the air temperature in the surroundings of the PV cells, enabling a higher efficiency of PV panels. To achieve high albedo vegetation should be large leafed (i.e., high Leaf Area Index) and silvery (i.e., light colored) (Blanusa et al., 2013).

Three specific example of plant species that satisfy these three requirements are: the *Trifolium Repens*, the *Sedum Clavatum*, and *Cynodon dactylon* (Lamnatou & Chemisana, 2015). Additionally, the dense foliage of all these species confers high acoustic insulation properties, carbon sequestration abilities, urban temperature reduction potential, and stormwater absorption capabilities (Lamnatou & Chemisana, 2015). When considering the maintenance (i.e., nutrient, irrigation, and pest-protection) among the avoe examples, the *Sedum Clavatum* has the lowest requirements). In fact, in general sedum species have low maintenance requisites, a reason why in some areas they are preferred.

Directly below the growing medium, five other layers need to be interposed between the vegetation layer and the rooftop's bearing structure (Figure 3.2). Proceeding from top to bottom, a filter fabric is utilized to prevent small soil particles and plant debris from clogging the drainage layer underneath. Such a fabric is characterized by high tensile strength to withstand the load of the strata above and water permeability, conferred by small pores in the material (Vijayaraghavan, 2016). The drainage layer prevents waterlogging of the vegetation by rapidly removing the excess water into the roof drains (FLL, 2018). Below, a root barrier is installed, so to protect the waterproof layer underneath from root penetration. This layer also provides protection to the layers below from other possible mechanical damages (Catalano et al., 2018). Next, a thermal insulation layer may be installed in conformity to local or national energy efficiency standards. Nevertheless, the growing medium already provides an insulation of the roof (Berardi et al., 2014; Saadatian et al., 2013) thanks to its water content, which increases the roof's thermal inertia (Vijayaraghavan, 2016). At the same time the vegetation layer decreases the roof's surface temperature through shading, and aided by the soil in the growing medium, through evapotranspiration (Cristiano et al., 2021; Vijayaraghavan, 2016) during summer (Shafique et al., 2020). Lastly, a water vapor membrane prevents water and other liquids from entering the building underneath.

3.1.2.3 Structural design characteristics of photovoltaic-green roofs

Although Figure 3.2 displays a flat roof for visualization purposes, green roofs require a slope of at least 2% (i.e., 1.1°) to avoid undesired water accumulation in certain parts of the roof, which could cause plant failure (FLL, 2018). At the same time, slopes higher than 8.8% (i.e., 5°) need adaptation measures in roof layers such as higher water storage, lower drainage capacity, and lower water requirement by the vegetation. Roof slopes should not be higher than 100% (i.e., 45°), although they become undesirable already beyond 36.4% (i.e., 20°) (Teotónio et al., 2018).

Considering the structural characteristics of PV modules, it is important noting that plants are shaded from rainfall by PV modules. Especially in arid climates, this could require ad hoc irrigation of the vegetation below the panels (FLL, 2018) . However, water flows coming off the lower edge of PV modules during precipitation events could be redirected with a water conduit to the area under the modules, avoiding any extra irrigation costs and water needs (Figure 3.2b).

The orientation and tilt angle of PV panels are displayed in Figure 3.3. If the PV panels are located in the northern hemisphere they should be facing the geographical, or true, south; conversely, if they are in the

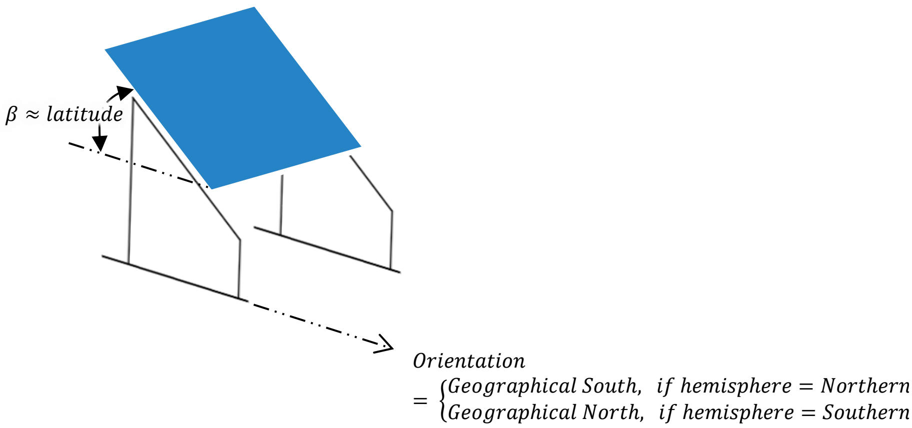


Figure 3.3. Orientation and tilt angle of photovoltaic panels.

southern hemisphere they should face the geographical north (Zhou & Frering, 2006). Such orientations ensure that the panels face the sun throughout the whole year. The optimal tilt angle β is approximately equal to latitude of the installation's location (Mehleri et al., 2010; Zhou & Frering, 2006).

Except for the first row of PV arrays, each of the other rows can be shaded by the row in front it. This may negatively affect the efficiency of the panels and reduce the electricity they generate. In addition, arrays of PV panels shade plants from sunlight. While this may be beneficial in certain climates (Shafique, Kim, & Rafiq, 2018), it may not always be desirable for all types of plants (FLL, 2018). Thus, a distance should be kept between one array and the other. A general formulation for the minimum distance d_{min} between rows of PV arrays is represented by a function of the height of the higher edge of the PV array from the roof h, the sun's elevation angle over the horizon α_s, and the solar azimuth (measured from the geographical south) γ_s (Figure 3.4):

Equation 3.1

$$d > \underbrace{\frac{h}{tan(\alpha_s)} cos(\gamma_s)}_{d_{min}}$$

Such a length is the minimum distance to keep between rows of PV arrays, so to avoid shading of PV panels. Detailed trigonometric calculations to derive such function are provided in Appendix B.

The sun's elevation and the solar azimuth are dependent on the installation's location and on the time of the year: $\gamma_s = \widetilde{\gamma_s}(latitude, longitude, time)$ and $\alpha_s = \widetilde{\alpha_s}(latitude, longitude, time)$. Thus, to determine a numeric value for d_{min}, the geographic location of the PV installation and the time of the year for which the PV panels need to be optimized, have to be specified. As an example, in the case of Esch-sur-Alzette (Luxembourg), ensuring PV panels receive sun even in the worst-case scenario (i.e., the winter solstice), d_{min} equals $0.65 \cdot h$, or 65% of PV arrays' height (Appendix B).

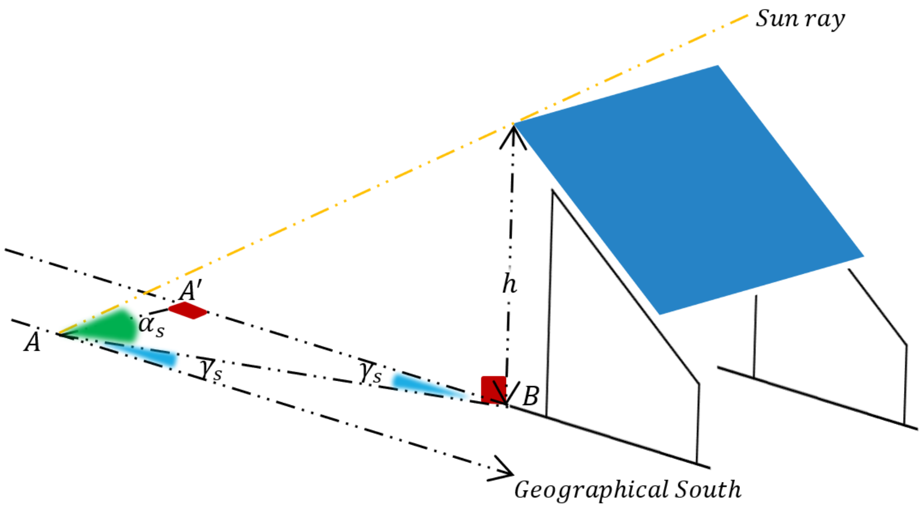


Figure 3.4. Inter-row distance of PV arrays. The figure shows the case of an array facing south, for simplicity of visualization. The case where PV arrays face north is analogous.

3.2 The Costs and Benefits of Photovoltaic-Green Roofs as Part of PGECs

The physical layer of PGECs generates a wide array of costs and benefits (Shafique et al., 2020), including installation and maintenance costs, as well as biodiversity (Nash et al., 2016), and air quality enhancement (Yang et al., 2008), CO_2 emission reductions (Claus & Rousseau, 2012, p. 6) and energy bill's savings (Ascione et al., 2013). The institutional layer may also add costs such as transaction costs (e.g., to legally form the PGEC, and to agree on a common electricity sharing key) and other benefits (e.g., the sense of community and identity).

An in-depth analysis of costs and benefits of the institutional layer is deemed out of the scope of this research. Such an analysis would require an evaluation of the effects stemming from social interaction between PGEC members or shareholders, as well as their interaction with external actors. Nevertheless, photovoltaic-green roof energy communities are still a conceptual community model, for which empirical research would be difficult as practical applications are still missing. Even the closest community adopted in practice, renewable energy communities, do not include green roofs, a key component of PGECs. When the real system may not be engaged, simulation tools (Sokolowski et al., 2009) such as agent-based modelling, could be used. Nevertheless, the parametrization and validation of such a model would remain a challenge. Therefore, this section focuses on the costs and benefits associated with the physical layer of PGECs only: PV-green roofs. Section 3.2.1 describes the methods and section 3.2.2 presents and discusses the results.

3.2.1 Methods: A Systematic Literature Review

As Cristiano et al. (2021) observed, most of the time green roof benefits are investigated using a "silo approach", whereby studies focus on one or few benefits only. For this reason, the authors stress the need to perform integrated assessments of all the benefits of these solutions, so to be able to fully evaluate them. This viewpoint is shared by Berndtsson (2010), who notes how specialists only focus on their own field when conducting research on green roofs, generalizing the other aspects. In this light, the author contends that decisions regarding green roof construction and design need to be based on an analysis of multiple benefits, instead of treating them as a solution for one engineering problem only. Thus, to identify all the costs and benefits associated with PV-green roofs, this research performs a systematic review of cost-benefit analyses published as peer-reviewed papers to date. In this way an overview of costs and benefits of green roofs, as well as of their monetization will be elicited.

Although green roofs are not PV-green roofs, no cost-benefit analysis specifically centered on PV-green roofs could be found to date[2]. Conversely, there exists a variety of cost-benefit analyses for green roofs, whereby the coupling with photovoltaic panels is sometimes also considered. For this reason, the review of CBAs of green roofs was deemed an appropriate method to gain an overview of the costs and benefits of the physical layer of PGECs.

Additionally, since to date authors make different assumptions in the structure of the CBA, and often various benefits are neglected from analyses, a high variability of CBA results can be observed. In this respect, Teotónio et al., (2021) voiced the need for a consistent, transversal and all-inclusive methodology which considers costs, benefits and co-benefits of green roofs to better support policymaking. In this

[2] The Scopus online database was queried with the search string: TITLE-ABS-KEY ("photovoltaic-green roof" AND ("cost benefit analysis" OR "benefit cost analysis")) without finding any result. Similarly, when utilizing the search string: TITLE-ABS-KEY ("photovoltaic panel" AND "green roof" AND ("cost benefit analysis" OR "benefit cost analysis")) only one result was found (Statler et al., 2017), which however does not consider the integration of photovoltaic panels on green roofs, but rather the alternative use of either green roofs or photovoltaic panels.

section an attempt to provide a more consistent, transversal, and all-inclusive methodology to conduct CBAs of PV-green roofs is provided. Of course, this methodology can be applied to green roofs only as well.

3.2.1.1 Structure of the Systematic Literature Review

The review is composed of two phases (Figure 3.5). In the first and main phase, cost-benefit analyses conducted on green roofs were searched using the Scopus database. In the second phase, additional articles specifically focusing on the quantification of PV panels' output increase were analyzed to compensate for the low number of CBAs including this benefit. A very recent study (Manso et al., 2021) reviewing multiple articles on this benefit was used as the source of academic papers for this phase.

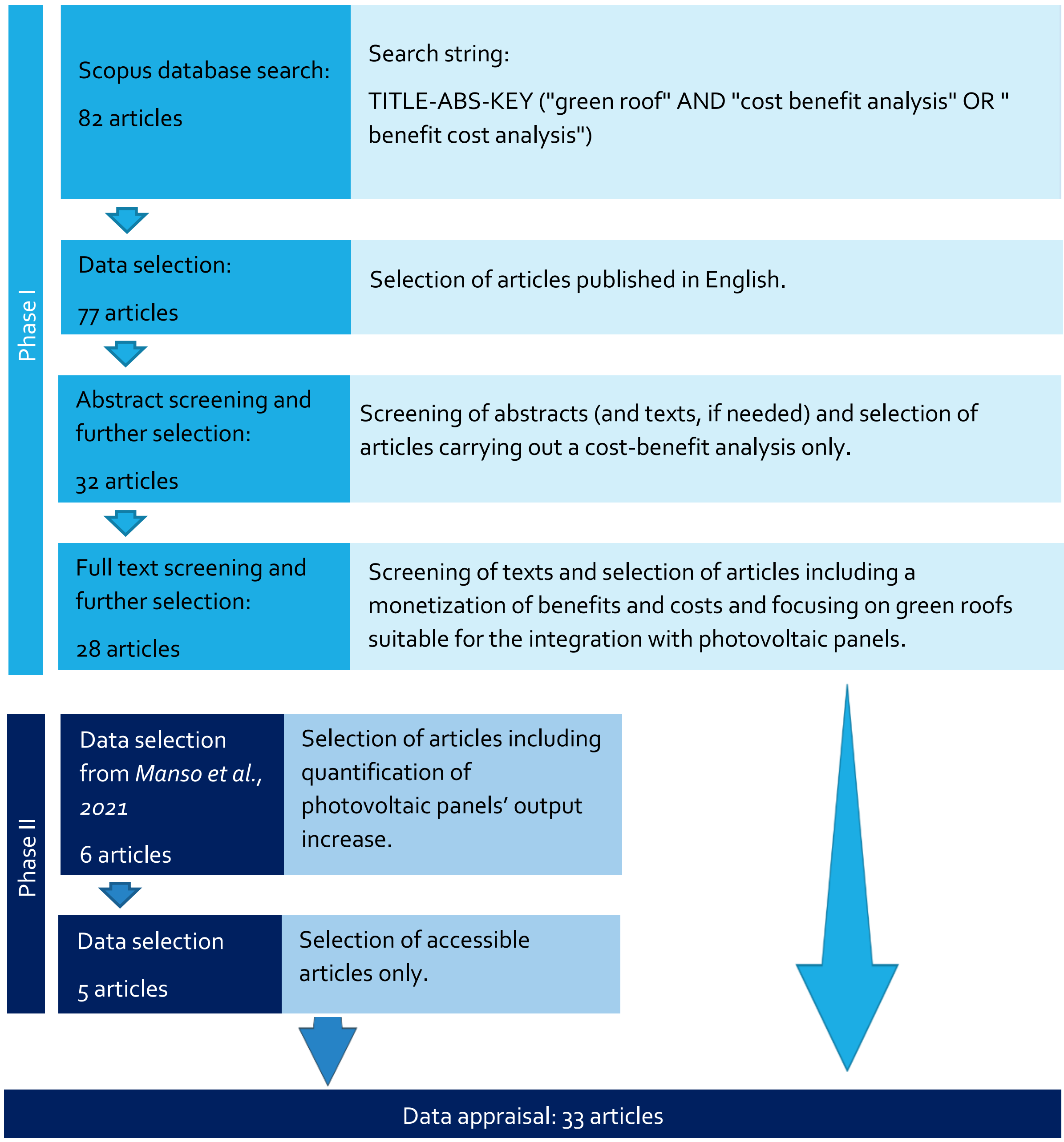


Figure 3.5. Two-phase systematic literature review of academic articles concerning green roofs and PV green roofs. The first phase regards cost-benefit analyses, while the second one integrates studies focused on photovoltaic panels' power output increase due to green roofs underneath.

The first phase consists of four steps. First, all articles containing the phrase "green roof" and either the phrase "cost benefit analysis" or "benefit cost analysis" in the title, abstract or keywords were gathered. Because of the Scopus portal's search conventions, also plurals and phrases containing hyphens were automatically included in the search. Second, articles not in English were excluded. Third, the abstract (and, in case of ambiguity, the text) of the remaining 77 articles were screened so that only studies containing a cost-benefit analysis were selected. This step provided a total of 32 CBAs. In the fourth step, articles' texts were screened and only studies focusing on extensive or semi-intensive green roofs, providing intermediate monetary values before the final outcomes (i.e., NPVs, or Cost/Benefit ratios), as well as their accounting year, were selected. This last step provided a total of 28 articles.

In the second phase, only one selection step was performed, whereby the article not accessible online was excluded from the review. This second phase provided 5 articles specifically focusing only on PV performance of PV-green roofs, which often provided physical rather than monetary values. For this reason, those articles not providing any information about the monetary benefit of PV electricity generation were not converted into a monetary figure for the purpose of this chapter.

Each of the 28 usable CBAs contained one or more case-studies in which the costs and benefits associated to the implementation of a new technology (e.g., green roof, PV-green roof) were valued compared to the implementation of a base case technology (e.g., black, gravel, or white roof). Such case-studies were located in a particular city and took place in a particular year.

At the data appraisal stage, the physical features of the new and base case technologies were recorded. 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 base case technology type, including its insulation properties. The new technology was associated to a series of costs and benefits which were also recorded. Lastly, the geographical, time, and climate features of the case-study were recorded as well. An overview of the features recorded is provided in Table 3.1.

Table 3.1. Overview of features recorded in the literature review.

	Recorded Feature	Feature values
New technology features	New technology	Green roof, PV-Green roof
	New technology's lifetime	Numerical value.
	If technology was 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 technology was 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.
	Distance PV panels – base case roof	Numerical value.
Cost / Benefit features	Item (i.e., cost or benefit)	Various.
	Item type	Cost, or Benefit.
	Monetary value (with time and currency)	Numerical value.
	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.
Base case features	Base case technology	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	Various.
	City	Various.
	Climate	One of the Koppen-Geiger climate classes.
	Season	Summer, or Annual average
Article features	Authors	Various.
	Article year	Publication year.
	Title	Various.
	Study type	Cost-Benefit Analysis, or Photovoltaic performance analysis.

3.2.1.2 The Recording of Features

The reviewed cost-benefit analyses focused on two main ***new technologies***: green roofs and PV-green roofs. In fact, green roofs are just a component of PV-green roofs, and thus CBAs of green roofs can be seen as studies focusing on just a part of PV-green roofs. Accordingly, from here onwards all new technologies will be regarded as PV-green roofs. Naturally, as an implication, a larger number of costs and benefits was recorded for the green roof part of PV-green roofs, while costs and benefits related to PV panels and to their integration with green roofs were fewer.

Important features are the costs and benefits of the PV-green roofs, which from here onwards will be referred to as ***items***. These can be various, and they include - among others - the property's aesthetics increase, energy consumption reduction, electricity generation, and CO_2 emission reduction.

Whenever provided, the **monetary value** of PV-green roof's items was recorded. Specifically, these are monetary valuations of the costs and benefits associated with the implementation of a PV-green roof with respect to a *base case*.

Since the studies were carried out in different years and locations, monetary values needed to be adjusted to be comparable. To this end, according to the unit value transfer methodology (Petucco et al., 2018) monetary values were:

1. corrected for inflation from the year of the case-study to 2020 values, using the GDP deflator indexes provided by the World Bank (2021a). In this step, the indexes always referred to the same country where the case-study was carried out;
2. converted 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, 2021b);
3. when monetary values represented a willingness to pay, they were also corrected for the difference in income between the original case-study's location and the European Union's (EU27) case. In this step, the income elasticity of willingness to pay was considered to be unitary, following the literature's recommendation (Tyllianakis & Skuras, 2016; Petucco et al., 2018).

An overview of the equations used for the three steps presented above is provided in **Error! Not a valid bookmark self-reference.**.

Table 3.2. Equations used for unit value transfer.

Variable adjusted	Equation	Equation's variables
Price level	$v' = v \cdot \left(\frac{D'}{D}\right)$	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	$v' = E \cdot v$	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	$WTP' = WTP \cdot \left(\frac{Y'}{Y}\right)^{\varepsilon}$	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

Base cases found in the literature were of two main types: (1) the implementation of a base case technology (i.e., either a conventional black, gravel, or white roof), and (2) a situation in which no technology was implemented at all.

Being significantly more numerous, this dissertation only considered differential items between new and base case technology. Items were either directly recorded from the articles or, whenever not provided, they were indirectly derived from the other data presented.

To compare PV-green roofs to a base case, two scenarios were devised:

1. **A global analysis of results**, whereby all base case bare roofs (i.e., black, gravel, and white roofs) were considered, utilizing studies carried out in all climates and locations.
2. **A local analysis of results**, only considering data relevant to Esch-sur-Alzette, Luxembourg, i.e., the case-study of this dissertation. For this purpose, only data keeping black roof as the base case technology were considered, and among these, only studies carried out in Europe and in equivalent climatic conditions of Esch-sur-Alzette were taken into account.

Spatially, the global analysis shows which are the areas around the world that have been hitherto studied and those that have been neglected instead. Numerically, this analysis provides insight into the value range that can be expected around the world for each of the items of the physical layer of PGECs.

The local analysis considers the fraction of the recorded data that is more compatible with the location of Esch-sur-Alzette. This analysis provides insight into the range of values that can be expected for this geographical location and climatic condition.

The comparability of the adjusted monetary values is further discussed on a case-by-case basis, considering the specificity of the items at hand.

In the following section, the items recorded for both these two scenarios are presented and discussed.

3.2.2 Results and Discussion

The global analysis consists of a total of 33 articles: 28 CBAs and 5 analyses of PV performance. Except for one article (Bianchini & Hewage, 2012), which did not have a specific geographical focus, all the remaining ones concentrated on one or more specific locations, sometimes even within the same city. Hereafter, the geographically bound studies of the articles will be referred to as *case-studies*. A complete list of all articles included in the global and local analysis is provided in Appendix C.

In the following sections the spatial characteristics of the case-studies will be reviewed (section 3.2.2.1), followed by a review of their time characteristics (section 3.2.2.2). Next, the main methodological characteristics of the articles underlying the case-studies will be illustrated and discussed (section 3.2.2.3). Subsequently, the characteristics of costs and benefits identified from the case-studies will be provided and discussed at a general level (section 3.2.2.4) and at a more detailed level for specific costs and benefits (sections 3.2.2.5 to 3.2.2.11). Lastly, the relation between the identified benefits and the European Green Deal's objectives will be presented (section 3.2.2.12).

3.2.2.1 Spatial characteristics of the case-studies

Overall, there are 43 case-studies spanning across four continents and 15 countries, although some continents are barely studied while others feature a wealth of analyses in comparison. Most case-studies are based in Europe (20), although, as a country, the United States features the majority of the case-studies (15). An overview of the geographical distribution of the case-studies is provided in Figure 3.6 for both the global and local analysis.

As it can be seen from Figure 3.6a, no case-studies were carried out in Africa, only one case-study was found for South America and one for Oceania. In contrast, Europe and the United States of America (US) are home to the great majority of case-studies. This result highlights the geographical focus of the literature on a restricted area of the globe, while South America, Africa, Asia, Oceania, as well as other countries of North America other than the US remain largely unexplored.

As for the local analysis, Figure 3.6b shows that only five case-studies satisfied both the geographical constraint (belonging to Europe) and the climate constraint (same climatic condition of Esch-sur-Alzette). It can be noted that these case-studies are the five geographically closest analyses to Esch-sur-Alzette.

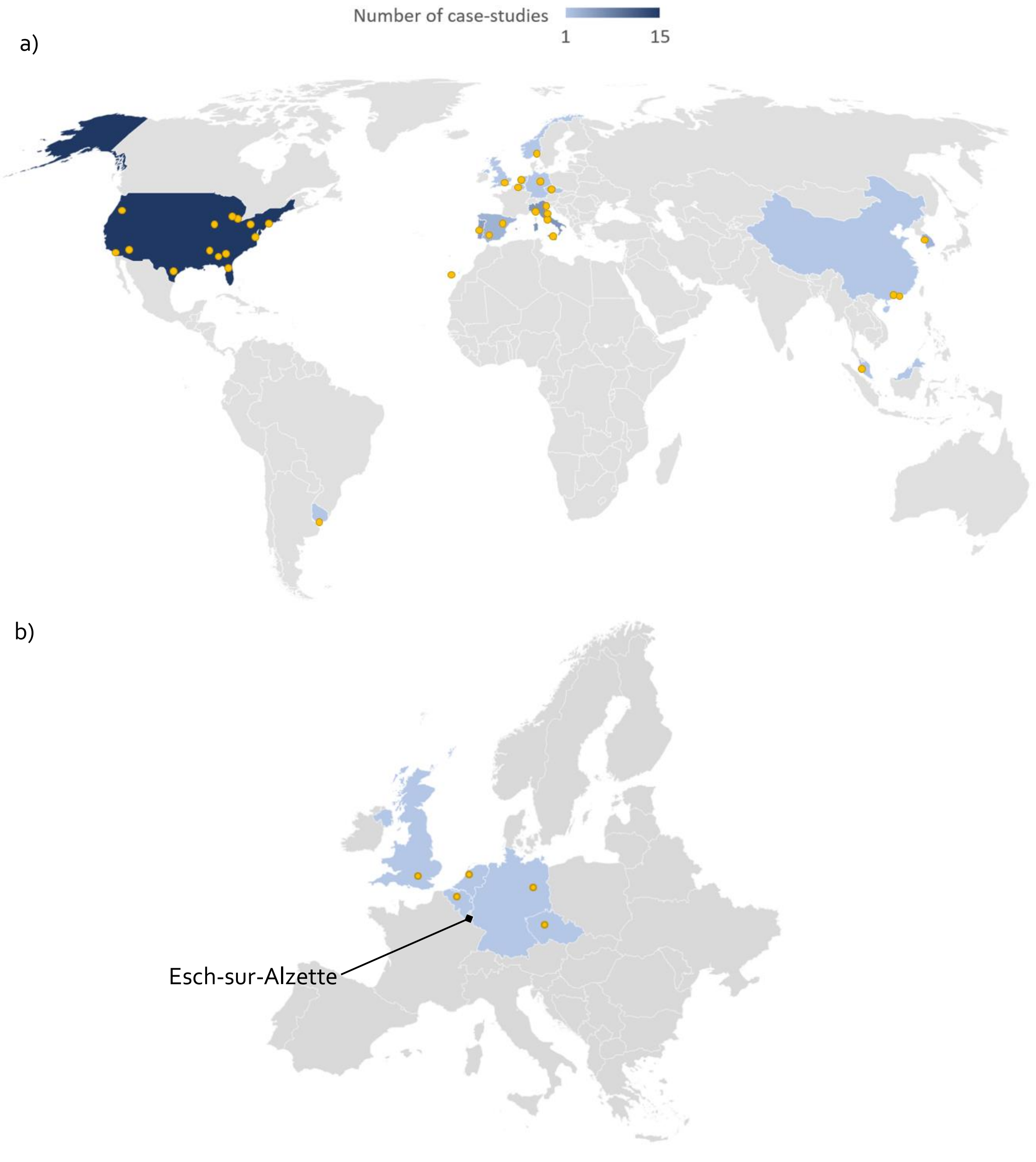


Figure 3.6. Geographical distribution of case-studies examined in the literature review for the global analysis (a) and for the local analysis (b). Due to the absence of case studies and its peculiarly different climate, Antarctica was omitted from the figure.

To visualize the climatic conditions of Esch-sur-Alzette and of the other geographical locations where the literature focused on, the Koppen-Geiger climate classification was used in its 2017 updated form (Kottek & Rubel, 2017). This frequently used categorization distinguishes 30 climates in the world and is based on vegetation, air temperature and precipitation characteristics (Kottek et al., 2006). The case-studies reviewed are located in a total of 9 different climates, which are displayed in Figure 3.7a.

The local analysis relies on the temperate oceanic climate (Cfb) observed in Esch-sur-Alzette. Figure 3.7b visualizes the geographical extent of this climate. It is important noting that while climate classes are displayed statically, they are expected to evolve in the coming decades (Kottek & Rubel, 2017).

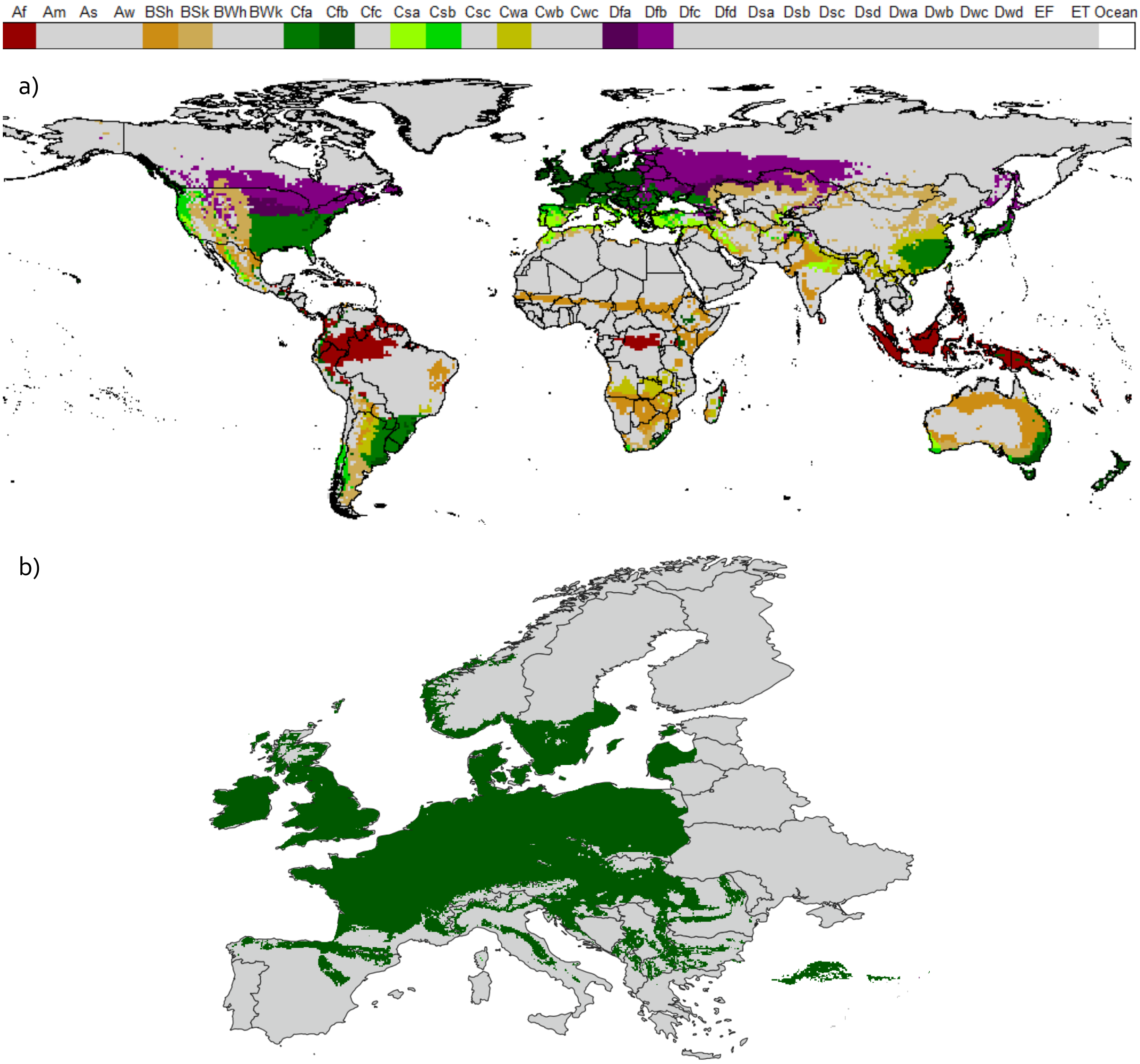


Figure 3.7. Koppen-Geiger climates covered by the literature review in the global (a), and local analysis (b). Af: Tropical rainforest; Am: Tropical monsoon; As: Tropical dry savanna; Aw: Tropical wet savanna; Bsh: Hot semi-arid (steppe); BSk: Cold semi-arid (steppe); BWh: Hot deserts; BWk: Cold deserts; Cfa: Humid subtropical; Cfb: Temperate ocenaic; Cfc: Subpolar oceanic; Csa: Hot-summer Mediterranean; Csb: Warm-summer Mediterranean; Csc: Cold-summer Mediterranean; Cwa: Monsoon-influenced humid subtropical; Cwb: Subtropical highland or temperate oceanic with dry winters; Cwc: Cold subtropical highland or subpolar oceanic with dry winters; Dfa: Hot-summer humid continental; Dfb: Warm-summer humid continental; Dfc: Subarctic; Dfd: Extremely cold subarctic; Dsa: Hot and dry-summer continental; Dsb: Warm and dry-summer continental; Dsc: Dry-summer subarctic; Dsd: Cold, dry summer, very cold winter; Dwa: Monsoon-influenced hot-summer humid continental; Dwb: Monsoon-influenced warm-summer humid continental; Dwc: Monsoon-influenced subarctic; Dwd: Monsoon-influenced extremely cold subarctic; EF: Polar ice cap; ET: Polar tundra.

