POLITECNICO DI TORINO

Master's Degree in Environmental and Land Engineering

Specialization in Climate Change

Master's Degree Thesis

Carbon offsetting in the framework of Net Zero Carbon Buildings

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Academic year 2022/2023

Summary

According to the World Green Building Council, buildings and construction are responsible for 39% of the global carbon emissions related to energy generation. In Europe, buildings account for 40% of the energy demand and 36% of greenhouse gas emissions. Consequently, several frameworks and guidelines have been developed to achieve Net Zero Carbon Buildings in recent years. The term Net Zero Carbon describes a scenario in which anthropogenic removals of carbon dioxide from the atmosphere equal the amount of anthropogenic carbon dioxide emitted within a certain time frame. To achieve this state, emissions must be reduced and avoided, and those that remain must be captured at the source or removed from the atmosphere. In this context, uncertainty has arisen about how to compensate or offset the remaining emissions to reach Net Zero, which underlines the need for further clarification and guidance.

This study examines the role of carbon offsetting in achieving Net Zero Carbon Buildings. In particular, the report analyses the voluntary and compliance carbon markets, the standards available in this field, and the principles that should be followed when offsetting GHG emissions. It will also present criteria for ensuring the use of high quality offset credits, an overview of carbon offsetting programmes available at national and international level, and existing projects eligible for carbon credit issuance.

Based on the embodied and operational emissions resulting from Life-Cycle Assessments carried out for real cases, an offsetting strategy that follows the "Oxford Principles for Zero Net Carbon Offsetting" will be applied. This strategy will be implemented for a residential, an office, and an industrial building. Cost projections related with this solution will also be evaluated based on forecasted prices for carbon offsets. Additionally, it will be assessed how the specific use of the building influenced the total amount of emissions that need to be compensated to achieve Net Zero Carbon Buildings. Finally, two scenarios in which the number of photovoltaic panels is increased with respect to the minimum requirements established by the Italian Legislative Decree n.199 will be hypothesised, with the aim of highlighting the benefits of reducing emissions from an economic point of view.

Acknowledgements

I would like to express my deepest gratitude to my supervisors, Engineer Teodoro Maiorano, Professor Giovanni Andrea Blengini, and Professor Marco Filippi. They have guided me through this work with their expertise and have shared with me priceless knowledge.

I am most grateful to Universidad Nacional de Córdoba and Politecnico di Torino for allowing me to achieve this Double Degree and for providing me with state-of-the-art education.

My thanks also go to GET Consulting for entrusting me with this project. This study would not have been possible without their support.

My sincere thanks must also go to Candela, Camila, Federica, and Lucia, who have been my pillars and inspiration since the beginning of this journey.

I deeply thank my family for their unconditional trust, enormous support, and timely encouragement.

Lastly, I would like to thank Alejandro and my friends, especially who I recognise as my family in Turin, who always cheered me on and celebrated every accomplishment as their own.

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Acronyms

AAU
: Assigned Amount Units

ACR
: American Carbon Registry

AFOLU
: Agriculture, Forestry and Other Land Use

ANSI
: American National Standards Institute

ARR
: Afforestation, Reforestation, or Revegetation

A/R
: Afforestation/Reforestation

BC
: Black Carbon

BECCS
: Bioenergy with Carbon Capture and Storage

Ca
: Calcium

CAP
: Common Agriculture Policy

CAR
: Climate Action Reserve

CCB
: Climate, Community and Biodiversity

CCS

Carbon Capture and Storage

CCUS

Carbon Capture, Utilisation and Storage

CDM

Clean Development Mechanism

CDP

Carbon Disclosure Project

CDR

Carbon Dioxide Removal

CE

Carbon Engineering

CER

Certified Emission Reduction

CH_4

Methane

CIFF

Children's Investment Fund Foundation

CO_2

Carbon Dioxide

CO_2e

Carbon Dioxide Equivalent

COP

Conference Of Parties

CORSIA

Carbon Offsetting and Reduction Scheme for International Aviation

CRREM

Carbon Risk Real Estate Monitor

CRT

Climate Reserve Tonne

DAC

Direct Air Capture

DACCS

Direct Air Capture with Carbon Storage

D.Lgs.

Decreto Legislativo (Legislative Decree)

DGNB

Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)

DNV

Det Norske Veritas

DOP

Domestic Offset Programme

EAC

Energy Attribute Certificate

EEA

European Economic Area

EEF

Enhanced Efficiency Fertiliser

EPA

Environmental Protection Agency

EPBD

Energy Performance of Buildings Directive

EPC

Energy Performance Certificate

EPD

Environmental Product Declarations

ERF

Emission Reduction Fund

ERPA

Emission Reduction Purchase Agreement

ERT
: Environmental Resources Trust

ERU
: Emission Reduction Unit

ETS
: Emission Trading System

EU
: European Union

EUA
: European Emission Allowance

FLAG
: Forest, Land-Use and Agriculture

GBC
: Green Building Council

GFA
: Gross Floor Area

GHG
: Greenhouse Gas

GmbH
: Gesellschaft mit beschränkter Haftung

GO
: Guarantee of Origin

GS
: Gold Standard

GSE
: Gestore dei Servizi Energetici

GWP
: Global Warming Potential

H_2S
: Hydrogen Sulfide

HFC
: Hydrofluorocarbon

HV
: High Voltage

i-REC
: International REC Standard

IAM
: Integrated Assessment Model

ICROA
: International Carbon Reduction and Offset Alliance

IEA
: International Energy Agency

IEA EBC
: International Energy Agency Energy in Buildings and Communities

IEMA
: Institute of Environmental Management and Assessment

IET
: International Emission Trading

IETA
: International Emissions Trading Association

INDC
: Intended Nationally Determined Contributions

IPCC
: Intergovernmental Panel on Climate Change

ISO
: International Organization for Standardization

JI
: Joint Implementation

L-DAC
: Liquid Direct Air Capture

LCA
: Life Cycle Assessment

LULUCF
: Land Use, Land Use Change and Forestry

LV
: Low Voltage

MEP
: Mechanical, Electrical and Plumbing

Mg
: Magnesium

N_2O
: Nitrous Oxide

NCS
: Natural Climate Solutions

NDC
: Nationally Determined Contribution

NET
: Negative Emission Technology

NGO
: Non-governmental organisation

NZCB
: Net Zero Carbon Building

O_3
: Ozone

OPR
: Offset Project Registry

PAH
: Polycyclic Aromatic Hydrocarbons

PCU
: Peatland Carbon Unit

PFC
: Perfluorocarbon

PIU
: Pending Issuance Unit

PM
: Particulate Matter

PPA
: Power Purchase Agreement

PV
: Photovoltaic

PVC
: Plan Vivo Certificates

REC
: Renewable Energy Certificate

REDD
: Reducing Emissions from Deforestation and forest Degradation

REGO
: Renewable Energy Guarantee of Origin

RO
: Renewable Obligation

RPS
: Renewable Portfolio Standard

RSL
: Reference Service Life

S-DAC
: Solid Direct Air Capture

SBTi
: Science Based Targets initiative

SDG
: Sustainable Development Goal

SD VISta

Sustainable Development Verified Impact Standard

SF_6

Sulphur Hexafluoride

TSVCM

Taskforce on Scaling Voluntary Carbon Markets

UKGBC

UK Green Building Council

UNFCCC

United Nations Framework Convention on Climate Change

USA

United States of America

UPM

Umwelt-Projekt-Management

VAM

Ventilation Air Methane

VCM

Voluntary Carbon Market

VCMI

Voluntary Carbon Markets Integrity Initiative

VCS

Verified Carbon Standard

VCU

Verified Carbon Unit

VVB

Validation and Verification Body

WBCSD

World Business Council for Sustainable Development

WCC

Woodland Carbon Code

WCU
Woodland Carbon Unit

WDR
Wetlands Drainage and Rewetting

WGBC
World Green Building Council

WLCA
Whole Life Cycle Assessment

WRI
World Resources Institute

WWF
World Wildlife Fund

Chapter 1

Understanding Carbon Markets

1.1 Introduction

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has warned society and policymakers about the consequences of exceeding the limit of 1.5ºC increase in global temperature, which could lead to much more severe climate hazards than the expected below this level. Throughout this report, the IPCC emphasizes the need to scale up existing policies and market-based tools, and urges governments to commit to more ambitious climate policies [1, 2].

The global emissions trends projected to limit the world's temperature rise to 1.5ºC require reducing greenhouse gas (GHG) emissions from 2019 by 43% in 2030 and 84% by mid-century. To achieve this goal, net zero carbon dioxide shall occur between 2050 and 2055, and both CO_2 and GHG emissions should reach their peak no later than 2025 [3]. Over the period between 2011 and 2020, the global surface temperature rose by 1.09ºC compared to 1850-1900, with land experiencing greater rises than oceans [1].

In December 2015 at the 21st Conference Of Parties (COP), 195 Parties signed the Paris Agreement, which main objective is to limit global temperature increase possibly below 1.5ºC and no higher than 2ºC [4, 5]. The basis of the Agreement are the Nationally Determined Contributions (NDCs), which are the commitments made by countries to reduce GHG emissions and adapt to climate change impacts. Implementing renewable energy, improving the efficiency of energy systems and land use practises, and protecting natural ecosystems, are some of the key actions to achieve the NDCs [6].

The term "net zero" (or "net zero emissions") describes a scenario in which anthropogenic removals of GHGs from the atmosphere equals the amount of anthropogenic GHGs emitted within a certain time frame [7, 8]. To attain net zero emissions, emissions must be reduced and avoided, and those that remain must be captured at the source or removed from the atmosphere [7]. Instead, to reach carbon neutrality, or net zero CO_2 emissions, only anthropogenic carbon dioxide releases and removals from the atmosphere have to be balanced [8].

Although the emissions of individual organisations are taken into consideration when determining the carbon targets of the nations in which they operate, many of these organisations have made their own net zero commitments [9]. In order to define the scope, timing, and approach to achieve their net zero pledges, organisations follow voluntary schemes and guidelines [9]. Many of these voluntary schemes are partnered with the Race to Net Zero campaign developed by the United Nations, such as Business Ambition for 1.5, for businesses, Health Care Without Harm, for sector-specific corporations, Cities Race to Zero, focused on cities, and the Paris Aligned Investment Initiative, for the financial sector [9, 10]. The progress accomplished by these organisations along their decarbonisation pathway can be evaluated by frameworks like CDP (Carbon Disclosure Project) and the Transition Pathway Initiative [9].

1.2 Carbon offset credits and carbon markets: An overview

1.2.1 Carbon offset credits

Carbon markets exist under compliance and voluntary schemes. The compliance market is regulated by mandatory international, national or regional carbon reduction regimes, while voluntary markets are neither enforced nor legally required [11]. Carbon offset credits are present in both market mechanisms, but their price and application vary according to the market under which they are traded.

The concept of carbon markets appeared in the 1990s, and was introduced as a mitigation solution for climate change mainly by the United Nations Framework Convention on Climate Change (UNFCCC) and some voluntary approaches [12, 13]. The principle of offsetting has been embraced by both the voluntary and the regulatory market, under which are implemented activities that reduce GHG emissions in one place to compensate for emissions that occurred somewhere else [12, 13].

Carbon offset credits represent the reduction of one metric tonne of CO_2 or CO_2e[1] emissions that have been certified by an independent certification body or a government [14]. Carbon credits are transferred from the entity that achieved the removals or reductions of GHG emissions to another entity that retires these credits to offset or compensate for their own emissions [14, 15].

Carbon offset credits are typically known as carbon credits or carbon allowances under the regulatory market, and as carbon offsets, or simply offsets, under the voluntary market[2]. Carbon credits are produced by carbon offset projects, which are composed of a wide range of activities aimed at reducing GHG emissions or increasing the absorption. These projects may involve the development of renewable energy, carbon sequestration, and reforestation actions [15].

[1]Carbon dioxide equivalent is a unit of measurement adopted to compare the effects that different GHGs have on the climate according to their global warming potential.

[2]For the purpose of this study, carbon credits, carbon offset credits, carbon offsets, offset credits, and offsets are used indistinctly.

The benefits of carbon offset projects often extend beyond just GHG reductions, and may include enhanced air quality, improved employment opportunities and increased biodiversity. Achieving a balanced portfolio of benefits is important to most offset credit buyers, which is why carbon offsets could be an important component of a comprehensive strategy for corporate social responsibility [15]. To ensure the quality of carbon offsets, standard-setting organisations have been established, knwon as carbon offset programmes. These programmes can be conducted by international or governmental regulatory bodies as well as by independent NGOs [15].

1.2.2 Compliance carbon market

The Kyoto Protocol, adopted in Japan in 1997, established in its Annex B GHG emissions reduction targets for industrialised countries and economies in transition [12]. These targets were defined as amounts of allowed emissions, which were partitioned and allocated to countries into Assigned Amount Units (AAUs) [16]. According to the Protocol, Annex B countries, i.e. countries for which emissions reduction targets were established, must achieve their targets primarily through the implementation of national policies. However, the Protocol also introduced three market-based mechanisms through which countries were allowed to trade emissions permits: the International Emission Trading (IET), the Clean Development Mechanism (CDM), and the Joint Implementation (JI) [16].

These mechanisms should promote the reduction of GHGs in a cost-effective way, and Annex B Parties were therefore allowed to begin GHG abatement measures in developing countries, where it is most economical UNFCCC0. The adoption of this approach could have the side benefit of stimulating investments that support the protection of the environment and contribute to sustainable development in developing countries. It should also enhance the involvement of the private sector in reducing and stabilising GHG emissions [16].

1.2.2.1 Mechanisms under the Kyoto Protocol

1. **The Clean Development Mechanism**

   Through the CDM, Annex B Parties were allowed to implement projects in developing countries that derived in emissions reductions [17]. These projects issued Certified Emission Reduction (CER) credits, that represented the reduction of one tonne of CO_2 and could be used to achieve the mitigation targets defined in the Kyoto Protocol. The CDM, which is described in Article 12 of the Protocol, was the world's first global environmental investment and credit scheme [17].

2. **Joint Implementation**

   This mechanism, established in Kyoto Protocol's Article 6, allowed Annex B countries to achieve their targets by using Emission Reduction Units (ERUs), equivalent to one tonne of CO_2 [18]. These credits were issued by GHG emissions reductions or removal projects located in another Annex B country. In this way, the host country benefited from technology transfer and investments made by the country claiming the emissions reductions, while the country that invested in the projects was able to achieve the targets established by Kyoto Protocol through ERUs [18].

3. **International Emissions Trading**

   Through the International Emission Trading mechanism, defined in Article 17 of the Kyoto Protocol, Annex B Parties were allowed to sell their AAUs to another Annex B Party to claim for emissions reductions, provided that the Party that sold the assigned units had already achieved its own targets [19]. In this way, GHG emissions reductions became a new commodity traded in the market, broadly known as the carbon market [19].

Although the Kyoto Protocol was superseded by the Paris Agreement when it entered into force in 2016, it remains one of the most relevant environmental policies.

1.2.2.2 Article 6 of the Paris Agreement

The ratification of Article 6 - the Paris Agreement's rulebook governing carbon markets - was one of the significant accomplishments of the COP26 in Glasgow [20]. Article 6 of this Agreement allows Parties to work together on a voluntary basis to accomplish emission reduction objectives outlined in their NDCs. Article 6.2 of the Agreement establishes the framework for GHG emission reductions trading across countries, while Article 6.4 determines the creation of a mechanism which enables achieving the Sustainable Development Goals (SDGs) and the mitigation of GHG emissions, likely to be similar to the CDM [20].

To prevent double-counting, Article 6 introduced an accounting procedure called "corresponding adjustment" [20, 21]. This accounting criteria might also apply to the voluntary carbon markets, such as the International Civil Aviation Organization's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), a market-based mechanism for airlines, that will probably need a comparable adjustment for exchanged credits [20].

The VCM will need to adapt to the new rules established by the Paris Agreement, mainly regarding the principles supporting the quality of voluntary carbon credits, such as additionality, avoidance of double counting, and setting conservative emissions baselines. Until 2020, the VCM had been developed in the framework of the Kyoto Protocol, and many standard-setting organisations have adopted instruments of the CDM. In the context of the Paris Agreement, organisations willing to offset their emissions will have to acquire carbon credits that are not accounted for in their host country's NDC and that can prove to be additional and in line with the new accounting norms [22].

The transition of the CDM to the mechanisms established by the Paris Agreement starts with the conclusion of the second phase of the Kyoto Protocol in 2020 [23]. Under the following circumstances, projects registered in the CDM could be eligible to shift to the mechanisms outlined in Article 6.4 [23]:

- By December 31, 2023, a request to transition the CDM activity to Article 6.4 must be submitted. Such transitions must obtain host country permission by

December 31, 2025 [23].

- The activity may continue following its current approach after receiving approval until the end of its current crediting term or December 31, 2025 (whichever is earlier). It will be required to adhere to the procedures outlined in Article 6.4 after this date [23].

- If an activity was registered on or after January 1, 2013, certified emission reductions issued under the CDM may be used to attain first NDCs. There will be no requirement for the host nation to make a similar change. The host country will not be compelled to make any adjustments [23].

Even though the Article 6.4 mechanism is based on the CDM's previous experience, it will have its own set of rules, modalities, and procedures [23].

1.2.2.3 Carbon taxes and emission trading systems

Carbon pricing is a policy instrument used by governments to achieve their goals in terms of climate ambition [23]. When GHG emissions are priced, there is a financial incentive to lower emissions or increase their removal from the atmosphere. Carbon pricing can support low-carbon development by incentivising changes in the current production, consumption, and investment practices driven by economic decisions [23].

Carbon pricing mechanisms can be categorised in two different groups: direct and indirect carbon pricing instruments [23]. Direct carbon pricing mechanisms set a price incentive that is directly proportional to the GHG emissions associated to a product or released during a specific activity. The main direct pricing mechanisms are carbon taxes, Emission Trading Systems (ETSs), and carbon crediting mechanisms. While the participation in carbon crediting mechanisms is usually voluntary, ETSs and carbon taxes are generally included in the compliance market. In contrast to carbon taxes and ETSs, carbon crediting does not establish a broad-based price on carbon, but it subsides the reduction of GHG emissions through emissions reductions or removals activities [23]. Indirect carbon pricing, instead, are instruments that alter the price of goods linked to carbon emissions through mechanisms that do not modify the price proportionally to those emissions. These mechanisms send out a signal about the price of carbon, but are generally adopted to meet different socioeconomic goals. Taxes on fuels and other commodities, as well as fuel subsidies, are examples of indirect carbon pricing [23].

The primarily direct carbon pricing instruments adopted by governments are carbon taxes and ETSs [23]. In an ETS, emitters trade emission units to meet their emission targets [24]. Participants in an ETS are generally identified by governments, according to their carbon intensity, industry or size [25]. Emission targets can be achieved at the lowest cost by implementing internal abatement measures or buying emission units in the carbon market, depending on their relative costs [24]. An ETS establishes a market price for GHG emissions by creating supply and demand for emissions units. ETSs are classified into two types: cap-and-trade and baseline-and-credit. In the first approach, the ETS imposes a cap or absolute limit on emissions, and emissions permits are given, either for free or through auctions, for the quantity of emissions equal to the cap. Instead, in a baseline-and-credit system, baseline emissions levels for specific regulated entities are specified, and credits are granted to entities that have reduced their emissions below this level. These credits can be sold to other companies that release more than their baseline levels [24].

A carbon tax is a policy tool used by governments to impose a price on GHG emissions, through which a financial incentive to reduce emissions is provided. Under this instrument, the market decides if it is more convenient to reduce the emissions or to pay the tax, according to the price established by the government [23]. One of the main differences between a carbon tax and an ETS is that a carbon tax does not predetermine the emission reduction outcome, while an ETS does. By specifying a tax rate on GHG emissions or on the carbon content of fossil fuels, i.e., a price per tonne of CO_2e, a carbon tax explicitly establishes a price on carbon [24].

The percentage of GHG emissions covered by implemented carbon pricing mechanisms, mostly through carbon taxes and emission trading systems, are presented in **Figure 1.1**. Due to the enter into force of China's ETS, this share has tremendously increased in the last two years, from 13.25% in 2020 to 23.17% in 2022 [26].

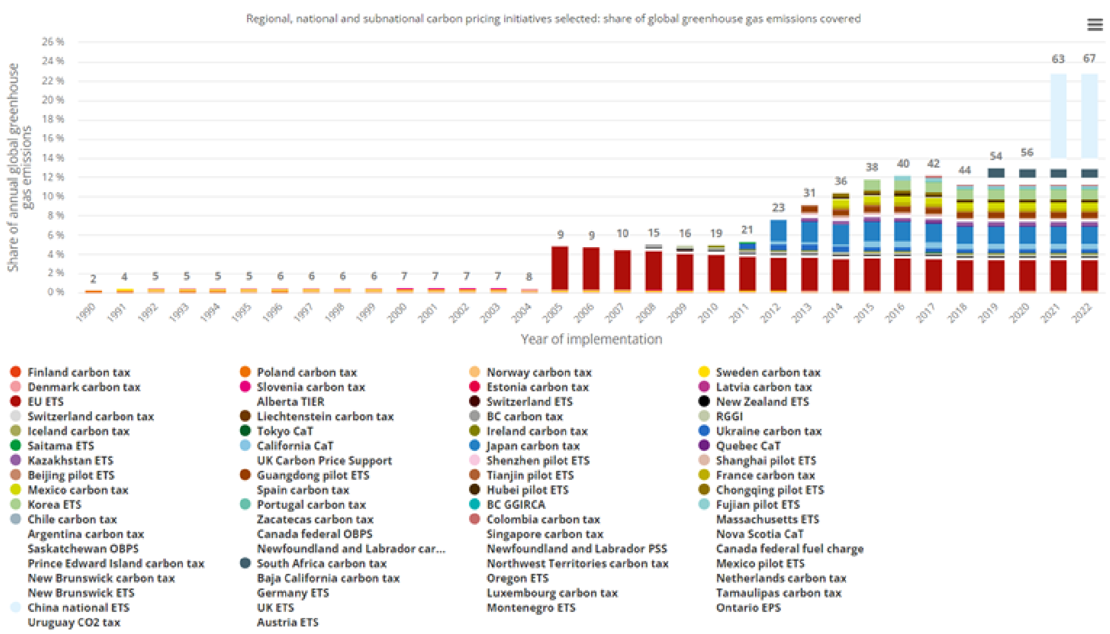


Figure 1.1: Share of GHG emissions covered by implemented carbon pricing initiatives. Source: The World Bank, Carbon Pricing Dashboard, last updated in April 2022 [26]

The world's first global emissions trading system is the EU ETS. The amount of GHGs that can be released into the atmosphere each year by the EU is limited, and enterprises are required to hold an European Emission Allowance (EUA) for each tonne of CO_2 they release within one calendar year. The EU ETS, implemented in 2005, is in its fourth phase since January 2021 [27].

The gases and sectors covered by the EU ETS are the following [27]:

- Carbon dioxide (CO_2) from:
  - production of electricity and heat
  - industries that require large amount of energy, such as production of aluminium, metals, cements, works with steel, oil refineries, among others.
  - commercial flights in the European Economic Area (EEA)
- Nitrous oxide (N_2O) from glyoxal, nitric, adipic, and glyoxylic acids
- Perfluorocarbons (PFCs) from the generation of aluminium

In 2021, the cap consisted of 1572 $MtCO_2e$ and it will be reduced by 2.2% instead of 1.74% every year from then on. There are also programmes in Switzerland, Canada, the United States, China, and systems that are being developed all over the world [26]. If the emissions cap is not ambitious (i.e., higher than the expected business-as-usual emissions), oversupply may occur. In this scenario, a country's or region's cap-and-trade programme has little to no impact on emissions from covered sources. An oversupplied market may be evidenced by auction prices that are close to the programme's price floor [28].

In an effort to address growing emissions from the building and road transport sectors in a cost-effective manner, the EU proposed a new ETS that is currently under consideration [29]. Instead of regulating consumers directly, the new ETS would cover upstream emissions generated by fuels utilised in buildings and road transportation. It is expected that the system will be operational by 2026, and allowances will only be distributed via auctions [29]. Currently, the EU ETS only covers indirect emissions from road transport and buildings, which are emissions attributed to energy carriers, such as electricity, steam or district heating plants [30]. The new ETS would lower the cap every year, resulting in a 43% reduction in emissions by 2030 compared to 2005 [30]. A quarter of the revenues from the new trading system would go to the Social Climate Fund to invest in more energy-efficient cars and buildings, and to directly assist people affected by rising gas and heating prices [29].

The EU ETS was created with the intention of becoming part of the developing global carbon market and assisting in its growth [31]. Owners of regulated installations were permitted to use Certified Emission Reductions (CERs) and Emission Reduction Units (ERUs), produced by the Clean Development Mechanism (CDM) and Joint Implementation (JI), respectively, to fulfil their compliance obligations under the EU ETS, which was directly linked to the Kyoto system. By certifying the reduction of one tonne of CO_2 in a sector or region not covered by the EU ETS, CERs and ERUs allowed businesses with activities covered by the EU ETS to release one more tonne of CO_2 [31]. However, restrictions on the use of international credits were implemented as a result of the European carbon market's significant oversupply. In Phase II were introduced the first quantitative restrictions, which were further reduced by Phase III and supported by qualitative restrictions. The use of these credits was finally prohibited in Phase IV (2021-2030) [31].

In addition to the need to limit oversupply in order to preserve the EU ETS's cost-effectiveness, the use of carbon offsets was heavily criticised by researchers and NGOs due to the low environmental integrity of most of these offset projects [31]. Based on a study conducted by DG Clima, only about 7% of the potential CER provision for the years 2013 to 2020 are likely to have reduced emissions in a meaningful, measurable, and additional way [31].

A company or entity desiring to claim voluntary emissions reductions could also consider to purchase and cancel allowances from a cap-and-trade system, provided that the cap-and-trade programme is not oversupplied [28]. The use of allowances to claim voluntary emission reductions reduces their supply, lowering emissions that can be emitted by sources covered by the cap (e.g., large industries or power plants) and forcing these sectors to accomplish greater emission reductions [28].

Currently, EU ETS prices reflect the implemented oversupply adjustments of Phase IV, which increase the effectiveness of the emissions reduction scheme. In the last five years, the price of EU ETS has skyrocketed, rising from around €7.4 in December 2017 to €87.7 in December 2022 [32]. Therefore, cancelling EU ETS allowances has become a plausible alternative for offsetting GHG emissions. The biggest disadvantage of this strategy is that it does not generate the additional benefits that certain carbon offset projects provide [28].

1.2.3 Voluntary carbon market

Voluntary Carbon Markets (VCMs) allow carbon emitters to offset their unavoidable GHG emissions to claim carbon neutrality or to meet other environmental targets. Corporate social responsibility, climate commitments, and environmental and social benefits are some of the motivations that drive companies to purchase carbon credits in the VCM [33, 34].

The VCM is essential to help finance climate protection and projects of carbon reduction or removal from the atmosphere, accelerating the transition to a low-carbon economy. Well-designed carbon offsetting can contribute to zero-emission strategies, especially in hard-to-decarbonise sectors, like aviation and agriculture [35]. The flexibility and fast growth of voluntary carbon credits triggers investments into technological and market innovation, and in some cases it has even influenced the regulatory market. In Mexico and South Africa, for example, voluntary offset credits have been considered eligible for complying with carbon tax requirements [11].

Since voluntary offset projects are smaller in size, have a stronger focus on sustainable development, and have lower transaction costs, they are generally considered to have a higher potential for delivering positive impacts on the development of local communities. However, voluntary offsets lack international standardised measurements and monitoring practices, which jeopardises the integrity of these projects and the transparency of the whole voluntary market [13].

1.2.3.1 How to acquire carbon offsets in the voluntary carbon market

There are different options available to acquire carbon offset credits. Prices and delivery risks vary according to the offset's lifecycle phase in which the buyer gets involved, as explained by Broekhoff et al., 2019 [15]:

1. **Development of the methodology**

   The development of a methodology for a new project type not already included in existing offset programmes may be sponsored by a prospective buyer of offset credits [15]. Even though it is resource-intensive and risky, this could be useful for organisations interested in the development of new types of projects [15].

2. **Development, validation, and registration of the project**

   Another possibility is to directly invest in offsets projects in exchange for a given percentage of the credits generated by those projects [15]. This approach enables a deeper engagement with the project and a better understanding of its strengths and weaknesses.

   A commonly used alternative is to establish a contract directly with a project developer to purchase carbon offset credits as they become available. These contracts are commonly referred to as Emission Reduction Purchase Agreements (ERPAs). ERPAs provide project developers the certainty that they will be able to sell a reliable volume of offset credits, while they enable buyers to lock in a price below market prices, though being exposed to delivery risk to some extent [15]. ERPAs enable the delivery of carbon credits from one party to another under a legally binding contract. Before signing this contract, all parties must agree on the amount of emissions to be reduced, the means to achieve it, the amount to be financed, and the performance metric that will trigger payments [36].

3. **Implementation of the project, verification, and issuance of carbon offsets**

   Carbon credits could also be acquired directly from project developers with unsold credits, avoiding some transaction costs [15]. However, this could raise some quality concerns, mostly regarding additionality. For a project to qualify as additional, it must proof that it would have not occurred in a business-as-usual scenario (**Section 1.3**).

4. **Transfer of offset credits**

   For purchasers seeking a fast acquisition of different numbers of offset credits without committing to long-term contracts, the purchase through brokers that transfer or retire offset credits on their behalf may be an interesting option [15]. This method could bring pricing efficiencies, but it may compromise the broker's ability to remain objective about the credits they sell.

   It is also possible to buy offset credits from an exchange. A number of environmental commodity exchanges, primarily in North America and Europe, publish carbon offset credits for sale and collaborate with registries to facilitate transfers. Purchasing offset credits on an exchange might be quick and straightforward, but obtaining the information needed to evaluate the quality of these credits may be difficult [15].

5. **Retirement of offset credits**

   In the case of small companies or individuals looking to acquire only a small number of offset credits, going through a retailer might be the most feasible option [15]. Retailers can offer consumers access to offset credits from a variety of projects and can retire them on their behalf.

1.3 Carbon offset programmes

A network of standards and certification bodies, project creators, and verifiers exists to ensure that only emissions reductions that can prove to be real, measurable, and that meet additionality are recognized in voluntary and compliance markets [37]. In order to comply with these core principles and minimum quality thresholds, a number of factors are relevant, including monitoring data quality and accuracy, credibility of the crediting baseline, accuracy of impact quantification, the use of conservative and credible methods, and the reliability of objective verifications [37].

The “Carbon Offset Guide”, an initiative of the Stockholm Environment Institute and the Greenhouse Gas Management Institute, specifies five criteria that offsets should meet to be considered of high quality (Broekhoff et al., 2019) [15]:

- **Additionality**

  GHG reductions are considered additional if they would not have occurred in the absence of an offset credit market [15]. A solar plant in a jurisdiction that already has a renewable portfolio standard or other renewable energy obligation, for example, would not be eligible for carbon offset credits under a properly operated scheme [37]. Similarly, if state regulations require such equipment, a landfill with a methane collection system would not be eligible for credits [37]. In order to determine if an activity is additional, it is necessary to evaluate if the project would be feasible without profits from carbon offset sales [15]. According to the Taskforce on Scaling the Voluntary Carbon Market, initiatives that are additional provide larger GHG reductions than the business-as-usual scenario and must go above and beyond regulatory standards [38].

- **Avoiding overestimation**

  The overestimation of GHG reductions can occur either by overestimating baseline emissions, which are used as a reference to calculate GHG reductions, or by underestimating the actual emissions of a project [15]. Overestimation can also occur when indirect GHG emissions of an activity are not considered or when carbon credits are issued for future emission reductions [15].

- **Permanence**

  Since a reversible emission reduction or removal cannot be used to offset GHG emissions, offset credits must be linked to permanent emission reductions [15]. Some offsets, such as the destruction of recovered, phased-out fluorochemical refrigerants, reflect avoided GHG emissions that are inherently irreversible. Instead, permanence of CO_2 capture initiatives is less certain and depends on how the carbon captured is utilised. While nature-based initiatives like forestry and soil carbon enhancement may store carbon for several decades, the risk of reversal must be considered and managed through buffer pools or other safeguards [37].

- **Exclusive claim to GHG reductions**

  Double counting can be caused by double issuance, meaning that more than one offset credit is issued for a single GHG reduction, by double use, which happens when two entities claim the same offset credit for their emission reduction, or by double claiming, which occurs when an offset credit is issued to a project but is also used to count towards the emission reduction targets of another entity (e.g., a government or private company) [15].

- **No substantial social or environmental harms associated**

  A project should not significantly contribute to social or environmental problems in order to produce high quality offset credits [15]. For instance, a project must show that it complies with all applicable laws in the area in which it is located and may conduct additional evaluations and precautions to avoid unexpected impacts that are not related to GHG emissions [15].

If using a carbon offset credit instead of lowering your own emissions does not results in an increase of global GHG emissions, then the offset credit is considered to preserve "environmental integrity" [15, 39].

1.3.1 Functioning of carbon offset programmes

Carbon offset programmes, run by NGOs, international bodies, or regulatory entities, aim at setting standards and ensuring the quality of carbon offsets [15]. Offset programmes, who generally call themselves "standards", identify and implement initiatives that benefit society more cost-effectively than would be possible with other types of policy tools [40]. Offset programmes must specify eligibility criteria and norms for creating and conducting carbon offset projects, as well as guidelines for their monitoring, reporting, validation, and accreditation [41].

One of the main components of offset programmes are mechanisms of enforcement, which ensure that agreements explicitly indicate the project's owner and the person or entity who would be responsible in case of project failure [42]. Offset programmes must also use offset registries, which are used to track offset projects and the credits issued [41]. Registries also provide information about offsets purchases and retirements, and are essential to maintain the credibility of carbon markets. The requirements that a project needs to meet in order to be additional are defined by Offset Project Protocols (or Mechanisms). Offset programmes may adopt mechanisms created by other programmes or develop their own protocols . Standards set by offset programmes serve as guidelines and criteria that projects should meet in order to be eligible for that programme. Since standards do not include either a registry system nor an enforcement mechanism, they cannot be used alone to ensure the quality of carbon offsets [41].

Throughout the design, validation and verification process of an offset project, carbon offset programmes sometimes use stand-alone standards, such as ISO 14064 [41]. ISO 14064 is a standard developed by the International Organization for Standardization and was issued in March 2006 [43]. It was created with the aim of providing a widely applicable product in the field of environmental sustainability, which shall be consistent across countries and should support the participation in Kyoto's Protocol. It is composed by three parts, each focused on specific technical areas [43]:

- Part 1, named "Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals", concerns with an organisation's GHG emissions inventory, including specifications for its creation, administration, reporting, and verification [43, 44]. The procedures for establishing boundaries of GHG release and removal are also included, as well as the identification of corporate behaviours or actions with the purpose of enhancing GHG management. Additionally, it contains guidelines for conducting reports, performing internal audits, and the organization's roles in verification operations [44].
- Part 2, called "Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements", addresses the measurement and disclosure of a project's GHG emission reduction, and the framework for validating and verifying GHG projects [43, 44]. It assesses the criteria that a project aimed at reducing GHG emissions should follow, the determination of GHG sources, sinks, and reservoirs, as well as guidelines to monitor, calculate, and report the performance of a GHG project [44].
- The last part, called "Specification with guidance for the verification and validation of greenhouse gas statements", specifies a procedure for the verification of a GHG statement, which can be applied to GHG statements of an organisation, a project, or a product [43,44]. It outlines the verification or validation procedure, including planning for verification or validation, evaluation strategies, and assessments of the different types of GHG statements [44].

ISO 14064 is related with other standards of the family ISO 14060, as it is illustrated in **Figure 1.2**. ISO 14065 specifies requirements and accreditation basis for Validation and Verification Body (VVBs) regarding objectivity, expertise, and consistency. ISO 14066 provides principles and competence prerequisites for validation and verification teams according to the activities they should be able to perform [44]. The principles, specifications, and rules for calculating a product's carbon footprint are defined in ISO 14067, aimed at calculating GHG emissions linked to each stage of a product's life cycle [44].

Additionality sets offsets apart from economic subsidies, and it is essential for an offset's definition [40]. However, as long as there is no reliable method for assessing additionality and baselines within an offset scheme, any potential public benefit could be undermined [40]. Carbon offset programmes can be classified as voluntary or domestic carbon programmes, which will be presented in **Sections 1.3.2** and **1.3.3**.

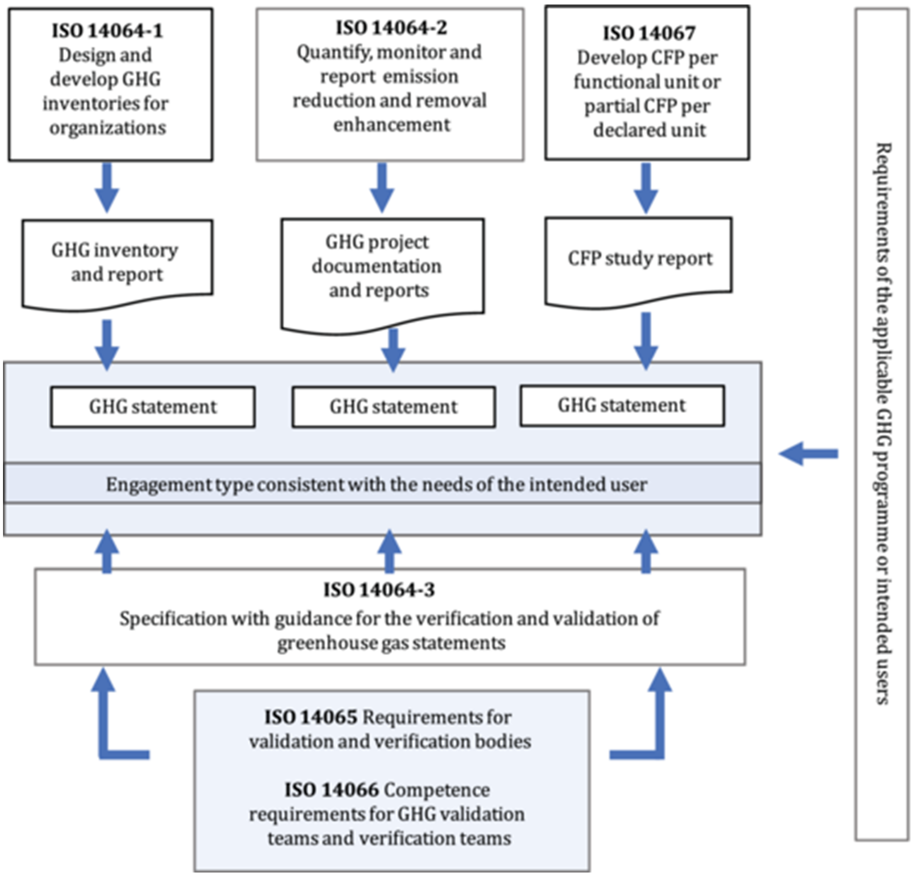


Figure 1.2: Relation of ISO 14064 with other standards of the family ISO 14060. Source: ISO 14064-3:2019 [44]

ICROA, a non-profit initiative of the International Emissions Trading Association (IETA), offers a framework for ethical corporate climate action [45]. Its objectives are focused on promoting the use of high-quality offsets, which deliver real beneficial impacts and are traded in a market with high environmental integrity. One of the ways in which ICROA delivers its objectives is through its accreditation programme, which identifies and stimulates the use of current best practices for the procurement of high-quality emissions reductions and use of offset credits. The programme is designed for organisations that deliver carbon offset services. In order to participate in the programme, members must be members of IETA and undergo an annual independent audit to ensure compliance with the ICROA Code of Best Practice [45].

The standards endorsed by ICROA can be programmes launched by governments, such as the UK Woodland Carbon Code and the Emissions Reduction Fund (ERF) of the Australian Government, or by the United Nations, known as UNFCCC Mechanisms (CDM, JI, and IET) [46]. Other independent standards endorsed by ICROA include the Verified Carbon Standard, Gold Standard, American Carbon Registry, Climate Action Reserve, and Plan Vivo [46].

1.3.2 Carbon offset programmes

Voluntary carbon offset programmes such as Gold Standard, Climate Action Reserve, and Verified Carbon Standard have emerged as leader organisations in guaranteeing offset purchasers the quality of the carbon credits acquired. Nevertheless, the way in which these programmes approach critical aspects like additionality, leakage, permanence, and verification may differ a lot among programmes [47]. The following paragraphs provide an overview of the most well-known carbon offset programmes at the global level:

- **Gold Standard (GS)**

Founded in 2003 by the World Wildlife Fund (WWF) and complementary NGOs, Gold Standard supports the creation and development of 2600 projects in 98 countries aimed at reducing GHG emissions and contributing to the achievement of the SDGs, and can be employed for voluntary and CDM's projects [48]. Carbon credits issued by this programme are immediately retired from the "Impact Registry" when they are purchased by an individual or corporation [49].

Offset credits issued under Gold Standard are produced by projects that bring along community services (e.g. waste management, water and sanitation activities), projects that supply renewable energy to a national or regional grid network, as well as afforestation and reforestation projects [50]. Gold Standard is making efforts to align with the Paris Agreement's rules on market mechanisms, and is currently one of the key players advancing the cause to guarantee climate integrity in the market after 2020 [51].

Regarding the assessment of additionality, Gold Standard will modify its requirements for new projects and those updating their crediting period in order to comply with recommendations of Article 6 of the Paris Agreement [51]. Additionality is even more crucial in terms of finance and regulation as a result of the pledges made by countries in their NDCs [22]. Principles and requirements for projects carried out in the framework of Gold Standard are defined in the document "Gold Standard for the Global Goals" [52].

According to O'brien, J., permanence is not particularly taken into account under Gold Standard, though each project must prove emission reduction or removal, or promote the adaptation of current conditions to climate change [47]. Under the programme's measurement principle, leakage is considered, but is restricted only for reforestation and agriculture projects [47].

A recognised Validation and Verification Body (VVB) performs a revision of the documentation and a field inspection in order to validate the adherence of the project to the requirements of Gold Standard and the verification of reduced or avoided GHG emissions [53]. Project monitoring, instead, shall be carried out by the project's developer following the Gold Standard's monitoring plan. Performance review and certification, the last two steps of the process to certify a project under GS, are conducted by SustainCERT [53].

- **Verra**

Verra is a non-profit organisation that manages the Verified Carbon Standard (VCS), the Sustainable Development Verified Impact Standard (SD VISta), and the Climate, Community and Biodiversity (CCB) Standard [51]. With about 1600 projects registered in more than 82 countries, VCS claims to be the largest voluntary carbon offset programme in the world [54]. The projects covered by VCS include emissions reductions or removal activities such as land use projects, as well as waste management and disposal activities [55]. VCS certified programmes can be issued Verified Carbon Units (VCUs), which are exchangeable carbon credits that can be sold in the voluntary market and retired from Verra's registry by corporations that acquire them to compensate for their GHG emissions [55].

Compensate's report "Reforming the voluntary market" states that the vast majority of VCS projects of protection and reforestation are located in countries that are prone to political and corruption risks, which threats the project's permanence when it is finished [51]. Even if some projects sign contracts to maintain the management and protection of forest for three or six decades, sometimes even for 100 years, these cannot completely guarantee that the emission reductions will be permanent in the future [51]. However, Verra is working on a long-term reversal monitoring system to help identifying losses and calculate reversals in VCS AFOLU (Agriculture, Forestry and Other Land Use) initiatives after the expiration of their crediting periods using remote sensing and innovative technologies [56]. Validation and verification processes are conducted by independent VVBs in order to evaluate if a project is in line with VCS Programme's rules and the criteria of the methodology adopted. Instead, monitoring and emission reduction measurements are performed by the project's developer [55].

Projects of Afforestation, Reforestation, or Revegetation (ARR) under the VCS programme followed the afforestation/reforestation (A/R) procedures of the CDM, thus in line with Kyoto's Protocol. In May 2020, Verra announced the "Development of a VCS Afforestation, Reforestation, and Revegetation (ARR) methodology, activity method module and leakage tool", with the aim of creating a unified methodology that incorporates the activities addressed by the four current CDM A/R techniques in order to have better oversight of the content, its updates and modifications of these methodologies [57]. The ARR methodology, activity method module and leakage tool is planned to be designed by an independent consultant. The ARR activity method module aims at accelerating the assessment of additionality without compromising accuracy, while the ARR leakage tool's objective is to develop a standard procedure for leakage quantification [57].

CCB Standard released its first edition on 2005, and since 2014 is managed by VCS [58]. This programme has to date more than hundred registered projects, and its scope is to evaluate land management initiatives that result in positive impacts for local populations, biodiversity protection, and mitigation for climate change. This programme can be used for any land management project, including initiatives covered by VCS [59]. If a project is eligible for dual certification under the VCS and CCB Standards, it could guarantee that it is advantageous for nearby communities and the environment, in addition to providing quantifiable emission reductions [60].

- **Climate Action Reserve (CAR)**

Another large carbon offset programme is the Climate Action Reserve, which covers projects in North America. It acts as an Offset Project Registry (OPR) for California's Cap-and-Trade programme. Projects include nitrogen management, boiler's energy efficiency in Mexico, reforestation and urban forest management, among others [61]. Carbon credits issued to these projects are called Climate Reserve Tonnes (CRTs), and can be retired from CAR's registry [61]. Verification is carried out by independent verification bodies registered in the American National Standards Institute (ANSI) [61]. In order to calculate actual GHG emission reductions, adjust baseline emissions, and assess the project's performance, project proponents have to develop monitoring plans, which should include the techniques that will be used to determine additionality [62].

For CAR, a project is established as permanent when it proves to be equivalent to the advantages of carbon dioxide removal in terms of radiative forcing for at least 100 years, and requires the compensation of any reversal in order to safeguard the integrity of CRTs and their ability to offset GHG emissions [62]. This programme does not require a specific method to account for leakage [62], but it maintains that both beneficial and harmful effects should be detected during the quantification of a project's actual GHG emission reduction [47].

- **Plan Vivo**

Plan Vivo started in 1994 with a reforestation project in Chiapas, Mexico, which then evolved into 27 initiatives in more than 20 countries [63]. Projects can be classified as REDD, afforestation/reforestation, assisted natural regeneration, improved land management, or agroforestry [64]. REDD stands for "reducing emissions from deforestation and forest degradation", while REDD+ includes also the importance of maintaining forests in a sustainable manner and enhancing their carbon reserves in developing nations [65]. REDD+ establishes the guidelines for forest interventions aim at reducing GHG emissions from deforestation and forest deterioration [66]. Carbon credits emitted by Plan Vivo are called Plan Vivo Certificates (PVCs), which can be retired for voluntary offsetting on the Markit Environmental Registry [67].

A project developer must establish the methods used by the initiative to demonstrate additionality, which should also outline the procedures for revising the baseline scenario and re-evaluating additionality once every ten years. In addition, the techniques used to predict potential leakage, or the discounts in credits brought on by leakage sources, should be described on a project's documentation [68].

New projects can adopt methodologies approved by Plan Vivo or methods authorised by other renowned carbon offset programmes. A new technique must be presented to Plan Vivo for approval if there are no existing methodologies that are suitable for an emergent project [68]. Also in these programme, validation and verification is carried out by independent VVBs, which shall be listed within Plan Vivo's approved VVBs [69].

In order to account for reversal risks, projects covered by Plan Vivo are required to issue a share of climate benefits in a risk buffer which will not be sold. Each project's risk buffer varies according to the level of risk to which it is exposed, from 10 to 50 percent, assessed by Plan Vivo's Technical Advisory Committee [70].

- **American Carbon Registry (ACR)**

The first private voluntary carbon offset programme was the American Carbon Registry (ACR), which was founded in 1996 by Environmental Resources Trust (ERT), a non-profit enterprise owned by Winrock International [71]. Due to its approval as Offset Project Registry for California's Cap-and-Trade mechanism in 2012, this programme started to participate also in the compliance market [71].

ACR covers a huge variety of projects, including A/R of degraded lands, Carbon Capture and Storage (CCS) technologies, transport efficiency improvements, among others [72]. Even though the vast majority of ACR projects are located in the US, there are several initiatives working in other countries [73].

Regarding additionality, ACR requires that project developers demonstrate that the emission reductions or removals of a project are above the "business as usual" situation. Projects must either achieve an established level of performance and pass the additionality test, or satisfy a three-pronged test, which shall determine if the scenario of "business as usual" was surpassed [74].

Projects having a reversals risk are required to evaluate and mitigate risk, as well as monitor, disclose, and compensate for reversals [74]. Agriculture, Forestry, and Other Land Use (AFOLU) projects should assess risks applying the Risk Analysis and Buffer Determination tool proposed by ACR. The mitigation of leakage risks consists on a "ACR Buffer Pool Account", and the amount of offset that a project has to deposit on it depends on its risk of reversal [75].

According to the pertinent sector criteria and methodology constraints, ACR mandates that project proponents identify and compensate for specific types of leakage. While monitoring is intended to be conducted by the project's developer, verification and validation must be conducted by independent VVBs, accredited by ISO 14065 [74].

1.3.3 Domestic carbon standards

Annex I countries in the framework of the Kyoto Protocol were allowed to finance carbon offset projects under the Joint Implementation scheme, which encouraged the interest of private corporations in the voluntary carbon market [76]. Since the operation of the JI required technical expertise and the development of institutional criteria to guarantee the environmental integrity of projects, when it collapsed in 2012 together with the Clean Development Mechanism due to the decline in demand from European businesses, some European countries focused on the creation of domestic carbon standards. Some examples are the Label Bas Carbone, launched by the French government in 2019, MoorFutures established in Germany since 2011, and the Peatland Code in the United Kingdom, active since 2015 [76]. Italy implemented some forest initiatives, such as the Forest Carbon Code and projects issuing ecosystem services certificates under the Forest Stewardship Council's structure, but did not go forward with the establishment of a programme at the national level [76]. A major factor in this decision was the identification of potential double-counting risks because forest management started to be subject of the Kyoto Protocol's accounting [76].

The Kyoto Protocol's carbon market mechanisms restricted the implementation of domestic carbon standards, or Domestic Offset Programmes (DOPs), to only those activities subject to voluntary GHG accounting [77]. Therefore, only Land Use, Land Use Change and Forestry (LULUCF) activities subject to account for its GHG sources and sinks on a voluntary basis were eligible to issue carbon credits under a DOP to be aligned with the Kyoto Protocol [77]. In Europe, peatlands were drained for agricultural purposes. When they are damaged, they release a huge amount of GHGs. Since the reporting of peatlands emissions were included in the Kyoto accounting only to a limited extent, which lowered the risk of double-claiming, countries like Germany, Switzerland, the United Kingdom, and The Netherlands, focused on the development of initiatives based on peatlands restoration [76]. Moorfutures, developed at regional scale in Germany, was the first programme to issue carbon credits from peatland restoration activities, and was then followed by the Peatland Code in 2017 [78], which is a voluntary programme launched at national level in the UK in 2015 [76].

The European Parliament emphasised on the potential that soil conservation and sustainable practises in agriculture have on reducing GHG emissions, and it stressed the necessity to align also the Common Agriculture Policy (CAP) to the Paris Agreement [78]. The Paris Agreement requires the definition of stronger and new additionality rules after 2020, in order to guarantee that voluntary projects under DOPs do not interfere with initiatives under the new market-based mechanisms agreed on the COP26 [77].

The Woodland Carbon Code (WCC) is a voluntary domestic carbon standard which was established in 2011 [76] and aims at ensuring the development of high-quality woodland projects in the UK [79]. A Woodland Carbon Unit (WCU) is equivalent to 1 tonne of CO_2 sequestered by a verified woodland project [14]. It is possible for companies to offset their emissions in the UK by retiring WCUs, though these credits cannot by used to compensate for emissions generated by international shipping or aviation activities [79]. Offsets issued by the WCC can be used to claim carbon neutrality of activities, products, services or buildings via PAS 2060:2014, and to achieve net emissions reductions, as implied by the "Environmental Reporting Guidelines" developed by the UK government [79]. PAS 2060:2014 is a standard that outlines the requirements that an entity should meet to prove carbon neutrality [80]. Information about the ownership and retirement of credits of the WCC is available in the UK Land Carbon Registry [79].

Another voluntary domestic offset programme of the UK is the Peatland Code, which was launched in 2015 with the aim of restoring damaged peatlands, which represent approximately 10% of the country's land territory and up to 80% of them are estimated to be damaged [81]. Peatlands recovery is not only beneficial to climate change mitigation but can also improve biodiversity and drinking water quality, as well as prevent flooding by reducing surface water flow [81]. In comparison to the WCC, the projects under the Peatland Code are issued Pending Issuance Units (PIUs), which represent 1 tonne of CO_2 that is predicted to be sequestered through the project [14]. These credits can only be used to claim emissions reduction in the UK at least 5 years after the project started, when verification takes place and PIUs issued for that timelapse are converted into Peatland Carbon Units (PCUs) [14, 81]. Even though PIUs cannot be utilized to claim carbon neutrality at the time of acquisition, they can be included in a corporation's path to claim net zero emissions in the future [14].

Currently, PIUs are being sold at £10 – £20 per tonne of CO_2e within the UK, while the price of WCUs cannot be yet determined due to its market immaturity [82]. As a result of companies planning to achieve net zero before 2030, PIUs scheduled to be verified before 2030 are sold at a premium price, around £30/tCO_2e [83].

In light of the current discussions on how carbon credits issued by domestic programmes should be accounted for in the framework of the Paris Agreement and the NDCs, the UKGBC recommends reporting domestic offsets separately from international offsets [14].

According to the Réseau Action Climat, the French Label Bas Carbone, or Low-carbon standard, must be considered as a way to help the achievement of France's climate goals, not as an offsetting mechanism [84]. A similar argument could be made about other domestic offset programmes, where it can be considered that these carbon credits should be used by corporations to contribute to the achievement of a country's NDC, not to achieve net zero emissions.

Chapter 2

The role of Offsetting in the Net Zero scenario

2.1 The concept of Offsetting

An increase in the concentration of GHG in the atmosphere has led to a change in the Earth's energy balance, generating a warming effect that has increased by 45% from 1990 to 2019 [85]. There is a high confidence that the warming of the climate system is mainly caused by an increase in the concentration of GHGs in the atmosphere [86]. Since GHGs mix in the atmosphere at the global level, it should make no difference in terms of global warming where the emissions are reduced[1] [87]. Carbon offsetting is based on this concept, in which offset credits are used to transfer a net climate benefit from one entity to a different one [87].

Offsetting is the process of compensating for an actor's GHG emissions through activities that provide an equivalent GHG reduction or removal elsewhere [88]. Offsetting should be used to mitigate residual emissions that organisations are not capable to avoid with current technologies in a cost-effective way [89]. Usually, offsetting is organised through an exchange system or a market for carbon credits. A carbon offset credit is a transferable instrument or certificate that represents a reduction of one metric tonne of equivalent carbon dioxide (CO_2e). Once the emission reduction is claimed, the carbon credit is retired and is no longer tradeable [15].

Through carbon offsetting, companies and corporations can contribute to achieving global climate neutrality. Climate neutrality refers to the state of no net impact of human activities on the climate system [8]. In order to accomplish this condition, it is essential to consider local or regional biogeophysical impacts of human activities in addition to balancing residual emissions with emission reductions [8]. For example, an activity's effects on the surface albedo, which is the fraction of solar radiation reflected by a surface or object, and its impact on local climate should be considered [8].

According to Net Zero Climate, hosted by the University of Oxford, offsetting can

[1] However, activities that release GHG emissions can also produce pollutants that have a local effect at the site of emission. This aspect should always be considered [87].

be adopted to claim the status of net zero only if it is "like for like" with any remaining emission [88]. "Like for like" means that there is a correspondence regarding the warming impact, the timescale, and the durability between an emissions source and an emissions sink [88].

2.2 How to approach offsetting: Codes of practice and Oxford's Offsetting Principles

2.2.1 Voluntary initiatives providing guidance

The Voluntary Carbon Markets Integrity Initiative (VCMI) was created in 2021 to boost the potential of directing private funds into a credible and net-zero aligned voluntary carbon market [90]. VCMI brings stakeholders together around a common vision for voluntary carbon markets that contributes to limiting the rise of temperature to 1.5ºC in line with the Paris Agreement, while simultaneously supporting the accomplishment of the SDGs adopted by the United Nations [90]. It is co-founded between the UK Government and the Children's Investment Fund Foundation (CIFF) [90]. With its Provisional Code of Practice, the VCMI intends to provide a guidance for corporations willing to acquire credible carbon credits to reduce their emissions along their supply chains [90]. The final Claims Code is expected to be issued at the end of 2022 or the beginning of 2023, after undergoing public consultations and "road testing" on companies [90].

In order to define decarbonisation goals for corporations in the short-run consistent with 1.5ºC increase of temperature with no or minimal overshoot, VCMI adopts the framework developed by the Science Based Targets initiative (SBTi) [90]. The World Resources Institute (WRI), the United Nations Global Compact, CDP, and WWF are partners in the SBTi [91]. This initiative defines the GHG emission reductions goals that enterprises and investment firms need to achieve in order to align with the scenario of 1.5ºC global warming above pre-industrial levels [91]. By establishing science-based net zero targets and best practices in GHG emissions reductions, the SBTi assists businesses to set their climate goals in accordance with current climate science researches [91]. The SBTi encourages the private sector to fight climate change while increasing its competitiveness and maximising its advantages as we move towards a net-zero economy [91].

SBTi's Corporate Net-Zero Standard was released in October 2021 to guide companies while defining their path to net zero and help them contribute to climate change in a credible way [91]. Since there are sectors that require sector-specific guidance and specialised methodologies to set their science-based targets, the SBTi has developed guidelines for sectors such as Buildings, Cement, Forest, Land-Use and Agriculture (FLAG), Iron and Steel, and Power Generation, among others [92]. The final publication of the buildings-specific guidelines is expected for July 2023 [93]. The climate goals established can be absolute targets, where absolute emissions reductions are defined, or intensity targets, in which a decrease in emissions compared to a particular business metric is specified [92]. In the building sector, the SBTi recommends to set either absolute or intensity targets when using the pathway relative to residential or service buildings, but only absolute targets for cross-sector pathways [94].

2.2.2 The Oxford Principles for Net Zero Aligned Carbon Offsetting

The Oxford Principles for Net Zero Aligned Carbon Offsetting presented below provide guidelines to correctly approach offsetting [35]. Acquiring high-quality carbon credits, avoiding greenwashing, and preventing unintended impacts, such as the loss of agricultural land and biodiversity reduction due to poorly diversified tree plantations, are crucial when planning an offsetting strategy.

Principle 1: Reduce emissions, utilize high quality offsets, and re-examine the strategy to follow best practices

Best practices consist in prioritising the cut of emissions to limit the amount of offsets needed and securing environmental integrity [35]. It also implies being transparent in the type of compensation used and in the target to achieve carbon neutrality. It is important to take into account both direct emissions and indirect GHG emissions along the value chain. Offsets purchased should meet the criteria of additionality, meaning that the emission reduction would have not occurred without the offsetting activity, and shall not cause unintended negative effects. Nature-based offsets could bring along other advantages, such as protection of biodiversity and native communities, social engagement and local revenues, providing that they have high environmental integrity [35].

Principle 2: Switch to carbon removal mechanisms

Adopting a long-term strategy to gradually increase the share of carbon removal solutions in the offset portfolio will help to incentivise this market. Carbon removal projects absorb from the atmosphere CO_2 emissions that have been released in the past instead of avoiding future emissions. It will allow corporations to remove from the environment more GHGs than what they emit, becoming “carbon negative” and supporting a transition to a more sustainable society. This methodology can be based on natural processes, such as carbon absorption through reforestation and afforestation, or on artificial technologies, like Direct Air Capture with Carbon Storage (DACCS), Bioenergy with Carbon Capture and Storage (BECCS) and mineralisation. While carbon removal strategies necessarily imply the storage of carbon, there are some offsetting mechanisms of emission reduction that do not require to store carbon, such as projects that develop renewable energy power plants or that abate methane releases into the air. Both carbon removal and emission reduction offsetting can be further classified according to the endurance of the carbon stored, as it is illustrated in **Figure 2.1** [35].

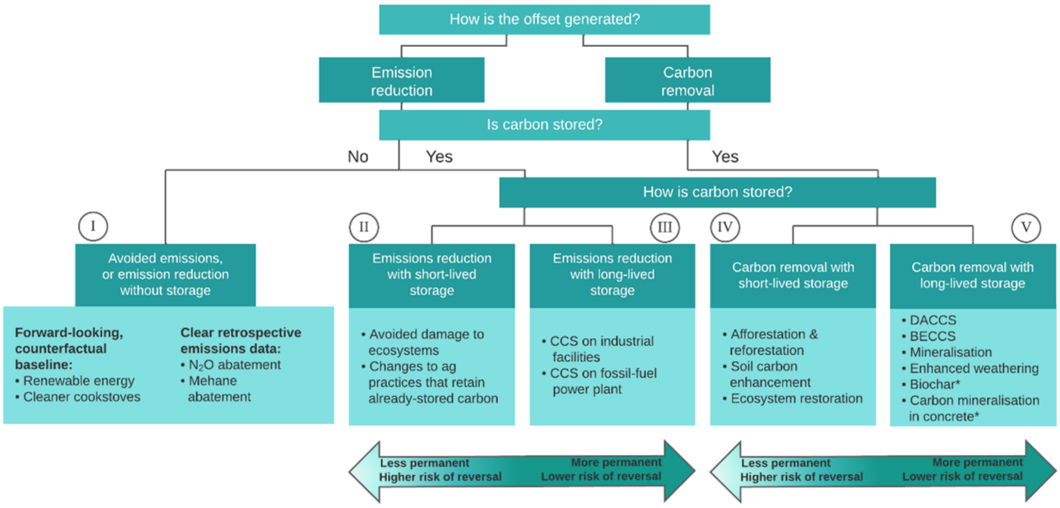


Figure 2.1: Taxonomy of Carbon Offsets. Reproduced from the Oxford Principles for Net Zero Aligned Carbon Offsetting [35]. **These categories were added to the original diagram developed by Oxford*

Principle 3: Switch to long-lasting storage

In order to guarantee the balance between sinks and sources in the future, it is necessary to embrace solutions that have minimum risk of being re-released over long periods (centuries to millennia) [35]. Nature-based solutions bring along many other benefits, but their capacity to store carbon over long periods can be threatened by external causes, such as wildfires and social or political conflicts. Carbon removal technologies with long-term storage are already available, but they are limited in supply and expensive compared to other methods. Shifting investments to these strategies now is essential for achieving net-zero carbon markets in the future [35].

Figure 2.2 provides a possible offsetting trajectory that is aligned with this principle. The strategy adapts to the present situation in which it is still difficult to acquire carbon removal offsets with long-term storage (Type V) due to their high costs, but it implies that their share in the offset portfolio should gradually increase over the years, reaching 100% by 2050. In 2020, it is envisaged that avoided emissions and emissions reductions with short-lived storage (Type I & II) will constitute about 50% of the portfolio of offsets. However, their contribution should progressively decline until their participation ceases entirely by 2050. For Type IV offsets (carbon removals with short-lived storage) it is expected a similar development. In contrast, emissions reductions with long-lived storage (Type III offsets) should gradually increase their percentage in the portfolio until they reach their maximum participation near 2040, with a contribution of about 30% of the total required amount of offsets. After this maximum, the trend is inverted and also Type III offsets should be replaced by carbon removals with long-lived storage.