Reasonably, the more case-studies are carried out in each climate class, the more representative the results for this class. The number of case-studies for each class was quantified and they are displayed in Figure 3.8. The most represented climate class is the humid subtropical climate (Cfa), followed by the hot-summer Mediterranean climate (Csa), both belonging to the group of temperate climates. Conversely, analyses in the group of tropical (Af, Am, As, Aw) and dry climates (BSh, BSk, BWh, BWk) are very few.

As far as the local analysis is concerned, Figure 3.8 shows that the five case-studies on which it relies are all CBAs and not analyses of electricity generation only.

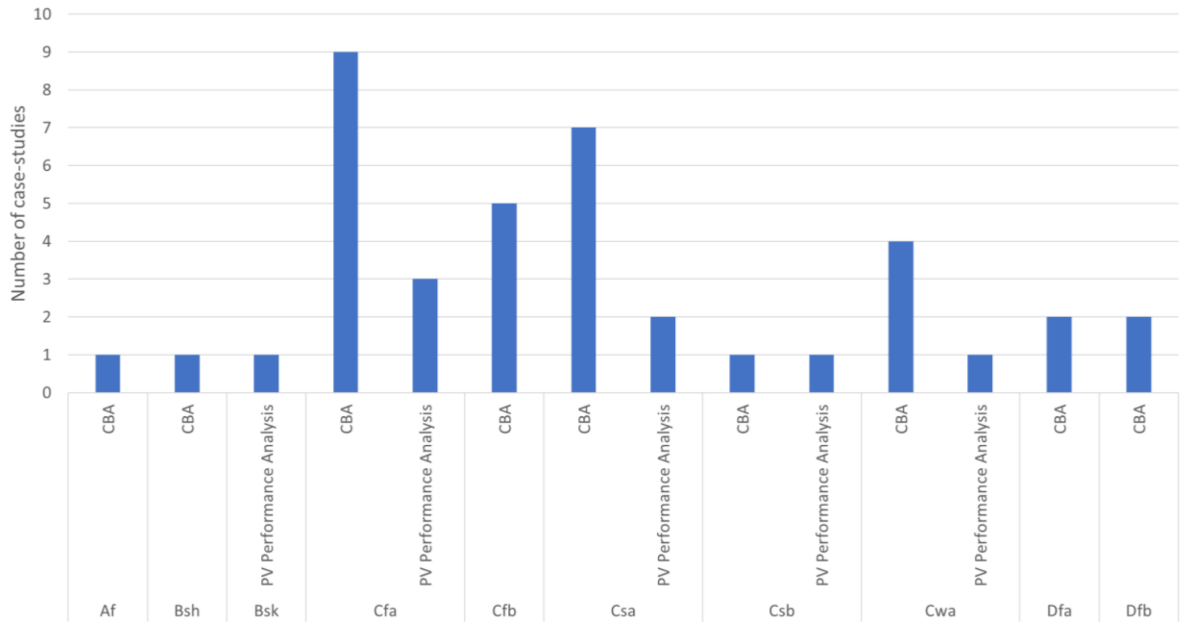


Figure 3.8. Number and type of case-studies carried out in each climate class.

3.2.2.2 Temporal characteristics of the case-studies

With regard to the dimension of time, the number of case-studies and articles being published has increased in recent years (Figure 3.9a). The particularly high number of case-studies carried out in 2013 is not caused by a high number of articles published, but rather is due to three articles containing a large number of case-studies.

Since the oldest case-studies date back to 2008 for the global analysis (Figure 3.9a), and to 2012 for the local analysis (Figure 3.9b), no articles were deemed excessively dated to be excluded from the two analyses. In any case, the different years in which the articles assessed the costs and benefits of PV-green roofs required a correction for inflation, as explained in section 3.2.1.2.

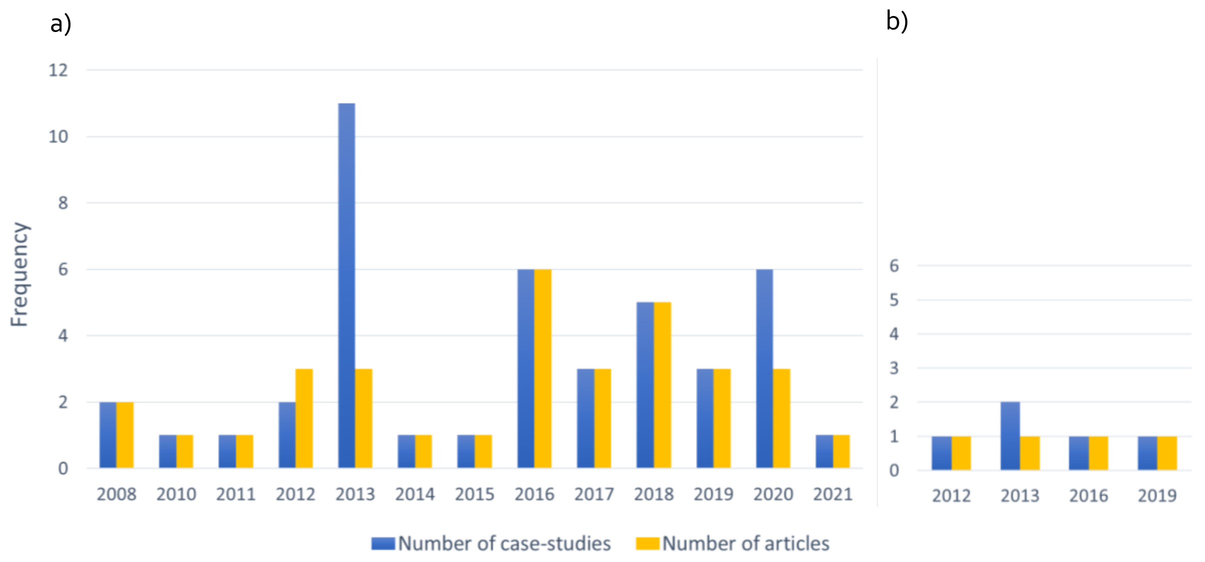


Figure 3.9. Distribution over time of the global (a) and local (b) analysis' case-studies and articles. The study by Bianchini & Hewage (2012) is displayed as an article of the global analysis, nevertheless, due to the absence of a gegraphical focus it was not considered to be providing additional case-studies.

3.2.2.3 Methodological characteristics of the articles

Since methodological details are shared by all case-studies of the same article, this section considers the articles published, instead of the case-studies that they contain.

From a methodological standpoint, the articles reviewed were observed not to always state the **base case** adopted in the analysis. On the one hand, it was possible to distinguish CBA results that are differentials between the implementation of two alternative technologies from those that are differentials between implementing and foregoing PV-green roofs. On the other hand, however, for two articles the base case roof was not explicitly stated, and it was inferred from the data given, while for three articles it was not possible to identify the base case roof considered. Since CBA results are always differentials between a base case and an alternative situation (Harris & Roach, 2018; Romijn & Renes, 2013), specifying this information is particularly important.

With regard to the time dimension, the most frequent **time horizon** chosen in the CBAs reviewed was 40 years (Figure 3.10), which is also the average service life of green roofs (Sproul et al., 2014). As it can be seen in Figure 3.10, a smaller group of studies used a shorter time horizon between 10 and 30 years, although studies seldom included the residual value of green roof in the last year of the CBA. In fact, 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

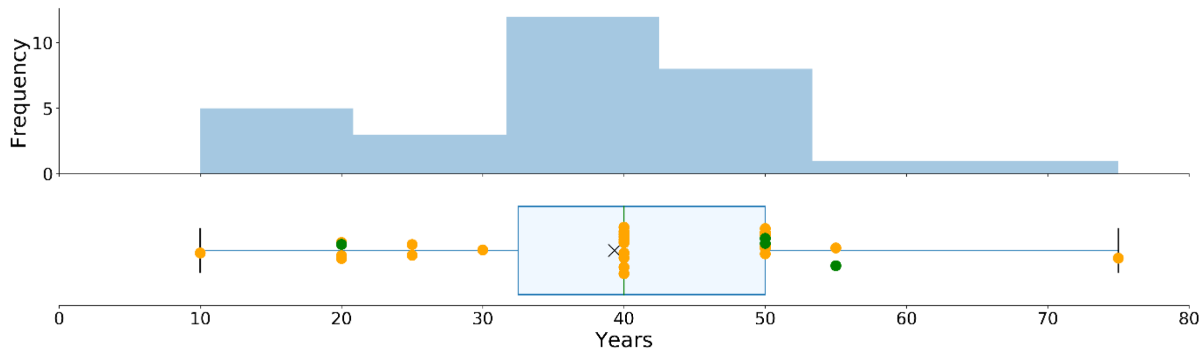


Figure 3.10. Time horizon of CBAs reviewed. Studies belonging to the global analysis are displayed in **orange**, while those belonging to the local analysis are depicted in **green**.

means that CBA results may lack a positive cash flow, which, depending on the time horizon chosen, may be significant.

In order to convert future cash flows of costs and benefits to a present value in the investment year, the articles used *social* and/or *private* **discount rates**. If the CBA limited its study to the costs and benefits affecting individual owners of PV-green roofs (or green roofs), the analysis was considered *private*. In contrast, if the CBA included costs and benefits affecting society more at large it was defined as *social*. In the present discussion the focus is on all costs and benefits that are associated to PV-green roofs, therefore only social discount rates are considered, while an overview of private discount rates is provided in Appendix C.

The average social discount rate observed across the articles of the global analysis was 4.13% (Figure 3.11a). There is however a significant variability in the choice of this rate, as the minimum was as low as 2% and the maximum as high as 8%. The highest social discount rate was observed in the study by Bianchini and Hewage (2012), who considered a range of discount rates, whereby 8% was the highest value contemplated. When comparing this value with the social discount rates used by the other authors, 8% appears to be an outlier. Similar values can be found for the local analysis' articles, whereby the social discount rate ranges from 2 to 8% (Figure 3.11b).

In general, the higher is the discount rate, the lower is the present value assigned to future costs and benefits in the CBA accounting. In the case of PV-green roofs, benefits are spread over the entire technology's lifespan, meaning that the present value of later years' benefits will be lower. In contrast, the main cost of PV-green roofs is the initial investment cost, which occurs in the first year of the project's lifespan and is not discounted. It can therefore be observed that benefits overall receive less weight compared to costs.

Interestingly, the range of social discount rates found seems roughly in line with the descriptive approach taken by Nordhaus (2007), whereby the choice of this rate is based on the observation of historical long-term returns to stock market, real estate, and land investment. According to this perspective, since empirical evidence shows that such long-term returns are about 4%, so is the social discount rate. The

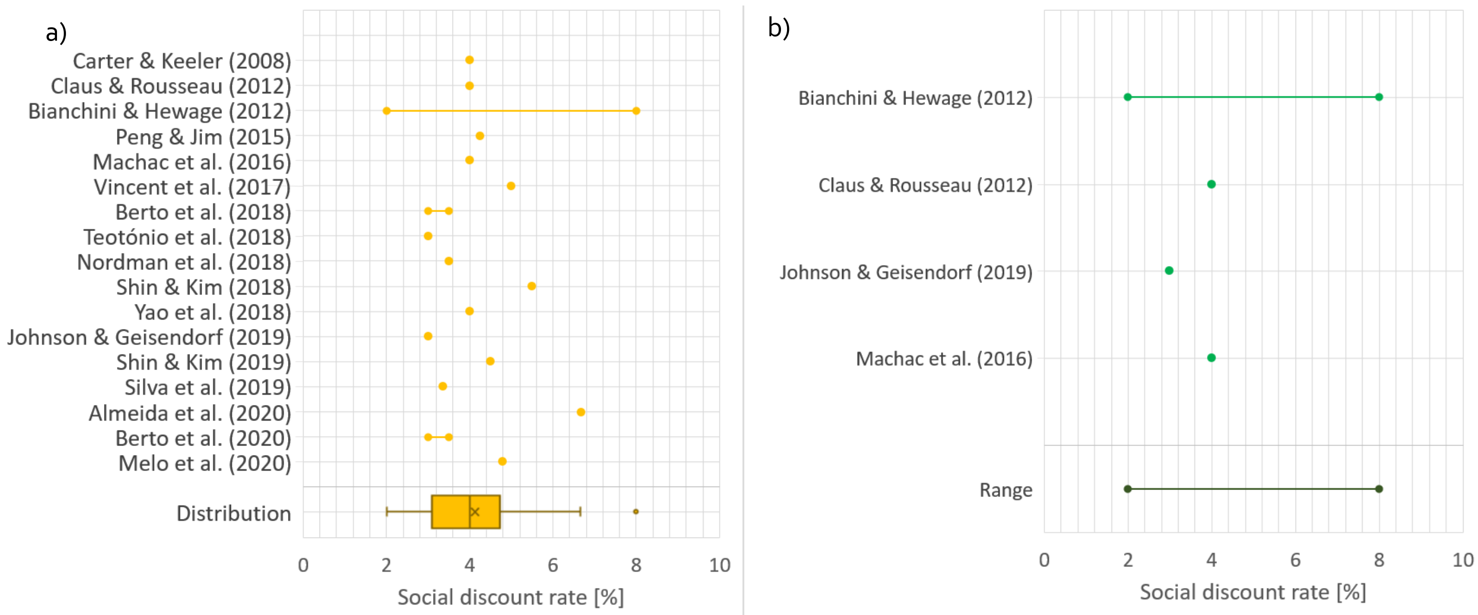


Figure 3.11. Social discount rates used in the articles of the global (a) and local (b) analysis. Due to the modest number of studies in the local analysis the value range was depicted instead of the distribution boxplot. Note that only articles using a social discount rate are displayed.

underlying reasoning is that society always has an alternative opportunity to invest money right away in the stock market, in real estate or in land and earn 4% on average.

A different value for the social discount rate could be obtained if instead of a descriptive approach, a prescriptive approach was used. In such case, the discount rate would be set based on ethical and normative judgements, including inter-generational justice considerations and the precautionary principle into the discount rate choice (Harrison, 2010). An example of this approach is provided by Stern (2007), who discounted future climate change impacts at a rate of approximately 1.4%.

A prescriptive approach for PV-green roofs can be argued based on the fact that this technology contributes mitigating climate change impacts such as extreme weather events (e.g., floods, and the urban heat island effect) and the greenhouse effect, through the avoided CO_2 emissions in electricity generation and CO_2 uptake (Shafique, Kim, & Rafiq, 2018; Teotónio et al., 2018). Since the average project's time-horizon can be estimated to be 40 years (Almeida et al., 2021; Silva et al., 2019), approximately two generations would be concerned. Thus, the type of avoided damages and the time-horizon of this technology would make the precautionary principle and inter-generational equity considerations relevant for PV-green roofs as well.

3.2.2.4 Overview of the costs and benefits of photovoltaic-green roofs

From the articles reviewed, over 700 items were recorded and a complete spreadsheet is available in Appendix D. A consistent set of the items identified, including those that were only mentioned by authors but not quantified, is provided in **Table 3.3**.

Table 3.3. Overview of all items cited in the articles reviewed.

Item	Item effect	Item scale	Item type
Energy consumption reduction (from heating and cooling)	Benefit	Building	Financial
Fire risk reduction (insurance discount)	Benefit	Building	Financial
Longevity increase	Benefit	Building	Financial
Sound insulation	Benefit	Building	Economic
Electricity generation	Benefit	Community-wide	Financial
Aesthetics increase	Benefit	Community-wide	Economic
Air quality enhancement	Benefit	Community-wide	Socio-environmental
Urban noise reduction	Benefit	Community-wide	Socio-environmental
Urban heat island effect mitigation	Benefit	Community-wide	Socio-environmental
Biodiversity enhancement	Benefit	Urban	Socio-environmental
Stormwater management	Benefit	Urban	Socio-environmental
Water runoff quality increase	Benefit	Urban	Socio-environmental
CO2 uptake	Benefit	Societal	Socio-environmental
CO2 emission reduction	Benefit	Societal	Socio-environmental
Installation of green roof	Cost	Community-wide	Financial
Maintenance of green roof	Cost	Community-wide	Financial
Replacement and disposal of green roof	Cost	Community-wide	Financial
Installation of PV panels	Cost	Community-wide	Financial
Air pollution from green roof production	Cost	Urban*	Socio-environmental
CO2 emission from green roof production	Cost	Societal	Socio-environmental

(*) Air pollutant emissions due to the production of green roof affect the urban area or areas where the green roof is manufactured, which may not coincide with the urban area where the green roof is installed.

Items' characteristics can be identified using two dimensions: the item's effect (i.e., cost or benefit), and scale (i.e., building, community-wide, urban, or societal). A third dimension, item type, is taken from the previous literature on CBA of green roofs (Teotónio et al., 2018), so to locate this dissertation's analysis in the current literature.

The item's effect and scale

The effect of an item is either positive (benefit) or negative (cost) and is enjoyed or borne by specific individuals.

The distribution of costs and benefits associated to PV panels is different than that of green roofs. On the one hand, PV panels are collectively owned by the PGEC members and shareholders, and, according to the RED II provisions, their monetary benefits and costs need to be shared by the entire community in a collectively agreed manner. On the other hand, some green roof benefits only affect the building residents, while other benefits affect the whole community, the urban area, or even society more at large. The costs of each green roof can thus be borne by the relative building's residents, or by the PGEC members and shareholders as in the case of PV panels. In this dissertation the latter case is considered: the coupled technology of PV-green roofs is collectively owned by the PGEC, and therefore its (financial) costs are borne by the PGEC, in a collectively agreed way.

Treating green roofs with PV panels as a single technology enables the PGEC to be entitled to receive support schemes tailored to such hybrid energy and environmental technology, as one of the REC's specificity (art. 22 para. 7). Nevertheless, it is important recognizing that PGEC members and shareholders may not want to share financial costs of green roofs that are installed in other community buildings, even though they receive various of their benefits. It is reasonable believing that this instance could likely occur for building residents whose green roof would have financially cost less than the collectively agreed cost of the community's PV-green roofs. In such a situation a community space for decision-making where all members' concerns can be heard is expected to be crucial.

In practice, each PGEC can distribute costs differently as long as it defines this in its community statutes. Nevertheless, for the scope of this dissertation, it is sufficient being able to distinguish building, community-wide, urban and societal items. This distinction allows to perform different kinds of CBAs, either a building, a community-wide, an urban, or a social CBA. Specifically, community-wide analyses consider both community-wide and building items, urban analyses include urban, community-wide, and building items, and social CBAs include all items. As it can be seen, grouping items based on their scale implies that CBAs of different scales take on different individuals' perspectives: either the building owners' one, the community, the urban or the societal perspective.

Building items originate in one PV-green roof and affect the residents of the building in which the PV-green roofs are installed. These are for instance the energy consumption reduction benefit due to the thermal insulative property of green roofs and the sound insulation brought by green roofs to the same building where they are installed.

Community-wide items originate in one PV-green roof but have an effect on all members or shareholders of the PGEC, which according to art.2(16) and recital 71 of the RED II need to be in the proximity of the PGEC's installations. As described in section 2.2.2.1, the proximity criterion and thus PGECs' maximum geographical extents need to be specified further by each EU Member State, nevertheless the national transpositions reviewed in chapter 2 specify that the PGEC's size is that of a neighbourhood connected to the same medium-voltage (or high-voltage) / low-voltage transformer substation. Examples of these items are the electricity generation of PV panels, enhanced by the green roof underneath, and the air quality enhancement in the proximity of green roofs, thanks to the air pollutants uptake by plants.

Urban items have an effect on the wider urban area (i.e., the urban settlement) where the PGEC is located. Examples are the lower rainwater treatment costs due to green roofs' water filtration, and the reduction in stormwater management as well as flood damage costs, thanks to green roofs' water retention.

Societal items affect society more at large. In practice, they are CO_2 emission, uptake and emission reduction, since CO_2 represents a greenhouse gas affecting the entire atmosphere, and thus the entire society (Ahmed Ali et al., 2020).

Reasonably, the last two item scales are achieved whenever multiple PV-green roofs are installed, as in the case of PGECs.

The item's type

Teotónio et al., (2018) proposed a categorization of items for CBAs of green roofs that groups costs and benefits into financial, economic, and socio-environmental items. This distinction paves the way to define what kind of cost-benefit analysis one can perform: either a purely financial, an economic, or a socio-environmental analysis, where the economic incorporates both financial and economic items, and the socio-environmental incorporates all item types. In fact, the difference in CBA kinds resides in the perspective taken by the analysis. According to the authors, financial items are those affecting investors, economic items affect the local economy, while socio-environmental items refer to social equity and environmental protection (Teotónio et al., 2018, p. 1). This categorization has been used in recent CBAs of green roofs (Almeida et al., 2021; Melo et al., 2020; Silva et al., 2019), but it was not applied to the case of a community-owned PV-green roof, where costs and benefits shall be shared among members in conformity with the community's statutes.

As the whole PGEC owns and manages the PV-green roofs, the entire community is considered to be the investor, a collective actor, characterized by joint action of the members (Scharpf, 2018). Accordingly, "financial" items would be those affecting the PGEC members (i.e., building and community-wide items). However, since the community includes several buildings, and many building owners, various community-wide items may also contribute to the local economy, thus also being "economic" items. A clear example of this overlap is given by the benefit of electricity generation by PV panels, for which both the PGEC as a legal entity, i.e., the investor, and the local economy may benefit from such activity. A similar situation occurs for the benefit of energy consumption reduction.

In addition to potential ambiguity in applying item types to the community-owned PV-green roofs, there is an ambiguity in how the item type definitions were used. Specifically, sound insulation was seen by the authors of the categorization as an economic item, nevertheless this benefit is only perceived by the building last floor's inhabitants (Teotónio et al., 2018, p. 6), as it consists of the lower sound transmission of the roof.

To avoid any ambiguity the item types proposed by Teotónio et al., (2018) in their categorization of CBA items, this dissertation proposes to refine item types' definitions as follows.

The item scale (i.e., building, community-wide, urban, and societal) is used to identify items based on the individuals affected. In contrast, the item's type characterizes the way in which the effect is enjoyed or borne.

Financial items are here defined as those costs or benefits directly relatable to a money flow, this means an avoided or performed payment of money to or by the owner(s) of the new technology at a specific moment in time. This same money flow is also the *cash flow* accounted in the CBA at the relative time of the investment. To be precise, here the term cash flow is used in its capital budgeting definition (Soenen, 1973): each of the inflows and outflows accounted in a project's lifetime, due to the project's initiation. Examples of financial items are installation and maintenance costs, as well as fire insurance reduction benefits.

When an item does not feature a directly relatable cash flow, it can either be an economic or socio-environmental item. Economic items are beneficial or detrimental effects for the owner(s) of the new technology or individuals in the direct surroundings, rather than the natural environment or society more at large. These are sound insulation and the increase in the aesthetics of the building. Socio-environmental items are beneficial or detrimental effects on the natural environment, society more at large, or segments of it, but not just the owners of the technology or individuals' in the technology's surroundings. Examples are CO2 reduction, CO2 uptake, biodiversity as well as air quality enhancement.

The new definitions set forth allow using the existing literature's categorization of CBA items for the present case, while refining its concepts for more transparent future use.

In the next sections, a more detailed description and discussion of the main costs and benefits is provided. The most important inconsistencies are highlighted and suggestions for a more coherent CBA methodology are offered.

3.2.2.5 CO_2 reduction, CO_2 uptake, and air quality enhancement

In this section three different benefits that appeared to overlap in the articles reviewed are presented, a rationale and way to distinguish them is provided, and their characteristics are discussed. These three benefits are CO_2 reduction, CO_2 uptake, and air quality enhancement.

While both CO_2 reduction and CO_2 uptake refer to the lower concentration of carbon dioxide in the atmosphere thanks to the installation of green roofs, these benefits are actually different.

CO_2 reduction refers to the lower emission of CO_2 due to the lower energy consumption in the building. The original cause of this resides in the albedo and evapotranspiration effect of the green roof, which reduces the cooling needs during summer (Shafique, Kim, & Rafiq, 2018). In addition, there may be lower heating needs during winter, thanks to the insulative properties of the vegetation layer and the growing medium installed on top of the roof (Wong et al., 2003; Zhao & Srebric, 2012), however other authors located in a different climate and building conditions did not find any benefit during this season (Santamouris et al., 2007). For this reason, CBAs including this benefit should consider studies carried out with a climate, rooftop, and plant species equivalent to the ones at hand when performing benefit transfer.

CO_2 uptake refers to the capacity of plant species to absorb carbon dioxide in the atmosphere. This benefit was found to depend on the plant species employed (Lamnatou & Chemisana, 2015), and specifically on the density of their foliage. Foliage density is defined as the total leaf surface area per unit of canopy volume [m^2/m^3] (Jain et al., 2010), thus the higher foliage density, the higher carbon dioxide sequestration (Lamnatou & Chemisana, 2015).

Often CO_2 was grouped together with other pollutants, such as nitrogen oxides, (NO_x), sulfur oxides (SO_x), ground-level ozone (O_3), and particulate matter in its various sizes (PM_{10}, $PM_{2.5}$). As a result, the benefit of **air quality enhancement** often contains CO_2 emission reduction or uptake. This however should not be the case as CO_2 is not considered an air pollutant (EU Directive 2008/50/EC; US EPA, 2014a), but rather a greenhouse gas (Lienhard & Lienhard, 2019, p. 596; Fay & Golomb, 2012). This distinction is important since the effect of air pollutants (e.g., NO_x, SO_x, ground level O_3, PM, carbon monoxide, volatile organic compounds) is different than that of greenhouse gases (e.g., CO_2, CH_4, N_2, non-ground level O_3, as well as chlorofluorocarbons and hydrofluorocarbons). Air pollutants deteriorate local or regional ambient air quality, while greenhouse gasses affect the atmosphere at a global level (European Commission, 2004; World Bank, 1992), contributing to climate change (Ahmed Ali et al., 2020). Hence, while the scale of air quality enhancement is urban, that of CO_2 reduction and uptake is societal.

Due to the different natures of the three benefits, the ranges of values provided by the literature for these benefits are different (Figure 3.12). The 50^{th} percentile, or median, instead of the mean value of the distributions was used to summarize the distributions. This choice is due to the median being a statistically more robust central tendency index than the mean (Montgomery et al., 2011). In fact, the 50th percentile is significantly less sensitive to outliers in the distributions than the mean.

When considering the global analysis' pool of studies, air quality enhancement and CO_2 emission reduction exhibit the highest median, equal to 0.13 €/m²/year, while the median value of CO_2 uptake totaled to only 0.001 €/m²/year.

The local analysis relies on a smaller pool of articles, which do not always consider these three benefits. The fewer valuations generate different distributions of values and therefore different median monetary values for these benefits. The median value for air quality enhancement is 0.2 €/m²/year, while that of CO_2 emission reduction and CO_2 uptake are lower, equal to 0.03 and 0.003 €/m²/year, respectively.

In general, it can be noted that these benefits are not significant when compared to the investment costs of green roofs, which is on average 64 €/m² in the local analysis.

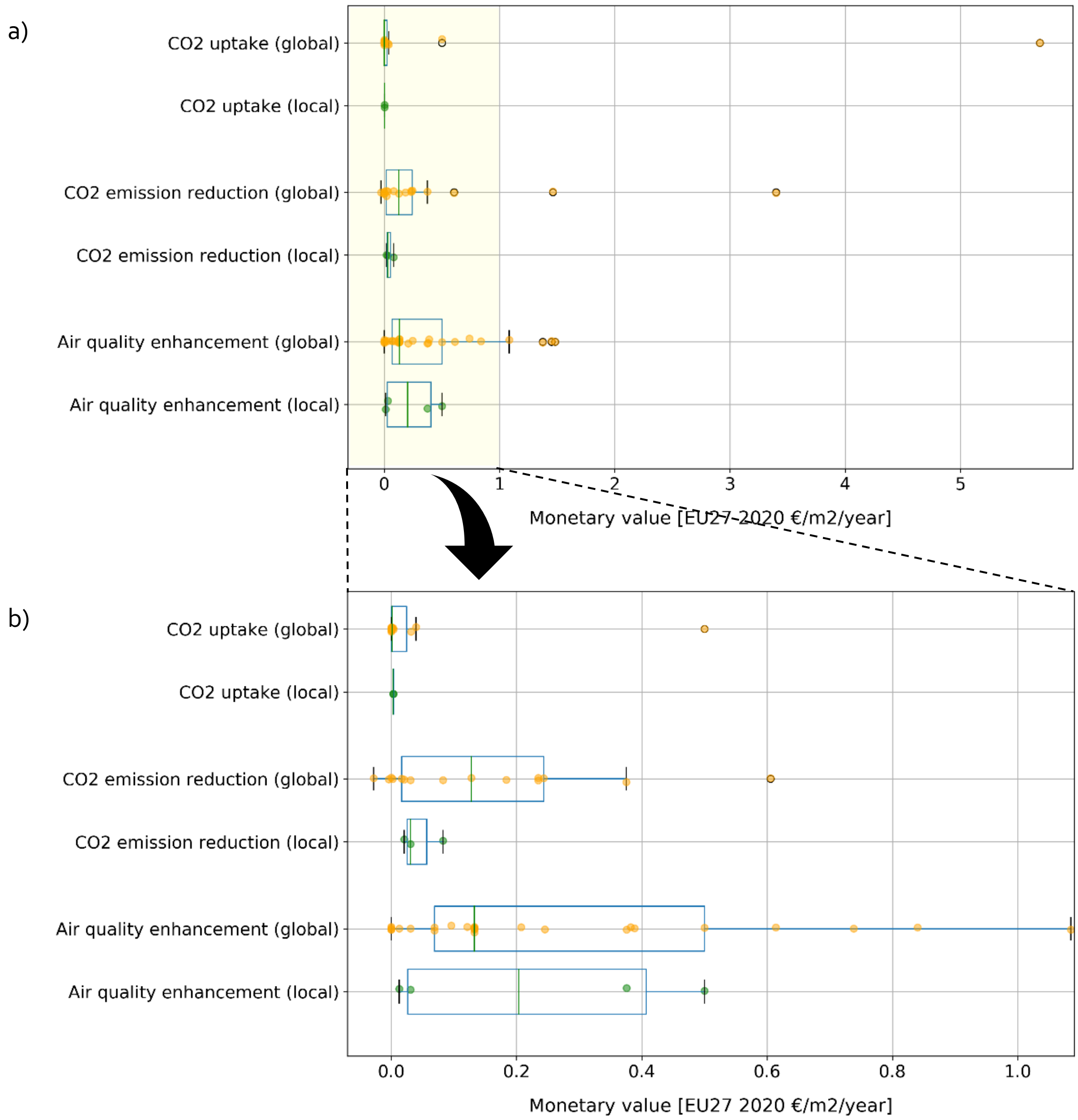


Figure 3.12. Air quality enhancement, CO2 emission reduction and CO2 uptake values in the global (**orange**) and local (**green**) analysis (a) and zoom on the interval [0; 1] €/m²/year (b).

The variability of air quality enhancement values

The variability in the air quality benefits' values may be explained by two factors. First, not all analyses reviewed considered all pollutants. While NO_x was included in almost all articles, SO_x, ground level O_3, or particulate matter were not mentioned in various analyses. Reasonably, the fewer pollutants are considered, the lower the monetary benefit of this item. Second, the methods used relied on parameters subject to uncertainty, which will be described below.

From a methodological point of view, the literature reviewed almost exclusively relied on the avoided cost method. In particular, for the cases where the details of the method used were provided, NO_x, SO_x, ground level O_3, and particulate matter were considered to be responsible for both mortality and morbidity.

Mortality's costs were evaluated proportionally to the so-called *value of statistical life*, which represents the amount of money that society would be willing to spend in order to prevent a single unidentified death (Andersson, 2020). In this regard, it is important recognizing that this estimate has important limitations. First, the value of statistical life may be considered morally offensive by some, as it places a monetary value on a human life (European Commission, 2004), or it may be rejected altogether by others, on the grounds that human life is inhenerntly priceless (Harris & Roach, 2018). Second, the valuation of human lives may not be a merely economic issue but a political one as well. In fact, the value of statistical life used by federal agencies in the US changed over time with changes in presidencies. While during the Bush adminstration the value used by the US Environmental Protection Agency was \$6.8 million, this value increased to \$9.1 million in a 2010 CBA on air pollution standards, published by the same agency (Appelbaum, 2011). In 2016, the agency further increased the utilized value of statistical life to \$10 million (Merrill, 2017). A higher value of statistical life implies that CBAs assessing environmental or safety policy measures could find them less expensive. In fact, based on a higher value of statical life, the US Transportation Department imposed regulations such as requiring stronger car roofs, while such measures were deemed too expensive in the previous Bush Administration (Appelbaum, 2011). In practice different values of statistical life were used by some CBAs of green roofs, although it was not always possible to determine this value, due to the lack of details provided by the CBAs reviewed.