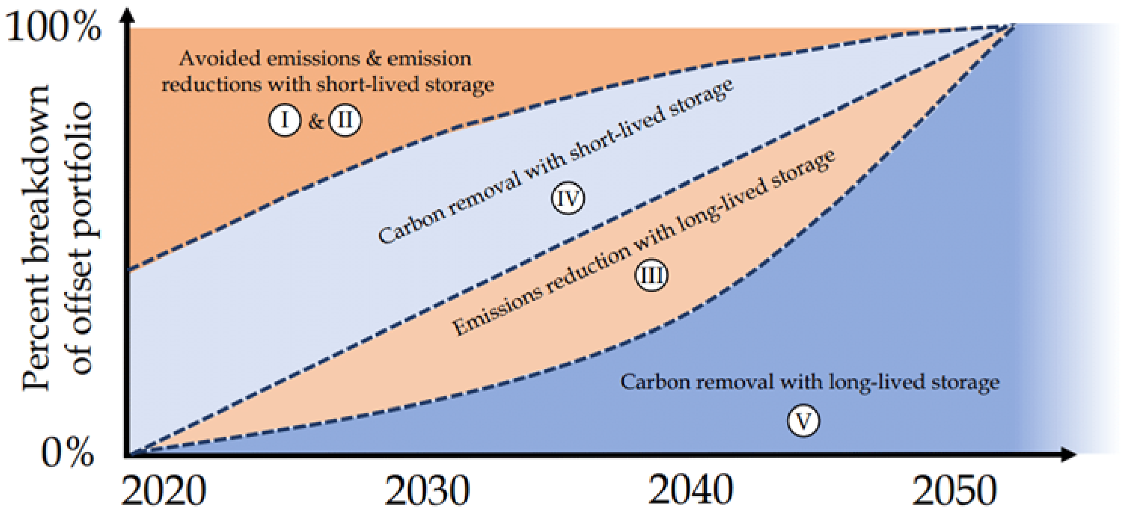


Figure 2.2: Example net zero aligned offsetting trajectory. Source: The Oxford Principles for Net Zero Aligned Carbon Offsetting [35]

Principle 4: Encourage the evolution of net zero aligned offsetting

Working in collaboration with entities from the same industrial sector can encourage the development of a carbon market that is aligned with the net zero path [35]. In addition, establishing long-term agreements with offset projects' developers provides certainty for both parties. Supporting the restoration and protection of natural habitats will contribute to improving a long-lived storage and will increase the resilience of ecosystems to respond to perturbations in the climate, generating at the same time a huge variety of environmental and social benefits. In order to increase and maintain the integrity of offsets and carbon storage, standards that incorporate the Oxford Principles should be established [35].

2.3 Types of carbon offset projects

There is a large portfolio of projects driving emissions reductions or carbon removals from the atmosphere. Even though carbon offset programmes and standards improve the reliability of carbon credits, as presented in **Section 1.3**, each type of project is associated with a certain level of quality risk [15]. In order to avoid low-quality offset credits, the purchaser should investigate the diligence of the project, focusing on qualitative factors such as additionality, monitoring methods, permanence, and leakage control [95]. Even though it is recommended to choose projects associated with lower risk, it is possible that these type of projects are not available at the time of acquisition or do not meet with the buyer's climate and social targets [15]. In that case, the organisation willing to acquire offset credits could decide to purchase offsets through a reliable retailer or engage a consultant's services [15]. When assessing the quality of a given project, enterprises who have the time and resources to do so, or who cannot afford a consultant, can follow the Carbon Offset Guide's list of "due diligence" questions [15].

Offset projects are classified in five different types in Oxford's report on Offsetting Principles [35]:

- Type I: Avoided emissions, or emissions reduction, without storage
- Type II: Emissions reduction with short-lived storage
- Type III: Emissions reduction with long-lived storage
- Type IV: Carbon removal with short-lived storage
- Type V: Carbon removal with long-lived storage

The most common types of offset projects will be presented below, indicating their main characteristics, level of quality risk according to the Carbon Offset Guide [15], and their classification according to the typology presented before [35].

2.3.1 Renewable energy: small scale (medium risk), large sale (high risk) – Type I

Renewable energy projects are designed to develop generation units of renewable energy, such as photovoltaic (PV), tidal or wave, wind, hydro, geothermal, non-fossil biomass, and waste [96]. Besides electric power, these projects provide many other services to the community, such as creating local jobs, reducing pollution, and achieving the Sustainable Development Goals [15, 96].

The largest amount of offset credits have traditionally been issued by large renewable energy projects located in countries like China, India, and Brazil, which generated large amounts of credits. However, as renewable energy becomes competitive with fossil fuels in price, the current scenario has evolved [97]. Due to the fact that projects of renewable energy located in middle- and high-income countries are unlikely to meet additionality, offset programmes like Gold Standard and Verified Carbon Standard no longer fund them [97].

In January 2021, Gold Standard updated their "Renewable Energy Activity Requirements", where it expressed that only project located on least developed countries, small islands in developing state, or in landlock developing countries were eligible for renewable projects with grid connections [96]. For low and low-middle income countries to be eligible for this projects, the constructed renewable energy has to account for less than 5 percent of the total network grid capacity installed [96].

Since two of the largest offset programmes stopped covering these projects, new programmes are being created to fill this gap. This is the case of the "Global Carbon Council" and some regional programmes, such as the "Universal Carbon Registry" and "Carbon Registry – India", both based in India and created after 2020 [97]. Many renewable energy projects which did not pass additionality tests of existing programmes can try to make revenues from selling low-priced carbon credits accepted by these new standards, which might further harm the reputation of the voluntary carbon market. Some projects developers, instead, have decided to move towards the RECs market [97].

According to the Carbon Offset Guide, the quality risk of renewable energy projects depends mainly on the scale of the facility, and considers projects under 15 MW being of medium risk, and large scale renewables as high risk projects [15]. Small scale projects, such as micro hydro, solar, wind, geothermal, and solid waste power sources, face great uncertainty for meeting the additionality requirement since it is not clear if these projects actually lead to higher investments in these technologies [15]. Non-conventional large-scale renewables, instead, typically undergo financial difficulties and require enormous investments for research and construction. However, the incomes from selling credits are not likely to be a key factor for developing a new facility [15].

Large-scale hydropower and wind projects face the greatest additionality risks because they are considered common practices in the development plan of a country [15]. Regarding the quantification of emissions reduction, there is some level of uncertainty with the baseline adopted, but many protocols used to quantify these baselines address them in a conservative way. For large-scale hydropower projects there is a particular risk for over-crediting due to existing quantification methodologies that do not take into account methane emissions from plant materials accumulated in from dams [15]. The main co-benefit associated with this type of projects is improved air quality. However, there are also significant harms associated with hydropower plants, like the displacement of local communities and the impacts on aquatic species, that should not be disregarded [15].

2.3.2 Cleaner cookstoves: medium risk – Type I

These projects consist of technology-based emissions reduction or avoidance by replacing traditional cookstoves with clean and efficient technologies [38]. Traditional cookstoves generally use solid fuels, and the extraction and utilisation of biomass as fuels significantly contributes to deforestation and the deterioration of forests [98]. Combustion from unsustainable cookstoves results in indoor air pollution and is a source of many pollutants such as black carbon (BC), primary particulate matter (PM), and polycyclic aromatic hydrocarbons (PAHs) [99]. 4.1% of global deaths are attributed to low indoor air quality, though the percentages are much higher in low-income countries, mainly in Africa and Asia [100]. Traditional cookstoves also contribute to gender disparities because in these countries women are usually the ones spending hours cooking while being exposed to the smoke [98]. Wood-powered cookstoves also affect children because they are generally in charge of collecting the wood. This activity may demand a lot of time and could expose them to additional risks [98]. Improved cookstoves are designed to use less firewood or to use different fuels, which would decrease the release of GHGs and reduce deforestation [98]. A study conducted in India in 2008 highlighted a positive correlation between the use of traditional cookstoves and respiratory illness (Duflo, Greenstone and Hanna, 2008 [101], as cited in Dissanayake et al., 2018 [98]).

According to a study conducted by the World Bank Group, the attributes of improved cookstoves that make that households are willing to pay for them are mainly their durability and the decrease of fuel needed [98]. The reduction of smoke and cooking time could also influence this decision but on a smaller scale [98]. According to this study, the cookstove used in their experiment, the Mirt, could be used for reducing GHG emissions in a cost-effective way [98]. They suggest that at a cost of around US $5 per tonne of CO_2 paid through international programmes such as REDD+, the Mirt has a high potential to achieve GHG emissions reduction [98].

Gold Standard, for example, hosts projects of improved and clean cookstoves in Guinea, Rwanda, Peru, India, Uganda, among others [102]. The projects involve installing cookstoves that use less wood, cook faster, produce less smoke, and at the same time contribute to achieving the SDGs [102].

The Carbon Offset Guide considers improved cookstoves projects to be of medium quality risks [15]. There is a considerable risk of carbon storage reversal and uncertainty for quantifying avoided emissions, which could lead to the issuance of more credits than the emissions actually achieved. However, they are also associated with many co-benefits, like improved air quality, the creation of local jobs, and the conservation of forests [15].

2.3.3 N_2O abatement: low risk – Type I

Adipic acid is one of the 12 most important platform chemicals and is essential for the production of nylon, food, and pharmaceuticals [103]. Adipic acid production is currently a major source of GHG emissions and depends on petrochemical resources that are not renewable [103]. This process is responsible for about 10% of the world's annual emissions of N_2O, a by-product with 300 times higher GWP than carbon dioxide [104].

Climate Action Reserve released the Adipic Acid Production Protocol in September 2020 to outline the quantification, reporting and verification methodologies for GHG reductions achieved through an adipic acid production project [105]. The emissions reductions shall be achieved through the incorporation of a new or improved control technology to abate N_2O emissions. Financial obstacles prevent both new installations and improvements to adipic acid projects from being implemented on a large-scale. The installation of technological upgrades requires a substantial investment, which satisfies the performance threshold of the protocol to guarantee that the project is additional. The eligible technologies for nitrous oxide emission reduction are catalytic and thermal destruction, recycling of N_2O to produce nitric acid, and technologies of recycling/utilization of N_2O. These projects can be credited for ten years, or until a regulatory requirement to adopt them is in place [105].

Another industrial process responsible for large amounts of N_2O emissions is the production of nitric acid [106]. Nitric acid is mainly produced through the catalytic oxidation of ammonia and is principally used for manufacturing commercial fertilizers [106]. Projects eligible for this programme consists of the installation of technologies to abate N_2O emissions at an existing or upgraded plant where nitric acid is produced. It includes secondary and tertiary catalyst projects, which involve installing and operating nitrous oxide abatement technologies immediately below the Ammonia Oxidation Reactor or after the absorption tower, respectively [106].

In June 2021, Gold Standard announced the development of a new methodology to reduce nitrous oxide emissions from nitrogen fertilisers [107]. The approaches proposed include the implementation of best practices and optimisation for the use and management of fertilisers, the application of Enhanced Efficiency Fertiliser (EEF) and fertilisers of slow release, and reductions in the use and loss of fertilisers [107]. Climate Trust estimated in 2015 that nutrient management methodologies in the agricultural sector could produce between 770,000 and 2.7 million offsets, and expected that the crediting based on nutrient management would be fully-scaled in the following 5 to 10 years [108]. Many countries have started working on policies and initiatives to improve nutrient management and the use of fertilisers, but comprehensive measures must still be taken in the agricultural sector to cut emissions before 2050.

In June 2022, the European Commission launched a public consultation on an action plan for nutrient management, which is planned to be adopted by the end of 2022 [109]. The Integrated Nutrient Management Action Plan aims to help achieve the 2030 Green Deal target of reducing nutrient losses by 50% and fertiliser usage by no less than 20% [110].

The Smart Prosperity Institute, a Canadian research group, identified five policy approaches to improve the efficiency of nitrogen fertilisers, among which carbon offsets are included [111]. The introduction of carbon offset projects is recognized as an opportunity for incentivising the reduction of GHG emissions in sectors where traditional pricing strategies are not straightforward to apply, as is the case of the agricultural sector. Moreover, since the costs of compliance with GHG policies could be reduced if a carbon market is established, it could raise the acceptance among farmers and the stakeholders involved. The revenues coming from carbon offset sells shall compensate the farmer for the risks associated with the production and would help decrease the costs of adopting new methodologies [111].

The Carbon Offset Guide considers that N_2O destruction or avoidance projects in the industrial sector can achieve GHG emissions reductions at comparatively low costs without compromising its environmental integrity, and therefore are classified as projects with low quality risks [15]. However, these projects have a much lower potential to offer co-benefits for society or the environment [15].

Regarding N_2O abatement projects at adipic acid production plants, it should be considered that studies have evidenced that some adipic acid plants have increased their production to generate larger quantities of nitrous oxide to abate with the aim of selling more carbon offsets [15]. This poses relevant concerns about projects of N_2O avoidance at adipic acid plants, but these should be reduced if trustworthy protocols are followed [15].

2.3.4 Methane destruction/capture and utilization for energy: medium risk – Type I

According to the US Environmental Protection Agency (EPA), methane (CH_4) has a 30-fold higher GWP than carbon dioxide for a time horizon of 100 years [112]. Although its permanence is much shorter than carbon dioxide's, methane is also a precursor to ozone (O_3), which is a potent short-lived GHG [112]. At least 50% of the global methane emissions are caused by human activities, mainly in the agricultural, energy and industrial sectors [113]. In Italy in 2019, methane emissions coming from agriculture were about 44%, while methane from waste and energy production accounted for 38% and 18%, respectively [114]. **Figure 2.3** shows Italy's national

CH_4 emissions classified by sector, from 1990 to 2019 [114].

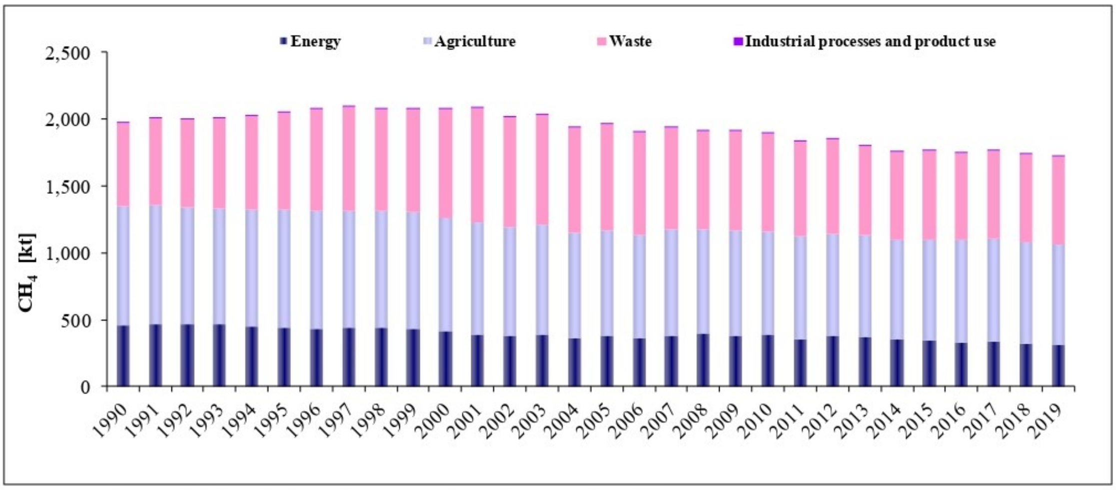


Figure 2.3: Italy's national methane emissions by sector from 1990 to 2019. Source: ISPRA, www.isprambiente.gov.it [114]

Initiatives focused on methane reduction/avoidance can either be projects of methane destruction, where methane is turned into carbon dioxide and water through combustion, or of methane capture and utilisation [15]. Methane destruction projects include landfill gas flaring and Ventilation Air Methane (VAM) destruction in coal mines. Projects where methane is captured and then utilised are instead more frequent, and include methane capture in livestock anaerobic digestors, landfills, industrial solid waste management facilities and waste water treatment plants, among others [15]. For methane destruction projects, financial additionality is generally not a major concern, and therefore they are considered to implicate fewer quality risks than methane capture and utilisation initiatives [15].

Landfill gas flaring projects, instead, are likely to be additional in developing countries, but in developed countries these initiatives could be used to meet existing regulations or regulations that are expected to be implemented in the future, in which case the project would not meet regulatory additionality [15]. Regarding baseline emissions for projects in landfills, there may be some uncertainties with the quantification methodologies, but this issue should be addressed by following thorough rules for the quantification of avoided methane emissions [15]. The main benefit of this type of project is their potentiality to create local jobs and eliminate odor inconveniencies produced from hydrogen sulfide (H_2S) present in landfill gases [15].

Gold Standard certifies a project of landfill gas recovery in Xinyang, China, which is developed by the German UPM (Umwelt-Projekt-Management) GmbH [115]. The project implemented a technology that transforms the gas released in the municipal solid waste landfill into electricity that feeds the Chinese central power grid [115]. The reduction of GHGs is achieved through the recovery of methane and the avoided combustion of fossil fuels to generate electricity. It is expected that this project will avoid the emission of 21,259 tonnes of CH_4 and will produce 117 GWh during its 10-year crediting period [115].

Methane emissions coming from coal mining accounted for 6% of the overall methane emissions in the USA in 2020 [113]. Ventilation Air Methane destruction in coal mines can destroy 95% or more of CH_4 that passes through the VAM oxidisers [116], and its destruction reduces the risks of explosions in coal seams, which is explosive in concentrations between 5 to 15% [117]. The heat generated during this process can be used to produce electricity, but this is difficult in economic terms [116]. Additionality is typically not a top priority due to its high costs, but it could be argued projects based on coal mines support the coal industry and is thus inconsistent with environmental sustainability in the long run [15].

For projects of CH_4 capture and utilisation, such as manure management, livestock, industrial solid waste, and waste water, it is important to evaluate regulatory drivers and to assess whether other funding and revenue sources could support the implementation of certain projects without relying on carbon revenues [15].

2.3.5 Nature-based projects

The TSVCM categorises Natural Climate Solutions (NCS) into avoided natural loss and nature-based sequestration [38]. Avoided deforestation, prevented damages on peatlands, and conservation of coastal mangroves and seagrasses are examples of projects that avoid environmental and habitat losses (Type II projects) [38]. Instead, reforestation, afforestation, peat and coastal recovery, sustainable agricultural practices, and cover crops are examples of nature-based initiatives aimed at sequestering carbon (Type IV projects) [38].

- **Type II projects:** Projects aimed at improving agricultural practices and avoiding deforestation and other damages to ecosystems are activities of GHG emissions reductions with short-lived storage [35]. Projects of this type have high additionality and permanence risks, but also provide numerous co-benefits, such as enhancing biodiversity and land productivity, decreasing runoff and recharging aquifers through the infiltration of water, as well as improving the livelihood of local people [15].

- **Type IV projects:** Activities of afforestation and reforestation, enhancement of carbon stored in soils, and restoration of natural ecosystems are considered carbon removal strategies with short-lived storage. These projects absorb carbon directly from the environment, but have also risks of reversal and permanence [35].

  - **Afforestation and reforestation:** Afforesatation requires to convert into a forest land that historically was not a forest [118]. Reforestation, instead, is to convert to forest land that was originally a forest but that has been converted to other land use [118].
  - **Soil carbon enhancement:** It includes different agricultural and land management practices, such as compost manure, agricultural waste, rotation of crops, conservation tillage, among others, which are employed to improve soil carbon storage or to reduce soil carbon losses (Liniger et al., 2011

[119], as cited in Ng'ang'a et al., 2019 [120]). Soil texture and structure, temperature, and farming practices affect the amount of carbon sequestered, and thus it is important to analyse which is the most suitable practice for each project [121]. It is also necessary to consider economic, social and agro-ecological conditions of each location [120].

– **Ecosystem restoration:** It consist of activities aimed at restoring damaged environments, and includes practices such as mangrove forest recovery and peatland restoration. The restoration of peatlands comprises steps to restore their natural state and to reinstate the environmental services they once offered [122]. The main task of restoration is site hydrology management, which also contributes to the reduction of GHG emissions. Drain blocking may be necessary to rewet peatland sites depending on their starting point. This can be done using a variety of methods, such as control of pollution and grazing, peat dams, plastic piling, and removal of plantations [122].

Many of the natured-based projects provide short-lived storage, such as afforestation, reforestation, enhancement of soil carbon, and ecosystem recovery [35]. These methods have high risk of reversal over time due to uncontrollable human and natural hazards, such as wildfires, political decisions, and economic interests. However, if projects are conducted following conservative approaches in regions with low risk of geopolitical conflicts and other threats, these projects could provide low-risk carbon storage in the long run [35].

The conservation and recovery of ecosystems is crucial because society depends on the products and services that they provide for the environment [35]. In addition, their restoration may contribute to a positive synergistic effect that could enhance society's resilience to climate change and provide long-term carbon storage. However, it is argued that these types of projects should be supported due to the wide range of environmental benefits that they provide, rather than as a means of carbon offsetting [35].

Some of the possible unintended impacts caused by offsetting through nature-based projects are reduced biodiversity in monoculture tree plantations or from planting trees on habitats characterised by low tree cover, unforeseen changes in climate and natural cycles, agricultural field losses, infringements on the land rights of local communities, and other unintended negative effects for the environment and society [35]. Project developers should focus on minimising the risk of potential negative effects and maximising the benefits for the environment and society, procuring to design projects that safeguards local communities' rights and incomes and provide resilient and biodiverse ecosystems [35].

The determination of baseline emissions for nature-based projects involves much higher uncertainties than for other projects, and monitoring and verification methodologies are frequently diverse and less standardised [15]. Since a displacement of agricultural and deforestation activities could occur as a side-effect of these projects, the effectivity of these projects to reduce GHG emissions [15] could be severely undermined.

While both the Oxford Principles and the TSVCM emphasize the importance of transitioning to carbon removal projects with long-term storage in order to achieve the Paris Agreement goals, they also recognise that financial support for all types of projects is required in the near term to avoid overstepping the 1.5ºC limit [35, 38].

Old-growth forest protection projects are expected to provide the greatest benefits in terms of carbon mitigation. In spite of the challenges that affect REDD+ projects, high integrity bio-sequestration projects can absorb large amounts of carbon dioxide and create economic opportunities for local people, while at the same time help to improve and maintain biodiversity and watersheds [123].

Since afforestation and reforestation initiatives have less uncertainty for baseline estimations, it is possible to restrict biological sequestration projects only to these type of activities until more comprehensive quantification mechanisms are developed [123]. Some carbon offset programmes address permanence concerns by creating buffer pools, which aim at maintaining a share of unsold carbon credits that would compensate for leakage in the event of carbon stock damage or loss. Another strategy to deal with permanence issues is to require the monitoring of carbon sequestration during the entire the crediting period and suspend and revoke credits if monitoring activities stop or indicate reversals [123].

2.3.6 Carbon Capture and Storage (CCS) – Type III

Carbon Capture and Storage (CCS) is a process that captures CO_2 emissions from emissions flows and injects them in the underground, where the emissions remain stored in geological formations, such as deep saline aquifers or abandoned gas reservoirs [124, 125]. This technology can be used to reduce emissions from hard-to-abate industries, such as chemical industries, and cement and steel production [126]. Since it is not possible to adopt one single solution to every case, the CCS process must be modified to satisfy site-specific requirements, such as the reservoir's availability for CO_2 storage and the infrastructure necessary for its transportation [124].

The American Carbon Registry (ACR) published in September 2021 a methodology for the development of eligible CCS projects, which includes variable anthropogenic sources of CO_2, such as power production plants, industrial and polygeneration facilities [127]. However, projects based on CCS may be controversial if they are used to divert investments and reinforce the fossil fuel market [125].

The possibility to integrate CCS into already-existing energy systems without making significant changes to the system itself is one of the largest advantages of CCS [126]. Moreover, this technology can be used in conjunction with BECCS (Bioenergy with Carbon Capture and Storage), an innovative low-carbon solution to produce negative emissions using biomass [126].

Although CCS has been identified as a key mitigation technology for the decarbonisation scenarios of the Integrated Assessment Models (IAMs), implementation has hardly progressed to the levels predicted by IAM forecasts and the International Energy Agency (IEA) roadmaps [126]. By offering a quantitative description of important processes in the human and earth systems, including the interactions among them, Integrated Assessment Models (IAMs) attempt to provide information of global environmental change and sustainable development challenges relevant for the development of policies [128]. Only a small number of the Intended Nationally

Determined Contributions (INDCs) that nations made at the Paris climate discussions include CCS as a priority area [126]. According to IPCC's Special Report of 1.5ºC, in order to stay in the pathway of 1.5ºC global warming, the percentage of coal needs to be reduced to 1–7% by 2050, using a significant share of the remaining coal combined with carbon capture storage (CCS) [129].

As stated by the World Resources Institute, CCS should be implemented only if human health, safety, and the preservation of the environment are ensured [124]. It is also fundamental that this technology aids fast and cost-effective deployment, providing at the same time assurance that emissions are being reduced by following thorough quantification procedures [124]. Water contamination, increased seismic activity, and impacts on human health and the environment if leakage occurs are additional potential concerns linked with CCS [130]. However, geological storage has great capacity and low vulnerability, and therefore has no saturation or permanence issues [130].

2.3.7 Direct Air Capture and Carbon Storage (DACCS) – Type V

Technologies known as Direct Air Capture (DAC) remove CO_2 directly from the environment [131]. Carbon dioxide can be stored by injecting it into deep geological reserves [131], usually at depths of 800 metres or more, where it remains trapped due to four trapping mechanisms: structural, residual, solubility, and mineral trapping [132]. The storage of CO_2 in geological formations is designed to be permanent and is associated with limited impacts on land and water [131]. The CO_2 captured could also be used in the production of synthetic fuels and food processing, but in this case CO_2 would not remain permanently stored [131].

The main drawback of this technology is that it requires large amounts of energy to capture CO_2 from the atmosphere. Since carbon dioxide is substantially more dilute in the atmosphere than at the point of emission, removing CO_2 directly from the air requires larger amounts of energy and implicates higher costs [131].

The critical factors to select the location for the construction of a DACCS plant are the availability of renewable energy and a geological reservoir to store CO_2 [131]. Iceland's total primary energy supply is produced from renewable sources, with almost 100% of electricity being generated by hydropower (73%) and geothermal energy (27%), and has currently the largest percentage of renewable energy in their energy mix than any country in the world [133]. Furthermore, Iceland has a great potential to store CO_2 in basaltic rocks, which are recognised as an excellent geological formation for storing CO_2 through mineralisation [134].

To date, there are 18 DAC plants in operation in Europe, the USA and Canada, which capture about 0.01 Mt of CO_2 per year, but only two of them store CO_2 in geological reservoirs [131]. Most of the plants capture CO_2 for its utilisation, and only a small number of financial contracts were signed to sell or store the CO_2 recovered [131]. In order to achieve Net Zero by 2050, DAC should be scaled up to 60 Mt CO_2 per year by 2030 [131]. According to a report published by the IEA in September 2022, this level of deployment is still feasible, but for the technology to be refined and capture costs to be reduced, several large-scale demonstration plants will be needed [131].

In 2021, however, a more favourable environment for investment resulted in the announcement of various new DAC projects [131]. Climeworks, for example, proclaimed the construction of Mammoth, a large DAC plant with the capacity to capture 36,000 tonnes of CO_2 per year and should enter into operation by 2024 [131]. Climeworks was founded in 2009 by two doctoral researchers of ETH Zürich, and since then they have been raising funds for the development CO_2 collectors [135]. In 2021 they launched Orca, the largest DACCS plant in the world, which is located in Iceland [135]. They worked in partnership with DNV (Det Norske Veritas) to develop the first certification procedure of Carbon Dioxide Removal (CDR) through DACCS that takes into account the full value chain [136]. This methodology has been validated independently by DNV in line with ISO 14064-2, and is now applied to DACCS projects to provide certification of the CDR [136]. They are collaborating with the GHG Protocol to develop an accounting standard for CO_2 removal, and are working with Verra and Gold Standard to include in their registries Climework's CDRs [136]. By 2023, they plan to offer international CO_2 removal certifications [136], which would be a significant development for the emerging carbon removal market.

Currently, the two approaches available to capture carbon dioxide from the atmosphere are Solid (S-DAC) and Liquid (L-DAC) Direct Air Capture [131]. S-DAC uses solid adsorbents that operate at low or ambient pressures and at temperatures around 80 to 120 ºC. L-DAC, instead, adopts aqueous basic solutions that through a sequence of units operating at temperatures between 300ºC and 900ºC release the CO_2 that was captured from the air [131].

Carbon Engineering (CE) was founded in 2009 in Calgary, Canada [137]. In 2015 they constructed a DAC pilot plant, to which it was added the capability to synthetise fuels in 2017 [137]. With this incorporation, they created AIR TO FUELS, which allowed them to generate fuels from the carbon dioxide captured from the atmosphere [138]. In 2022, they started the development of their first large-scale commercial facility that employs their DAC technology in the Permian Basin, USA, in partnership with 1PointFive [137]. In June 2022, 1PointFive announced that under existing policies and voluntary and regulatory markets, they project the deployment of 70 DAC plants by 2035, each with an estimated capacity of about one million tonnes per year [131].

Carbon Engineering provides entities or companies three solutions to achieve their net zero commitments and their sustainability targets: Permanent Carbon Removal, Low-carbon fuels, and Low-carbon products [139].

- **Permanent Carbon Removal:** CE provides carbon removals through DACCS, which can be pre-purchased through CE's network of partners, such as 1PointFive (USA), Carbon Removal (Norway), and Storegga (UK) [139]. The selected partner should supervise the removal of CO_2 and provide verification to be included in the purchaser's sustainability report [139].

- **Low-carbon fuels:** AIR TO FUELS facilities produce a synthetic fuel that can be converted into diesel, gasoline or Jet-A by capturing CO_2 from the atmosphere and combining it with green hydrogen [139, 140]. It provides fuel refiners, fuel suppliers, and large-scale fuel consumers the possibility to incorporate a low-carbon fuel option for the transition toward a net zero economy [139].

- **Low-carbon products:** The CO_2 captured on the DAC plants can also be used to produce materials with a lower carbon footprint, such as construction materials (e.g. steel, cement, coatings, and fillers), chemicals, and other products [139]. Through DAC, pure and compressed CO_2 captured from the air can be used for the required manufacturing process, and could be a cost-effective way to reduce emissions in hard-to-abate sectors [139].

2.3.8 Bioenergy with Carbon Capture and Storage (BECCS) – Type V

Bioenergy with Carbon Capture and Storage (BECCS) is a technology-based removal approach that combines geological carbon storage with biomass combustion to produce energy [141]. During its growth, biomass absorbs CO_2 from the atmosphere [141]. The combustion of biomass releases into the atmosphere the carbon atoms assimilated into plant fibres through photosynthesis, where they interact with the oxygen to create CO_2 [141]. By utilising BECCS, the CO_2 that was previously bound to biomass is removed from the atmosphere and injected into geological reservoirs for long-term storage, creating a flow of carbon dioxide captured from the air into the underground [141]. Trees, plants, and agricultural crops release a significant amount of CO_2 by biological processes as combustion, fermentation, putrefaction, biodegradation, and others [141]. Examples of industries that use these processes include the pulp and paper industries, and the production of steel, ethanol, and biogas [141].