Morbidity's costs considered the development of chronic bronchitis due to air pollution. This was considered to cause cardiac and respiratory diseases and consequent hospital admission, consultation with physicians, as well as restricted work activity. Nevertheless, not all CBAs included all such costs.

Because of the charactersitics described above, air quality anhancement values need to be understood as subject to deep uncertainty. Indeed, not only different groups of pollutants may be considered by different CBAs, but also different morbidity's costs and values of statistical life may be considered by different authors.

A last note regards the highest value for air quality benefits (equal to 1.48 €/m^2/year), which used a markedly different valuation method. In this case, air quality enhancment benefits were valued with the avoided costs of air pollution control measures. Nevertheless, it seems questionable whether the adoption of green roofs could enable foregoing air pollution control measures, since this would require the recognition of green roofs as official substitutes of pollution abatment measures by local authorities. The markedly different methodology used may have signficantly contributed to the obtaining of a higher value compared to other authors' findings (Figure 3.12a).

The valuation methods of CO_2-related benefits

The details related to the valuation of CO_2 uptake and emission reduction appeared rather limited in the articles reviewed. Various studies performed the valuation of these benefits as an avoided carbon tax, whose level was defined by the Kyoto protocol. In other cases, the sources underpinning the carbon tax chosen were not provided. A second way to value CO_2 uptake and emission reduction was the average CO_2 trading value in the European Climate Exchange, or the EU Emission Trading Scheme's value. In these cases, however, details regarding the exact time period from which the values were extrapolated are missing. A third valuation method, although only used in two articles (D. Johnson & Geisendorf, 2019; Yao et al., 2020), consisted of the (avoided) social cost of carbon. The social cost of carbon can be defined as the cost of an additional ton of CO_2 that is emitted in the atmosphere or the overall value of damages associated with an incremental carbon emission unit (Diez, 2011; Wang et al., 2019). Unfortunately, the two articles utilizing this valuation method did not specify the details with which the social cost of carbon was determined in their analyses. In one case it seems that a national (German) estimate was utilized, while it is not clear for the other article. Considering CO_2 emissions as a global externality (Gayer & Viscusi, 2016), the social cost of carbon is often provided as a global figure (Wang et al., 2019). Nevetheless, there exist national estimates for the social cost of carbon, which are smaller in richer countries and larger in poorer countries with large populations (Tol, 2019) . In general, the social cost of carbon varies depending on the techno-economic model used for its estimation, which also includes the modellers' choice of social discount rate. In the absence of knowledege regarding these details, no further correction was performed on the monetary values recored from the literature, while recognizing that differing models, with different discount rates and impact functions could have been used.

Considering the variety of methods used to value CO_2 uptake and emission reduction benefits, and the lack of details reagarding carbon taxes and the social cost of carbon, it was deemed not appropriate to only adjust some articles' values while leaving others untouched. In fact, more recent estimates of the social cost of carbon could be adopted, but – among others – the choice of the country, the techno-economic model, and the discount rate with which to operate this value update would ultimatly embed additional assumptions to a subset of the data hereby presented. This selected update was not undertaken, in favor of a uniform treatment of the data recorded.

3.2.2.6 Aesthetics increase

From the CBAs reviewed, it was found that green roofs increase the aesthetics of a property, a benefit which, although subjective, was monetized by several CBA authors. In order to value this economic benefit, the CBAs that provided a description of the method used based their valuations on the stated preference or the hedonic pricing method. The stated preference method aims at eliciting individuals' willingness to pay for a good or service that increases their well-being, or their willingness to accept an action that reduces it (Harris & Roach, 2018). The most common stated preference method is *contingent valuation*. According to this method, a group of participants is asked, through questionnaires, to state their willingness to pay or willingness to accept in response to a proposed hypothetical scenario in which their well-being is changed (Whitehead, 2006). Hedonic pricing is a revealed preference method, namely an economic valuation method that estimates the value of a good or service based on the observation of individuals' market behaviors (Guerry et al., 2013; Harris & Roach, 2018). In particular, hedonic pricing attempts to estimate how the prices of otherwise similar goods, such as houses, are affected by different environmental characteristics (European Commission, 2004), such as the proximity to green roofs or green areas.

Since the application of contingent valuation and hedonic pricing requires considerable resources, the CBAs reviewed did not carry out surveys to determine individuals' stated preference, nor did they carry out statistical analyses to determine the effect of green roofs on properties' values. Rather, CBAs' valuations were based on contingent valuation results and hedonic pricing intermediate results obtained in other studies. When CBA authors based their valuation on stated preference, they relied on results by Rosato & Rotaris (2014), who studied the effect of green roofs on residential property values in Trieste (Italy). The authors found that individuals were willing to pay for seeing a green roof in the surrounding of their living area between 82€ and 205€ per property area unit. These results were adapted and used by the authors of several CBAs, which were based in the same city or other Italian cities. When CBAs based their valuation on the hedonic pricing method, authors relied on the findings by the United Kingdom's Commission for Architecture and the Built Environment (2005). This study estimated that properties with a direct view or in the close proximity of local parks benefitted from an increase in their property value of 11.3% and 7.3% respectively. Since extensive green roofs are not equivalent to parks, lower estimates ranging from 2% to 5% were chosen by CBA authors (Bianchini & Hewage, 2012; D. Johnson & Geisendorf, 2019; Teotónio et al., 2018).

The valuations included in the global analysis range between 2.0 to 154 €/m², with a median value of 75.5 €/m² and an outlier at 328 €/m² (Figure 3.13a). In contrast, the local analysis can rely on one case-study only, since no other case-studies reviewed satisfied the geographical, climatic, and building conditions of this type of analysis. In particular, the comparison with the rest of the distribution shows that this value is actually an outlier.

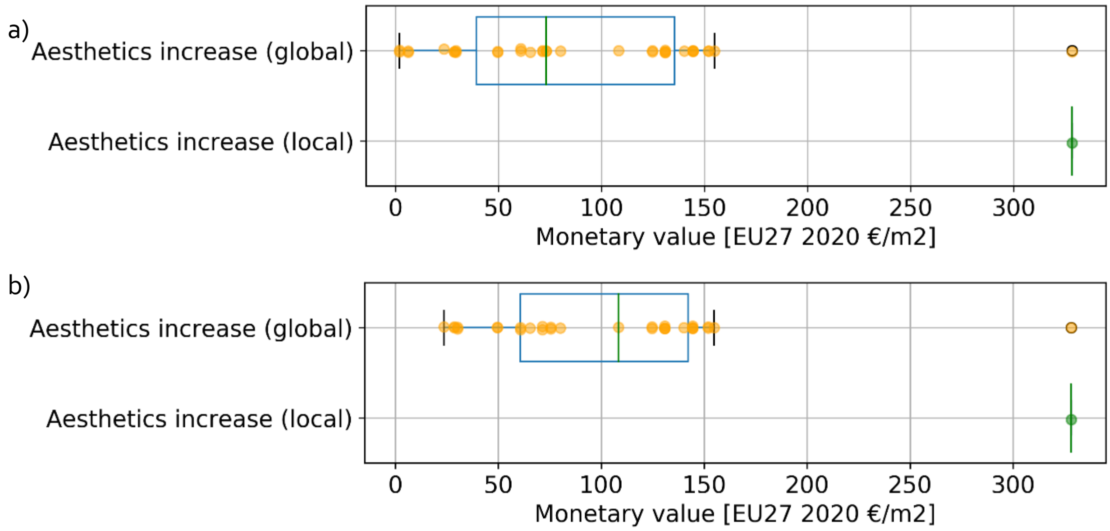


Figure 3.13. Distribution of values for the aesthetics increase benefit in the global (**orange**) and local (**green**) analysis. Figure (a) shows all case-studies' values, while (b) considers results based on hedonic pricing that is applied to the same object only: the whole property's value.

The variability of aesthetics increase values

No significant difference in monetary values was found between studies relying on hedonic pricing and those relying on contingent valuation. Rather, it seems that the high variability of aesthetics benefits based on hedonic pricing can be explained by three factors.

First, contrary to the other studies that described the methods used, Bianchini & Hewage (2012) estimated the aesthetics increase benefit as a percentage increase of the green roof value rather than of the whole property's value. The choice of the authors may be explained by their inclusion of the property value's increase as another separate benefit in the CBA. This approach seems questionable since there exists a possible overlap between these benefits, and a consequent risk of double counting. Hedonic pricing treats a property as a sum of individual goods (e.g., green roofs' benefits and other elements) that cannot be sold separately in the market, and it estimates the contribution of each of these individual goods to the price of the property (Montero & Fernández-Avilés, 2014). Thus, if property value's increase was considered as a benefit, the aesthetics increase benefit would not have to be included, since conceptually it is already embedded in the property's value increase itself. Conversely, if the aesthetics benefit was included, then other benefits contributing to the increase in the property's value, such as sound insulation, should also be included, but the whole property's value increase should not be considered (again). The application of hedonic pricing to the price of green roofs instead of that of that of the whole property produced the lowest values in the distribution, ranging from 2.0 to 6.3 €/m², which may be considered not comparable with the remaining values. Figure 3.13b shows the distribution without these values, whereby a higher median value of 108.4 €/m².

Second, the different locations of the case-studies reviewed are characterized by different average property values. Thus, more expensive city districts may result in higher monetary values for the aesthetics' increase benefit.

Third, CBA authors reduced in different ways the estimates by United Kingdom's Commission for Architecture and the Built Environment (2005). Some authors considered the range of values 2-5% (Bianchini & Hewage, 2012) as the correct one, while other authors based their choice on Bianchini and Hewage's range, and took intermediate values within this range. For instance, 3% was taken for residential buildings, while 5% for commercial ones in the view of Teotónio et al. (2018) proposed to assume a 3% increase in residential properties values, and 5% increase in commercial properties' one. In contrast, Almeida et al., (2021) assumed a single value of 3% increase for school buildings in the same city. Other authors preferred a "moderate" estimate of 3.5% (D. Johnson & Geisendorf, 2019).

While the second cause of variability can be dealt with by considering the percentages of the property value increase instead of monetary values, the third cause of variability can hardly be resolved in favor of a reduced values' variability. In practice, in the face of limited primary data from hedonic pricing analyses, it is difficult to determine which percentage increase among the ones proposed by the literature should be regarded as correct. As a result, the uncertainty in the choice of percentage increase of properties' values, as an adjustment of the available primary data, may seem an irreducible uncertainty.

The variability of aesthetics benefit valuations based on contingent valuation results seems mainly due to one factor: the case study's location. In practice, depending on the city where the green roofs were installed, different values were found, while the same method and data sources were used by CBA authors.

3.2.2.7 Sound insulation

Another benefit provided by green roofs is sound insulation, which is ensured to building residents thanks to the green roofs' vegetation, soil, and other layers underneath (Lamnatou & Chemisana, 2015). In order to value such economic benefit, the CBAs that included a description of the method used based their valuations on the replacement cost or the hedonic pricing method.

The replacement cost method values an ecosystem service or environmental good by considering the costs of actions providing human-made substitutes for such ecosystem service or environmental good (Harris & Roach, 2018). CBAs utilizing this method either considered the costs of thermaltone, polytone and cineplextone acoustic insulation panels (Mahdiyar et al., 2016) or acoustic insulation based on drywall boards (Machac et al., 2016). When the replacement cost is based on acoustic insulation panels, monetary benefits are higher. This is both due to the costs of these technologies and the higher noise reduction capabilities. As suggested by Harris & Roach (2018), when multiple replacement alternatives are available the least-cost option should be used, as it is assumed that society would prefer the least-cost option. This means that drywall-based solutions should be used in the replacement cost method.

CBAs relying on hedonic pricing, based their valuations on the results by Proost and Rousseau (2007), who found that the value of a property decreases by 0.6% as the ambient noise increases by 1 dB in the Flanders (Belgium). Furthermore, according to the Belgian Scientific and Technical Center for the Construction Industry (2006) green roofs' sound insultation can be quantified at around 38-40 dB. For CBAs based on hedonic pricing, the variability of results may be attributed to the number of floors considered to be benefitting from sound insulation. Some studies attributed this benefit only to the last floor, others applied this benefit for the whole building, resulting in very different estimates. In fact, however, sound benefits are not reaped by floors below the highest (Teotónio et al., 2018). For this reason, it is advisable to consider the (average) number of floors in the buildings analyzed, and when more than one, to attribute this benefit only to the top floor.

In the global analysis, without considering outliers, sound insulation ranges from 0.3 to 2.5 €/m²/year, with a median value of 2.02 €/m²/year. In contrast, the local analysis features a more limited range, from 0.3 to 0.5 €/m²/year (Figure 3.14a and b). In contrast, when only the least-cost option is used for CBAs using replacement cost, and only hedonic pricing results focusing on the last floor's property value are considered, the range of monetary values is significantly reduced (Figure 3.14c).

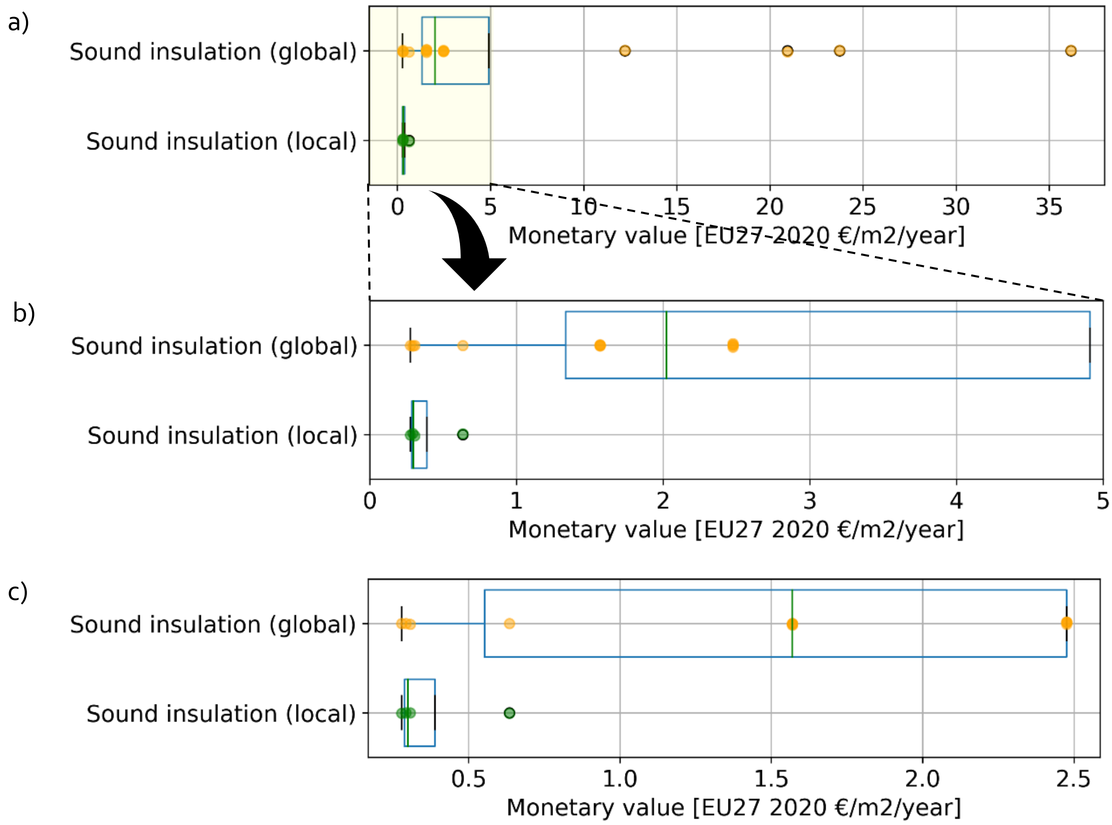


Figure 3.14. Distribution of values for the sound insulation benefit in the global (**orange**) and local (**green**) analysis. All values are presented in (a), a zoom on the interval [0; 5] €/m²/year is provided in (b), instead, the distribution of case-studies applying hedonic pricing to the last floor only, or considering the least-cost replacement option is provided in (c).

As noted for the benefit of aesthetics increase, when hedonic pricing is used to value the sound insulation, property value increase should not be used as a separate additional benefit. For the same reasoning provided in section 3.2.2.6, the inclusion of both benefits would result in a risk of double counting of benefits.

3.2.2.8 Stormwater management

In the case of intense precipitation, the quantity of water flowing in the sewage system of an urban settlement becomes considerably high. Undesired consequences of these events are the high water transportation and treatment costs, as well as the risk of floods in the urban settlement. Green roofs are capable of retaining part of the precipitation, releasing it both through evapotranspiration and as runoff water in the sewage system (Claus & Rousseau, 2012). In particular, the volume of water discharged in the sewage system is reduced and peak discharge is delayed (Shafique, Kim, & Kyung-Ho, 2018). The consequent benefits are a lower risk of floods as well as lower water transportation and treatment costs in the operation of the sewage system. In multiple case-studies the avoidance of municipal stormwater fees, which would need to be paid by individuals residing under impervious surfaces, was also considered.

Case-studies reviewed in the global analysis feature a stormwater management benefit that ranges from 0.002 to 1.5 €/m²/year, with a median value of 0.1 €/m²/year. The global analysis' distribution however, is characterized by outliers that extend up to 340 €/m²/year, considerably increasing the overall range. In contrast, the local analysis' values are concentrated in a smaller range, between 0.1 and 1.5 €/m²/year with a median value of 0.9 €/m²/year (Figure 3.15).

Two factors can be identified as the main contributors to the variability of the values recorded.

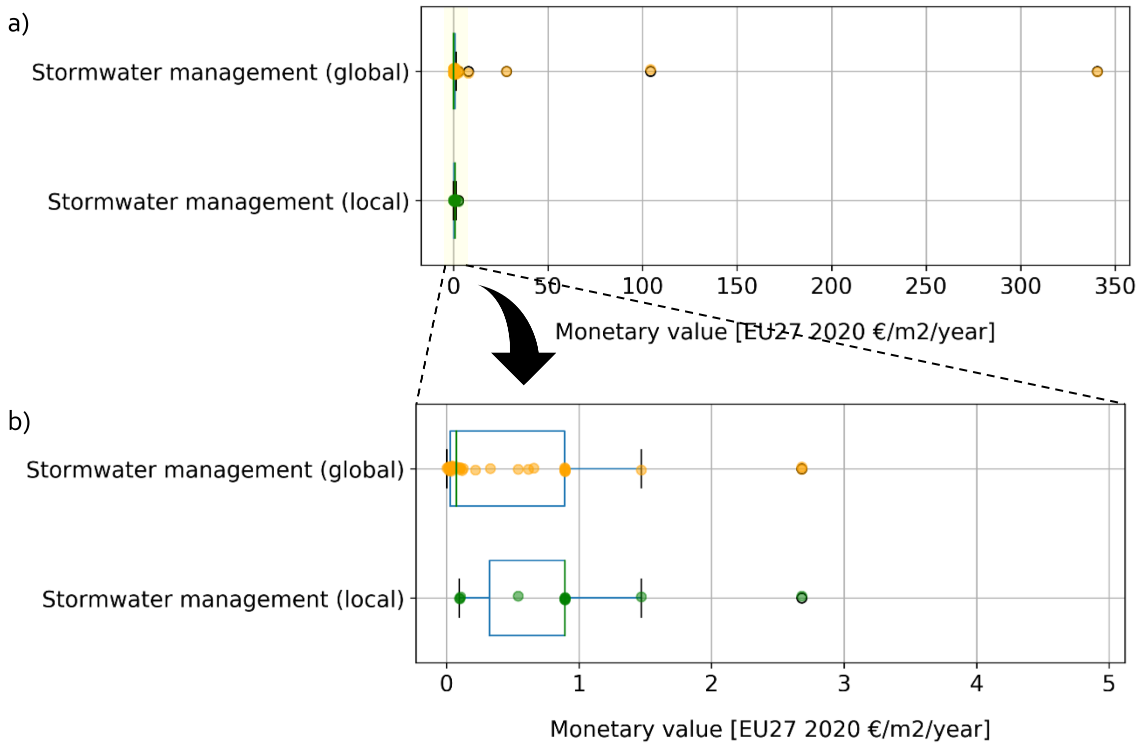


Figure 3.15. Distribution of values for the stormwater management benefit in the global (**orange**) and local (**green**) analysis. All values are presented in (a), while a zoom on the interval [0; 5] €/m²/year is provided in (b).

First, not all studies considered the value of flood risk reduction in their analysis, focusing solely on lower water transportation costs and (in some cases) on lower water treatment costs. Whenever considered, flood risk reduction was valued through the avoided cost method, taking into account damage costs that would be caused by floods in the case-study area at hand (e.g., Bianchini & Hewage, 2012; Shin & Kim, 2019). In particular, the value of damages can change depending on the type of urban settlement.

Since not all areas are equally prone to floods, it is reasonable expecting higher flood damage costs, and high stormwater benefits in areas close to rivers and/or subject to intense precipitation events. Conversely, other areas at low flood risk may consider this issue as irrelevant. (cf. Carter & Keeler, 2008; Shin & Kim, 2015). Thus, stormwater benefit is highly dependent on the case-study at hand, and valuations should as much as possible rely on site-specific information when possible.

Secondly, a subset of analyses (e.g., Berto et al., 2018; Niu et al., 2010; Teotónio et al., 2018) maintained that green roofs could avoid the necessity of future (infrastructural) interventions in the sewage system aimed at preventing combined sewage waterflow. This consideration was however omitted in other analyses.

With regard to the particularly high outlier values recorded, it is difficult determining with certainty the causes of their high valuation of stormwater benefits. In fact, no additional details are provided about the main responsible factors for these high values other than the classification of the avoided costs as 'avoided storm water in drainage system'.

3.2.2.9 Energy consumption reduction

Another important benefit of green roofs is represented by the energy consumption reduction. As already mentioned in section 3.2.2.5, lower cooling needs during summer are documented by several studies (Wong et al., 2003; Zhao & Srebric, 2012), while lower heating needs during winter are not recorded in all building types and climates (Santamouris et al., 2007; Vijayaraghavan, 2016). Thus, in view of a consistent CBA methodology, it is important to specify both types of energy consumption reductions and provide a figure for both; a practice which is still not common to date. According to the climatic and building conditions of the case-study at hand, one of the two benefit types may be absent or particularly low. From a transparency viewpoint, this way of accounting would be more desirable than neglecting one of the two benefit types.

When considering both the reduction in cooling and heating needs, the monetary value for energy consumption reduction was found to range from -0.4 to 3.9 €/m²/year in the global analysis, with a median value of 0.8 €/m²/year. Nevertheless, several outliers can be found up to the value of 54 €/m²/year (Figure 3.16a and b). In contrast, the case-studies reviewed in the local analysis appear to be concentrated in a

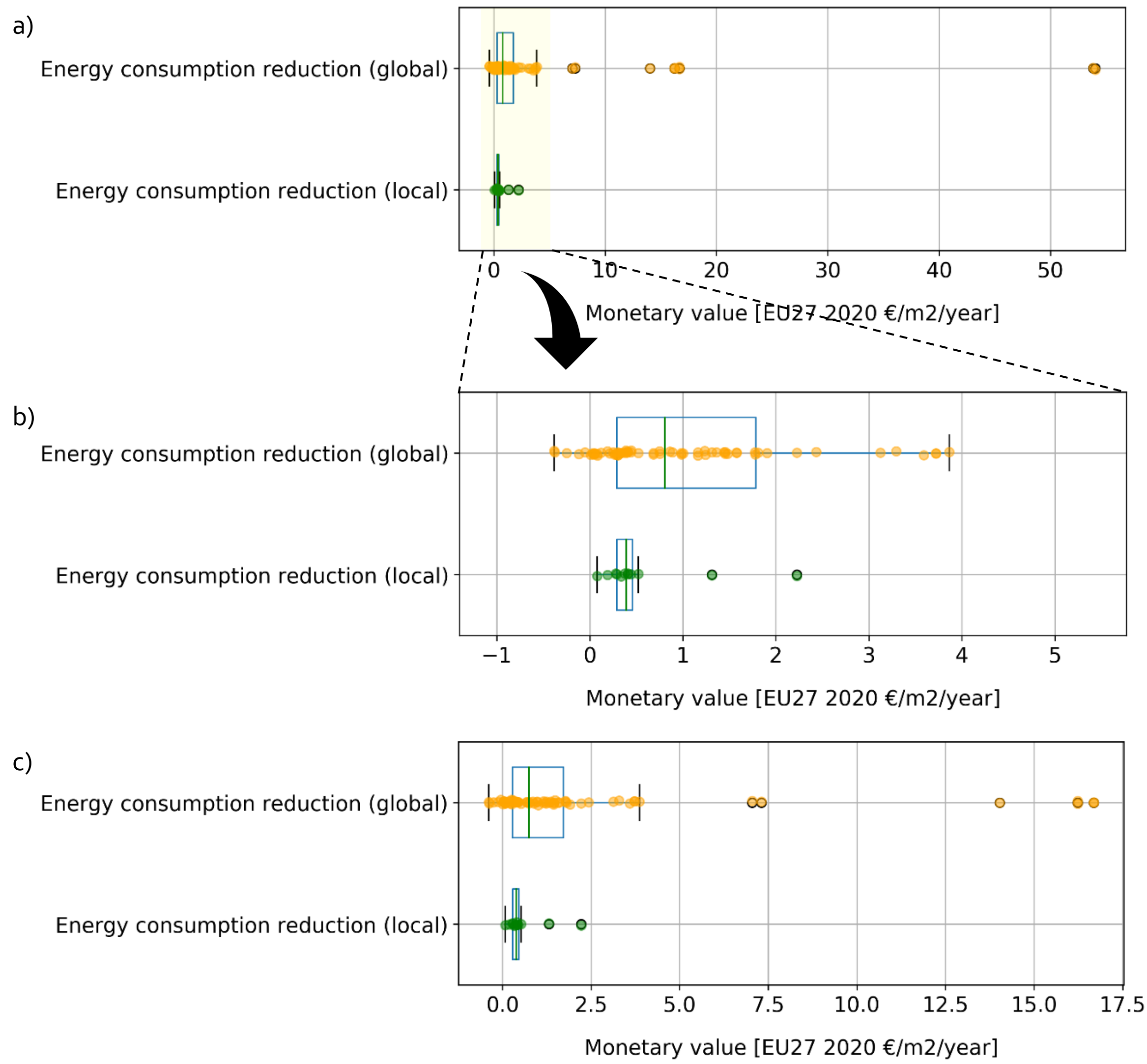


Figure 3.16. Distribution of values for the energy consumption reduction benefit in the global (**orange**) and local (**green**) analysis. All values are presented in (a), a zoom on the interval [-1; 5] €/m²/year is provided in (b), instead, the distribution of case-studies valuing energy consumption reduction for the whole year is provided in (c).

smaller range, between 0.1 and 0.5 €/m²/year, with a median of 0.4 €/m²/year. Even in this case some outliers can be identified, although they are at most equal to 2.2 €/m²/year (Figure 3.16a and b).

The few negative values observed in some of the case-studies reviewed in the global analysis indicate that in some cases the base-case technologies outperformed green roofs. In these particular cases, buildings with black or white roofs required lower energy consumption for heating and cooling purposes than buildings with green roofs. However, as Figure 3.16b shows in the great majority of the cases green roofs outperformed base-case technologies (i.e., black, white, and also gravel roofs). In comparison, all case studies reviewed in the local analysis demonstrate the higher energy consumption reduction benefit of green roofs compared to other base-case technologies.

To value this benefit, the avoided cost method was consistently used across the CBAs reviewed. Specifically, the avoided energy consumption for heating or cooling the building's indoor environment represented the benefit of the installation of green roofs. The variability in the values recorded can mainly be attributed to difference in climatic and weather conditions of the case-studies where the valuations took place. Indeed, when a single climate and base-case roof are considered (i.e., in the local analysis), the range of monetary values is significantly reduced.

A methodological difference was found between, on the one hand, the two highest outliers recorded in the global analysis and, on the other hand, all the rest of the valuations. It was found that the particularly high valuations observed in the study by William et al. (2016), were based on measurements carried out in summer months only. In contrast, the other studies reviewed performed their valuations in a representative period for the whole year. Considering that during summer green roofs are particularly effective in reducing cooling needs (Wong et al., 2003; Zhao & Srebric, 2012), this methodological difference may explain the high values observed. Excluding these summer-based values, Figure 3.16c shows the distribution of estimates that are based on a representative period for the whole year.

3.2.2.10 Other benefits

In this section a review of the remaining benefits of PV-green roofs found in the literature reviewed is provided.

Urban heat island effect mitigation

The urban heat island effect can be defined as the difference in the equivalent temperatures of, on one hand, the city as well as its parts, and, on the other hand, the surrounding natural non-urbanized areas (Stewart & Mills, 2021). Urban areas, and especially large metropolitan areas, are significantly warmer than the surrounding rural areas (Islam & Hasanuzzaman, 2020). The US Environmental Protection Agency (2014b) identifies five main causes of this effect: (1) the sparse presence of vegetation and water bodies, which would provide shade and air-cooling through evaporation; (2) the use of dry, low-reflecting and high heat absorbing materials in the built-up environment, (3) urban geometry, which often generates large thermal masses unable to readily release the absorbed heat, (4) heat produced from human activities, such as air conditioning, or other industrial and building activities emitting waste heat in their environment, and (5) weather conditions, whereby clear and calm weather maximize solar energy reaching urban surfaces and minimize the heat that is carried away by winds.

Green roofs release the heat experienced in an urban area through evaporation and transpiration from its vegetation and soil layers (Shafique, Kim, & Rafiq, 2018). Overall, according to a recent literature review by Manso et al. (2021), green roofs were found to reduce the surrounding air temperature by a minimum average of 1 to a maximum average of 2.3 °C across the studies reviewed. The temperature reduction could depending on plant species as well as climatic conditions (Santamouris, 2014).

All CBAs including this benefit relied on the avoided cost method, considering the electricity consumed for cooling needs that would be avoided due to a lower urban air temperature in the surrounding of green roofs. The case-studies reviewed in the global analysis provided valuations of this benefit ranging from 0 to 3.2 €/m²/year, with a median value of 0.1 €/m²/year. The fewer valuations included in the local analysis considered this effect as negligible (Figure 3.17).

Since the same valuation method was used across the CBAs reviewed, the variability in the monetary valuations may be explained by the same causes of variability for the air temperature reduction estimates, that is, different plant species and climatic conditions.

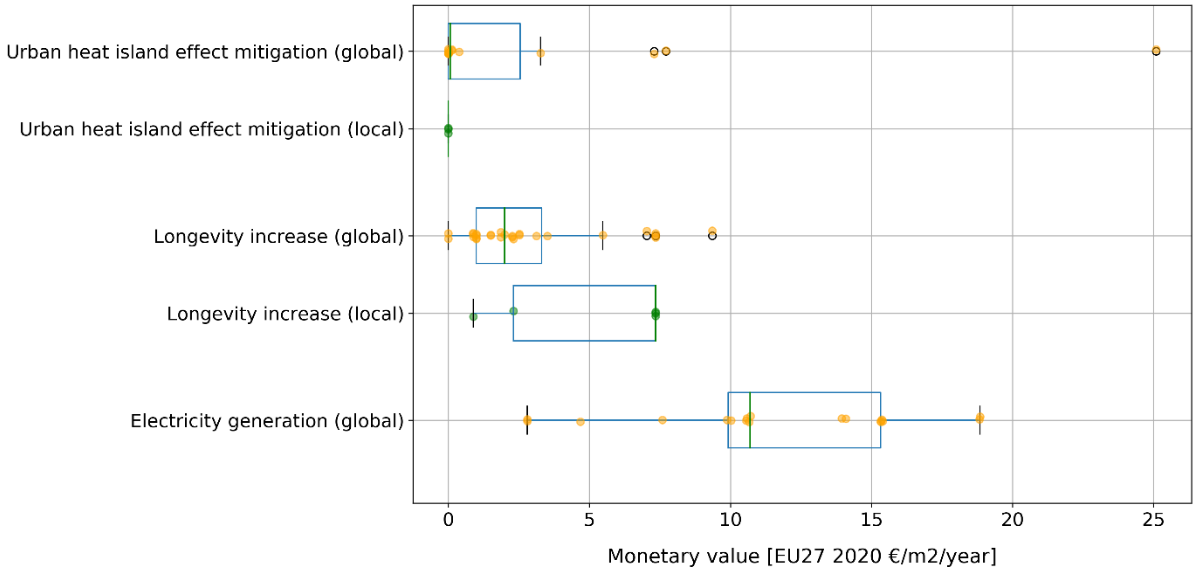


Figure 3.17. Distribution of values for electricity generation, urban heat island effect mitigation, and longevity increase benefits in the global (**orange**) and local (**green**) analysis.

Longevity increase

Another significant benefit is provided by the longer service life of green roofs compared to conventional black roofs. There is an overall consensus in the reviewed literature that green roofs last at least twice as long as conventional roofs (D. Johnson & Geisendorf, 2019; Perini & Rosasco, 2016; Teotónio et al., 2018; William et al., 2016). Specifically, 40 to 50 years, compared to 20-25 years. This implies an avoided replacement of the conventional roof if the green roof is installed. Accordingly, the avoided cost method was used to value this benefit in all case-studies that included this item.

Case-studies reviewed in the global analysis valued the longevity increase benefit between 0 and 5.5 €/m²/year, with a median value of 2.0 €/m²/year. Nevertheless, some outliers extended up to 9.4 €/m²/year. In contrast, the local analysis relied on fewer case-studies, whose values ranged between 0.9 and 7.3 €/m²/year (Figure 3.17).

Since the valuation method used by all CBAs reviewed was the avoided cost method, which is based on the market price of the conventional roof's substitution, the variability of monetary valuations of this benefit can be interpreted as variations in roofs' market values across regions.

Electricity generation

When considering photovoltaic panels, the electricity generated during the sunny hours can be sold to the electricity market. In this case, the monetary valuation of this benefit is related to the electricity market price, which varies depending on the location of the case-study and its regulatory conditions. Feed-in tariffs for small-scale PV installations were considered as the electricity selling price in Europe, while average electricity market prices were estimated by authors focusing on other areas of the world.

For the monetary valuation of this benefit no case-studies were found in the local analysis, while monetary values in the global analysis ranged from 2.8 to 18.9 €/m²/year, with a median value of 10.7 €/m²/year (Figure 3.17).

The variability found in the valuations of this benefit can be explained by two main factors. First, from an economic point of view, electricity market prices differ around the world, and from feed-in tariffs. Second, from a physical standpoint, climatic and weather conditions influence the annual electricity generation of PV modules. In the absence of case-studies of the local analysis considering this benefit, a valuation of electricity generation for the case of Esch-sur-Alzette cannot be determined, since global analysis values are too diverse to attempt a benefit transfer from them. Results from the global analysis, however, show that a significant yearly monetary benefit can be expected from PV-green roofs.

Biodiversity enhancement

Green roofs provide a refuge for nature as plant species may attract various types of honeybees, butterflies or insects (Lamnatou & Chemisana, 2015). Additionally, in a case-study in London by Nash et al., (2016), PV panels were found to contribute to the niche diversity of green roofs. Specifically, the vegetation was found to be more species-rich adjacent to PV panels, especially during dry weather. According to the authors, PV panels may provide microclimates that enable a broader range of plant species to survive particularly dry conditions. In fact, as reported by Cook and McCuen, (2013) PV panels alter the climate underneath the modules, by providing shade and concentrated moisture patches from rainfall runoff below the edges of the panels.

Biodiversity enhancement proved however difficult to quantify (Manso et al., 2021), and various studies omitted this benefit from the CBA either by acknowledging the benefit qualitatively only, or by simply not mentioning it. When quantified, this benefit was valued through the avoided cost or the replacement cost method. When the avoided cost method was used, Green roofs were considered to allow avoiding a fraction of the costs of metropolitan or regional biodiversity preservation programs (Berto et al., 2018; Teotónio et al., 2018), or of restoration of natural areas (Berto et al., 2020; Bianchini & Hewage, 2012). In comparison, when the replacement cost method was used, the cost of hypothetical natural habitat restoration and protection programs was considered.

Overall, case-studies reviewed in the global analysis estimated this benefit in a range between 0 and 0.7 €/m²/year, with a median value of 0.1 €/m²/year. Unfortunately, among these, only one case-study satisfied the conditions to belong to the local analysis, and valued biodiversity enhancement at 0.2 €/m²/year (Figure 3.18).

The variability found in the global analysis can be mainly explained by the different biodiversity protection or restoration actions and programs considered. These actions and programs' costs may vary depending on the political commitment in the region at hand as well as the amenity of the area. For these reasons, it is of crucial importance considering site-specific data to value this benefit.

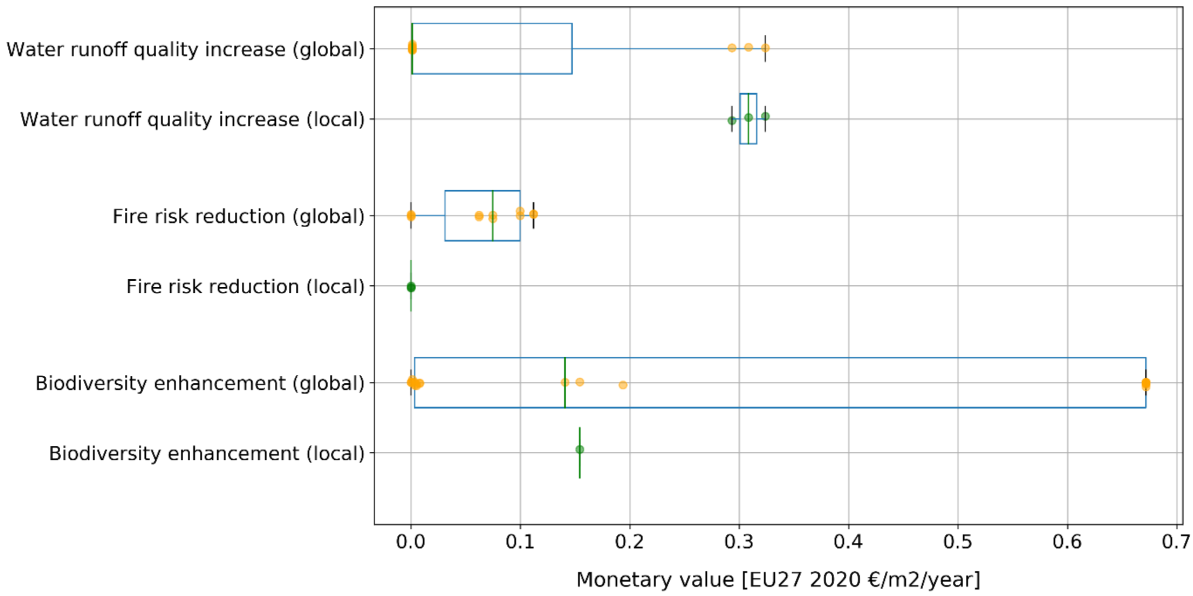


Figure 3.18. Distribution of values for water runoff quality increase, fire risk reduction, and biodiversity enhancement benefits in the global (**orange**) and local (**green**) analysis.

Water runoff quality increase, fire risk reduction, and urban noise reduction

Water runoff quality increase refers to the capability of green roofs to filter precipitation and possibly reduce its pollutants. While some CBA authors (Claus & Rousseau, 2012; Teotónio et al., 2018) included this item as a benefit in their analyses, there are contradictory results with regard to green roofs' water treatment capabilities (Berndtsson, 2010). While green roofs were found to retain cadmium, copper, zinc, and lead from precipitation (Berndtsson, 2010), they were also found to increase the runoff pH, bicarbonate, orthophosphate, dissolved organic carbon, nitrogen, bicarbonate, magnesium and sodium (Aitkenhead-Peterson et al., 2011). In general it seems that green roofs' water treatment capabilities are contingent on the fertilizers used, the plant species as well as the soil layer utilized (Hashemi et al., 2015). Case-studies included in the global analysis ranged between 0 and 0.3 €/m²/year, while those in the local analysis valued this benefit at 0.3 €/m²/year (Figure 3.18).

Fire risk reduction refers to the capability of green roofs to reduce the risk of fire ignition and spread compared to other roof technologies (Breuning, 2008). The valuation of this benefit was carried out with the avoided cost method. In practice, to value this benefit a reduction in the fire insurance was considered if green roofs were installed (Teotónio et al., 2018). As Figure 3.18 shows, this benefit amounted to very low values: the case-studies included in the global analysis provided a monetary value of 0 to 0.1 €/m²/year, while local analysis' case-studies considered this benefit as negligible.

A last benefit recorded in the present literature review is urban noise reduction. Extensive green roofs can contribute reducing noise in the surrounding areas where they are installed by more than 10 dB (Van Renterghem & Botteldooren, 2011). When green roofs are installed in cities subject to traffic or other sources of urban noise, this benefit should not be omitted. Among CBAs reviewed in the global analysis, however, only two case-studies valued this benefit, providing only two estimates based in Lisbon, which are equal to 1.7 and 2.3 €/m²/year. Being Lisbon in the hot-summer Mediterranean climate (Csa), no valuations were found in the local analysis.

3.2.2.11 Costs

Green roofs' costs can either occur at a single event or on a yearly basis. One-off costs are the air pollution and CO_2 emissions due to green roofs' production, their installation, as well as their replacement and disposal. On a yearly basis, green roofs entail maintenance costs.

Estimates for installation, maintenance, as well as replacement and disposal costs were obtained by CBA authors from market prices, as there exists a market for each of these services. Instead, when a description of the method used was provided, air pollution and CO_2 emissions were valued using the avoided cost method, based on the NO_x tax and carbon tax costs, respectively.

As Figure 3.19a shows, the highest one-off cost is represented by the installation of green roofs, which ranges between 18.6 and 116.8 €/m², with a median value of 62.3 €/m² in the global analysis. Similar values are found in the case-studies included in the local analysis, which ranged between 18.6 and 97.1 €/m², with a median value of 72.9 €/m². As described in section 3.2.1.2 , these are differential costs, with respect to base-case roofs (i.e., mainly black roofs, and in few cases white roofs and gravel roofs for the global analysis, and only black roofs for the local analysis). Since all studies used the same valuation method, the main factor responsible for the variability of monetary values is the difference in (geographical) green roof markets where green roofs were bought and installed.

The second most significant cost is roof's replacement and disposal, which occurs at the end of the green roof's lifecycle. In this case, values recorded in the global analysis fell within the range 19.8 – 58.7 €/m², although an outlier was found to be as high as 103.8 €/m². As an indication of the central tendency of the distribution, the median value was equal to 25 €/m² (Figure 3.19a). In this case, reasons for the variability of results other than the different markets where these services were required and performed cannot be easily identified. Indeed, often no details were provided regarding this cost. A possible reason for the

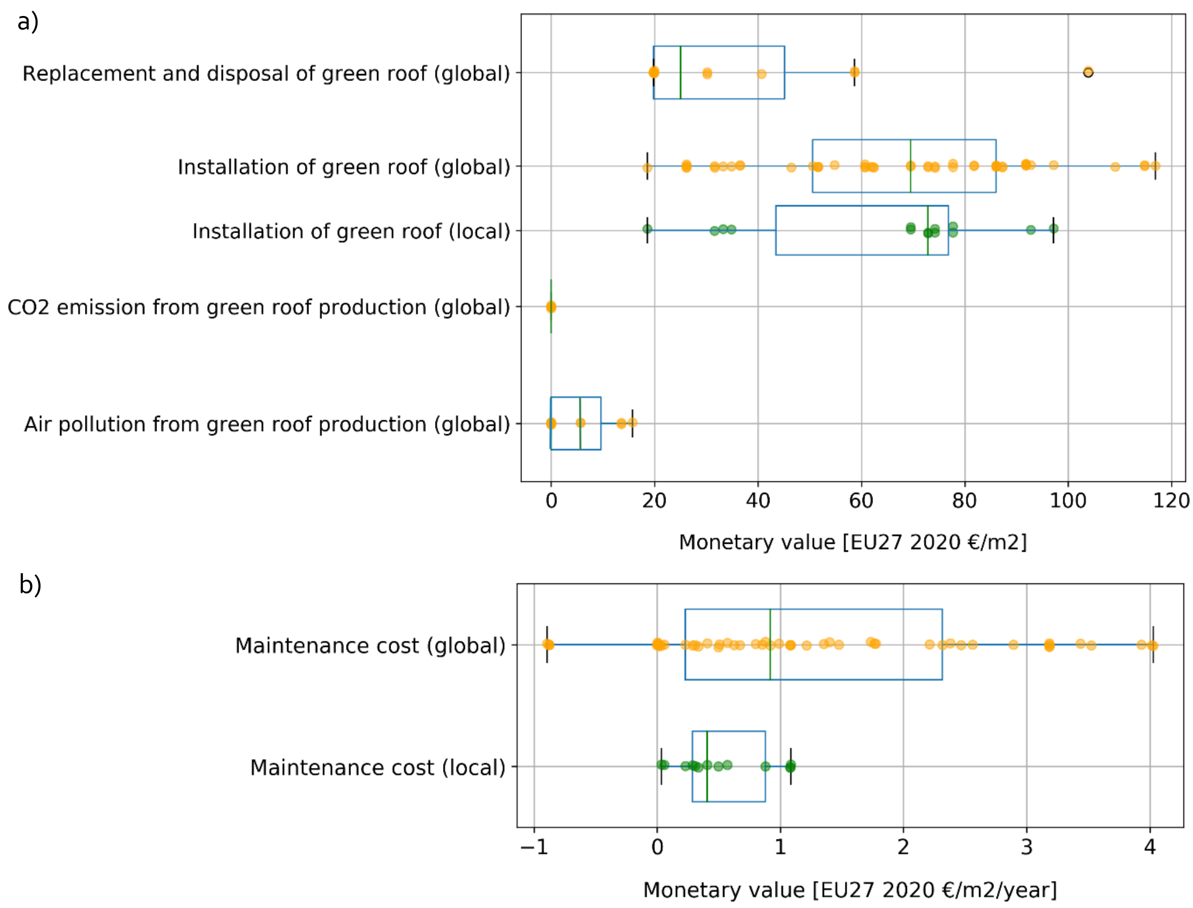


Figure 3.19. Distribution of cost values in the global (**orange**) and local (**green**) analysis. One-off costs are displayed in (a), while yearly recurring costs are depicted in (b).

variability of results can be inferred from the CBA by Teotónio et al. (2018), who distinguished the green roof replacement from that of the drainage layer and other layers, which occurred multiple times during the green roof's lifetime, at different frequencies. In the present analysis the replacement of selected green roof layers were considered as part of maintenance costs, since they occur multiple times during the lifetime of the green roof, nevertheless other authors might have used different assumptions to separate these costs.

An often-neglected cost in the CBAs reviewed is that of CO2 emissions and air pollution generated from green roofs' production. The valuation of the former was found at 0.7 €/m², while the valuation of the latter was found to range between 0 and 13.6 €/m². The few analyses including this benefit did not consider all materials composing a green roof, but rather only its polymers content. During the manufacturing of green roofs, both CO_2 and NO_x emissions were estimated and valued considering taxes for the respective particles emitted. Since, carbon taxes and other air pollution taxes vary from country to country, this cost is very site-specific. In addition, since materials used for green roofs vary depending on the manufacturer, this cost should be associated to specific green roof models.

The only cost occurring on a yearly basis was the green roof maintenance cost, whose valuations in the global analysis ranged between -0.9 and 4.0 €/m²/year, with a median value of 0.9 €/m²/year. The valuations included in the local analysis were concentrated in a smaller range, between 0.03 and 1.1 €/m²/year, with a median value of 0.4 €/m²/year (Figure 3.19b). Negative costs, namely benefits, were recorded if green roofs maintenance was compared to the maintenance of white roofs in a case-study in Trieste (Italy). Nevertheless, Figure 3.19 shows that in the great majority of the cases green roofs entail higher maintenance costs than other base-case roofs. For this cost, the difference in markets and the possible inclusion of selected layers' replacement costs are the main reasons of values' variability.

A last note regards the installation costs of PV panels, for which only one value dating back to 2017 was recorded. Due to the fast rate of technological and price change of PV panels (Harris & Roach, 2018), this cost was considered misleading and was excluded from the analysis.

3.2.2.12 How Photovoltaic-Green roof Energy Communities address the European Green Deal

Framed as a response to climate and environmental challenges, the European Green Deal is a strategy set out by the European Commission to transform the EU into a society with no net emissions of greenhouse gases in 2050 (European Commission, 2019, p. 2). The EGD can be decomposed into a total of eight elements (Figure 3.20). Among these, five EGD objectives stand out as particularly relevant for PGECs.:

(1) the provision of clean, affordable, and secure energy;
(2) the restoration and preservation of ecosystems and biodiversity;
(3) a zero pollution ambition for a toxic-free environment;
(4) climate neutrality and strengthened efforts on climate change mitigation and adaptation;
(5) the building and renovation in an energy efficient way.

Additionally, PGECs appear to be pertinent with a 6th objective of the EGD: the goal to mobilize a circular economy.

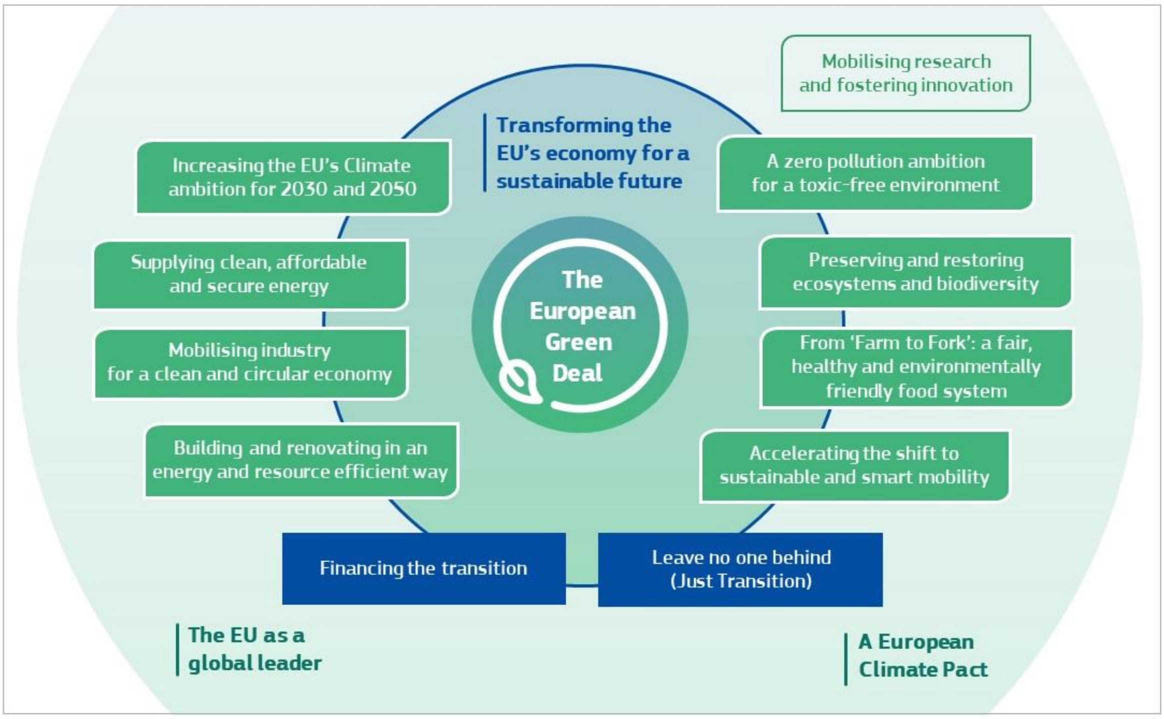


Figure 3.20. The elements of the European Green Deal (European Commission, 2019). The Climate ambition is specified further by the European Climate Law as the objective of climate neutrality (EP and EC, 2021) and by the climate strategy, as climate change adaptation and mitigation (European Commssion, 2021).

The literature reviewed in the previous section clarified the variety of benefits and co-benefits that PV-green roofs bring to the residents of building where they are installed, to the urban area where they are located, and to society more at large. The relationship between these technologies and the 5 relevant EGD objectives is displayed graphically in Figure 3.21 through a highly aggregated causal map. Such a map was drawn following causal maps' diagrammatic conventions as set out by Enserink et al. (2010).

In the causal map, two *means* are present: the installation of photovoltaic panels, and the implementation

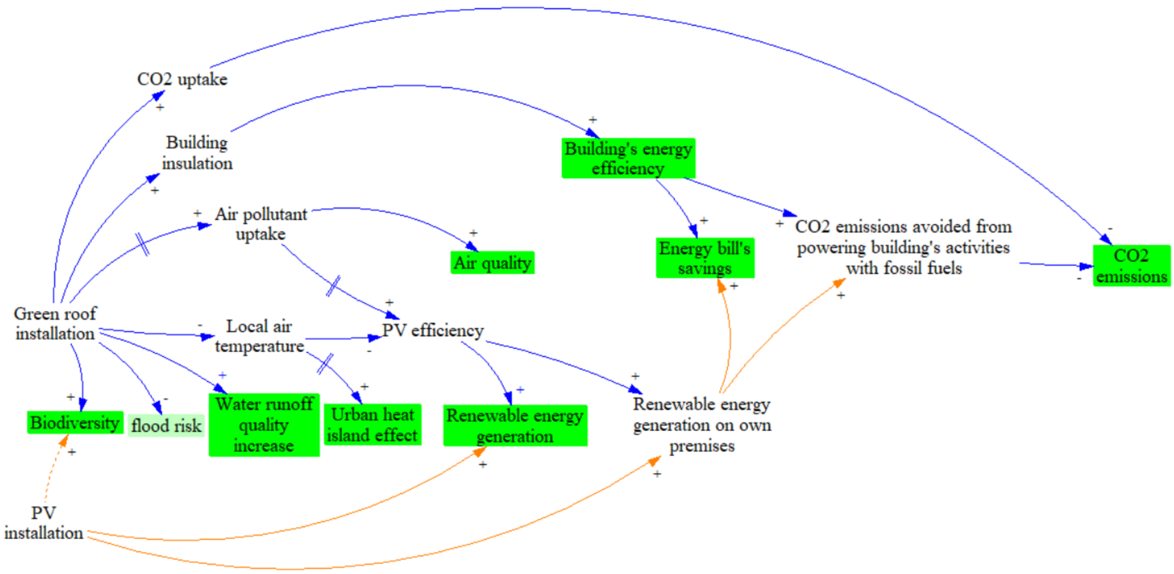


Figure 3.21. Highly aggregated causal map displaying the relationship between photovoltaic-green roofs and EGD objectives. Each node represents a factor causally connected to the others, two means are depicted on the right, and they are connected through causal paths to the *ends* of the map. To facilitate the visual tracking of each effect to its root cause, causal links were colored according to the two causal roots present.

of green roofs. Nine *ends* are depicted in dark and light green, these are the benefits of the means, as documented by the literature reviewed in section 3.2. In particular, dark green ends refer to EGD objectives. Although each of them is not a EGD objective directly, they represent parts of such objectives, so that EGD objectives consist of combinations of dark green ends. 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.

When installing photovoltaic panels only, an increase in renewable energy generation is obviously obtained. Additionally, the availability of energy on one's premises enables the reduction of energy bought from other market parties, as well as the sale of the excess energy to the electricity market. This has an overall reduction effect on the energy bill of the PGEC members, and thus contributes achieving the EGD goal of providing a *"clean and affordable energy"*. Moreover, considering that PGECs generate energy that can be consumed in the same country, PGECs also contribute to *secure* energy generation.

The reduction in energy consumption due to generation on the PGEC's premises enables avoiding CO2 emissions. Indeed, such emissions would have occurred if the PGEC had consumed energy from the grid, as energy would have been generate also from fossil fuel-based power plants, at a percentage depending on the country energy mix. Given that fossil fuels occupy more than 70% of the European energy mix (Eurostat, 2020), the lower energy demand means lower carbon dioxide (CO_2) emissions. This effect contributes to the EGD objective of *climate neutrality*.

Shifting the focus on green roofs, their implementation also reduces CO2 emissions thanks to the plants' uptake of CO2, although then magnitude of this effect depends on plant species (section 3.1.2.2).

Additionally, green roofs' layers increase the building roof's insulation, which further enhances the efficiency of the building. A higher energy efficiency in turn reduces the average energy needs, increasing energy bill's savings, and in this way, it avoids the associated CO_2 emissions. Such causal links further contribute achieving the EGD of carbon neutrality and also that of *building and renovating in an energy efficient way*.

The installation of green roofs enables plant species to also uptake air pollutants (e.g., NO_x, SO_x, O_3, and PM), although featuring a limited magnitude (labelled with a delay mark on the causal link). This effect enhances ambient air quality, attending to the EGD goal of a *"zero pollution ambition for a toxic-free environment".*

Furthermore, the higher air pollutant uptake, the lower the concentration of pollutants near the surface of PV panels, and thus the lower the dust on the PV panels' surface. This effect, although limited in magnitude is document by the literature (Shafique et al., 2020), and enhances the efficiency of PV cells. An increase in photovoltaic efficiency is also obtained through the evapotranspiration effect of the vegetation and soil, which cools the air surrounding the PV panels. As a result, a higher renewable energy generation, energy savings, and CO_2 reductions are achieved.

Evapotranspiration, together with the shading provided by PV modules and the vegetation layer helps curbing the increase in roof surface temperature and thus reduces the heat island effect. As a result, this effect contributes to strengthening the efforts on climate change adaptation, as provided for by the EGD.

Green roofs' vegetation and soil layers are able to delay stormwater peaks and reduce stormwater runoff, reducing the risk of floods. Although this benefit is not directly framed as a EGD objective, it still helps achieving some of the sub-objectives of the zero-pollution ambition. In fact, the EGD strategy foresees for this goal to also restore the ground and surface water's natural functions, so as to prevent and limit damage from floods (European Commission, 2019, p. 14). Additionally, although limited, and conditional on the little use of fertilizers, water quality runoff can also be increased with the installation of a green roof.

Green roofs were also found to attract honeybees, butterflies and various insects providing a refuge for nature and enhancing the biodiversity of the area where they are installed. Provided that PV panels are implemented in combination with green roofs, a higher variety in habitat niches can be provided in the proximity of the PV modules. This coupled effect contributes to the EGD objective of *"protecting, conserving and enhancing the EU's natural capital"*.

It is important noting how PV-green roofs contribute to each of the five considered EGD objectives with a combined effect from both their PV panels and green roofs. This means that the combination of these technologies can be particularly valuable as a lever for policymakers.

A last benefit relevant for the EGD is the longevity increase of green roofs, which increases the durability of products in the buildings' stock. This effect is in line with the EGD goal *"to mobilize a circular economy industry"*. Indeed this goal was specified -among other things- with a set of measures to encourage businesses to allow consumers to choose durable products (European Commission, 2019, p. 8).

3.3 Conclusion

The aim of this chapter was to address the second and third sub-research questions:

What are the financial, economic, and socio-environmental costs and benefits associated with the installation and operation of PV-green roofs, as a part of a PGEC?

How would PGECs address the wider objectives of the European Green Deal?

In this chapter PGECs' institutional and physical layers were identified first. The main institutional statements structuring the social interaction within PGECs and between PGEC members and external actors were determined using the ADICO grammar of institutions. The main characteristics of PV-green roofs, and their design characteristics were also determined. This first phase provided a clear picture of what PGECs may look like, both institutionally and technically.

Having defined the components of PGECs, a systematic literature review of academic CBAs on green roofs was conducted and complemented with studies focusing on the specific benefit of PV power output increase. The review enabled the identification of five costs and more than 15 benefits stemming from the whole lifecycle of PV-green roofs. A classification for costs and benefits was defined, and it was then applied to the items found in the literature review. Items were classified as financial, economic, and socio-environmental and they were further categorized according to their building, urban, or societal scale.

From a methodological standpoint, the review of the CBAs allowed the identification of inconsistencies across articles. A first one was found with regard to how CO_2 emission reduction, uptake, and air quality enhancement, are treated by CBAs. Various case-studies grouped combinations of these benefits together, although the underlying physical effect of air pollutants is different than that of CO_2 emissions.

In a similar way, another inconsistency emerged in how aesthetics increase, sound insulation, and property value increase were accounted. In fact, the first two benefits are conceptually included in the third, and thus a consistent CBA methodology should either provide a combination of the first two, or only the third.

At a quantitative level, the distributions of items' values were elicited and provided for the main costs and benefits, namely for all those recurring in at least more than one article. Results were shown for a global analysis first, which considered all the case-studies reviewed, and for a local analysis as well, which only considered case-studies performed in Europe, in the same climatic and building conditions as the Quartier Alzette, in Esch-sur-Alzette (Luxembourg). The variability of cost and benefit values in the local analysis was often reduced compared to that of the global analysis, and sometimes by a significant amount. Nevertheless, for some costs and benefits the local analysis was found to rely on only few case-studies.

The highest costs were found to be those associated with the installation and replacement of the green roof, with median values of 62.3 €/m^2 and 25 €/m^2, respectively (global analysis). The highest yearly benefits recorded were the aesthetics increase and the electricity generation, with median values of 75 €/m^2/year and 10 €/m^2/year, respectively (global analysis). An important value omitted in almost all of the CBAs reviewed were PV installation costs, while no analysis was found to include PV maintenance costs. When considering the local analysis, aesthetics and longevity increase benefits were found to be the highest.

Both in the global and, at a more limited extent, in the local analysis, cost and benefit values exhibited a variability that was generated by multiple causes. In most cases these reasons are specific to the cost and benefits at hand, but in general, three high-level causes for the values' variability can be identified.

First, climatic, building, and geographic conditions influenced cost and benefit values. This cause of variability was addressed by devising a local analysis. Nevertheless, there still exists the possibility of values' variations. In particular, variability could occur as a result of different microclimates within the same climate classes and different roof specifications within the same roof type. Second, several benefits did not have a market value which could be directly used as a cash flow in a consistent way across various CBAs. This is the case for the socio-environmental as well as the economic items that were reviewed, and consequently alternative valuation methods were used. Third, monetary valuations were often based on different assumptions, which could not be easily distinguished into right and wrong. For instance, this is the case for the choice of value of statistical life in the valuation of air quality enhancement. It is also the case for the aesthetics' increase benefit, in which the primary hedonic pricing studies' results needed to be adjusted in order to be used in the CBAs of green roofs. In this situation, authors' different adjustment choices could not be easily recognized as right or wrong.

All of the benefits found in the literature were then linked to the European Green Deal's strategy, showing how the implementation of PV-green roofs can address up to five major EGD policy objectives. Importantly, except for the reduction in flood risk, the mitigation of the urban heat island effect, and the air quality enhancement, all other benefits contributing to the EGD objectives featured a combined effect of both PV panels and green roofs. Such a result underscores how PV-green roofs can be a particularly valuable lever for EU as well as national policymakers in addressing the European Green Deal objectives.

4

The Economic Convenience of Photovoltaic-Green Roofs

Chapter 3 delineated the institutional and physical layers of PGECs, identified all the costs and benefits associated to their physical layer, and showed how PGECs address the policy objectives of the European Green Deal. This chapter aims at identifying the conditions for which PV-green roofs are economically convenient for (1) society and for (2) PGEC members. To determine the former, exploratory modelling was performed by means of a probabilistic social cost-benefit analysis (probabilistic SCBA), complemented with Scenario Discovery. To determine the latter a probabilistic private cost-benefit analysis (probabilistic PCBA) was performed instead.

First, the motivation for utilizing a probabilistic cost-benefit analysis and exploratory modelling is examined in section 4.1. Next, an overview of the methods used is provided in section 4.2. Lastly, section 4.3 presents and discusses the exploratory modelling results.

4.1 A variety of scientific results

The literature review conducted as part of this dissertation showed a high variability of the monetary values associated to each of the costs and benefits of PV-green roofs. Such results' variability was found to be due to three high-level causes. First, climatic, building, and geographic conditions influence the values of green roofs' costs and benefits. Second, since several benefits did not have a directly usable market value, alternative valuation methods had to be used. Third, some monetary valuations were based on different assumptions that could not be easily distinguished as right and wrong.

While the variability associated to the first cause can be reduced by selecting only the values obtained in similar geographic, climatic, and building conditions, the variability due to the second cause cannot always be reduced. In fact, when alternative methods are applied and few details are provided, elements for excluding some valuations while keeping others may be lacking. Lastly, the third cause is deemed a source of irreducible variability, as it is dependent on the ethical or epistemological stance of authors.

The monetary valuations' variability is acknowledged in the literature (Manso et al., 2021; Teotónio et al., 2018) and it is seen as an issue that could potentially hamper decision-making and policymaking (Teotónio et al., 2021). In particular, scientific knowledge represented by CBA results, has become subject of debate (Vijayaraghavan, 2016), whereby academic studies can be found contradicting one another, with opposing views and results (see for instance, Jim & Tsang, 2011; Santamouris et al., 2007; Zhao & Srebric, 2012). Not only there is disagreement with regard to the outcomes of CBAs (Teotónio et al., 2021), but also with regard to their input values, as some benefits are disregarded or considered negligible by some, while being valued by others (see for instance Melo et al., 2020; Shin & Kim, 2019). To some extent, the variety of differing assumptions made by authors may also be seen as an uncertainty on the inner working of the system under study.

Such a context of uncertainty and disagreement over inputs to CBAs, namely costs and benefits' valuations, has traditionally been dealt with probabilistic CBAs (Nassar & Al-Mohaisen, 2006). According to such a method, input variables can take a range of values as opposed to being fixed to a single one, and as a result, multiple net present values are obtained from the CBA, each of which with a different probability.