The opportunity provided by BECCS to permanently reduce carbon emissions — that is, to remove CO_2 from the atmosphere — has drawn the most attention [141]. The integration of energy generation from biomass combustion and CCS is considered among the most feasible methods for the mitigation of carbon dioxide [142]. From the perspective of an Integrated Assessment Model, BECCS is consider an attractive and cost-effective solution since it contributes both to emissions reductions and energy production [143].

Biomass is commonly utilised to provide energy and heat, and it can also be converted into biofuel for transportation or other applications [142]. A variety of biomass feedstocks can be employed as bioenergy sources, such as the organic portion of municipal solid waste, wet organic wastes, sewage sludge, animal manure, and organic liquid effluents [144]. The annual CO_2 removal potential of BECCS was estimated to be between 0.5 and 2 Gt, at a cost of US$100 to 200 per tonne of CO_2 (Fuss et al., 2018 [145], as cited in Erbach et al., 2021 [130]). These estimations are considered to be cautious in comparison to the rest of the literature since they take into account sustainability issues associated with the production of bioenergy [130].

Possible side effects of bioenergy production are changes in land-use, disputes over land ownership, impacts on the environment due to fertilisers utilisation, water pollution, and harmful effects on biodiversity [130]. The concerns regarding CCS mentioned before also apply for BECCS. Due to its limited social and political acceptance and necessary infrastructure, there are concerns about the viability of scaling up BECCS in the required timescale [130].

2.3.9 Biochar – Type V

Biochar is a stable and carbon-rich material obtained from pyrolysis of organic biomass, such as sewage sludge and agricultural waste, at temperatures between 300 and 600 ºC [146, 147]. When biochar is applied to soil, it increases its capacity to sequester carbon and improves its fertility [146], and it is therefore considered as a promising Negative Emission Technology (NET) [148]. IPCC's Special Report on Global Warming of 1.5ºC estimated that the application of biochar to agricultural soils has the potential to sequester from 1 to 35 Gt of CO_2 per year, but it recognises that it is still susceptible to uncertainties due to the immaturity of this approach [149].

Biochar has also been applied to ameliorate and remediate soils polluted by organic contaminants and heavy metals [147]. In addition, it has also proven to be effective for removing organic and inorganic pollutants from contaminated water through adsorption (Ahmed et al., 2016, as cited in Wang et al., 2019 [147]). It was also found that the application of biochar to soils with low fertility and low content of organic carbon had a greater effect on carbon mineralisation than in soils with high fertility and high carbon content (Wang et al., 2016 [150], and Zimmerman et al., 2011 [151], as cited in Wang et al., 2019 [147]).

Because of its densely condensed aromatic structure, biochar typically has a strong resistance to biodegradation [152]. However, since different biochar have specific physical and chemical properties, its stability should be considered during the analysis of its toxicity and potential impacts on the environment [147]. Huang (2019) found that biochar's instability could cause that its organic matter dissolves when it interacts with heavy metals, and the dissolved matter could cause an increase of carbon content release if applied to wastewater treatment [153]. Since biochar may potentially be harmful to microorganisms, biochar's impacts should be considered for the particular application to which it is applied [147].

2.3.10 Mineralisation – Type V

Carbon dioxide can be removed from the atmosphere through a natural process known as carbon mineralisation, in which the gas is bonded in rock formations as a solid mineral [154]. Some elements found in rocks, such as Calcium (Ca) and Magnesium (Mg), are bonded by carbon dioxide when certain rock formations interact with CO_2, producing carbonate minerals [154]. Carbonate minerals capture CO_2 in stable, solid, and non-toxic forms so that it can be permanently removed from the air [154]. According to Sandalow et al., 2020, this process naturally removes about 0.3 Gt of CO_2 per year from the atmosphere, but this quantity can be increased following two different strategies: In-situ mineralisation, where fluids rich in CO_2 are injected into deep rock formations, and ex-situ or surface mineralisation, which occurs when gases containing CO_2 are exposed to pulverised rocks or industrial waste located on the surface of the Earth [154].

The main drawback of superficial mineralisation is the large area needed in comparison to in-situ mineralisation, which has a huge storage capacity and a limited surface requirement [155]. However, even though both approaches can have similar costs, there are many uncertainties regarding in-situ mineralisation with respect to its permeability, reactive area, and rate of reaction [155]. According to Kelemen et al., 2020, in situ mineralisation could be cost-competitive with DACCS [155].

CCS is the most widely used approach for carbon mitigation, although it involves significant costs and risks [156]. The most promising alternative to geological CO_2 storage is carbon mineralisation, in which carbonate minerals with metal cations are obtained as a result [156]. The construction sector provides the best application potential for mineral carbonates in terms of overall CO_2 emissions reduction [156], which have a huge demand of carbonates, such as limestone and dolomite [157].

One of the main advantages of carbon mineralisation compared to other removal strategies is the wide distribution and abundance of the mineralisation resources, as illustrated in **Figure 2.4**, so that it could be applied as a large-scale removal solution in many regions [154]. Furthermore, building materials with a marketable value, such as concrete aggregate, can occasionally be produced from geological resources or industrial waste by carbon mineralisation [154]. Industrial wastes are generally released by manufacturing facilities that emit large amounts of CO_2, and therefore this approach could be used as a mitigation solution near the source of pollution [154]. Even though this approach does not provide the wide range of co-benefits that other nature-based carbon sequestration strategies have, such as reforestation, it provides long-term storage with lower risks of leakage [154]. In addition, since mineralisation does not require energy inputs, its operation can be cost-effective [154].

The cost of carbon mineralisation can range from \$10 to 1000 t/CO_2, depending on the resource's quality and the methodology used (Engineering National Academies of Sciences & Medicine, 2019 [158], as cited in Sandalow et al., 2020 [154]). However, more information on actual costs and ways to reduce them is expected to be available thanks to new initiatives and businesses like CarbFix and Heirloom Carbon Technologies [154].

In spite of the potentialities of carbon mineralisation, a number of significant challenges need to be addressed before it can be employed as a carbon removal strategy at large-scale [154]. One of the main concerns is with respect to the slow rate at which carbon mineralisation naturally occurs [154]. Even though this process can be sped up by increasing the surface of minerals through "reaction-driven cracking", by adding heat or reagents, or by drilling to accelerate the transport of subsurface CO_2, these measures are likely to increase the costs and the CO_2 emissions associated with the process [154]. Another difficulty associated with this process is the scarce knowledge about the localisation of the mineral resources required for mineralisation [154]. In addition, the lack of policy and the low commercial value of the products that derive from carbon mineralisation result in a low incentive for investment and change of practices [154]. Therefore, further geological exploration and demonstration projects are needed to scale up this strategy and make it possible to apply it at a large-scale [154].

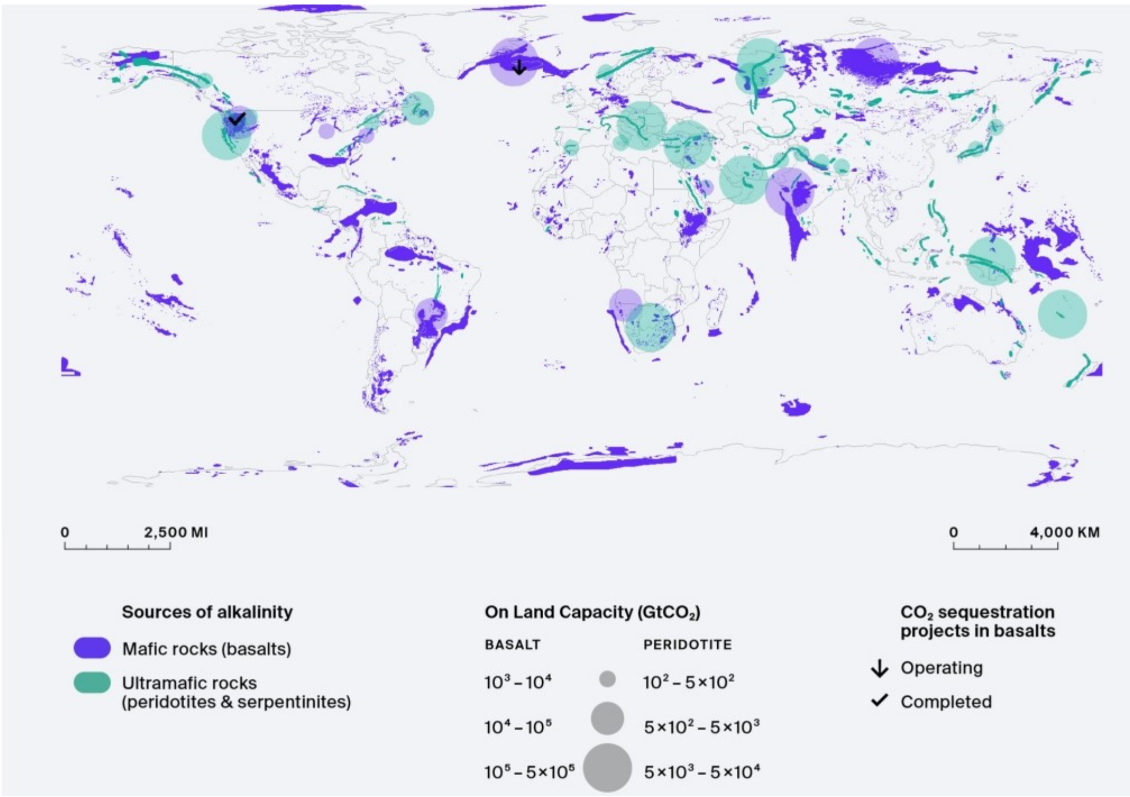


Figure 2.4: Distribution of carbon mineralisation resources. Source: CDR Primer, Chapter 3, 2021. Adopted from Sandalow et al., 2021 [154]

2.3.11 Enhanced weathering – Type V

The natural process of breakdown or dissolution of rocks and minerals is known as enhanced weathering [130]. Since this process requires the input of CO_2 from the atmosphere, accelerated weathering can be used to sequester large amounts of carbon dioxide from the environment [130]. This can be achieved by strengthening one of the components that govern the weathering process [130]. For example, spreading silicate or carbonate mineral powder over land, coastal zones, or ocean waters might enhance the reactive surface, leading to an acceleration of the process [130]. In some cases, depending on the kind of rock employed, spreading powdered rock on soils can enhance soil quality due to the addition of nutrients [159].

According to Erbach et al., 2021, enhanced weathering could achieve an annual reduction of 2-4 Gt of CO_2, with costs between US$50-200 per tonne of CO_2 reduced [130]. However, Erbach et al. recognise that these estimates are subject to significant uncertainties, and emphasise the need of large-scale demonstration projects to fully comprehend the impacts of this technology [130].

Another similar approach, generally considered as a kind of enhanced mineralisation, is ocean alkalinisation, in which alkaline substances (e.g. lime) are spread in the ocean to sequester CO_2 [159]. Since this alternative increases the pH of ocean waters, it has also the capacity to reduce oceans' acidification [159].

Possible negative side effects of this technology involve soil and groundwater pollution due to the release of heavy metals, health impacts due to release of respirable-sized particles in the air, and energy and infrastructure requirements [130]. Furthermore, since enhanced weathering generally requires mining activities and raw material processing, there are concerns related to the impacts on the environment and human health [159].

Even though the technology and chemistry behind enhanced weathering are well established, the application of enhanced weathering as a CO_2 mitigation method is still in its early stages [159]. To enable a widespread implementation of enhanced weathering as a removal strategy, incentives and policies that encourage its adoption and guarantee its development in an environmentally safe manner are required [159].

2.3.12 Carbon mineralisation in concrete – Type III/V*

** Since it involves both emission reductions for the production of concrete and carbon removal due to mineralisation, it could be considered type III or V.*

Made by mixing cement, water, and aggregates (i.e. sand and gravel), concrete is the second most consumed commodity in the world (Cao et al., 2021 [160], as cited in Rosa et al., 2022 [161]). According to the IEA, the production of cement is responsible for 7% of the world's industrial energy consumption, and 60 to 70% of the overall CO_2 emissions occur during calcination, where limestone is converted into lime (IEA, 2018 [162]).

Through carbon dioxide mineralisation, concrete can permanently store carbon dioxide, and therefore the concrete industry provides an alternative for long-term CO_2 storage [161]. In this process, CO_2 is permanently fixed as calcium carbonate in recycled concrete aggregates, which is then employed to create new concrete (Kaliyavarandhan and Ling, 2017 [163]; Hepburn et al., 2019 [164]; Kelemen et al. [165], 2020; Ostovari et al., 2020 [166]; Tiefenthaler et al., 2021 [167], as cited in Rosa et al., 2022 [161]).

Since carbon mineralisation does not require additional energy inputs to capture CO_2, it is considered a very attractive strategy for carbon dioxide removal (Ostovari et al., 2020 [166]; Strunge et al., 2022 [168], Rosa et al., 2022 [161]). Rosa et al., 2022, estimated that in Europe about 8 million tonnes of CO_2 could be permanently stored in recycled concrete aggregates through carbon dioxide mineralisation [161]. **Figure 2.5** shows the technical and theoretical potential of recycled concrete aggregates to fix CO_2 by country, used by Rosa et al. to make their estimations (Eurostat, 2021 [169]) [161]. The bars indicate the sensitivity of the results to diverse rates of concrete recycling.

In Europe, recycling rates range from about 10% to more than 90%, which is strictly related with the amount of building and demolition debris that are recovered (European Environmental Agency, 2021 [170], as cited by Rosa et al., 2022 [161]). The comparison between countries is challenging because there is not a common definition of building and construction waste [161]. However, as a result of the Waste Framework Directive's adoption in 2008, it is expected that the amount of waste generated by construction and demolition will increase, bringing optimistic perspectives to this approach [161].

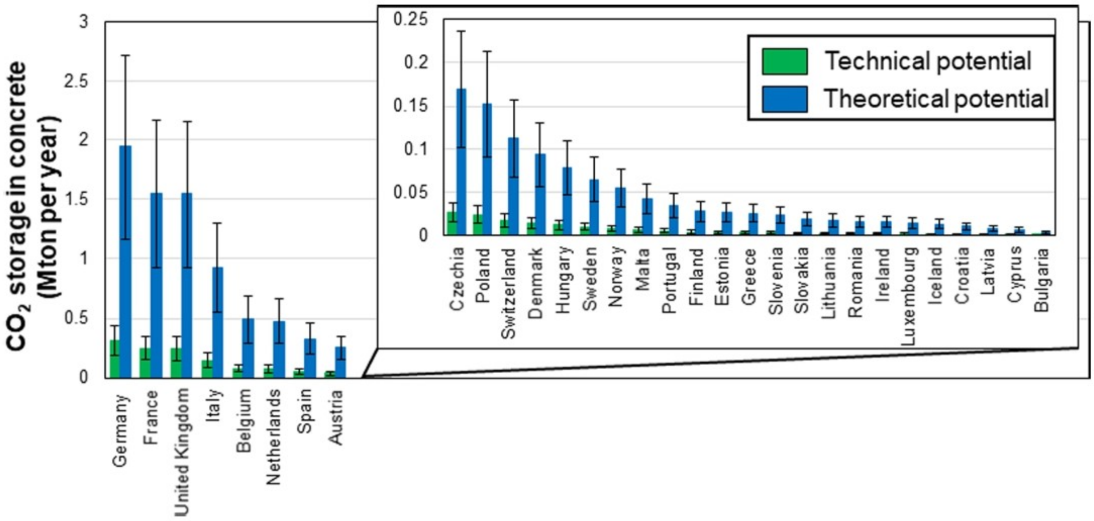


Figure 2.5: Technical and theoretical CO_2 fixation potential in recycled concrete aggregates through carbon mineralisation in Europe. Source: Eurostat, 2021 [169]. Adopted from Rosa et al., 2022 [161]

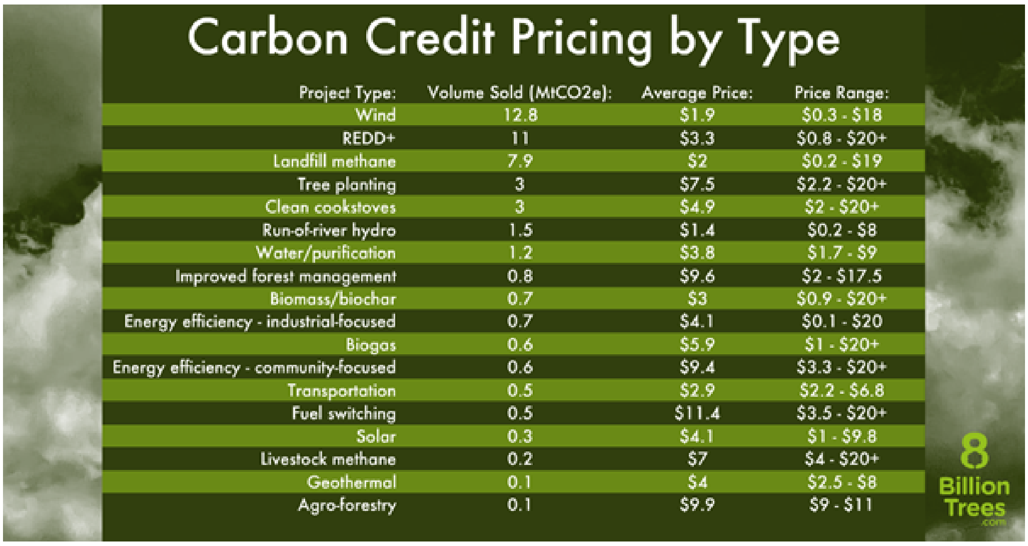
Mineral carbonation in raw materials with high content of calcium or magnesium (e.g. concrete made out of cement, olivine) can store large amounts of CO_2 [171]. The utilisation of carbonated materials to develop new building materials can reduce CO_2 emissions associated with them, and it could potentially lead to the production of CO_2-negative materials [171]. However, these applications are still in early stages and further research is needed to understand the mechanical properties, durability, and characteristics of innovative materials employing carbonated substances [171].

Currently, CarbonCure is carrying out a project of carbon removal through carbon mineralisation in concrete [172]. Carbon credits can be acquired on their website at a price of US$165 per tonne of mineralised and reduced CO_2 every month [172]. This credits are used to finance the immediate adoption and continued development of Carbon Capture, Utilisation and Storage (CCUS) technologies that contribute to the decarbonisation of the concrete manufacturing [172]. In addition, Climate Reserve Action is developing a protocol for Low-Carbon Cement projects in order to provide guidance for quantifying, monitoring, and reporting GHG emissions reductions achieved through these projects, which is expected to be published in March 2023 [173].

The TSVCM encourages corporations to acquire carbon credits within their own supply chain to reduce their Scope 3 emissions [38]. By investing in abatement technologies within their value chain, organisations can incentivise the market and cut down costs of technologies that are hard to implement on a large scale, leading to a long-term reduction in Scope 3 emissions associated to that sector [38]. Therefore, carbon mineralisation in concrete could be a potential strategy to compensate for unavoidable emissions in the construction sector.

2.4 Prices of carbon offset credits

Since carbon credits issued by compliance offset programmes are created and traded in order to comply with regulatory requirements, they are generally priced as commodities, where they are priced in accordance with supply-and-demand dynamics, regardless of the type of project and other attributes [174]. For voluntary carbon offsets, prices depend on the type of project, the offset programme under which the project is developed, the co-benefits associated with it, and the location of the offset project [175]. **Figure 2.6** provides an overview of average prices of carbon offsets issued by voluntary programmes, developed by 8 billion trees and updated in September 2022 [176].



Carbon Credit Pricing by Type

Project Type:	Volume Sold (MtCO2e):	Average Price:	Price Range:
Wind	12.8	$1.9	$0.3 - $18
REDD+	11	$3.3	$0.8 - $20+
Landfill methane	7.9	$2	$0.2 - $19
Tree planting	3	$7.5	$2.2 - $20+
Clean cookstoves	3	$4.9	$2 - $20+
Run-of-river hydro	1.5	$1.4	$0.2 - $8
Water/purification	1.2	$3.8	$1.7 - $9
Improved forest management	0.8	$9.6	$2 - $17.5
Biomass/biochar	0.7	$3	$0.9 - $20+
Energy efficiency - industrial-focused	0.7	$4.1	$0.1 - $20
Biogas	0.6	$5.9	$1 - $20+
Energy efficiency - community-focused	0.6	$9.4	$3.3 - $20+
Transportation	0.5	$2.9	$2.2 - $6.8
Fuel switching	0.5	$11.4	$3.5 - $20+
Solar	0.3	$4.1	$1 - $9.8
Livestock methane	0.2	$7	$4 - $20+
Geothermal	0.1	$4	$2.5 - $8
Agro-forestry	0.1	$9.9	$9 - $11

Figure 2.6: Carbon Offset Pricing. Source: Carbon Credit Pricing Chart: Updated 2022, 8 Billion Trees [176]

Local conditions, the role of the carbon pricing instruments, the impact of other climate policies, and technological progress influence the appropriate carbon price [177]. Setting a proper price on GHG emissions is critical for internalising the external cost of climate change in the broadest range of economic decision-making [24]. Also, it can significantly accelerate the financial investments needed to support clean technology and market innovation, thereby powering new and low-carbon economic drivers [24].

2.4.1 Price scenarios

One of the major difficulties related with offsetting is the high uncertainty of offsets' prices. Since the vast majority of transactions are not made public and many offset prices are agreed among the interested parties, it is not straightforward to estimate the average price for each type of offset. Therefore, for the case studies presented in **Chapter 4**, three different price scenarios will be analysed, which will be then used as basis to perform the projection of future offsetting costs.

- **Price scenario I:** Current average prices

  Current offset prices in the voluntary market are around \$3-5/tCO_2e weighted average, which is extremely low and require a sharply increase to guarantee their environmental integrity [178]. These values are also consistent with Ecosystem Marketplace, who published in 2021 the following price values **(Table 2.1)** [179]:

	2021 (through August)			
	Volume (MtCO2e)	**Volume % Change from Prior Year**	**Price per ton (USD)**	**Value (USD)**
Forestry and Land Use	115.0	139.4%	\$4.73	\$544.0M
Renewable energy	80.0	-0.3%	\$1.10	\$88.4M
Energy efficiency/ Fuel switching	16.1	-48.9%	\$1.57	\$24.2M
Agriculture	3.4	876.8%	\$1.36	\$4.6M
Waste disposal	2.7	-67.5%	\$3.93	\$10.6M
Transportation	2.1	99.3%	\$1.00	\$2.1M
Household devices	1.8	-49.8%	\$5.75	\$10.4M
Chemical processes/ Industrial manufacturing	1.1	-11.2%	\$3.22	\$3.5M

Table 2.1: Size of the Voluntary Carbon Market by project type. Source: Reproduced from Ecosystem Marketplace, a Forest Trends Initiative [179]

- **Price scenario II:** Projected average prices

  For this scenario are considered prices projected by Trove Research [178] in three different periods:

  - **Current prices:** Trove Research considers that current offset prices of scenario I are in part unsustainably low due to an oversupply of offset credits, and that in the case of no surplus, offset prices would not be less than \$10/tCO_2e higher, which would be about \$13-15/tCO_2e.
  - **By 2030:** For this period, if the demand of the VCM increases as projected, average offset prices would be around \$20-50/tCO_2e.
  - **By 2040:** In the case of a further rise in VCM demand, the price of carbon offsets is expected to grow over \$50/tCO_2e.

  Considering these projections, the following prices have been adopted for this scenario **(Table 2.2)**:

Period	Price per tCO_2e
2023-2030	$13-15
2030-2040	$20-50
2040-2050	$60-80
2050-2073	$70-100

Table 2.2: Carbon offset prices considered in Price scenario II

- **Price scenario III:** Current offset prices by type

  In September 2022, a Co-Founder of Abatable, a carbon offsetting procurement platform, published on their website the following summary table **(Table 2.3)** [180]:

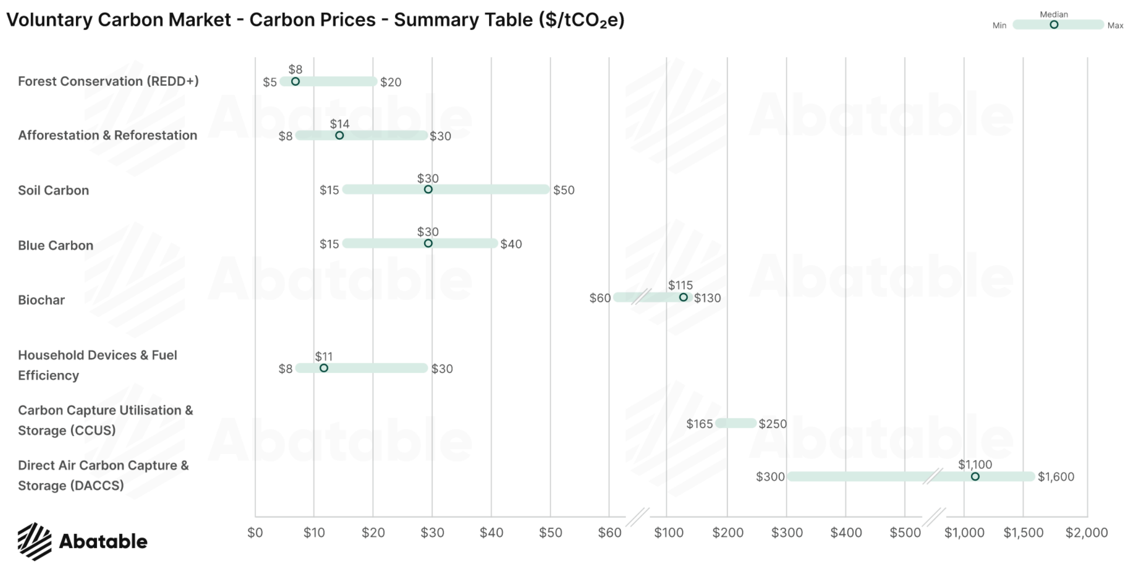


Table 2.3: Carbon offset prices by project type. Source: Abatable as of August 2022 [180]

Adopting these values as basis, the different projects have been classified according to Oxford's project typology. **Table 2.4** presents this classification and provides an example of project for each type with its current price.

Offset type	Project type	Example project	Price ($/tCO2e)	Carbon Offset Programme
Type I	Household devices & Fuel Efficiency	Myanmar stove campaign	$18	Gold Standard
Type II	Forest Conservation (REDD+)	Kasigan Corridor II REDD+ Forest Conservation	$20	VCS
Type III	CCUS	CarbonCure	$165	
Type IV	Afforestation & Reforestation and Soil Carbon	Planting Biodiverse Forests in Panama	$32.5	Gold Standard
Type V	DACCS and Biochar	Climeworks	$1,000	

Table 2.4: Project types included in each offset typology

In order to determine the minimum, maximum, and median prices for each typology, the average values have been considered. **Table 2.5** shows the values employed in this scenario.

	Price (\$t/CO_2e)		
Offset type	**Minimum**	**Maximum**	**Median**
Type I & II	\$6.5	\$25	\$9.5
Type III	\$165	\$250	\$207.5
Type IV	\$11.5	\$40	\$22
Type V	\$180	\$865	\$607.5

Table 2.5: Carbon offset prices considered in Price scenario III

Chapter 3

Standards for buildings and GHG accounting

3.1 Background and motivation to shift toward a carbon neutral construction industry

According to the World Green Building Council, buildings and construction are responsible for 39% of carbon emissions globally [181]. 28% of those emissions come from energy consumption during its operation and 11% are due to embodied carbon, which refers to emissions attributed to construction materials [181]. In Europe, buildings account for 40% of the energy demand and 36% of GHG emissions during the construction phase, their use, refurbishment, and demolition [182]. Therefore, decarbonisation is urgently required in this sector, both in the phases of operation and construction.

3.1.1 Legislative regime in the European Union

The EU must reduce 60% of GHG emissions from buildings, 14% of their energy demand, and 18% of their heating and cooling energy consumption to accomplish the target of 55% emissions reduction by 2030 [183]. This reduction, which was set by the European Commission in September 2020, is with respect to levels in 1990 [183]. As part of the current European policy, new buildings with a useful floor surface greater than 2,000 m^2 must achieve zero-emissions by 2027, and all new buildings by 2030 [184]. A zero emission building is defined as a building with an outstanding energy performance, powered by renewable sources to the maximum possible extent, and not associated with on-site CO_2 emissions from fossils. Zero emission buildings must also disclose on their Energy Performance Certificate their GWP related with the building's life cycle [184].

Energy Performance Certificates (EPCs) inform customers about the energy efficiency of buildings they intend to acquire or rent [185]. They contain recommendations for cost-effective enhancements as well as an energy performance rating [185]. EPCs were first established in the Energy Performance of Buildings Directive (EPBD) of 2002, and the recast of the EPBD in 2010 included a number of specifications to enhance the quality, accessibility, and acceptance of EPCs [186].

The Energy Efficiency Directive 2017/27/EU is complementary to the EPBD 2010/30/EU, and together establish a legal framework that aims at enhancing buildings' energy performance [187]. As part of the programme "Clean energy for all Europeans", in 2018 and 2019 both directives were revised, and with the Directive amending the 2018/844/EU Directive, the EU reinforced its commitment to modernise the construction industry and boost building refurbishments [187]. In December 2021, a new proposal for revising the EPBD as part of the programme "Fit for 55" was announced by the European Commission (COM(2021) 802 final) [187]. It outlines how EU Members may completely decarbonise their building stock and attain zero emissions by 2050 [187]. The recommended modifications should accelerate the renovation rates and enable more targeted investments in buildings, while at the same time contributing to the legal EU framework assisting vulnerable customers and combating energy poverty [187].

In Italy, the Legislative Decree of 10 June 2020, n. 48 (D.Lgs. n. 48/2020), transposes the EU Directive 2018/844 regarding Buildings' Energy Performance [188]. Included in its post-pandemic recovery plan, the Italian government established the "Superbonus 110%" programme to subsidise the upgrade of energy systems and anti-seismic renovations in residential buildings [189, 190]. This programme covers interventions like installation of facilities to produce renewable energy, measures to improve the insulation of buildings, heat pumps, and switching to more energy-efficient window frames [189,190]. The financial support is provided as a tax deduction to the subject that performs the intervention, with a deferral of 5 years [190].

Even though policies have been successful in increasing the energy performance of new buildings, 85% of the buildings in the EU were constructed before 2001, and between 85% and 95% are likely to still be standing in 2050 [183]. Therefore, the European Commission launched in 2020 the "Renovation Wave", with the objective of achieving a two-fold increase in the yearly energy renovation rates in the following ten years [183].

3.2 GHG emissions accounting and reporting

3.2.1 GHG Protocol categorisation: Scope 1, 2 & 3 emissions

The GHG Protocol creates extensive, globally recognised frameworks for measuring and managing GHG emissions released by supply networks, public or private operations, and mitigation activities. The GHG Protocol, which collaborates with governments, business groups, NGOs, and other organisations, was convened by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) [191].

Companies and other businesses can refer to the guidelines and requirements laid out in the "Corporate Accounting and Reporting Standard" of GHG Protocol to determine their GHG emissions inventory. The standard addresses the six GHGs included in the Kyoto Protocol – carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) [192].

The "Global Protocol for Community - Scale Greenhouse Gas Inventories" was developed to assist cities during the creation of thorough and reliable GHG inventories, the determination of reduction targets, and the monitoring of progresses [193]. It seeks to guarantee consistency and transparency during the accounting and reporting phases and to showcase the crucial role that cities play in fighting climate change [193]. The GHG Protocol also provides principles, techniques, and strategies for calculating emissions reductions or removals from carbon offset projects [191].

In order to effectively manage GHG emissions, the GHG Protocol categorises the emissions in three different scopes, which helps companies to set operational and organisational boundaries [192].