A complementary approach supporting decision-making in the situation of uncertainty and disagreement at hand is represented by *exploratory modelling* (Kwakkel, 2017). Instead of beginning with the assignment of agreed-upon values to all CBA inputs so to then derive CBA results, (the application of) exploratory modelling consists in acknowledging a wider range of stances with regard to valuations and methods, so to then explore the consequences of these different stances (cf. Lempert, 2014).

In practice, when the variability in the cost and benefit valuations cannot be reduced any further, due to different ethical, theoretical or epistemological stances, exploratory modelling would take such inputs as irreducible uncertainties and explore the consequences of such uncertainties, with the aid of model-based scenario techniques capable of simulating a wide variety of possible futures (Bankes et al., 2013). As a result, instead of following the traditional CBA approach, termed by Kalra et al. (2014) as "*agree-on-assumption*" approach, exploratory modelling pursues a reverse approach (Lempert, 2014). It defers any agreement on assumptions until (1) the consequences of such alternative assumptions have been studied and (2) those differences in assumptions that could make a relevant difference in the CBA outcomes are identified.

4.2 Methods

In order to perform exploratory modelling to determine PV-green roofs' economic convenience, first the definition of the system under study, the problem associated to this system and the problem owner are provided in section 4.2.1. Second, the description of the probabilistic social cost-benefit analysis (SCBA) used is provided in section 4.2.2, and the way this probabilistic SCBA can be treated as a model and simulated multiple times is shown in section 4.2.3. Next, in section 4.2.4 Scenario Discovery is described as the tool used to find the conditions enabling PV-green roofs' economic convenience for society. Lastly, in section 4.2.5 a probabilistic private cost-benefit analysis (PCBA) is described as the tool used to determine the incentive level ensuring economic convenience of PV-green roofs for PGEC members.

4.2.1 Definition of the System and the Point of View of the Analysis

For the analysis of this chapter, the ***system*** under study was identified as the collection of PV-green roofs that belong to a photovoltaic-green roof energy community to be located in the Alzette district of Esch-sur-Alzette (Luxembourg). This district, also termed as Quartier Alzette, consists of an ex-industrial area that used to host the steelworks Esch-Schifflange and is displayed in its current state in Figure 4.1a. Following an urban design competition in 2019, the winning team of Danish architects COBE, Urban Creators, Urban agency and the Luxembourgish Luxplan developed the "Stadfabrik" conceptual masterplan for the development of the district (AGORA, 2020). An aerial view of the winning project is provided in Figure 4.1b. Due to the nature of the competition and of the master plan, the development of Quartier Alzette is still in its very early stages. Future rounds of refinements and approvals await the project proposal and further specifications can be expected in the following years. Nevertheless, the Stadfabrik masterplan did not present incompatibilities with the development of a PGEC in the form of a REC as defined in the EU law. Establishing under what conditions the collection of PV-green roofs located in the Alzette district is economically convenient was considered as the system's associated ***problem***.

Although PV-green roofs of PGECs are purchased by the energy community, acting as a legal entity, in this analysis the ***problem owner*** was considered to be the Government of Luxembourg. This is because according to the RED II, set out by the EU in 2018, EU Member States need to regulate and – to the extents provided by the law – promote renewable energy communities within their national borders. Thus, understanding under what conditions the benefits of PV-green roofs outweigh their costs is in the interest of EU national governments.

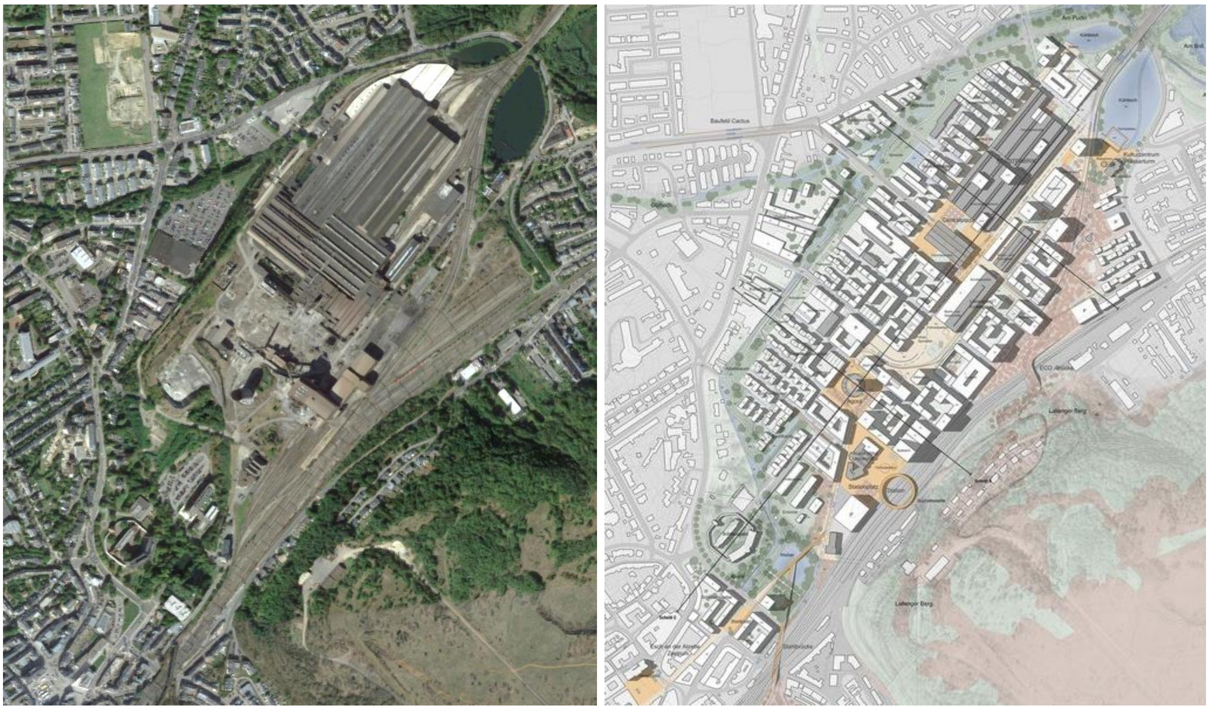


Figure 4.1. Aerial view of Quartier Alzette . The current state of the district is displayed on the left (a) while the winning project for the renovation of the district (AGORA, 2019) is depicted on the right (b).

4.2.2 The Use of a Probabilistic Social Cost-Benefit Analysis

To determine whether the benefits of the system under study outweigh its costs, a probabilistic SCBA was used.

The CBA carried out is *social* since SCBAs attempt to monetize all costs and benefits of a project, namely not only the items that are borne or enjoyed by community members but by society more at large. In particular, since the system under study is represented by a PGEC in Esch-sur-Alzette, only the items' values that were recorded in the local analysis of Chapter 3 were considered. This means that the SCBA aimed at including all financial, economic, and socio-environmental items found in the literature to date, but it only uses valuations obtained for case-studies similar to the conditions of Esch-sur-Alzette. Specifically, the conditions imposed on items' valuations for taking part in the local analysis were defined in section 3.2.1.2, and they required that:

- The case-study containing items' valuations was carried out in Europe;
- The case-study is subject to the same climate as the one in Esch-sur-Alzette; and

- The monetary valuations are differential with respect to the implementation of a conventional black roof, which represented the base-case technology.

In practice, items satisfying these conditions belonged to five articles, and five case-studies. Four articles based their valuations on location-specific case-studies, which were in Amsterdam (the Netherlands), London (United Kingdom), Berlin (Germany), Dilbeek (Belgium), and Jinonice (Czech Republic). Instead, the article by Bianchini & Hewage (2012) did not focus on one specific geographical area, but rather it used valuations obtained from different locations. In the same way as for all other items' valuations, only the valuations that satisfied the three conditions set out above were used from this article.

The SCBA carried out is *probabilistic* in order to consider the ranges of cost, benefit, and discount rate values that were observed in chapter 3 for the monetary valuation of items and the CBAs' execution. By considering the local as opposed to the global analysis' results, the variability due to climatic, geographic, and base-case building conditions was reduced. Thus, the probabilistic SCBA focused on the remaining variability, which was mainly due to different methods, employed providing few details about their application, or different ethical or epistemological stances of authors.

4.2.3 SCBA Modelling and Simulation

In the present research, the probabilistic SCBA was treated as a function of uncertain variables delivering a quantitative outcome of interest, and also as a model of the system of interest defined in section 0. In the next section, the SCBA function and model will be described (section 4.2.3.1). Subsequently, the details regarding the simulation of such model will be provided (section 4.2.3.2).

4.2.3.1 SCBA modelling

The probabilistic SCBA can be 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.

For the system considered in the present dissertation, the cost, benefit, and discount rate variables represent *uncertainties*. Indeed, these variables' values can vary within the ranges defined by the literature's findings, which were presented in the local analysis results of Chapter 3. The *relation* between the cost, benefit, and discount rate variables is expressed by Equation 4.1. Such equation also defines the model's *performance metric* as the net present value of the PV-green roofs of the PGEC at hand.

Equation 4.1. Analytical formulation of the SCBA model. Several cost variables ($\boldsymbol{c_1, \dots, c_m}$) and benefit variables ($\boldsymbol{b_1, \dots, b_n}$) exist for the system at hand, and they are accounted for each year $\boldsymbol{t}$ within the project's lifetime $\boldsymbol{T}$. The algebraic sum of cost and benefit variables is discounted by means of the social discount rate variable $\boldsymbol{r}$.

$$NPV = f(b_1, \dots, b_n, c_1, \dots, c_m, r, t) = \sum_{t=0}^{T} \frac{b_{1,t} + \dots + b_{n,t} - (c_{1,t} + \dots + c_{m,t})}{(1+r)^t}$$

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

As it can already be noted in Equation 4.1, the SCBA is to be intended as a vectorial function f that maps multiple uncertainties $x_1, \dots, x_n$ (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). This is made explicit in Equation 4.2 whereby the group of all uncertainties was summarized as a single vector of uncertainties $\boldsymbol{x} = (x_1, \dots, x_n)$.

Equation 4.2. The SCBA as a vectorial function. Vectors are written in **bold**, while one-dimensional variables are in normal font.

$$m = f(x_1, \dots, x_n) = f(\boldsymbol{x})$$

The range of possible values for each uncertainty x_i was defined as the upper less the lower whisker of the monetary value observed for that cost, or that benefit, or of the social discount rate in the local analysis of Chapter 3. This means that outliers recorded in the local analysis were excluded, favoring the consideration of the central part of distributions, identifiable by means of boxplots. When considered together, the ranges of possible values defined for each uncertainty compose the *uncertainty space* X, or the domain of f. Thus:

Equation 4.3. Domain and Codomain of the SCBA function.

$$f: X \rightarrow M \mid m = f(\boldsymbol{x}) \in M, \forall\, x \in X$$

The list of the 13 uncertainties included in the SCBA probabilistic analysis together with their value ranges is provided in Table 4.1. The ranges were taken from Chapter 3's local analysis' results.

Table 4.1. Uncertainty space's limit values.

Uncertainty	Minimum value	Maximum value	Unit of measure
Installation of green roof	18.61	97.14	€/m²
Maintenance of green roof	0.03	0.29	€/m²/year
Aesthetics increase	0.00	328.24	€/m²
Air quality enhancement	0.01	0.50	€/m²/year
Biodiversity enhancement	0.15	0.15	€/m²/year
CO2 emission reduction	0.02	0.08	€/m²/year
CO2 uptake	0.0028	0.0034	€/m²/year
Energy consumption reduction	0.08	2.22	€/m²/year
Longevity increase	0.89	7.34	€/m²/year
Sound insulation	0.28	0.64	€/m²/year
Stormwater management	0.10	2.67	€/m²/year
Water runoff quality increase	0.29	0.32	€/m²/year
Social discount rate	2	8	-

Considering the high value obtained for aesthetics increase, and the limited data (amounting to one value only) for the local analysis results, a range starting from 0 was assumed for this benefit.

Up to now the probabilistic SCBA was termed and framed as a function, nevertheless, it can be intended as model of the system of interest as well. This interpretation is key to understand how exploratory modelling can be applied to the SCBA at hand. A model of a system is another system, similar to the first system in some respects, and the study of which is useful for the understanding of the first system (Kaplan, 1998). The probabilistic SCBA, a vectorial function represented explicitly by Equation 4.1 or in compact form by Equation 4.2, can be defined as a model representing only the relevant aspects of the system of interest. Such model of PV-green roofs in Quartier Alzette is composed of (1) cost and benefit variables, and (2) a discount rate variable, both of which could take different values within the range identified by the studies reviewed; it is also composed by (3) a time variable, enabling the differentiation of cost and benefits' values in different years. Executing the SCBA model is therefore equivalent to computing the SCBA vectorial function.

4.2.3.2 SCBA simulation

To run the SCBA model, the function f was implemented in Python and the complete code is available in appendix E. In order to obtain multiple NPVs, the SCBA model had to be computed multiple times. Each of the NPV was derived from a specific set of values sampled from the uncertainty space X, one for each uncertainty. The set of all uncertainties' values sampled together for one model run generating one NPV is called a *scenario*, and it can be denoted with: $\tilde{\boldsymbol{x}}_{\boldsymbol{\iota}} = (\widetilde{x_1}, \dots, \widetilde{x_{13}})$.

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 $\tilde{x}_\iota$. It is important 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 SCBA 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 $\tilde{\boldsymbol{x}}_{\boldsymbol{\iota}}$ were identified, and the same number of NPV values $\widetilde{m_j}$ were obtained. A schematic representation of the SCBA model simulation is provided in Figure 4.2.

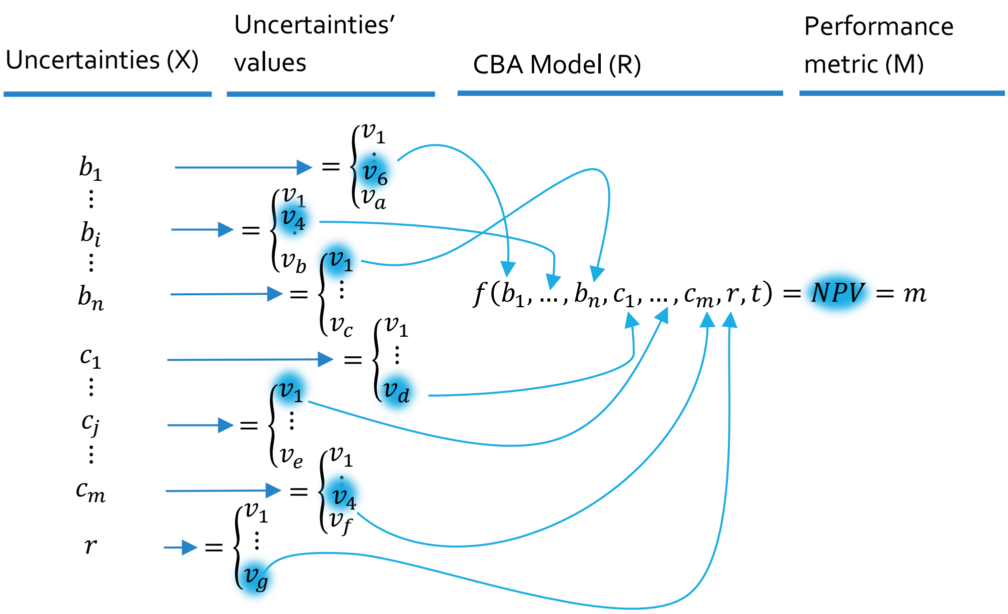


Figure 4.2. A simulation run of the SCBA model. Each simulation of the model produced a single NPV value, generated by a specific set of uncertainty values. Graphically, the uncertainties' values and the performance metric's value belonging to the same simulation run are highlighted in **blue**.

As it can be seen, each simulation run uses a different set of values as inputs to the SCBA. This means that each simulation run, and each NPV corresponds to a different valuation of costs, benefits and/or choice of discount rate. Therefore, simulations can be interpreted as valuations of PV-green roofs, as they in fact are a set of different cost and benefit values of the PV-green roofs at hand, with a discount rate value used for the NPV quantification.

4.2.4 Scenario Discovery

Once the 100.000 NPVs $(m_1, \ldots, m_{100.000})$ were obtained from repeated simulations, Scenario Discovery (Kwakkel, 2017) was performed. Scenario discovery is a method aimed at finding the subspace of the whole uncertainty space X that maps each scenario $\tilde{x}_i$ 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 service life.

In particular, the Patient Induction Rule (PRIM) algorithm (Friedman & Fisher, 1999) was used to perform Scenario Discovery. The algorithm iteratively calculates at each step a subspace of the initial uncertainty space, trying to maximize the *coverage* (the fraction of scenarios that fall within the new selected subspace, out of all sampled scenarios available) and the *density* (the fraction of scenarios that lead to a desired outcome). 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 out of all of the sampled ones.

4.2.5 Assessment of possible Incentives

The previous sections focused on an analysis of all costs and benefits available from the relevant literature, taking the perspective of the government of Luxemburg. If the NPVs obtained from the probabilistic SCBA were positive, the PV-green roofs would bring benefits to the overall society. However, at a practical level this would not occur if individuals who actually purchase PV-green roofs concluded that such investment was not economically convenient for them.

In fact, many of the benefits outlined in Table 4.1 may not be taken into account by individuals who actually purchase PV-green roofs and would form a PGEC. In this dissertation it was assumed that only benefits entailing a direct tangible money flow to individuals are considered by the (potential) PGEC members. These benefits are termed as *private*, while the remaining ones as *non-private*. Thus, non-private benefits may affect the urban settlement where the PGEC is located and society more at large, as well as the same PGEC members and building residents, but only in an indirect intangible way. For instance, sound insulation does not entail any direct and tangible money flow perceived by building residents, and therefore it was considered as non-private. A classification of private and non-private costs and benefits is provided in **Error! Reference source not found.**.

Table 4.2. Classification of uncertainties into private and non-private.

Uncertainty	Perspective
Installation of green roof	Private
Maintenance of green roof	Private
Aesthetics increase	Non-private
Air quality enhancement	Non-private
Biodiversity enhancement	Non-private
CO_2 emission reduction	Non-private
CO_2 uptake	Non-private
Energy consumption reduction	Private
Longevity increase	Private
Sound insulation	Non-private
Stormwater management	Non-private
Water runoff quality increase	Non-private

As it can be seen in **Error! Reference source not found.**, non-private uncertainties are only benefits for the case-study at hand.

If the investment in PV-green roofs was not economically convenient from the perspective of the (potential) PGEC members, it is reasonable to believe that such individuals would not purchase PV-green roofs and would not form the community at all. This would occur even if PV-green roofs resulted in positive NPVs from the SCBA, namely even if this technology provided society with overall positive net benefits (i.e., benefits that outweighed costs). By doing so, individuals would prevent society from obtaining positive net benefits associated to PV-green roofs, due to their *private* perspective.

As opposed to the perspective of PGEC members, the problem owner of the present analysis, i.e., the national government of Luxembourg, is assumed to be interested in enabling all individuals to receive the highest possible net benefits from PV-green roofs. Since this could not occur if individuals made their market decision without consideration of non-private benefits, the problem owner could provide them with an incentive to purchase PV-green roofs.

To determine whether an incentive is necessary, once the probabilistic SCBA was carried out and it was possible to determine that positive NPVs occurred at a social level, a probabilistic private CBA was carried out as well. Such private CBA aimed at determining whether individuals would purchase PV-green roofs without an incentive. To capture the perspective of individuals, the private CBA included only the private costs and benefits outlined in **Error! Reference source not found.**.

If results from the private CBA showed that this technology is not economically convenient from the perspective of PGEC members, an incentive would be deemed necessary. The estimate of such incentive is such that the private NPVs are non-negative, namely that private benefits at least equal private costs. In mathematical terms:

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

Such that:

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

Whereby b^p denote private benefits, c^p private costs, and r^p the private discount rate, which was found to range between 0 and 6.7% (Figure 3.11b).

4.3 Results and discussion

In this section the results from the probabilistic SCBA are presented first (section 4.3.1), showing the overall range of NPVs obtained from the point of view of the government. Next, the conditions enabling PV-greens to be economically convenient are found and discussed (section 4.3.2). Lastly, the level of the incentive enabling PV-green roofs to be economically convenient for PGEC members is presented (section 4.3.3).

4.3.1 Results of the Probabilistic Social Cost-Benefit Analysis

The probability distribution of the NPVs obtained as a result of the simulation are presented in Figure 4.3. As it can be seen, NPVs range from -108 €/m² to 150 €/m². This means that across different valuations of PV-green roofs (i.e., different cost, benefit, and discount rate values), within the uncertain ranges found in the literature, NPVs can be valued as low as 108 €/m², up to 150 €/m². Although the maximum NPV observed is higher in absolute value than the minimum NPV, the distribution is right skewed, with a median value of -21 €/m² and a mean of -18 €/m². The higher value of the mean compared to the median can be explained by the presence of high positive values, which nevertheless are few. At a general level, there is a probability of 28% that the NPV of PV-green roofs in the case-study at hand is positive, when considering the ranges of social costs, benefits, and social discount rates found in the local analysis' results. In other words, the SCBA results show that PV-green roofs can bring positive net benefits to society in 28% of all possible valuations simulated, whereby simulations were based on (irreducible) uncertainty ranges identified from the CBAs' literature.

In the majority of the simulated valuations PV-green roofs for the case-study at hand bring higher costs than benefits over their service life. However, two important considerations need to be made to interpret these results.

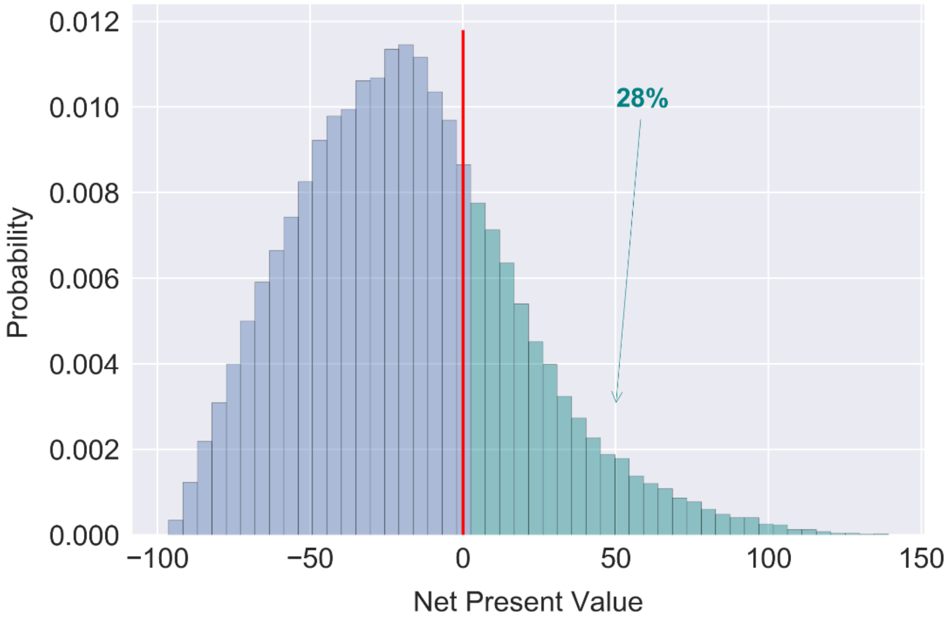


Figure 4.3. Social cost-benefit analysis results.

First, the cost and benefit variables found for the local analysis were less than those recorded in the global analysis, because valuations of costs and benefits satisfying the requirements of the local analysis were only few. Specifically, five benefits and three costs recorded in the global analysis were not found in the articles of the local analysis. These benefits are fire risk reduction, electricity generation, urban noise reduction, and urban heat island effect mitigation. Instead, missing costs are the air pollutant and CO_2 emission from the production of green roofs, as well as the replacement and disposal of green roofs. As a result, while the present probabilistic SCBA aimed at including all costs and benefits recorded in the literature for PV-green roofs, several cost and benefit valuations could not be included due to low transferability of such values to Esch-sur-Alzette.

If the missing benefits and costs could be included the SCBA positive NPVs would change, but it is difficult to foresee whether positive NPVs would be more numerous. In fact, estimates for these items are only available from the global analysis which proved to be different from local analysis' ranges. Such estimates include the second highest benefit, electricity generation, with a median value of 10.7 €/m²/year, and the third highest benefit, namely noise reduction, with a median of 2.3 €/m²/year). In contrast, replacement and disposal costs, although occurring only one time, amount to 25 €/m², and CO2 emission from the production of green roofs feature a median of only 13.7 €/m²/year.

Second, some costs related to PV panels are still missing in the articles reviewed in both the global and local analysis. These are PV panels' installation and maintenance costs, which may be a significant additional cost (Reindl & Palm, 2021; Xue et al., 2021). Unfortunately, only one case-study based in Portland, Oregon (US) included PV installation costs, which were valued at 568 $/m² in 2017. As it was already mentioned in section 3.2.2.11, due to the fast rate of technological and price change of PV panels (Harris & Roach, 2018), this value can be misleading.

As part of the present dissertation, multiple attempts to contact Luxembourgish experts who could provide an overview of PV-related costs in Esch-sur-Alzette were made, but without success. As a result, this cost could not be included for specific case of Quartier Alzette.

4.3.2 Scenario Discovery Results

Scenario discovery was utilized in this dissertation to identify the conditions under which PV-green roofs installed as part of a PGEC in the Alzette District could become economically convenient. This was done making use of the PRIM algorithm, whose results are provided in **Error! Reference source not found.**. The algorithm iteratively calculates at each step a subspace of the initial uncertainty space, which is visualized as a point in Figure 4.4. At each step, the algorithm peels the original space, trying to maximize both the *coverage* and *density* of scenarios. The objective of peeling the original uncertainty space into smaller subspaces was to find a subspace (of cost, benefit, and discount rate variables) with enough scenarios leading to a positive NPV, but still covering a significant number of scenarios out of all of the sampled ones.

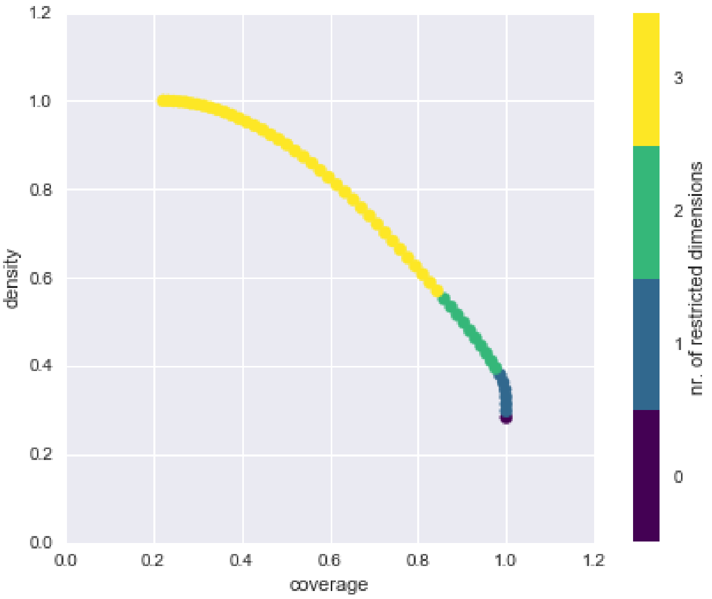


Figure 4.4. PRIM results shown in the form of a density-coverage-restricted dimensions chart.

In order to strike a balance between a high coverage and a high density, the uncertainty subspace with a coverage of 62% and a density of 81% was selected. Consequently, the number of dimensions of the uncertainty space being limited by the algorithm were only three: the installation cost of green roofs, the aesthetics increase benefit, and the discount rate. Specifically, as shown in Figure 4.6, aesthetics increase benefits need to be higher than 130 €/m², while installation costs need to be lower than 57 €/m², and a social discount rate should not exceed 6.4% in order for the PV-green roof to feature a positive NPV in the majority of the cases. An overview of the sampled scenarios leading to desired (i.e., positive) and undesired (i.e., negative or null) NPVs is provided in Figure 4.5, where green dots represent those scenarios leading to a positive NPV.

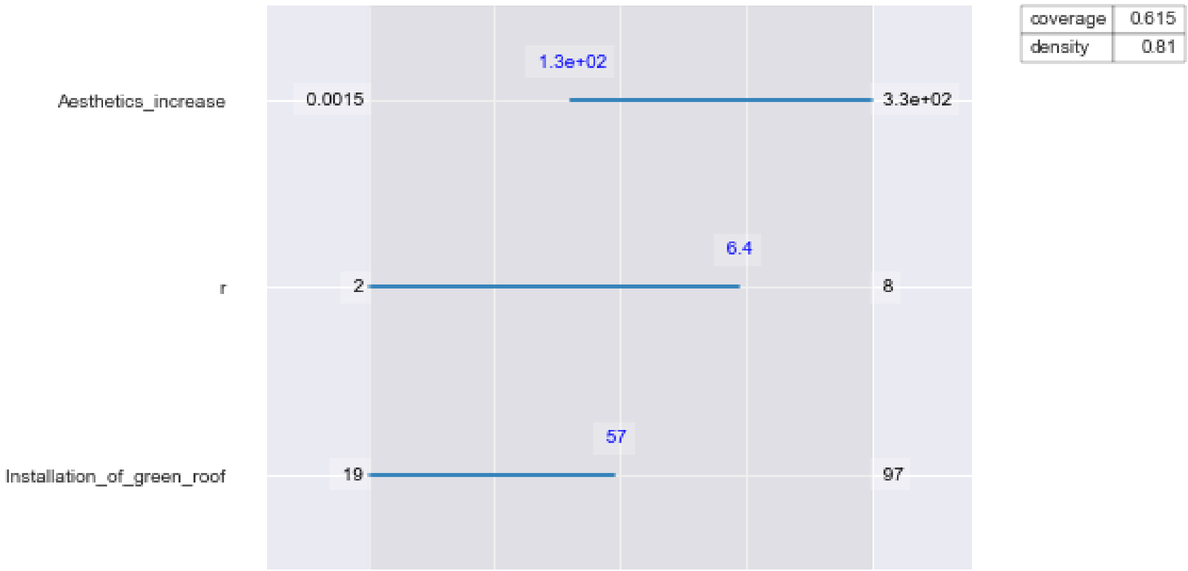


Figure 4.6. Uncertainties to be restricted, in order to obtain positive NPVs.

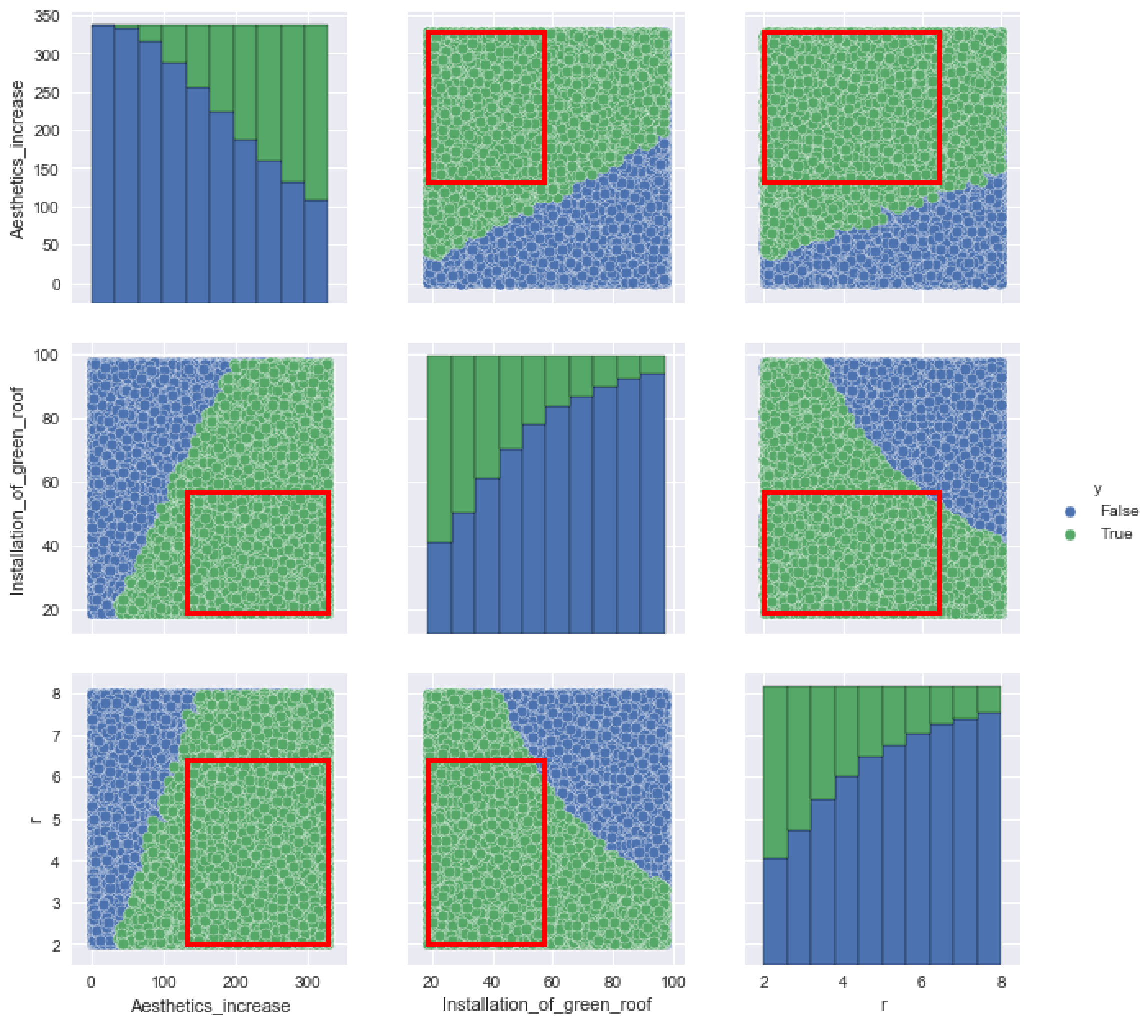


Figure 4.5. Scenario Discovery results. The most influential constraints need to be set on the installation cost of green roofs, as well as on the valuation of aesthetics benefits. By devising such constraints (displayed as red boxes), outcomes with a positive net present value are primarily obtained (i.e., true values, displayed as **green** dots).

The Scenario Discovery results show that the aesthetics increase benefits, the installation costs, and the choice of social discount rate can make the PV-green roof technology a convenient investment with a positive NPV. In order to interpret these results four important considerations are to be made.

First, Scenario Discovery results rely on a coverage of 62% and a density of 81%. This means that the constraints identified for the three uncertainties do not ensure a positive NPV in 100% of the cases. In other words, these modelling results are not a mere prediction of the future given specific conditions. Instead, out of 100.000 different hypothetical futures, sampled within the ranges of cost, benefit and discount rate values identified by the relevant literature, a positive NPV can be obtained in 81% of the cases, which covered 62% of all the scenarios generated.

Second, the most critical benefit found is represented by that of aesthetics increase. While the local analysis of chapter 3 showed that the monetary valuation of this benefit was as high as 328 €/m², when this valuation is compared to other results of the *global* analysis, it appears to be an outlier. In practice, however it should be reminded that the case-study at hand is based in Esch-sur-Alzette (Luxembourg), where prices of houses are particularly higher than in other countries around the world (OECD, 2021a). Specifically, in their world analysis of housing prices, the OECD (2021a) assigns to Luxembourg the fourth highest housing price index, which covers the sales of both newly-built and existing dwellings. A recent review of the Luxembourgish housing market by the Banque Internationale à Luxemburg (2019) found that residential housing prices in Luxembourg are around 6.000 €/m². This figure would make the value of 328 €/m² amounting to only to 5%, which is consistent with the percentage values considered by other authors (Bianchini & Hewage, 2012). Thus, although the aesthetics increase benefit's limit value of 328 €/m² may appear high at first sight, it can be deemed realistic for the case-study at hand.

Third, it has to be reminded that the installation cost is a differential cost with respect to the construction of an alternative conventional black roof.

Third, the social discount rate of 6.4% although falling within the range of discount rates used in the other CBAs' reviewed, represents a quite extreme case (cf. Figure 3.11). According to such view, yearly benefits in the future have a particularly low value with respect to benefits and costs occurring in the present year. Nevertheless, these positions can be taken, as it was demonstrated by the literature review carried out in Chapter 3 (section 3.2.2.3), and for this reason this number was deemed a realistic limit value.

4.3.3 Monetary Incentive

In this last section, an estimation of the monetary incentive enabling the economic convenience for PGEC members and potential members is provided. Such individuals are the individuals purchasing PV-green roofs and subsequently forming a PGEC or already part of a PGEC. From here onwards, they will be referred as investors for simplicity.

The results from the probabilistic SCBA indicate that PV-green roofs for the study at hand may not always bring positive net benefits to the overall society. Nevertheless, depending on the monetary valuations undertaken, a positive NPV is obtained in 28% of the cases. As a consequence, the need of a public incentive for PV-green roofs can still be argued for, and an estimate of its value was determined below.

When taking the perspective of potential investors, the results of a probabilistic *private* CBA needs to be taken into account. These results are displayed in Figure 4.7.

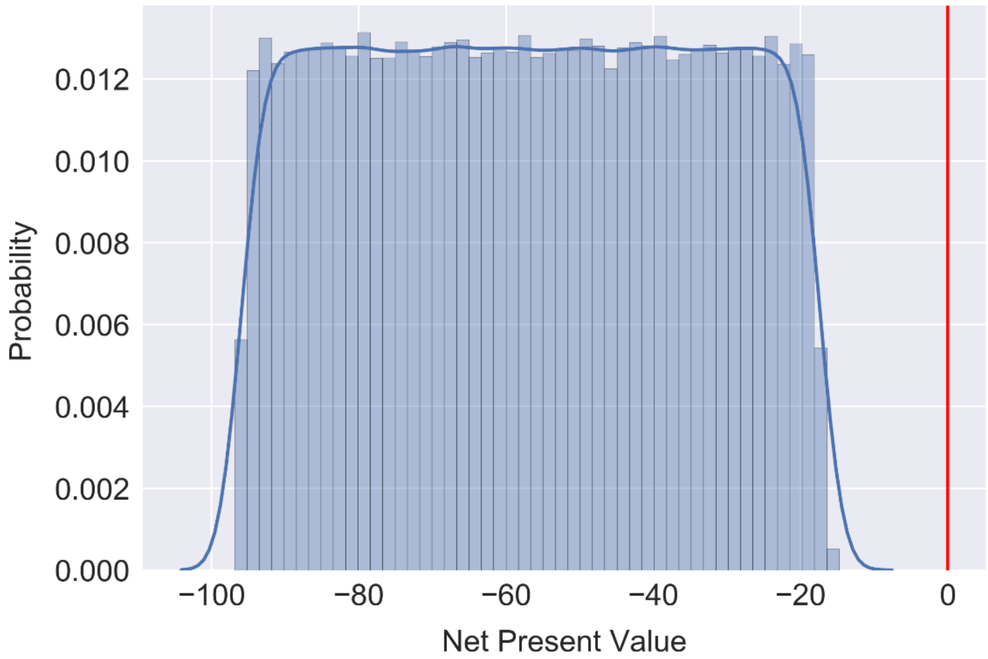


Figure 4.7. Private cost-benefit analysis results.

As it can be seen, PV-green roofs for the conditions of the case-study at hand are not economically convenient from the perspective of investors. When investors only look at private costs and benefits, NPVs range from -97 to -15 €/m², with an average and median value of 57 €/m².

The optimal incentive can be determined as the amount of money that has to be given to investors purchasing PV-green roofs, such that the private NPVs becomes non-negative. This means that the incentive that makes PV-green roofs become economically convenient from the perspective of investors (i.e., PGEC members or potential members) ranges between 15 and 97 €/m². In particular, when a maximum incentive of 97€/m² is provided, PV-green roofs become an economically convenient investment according to all valuations of costs and benefits and for any private discount rate within the ranges defined by the literature.

It is important noting that the estimated incentive does not appear in the SCBA since in such analysis the incentive would need to be added and subtracted, resulting in a net zero sum. Indeed, the incentive amount would be gathered from society through taxes, and it would be again given to society in the form of a monetary incentive. Of course, in the process, a redistribution of wealth within society is performed.

Evaluating whether to grant a monetary incentive to PGECs and estimating its value is not only an exercise of welfare economics (Harris & Roach, 2018), but it also has high policy relevance. From a policy perspective it is important recognizing that the provision of affordable energy for consumers and businesses falls within the main objectives of the European Green Deal (European Commission, 2019, p. 6). In addition, according to the RED II, national governments are required to promote and facilitate the development of renewable energy communities, taking into account their specificity (art.22).

4.4 Conclusion

The aim of this chapter was to address the fourth sub-research question:

What conditions enable PV-green roof energy communities to be economically convenient?

Based on the Luxembourgish case-study of a PGEC located in Esch-sur-Alzette, a social cost-benefit analysis was carried out. To this end, the cost and benefit values, as well as the discount rates found in the literature and transferrable to the case-study at hand were considered. Operationally speaking only cost and benefit valuations based in Europe, in locations exhibiting the same climatic conditions as Esch-sur-Alzette, and consistently using the black roof as a base-case technology, were taken into account. Despite the fact that this procedure reduced the overall variability of cost and benefit estimates in the literature, values still exhibited a range of possible valuations. Such variability was less due to geographic, climatic, and building conditions, and more due to different methods employed in the literature providing few details about their application, or due to different ethical or epistemological stances of authors. Importantly, the uncertainty in the cost, benefit, and discount rate variables stemming from both these two sources was deemed difficult to be reduced. In fact, elements with which certain values could be excluded and other retained as correct were not available due to limited descriptions of the methods used, while the exclusion of certain stances of authors can be problematic.

In the face of such irreducible uncertainties a probabilistic SCBA was carried out, sampling the cost, benefit, and discount rate values within ranges identified from the literature's valuations. The SCBA was conceptualized as a model and simulated 100.000 times, whereby each simulation run used a different set of values as inputs to the SCBA. This means that each simulation run, and each NPV corresponded to a different valuation of costs, benefits and/or choice of discount rate. As a result, the SCBA performed showed that while NPVs as high as 150 €/m² can be expected across the simulated possible valuations, NPVs are positive only in 28% of the valuations, with a median NPV of -21 €/m². Such results indicate that PV-green roofs for the case-study in Esch-sur-Alzette bring higher costs than benefits over their service life, in the majority of the simulated cases.

Importantly, the probabilistic SCBA could not include some costs and benefits that are believed to be comparable to the highest costs and benefits currently included in the analysis. These are the installation and maintenance costs of PV panels, and electricity generation benefits. Such missing values were due to unavailability of relevant data for the case-study at hand.

In order to determine the conditions for the PV-green roofs valuation that could enable such technology to be economically convenient, scenario discovery was carried out using the PRIM algorithm. Three main conditions were found to enable the economic convenience of PV-green roofs from a societal perspective. These are a low installation cost, below 57 €/m², a high aesthetics' increase benefit, above 130 €/m²/year and a low discount rate below 6.4%. Such limit values were deemed to be realistic for the Luxembourgish case-study of Quartier Alzette, especially when considering that Luxembourg's housing prices are among the highest in the world.

Finally, in order to determine the conditions enabling the economic convenience from the private perspective of PGEC members, a probabilistic PCBA was performed. This analysis revealed that PV-green roofs are not economically convenient from investors' point of view, but a monetary incentive higher than 15 €/m² can make the investment become economically convenient. The higher the incentive, the higher the probability that the investment is economically convenient under different valuations of PV-green roofs. Concretely, this means that a wider group of cost, benefit, and discount rate choices would still lead to conclude that PV-green roofs are an economically convenient investment.

5

Conclusion

This study has hitherto focused on three main elements. First, the definition of photovoltaic-green roof energy communities (PGECs) within the European legislative framework. Second, the technical and institutional characterization of PGECs, as well as the identification of the costs and benefits associated with PGECs' physical layer. Third, the identification of the most critical costs and benefits that may enable the physical layer to be an economically convenient investment from both a societal and private perspective. This chapter reviews how the research question and sub-research questions were addressed (section 5.1). Subsequently, it further discusses the results of the study, methodological advantages and limitations, showing how answering the research questions is indeed more nuanced (section **Error! Reference source not found.**). Finally, avenues for future research and for policy recommendations are presented (section 5.4).

5.1 Main Conclusion

In order to contextualize the answer to the main research question of this study, the four sub-research questions described in section 1.3.2 are reviewed first.

5.1.1 Addressing the sub-research questions

How would photovoltaic-green roof energy communities (PGECs) fit in the EU definition and regulation of Renewable Energy Communities (RECs)?

Four decentralized generation models exist within the EU-level legislation. These are Renewable Energy Communities, Renewable Self-Consumers, Jointly Acting Renewable Self-Consumers, and Citizen Energy Communities. Among these, the most suitable legal model for PGECs was found to be that or RECs. Accordingly, this model was used to identify PGECs' defining characteristics.

A PGEC can be defined as a legal entity:

- *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 PGEC's photovoltaic-green roofs, who nevertheless enable the community to remain *autonomous*, and
- with the *primary 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.

These characteristics are deemed the most suitable to PGECs in the European Union, since the underlying REC legal model best captures in the purpose for RECs the socio-environmental community benefits provided PGECs. Additionally, the support schemes that RECs are entitled to receive can be tailored to PGECs' case, thus reducing the significant upfront costs of these communities.

What are the financial, economic, and socio-environmental costs and benefits associated with the installation and operation of photovoltaic-green roofs, as a part of a PGEC?

Six costs and 15 benefits stemming from the whole lifecycle of photovoltaic-green roofs were identified as a consistent group of items. These costs occur at building or societal scale and correspond to implementation actions or management actions (i.e., installation, maintenance, replacement, disposal of green roofs and PV panels) or impacts derived from them (i.e., and air pollutant and CO_2 emissions generated due to the production of these technologies). The benefits identified occur at building, urban, or societal scale. They correspond to a reduction of expenses (i.e., energy consumption), mitigation of environmental impacts (i.e., urban noise, air pollution, urban heat island, CO2 emission, habitat loss, stormwater management), reduction of risks (i.e., fire risk), and enhancement of building characteristics (i.e., longevity of the roof, aesthetics, sound insulation, and energy generation from the PV).

How would PGECs address the wider objectives of the European Green Deal?

The implementation of photovoltaic-green roofs contributes addressing five EGD objectives. First, they provide *clean, affordable, and secure energy*, through the decentralized power generation of PV panels, which is enhanced by the proximity of green roofs. Second, PGECs through green roofs' contribute to restore the biodiversity lost in urban settlements by providing habitats to different flora and fauna. Moreover, by adding PV arrays the heterogeneity of habitats increase, enhancing niche diversity. Third, PGECs contribute reducing air and water pollution, thanks to the air pollutant uptake and water filtration of green roofs (the latter of which is conditional on low use of fertilizers and pesticides). Fourth, PGECs contribute reducing the atmospheric concentration of CO_2 thanks to the lower consumption of fossil fuels, which is enabled by the local energy generation of PV panels, and it is enhanced by the proximity of green roofs. Green roofs contribute reducing CO_2 concentrations further through the uptake of CO_2 by plant species. They mitigate the urban heat island effect, thanks to the increase of the albedo, shading of the roof and the evapotranspiration process. Fifth, the application of PGECs to new and existing building provides a higher energy efficiency for the building stock under consideration.

What conditions enable photovoltaic-green roof energy communities to be economically convenient?

Three main conditions were found to enable the economic convenience of PV-green roofs from a societal perspective. These are a low installation cost, below 57 €/m^2, a high aesthetics' increase benefit, above 130 €/m^2/year and a low discount rate below 6.4%. Such conditions are to be intended for PV-green roofs within a PGEC in Esch-sur-Alzette (Luxembourg), as the analysis was carried for this specific case-study.

From the private perspective of individuals who purchase PV-green roofs and later form a PGEC or who are already part of a PGEC (termed as investors), PV-green roofs are not economically convenient. Thus, investors require an incentive to purchase this technology and bring positive net benefits to society as a whole. Such incentive represents the condition enabling the PV-green roofs' economic convenience from the private perspective of investors. A monetary incentive higher than 15 €/m^2 can make the investment become economically convenient. The higher the incentive, the higher the probability that the investment is economically convenient, across different valuations of PV-green roofs. At an incentive rate of 97€/m², PV-green roofs become an economically convenient investment according to all valuations of costs and benefits and for any private discount rate within the ranges defined by the literature.

5.1.2 Addressing the main research question

The main research question of this study was:

> *Under what conditions does the combination of photovoltaic panels and green roofs, as part of Renewable Energy Communities, meet the European Green Deal's objectives in an economically viable manner?*

From the point of view of society, three main conditions enabling the economic convenience of PV-green roofs were identified in the Luxembourgish case-study of Quartier Alzette: a green roof installation cost below 57 €/m², an aesthetics' increase benefit above 130 €/m²/year and a discount rate below 6.4%. These conditions enable PV-green roofs to provide higher benefits than costs to society. Additionally, a monetary incentive of at least 15 €/m², and possibly as high as 97 €/m², was identified as a necessary measure to make the investment become economically convenient from the private point of view of investors. This means that with particularly favorable monetary valuations of private benefits (i.e., high monetary valuations for energy consumption reduction and longevity increase) and private costs (i.e., low valuations of the installation and maintenance costs), and with a low private discount rate choice, the monetary incentive of 15 €/m² could be enough to make private benefits higher than private costs. A higher incentive, up to 97 €/m², would ensure private benefits to be higher than private costs under a higher range of cost and benefit valuations as well as discount rate choices.

These conditions refer to the physical layer of photovoltaic-green roof energy communities, a specific type of renewable energy community, as defined by the Renewable Energy Directive 2018/2001. Thus, any natural person, small or medium-sized enterprise, or authority situated locally with respect to photovoltaic-green roofs can voluntarily set up or participate in a PGEC, which owns such energy projects. As defined by the RED II, the PGEC is entitled to receive a support scheme by the national government, which may take into account its specificity of owning PV panels and green roofs. Additionally, the PGEC may sell electricity generated on site and not consumed, nevertheless, no activity within the PGEC may be the primary professional or commercial activity of private members or shareholders.

The photovoltaic-green roofs owned by PGECs contribute addressing five main policy objectives of the European Green Deal. Photovoltaic-green roofs provide renewable and more affordable energy to the members or shareholders, while contributing to the European energy security. This technology helps restoring and preserving biodiversity in urban areas, while also enhancing the air and, to an extent, stormwater runoff quality of such areas. Photovoltaic-green roofs contribute to the European climate neutrality objective by reducing CO_2 in the atmosphere through multiple mechanisms, and they represent a climate adaptation measure reducing the urban heat island effect. The adoption of such a technology, lastly, increases the roof's insulation of buildings where they are installed, contributing to the EGD policy objective of building and renovating in an energy efficient way.

In short, satisfying the economic conditions of a low installation cost and discount rate, a high value of aesthetics' increase benefits, and a monetary incentive not inferior to 15 €/m² and possibly as high as 97 €/m² would enable the economic convenience of PV-green roofs, and thus unlock the financial, economic, and socio-environmental benefits addressing five main EGD objectives.

5.2 Discussion

5.2.1 Limitations

5.2.1.1 Regarding the variability of items' valuations in the local analysis

Each of the items analyzed in Chapter 3 relied on a pool of valuations observed in the articles reviewed as part of the chapter's systematic literature review. Due to the variability of climatic, geographic, and base-case conditions in which these valuations were performed, a selection of those valuations carried out in a specific continent, climate, and compared to a specific base-case roof was operated. The valuations selected were called as part of the *local* analysis, while all valuations, taken together, were considered to part of the *global analysis.* For the purpose of Chapter 4's probabilistic CBAs, which was focused on the case-study of Quartier Alzette, the local analysis chose continent, climate and base-case roof conditions that were characteristic of this case-study. In this way, only articles that included valuations obtained for similar conditions of Chapter 4's case-study at hand were retained and used in the probabilistic social and private CBAs.

While the distinction between items valuations belonging to the global and local analysis reduced the variability of valuations for the case-study of Chapter 4, two additional sources of reducible variability exist for these valuations, and they are discussed below.

First, it is possible that microclimates within the general Cfb climate class of the local analysis may still contribute to the variability of these valuations. Nevertheless, no further data selection was possible with the climate data available to this research. Additionally, the fact that the Cfb climate extends for the whole Luxembourg is convenient for the national scope of Chapter 4's incentive estimation. In contrast, if a smaller climate class had been chosen, the validity of the incentive's estimate would have been compromised.

Second, several building conditions, in addition to the adopted conventional black base-case roof could be responsible for the variability of valuations. Such other building conditions include the presence or not of an insulation layer in the base-case roof, the rooftop's slope, and the building's type (e.g., residential, commercial, school, etc.). These were recorded for only some articles, while they were not available for many others. Since the three conditions used to group articles in the local analysis already could already not find any data for 2 costs and 3 benefits, while 4 other items only consisted of one valuation only, it was preferred not to further limit the local analysis' conditions, so to lose further items from the analysis. An alternative way to deal with this trade-off would have been to consider fewer costs or benefits in the CBA, but which are more similar to the conditions of Quartier Alzette.

5.2.1.2 Regarding the variability of items' valuations in the global analysis

Valuations included in the global analysis had a much larger range of monetary values. Causes of variability were discussed for each item in Chapter 3. Nevertheless, at a general level the choice of the statistical index used to summarize these distributions needs to be discussed.

The median instead of the mean value was used as an index to summarize each item's distribution. This index was preferred since it is a statistically more robust central tendency index of a distribution than the mean (Montgomery et al., 2011). In fact, the 50^{th} percentile is significantly less sensitive to outliers in the distributions than the mean.

With regard to using a central tendency index for items' distributions in general, it has to be noted that this approach has some limitations. In fact, the items' valuations that compose distributions often are obtained from the use different methods or of different assumptions in the use of such methods. As a result, the median value of the global analysis should be used with care. Nevertheless, since all monetary valuations related to the same item aim at expressing the same cost or the same benefit, they attempt to represent the same concept. Thus, a median value of items' valuations of one same concept (e.g., a specific benefit) could provide an indication of the monetary value of that same concept. Median values, in any case, need to be read while acknowledging that different methods and ways to employ methods to value such concept were used.

As far as the time dimension is concerned, the oldest study in the literature review included in the global analysis dates back to 2008. It is difficult to determine whether the prices of green roofs have changed in various areas around the globe over time, as green roofs manufacturing companies do not publicly provide these data. With regard to the benefits evaluated, in some cases the methods used (e.g., stormwater fees, and NO_x emission permit values) could have been changed to more recent values for the same locations. Nevertheless, since this approach would have updated only few benefits valuations while leaving others untouched due to lack of details about the method, or of data about updated values, it was preferred using a common approach to all benefit and cost value, and as it was described in section 3.2.1.2, monetary values were corrected for inflation over time.

5.2.1.3 Regarding the conditions enabling economic convenience of PV-green roofs

When considering the Scenario Discovery results, we can note that the aesthetics' increase benefit and the installation costs are the two item valuations which, together with the choice of the social discount rate enable the economic convenience of PV-green roofs at a social level.

It is important noting that the conditions set on installation costs of PV-green roofs, on the value of their aesthetics increase benefit, and on the social discount rate are not an infallible assurance of PGECs' economic viability. In fact, the Scenario Discovery finds a positive NPV for projects satisfying these three conditions in 81% of the cases. In addition, the 100.000 simulations generated do not represent all possible futures, but just a subset of them, and the coverage of the ones generated was also limited to 62%.

An important limitation that is common to the probabilistic social and private CBAs, as well as the Scenario Discovery results, is the lack of PV installations and maintenance costs, whose data was not possible to be retrieved for this dissertation. Since this technology has rapidly evolved in recent years, only very recent figures for these costs should be considered.

Lastly, due to the limited time available for this project and the difficulty in their estimation, this study did not attempt to quantify rebound effects that would stem from the large-scale adoption of photovoltaic-green roofs. While direct rebound effects are not expected to be particularly high, indirect ones, although more difficult to quantify, might be non-negligible. Indeed, PGEC members or shareholders might use the cost savings from energy efficiency improvements to increase consumption in other products or services that require more energy (or CO_2 emissions) to be produced or provided. Nevertheless, it is reasonable to believe that consumption related to heating and cooling within a building would not increase thanks to the energy savings unlocked by photovoltaic-green roofs. In fact, once the thermal comfort is reached, the energy savings obtained do not provide an incentive to further consume energy for heating or cooling.

5.2.2 Advantages

The approach used in this dissertation considered the legislative system boundaries for the adoption of the proposed technology, which is often neglected or briefly mentioned in CBAs of green roofs. This provides a clear description of the legal requirements to be met in order to practically adopt the technology proposed. In this way the gap between theory and practice was significantly reduced.

As for the costs and benefits associated to the proposed technology, considering all the items hitherto accounted for in the literature, before selecting the ones relevant for the case-study at hand, avoids overlooking important ones. Often CBAs as well as probabilistic CBAs exclude various benefits as well as costs from the quantitative analysis, either by providing only a qualitative description of them or by not mentioning them altogether. Such an approach was observed by other scholars to result in misleading figures, since entire items are omitted (Teotónio et al., 2021).

In addition, unlike various other CBAs, and probabilistic CBAs, the approach of this study uses a classification of costs and benefits (i.e., financial, economic, or socio-environmental; as well as building, urban, or societal) which can consistently be applied to other case-studies around the world, reducing the risk of incomparability or inconsistency of the results.

Lastly, the utilization of Scenario Discovery avoids the often contested "agree-on-assumptions" approach (Lempert, 2014), in which scholars and policymakers need to agree on the assumptions utilized to accept CBA results. Despite this being an often-used approach in CBAs (Kalra et al., 2014), this method provides vulnerable results that may be disregarded or discredited based on a (possibly even strategic) disagreement on assumptions. Conversely, the exploratory modelling approach used an "agree-on-decisions" approach (Lempert, 2014), in which various sets of cost and benefit valuations were considered first, and their monetary consequences (i.e. the resulting NPVs) were calculated. The corresponding "agreed" decision in this dissertation was 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 deferred any agreement on assumptions until the consequences of known, namely simulated, alternative cost and benefit valuations, and their consequences were evaluated. Then, only those monetary valuations and other uncertainties (i.e., the installation cost and aesthetics increase benefits and discount rate) that were found to "make a difference" in reaching the outcome of interest were obtained and provide the basis for discussion to reach consensus.

5.3 Reflection on the Relevance of this Research

5.3.1 Societal Relevance

In the face of a lack of specific actions addressing biodiversity, and health issues from within EU energy policies (European Commission, 2012), this dissertation conceptualized PGECs, a type of REC that could address environmental challenges while being grounded in the recent recast of the EU Renewable Energy Directive.

In particular, this work contributed addressing two knowledge gaps:

First, the legal boundaries, including those related to support schemes, for the implementation of photovoltaic-green roofs as part of renewable energy communities had not been studied to date. This dissertation reviewed in Chapter 2 all the EU legislation relevant to decentralized energy generation. It identified the legal requirements and characteristics of RECs and how they can be applied to photovoltaic-green roof energy communities. In addition, it analyzed how PGECs could benefit from REC support schemes, to reduce green roofs' upfront costs, which were often voiced as important limitations to their diffusion (Berto et al., 2020; Shin & Kim, 2019). If green roofs could be part of RECs, as it was conceptualized in this dissertation, then it is possible that their diffusion could be supported by the RED II incentives.

Second, Chapter 3 explicitly showed how PV-green roofs' benefits are related to four EGD objectives: the provision of clean and affordable energy, the restoration and preservation of ecosystems and biodiversity, the reduction of air and water pollution, and the adaptation to climate change. A discussion of the link between PV-green roofs and the comprehensive European policy objectives, promulgated in the Green Deal strategy, is currently missing in the literature. Caramizaru & Uihlein (2020) explicitly noted that more research is needed to clarify RECs' potential benefits for supporting EU's climate and energy goals.

Determining how PGEC's benefits address the Green Deal's objectives, not only contributed to bridging such knowledge gap, but it was also deemed helpful to national legislators. In fact, to date, a great number of European countries have not yet fully transposed the European legislation , nor the RECs' definition and their relative support schemes (Hinsch et al., 2021; Lowitzsch et al., 2020). This leaves an important policy window open, in which national governments are still defining the legal entity of RECs and the measures to incentivize their adoption. Hence in such policy window the recommendations of this dissertation about PGECs as a specific type of REC addressing multiple EGD objectives could be adopted.

5.3.2 Academic Relevance

As Cristiano et al. (2021) observed, most of the time green roof benefits are investigate by focusing on one or few benefits only. For this reason, the authors stress the need to perform integrated assessments of all the benefits of these solutions, so to be able to fully evaluate them. Berndtsson (2010) also shared such viewpoint and goes further noting how specialists only focus on their own field of expertise when conducting research on green roofs, generalizing the other aspects. In this light, the author contends that decisions regarding green roof construction and design need to be based on an analysis of multiple benefits, instead of treating them as a solution for one engineering problem only. In response to these needs voiced by scholars, this dissertation performed a systematic review of cost-benefit analyses published as peer-reviewed papers to date. In this way, an analysis of all the costs and benefits associated with PV-green roofs, as well as an analysis of their monetary valuations was developed.

Additionally, since authors make different assumptions in the structure of the CBA, and often neglect various benefits, a high variability of CBA results can be observed. In this respect, Teotónio et al., (2021) voiced the need for a consistent, transversal and all-inclusive methodology that considers costs, benefits and co-benefits of green roofs to better support policymaking. In Chapter 3 of this dissertation an attempt to provide a more consistent, transversal, and all-inclusive methodology to conduct CBAs of PV-green roofs was provided. For each cost and benefit reviewed methodological issues that could make CBAs inconsistent with one another were described, and whenever enough details were provided, possible solutions to avoid such inconsistencies in the future were provided.

Lastly, the literature review conducted revealed a high variability of the monetary values associated to each cost and benefit of PV-green roofs. This variability in monetary valuations is acknowledged in the literature (Manso et al., 2021; Teotónio et al., 2018) and it is seen as an issue potentially hampering decision-making and policymaking (Teotónio et al., 2021). Scientific knowledge represented by CBA results, has become subject of debate (Vijayaraghavan, 2016), and academic studies can be found contradicting one another, with opposing views and results (see for instance, Jim & Tsang, 2011; Santamouris et al., 2007; Zhao & Srebric, 2012). Not only there is disagreement with regard to the outcomes of CBAs (Teotónio et al., 2021), but also with regard to their input values, as some benefits are disregarded or considered negligible by some, while being valued by others (see for instance Melo et al., 2020; Shin & Kim, 2019).

Based on the literature review conducted in Chapter 3, this dissertation identified three high-level sources of variability (or uncertainty) in monetary values. As described in Chapter 4, this dissertation attempted to reduce the variability that could be reduced, by selecting one specific case-study for performing a CBA. Then, in this dissertation exploratory modelling (Bankes et al., 2013; Lempert, 2014) was applied to acknowledge the values' differences whenever the values' variability could not be further reduced (e.g., due to different ethical or epistemological stances, or due to the use of different methods for which few details were given). As a result of this strategy, instead of the traditional CBA approach providing different NPVs based on agreed-upon assumptions, this dissertation derived which are the conditions to be set on the monetary values that would allow obtaining a desired (i.e., positive) NPV.

While the theory of exploratory modelling already exists, it is deemed that the use of this method in the domain of PV-green roofs could demonstrate the usefulness of it to CBA authors in the domain of green roofs.

5.4 Recommendations

5.4.1 Recommendations for future research

Three main avenues for future research were identified, and they are presented below.

First, due to the lack of data, the present analysis could not include PV panels' installation and maintenance costs for the case-study at hand. Nevertheless, further research could attempt at estimating these values for the case-study at hand. Similarly, due to lack of data transferrable to case-study in Esch-sur-Alzette, the local analysis carried out in Chapter 3 could not include several costs and benefits that were observed in the global analysis. Further research could concentrate on estimating these missing monetary values so to widen the scope of the probabilistic SCBA conducted in this dissertation.

Second, future CBAs of green roofs or PV-green roofs could take advantage of the CBA items' classification set out in this dissertation (section 3.2.2.4) to reduce the risk of further inconsistency and incomparability of results between CBAs. As a result, it can be expected that the classification of CBA items could be expanded and further refined.

Third, a similar other avenue for future research consists of reconciling the classification of CBA items with the CASCADE framework proposed by Haines-Young & Potschin (2010; 2016), which consists of a classification for ecosystem services. In fact, although CBA items are not consisting only of ecosystem services, they often include them, and this framework has been increasingly utilized and refined in recent years in the field of ecosystem services (cf., La Notte et al., 2017).

5.4.2 Policy recommendations

Photovoltaic-green roof energy communities represent a technology at the edge of two main policy fields: energy, and environmental policy. Specifically, the analysis of PGECs carried out shows how environmental policy objectives such as biodiversity enhancement, air quality enhancement, as well as flood risk reduction can be achieved with energy policy levers, such as the support schemes for RECs. The design of renewable energy communities and of the relative support schemes, therefore, need not be based on energy market considerations only. Such a design of RECs and their support schemes would overlook a significant potential to meet environmental policy objectives set out in the European Green Deal strategy. It would also overlook the possibility for an energy technology, PV panels, to benefit from a typical environmental technology, green roofs, to better address typical energy policy objectives, such as higher renewable power output and higher buildings' energy efficiency. For this reason, it is important that the transposition of art. 22 para. 7 of the Renewable Energy Directive (Directive 2018/2001 recast) in Member States foresees environmental or "green" technologies as one of the "specificities" of renewable energy communities. In this regard it is also important that support schemes for RECs are designed to account for such a specificity.