Scope 1: Direct GHG emissions

This scope covers the emissions from sources that the corporation owns or controls. It mainly results from the following groups of activities [192]:

- Power generation in stationary sources (e.g. natural gas combustion in boilers)
- Materials, manufactured goods and employees transportation (e.g. fuel combustion during the transportation of final products by trucks controlled by the company)
- Physical/chemical processing and manufacturing (e.g. GHG emissions released during the manufacture of ammonia)
- Fugitive emissions (e.g. leakage of hydrofluorocarbons (HFCs) from air conditioners)

Carbon dioxide emissions from biomass combustion must be individually reported, while direct emission of GHGs different than those covered by the Kyoto Protocol can be voluntarily reported. None of them shall be accounted for in Scope 1 [192].

Scope 2: Indirect GHG emissions released by energy sources

The emissions released during power (electricity, steam, heat, or cooling) generation consumed by the company are accounted for in Scope 2 [192]. Since power consumption represents the largest GHG source for many companies, these indirect emissions are considered separately of other indirect emissions [192].

Scope 3: Indirect GHG emissions which were included in Scope 2

These emissions are also called "value chain emissions" because they take into account emissions from upstream to downstream activities [194]. While reporting Scope 3 emissions is optional, it can provide an opportunity to make a difference in GHG management and increasing a corporate's reputation [192]. However, since enterprises can decide which categories take into account based on the information they have available and their business targets, Scope 3 emissions may not provide a quantitative tool to compare the performance of different companies [192]. Companies may evaluate the impact of their emissions along the value chain following the "Corporate Value Chain (Scope 3) Standard".

The category of an activity's emissions shall be determined according to the organisational boundaries defined. Some of the most common activities for which emissions are covered under Scope 3 are listed below [192]:

- Materials/fuels extraction and production
- Transportation (e.g. of materials, waste or fuels, employees travels)
- Activities related to electricity consumption (not accounted for in Scope 2) (e.g. transportation of fuels used for energy generation)
- Emissions from leased assets, franchises, and external activities
- Usage of products and services sold by the company
- Waste disposal (e.g. disposal of waste from production activities or products at the end of life)

Figure 3.1 illustrates a company's organisational and operational boundaries and how they are related [192]. The consolidation approach used for establishing the organisational boundaries will determine what constitutes direct and indirect emissions. The consolidation approaches that can be used for corporate reporting are the equity share and the control approaches. In the case of equity share, the corporation accounts for GHG emissions from operations in accordance with its equity share in the operation [192]. The equity share represents economic interest, or the extent of a company's rights to the risks and benefits associated with an operation. Instead, under the control approach, the corporation accounts for the total GHG emissions released from operations over which the corporation has control. If a corporation follows a control approach, it should decide between the criteria of operational or financial control [192].

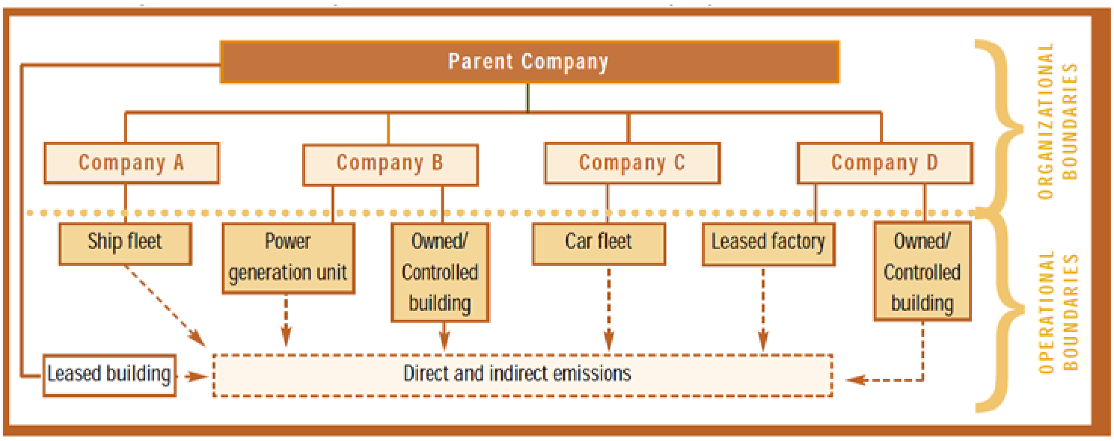


Figure 3.1: Organisational and operational boundaries of a company. Source: The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard, *WRI and WBCSD* [192]

3.2.2 GHG Management Hierarchy

The Institute of Environmental Management and Assessment (IEMA) developed a GHG Management Hierarchy, which is presented in **Figure 3.2**. The original hierarchy of 2009 was updated in 2020 to reflect the urgency to scale-up actions at all hierarchy levels and to consider the fact that the amount of potential emissions reductions may not always follow the hierarchical approach [195].

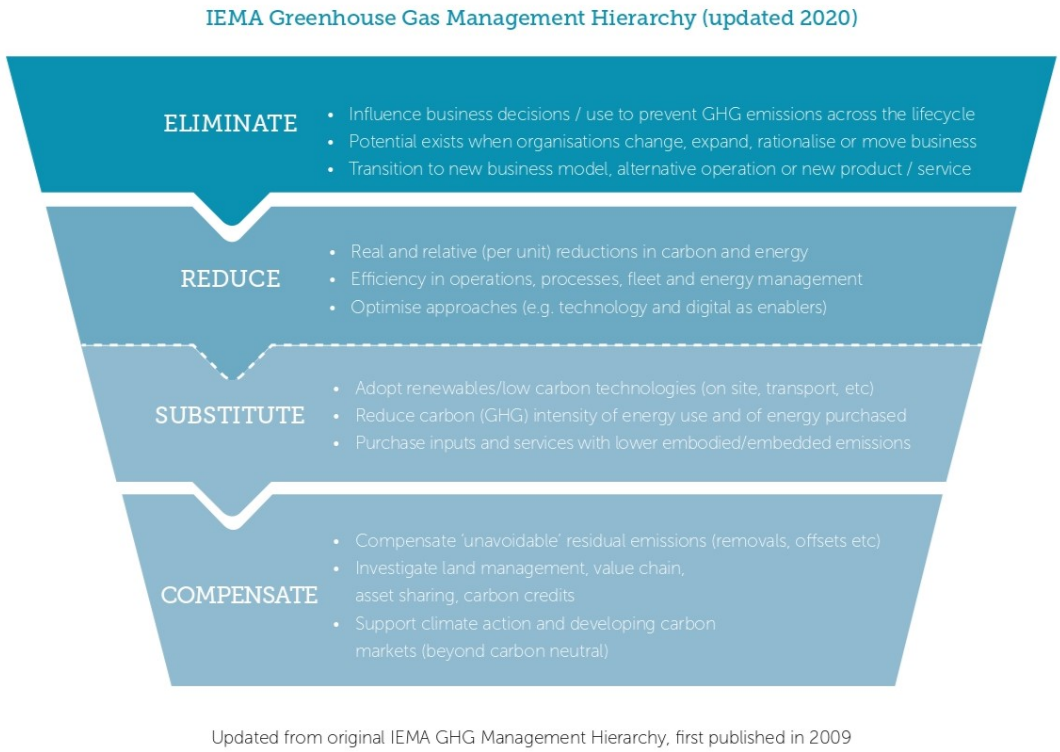


Figure 3.2: IEMA Greenhouse Gas Management Hierarchy. Last updated in 2020. Source: Pathways to Net Zero, Institute of Environmental Management and Assessment (IEMA) [195]

As the hierarchy indicates, it is essential to focus first on eliminating any source of GHGs across the entity's lifecycle. The next level concentrates on emissions and energy reductions, optimising processes and increasing the efficiency of all the operations involved. After that, obsolete technologies should be replaced by energy-efficient and low-carbon devices, and services acquired should embed as less as possible emissions. Finally, the last option is to compensate for unavoidable emissions by offsetting and contributing to climate activities and carbon markets ("beyond neutrality"). In order to maximise its potential contribution to the climate emergency, the voluntary carbon market needs to be promoted and strengthened, according to IEMA's "Pathways to Net Zero" [195].

Even though accounting methodologies for Scope 3 emissions are not yet mature, it is perceived as a key sector to reduce GHG emissions along the value chain. To claim for a real net zero target, corporations must collaborate with their suppliers to quantify and reduce indirect GHG emissions. However, a survey carried out by IEMA in 2019 suggests that only 43% of the participant organisations were quantifying Scope 3 emissions beyond employees commuting and travelling [195].

IEMA developed a possible timeline for emissions accounting to achieve net zero (**Figure 3.3**). At the beginning, since indirect GHG emissions along the value chain are quantified including only a limited amount of sources, Scope 1 and 2 emissions appear to account for the largest share of emissions. In the third year, accounting methodologies are fully developed and Scope 3 emissions seem to have increased. In year 15, an overall reduction of GHG emissions has been achieved, remaining only unavoidable emissions, which could be compensated through carbon offsetting to achieve net zero [195].

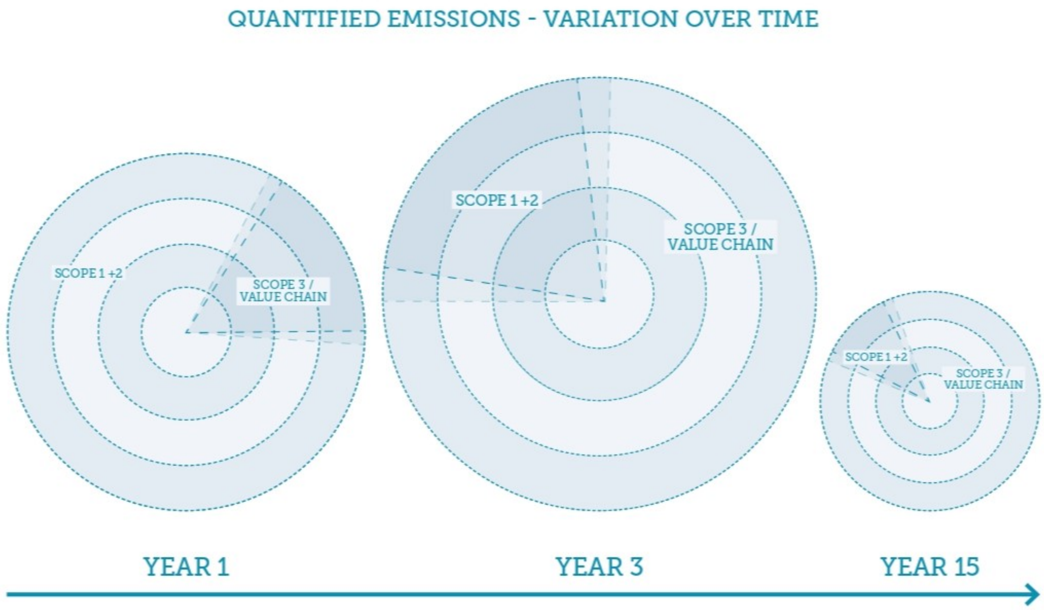


Figure 3.3: Variation of quantified emissions over time. Source: Pathways to Net Zero, Institute of Environmental Management and Assessment (IEMA) [195]

3.2.3 Life Cycle Assessment

By quantifying environmental impacts and help identifying practical ways to reduce them, Life Cycle Assessment (LCA) can be used to assess a building's sustainability performance [196]. **Figure 3.4** presents the different stages of a building's LCA, which can be classified into embodied impacts (product, construction, use, and end of life stages), operational impacts, and additional information.

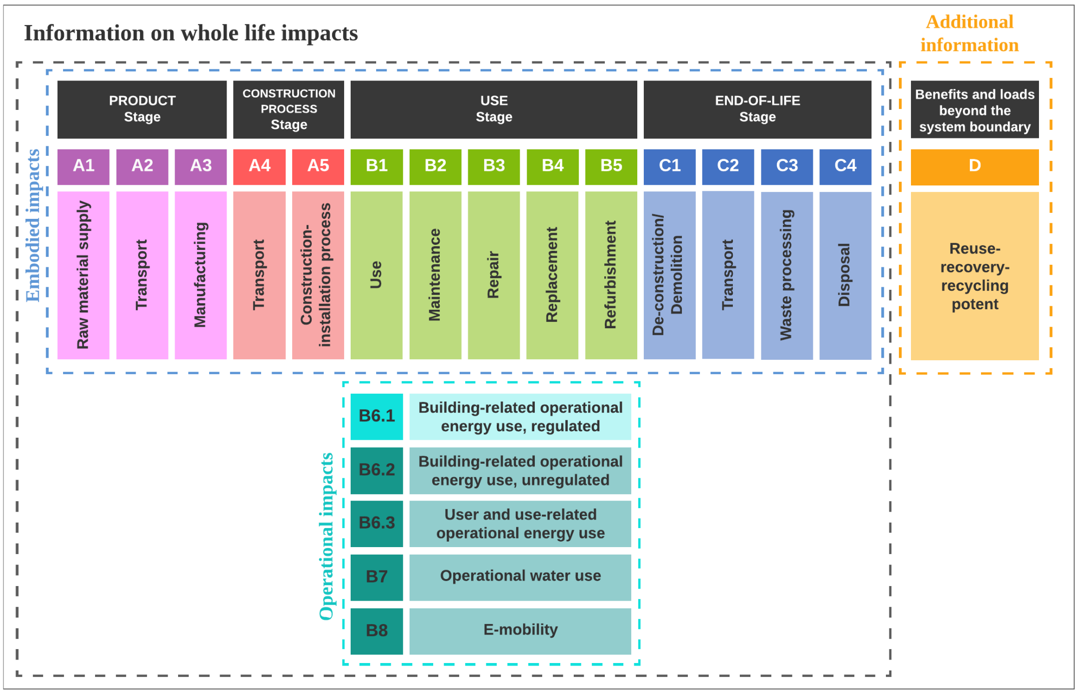


Figure 3.4: Stages of a building's Life Cycle Assessment. The dotted lines represent the impact's boundaries. Reproduced from Lützkendorf & Frischknecht (2020) [197]

3.2.3.1 Methodology - Description of life cycle stages

Embodied carbon

- **Product stage (A1-A3):**
  Includes the raw material extraction (A1), transport from the extraction site to the manufacturing facility (A2), and the manufacturing process (A3).
  Examples: Extraction of iron ore (A1), transport to melting factory (A2), steel manufacturing (A3).

- **Transport stage (A4):**
  Includes the transport from the manufacturing facility to the construction site.
  Examples: 500 km road transport from the manufacturer's facility to the construction site.

- **Construction stage (A5):**
  Includes the assembly and construction on site (typically energy, water, waste transport and management).
  Examples: Demolition of concrete floor from existing building; Assembly of interior walls, etc.

- **Maintenance and replacements (Use stage, B1-B5):**
  Includes the use (B1), maintenance (B2), repair (B3), replacement (B4) and

refurbishment (B5) of materials and equipment. It does not include the energy consumption of the equipment.
Examples: Replacement of external paint or Mechanical, Electrical and Plumbing (MEP) components after the lifespan.

- **End of life stage (C1-C4):**
Includes the de-construction and demolition (C1), transport from site to a recycling plant or landfill facility (C2), the waste processing of the materials (C3), and the disposal of the materials (B4).
Examples: Demolition of concrete structure (C1), transport to end-of-life facilities (C2) crushing for future use as recycled materials (C3) and landfill disposal of fraction not valid for recycling (C4).

Operational carbon

- **Operational Energy Use (B6):**
Includes carbon impact due to the energy consumption of the equipment to satisfy occupants needs (comfort, lighting, etc).
Examples: electricity consumption of luminaires and electrical equipment.

3.3 Towards Net Zero Carbon Buildings

The UKGBC published in April 2019 a framework that provides guidelines and requirements to achieve Net Zero Carbon in buildings [198]. It proposes a five-step pathway for buildings in operation and new or refurbished buildings, which is presented in **Figure 3.5** [198].

For buildings under construction and major renovations, it is necessary to carry out a comprehensive Life Cycle Assessment to quantify the emissions released during this phase, which shall be disclosed and offset upon completion [198]. The design of new buildings should aim to achieve carbon neutrality for operational energy by incorporating energy-efficient technologies and renewable energy sources at the time of construction, while existing buildings should undergo some interventions to be in line with these principles [198]. The amount of carbon that was not avoided in the previous stages, which should be at all costs minimised, should be offset following credible offsetting standards [198].

To provide clarity on the practical application of Steps 4 and 5, the UKGBC published in March 2021 a report focused on the procurement of renewable energy and carbon offsetting for achieving net zero carbon buildings in the UK [14]. **Section 3.3.1** provides a detailed analysis of the UKGBC's procurement solutions applied to international markets.

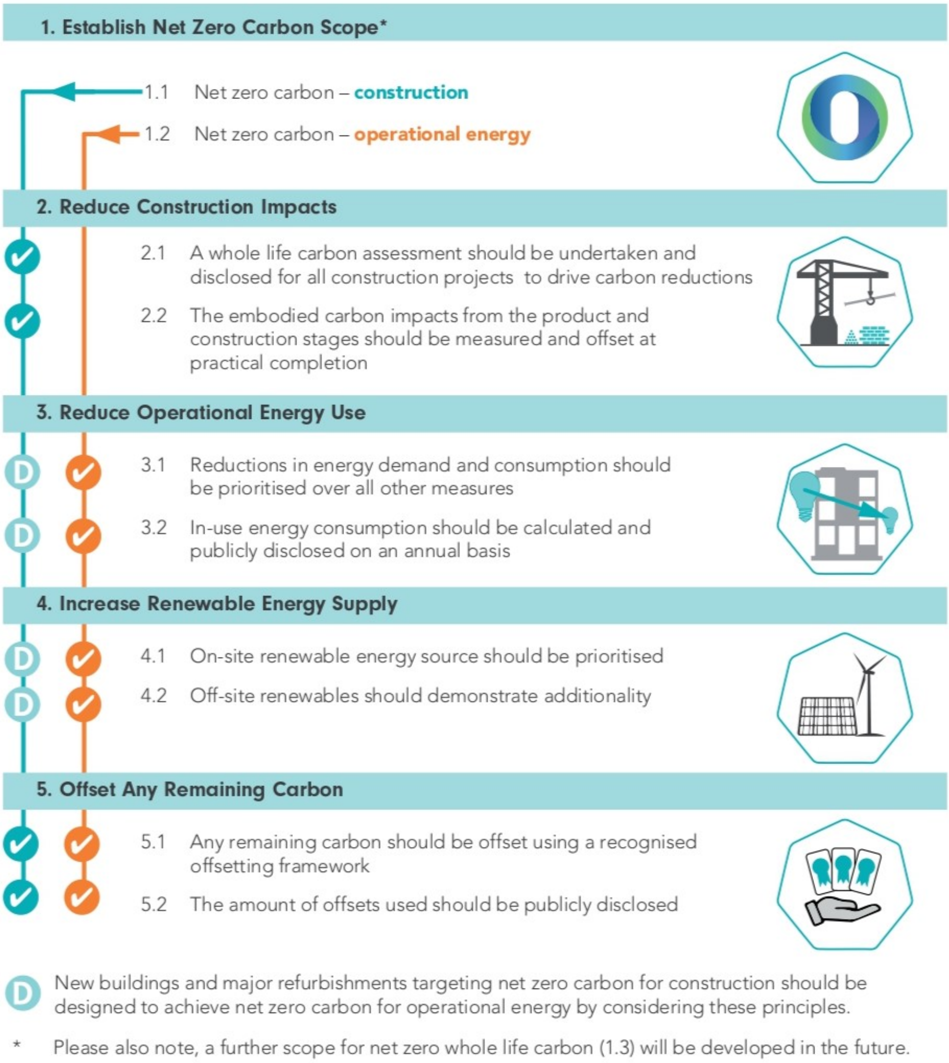


Figure 3.5: Steps to achieving a Net Zero Carbon Building. Source: Net Zero Carbon Buildings: A Framework Definition, UK Green Building Council [198]

3.3.1 Procurement of Renewable Electricity

According to the UKGBC, the following principles need to be followed to ensure high-quality electricity procurement [14]:

Energy attribute and exclusive ownership: The energy attributes of the renewable electricity are exclusively owned and claimed by generating on-site renewable energy or acquiring Energy Attribute Certificates (e.g. UK's Renewable Energy Guarantees of Origin (REGOs), or Guarantees of Origin (GOs) in the EU) [14].

Electricity from renewable sources: The electricity must be produced from non-fossil renewable sources, i.e. wind power, solar energy, hydropower, geo-, hydro- and aerothermal, biomass, and less conventional renewable sources, such as landfill gas, ocean energy, and biogas and gas from sewage treatment plants [14].

Additionality: This principle can be achieved by installing and consuming on-site renewable energy, or by closing a power purchase agreement that derives in the construction of a new power facility. In order to be additional, it must contribute to the generation of renewable energy power plants that would not have been constructed without the organisation's financial support [14].

Depending on the location, there are different methods available to accede to renewable energy. Since on-site measures contribute to the creation of new renewable facilities and decrease the demand on the grid network, on-site renewable energy should be prioritised (i.e. installed on the building, situated close to the building or linked by a private connection from a nearby site) [14]. It is important to consider that it is not possible to sell Guarantees of Origin for the energy consumed on-site [14].

The most common on-site procurement routes that meet the principles mentioned above are the installation of on-site renewable energy facilities (e.g. solar photovoltaic or small wind turbines), and the private connection to a non-subsidised renewable generation facility in the framework of a Power Purchase Agreement (PPA). When on-site methods are not available, electricity could be procured by off-site PPAs or green tariffs, provided that these meet high quality criteria [14]. Another option is to retire EACs, also known as Guarantees of Origin, which can be done on the consumer's behalf or by the green tariff supplier [14].

If renewable electricity is procured through methods that do not meet the three principles (e.g. when unbundled EACs or low-quality green tariffs are used), the electricity consumption should be compensated through carbon offsetting [14]. In order to calculate the residual emissions to be offset, location-based factors should be employed. The location-based method is based on average emission factors for energy production for specific areas, which is used to calculate Scope 2 GHG emissions [14].

3.3.1.1 Energy Attributes Certificates (EACs) (RECs, GOs and i-RECs)

Energy Attributes Certificates (EACs) are global instruments that guarantee that a certain quantity of electricity, typically 1 MWh, was generated from renewable sources [199]. These certificates are a particular kind of tradable environmental commodity that are in line with GHG Protocol's Scope 2 Guidance [199]. EACs can be purchased bundled with electricity or separately from the underlying power, which are referred to as bundled and unbundled EACs, respectively [14]. The most common EACs systems are GOs, RECs and i-REC [199].

The mechanism used by the European Union is a voluntary system called Guarantee of Origin (GO), which is an electronic document designed solely to prove to a final customer that a specific share or amount of energy was generated from renewable sources [200]. Plants with Guarantee of Origin (certified IGO plants) are able to issue a GO certificate for every MWh of renewable energy they input into the grid, pursuant to Directive 2009/28/EC [201].

Renewable Energy Certificates (RECs) are the primary tool used in the United States and Canada, and they exist under compliance and voluntary schemes [201]. RECs were originally used to meet legally mandated Renewable Obligations (RO) or Renewable Portfolio Standards (RPS), which specify minimum percentages of renewable energy sources in the energy mix of power or electricity providers [202].

Only renewable energy facilities that meet the RPS eligibility requirements can be issued an RPS Compliance REC [203]. As of now, RECs are also acquired by companies and consumers to claim the purchase of renewable electricity voluntarily [203]. In jurisdictions with oversupplied REC markets, wind farms or hydroelectric plants produce voluntary RECs, which are not eligible for RPS compliance [203]. RPS Compliance RECs can only be purchased in jurisdictions with an RPS regulation [203]. Although it is recommended that voluntary RECs are acquired from renewable generators close to the buyer, there is no requirement that enforces the purchaser to be in the same location where the renewable electricity is generated [203].

In other parts of the world where green energy certification systems do not yet exist, International REC Standards (i-RECs) are adopted [201]. Non-profit organisations act as brokers and allow that renewable energy producers can use this market to make their own clean energy traceable, transferable, and trustworthy, even in nations without their own certification systems [201].

EACs are generally defined as representing "attributes" or "benefits" related to the production of renewable energy, though the definition of what exactly those attributes and benefits are is frequently ambiguous and unclear [203]. The primary goal of acquiring voluntary RECs, or equivalent certificates, is to report net zero for Scope 2 emissions, which include all indirect emissions related with the consumption of purchased electricity [203]. Even though this method is unlikely to have negative side effects on local communities or the environment, it has a limited potential to generate the co-benefits that several carbon offsets generate [203].

According to a study conducted by M. Gillenwater, there is no guarantee that the retirement of a REC has an impact on emissions from the generation of electricity [204]. The author maintains that consumers of voluntary RECs are merely providing financial support to renewable energy generators, and because there are no common standards to quantify emission reductions and renewable generators are not likely to have the ownership of the impacts generated by renewable electricity, they are not able to transfer emissions reductions [204]. Since the environmental integrity of voluntary RECs is in many cases not guaranteed, it is not recommended follow only this approach to compensate for an organisation's GHG emissions [11].

An alternative to improve the use of voluntary RECs could be the acquisition of these certificates coupled with long-term Power Purchase Agreements (PPAs) [203]. Even though this approach is expected to have greater environmental integrity, there is currently no research that proves that it provides additional GHG emission reductions [203].

With respect to compliance RECs, according to the Carbon Offset Guide, some of the compliance REC markets are likely driving more investment in renewable energy as a result of the RPS goals' growing progressively [203]. The growth of the RPS goals' is evidenced by their significant price increase [203]. Therefore, acquiring and retiring compliance RECs from a scarce market could be used to credibly claim emission reductions [203]. It is important, however, that the purchaser quantifies the GHG reductions associated with this REC retirement, rather than simply claiming that it has obtained "green electricity" and adding a zero-emission factor to a company's GHG footprint [203]. A load dispatch analysis of spared fossil generation using current electric power industry models can be used to evaluate the marginal impact [203]. Although quantifying the GHG reductions could be complex, it is not expected to present a major technical challenge [203].

EACs prices in voluntary markets are solely determined by supply and demand dynamics [205]. In Europe, GOs agreements and expenses are generally not disclosed, and it is therefore difficult to predict the price of GO certificates [205]. In March 2021, in a national auction held in France, prices were between €0.30/MWh and €0.52/MWh [205].

In RPS compliance markets, instead, prices differ among regulatory jurisdictions as a result of varying and evolving programme regulations [206]. In New England, USA, class I prices rose to around $40/MWh in 2019, while in Mid-Atlantic region prices increased approximately to $10/MWh [206]. **Figure 3.6** illustrates the trend of RECs prices in the regional markets of New England and Mid-Atlantic for Primary Tier RPS Obligations [206]. Some states of the USA have established tiers or classes for the compliance REC market, either based on the date in which the renewable energy facility was installed or was available online, or according to the technology producing the RECs [207].

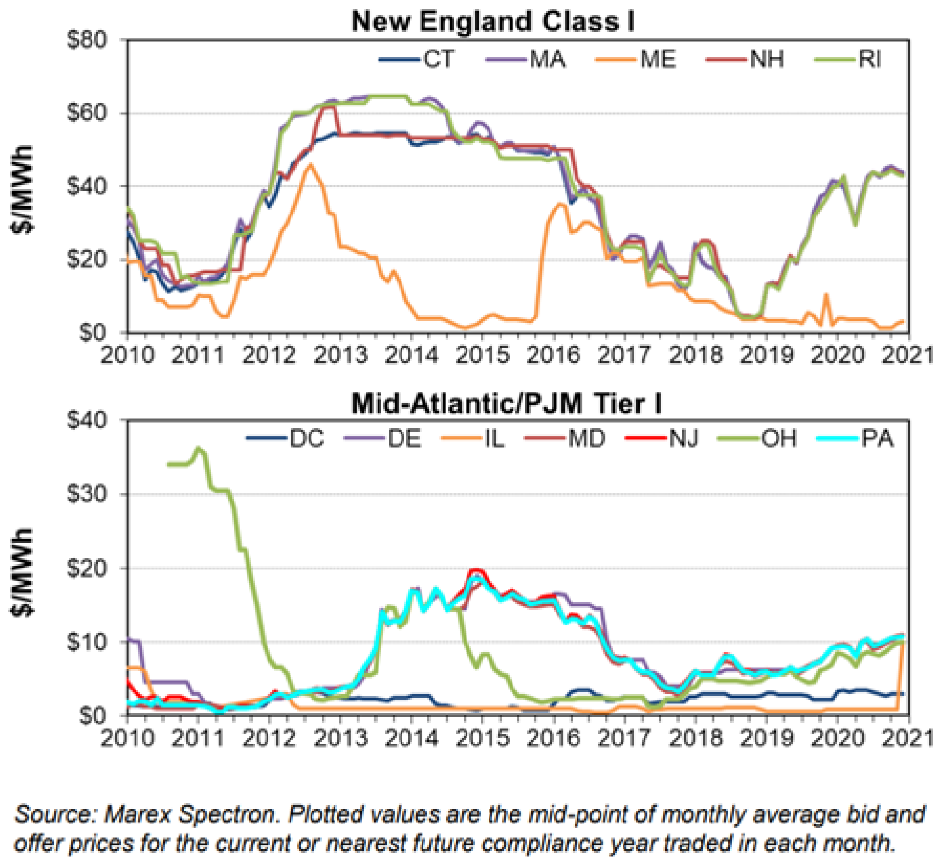


Figure 3.6: Pricing Trends of RECs for Primary Tier RPS Obligations. Source: Marex Spectron. Adopted from Barbose, G., U.S. Renewables Portfolio Standards, 2021 Status Update: Early Release, 2021 [206]

3.3.1.2 Renewable energy Power Purchase Agreements (PPAs)

A renewable energy Power Purchase Agreement (PPA) is a contract between renewable energy generators and customers that sets a quantity and price for the purchase of renewable energy over a prolonged period [208].

Unlike the previous method that involved the acquisition of compliance or voluntary EACs, the purchaser in this case enters into an agreement directly with a new manufacturer of renewable electricity, which includes the EACs for retirement [209]. In addition to purchasing renewable energy, PPAs give the client assurance and transparency on the wholesale pricing component of the costs of the energy delivered. Moreover, a corporate PPA may become an important and regular source of income for the producer and stakeholders [210]. A PPA imposes a cost on the purchase of power, but currently, there is no standard methodology for quantifying its emissions reduction impact, so estimating the price per metric tonne of CO_2e is not straightforward [211].

PPAs can be classified in virtual (or financial) PPAs and physical (or back-to-back) PPAs [14]. Virtual PPAs, illustrated in **Figure 3.7**, are most commonly used, where the electricity buyer is generally not within the same geographical area as the renewable energy project, so that the producer injects the energy into the grid, and the buyer purchases electricity from the grid at a predetermined price [208]. Instead, when the renewable power plant is located close to the buyer, a physical PPA can be established **(Figure 3.8)**. Corporations benefit from this scheme by gaining greater autonomy, but a high-level technical expertise is required [208]. In both cases, a guarantee of origin for the production of renewable energy should be given to the consumer by the renewable power producer [208].