With regard to the Luxembourgish case-study analysed, resources and efforts to determine the economic convenience of PV-green roofs could be focused on the valuation of aesthetics' increase and installation costs first, as these seem the items capable of enabling the economic convenience of such a technology. The often-limited resources for monetary valuation could in this way be used in an efficient and effective way.

In addition, when the private point of view of PGEC members and potential members was considered, PV-green roofs did not appear to be an economically convenient investment. However, PV-green roofs proved to bring positive net benefits to society in 28% of all possible valuations simulated, whereby simulations were based on ranges identified from the CBAs' literature. This means while at a societal level PV-green roofs can bring higher benefits than costs, they are likely to be disregarded by potential buyers, since from a private perspective they are not economically convenient. Based on these considerations, it is advisable to provide an incentive for the adoption of PV-green roofs as part of the incentives for RECs' specificities. In order to make PV-green roofs economically convenient from a private perspective, and unlock its benefits for the whole society, an incentive higher than 15 €/m^2 of PV-green roof is recommended in Luxembourg for houses whose roof still has to be constructed.

Appendix A

According to the Ethics' committee Data Plan, the complete transcripts of the interviews are available online at:

https://tud365-my.sharepoint.com/:f:/g/personal/fcruztorres_tudelft_nl/Eu_Ybuu1KWFMv1L72rnZZowBSjpq8anicr_CrbwpWEal7w?e=yz7Vh1

Appendix B

This Appendix presents a detailed explanation of the steps used to determine (1) a generic formulation for the minimum inter-row distance between PV arrays and (2) its specific value for Esch-sur-Alzette (Luxembourg).

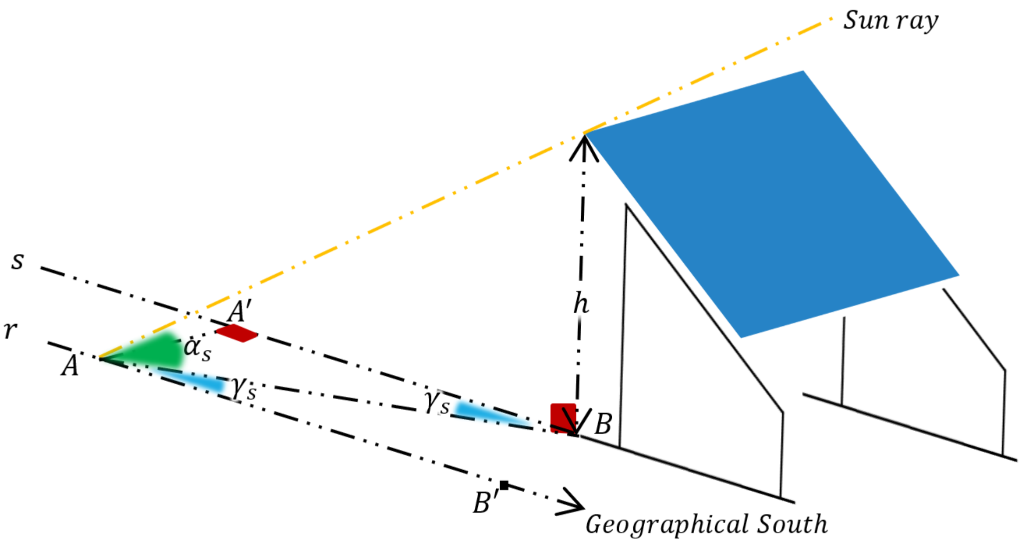


Figure B.1. Inter-row distance between PV arrays.

B.1 Generic Formulation

There are several ways to determine the minimum distance between arrays of photovoltaic panels (Chakraborty et al., 2015; Duffie & Beckman, 2020). However, the studies found did not consider the azimuth angle of the sun, namely the angular distance that the sun forms with the geographical south. Considering such angle would decrease the inter-row distance from being $\overline{AB}$ to $\overline{A'B}$ (Figure B.1), which is a shorter distance, thus saving up space on the roof. For this reason, in this dissertation, the distance $\overline{AB}$ distance will be corrected, taking into account the solar azimuth.

The sun's position is identified using two angles: its height from the horizon, i.e., the elevation angle α_s, and its angular distance from the geographical south, i.e., the solar azimuth[3] γ_s.

$\overline{AB} = \dfrac{h}{tan(\alpha_s)}$	By definition of the Tangent trigonometric function
$\widehat{B'AB} \cong \widehat{ABA'};$	Since $r\ //\ s$, and Since angles are alternate angles of such parallel lines
$\widehat{B'AB} \cong \gamma_s$	By definition of γ_s
$d_{min} = \overline{A'B} = \overline{AB} \cdot cos(\gamma_s)$	By definition of the Cosine trigonometric function

[3] Depending on the convention utilized, solar azimuth could be calculated as the angular distance between the sun and the geographical south, or the geographical north. In this dissertation the former is used.

As a result, the inter-row spacing between rows of PV arrays can be expressed as:

Equation B.1

$$d > \underbrace{\frac{h}{tan(\alpha_s)} cos(\gamma_s)}_{d_{min}}$$

B.2 Specification to the case of Esch-sur-Alzette

To determine a numerical value for the inter-row spacing d, its independent variables should be made explicit. The height of the PV array will be kept as a variable, as this depends on the distance to be kept from the vegetation underneath, and thus on the plant species chosen as well as on aesthetics considerations. The remaining two independent variables can be expressed numerically.

Considering the location of this dissertation's case-study, Esch-sur-Alzette (lat. 49.5° N, long. 5.99° E), α_s and γ_s can be found for this location. Such variables represent the position of the sun at any given moment in time, and can be derived using the sun path diagram for the location under consideration (Figure B.2).

The sun path diagram provided in Figure B.2 shows the path followed by the sun in the sky on specific days of the year in Esch-sur-Alzette as blue lines. These paths consist of the collection of coordinates (α_s as the y-axis and $\gamma_s$the x-axis) of the sun's location during the days under consideration.

The inter-row spacing is calculated for the worst-case scenario, namely when the sun is lowest on the horizon. This occurs on the winter solstice, namely on December 21. During such day, the main bulk of sunlight is assumed to be received within 9:00 and 15:00. As a consequence, the solar elevation α_s is approximately 10° from the horizon, while the solar azimuth (measured from the geographical south) γ_s is approximately 35°.

Utilizing Equation B.1, the inter-row spacing d necessary to avoid shading of PV panels by adjacent rows is:

Equation B.2

$$d > 0.65 \cdot h$$

Such a spacing allows PV panels not to be shaded within the 9:00-15:00 time window even in the worst-case situation, when the sun is lowest on the horizon, on the winter solstice. During the remaining days of the year the sun elevation and solar azimuth are such that the inter-row spacing is lower.

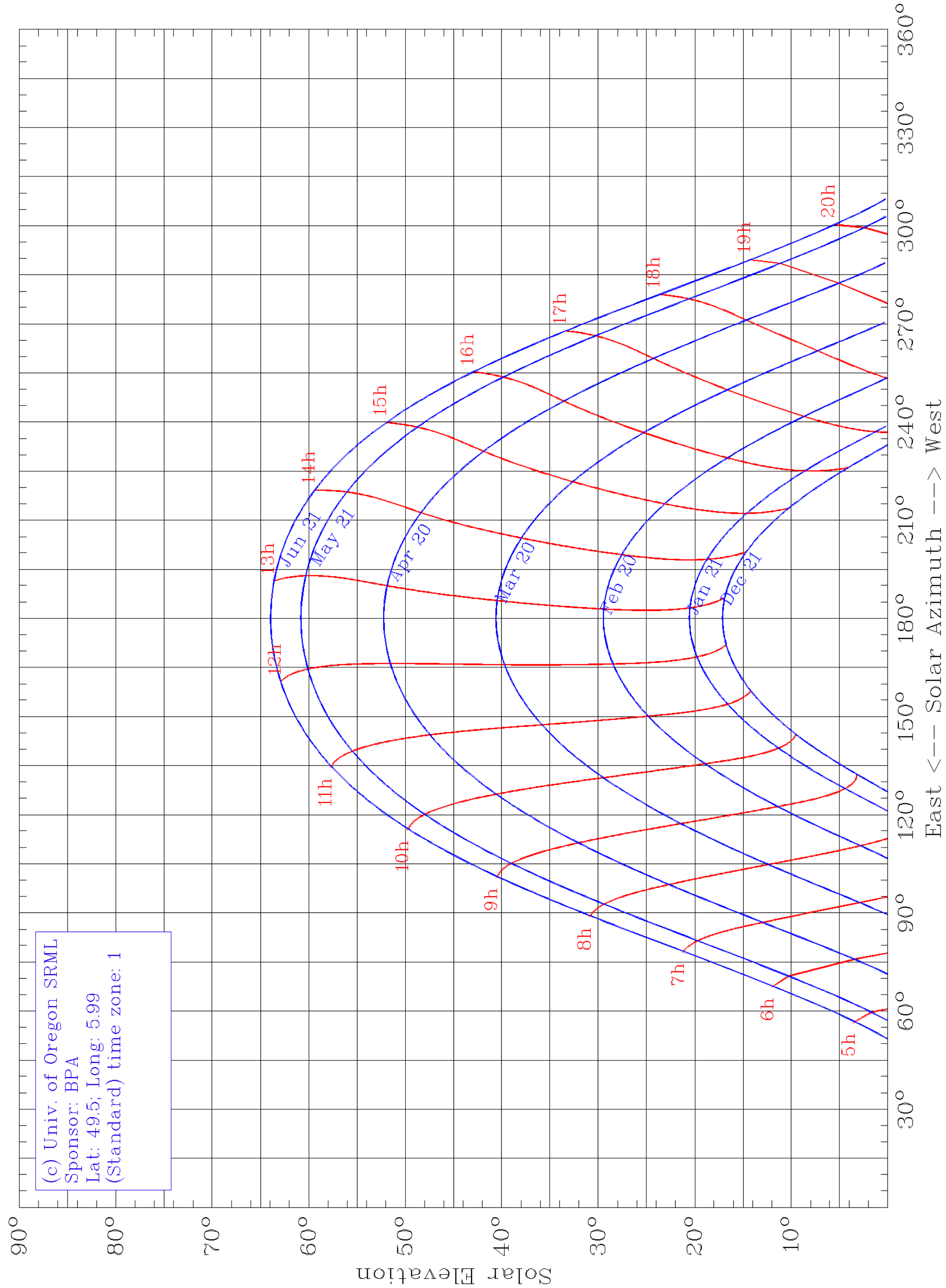


Figure B.2. Sun path chart of Esch-sur-Alzette (UO Solar Radiation Monitoring Laboratory, **2019**).

Appendix C

C.1 Articles Included in the Global Analysis

Table C.1 provides the list of articles included in the global analysis.

Table C.1. Articles included in the global analysis.

Study type	Authors	Year	Title	Case-study	Discount rate
Cost-Benefit Analysis	Almeida et al.,	2020	Socioeconomic feasibility of green roofs and walls in public buildings: The case study of primary schoools in Portugal	Almeida - Lisbon1	Social and Private
				Almeida - Lisbon2	Social and Private
	Ascione et al.,	2013	Green roofs in European climates. Are effective soluzitons for the energy savings in air-conditioning?	Ascione - London	Unspecified
				Ascione - Oslo	Unspecified
				Ascione - Rome	Unspecified
				Ascione - Santa Cruz	Unspecified
				Ascione - Sevilla	Unspecified
				Ascione-Amsterdam	Unspecified
	Berto et al.,	2018	Enhancing the environmental performance of industrial settlements. An economic evaluation of extensive green roof competitiveness	Berto 2018-Trieste	Social and Private
		2020	The Valuation of Public and Private Benefits of Green Roof Retrofit in Different Climate Conditions	Berto 2020 - Ancona	Social and Private
				Berto 2020 - Palermo	Social and Private

				Berto 2020 - Trieste	Social and Private
	Bianchini & Hewage,	2012	Probabilistic social cost-benefit analysis for green roofs: A lifecycle approach	Unspecified	Social
	Carter and Keeler,	2008	Life-cycle cost-benefit analysis of extensive vegetated roof systems	Carter & Keeler - Athens	Social and Private
	Clark et al.,	2008	Green roof valuation: a probabilisitc economic analysis of environmental benefits	Clark - Ann Arbor	Unspecified
	Claus and Rousseau,	2012	Public versus private incentives to invest in green roofs: a cost benefit analysis for Flanders	Claus Rousseau - Dilbeek	Social and Private
	Gwak et al.,	2017	Optimal location selection for the installation of urban green roofs considering honeybee habitats along with socio-economic and environmental effects	Gwak - Seoul	Unspecified
	Johnson & Geisendorf,	2019	Are Neighborhood-level SUDS Worth it? An assessment of the Economic Value of Sustainable Urban Drainage System Scenarios Using Cost-Benefit Analyses	Johnson & Geisendor - Berlin	Social and Private
	Machac et al.,	2016	Green and Blue Infrastructure: An Opportunity for Smart Cities	Machac - Jinonice	Social
	Mahdiyar et al.,	2016	Probabilistic private cost-benefit analysis for green roof installation: A monte carlo simulation approach	Mahdiyar - Kuala Lumpur	Private
	McRae,	2016	Case study: A conservative approach to green roof benefit quantification and valuation for public buildings	McRae - San Antonio	Private
	Melo et al.,	2020	What's the economic value of greening transport infrastructure? The case of the underground passages in Lisbon	Melo - Lisbon	Social and Private
	Mullen et al.,	2013	Green Roof Adoption in Atlanta. Georgia: The Effect of Building Characteristics and Subsidies on net Private, Public, and Social Benefits	Mullen - Atlanta	Unspecified
	Niu et al.,	2010	Scaling of economic benefits from green roof implementation in Wahsington, DC	Niu - Washington D.C.	Unspecified

	Nordman et al,	2018	Benefit-cost analysis of stormwater green infrastructure practices for Grand Rapids, Michigan, USA	Nordman - Grand Rapids	Social
	Peng & Jim,	2015	Economic evaluation of green-roof environmental benefits in the context of climate change: The case of Hong Kong	Peng & Jim - Hong Kong	Social
	Perini & Rosasco,	2016	Is greening the building envelope economically sustainable? An analysis to evaluate the advantages of economy of scope of vertical green systems and green roofs	Perini & Rosasco - Genoa	Private
	Shin & Kim,	2018	Analysing Green Roof Effects in an Urban Environment: A Case of Bangbae dong Seoul	Shin & Kim 2018 - Seoul	Social
		2019	Benefit-Cost Analysis of Green Roof Initiative Projects. The Case of Jung-gu, Seoul	Shin & Kim 2019 - Seoul	Social
	Silva et al.,	2019	The socioeconomic feasibility of greening rail stations: a case study in Lisbon	Silva - Lisbon	Social and Private
	Statler et al.,	2017	Optimizing angles of rooftop photovoltaics, ratios of solar to vegetated roof systems, and economic benefits, in Portland, Oregon, USA	Statler - Portland	Private
	Teotónio et al,,	2018	Eco-solutions for urban environments regeneration	Teotonio - Lisbon	Social and Private
	Vincent et al.,	2017	Enhancing the Economic Value of Large Investments in Sustainable Drainage Systems (SuDS) through Inclusion of Econsystems Services Benefits	Vincent - Montevideo	Social
	William et al.,	2016	An environmental cost-benefit analysis of alternative green roofing strategies	William - Champaign	Unspecified
	Xin et al.,	2021	Comprehensive performance Evaluation of Green Infrastructure Practices for Urban Watersheds Using an Engineering-Enviromental-Economic (3E) Model	Xin - Pearl river delta	Unspecified
	Yao et al.,	2018	Integrating cost-benefits analysis and life cycle assessment of green roofs: a case study in Florida	Yao - Gainesville	Social
Photovoltaic Performance Analysis	Chemisana & Lamnatou	2014	Photovoltaic-green roofs: An experimental evaluation of system performance	Chemisana & Lamnatou - Lleida	Not Applicable (PV performance analysis)

	Hui & Chan,	2011	Integration of green roof and solar photovoltaic systems	Hui & Chan - Hong Kong	Not Applicable (PV performance analysis)
	Nagengast et al.,	2013	Variations in photovoltaic performance due to climate and low-slope roof choice	Nagengast - Huntsville	Not Applicable (PV performance analysis)
				Nagengast - Phoenix	Not Applicable (PV performance analysis)
				Nagengast - Pittsburgh	Not Applicable (PV performance analysis)
				Nagengast - San Diego	Not Applicable (PV performance analysis)
	Ogaili & Sailor,	2016	Measuring the Effect of Vegetated Roofs on the Performance of Photovoltaic Panels in a Combined System	Ogaili & Sailor - Portland	Not Applicable (PV performance analysis)
	Perez et al.,	2012	Green-roof integrated PV canopies - an empirical study and teaching tool for low income students in the south bronx	Perez - New York	Not Applicable (PV performance analysis)

C.2 Articles Included in the Local Analysis

Table C.2 provides a list of the articles included in the local analysis.

Table C.2. Articles in the local analysis.

Study type	Authors	Year	Title	Case-study ID	Discount rate
Cost-Benefit Analysis	Ascione et al.,	2013	Green roofs in European climates. Are effective soluzitons for the energy savings in air-conditioning?	Ascione - London	Unspecified
				Ascione-Amsterdam	Unspecified
	Bianchini & Hewage,	2012	Probabilistic social cost-benefit analysis for green roofs: A lifecycle approach	Not Applicable	Social
	Claus and Rousseau,	2012	Public versus private incentives to invest in green roofs: a cost benefit analysis for Flanders	Claus Rousseau - Dilbeek	Social and Private
	Johnson & Geisendorf,	2019	Are Neighborhood-level SUDS Worth it? An assessment of the Economic Value of Sustainable Urban Drainage System Scenarios Using Cost-Benefit Analyses	Johnson & Geisendor - Berlin	Social and Private
	Machac et al.,	2016	Green and Blue Infrastructure: An Opportunity for Smart Cities	Machac - Jinonice	Social

C.3 Overview of private discount rates

In this last section of Appendix C an overview of the private discount rates is provided. To facilitate the comparison of the private discount rates with the social ones, both are displayed in Figure C.1.

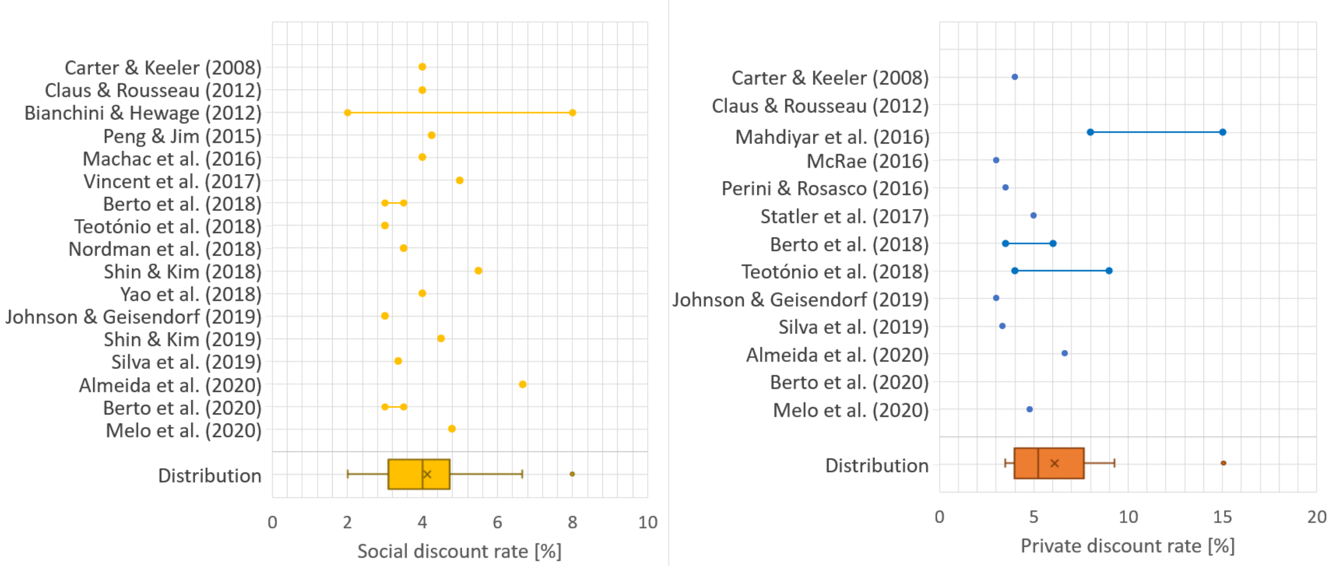


Figure C.1. Social and private Discount rates.

Appendix D

The complete spreadsheet is available online at:

https://tud365-
my.sharepoint.com/:f:/g/personal/fcruztorres_tudelft_nl/EmBsKQe2ajZIkp1HayiTJEEBPfhZ5rscZ5LRA4
WY5nej6g?e=xsn1sA

Appendix E

The complete code of the simulated CBA is available at:

https://github.com/fcruztorres/Photovoltaic_green_roof_energy_communities

References

AGORA. (2019, April). *Quartier Alzette: 1st prize*. Quartier Alzette. https://www.quartieralzette.lu/de/ergebnisse/1-preis

AGORA. (2020, October 23). *Presseinformation Eine urbane Zukunft für den früheren Industriestandort EschSchifflange*. https://www.agora.lu/fileadmin/AGORA/user_upload/06-presse/2020_10_23_Pressemitteilung_Go_Quartier_Alzette/2020_10_23_Pressemitteilung_Agora_QA_DE.pdf

Ahmed Ali, K., Ahmad, M. I., & Yusup, Y. (2020). Issues, Impacts, and Mitigations of Carbon Dioxide Emissions in the Building Sector. *Sustainability*, *12*(18), 7427. https://doi.org/10.3390/su12187427

Aitkenhead-Peterson, J. A., Dvorak, B. D., Volder, A., & Stanley, N. C. (2011). Chemistry of growth medium and leachate from green roof systems in south-central Texas. *Urban Ecosystems*, *14*(1), 17–33. https://doi.org/10.1007/s11252-010-0137-4

Almeida, C., Teotónio, I., Silva, C. M., & Cruz, C. O. (2021). Socioeconomic feasibility of green roofs and walls in public buildings: The case study of primary schools in Portugal. *The Engineering Economist*, *66*(1), 27–50. https://doi.org/10.1080/0013791X.2020.1748255

Andersson, H. (2020). Chapter Three—The value of a statistical life. In N. Mouter (Ed.), *Advances in Transport Policy and Planning* (Vol. 6, pp. 75–99). Academic Press. https://doi.org/10.1016/bs.atpp.2020.07.004

Appelbaum, B. (2011, February 16). As U.S. Agencies Put More Value on a Life, Businesses Fret. *The New York Times*. https://www.nytimes.com/2011/02/17/business/economy/17regulation.html

Ascione, F., Bianco, N., de' Rossi, F., Turni, G., & Vanoli, G. P. (2013). Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning? *Applied Energy*, *104*, 845–859. https://doi.org/10.1016/j.apenergy.2012.11.068

Baik, J.-J., Kwak, K.-H., Park, S.-B., & Ryu, Y.-H. (2012). Effects of building roof greening on air quality in street canyons. *Atmospheric Environment*, *61*, 48–55. https://doi.org/10.1016/j.atmosenv.2012.06.076

Bankes, S., Walker, W. E., & Kwakkel, J. H. (2013). Exploratory Modeling and Analysis. In S. I. Gass & M. C. Fu (Eds.), *Encyclopedia of Operations Research and Management Science* (pp. 532–537). Springer US. https://doi.org/10.1007/978-1-4419-1153-7_314

Bauduceau, N., Berry, P., Cecchi, C., Elmqvist, T., Fernandez, M., Hartig, T., Krull, W., Mayerhofer, E., Sandra, N., Noring, L., & others. (2015). Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities: Final report of the Horizon 2020 expert group on 'nature-based solutions and re-naturing cities.' *Publications Office of the European Union: Brussels, Belgium*.

Berardi, U., GhaffarianHoseini, A., & GhaffarianHoseini, A. (2014). State-of-the-art analysis of the environmental benefits of green roofs. *Applied Energy*, *115*, 411–428. https://doi.org/10.1016/j.apenergy.2013.10.047

Berndtsson, J. C. (2010). Green roof performance towards management of runoff water quantity and quality: A review. *Ecological Engineering*, *36*(4), 351–360. https://doi.org/10.1016/j.ecoleng.2009.12.014

Berto, R., Stival, C. A., & Rosato, P. (2018). Enhancing the environmental performance of industrial settlements: An economic evaluation of extensive green roof competitiveness. *Building and Environment*, *127*, 58–68. https://doi.org/10.1016/j.buildenv.2017.10.032

Berto, R., Stival, C. A., & Rosato, P. (2020). The Valuation of Public and Private Benefits of Green Roof Retrofit in Different Climate Conditions. In G. Mondini, A. Oppio, S. Stanghellini, M. Bottero, & F. Abastante (Eds.), *Values and Functions for Future Cities* (pp. 145–166). Springer International Publishing. https://doi.org/10.1007/978-3-030-23786-8_8

Bhatia, S. C. (2014). 4—Solar thermal energy. In S. C. Bhatia (Ed.), *Advanced Renewable Energy Systems* (pp. 94–143). Woodhead Publishing India. https://doi.org/10.1016/B978-1-78242-269-3.50004-8

Bianchini, F., & Hewage, K. (2012). Probabilistic social cost-benefit analysis for green roofs: A lifecycle approach. *Building and Environment*, *58*, 152–162. https://doi.org/10.1016/j.buildenv.2012.07.005

Biesenbender, S. (2015). The EU's Energy Policy Agenda: Directions and Developments. In *Energy Policy Making in the EU* (Vol. 28). Springer.

BIL. (2019). *Overview of the Luxembourg housing market*. Banque Internationale à Luxembourg. https://www.bil.com/Documents/brochures/bil-brochures-immoindex-en.pdf

Blanusa, T., Vaz Monteiro, M. M., Fantozzi, F., Vysini, E., Li, Y., & Cameron, R. W. F. (2013). Alternatives to Sedum on green roofs: Can broad leaf perennial plants offer better 'cooling service'? *Building and Environment*, *59*, 99–106. https://doi.org/10.1016/j.buildenv.2012.08.011

Bracco, S., Delfino, F., Ferro, G., Pagnini, L., Robba, M., & Rossi, M. (2018). Energy planning of sustainable districts: Towards the exploitation of small size intermittent renewables in urban areas. *Applied Energy*, *228*, 2288–2297. https://doi.org/10.1016/j.apenergy.2018.07.074

Bregha, F. (2006, February 7). *Energy Policy* [Encyclopedia]. The Canadian Encyclopedia. https://www.thecanadianencyclopedia.ca/en/article/energy-policy

Breuning, J. (2008). Fire & Wind on Extensive Green Roofs. *Proceedings of the Sixth Annual Greening Rooftops for Sustainable Communities*.

Buchan, D. (2017). *14. Energy Policy Sharp Challenges and Rising Ambitions* (Vol. 1). Oxford University Press. https://doi.org/10.1093/hepl/9780199689675.003.0014

Burszta-Adamiak, E., & Fiałkiewicz, W. (2019). A review of green roof incentives as motivators for the expansion of green infrastructure in European cities. *Przegląd Naukowy Inżynieria i Kształtowanie Środowiska*, *28*(4), 641–652. https://doi.org/10.22630/PNIKS.2019.28.4.58

CABE. (2005). *Does money grow on trees?* Commission for Architecture and the Built Environment.

Caramizaru, A., & Uihlein, A. (2020). *Energy communities: An overview of energy and social innovation.* [JRC Science for Policy Report]. Publications Office of the European Union. https://data.europa.eu/doi/10.2760/180576

Carter, T., & Keeler, A. (2008). Life-cycle cost–benefit analysis of extensive vegetated roof systems. *Journal of Environmental Management*, *87*(3), 350–363. https://doi.org/10.1016/j.jenvman.2007.01.024

Catalano, C., Laudicina, V. A., Badalucco, L., & Guarino, R. (2018). Some European green roof norms and guidelines through the lens of biodiversity: Do ecoregions and plant traits also matter? *Ecological Engineering*, *115*, 15–26. https://doi.org/10.1016/j.ecoleng.2018.01.006

CEC. (1985). *New Community Energy Objectives* (Communication from the Commission to the Council COM(85) 245 final). Commission of the European Communities. https://1library.net/document/oz1vrp3z-new-community-energy-objectives-communication-commission-council-final.html

CEC. (1988). *The internal energy market* (Commission Working Document COM(88) 238 final). Commission of the European Communities. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:51988DC0238&from=EN

Chakraborty, S., Sadhu, P. K., & Pal, N. (2015). Technical mapping of solar PV for ISM-an approach toward green campus. *Energy Science & Engineering*, *3*(3), 196–206. https://doi.org/10.1002/ese3.65

Chemisana, D., & Lamnatou, Chr. (2014). Photovoltaic-green roofs: An experimental evaluation of system performance. *Applied Energy*, *119*, 246–256. https://doi.org/10.1016/j.apenergy.2013.12.027

Ciambra, A., & Solorio, I. (2015). The Liberalisation of the Internal Energy Market: Is the EU Dancing at a British Tempo? In J. Tosun, S. Biesenbender, & K. Schulze (Eds.), *Energy Policy Making in the EU: Building the Agenda* (pp. 147–165). Springer. https://doi.org/10.1007/978-1-4471-6645-0_8

Clark, C., Adriaens, P., & Talbot, F. B. (2008). Green Roof Valuation: A Probabilistic Economic Analysis of Environmental Benefits. *Environmental Science & Technology*, *42*(6), 2155–2161. https://doi.org/10.1021/es0706652

Claus, K., & Rousseau, S. (2012). Public versus private incentives to invest in green roofs: A cost benefit analysis for Flanders. *Urban Forestry & Urban Greening*, *11*(4), 417–425. https://doi.org/10.1016/j.ufug.2012.07.003

Cook, L. M., & Larsen, T. A. (2021). Towards a performance-based approach for multifunctional green roofs: An interdisciplinary review. *Building and Environment*, *188*, 107489. https://doi.org/10.1016/j.buildenv.2020.107489

Cook, L. M., & McCuen, R. H. (2013). Hydrologic Response of Solar Farms. *Journal of Hydrologic Engineering*, *18*(5), 536–541. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000530

Correljé, A. F., Linde, J. van der, & Westerwoudt, T. (2003). *Natural Gas in the Netherlands: From cooperation to competition?* Clingendael International Energy Programme (CIEP). https://research.tudelft.nl/en/publications/natural-gas-in-the-netherlands-from-cooperation-to-competition

Crawford, S. E. S., & Ostrom, E. (1995). A Grammar of Institutions. *The American Political Science Review*, *89*(3), 582–600. https://doi.org/10.2307/2082975

Cristiano, E., Deidda, R., & Viola, F. (2021). The role of green roofs in urban Water-Energy-Food-Ecosystem nexus: A review. *Science of The Total Environment*, *756*, 143876. https://doi.org/10.1016/j.scitotenv.2020.143876

de Vries, L., Correljé, A., Knops, H., & van der Veen, R. (2019). *Electricity Market Design and Policy Choices*.

Diez, S. (2011). *The Treatment of Risk and Uncertainty in the US Social Cost of Carbon for Regulatory Impact Analysis* (Working Paper No. 64). Centre for Climate Change Economics and Policy.

Dinesh, H., & Pearce, J. M. (2016). The potential of agrivoltaic systems. *Renewable and Sustainable Energy Reviews*, *54*, 299–308. https://doi.org/10.1016/j.rser.2015.10.024

Duffie, J. A., & Beckman, W. A. (2020). *Solar engineering of thermal processes, photovoltaics and wind* (Fifth edition). Wiley.

Dutton, J. (2015). *EU Energy Policy and the Third Package* (EPG Working Paper No. 1505). Univesity of Exter - Energy Policy Group. https://ukerc8.dl.ac.uk/UCAT/PUBLICATIONS/EU_energy_policy_and_the_third_package.pdf

Eikeland, P. O. (2004). *The Long and Winding Road to the Internal Energy Market* (FNI Report No. 8/2004; p. 43). Fridtjof Nansen Institute.

Eikeland, P. O. (2011). The Third Internal Energy Market Package: New Power Relations among Member States, EU Institutions and Non-state Actors?: THE THIRD INTERNAL ENERGY MARKET PACKAGE. *JCMS: Journal of Common Market Studies*, *49*(2), 243–263. https://doi.org/10.1111/j.1468-5965.2010.02140.x

ENI. (2020). *The man and energy*. Eni School. http://www.eniscuola.net/en/argomento/the-energy-system/the-man-and-energy/the-energy-system1/

Enserink, B., Hermans, L., Kwakkel, J., Thissen, W., Koppenjan, J., & Bots, P. (2010). *Policy analysis of multi-actor systems*. Lemma.