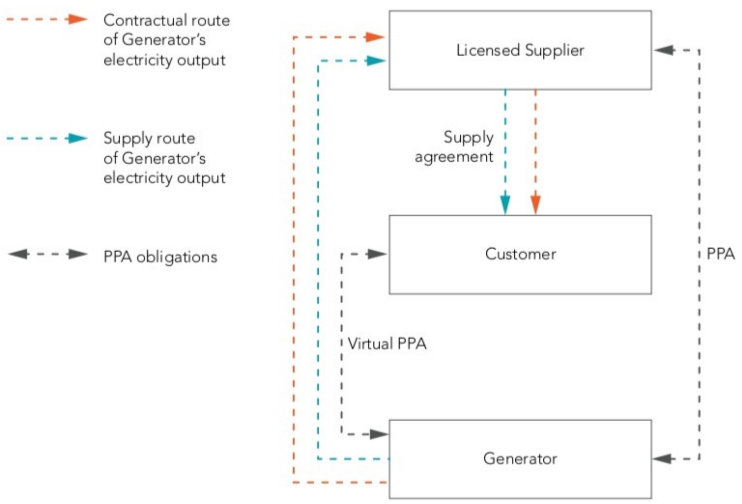


Figure 3.7: Virtual or financial PPA. Source: Renewable Energy Procurement & Carbon Offsetting: Guidance for net zero carbon buildings, UK Green Building Council [14]

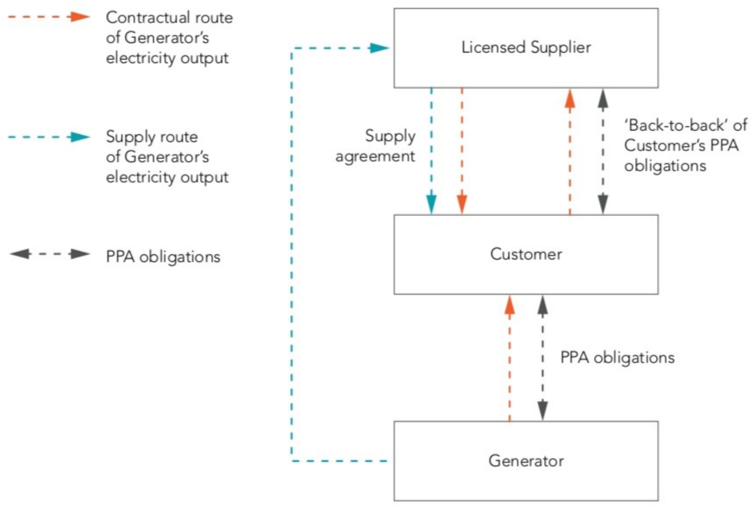


Figure 3.8: Physical or back-to-back PPA. Source: Renewable Energy Procurement & Carbon Offsetting: Guidance for net zero carbon buildings, UK Green Building Council [14]

Renewable sources on-site should be chosen over off-site solutions, as they increase the overall supply of renewable electricity and decrease the grid's demand [14]. Renewable energy systems are referred to as being "on-site" when they are integrated with the building's mechanical and electrical systems, when located close to the building on a shared LV/HV electrical network, or when connected through a private line [14].

PPAs with new and non-incentivised renewable production, as well as renewable sources owned by the consumer, such as rooftop photovoltaics, are examples of on-site methods to procure electricity from renewable sources that meet the three principles for high-quality electricity procurement [14]. When the application of on-site renewables is not available, off-site measures may be implemented, provided that they can prove additionality [14]. A virtual PPA with unsubsidised production, along with high-quality green tariffs from providers that only generate renewable electricity, might represent a meaningful alternative in this scenario [14]. In case that is not possible to choose a strategy for electricity procurement that meet the three principles at the same time, like off-site power purchase agreements that cannot demonstrate additionality, residual emissions must be compensated through a certified carbon offsetting programme [14]. Compared to voluntary EACs alone, PPAs offer a solution with higher environmental integrity, but it is uncertain how effective the different arrangements of PPAs are in practice [211].

3.3.1.3 Green tariffs

Energy suppliers that are renewable sourced can offer "green tariffs" to their customers, which state that a percentage or all of the energy acquired by a customer is powered by renewable sources [14]. High-quality green tariffs are provided by suppliers that only offer these type of tariffs and which either generate renewable electricity or acquire bundled EACs through PPAs [14]. Green tariffs provided by suppliers that are not 100% renewables sourced, and therefore do not meet the principle of "renewable sourced", are considered as being of low-quality. This is because these suppliers continue to drive investments to fossil fuels and offer renewable energy backed by unbundled EACs [14].

However, there are only a few suppliers that currently can prove to meet the three principles. In the UK, only Ecotricity, Good Energy and Green Energy have proven to meet additionality on a scale that is considerably greater than that provided by subsidies, regulations, or other compulsory measures [14].

According to the Climate Change Committee, PPAs and green tariffs in the UK are only contributing to a limited extent to reduce GHG emissions, because in most cases they do not derive in the construction of new renewable facilities or are being subsidised by the government through mechanisms such as Contracts for Difference [212]. Before selecting the appropriate solution, it should be investigated which is the current situation and availability of PPAs and green tariffs in the location of the acquirer.

3.4 Frameworks for sustainable buildings

The Net Zero Carbon Buildings Commitment announced by the World Green Building Council (WGBC) at the Global Climate Action Summit on September 2018 was signed by 136 businesses and organisations, 29 cities, and 6 governments by November 2022 [213, 214]. It requires the reduction of energy consumption and removal of emissions from energy and refrigerants from existing buildings by 2030 [214]. New buildings and major refurbishments are required to be highly efficient and to use only renewable energy sources by 2030 [214]. Compensation activities of residual emissions can be adopted to achieve carbon neutrality [214].

Since the adoption of the Paris Agreement, many cities have committed to achieve carbon neutrality by 2050. To accomplish their net zero pledges, numerous countries have developed national net-zero frameworks for various sectors. In this context, diverse definitions of net-zero or carbon neutral buildings have emerged, and the lack of international standardisation is causing confusion and difficulty in comparing national efforts to combat climate change [197]. Some of the national frameworks launched by Green Building Councils to define and develop Net Zero Carbon Buildings are the UKGBC, in the United Kingdom, the GBC Australia, and the DGNB, in Germany [215]. The International Energy Agency Energy in Buildings and Communities (IEA EBC) Programme Annex 72 is currently developing an evaluation of national and international standards, regulations, and guidelines regarding the environmental assessment and GHG emissions accounting in buildings (Frischknecht, 2018 [216], as cited in Lützkendorf et al., 2020 [197]).

3.4.1 A typology of the available building's assessments approaches

Lützkendorf & Frischknecht proposed a typology to classify buildings' carbon neutral approaches into four categories [197]:

A. Net-balance approach, which includes the alternatives Aa ("potentially avoided" emissions) and Ab ("allocation").

B. Economic compensation.

C. Technical reduction.

D. Absolute zero.

Approaches A, B, and C are considered net zero approaches, while approach D follows a zero emissions methodology.

Approach A (Net-balance approach)

The net-balance approach consists of two steps and can be adopted for both the operational phase and/or the whole life-cycle [197]. The first step requires to balance the energy demand with the energy generated on-site, which can be determined on a yearly, monthly or hourly basis. In the second step, there are two options available for assessing the balance [197]:

- **Aa. Potentially avoided emissions:** The benefits delivered by the export of energy produced on-site are only attributed to the building's GHG emissions.
- **Ab. Allocation:** The proportionate share of GHG emissions caused by the production of on-site energy is attributed to the exported energy and the potential benefits outside the system's boundary are not attributed to the building.

While approach Aa may be controversial because it depends on the theoretical assumption that the export of energy will avoid GHG emissions considering the actual energy mix, it is feasible to achieve net-zero in buildings following this approach [197]. In this case, the risk of double-counting the emission reductions by both the energy producer and the consumer should be taken into account.

With approach Ab, instead, net-zero buildings can only be achieved if it is integrated with approaches B or C. In order to report the total energy exported as additional information, the standard ISO 16475-1:2017 can be followed. Experts of the Technical Committee 350 of the European Committee for Standardization (CEN/TC 350) are debating if the potential benefits and loads beyond the boundaries of the system brought on by exported energy should be reported in module D of the life-cycle stages as supplementary information [197].

Approach B (Economic compensation)

In this approach, the GHG emissions of the construction, operational and end-of-life stages are quantified and compensated by acquiring carbon offset credits. While offsetting is proposed by the UKGBC to achieve net zero emission buildings, according to Lützkendorf et al., 2020, since the building still releases GHGs, it does not significantly support the worldwide net-zero GHG emission objective. Carbon offsets can only cut up a maximum of 50% of GHG emissions on a global level because for every tonne of GHG emissions reduced, another tonne is still emitted by the offset's purchaser [197].

Approach C (Technical reduction)

After determining the GHG emissions released during construction, operation, and end-of-life, technical-reduction techniques are financed to remove the same quantity of CO_2 from the atmosphere [197]. Negative Emission Technologies (NET) like "biological fixation" (e.g., reforestation), Bioenergy with Carbon Capture and Storage (BECCS), or Direct Air Capture with Carbon Capture and Storage (DACCS) are examples of technical-reduction techniques. This strategy enables the construction of carbon neutral buildings while also advancing the global carbon neutrality objective [197].

The major benefit of this solution is that it effectively reduces the concentration of the atmospheric CO_2 using technology [197]. However, the development of most NETs is still immature and there are many uncertainties regarding their economic viability and risks of leakage and non-permanence [197].

Approach D (Absolute zero)

To achieve absolute zero buildings, their construction should be done using zero-emissions materials and with proper management at their end-of-life [197]. During their construction and operation, buildings should only be powered by zero emissions fuels and electricity. Even though this strategy is currently not feasible to implement, it would allow for absolute zero GHG emissions buildings, contributing to achieve the worldwide net-zero GHG emissions target [197].

Although achieving on-site zero GHG emissions for buildings' operational phase may be feasible, it is unlikely that this will be the case for the value chains of the energy demand, construction materials, and components of the buildings [197].

This classification attempts to improve transparency and facilitate comprehension by categorising the various approaches and it can be used for the evaluation of GHG emissions that occur during the operational phase or throughout the life-cycle [197]. Concerns regarding how GHG emissions should be balanced and which compensation options should be implemented are issues for all net zero approaches [217]. The following items discussed by Satola et al., 2021, address the most crucial issues [217].

3.4.1.1 System boundaries for the production, acquisition, and evaluation of renewable energy

In order to compensate the remaining GHG emissions with the avoided emissions caused by the export of renewable energy, or to include the potential benefits as additional information in module D, it should be first determined which kind of renewable energy production is possible to attribute to the building and within which boundaries of the system [217].

Marszal et al., 2010, introduced different possibilities to define the boundaries of the system for the renewable energy generation, as presented in **Figure 3.9** [218].

- **Option I – Generation integrated in the building:** Facilities installed on the building are used to produce renewable energy from sources that do not need effort to be transported, such as wind and sun.
- **Option II – On-site production from on-site renewable sources:** In this case, the generation can take place also in facilities located on the sites surrounding the building, such as ground owned by the building and located adjacent to it.
- **Option III – On-site production from off-site renewable sources:** Energy carriers, such as biomass, are transported to the building site where they are used to produce energy.
- **Option IV – Off-site production:** The owner of the building invests on facilities that produce renewable energy, which is included in the building's energy balance.
- **Option V – Off-site procurement:** Green energy is acquired from the energy grid.

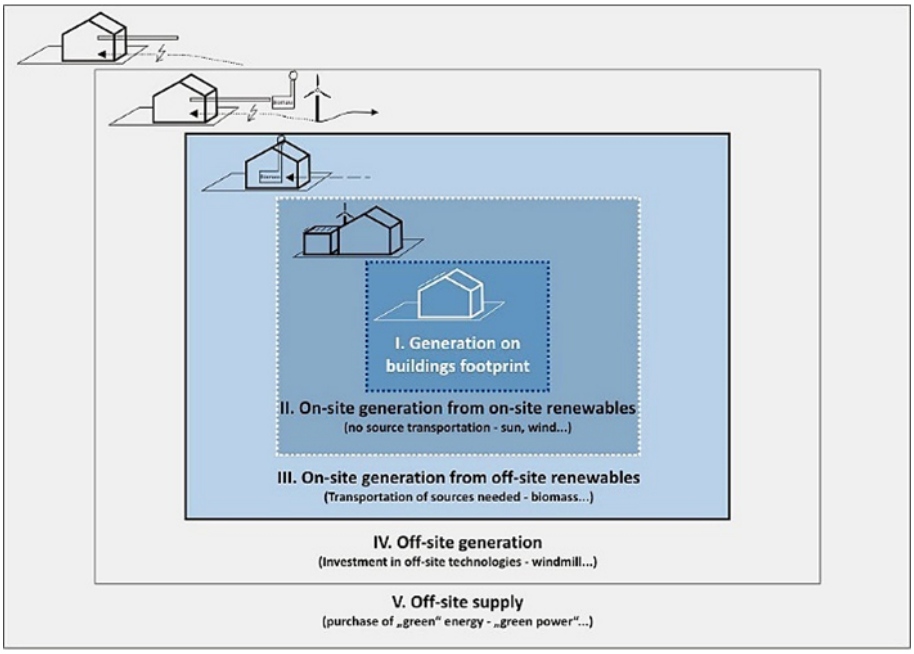


Figure 3.9: System boundaries for the generation of renewable energy. Source: Marszal et al., 2010 [218]

Options I and II are particularly significant because do not require to transport the energy carriers and, once the energy requirements have been satisfied, the excess of energy can be exported [217]. Since there are considerable environmental effects associated with the transport of energy carriers, option III is often less advantageous than options I and II [217].

Regarding option V, despite of being largely acknowledged as a practical and affordable method for cutting GHG emissions from electricity procurement, buildings adopting this approach could be seen as having little initiative to reduce the demand of energy and the associated environmental impacts [217].

The risk of double-counting is present both when the excess of on-site generated energy is exported to a third party, and when energy generated off-site is purchased by the building [217]. To lower this risk, it is recommended to retire EACs on behalf of the purchaser or seller claiming the environmental benefits associated with the production of each MWh of renewable energy [217].

3.4.1.2 Viability of Negative Emissions Technologies

The removal of GHG emissions from the atmosphere through technical solutions enables the achievement of net zero emissions buildings (approach C) and contributes to the global achievement of net zero emissions. However, its viability over the long run is still uncertain [217].

3.4.1.3 Purchase of offset credits

While the purchase of avoidance or removal offset credits is considered as a crucial instrument for enhancing sustainability and accelerating decarbonisation at the global level, the effectiveness and reliability of this approach is still controversial [217].

3.4.2 Compensations options in buildings' frameworks

Satola et al., 2021 [217], adopted Lützkendorf's [197] typology to compare compensation options included in national buildings' frameworks for GHG emissions management. A summary of the allowed compensation options is described in **Figure 3.10**.

While all the analysed frameworks allow to include the avoided GHG emissions caused by the production of on-site renewable energy on the building's energy balance (approach Aa, option I, II, and III), off-site production and off-site supply (options IV and V) are not considered on the building's frameworks from Finland, Germany, Norway, and Sweden [217]. The purchase of offset credits (approach B) is not allowed on the building assessment approaches from Finland, France, Germany, Norway, and Malmö (Sweden), and according to the UK and South Africa, the production of renewable energy should be prioritised. Approach C, adoption of technical reduction measures, is only considered by the frameworks from New Zealand, Sweden (both NollCO_2 and Local Roadmap Malmö), and the USA's Zero-carbon building. The negative-emission technologies included are primarily reforestation activities, investments on carbon sequestration, and the implementation of measures that increase the energy efficiency in existing buildings [217].

Type of compensation following Lützkendorf and Frischknecht, 2020 [49]		"Avoided" GHG emissions from renewable energy generation Type A.a					Type A.b	Type B	Type C	
Country	Building assessment approach	On building area	On-site from on-site renewables	On-site from off-site renewables	Off-site generation	Off-site supply		Renewable energy certificates/off-set credits	Implementation of negative carbon technologies	Timing of GHG emissions compensation
Australia	Carbon neutral	X	X	X	X[2]	X[2]		X		Annually
Canada	Zero-carbon building	X	X	X	X	X		X		Annually
Finland	Whole-life carbon assessment of buildings	X	X	X						Annually
France	EQUER	X	X	X	X	X				Building lifetime
Germany	Carbon-neutral building standard (DGNB) framework	X	X	X						Annually
Norway	Net zero-emission building	X	X	X						Building lifetime
New Zealand	The Zero-Carbon Road Map for Aotearoa's Buildings	X	X	X	X	X		X	X[a]	Annually
South Africa	Net zero and net positive carbon buildings	X	X	X	X[b]	X[b]		X[b]		Annually
Sweden	NollCO2	X	X	X	n/c	n/c		X	X[c]	Building lifetime
	Local Roadmap Malmö	X	X	X					X[d]	Building lifetime
United Kingdom	Net zero carbon	X	X	X	X[b]	X[b]		X[b]		Annually
USA	LEED zero carbon	X	X	X	X	X		X		Annually
	Zero-carbon building	X	X	X	X	X		X	X[e]	Annually

X: Allowed option.

[a] Reforestation, carbon reduction programs in developing countries, carbon sequestration investments.

[b] On-site renewable generation is prioritised.

[c] Life cycle GHG emissions can be compensated by implementing energy efficiency measures in other existing buildings.

[d] Carbon capture and storage.

[e] Renewable energy projects, reforestation projects, and landfill gas-to-energy projects where the methane would otherwise be released to the atmosphere.

Figure 3.10: Compensation options adopted by buildings' frameworks [217]

Chapter 4

Application of an offsetting strategy to case studies in the building sector

During the design of a long-term offsetting strategy, the planner generally faces challenges and uncertainties regarding the identification of the most appropriate compensation method, the current and future costs of the different types of offsets, their availability, the number of offsets needed, and the proper timing of the acquisition. In order to address these concerns and provide guidance on how offsetting can be applied in the building sector, two case studies were conducted[1]:

- **Case A:** Analysis of offsetting costs and comparison of the embodied, operational, and total emissions between a refurbished building, a new building, and a baseline building, for the following cases:
  - ➢ A building functioning as an **office** building
  - ➢ A building functioning as a **residential** building
- **Case B:** Analysis of offsetting costs and comparison of the embodied, operational, and total emissions for a new industrial plant.

In **Chapter 2** were introduced Oxford's Principles for Net Zero Aligned Offsetting, which highlight the importance of shifting toward long-term removal offsets. In order to graphically illustrate this concept, Oxford developed a possible offsetting strategy until 2050, which was presented in **Figure 2.2** [35]. This figure was digitised to more precisely quantify the type of offsets required each year to compensate for a building's emissions. With the set of data obtained from the digitisation, three curves were adjusted: two fifth-degree polynomial and one linear curve, obtaining as a result **Figure 4.1**.

[1]Both case studies are based on real data provided by GET Consulting. The specific location and information of both projects is maintained anonymous for privacy reasons.

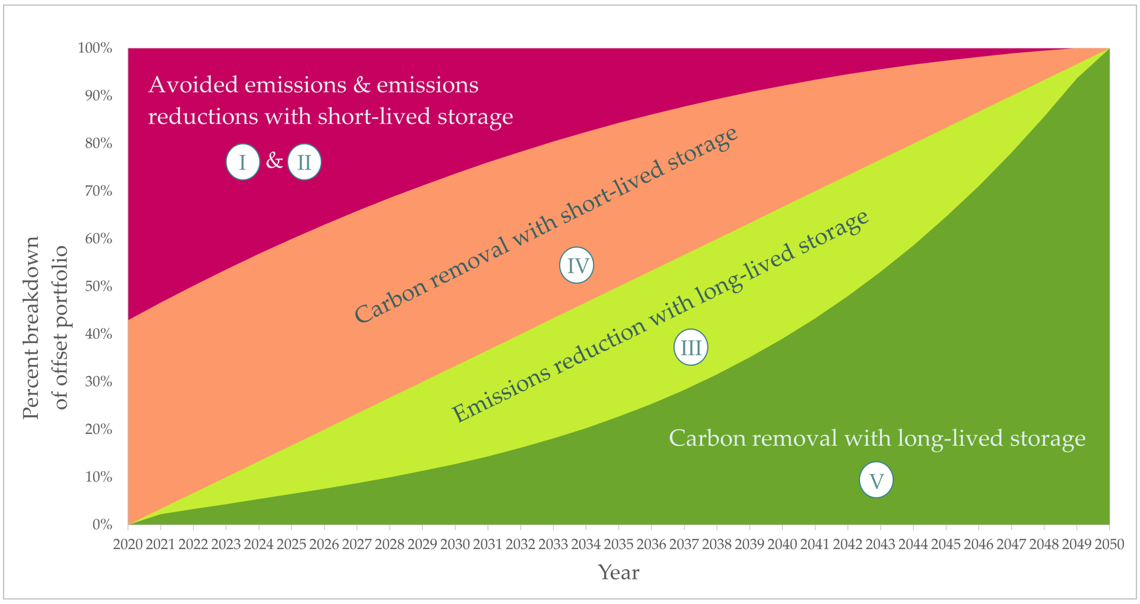


Figure 4.1: Example net zero aligned offsetting trajectory. Reproduced from Oxford's Principles for Net Zero Aligned Carbon Offsetting [35]

4.1 Case A: Comparison of emissions and offsetting approach for a refurbished, a new, and a baseline building

The present case study was performed on behalf of a landlord who desired to compare the CO_2 emissions associated with a refurbished building, a new building, and a baseline building. These results were obtained for office and residential uses. The aim of this study is to identify the least impactful scenario and present an offsetting solution to achieve a net zero carbon building. In addition, a forecast of costs for each scenario was performed, based on price projections for voluntary offsets and electricity.

4.1.1 Quantification of CO_2 emissions

A Whole Life Cycle Assessment (WLCA) was developed to quantify the emissions associated with each building case. According to the level of intervention conducted in the buildings, the whole life cycle carbon analysis was divided into two main scenarios:

- **Case A.1:** represents the building demolished and then rebuilt as a new construction
  - **Case A.1.a:** Office building
  - **Case A.1.b:** Residential building

- **Case A.2:** represents the building where energy efficiency upgrades and refurbishment interventions were proposed
  - **Case A.2.a:** Office building
  - **Case A.2.b:** Residential building

The baseline building, which is used as a reference, represents the operational carbon plus the carbon associated with any maintenance required until the end of the product's life cycle. Embodied carbon calculations were conducted for the four cases based on the data provided by the client. These results enable the comparison between the different scenarios and the identification of the interventions that directly impact the building's performance. The calculation of the operational impacts was performed considering only stage B6.1, "Building-related operational energy use, regulated". Stages B6.2, B6.3, B7, B8, and D were not included in this analysis. The building's life span considered is of 50 years, and the functional unit employed is embodied carbon of building per 1 m^2.

4.1.1.1 Assumptions – Databases and Carbon factors for Embodied Carbon

Databases:

Ecoinvent 3.8 database - SimaPro software (version 9.3.0.3)
Characterisation method CML-IA baseline (version 3.07)

A1-A3 stage assumptions:

The amount of materials for the Architectural part are based on assumptions and not on a specific bill of quantities. The calculation of MEP is also based on assumptions because the bill of quantities was not provided.

Heating pump: 1

Pumps: 16

DHW pump: 1

Hot water tank: 12

UTA (Air handling unit): 78

Elevators: 4

Amount of Heating pipework (m^2) - 2.5% of total floor area

Amount of Cooling pipework (m^2) - 2,5% of total floor area

Amount of DHW pipework (m^2) - 1% of total floor area

Amount of pipework insulation (m^3) - pipework area x 0,11mm thickness

Amount of supply ductwork (m^2) - 10% of total floor area

Amount of return ductwork (m^2) - 3% of total floor area

Amount of supply ductwork insulation (m^2) - 10% of total floor area

Amount of return ductwork insulation (m^2) - 3% of total floor area

Luminaires (LED) ratio - 6 W/m^2

Amount of cabling (m^2) - 2.5 m/m^2 of floor area

A4 stage assumptions:
Emission factor for transport has been extracted from SimaPro, and the following average travel distances considered:

Local materials: 100 km by road - Inert materials (e.g. concrete, stone, ceramic, etc.)

European materials: 500 km by road - any other materials

A5 stage assumptions:
Assumption: 4% of A1-A3 stage has been considered, based on LETI guide benchmark for commercial buildings [219].

B1-B5 stage assumptions:
B4 has been considered for reposition of materials and products with a service life inferior to the life span of the building considered (50 years).

Database with materials lifespan: IBO database used for Italian case studies (exported from CasaClima software).

C1-C4 stage assumptions:
C1: demolition of the building using dataset from Ecoinvent database.

C2: same assumptions as A4, considering local transport (100 km).

C3-C4: Ecoinvent 3.8 waste scenario per type of product.

4.1.1.2 Assumptions – Databases and Carbon factors for Operational Carbon

B6 stage assumptions:
The following emission factors have been considered, based on location **(Table 4.1)**:

	Unit	**Electricity 2023**	**Electricity 2050**	**Electricity 2073**
Italy	kg CO_2/kWh	0.283	0.110	0.110
PV panel	kg CO_2/kWh	0.070	0.070	0.070

Table 4.1: Emission factors considered for Stage B6 of the LCA

Emission factors from Italian Grid Mix from CRREM, considering the study period of 50 years 2023-2073 and the progressive decarbonisation of electricity national mix over time. Since CRREM provides emission factors only until 2050, from 2051 to 2073 these factors were considered constant, which would be a conservative approach. CRREM is a tool that enables portfolios to measure their carbon reduction performance to be aligned with the Paris Agreement [220].

PV emission factor: 0.070 kg CO_2e/kWh (Ecoinvent 3.8).

4.1.1.3 Results

The results obtained from the LCA are presented below. Total CO_2 emissions associated with a newly constructed building and a renovated building are presented in **Figures 4.2 and 4.3**. There is a reduction in the emissions associated with a renovated building with respect to a new construction for both uses, office (-27%) and residential (-28%).

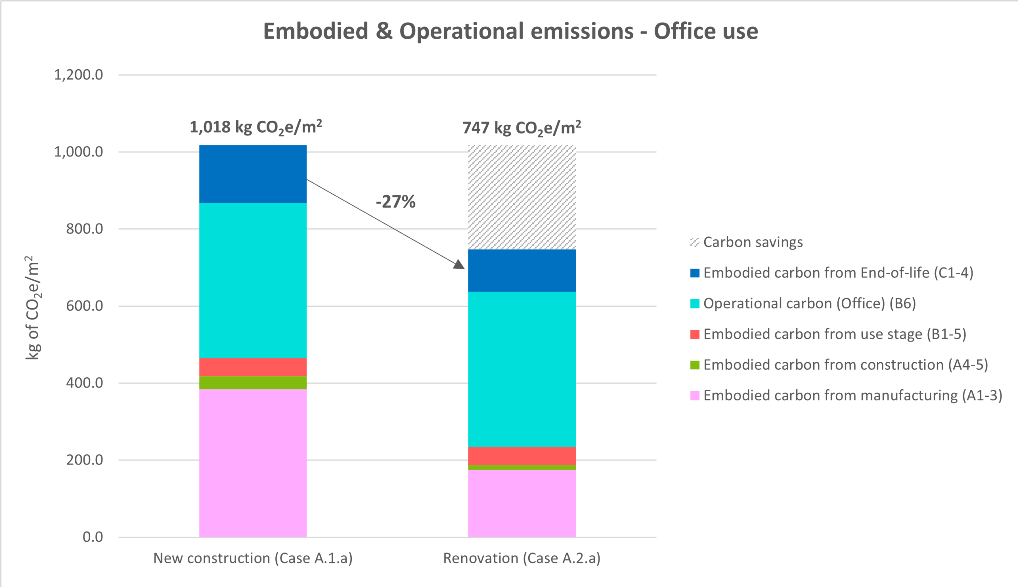


Figure 4.2: Comparison of emissions associated with a newly constructed building and those associated with a renovated building - Office use

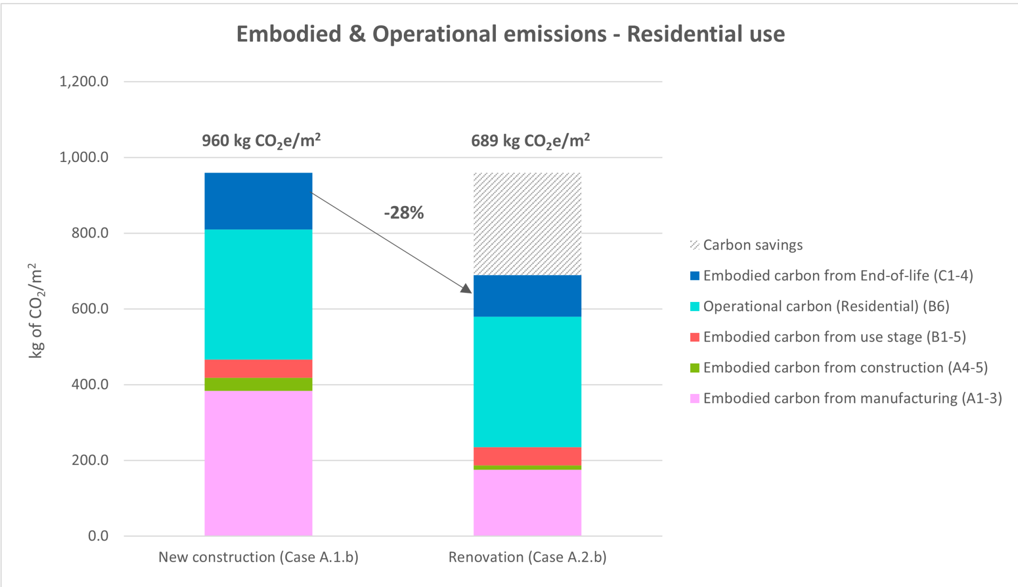
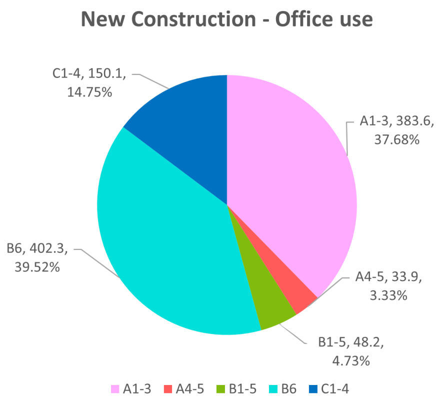


Figure 4.3: Comparison of emissions associated with a newly constructed building and those associated with a renovated building - Residential use

Figures 4.4 and 4.5 show a comparison of the total CO_2e emissions of a newly constructed office building with a new residential construction (case A.1.a and A.1.b, respectively). Values are in kg of CO_2e. The major contributor to the total emissions in the office scenario is operational energy use (B6), which is responsible for 40% of the emissions. For the residential scenario, the largest contributor is the product stage (A1-3), which accounts for 40% (residential) of the total carbon emissions. This phase includes raw material extraction, transportation to the plant, and manufacturing of the final product. In this case, the residential scenario has 6% less emissions associated with respect to the office scenario.



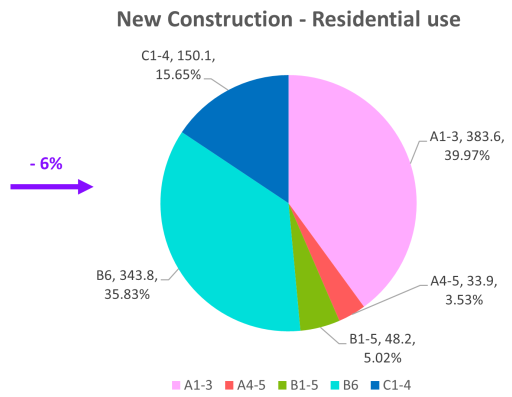


Figure 4.4: Embodied and operational emissions associated with a new construction (Office use). Total emissions in 50 years: 1,018 kg CO_2e/m^2

Figure 4.5: Embodied and operational emissions associated with a new construction (Residential use). Total emissions in 50 years: 960 kg CO_2e/m^2

Figures 4.6 and 4.7 present the same comparison for the case of a renovated building (case A.2.a and A.2.b). Values are provided in kg of CO_2e. In this case, the largest contributor to the total emissions is operational energy use for both scenarios, accounting for 54% (office) and 50% (residential) of the total emissions. As for the case of a new construction, the residential scenario has less emissions associated with respect to the office scenario, more specifically of 8%.

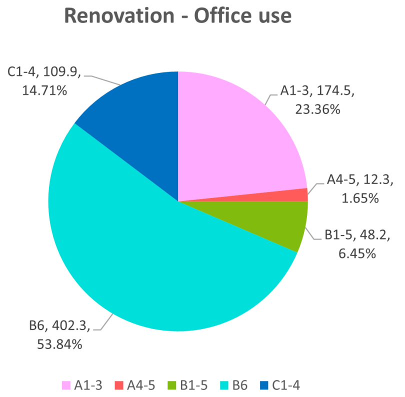


Figure 4.6: Embodied and operational emissions associated with a refurbished building (Office use). Total emissions in 50 years: 747 kg CO_2e/m^2

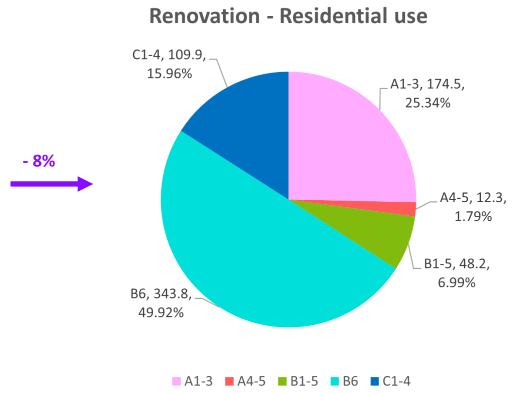


Figure 4.7: Embodied and operational emissions associated with a refurbished building (Residential use). Total emissions in 50 years: 689 kg CO_2e/m^2

Figure 4.8 compares the accumulated total CO_2e emissions (embodied carbon + operational carbon) of the newly constructed and refurbished building scenarios with a baseline building over a lifetime of 50 years (Office use). The embodied carbon will be offset by the operational carbon associated to the improvement in the year 2037. It should be noted that the embodied carbon for the renovation scenario does not account for all the building embodied carbon but only for the refurbishment carried out. **Figure 4.9** illustrates the accumulated total CO_2e emissions for the scenario of a residential building. As for the case of the office scenario, the embodied carbon will be offset by the operational carbon associated to the improvement in the year 2037.

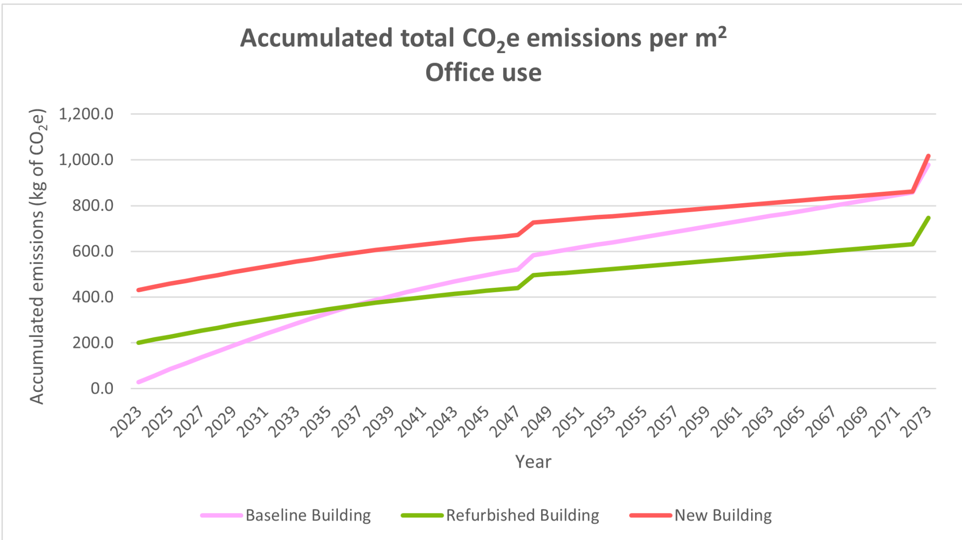


Figure 4.8: Accumulated total CO_2e emissions for the case of a new construction, a renovated building (Office use)

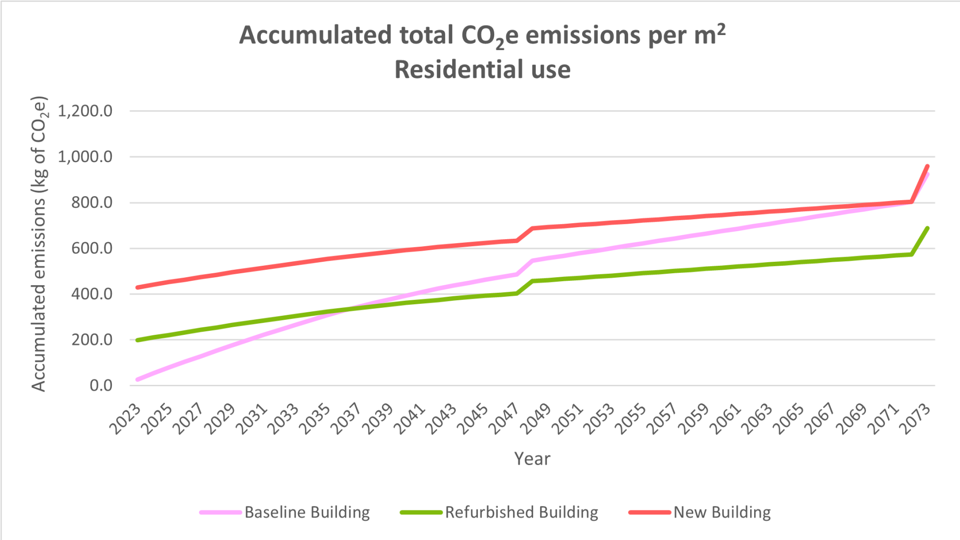


Figure 4.9: Accumulated total CO_2e emissions for the case of a new construction, a renovated building, and a baseline building (Residential use)

With the goal of illustrating how operational emissions evolve over the years, in **Figures 4.10, and 4.11** are presented the annual operational emissions for the office and residential scenarios, respectively. The study was originally performed considering for the buildings proposed the installation of the minimum values of renewable energy required by the Italian Legislative Decree n. 199 of 8 December 2021, which transposes Directive (EU) 2018/2001 of the European Parliament (RED II). In the scenario of the Baseline Building, instead, the total energy requirement is supplied by the Italian grid mix. The rest of the energy requirement is covered using the Italian grid mix. In **Section 4.1.4**, the same analysis will be performed but increasing the amount of solar PV installed.

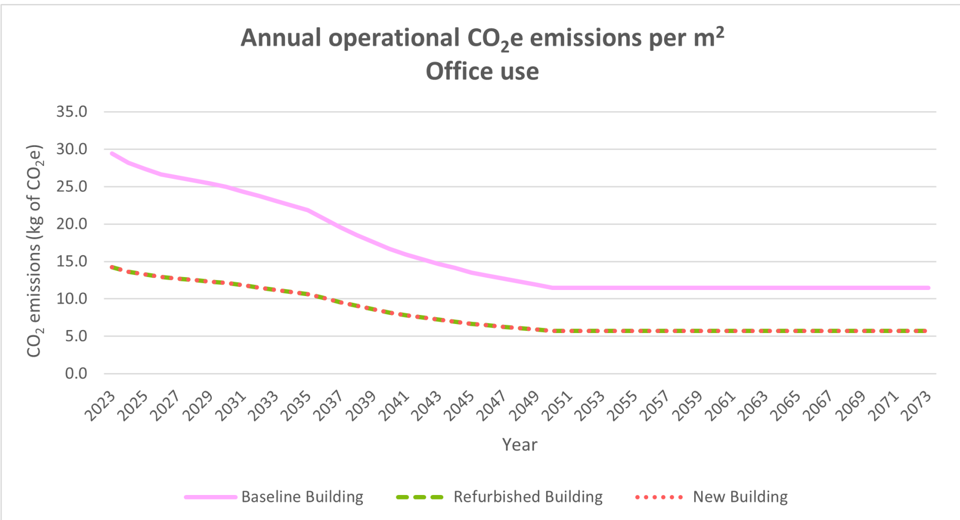


Figure 4.10: Annual operational CO_2e emissions for the case of a new construction, a renovated building, and a baseline building (Office use)

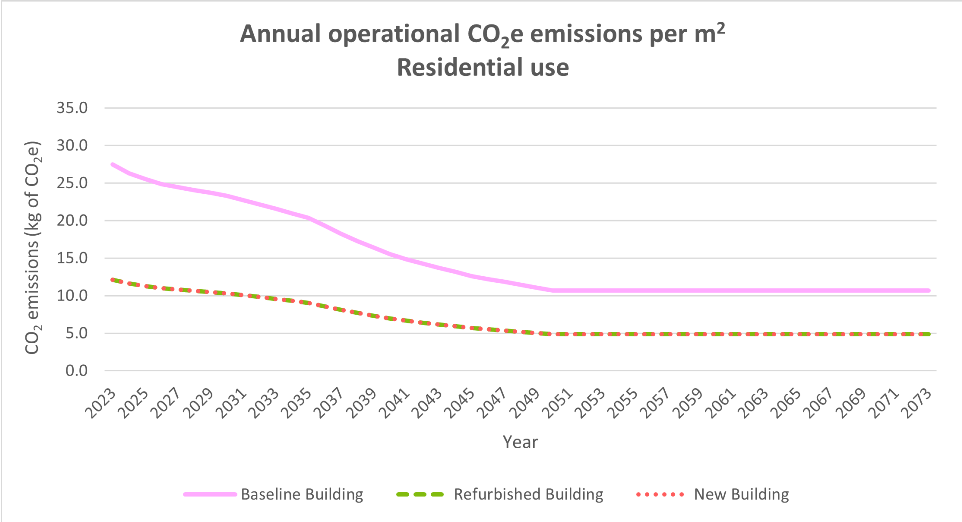


Figure 4.11: Annual operational CO_2e emissions for the case of a new construction, a renovated building, and a baseline building (Residential scenario)

Annual embodied CO_2e emissions for each case are presented in **Figure 4.12**. The embodied emissions are the same for both building uses (office and residential).

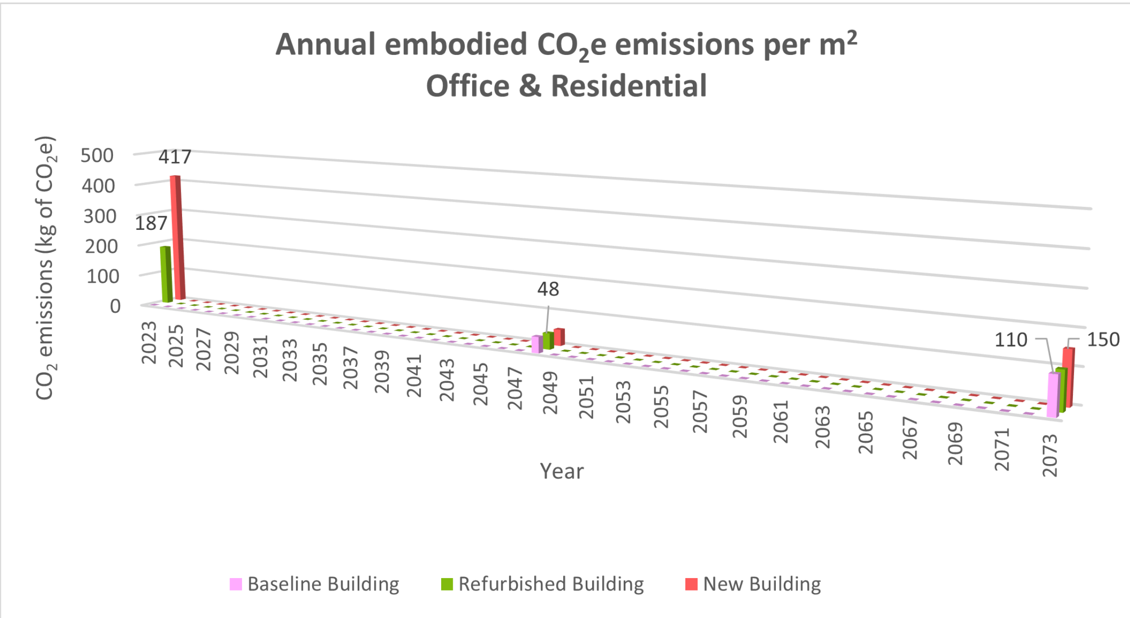


Figure 4.12: Annual embodied CO_2e emissions for the case of a new construction, a renovated building, and a baseline building

A further comparison of the total embodied emissions between a new construction and a renovation is shown in **Figures 4.13 and 4.14**. Total embodied emissions are reduced by 44% in the case of a renovation with respect to a newly constructed building.

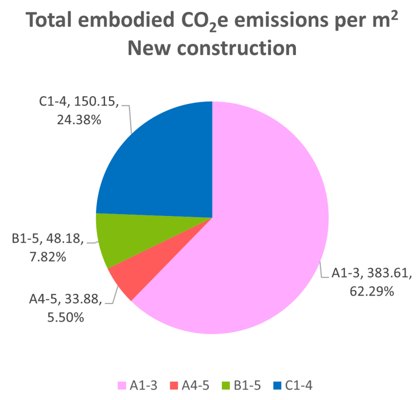


Figure 4.13: Total embodied CO_2e emissions for the case of a new construction. Total embodied emissions in 50 years: 616 kg CO_2e/m^2

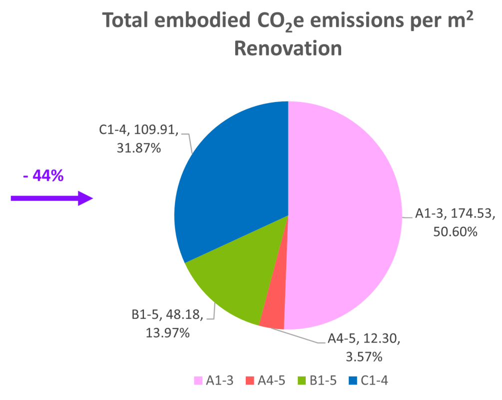


Figure 4.14: Total embodied CO_2e emissions for the case of a renovated building. Total embodied emissions in 50 years: 345 kg CO_2e/m^2

4.1.1.4 Conclusions

Since there is a significant impact reduction thanks to the materials kept from the existing building, the best decision in terms of environmental impacts would be to refurbish a building instead of developing a new construction.

Beyond the impact reduction achieved, the following strategies might contribute to lower the carbon impact:

- The selection of low-carbon materials instead of standard construction materials, such as bio-based materials, metals with high recycled content, or concrete with cement substitutions, would lower the embodied carbon of the interventions.
- From a whole life cycle perspective, it is worth considering circular strategies, such as removable and reusable materials or solutions to transform waste into future resources, or flexible distribution to avoid frequent refurbishments.
- It is also recommended a circular approach in the refurbishment, searching for opportunities to reuse dismantled materials within the building, such as steel beams, tiles, crushed concrete, etc.

4.1.2 Offsets required to achieve Net Zero Carbon

4.1.2.1 Office use

Based on the operational and embodied emissions provided in the previous section, the amount of offsets required to achieve carbon neutrality following the offset's trajectory suggested by Oxford **(Figure 4.1)** is presented in **Figures 4.15 to 4.20**.

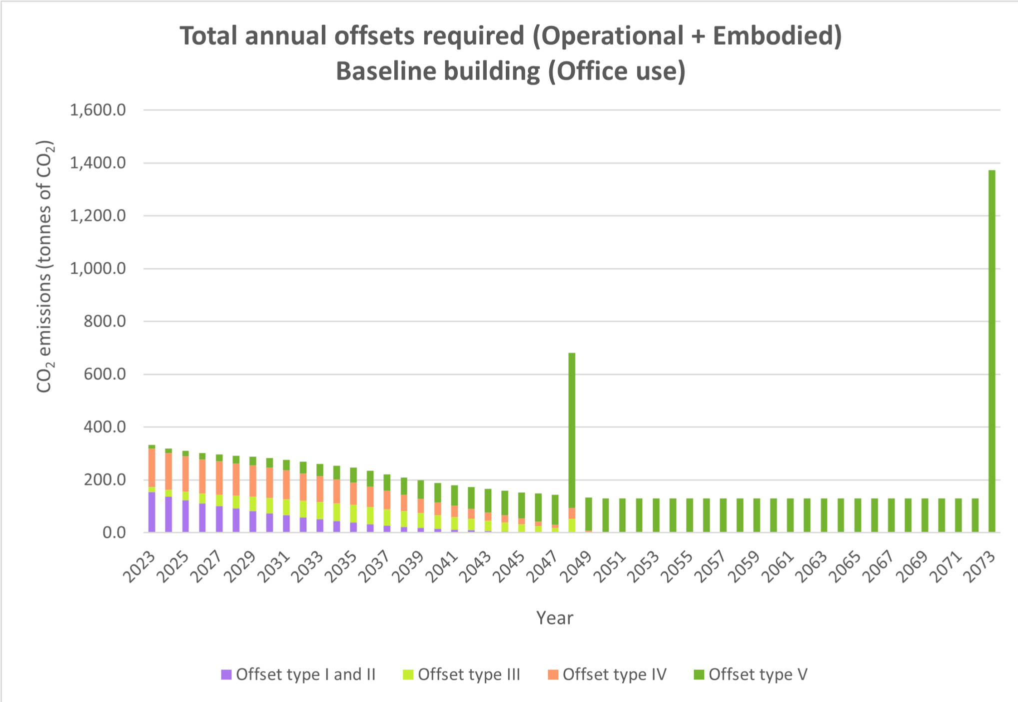


Figure 4.15: Annual offsets required to achieve carbon neutrality following Oxford's offsetting trajectory - Baseline building, office use

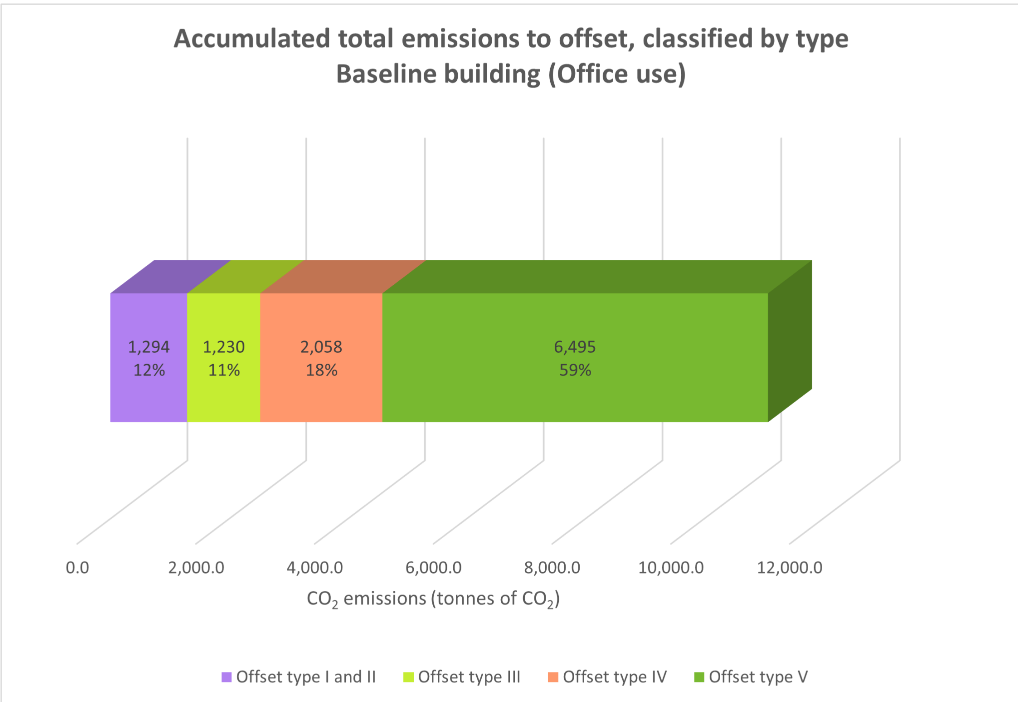


Figure 4.16: Accumulated total emissions to offset according to Oxford's classification of offsets - Baseline building, office use

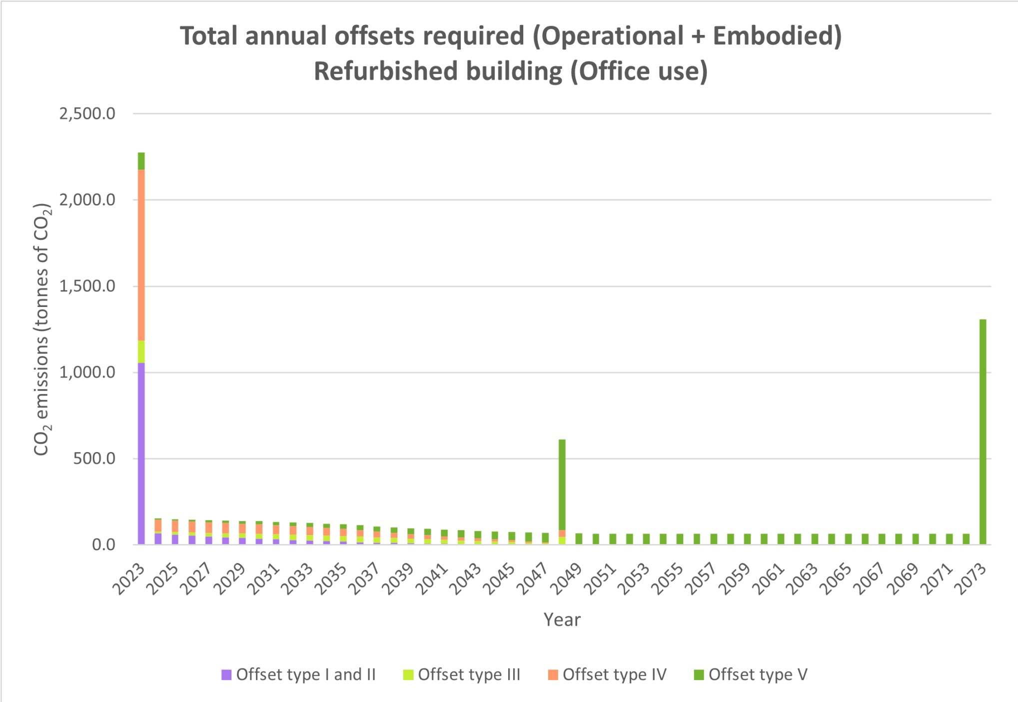


Figure 4.17: Annual offsets required to achieve carbon neutrality following Oxford's offsetting trajectory - Refurbished building, office use

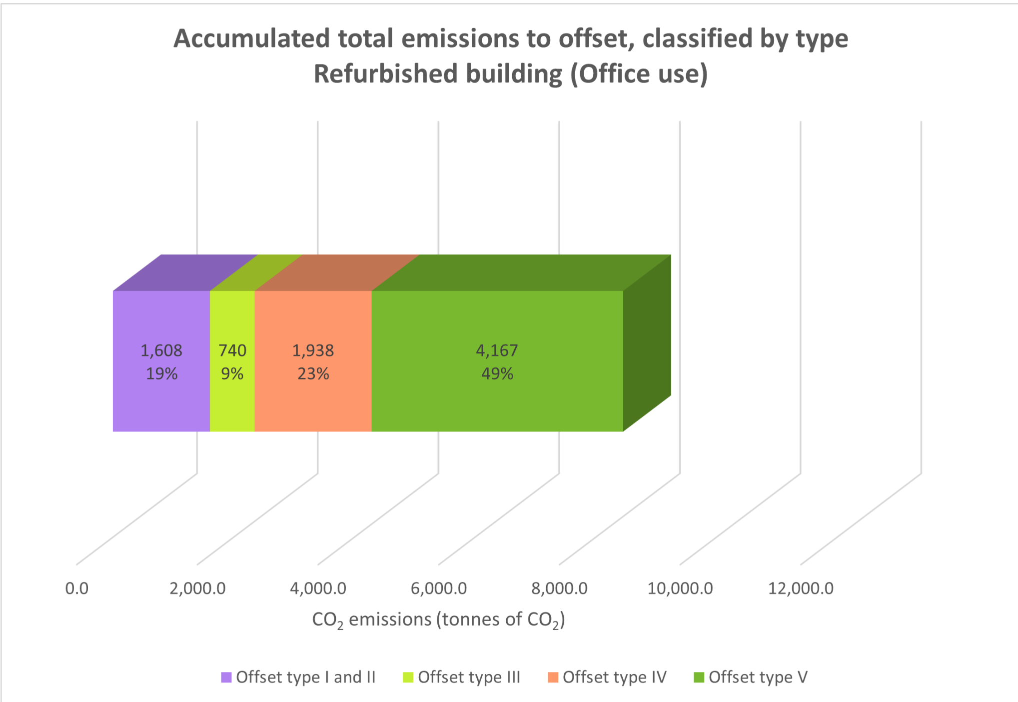


Figure 4.18: Accumulated total emissions to offset according to Oxford's classification of offsets - Refurbished building, office use

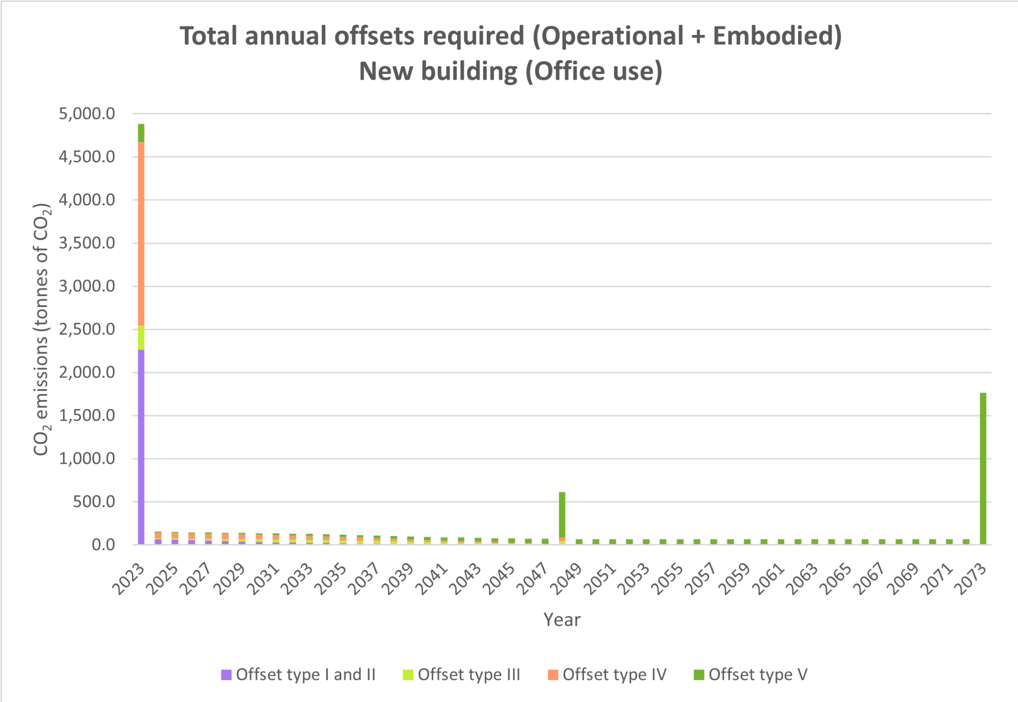


Figure 4.19: Annual offsets required to achieve carbon neutrality following Oxford's offsetting trajectory - New building, office use

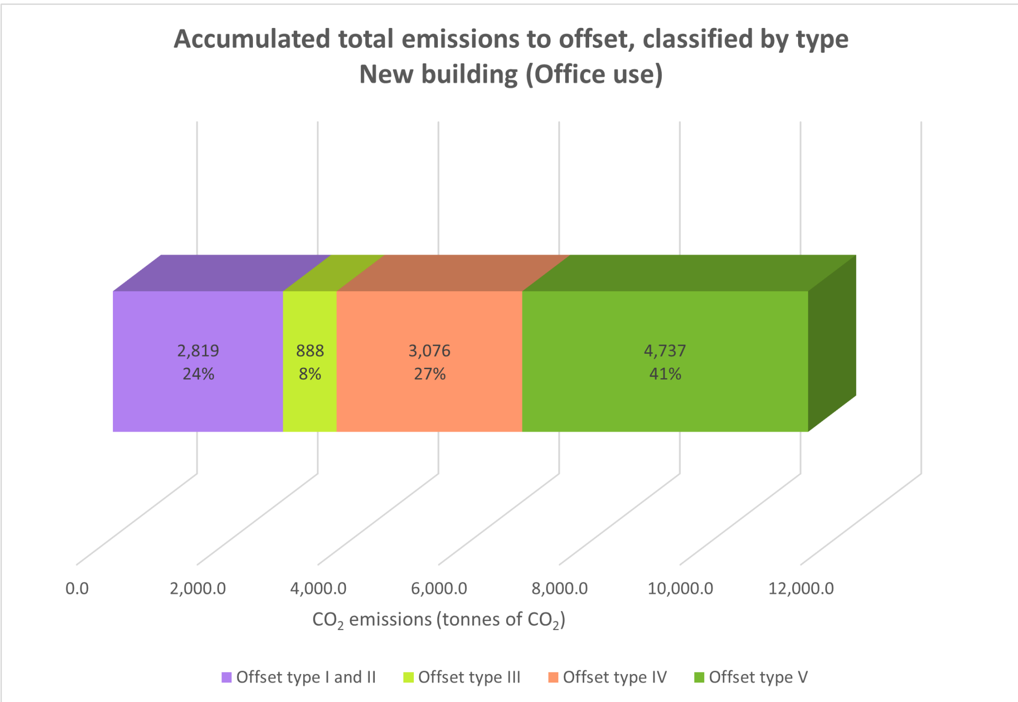


Figure 4.20: Accumulated total emissions to offset according to Oxford's classification of offsets - New building, office use

The new building scenario, with a total amount of 11,519.6 tonnes of CO_2, requires the largest amount of offsets to achieve carbon neutrality, followed by the baseline building scenario with 11,076.6 tCO_2 and by the renovation with 8,453.8 tCO_2[2]. For the new building and renovation scenarios, offsets are mostly required to compensate for embodied emissions at the time of construction, while for the case of a baseline building, the largest amount corresponds to the embodied emissions at the end-of-life. As a result, the distribution of the annual offsets required in the scenario of a baseline building is notably different from the other two scenarios: in the case of the baseline building, offsets are more equally distributed over the building's life-span, while for the other two scenarios, the amount of offsets required is concentrated in the years 2023 (construction), 2048 (renovation of MEP components), and 2073 (end-of-life).

The analysis of the annual distribution is relevant for this study because it determines the timing of the offsets' acquisition, and as a consequence, also the percentage of each offset type needed to be in line with Oxford's offsetting principles. Since the availability and prices are highly dependent on the type of offset, the acquisition strategy and the costs related with the offsetting phase will also be influenced by this distribution. A cost projection will be provided in **Section 4.1.3** for each scenario.

Carbon removal offsets with long-lived storage (type V), which are expected to cover 100% of the offsetting portfolio by 2050, are still under development and their prices are therefore much higher. Among the three scenarios, the baseline building is expected to need the largest amount of type V offsets to compensate for its CO_2e emissions, and as a consequence, it is also more vulnerable to be affected by the uncertainty of prices of this type of offsets, making it more difficult to project future costs in a reliable way.

4.1.2.2 Residential use

Figures 4.21 to 4.26 present the offsets required to achieve carbon neutrality for the case of a residential building. Since the embodied emissions are the same for the office and residential scenarios, only operational emissions vary.