European Commission. (2004). Protecting the environment and economic growth: Trade-off or growth-enhancing structural adjustment? In *The European Economy: 2004 review* (Vol. 6).

European Commission. (2012). *Impact Assessment accompanying the proposal for a new general Union Environment Action Programme to 2020. Annexes 2 and 6* (Commission Staff Wroking Document Impact Assesment SWD/2012/0398 final). European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52012SC0398

European Commission. (2019). *The European Green Deal*. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588580774040&uri=CELEX:52019DC0640

European Commission. (2020). *EU Biodiversity Strategy for 2030. Bringing nature back into our lives*. https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1590574123338&uri=CELEX:52020DC0380

European Commission. (2021). *Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions. Forging a climate-resilient Europe—The new EU Strategy on Adaptation to Climate Change* (COM(2021) 82 final; p. 23). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN

European Commission & DG Energy. (2019). *Clean energy for all Europeans.* http://publications.europa.eu/publication/manifestation_identifier/PUB_MJ0319092ENN

Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, 32018L2001, EP, CONSIL, OJ L 328 (2018). http://data.europa.eu/eli/dir/2018/2001/oj/eng

European Environment Agency. (2019a). *Adaptation challenges and opportunities for the European energy system: Building a climate resilient low carbon energy system.* Publications Office. https://data.europa.eu/doi/10.2800/227321

European Environment Agency. (2019b). *The European environment: State and outlook 2020 : executive summary.* Publications Office. https://data.europa.eu/doi/10.2800/48006

Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU, 32019L0944, EP, CONSIL, OJ L 158 (2019). http://data.europa.eu/eli/dir/2019/944/oj/eng

Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe, no. 2008/50/EC, European Union (2008).

Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council, no. 2018/1999, European Union (2018).

Regulation (EU) 2019/942 of the European Parliament and of the Council of 5 June 2019 establishing a European Union Agency for the Cooperation of Energy Regulators, 32019R0942, EP, CONSIL, OJ L (2019). http://data.europa.eu/eli/reg/2019/942/oj/eng

Eurostat. (2020). *Shedding light on energy in the EU - A guided tour of energy statistics*. https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2a.html#:~:text=In%202018%2C%20the%20energy%20mix,nuclear%20energy%20(13%20%25).

Fay, J. A., & Golomb, D. (2012). *Energy and the environment: Scientific and technological principles* (2nd ed). Oxford University Press.

Feng, H., & Hewage, K. N. (2018). Economic Benefits and Costs of Green Roofs. In *Nature Based Strategies for Urban and Building Sustainability* (pp. 307–318). Elsevier. https://doi.org/10.1016/B978-0-12-812150-4.00028-8

FLL. (2018). *Green Roof Guidelines. Guidelines for the Planning, Construction and Maintenance of Green Roofs* (No. 6). Landscape Development and Landscaping Research Society e.V. (FLL).

Foreman-Peck, J., & Millward, R. (1994). *Public and private ownership of British industry, 1820-1990*. Clarendon Press ; Oxford University Press.

Gayer, T., & Viscusi, W. K. (2016). Determining the Proper Scope of Climate Change Policy Benefits in U.S. Regulatory Analyses: Domestic versus Global Approaches. *Review of Environmental Economics and Policy*, *10*(2), 245–263. https://doi.org/10.1093/reep/rew002

Loi du 3 février 2021 modifiant la loi modifiée du 1er août 2007 relative à l'organisation du marché de l'électricité., no. Memorial A N.94, Grand-Duché De Luxembourg (2021).

Guerry, A. D., Ruckelshaus, M. H., Plummer, M. L., & Holland, D. (2013). Modeling Marine Ecosystem Services. In S. A. Levin (Ed.), *Encyclopedia of Biodiversity (Second Edition)* (pp. 329–346). Academic Press. https://doi.org/10.1016/B978-0-12-384719-5.00333-6

Haines-Young, R., & Potschin, M. (2010). The links between biodiversity, ecosystem services and human well-being. In C. L. J. Frid & D. G. Raffaelli (Eds.), *Ecosystem Ecology: A New Synthesis* (pp. 110–139). Cambridge University Press. https://doi.org/10.1017/CBO9780511750458.007

Hannoset, A., Peeters, L., & Tuerk, A. (2019). *Energy Communities in the EU - Task Force Energy* (D3.12.d). https://www.h2020-bridge.eu/wp-content/uploads/2020/01/D3.12.d_BRIDGE_Energy-Communities-in-the-EU-2.pdf

Harris, J., & Roach, B. (2018). *Environmental and Natural Resource Economics: A Contemporary Approach*. Routledge & CRC Press. https://www.routledge.com/Environmental-and-Natural-Resource-Economics-A-Contemporary-Approach/Harris-Roach/p/book/9781138659476

Harrison, M. (2010). *Valuing the future: The social discount rate in cost-benefit analysis*. Productivity Commission.

Hashemi, S. S. G., Mahmud, H. B., & Ashraf, M. A. (2015). Performance of green roofs with respect to water quality and reduction of energy consumption in tropics: A review. *Renewable and Sustainable Energy Reviews*, *52*, 669–679. https://doi.org/10.1016/j.rser.2015.07.163

Herweg, N. (2015). Against All Odds: The Liberalisation of the European Natural Gas Market—A Multiple Streams Perspective. In J. Tosun, S. Biesenbender, & K. Schulze (Eds.), *Energy Policy Making in the EU: Building the Agenda* (pp. 87–105). Springer. https://doi.org/10.1007/978-1-4471-6645-0_5

Hinsch, A., Rothballer, C., & Kittel, J. (2021). *Policy Brief 1 Renewable Energy Communities—Are we nearly there.pdf* (Policy Brief No. 1). ICLEI Europe - Local Governments committed to sustainable development. https://come-res.eu/resource?t=Policy%20Brief%201:%20Renewable%20Energy%20Communities%20-%20Are%20we%20nearly%20there?

Hodgson, G. M. (2006). What Are Institutions? *Journal of Economic Issues*, *40*(1), 1–25. https://doi.org/10.1080/00213624.2006.11506879

Hui, S., & Chan, S. C. (2011). Integration of green roof and solar photovoltaic systems. *Undefined*. /paper/Integration-of-green-roof-and-solar-photovoltaic-Hui-Chan/cca48bc31a8187823028cbe327cc81f07249096b

Islam, M. M., & Hasanuzzaman, M. (2020). Chapter 1—Introduction to energy and sustainable development. In MD. Hasanuzzaman & N. A. Rahim (Eds.), *Energy for Sustainable Development* (pp. 1–18). Academic Press. https://doi.org/10.1016/B978-0-12-814645-3.00001-8

Jain, M., Kuriakose, G., & Balakrishnan, R. (2010). Evaluation of methods to estimate foliage density in the understorey of a tropical evergreen forest. *Current Science*, *98*(4), 508–515.

Jim, C. Y., & Tsang, S. W. (2011). Biophysical properties and thermal performance of an intensive green roof. *Building and Environment*, *46*(6), 1263–1274. https://doi.org/10.1016/j.buildenv.2010.12.013

Johnson, D., & Geisendorf, S. (2019). Are Neighborhood-level SUDS Worth it? An Assessment of the Economic Value of Sustainable Urban Drainage System Scenarios Using Cost-Benefit Analyses. *Ecological Economics*, *158*, 194–205. https://doi.org/10.1016/j.ecolecon.2018.12.024

Johnson, J. (2012). *Britain must defend the single market* [Centre for European Reform Essays]. Centre for European Reform. https://www.cer.eu/publications/archive/essay/2012/britain-must-defend-single-market

Jones et al. (2011). *Cambridge business English dictionary*. Cambridge University Press.

Kalra, N., Hallegatte, S., Lempert, R., Brown, C., Fozzard, A., Gill, S., & Shah, A. (2014). *Agreeing on Robust Decisions. New Processes for Decision Making Under Deep Uncertainty* (Working Paper No. 6906; Policy Research). World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/18772/WPS6906.pdf?sequence=1&isAllowed=y

Kampman, B., Blommerde, J., & Afman, M. (2016). *The potential of energy citizens in the European Union* (16.3J00.75). CE Delft. https://www.ce.nl/publicatie/the_potential_of_energy_citizens_in_the_european_union/1845

Kaplan, A. (1998). Chapter VII: Models. In *The conduct of inquiry: Methodology for behavioral science*. Transaction.

Kohler, M, Feige, R., & Wiartalla, W. (2007, July). Interaction between PV-systems and extensive green roofs. *Proceedings of the 5. Annual International Greening Rooftops for Sustainable Communities Conference, Awards and Trade Show*. The 5. annual international greening rooftops for sustainable communities conference, awards and trade show, Minneapolis.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Kottek, M., & Rubel, F. (2017). *World Map of the Köppen-Geiger climate classification updated*. World Maps of the Köppen-Geiger Climate Classification. http://koeppen-geiger.vu-wien.ac.at/present.htm

Kwakkel, J. H. (2017). The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. *Environmental Modelling & Software*, *96*, 239–250. https://doi.org/10.1016/j.envsoft.2017.06.054

La Notte, A., D'Amato, D., Mäkinen, H., Paracchini, M. L., Liquete, C., Egoh, B., Geneletti, D., & Crossman, N. D. (2017). Ecosystem services classification: A systems ecology perspective of the cascade framework. *Ecological Indicators*, *74*, 392–402. https://doi.org/10.1016/j.ecolind.2016.11.030

Lamnatou, Chr., & Chemisana, D. (2014). Photovoltaic-green roofs: A life cycle assessment approach with emphasis on warm months of Mediterranean climate. *Journal of Cleaner Production*, *72*, 57–75. https://doi.org/10.1016/j.jclepro.2014.03.006

Lamnatou, Chr., & Chemisana, D. (2015). A critical analysis of factors affecting photovoltaic-green roof performance. *Renewable and Sustainable Energy Reviews*, *43*, 264–280. https://doi.org/10.1016/j.rser.2014.11.048

Lane, D. C. (2001). Rerum cognoscere causas: Part II—Opportunities generated by the agency/structure debate and suggestions for clarifying the social theoretic position of system dynamics. *System Dynamics Review*, *17*(4), 293–309. https://doi.org/10.1002/sdr.221

Lempert, R. J. (2003). *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*. Rand Corporation.

Lempert, R. J. (2014). Embedding (some) benefit-cost concepts into decision support processes with deep uncertainty. *Journal of Benefit-Cost Analysis*, *5*(03), 487–514. https://doi.org/10.1515/jbca-2014-9006

Liberalesso, T., Oliveira Cruz, C., Matos Silva, C., & Manso, M. (2020). Green infrastructure and public policies: An international review of green roofs and green walls incentives. *Land Use Policy*, *96*, 104693. https://doi.org/10.1016/j.landusepol.2020.104693

Lienhard, J. H., & Lienhard, J. H. (2019). *A heat transfer textbook* (Fifth Edition). Dover Publications, Inc.

Lowitzsch. (2019). *Energy Transition: Financing Consumer Co-Ownership in Renewables*. Springer International Publishing. https://doi.org/10.1007/978-3-319-93518-8

Lowitzsch, J., Hoicka, C. E., & van Tulder, F. J. (2020). Renewable energy communities under the 2019 European Clean Energy Package – Governance model for the energy clusters of the future? *Renewable and Sustainable Energy Reviews*, *122*, 109489. https://doi.org/10.1016/j.rser.2019.109489

Machac, J., Louda, J., & Dubova, L. (2016). Green and blue infrastructure: An opportunity for smart cities? *2016 Smart Cities Symposium Prague (SCSP)*, 1–6. https://doi.org/10.1109/SCSP.2016.7501030

Mahdiyar, A., Tabatabaee, S., Sadeghifam, A. N., Mohandes, S. R., Abdullah, A., & Meynagh, M. M. (2016). Probabilistic private cost-benefit analysis for green roof installation: A Monte Carlo simulation approach. *Urban Forestry & Urban Greening*, *20*, 317–327. https://doi.org/10.1016/j.ufug.2016.10.001

Mahmoud, A., Asif, M., Hassanain, M., Babsail, M., & Sanni-Anibire, M. (2017). Energy and Economic Evaluation of Green Roofs for Residential Buildings in Hot-Humid Climates. *Buildings*, *7*(4), 30. https://doi.org/10.3390/buildings7020030

Manohar, K., Ramkissoon, R., & Adeyanju, A. (2015). Cost Benefit Analysis of Implementing a Solar Photovoltaic System. *International Journal of Innovative Research in Science, Engineering and Technology*, *4*(12), 11696–11703. https://doi.org/10.15680/IJIRSET.2015.0412006

Manso, M., Teotónio, I., Silva, C. M., & Cruz, C. O. (2021). Green roof and green wall benefits and costs: A review of the quantitative evidence. *Renewable and Sustainable Energy Reviews*, *135*, 110111. https://doi.org/10.1016/j.rser.2020.110111

Matláry, J. H. (1997). Energy Policies in the EU Countries. In J. H. Matláry (Ed.), *Energy Policy in the European Union* (pp. 25–44). Macmillan Education UK. https://doi.org/10.1007/978-1-349-25735-5_3

McGowan, F. (1996). Energy Policy. In *The European Union and national industrial policy*. Routledge. http://site.ebrary.com/id/10058132

Mehleri, E. D., Zervas, P. L., Sarimveis, H., Palyvos, J. A., & Markatos, N. C. (2010). Determination of the optimal tilt angle and orientation for solar photovoltaic arrays. *Renewable Energy*, *35*(11), 2468–2475. https://doi.org/10.1016/j.renene.2010.03.006

Meister, T., Schmid, B., Seidl, I., & Klagge, B. (2020). How municipalities support energy cooperatives: Survey results from Germany and Switzerland. *Energy, Sustainability and Society*, *10*(1), 18. https://doi.org/10.1186/s13705-020-00248-3

Melo, C., Teotónio, I., Silva, C. M., & Cruz, C. O. (2020). What's the economic value of greening transport infrastructures? The case of the underground passages in Lisbon. *Sustainable Cities and Society*, *56*, 102083. https://doi.org/10.1016/j.scs.2020.102083

Merrill, D. (2017, October 19). No One Values Your Life More Than the Federal Government. *Bloomberg.Com*. https://www.bloomberg.com/graphics/2017-value-of-life/

Montero, J.-M., & Fernández-Avilés, G. (2014). Hedonic Price Model. In A. C. Michalos (Ed.), *Encyclopedia of Quality of Life and Well-Being Research* (pp. 2834–2837). Springer Netherlands. https://doi.org/10.1007/978-94-007-0753-5_1279

Montgomery, D. C., Runger, G. C., & Hubele, N. F. (2011). *Engineering statistics* (5th ed). John Wiley.

Nash, C., Clough, J., Gedge, D., Lindsay, R., Newport, D., Ciupala, M. A., & Connop, S. (2016). Initial insights on the biodiversity potential of biosolar roofs: A London Olympic Park green roof case study. *Israel Journal of Ecology and Evolution*, *62*(1–2), 74–87. https://doi.org/10.1080/15659801.2015.1045791

Nassar, K., & Al-Mohaisen, A. (2006). Simplified Approach to Probabilistic Cost Benefit Analysis: Architectural Lighting Example. *Cost Engineering*, *48*(1), 13–18.

Nesshöver, C., Assmuth, T., Irvine, K. N., Rusch, G. M., Waylen, K. A., Delbaere, B., Haase, D., Jones-Walters, L., Keune, H., Kovacs, E., Krauze, K., Külvik, M., Rey, F., van Dijk, J., Vistad, O. I., Wilkinson, M. E., & Wittmer, H. (2017). The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *Science of The Total Environment*, *579*, 1215–1227. https://doi.org/10.1016/j.scitotenv.2016.11.106

Niu, H., Clark, C., Zhou, J., & Adriaens, P. (2010). Scaling of Economic Benefits from Green Roof Implementation in Washington, DC. *Environmental Science & Technology*, *44*(11), 4302–4308. https://doi.org/10.1021/es902456x

Nordhaus, W. D. (2007). A Review of the Stern Review on the Economics of Climate Change. *Journal of Economic Literature*, *45*(3), 686–702. https://doi.org/10.1257/jel.45.3.686

Nordman, E. E., Isely, E., Isely, P., & Denning, R. (2018). Benefit-cost analysis of stormwater green infrastructure practices for Grand Rapids, Michigan, USA. *Journal of Cleaner Production*, *200*, 501–510. https://doi.org/10.1016/j.jclepro.2018.07.152

Nouicer, A., & Meeus, L. (2019). *The EU Clean Energy Package.* (2019th ed.). European University Institute. Robert Schuman Centre for Advanced Studies. https://data.europa.eu/doi/10.2870/33236

OECD. (2020). *Luxembourg. International Migration Outlook 2020*. OECD ILibrary. https://www.oecd-ilibrary.org/sites/b63ab219-en/index.html?itemId=/content/component/b63ab219-en

OECD. (2021a). *Housing prices. Indicator* [Data set]. OECD. https://doi.org/10.1787/63008438-en

OECD. (2021b). *Purchasing power parities (PPP) (indicator)* [Data set]. OECD. https://doi.org/10.1787/1290ee5a-en

Osma-Pinto, G., & Ordóñez-Plata, G. (2019). Measuring factors influencing performance of rooftop PV panels in warm tropical climates. *Solar Energy*, *185*, 112–123. https://doi.org/10.1016/j.solener.2019.04.053

Padgett, S. (2003). Between synthesis and emulation: EU policy transfer in the power sector. *Journal of European Public Policy*, *10*(2), 227–245. https://doi.org/10.1080/1350176032000059017

Perini, K., & Rosasco, P. (2016). Is greening the building envelope economically sustainable? An analysis to evaluate the advantages of economy of scope of vertical greening systems and green roofs. *Urban Forestry & Urban Greening*, *20*, 328–337. https://doi.org/10.1016/j.ufug.2016.08.002

Petucco, C., Babí Almenar, J., Rugani, B., Maider, A., Usobiaga, E., Sopelana, A., Hernando, S., Egusquiza, A., Yilmaz, O., Naneci, S., Aytac, B., Kraus, F., Regoyos Sainz, M., Paraboschi, A., & Massa, E. (2018). *Nature Based Solutions for re-naturing cities: Knowledge diffusion and decision support platform through new collaborative models. D4.2 – Development of a monetary value scale in MIMES* [Nature4Cities].

Pollak, J., & Slominski, P. (2011). Liberalizing the EU's Energy Market Hard and Soft Power Combined. In *The EU's Decision Traps*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199596225.001.0001

Potschin, M., & Haines-Young, R. (2016). Defining and Measuring Ecosystem Services. In *Routledge Handbook of Ecosystem Services*. Routledge.

LEGGE 28 febbraio 2020 , n. 8 recante disposizioni urgenti in materia di proroga di termini legislativi, di organizzazione delle pubbliche amministrazioni, nonche' di innovazione tecnologica, 8, Repubblica Italiana, 20G00021 (2020). http://www.normattiva.it/uri-res/N2Ls?urn:nir:stato:legge:2020-02-28;8

Legge 17 Luglio 2020, n. 77 recante misure urgenti in materia di salute, sostegno al lavoro e all'economia, nonche' di politiche sociali connesse all'emergenza epidemiologica da COVID-19., no. 77 (2020).

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., no. 162 (2021).

Prontera, A. (2009). Energy Policy: Concepts, Actors, Instruments and Recent Developments. *World Political Science*, *5*. https://doi-org.proxy.bnl.lu/10.2202/1935-6226.1063

Proost, S., & Rousseau, S. (2007). *Inleiding tot de milieueconomie (Introduction to Environmental Economics)*.

Prosser, T. (2005). *The limits of competition law: Markets and public services*. Oxford University Press.

Publications Office of the European Union. (2021). *About EUR-Lex*. About EUR-Lex. Access to European Union Law. https://eur-lex.europa.eu/content/welcome/about.html

Ramirez Camargo, L., & Stoeglehner, G. (2018). Spatiotemporal modelling for integrated spatial and energy planning. *Energy, Sustainability and Society*, *8*(1), 32. https://doi.org/10.1186/s13705-018-0174-z

Reindl, K., & Palm, J. (2021). Installing PV: Barriers and enablers experienced by non-residential property owners. *Renewable and Sustainable Energy Reviews*, *141*, 110829. https://doi.org/10.1016/j.rser.2021.110829

Romijn, G., & Renes, G. (2013). *General Guidance for Cost-Benefit Analysis*. Netherlands Bureau for Economic Policy Analysis and Netherlands Environmental Assessment Agency.

Rosato, P., & Rotaris, L. (2014). La scarsa diffusione delle coperture verdi in Italia: Bassa disponibilità a pagare o poca informazione? *Valori E Valutazioni*, *13*, 1–10.

RSE. (2020). *Gli schemi di Autoconsumo Collettivo e le Comunità dell'Energia. DossieRSE*. Ricerca sul Sistema Energetico (RSE). https://dossierse.it/17-2020-gli-schemi-di-autoconsumo-collettivo-e-le-comunita-dellenergia/

Ruin, S., & Sideén, G. (2020). *Small-Scale Renewable Energy Systems: Independent Electricity for Community, Business and Home*. https://www.routledge.com/Small-Scale-Renewable-Energy-Systems-Independent-Electricity-for-Community/Ruin-Siden/p/book/9780367030971

Saadatian, O., Sopian, K., Salleh, E., Lim, C. H., Riffat, S., Saadatian, E., Toudeshki, A., & Sulaiman, M. Y. (2013). A review of energy aspects of green roofs. *Renewable and Sustainable Energy Reviews*, *23*, 155–168. https://doi.org/10.1016/j.rser.2013.02.022

Santamouris, M. (2014). Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy*, *103*, 682–703. https://doi.org/10.1016/j.solener.2012.07.003

Santamouris, M., Pavlou, C., Doukas, P., Mihalakakou, G., Synnefa, A., Hatzibiros, A., & Patargias, P. (2007). Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece. *Energy*, *32*(9), 1781–1788. https://doi.org/10.1016/j.energy.2006.11.011

Sarbu, I., & Sebarchievici, C. (2017). Chapter 8—Solar Electric Cooling Systems. In I. Sarbu & C. Sebarchievici (Eds.), *Solar Heating and Cooling Systems* (pp. 315–346). Academic Press. https://doi.org/10.1016/B978-0-12-811662-3.00008-6

Sartori, D., Catalano, G., Genco, M., Pancotti, C., Sirtori, E., Vignetti, S., & Del Bo, S. (2015). *Guide to cost-benefit analysis of investment projects: Economic appraisal tool for cohesion policy 2014-2020*. European Union.

Sattler, S., Zluwa, I., & Österreicher, D. (2020). The "PV Rooftop Garden": Providing Recreational Green Roofs and Renewable Energy as a Multifunctional System within One Surface Area. *Applied Sciences*, *10*(5), 1791. https://doi.org/10.3390/app10051791

Scharpf, F. W. (2018). *Games Real Actors Play: Actor-Centered Institutionalism in Policy Research* (1st ed.). Routledge. https://doi.org/10.4324/9780429500275

Schoor, T. van der, Lente, H. van, Scholtens, B., & Peine, A. (2016). Challenging obduracy: How local communities transform the energy system. *Energy Research & Social Science*, *13*, 94–105. https://doi.org/10.1016/j.erss.2015.12.009

Shafique, M., Kim, R., & Kyung-Ho, K. (2018). Green Roof for Stormwater Management in a Highly Urbanized Area: The Case of Seoul, Korea. *Sustainability*, *10*(3), 584. https://doi.org/10.3390/su10030584

Shafique, M., Kim, R., & Rafiq, M. (2018). Green roof benefits, opportunities and challenges – A review. *Renewable and Sustainable Energy Reviews*, *90*, 757–773. https://doi.org/10.1016/j.rser.2018.04.006

Shafique, M., Luo, X., & Zuo, J. (2020). Photovoltaic-green roofs: A review of benefits, limitations, and trends. *Solar Energy*, *202*, 485–497. https://doi.org/10.1016/j.solener.2020.02.101

Shin, E., & Kim, H. (2015). Analysing Green Roof Effects in an Urban Environment: A Case of Bangbae-dong, Seoul. *Journal of Asian Architecture and Building Engineering*, *14*(2), 315–322. https://doi.org/10.3130/jaabe.14.315

Shin, E., & Kim, H. (2019). Benefit–Cost Analysis of Green Roof Initiative Projects: The Case of Jung-gu, Seoul. *Sustainability*, *11*(12), 3319. https://doi.org/10.3390/su11123319

Silva, C. M., Serro, J., Dinis Ferreira, P., & Teotónio, I. (2019). The socioeconomic feasibility of greening rail stations: A case study in lisbon. *The Engineering Economist*, *64*(2), 167–190. https://doi.org/10.1080/0013791X.2018.1470272

Soenen, L. A. (1973). THE CONCEPT OF CASH FLOW: Techniques for Speeding up the Flow of Cash. *Management Decision*, *11*(5), 314–322. https://doi.org/10.1108/eb001031

Sokolowski, J. A., Banks, C. M., & Sokolowski, J. A. (2009). What is Modeling and Simulation? In *Principles of Modeling and Simulation: A Multidisciplinary Approach*. John Wiley & Sons, Incorporated. http://ebookcentral.proquest.com/lib/delft/detail.action?docID=427580

Solorio, I., & Morata, F. (2012). Introduction: The Re-evolution of Energy Policy in Europe. In *European Energy Policy*. Edward Elgar Publishing. https://www.elgaronline.com/view/9780857939203.00008.xml

Sproul, J., Wan, M. P., Mandel, B. H., & Rosenfeld, A. H. (2014). Economic comparison of white, green, and black flat roofs in the United States. *Energy and Buildings*, *71*, 20–27. https://doi.org/10.1016/j.enbuild.2013.11.058

Statler, N. E., Adams, A. M., & Eckmann, T. C. (2017). Optimizing angles of rooftop photovoltaics, ratios of solar to vegetated roof systems, and economic benefits, in Portland, Oregon, USA. *Environment Systems and Decisions*, *37*(3), 320–331. https://doi.org/10.1007/s10669-017-9640-y

Stern, N. H. (Ed.). (2007). *The economics of climate change: The Stern review*. Cambridge University Press.

Stewart, I., & Mills, G. (2021). *The Urban Heat Island*. Elsevier. https://go.openathens.net/redirector/umoncton.ca?url=https%3A%2F%2Febookcentral.proquest.com%2Flib%2Fumoncton-ebooks%2Fdetail.action%3FdocID%3D6630985

Swiss Association of Engineers and Architects. (2013). *SIA 312—Begrünung von Dächern*. Begrünung von Dächern. Schweizerischer Ingenieur- und ArchitektenVerein.

Teotónio, I., Silva, C. M., & Cruz, C. O. (2018). Eco-solutions for urban environments regeneration: The economic value of green roofs. *Journal of Cleaner Production*, *199*, 121–135. https://doi.org/10.1016/j.jclepro.2018.07.084

Teotónio, I., Silva, C. M., & Cruz, C. O. (2021). Economics of green roofs and green walls: A literature review. *Sustainable Cities and Society*, *69*, 102781. https://doi.org/10.1016/j.scs.2021.102781

The twelve Member States: Belgium, Denmark, Germany, Ireland, Greece, Spain, France, Italy, Luxembourg, Netherlands, Portugal, United Kingdom. (1987). *Single European Act*. Official Journal of the European Communities. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:1987:169:FULL&from=EN

Tol, R. S. J. (2019). A social cost of carbon for (almost) every country. *Energy Economics*, *83*, 555–566. https://doi.org/10.1016/j.eneco.2019.07.006

Tosun, J. (2017). *Energy Policy* (Vol. 1). Oxford University Press. https://doi.org/10.1093/acrefore/9780190228637.013.174

Tosun, J., Biesenbender, S., & Schulze, K. (Eds.). (2015). *Energy Policy Making in the EU* (Vol. 28). Springer London. https://doi.org/10.1007/978-1-4471-6645-0

Tyllianakis, E., & Skuras, D. (2016). The income elasticity of Willingness-To-Pay (WTP) revisited: A meta-analysis of studies for restoring Good Ecological Status (GES) of water bodies under the Water Framework Directive (WFD). *Journal of Environmental Management*, *182*, 531–541. https://doi.org/10.1016/j.jenvman.2016.08.012

UN-Habitat. (2016). *Urbanization and development: Emerging futures*. UN-Habitat.

UO Solar Radiation Monitoring Laboratory. (2019, January 30). *Sun path chart program*. http://solardat.uoregon.edu/SunChartProgram.php

US EPA. (2014a, April 10). *Criteria for Air pollutants* [Official website of the United States government.]. US Environmental Protection Agency. https://www.epa.gov/criteria-air-pollutants/naaqs-table

US EPA. (2014b, June 17). *Heat Islands* [Overviews and Factsheets]. United States Environmental Protection Agency. https://www.epa.gov/heatislands/learn-about-heat-islands

Vaishnav, P., Horner, N., & Azevedo, I. L. (2017). Was it worthwhile? Where have the benefits of rooftop solar photovoltaic generation exceeded the cost? *Environmental Research Letters*, *12*(9), 094015. https://doi.org/10.1088/1748-9326/aa815e

Van Renterghem, T., & Botteldooren, D. (2011). In-situ measurements of sound propagating over extensive green roofs. *Building and Environment*, *46*(3), 729–738. https://doi.org/10.1016/j.buildenv.2010.10.006

Ventosa, M., Linares, P., & Pérez-Arriaga, I. J. (2013). Power System Economics. In I. J. Pérez-Arriaga (Ed.), *Regulation of the Power Sector* (pp. 47–123). Springer. https://doi.org/10.1007/978-1-4471-5034-3_2

Verde, S., & Rossetto, N. (2020). *The future of renewable energy communities in the EU: An investigation at the time of the clean energy package.* Publications Office. https://data.europa.eu/doi/10.2870/754736

Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations and trends. *Renewable and Sustainable Energy Reviews*, *57*, 740–752. https://doi.org/10.1016/j.rser.2015.12.119

Wang, P., Deng, X., Zhou, H., & Yu, S. (2019). Estimates of the social cost of carbon: A review based on meta-analysis. *Journal of Cleaner Production*, *209*, 1494–1507. https://doi.org/10.1016/j.jclepro.2018.11.058

Warf, B. (2010). *Encyclopedia of Geography*. SAGE Publications, Inc. https://doi.org/10.4135/9781412939591

Whitehead, J. C. (2006). A Practitioner's Primer on the Contingent Valuation Method. In *Handbook on Contingent Valuation*. Edward Elgar Publishing. https://doi.org/10.4337/9781845427917.00008

William, R., Goodwell, A., Richardson, M., Le, P. V. V., Kumar, P., & Stillwell, A. S. (2016). An environmental cost-benefit analysis of alternative green roofing strategies. *Ecological Engineering*, *95*, 1–9. https://doi.org/10.1016/j.ecoleng.2016.06.091

Wong, N. H., Chen, Y., Ong, C. L., & Sia, A. (2003). Investigation of thermal benefits of rooftop garden in the tropical environment. *Building and Environment*, *38*(2), 261–270. https://doi.org/10.1016/S0360-1323(02)00066-5

World Bank. (1992). *World Development Report 1992: Development and the Environment*. Oxford University Press. https://openknowledge.worldbank.org/handle/10986/5975

World Bank. (2021a). *GDP deflator (base year varies by country) | Data. World Bank national accounts data, and OECD National Accounts data files.* The World Bank Data. https://data.worldbank.org/indicator/NY.GDP.DEFL.ZS

World Bank. (2021b). *Population growth (annual %)—Luxembourg, European Union | Data*. The World Bank Data. https://data.worldbank.org/indicator/SP.POP.GROW?locations=LU-EU

WTCB. (2006). *Groendak (green roof). Technische voorlichting (Technical advice)*. http://www.wtcb.be/?dtype=publ&lang=nl&doc=TVN%20229.pdf

Xue, Y., Lindkvist, C. M., & Temeljotov-Salaj, A. (2021). Barriers and potential solutions to the diffusion of solar photovoltaics from the public-private-people partnership perspective – Case study of Norway. *Renewable and Sustainable Energy Reviews*, *137*, 110636. https://doi.org/10.1016/j.rser.2020.110636

Yang, J., Yu, Q., & Gong, P. (2008). Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment*, *42*(31), 7266–7273. https://doi.org/10.1016/j.atmosenv.2008.07.003

Yao, L., Chini, A., & Zeng, R. (2020). Integrating cost-benefits analysis and life cycle assessment of green roofs: A case study in Florida. *Human and Ecological Risk Assessment: An International Journal*, *26*(2), 443–458. https://doi.org/10.1080/10807039.2018.1514251

Zhao, M., & Srebric, J. (2012). Assessment of green roof performance for sustainable buildings under winter weather conditions. *Journal of Central South University*, *19*(3), 639–644. https://doi.org/10.1007/s11771-012-1050-1

Zhou, Y., & Frering, D. (2006). Photovoltaic Q&A. In *NLPIP Lighting Answers: Photovoltaic Lighting* (Vol. 9). https://www.lrc.rpi.edu/programs/nlpip/lightinganswers/photovoltaic/abstract.asp