[2]It is important to highlight that the analyses presented before were performed considering the amount of CO_2/m^2, while the results shown in this and the following sections correspond to total values, considering an area of 11,317 m^2.

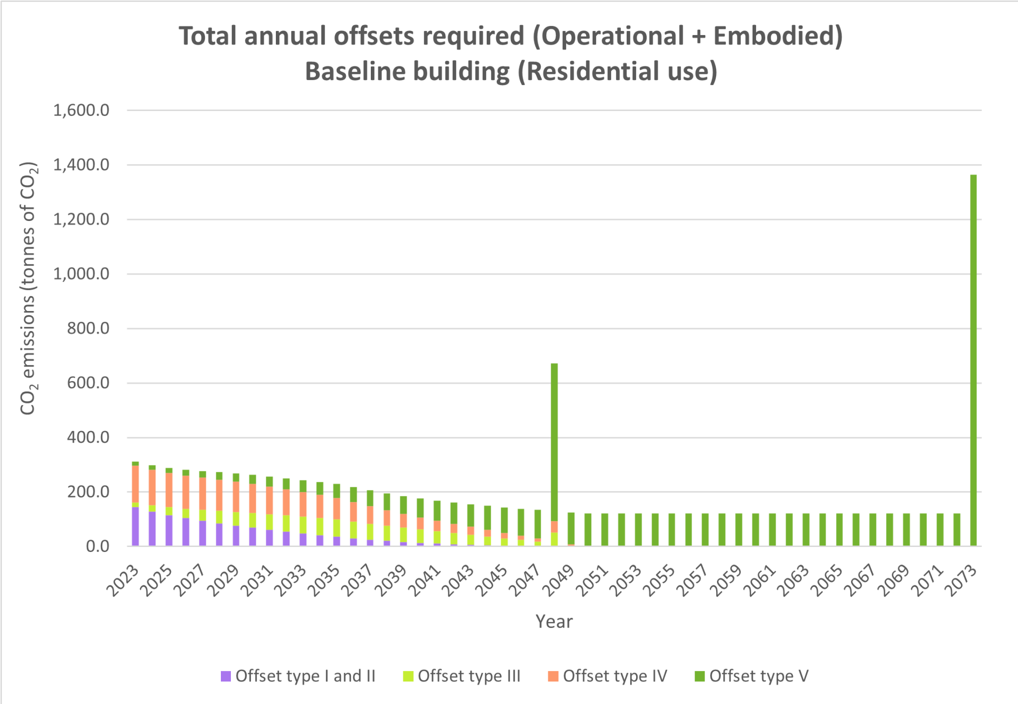


Figure 4.21: Annual offsets required to achieve carbon neutrality following Oxford's offsetting trajectory - Baseline building, residential use

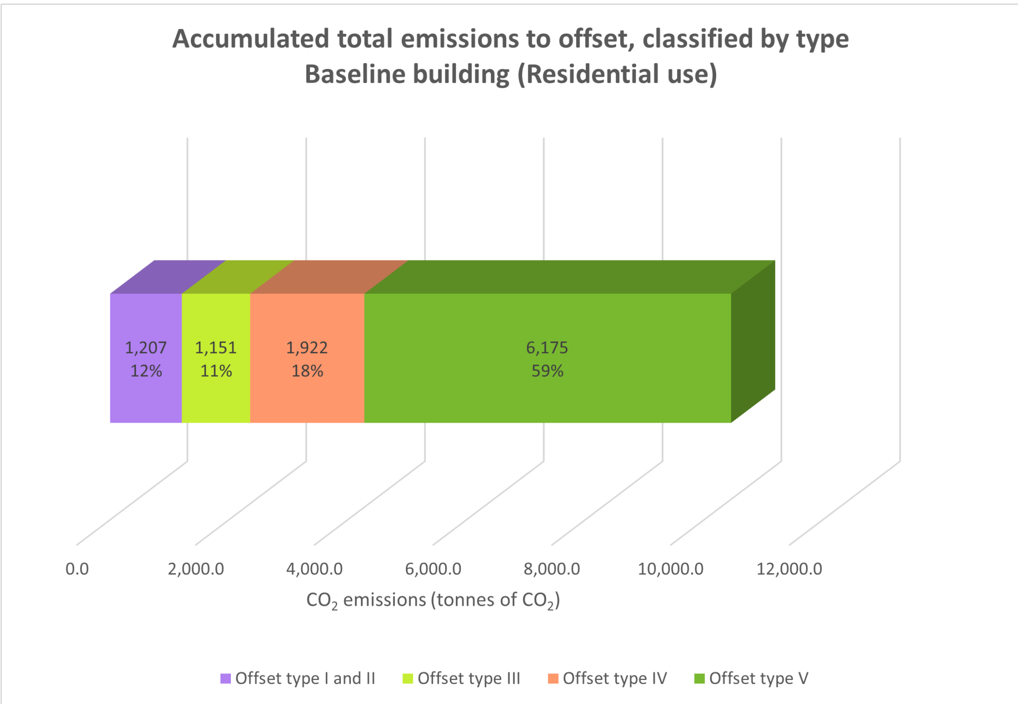


Figure 4.22: Accumulated total emissions to offset according to Oxford's classification of offsets - Baseline building, residential use

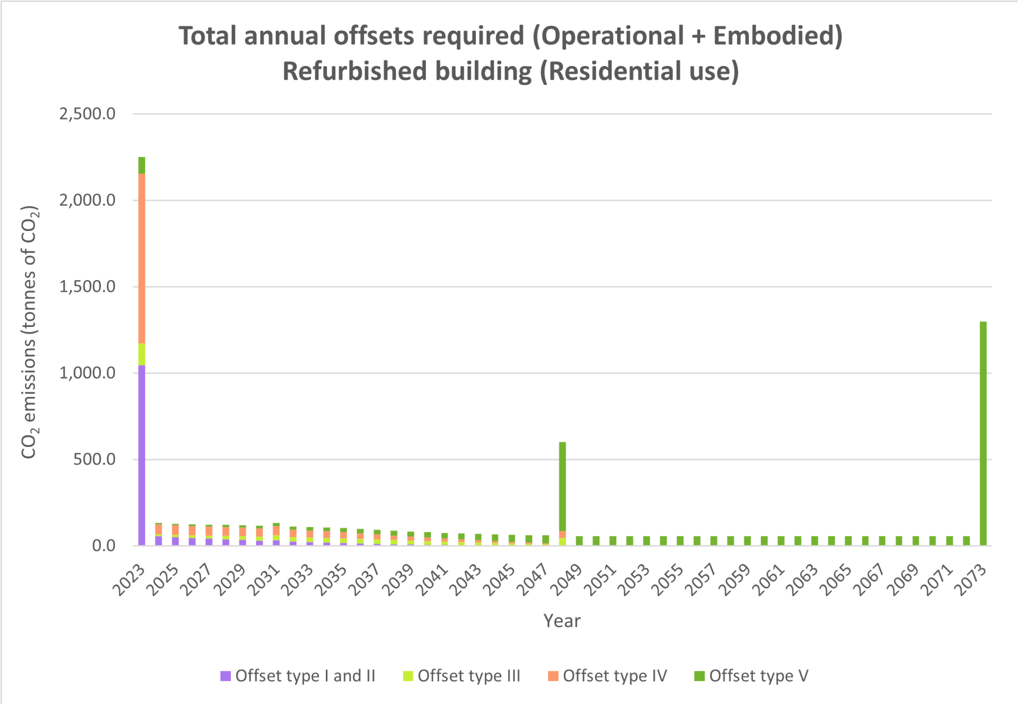


Figure 4.23: Annual offsets required to achieve carbon neutrality following Oxford's offsetting trajectory - Refurbished building, residential use

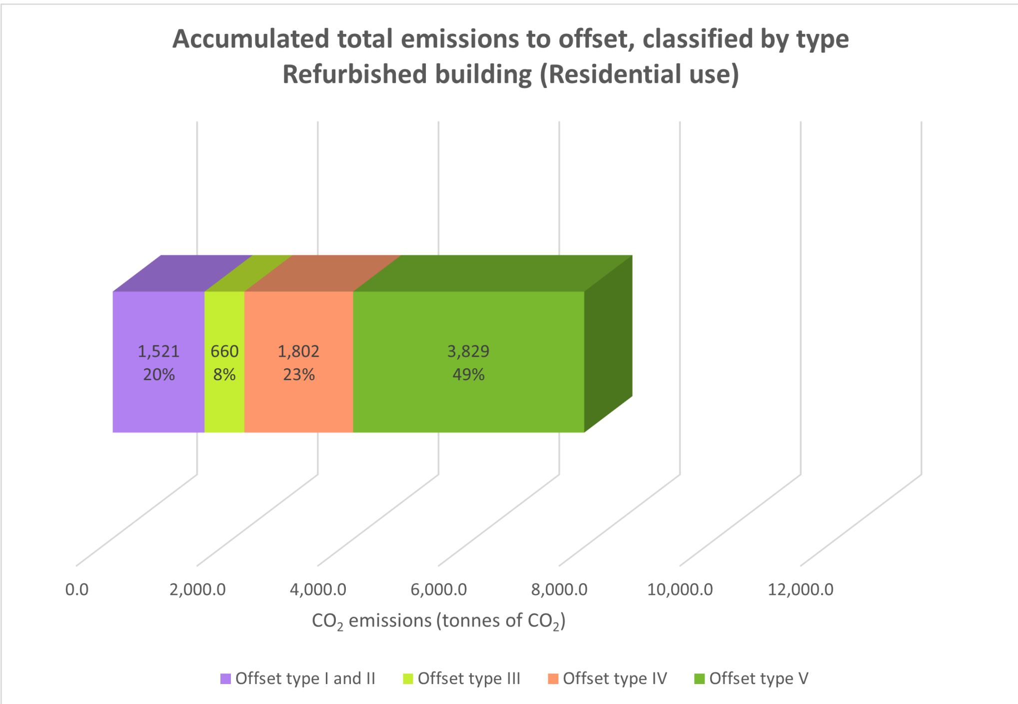


Figure 4.24: Accumulated total emissions to offset according to Oxford's classification of offsets - Refurbished building, residential use

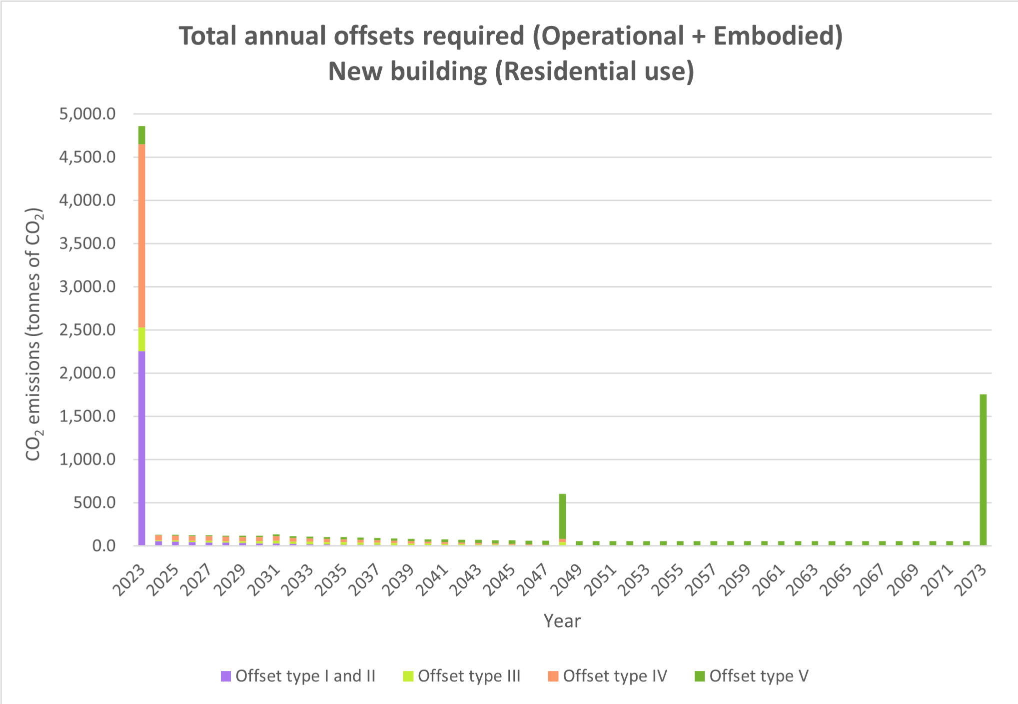


Figure 4.25: Annual offsets required to achieve carbon neutrality following Oxford's offsetting trajectory - New building, residential use

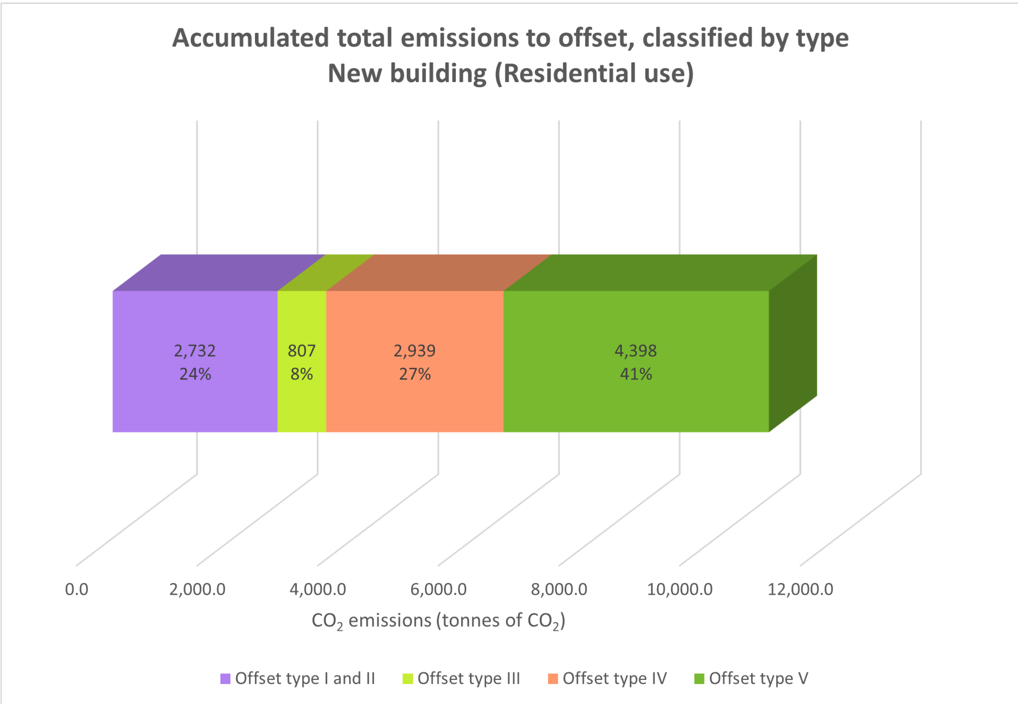


Figure 4.26: Accumulated total emissions to offset according to Oxford's classification of offsets - New building, residential use

For the residential scenario, the new building requires the most offsets, followed by the baseline and the renovated building, just as for the office scenario. **Table 4.2** provides a comparison of the results obtained for both buildings' uses.

Building case	**Unit**	**Office use**	**Residential use**
Baseline	tCO_2e	11,076.6	10,455.6 (-6%)
Renovation	tCO_2e	8,453.8	7,811.3 (-8%)
New construction	tCO_2e	11,519.6	10,877.1 (-6%)

Table 4.2: Comparison of total annual offsets required for the office and residential uses

4.1.3 Cost projections

In order to compare the three different options (for the landlord to rent a Baseline Building (BB), a Renovated Building (RB), or a New Building (NB)) from an economic point of view, three different cost projections were performed, adopting Price Scenarios I, II and III as basis, which were presented in **Section 2.4.1**. **Figures 4.27, 4.28, and 4.29** present the results for the office use. Solid lines represent average values for scenario I and II, and median values scenario III. Dashed and dotted lines illustrate maximum and minimum values, respectively.

Figure 4.27: Projection of accumulated costs for Price Scenario I (Office use)

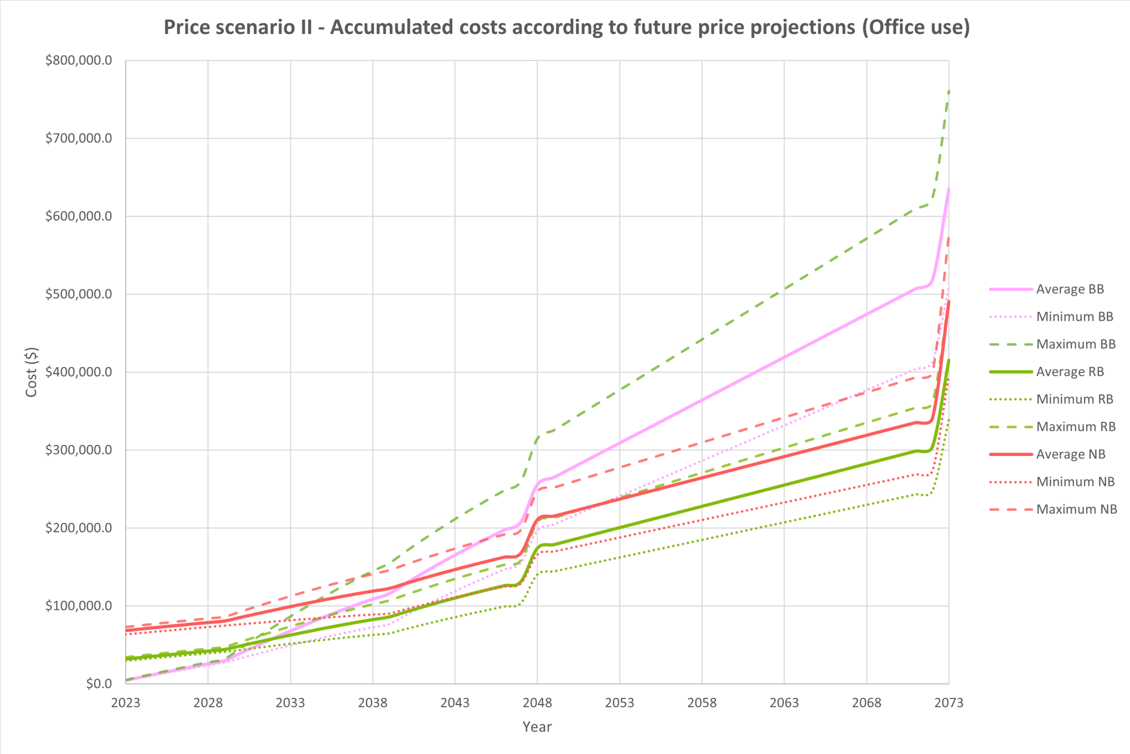


Figure 4.28: Projection of accumulated costs for Price Scenario II (Office use)

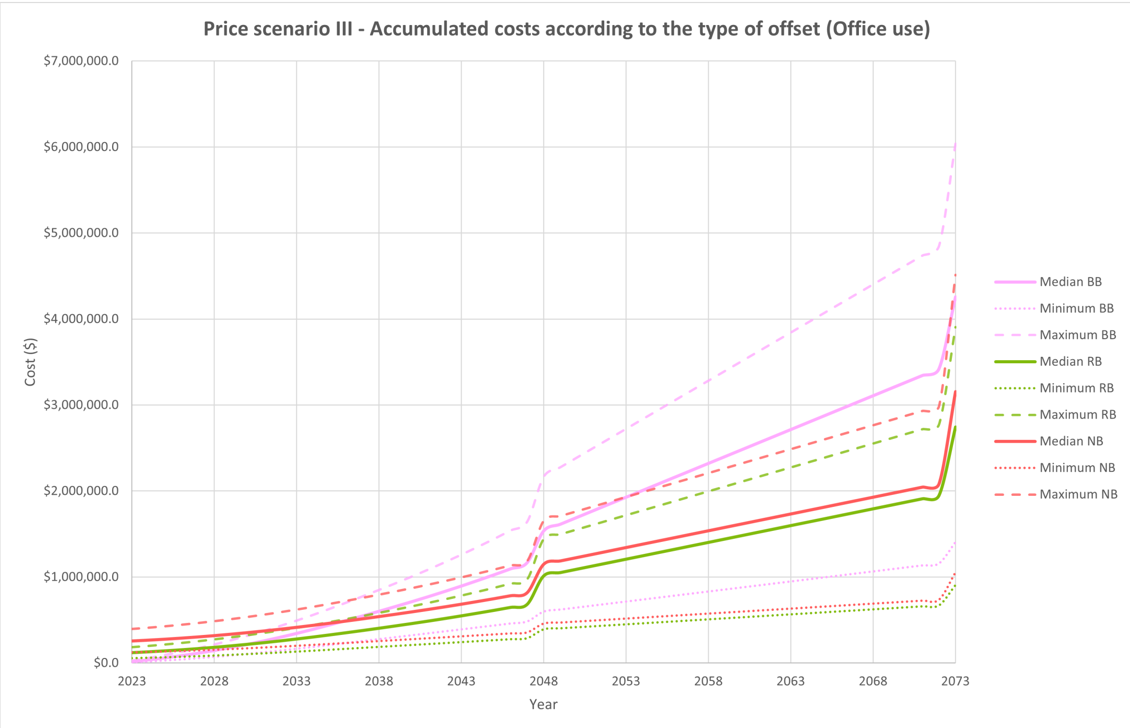


Figure 4.29: Projection of accumulated costs for Price Scenario III (Office use)

Figure 4.27 shows the total accumulated costs projected for Price Scenario I. This scenario has been proposed to contrast the total costs of an offsetting strategy performed acquiring low-quality offsets with a strategy that intends to follow Oxford's offsetting principles. **Figure 4.28** considers prices projected for the four different periods presented before, which coincide with the peaks that can be observed in 2030, 2040, and 2050[3]. **Figure 4.29**, instead, presents a projection of costs adopting current median values for each type of offset. In this case, the percentage of each type of offset adopted has been determined by following the net zero aligned offsetting trajectory shown in **Figure 4.1**. From 2050, it has been considered that 100% of the offsets acquired are of type V. Since a projection of future prices for each type of offset is not available, this scenario considers current costs to be the same also in the future, but it is very unlikely that current prices remain constant over the years.

Figures 4.30, 4.31 and 4.32 illustrate the results obtained for the case of a building with residential use.

Figure 4.30: Projection of accumulated costs for Price Scenario I (Residential use)

[3]The peak in year 2050 may be confused with the peak in 2048, which is not caused by an increase of prices but it is due to the renovation of MEP components

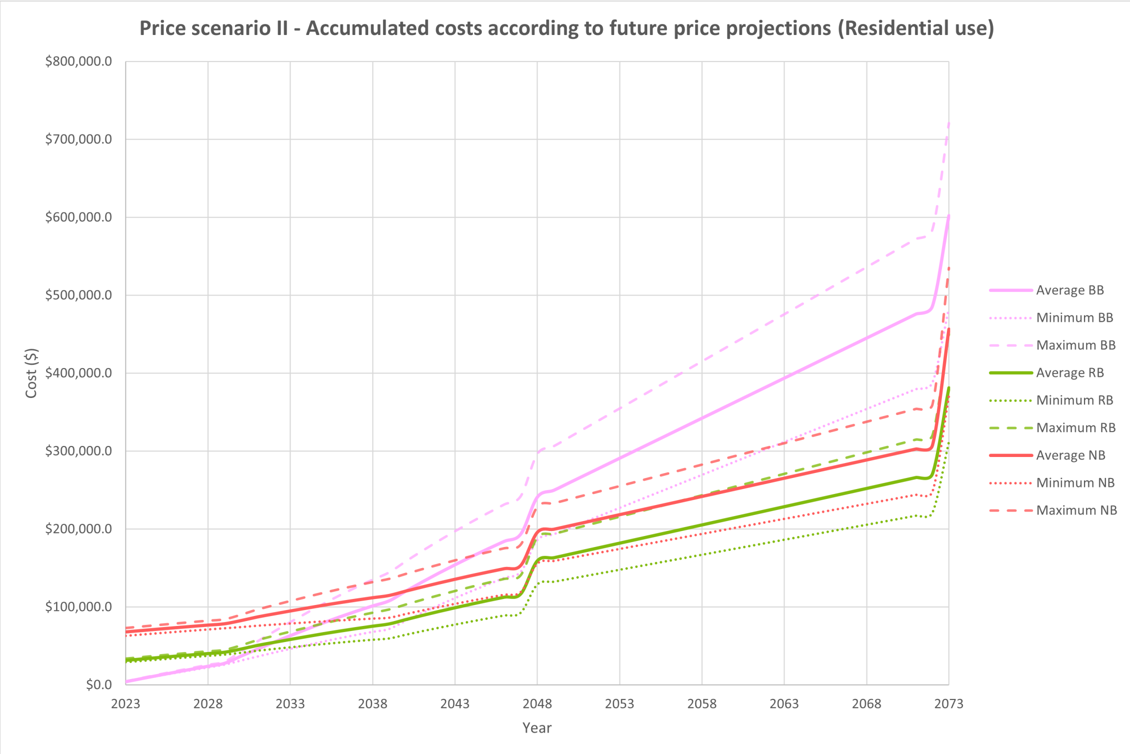


Figure 4.31: Projection of accumulated costs for Price Scenario II (Residential use)

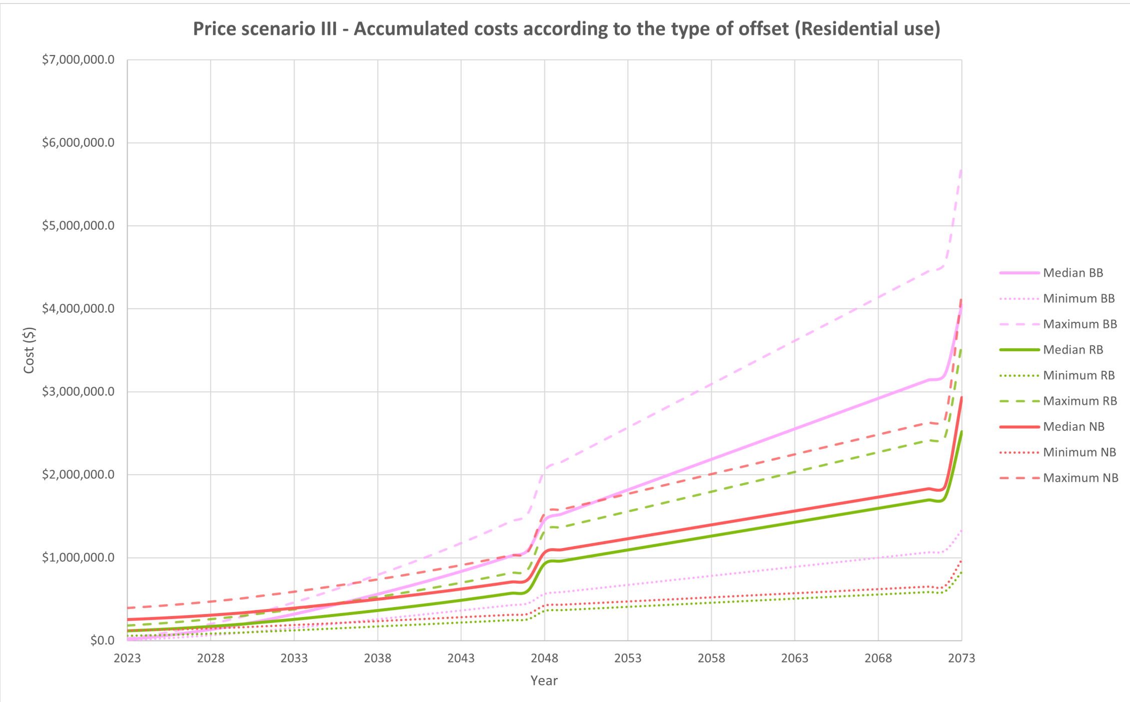


Figure 4.32: Projection of accumulated costs for Price Scenario III (Residential use)

4.1.3.1 Assumptions, considerations and limitations

- It is important to note that Scenario I and III consider current average prices constant over the years, but it is expected that the average values increase and that the price of certain project types decrease, mostly type V offsets (carbon removals with long-lived storage).
- Scenario I and II consider the average offset price without considering the average cost of each project, which makes it difficult to compare with a scenario that follows Oxford's offsetting principles.

4.1.3.2 Conclusions

Due to a high uncertainty of future offset prices, it is not possible to project future offsetting costs in a reliable way. However, these projections are useful to illustrate the huge contrast in prices according to the offsets used. For Price Scenario I, accumulated average costs are extremely low, discouraging emitters from reducing emissions instead of compensating them. Furthermore, offsets with very low prices in most cases do not meet the high-quality criteria explained in **Section 1.3**. For Price Scenario II, cumulative average costs are more credible and would not discourage emitters to reduce their own emissions instead of compensating them. Based on Price Scenario III, cost projections are the highest, mainly due to high current median costs of carbon removals with long-lived storage (type V offsets). However, it is expected that costs of type V offsets decrease in the following years, which would reduce in a considerable way future offsetting costs. **Tables 4.3 and 4.4** provide a summary of costs for the office and residential scenarios, respectively.

	Projection of accumulated costs - Office use								
	Scenario I			**Scenario II**			**Scenario III**		
	Avg	**Min**	**Max**	**Avg**	**Min**	**Max**	**Median**	**Min**	**Max**
Baseline Building	$44,319	$33,239	$55,399	$635,136 (+1,333%)	$509,558	$760,714	$4.258 M (+9,509%)	$1.404 M	$6.040 M
Refurbished Building	$33,826	$25,370	$42,283	$415,586 (+1,129%)	$339,470	$491,703	$2.742 M (+8,009%)	$904,938	$3.907 M
New Building	$46,090	$34,567	$57,612	$490,842 (+965%)	$396,929	$576,400	$3.156 M (+6,748%)	$1.052 M	$4.512 M

Table 4.3: Summary table of cost projections for Price Scenarios I, II & III (Office use). The percentages added to the Average and Median columns of scenario II and III, respectively, refer to the increase in percentage with respect to scenario I

	Projection of accumulated costs - Residential use								
	Scenario I			**Scenario II**			**Scenario III**		
	Avg	**Min**	**Max**	**Avg**	**Min**	**Max**	**Median**	**Min**	**Max**
Baseline Building	$41,835	$31,376	$52,294	$602,294 (+1,340%)	$483,500	$721,089	$4.043 M (+9,566%)	$1.331 M	$5.736 M
Refurbished Building	$31,257	$23,443	$39,071	$381,262 (+1,120%)	$312,083	$450,441	$2.516 M (+7,953%)	$828,681	$3.586 M
New Building	$43,520	$32,640	$54,400	$456,517 (+949%)	$370,629	$535,138	$2.930 M (+6,633%)	$976,511	$4.192 M

Table 4.4: Summary table of cost projections for Price Scenarios I, II & III (Residential use). The percentages added to the Average and Median columns of scenario II and III, respectively, refer to the increase in percentage with respect to scenario I

The main conclusions of this analysis are summarised below:

- For the three scenarios projected, the case of a refurbished building has the lowest offsetting costs.
- Due to the high uncertainty related to future offset prices, it is recommended to reduce the reliance on offsetting to the minimum possible extent. **Section 4.1.4** presents the analysis of a scenario in which the installation of PV is increased with respect to the minimum required.

4.1.4 Increase in the number of PV panels

While past analyses considered only the minimum required amount of PV, this section hypothesises a scenario in which the total amount of solar panels installed is increased. The objective of this analysis is to evaluate the decrease in operational emissions of the energy consumed from the electricity grid and assess the costs related to this reduction. Since an increase in the amount of solar PV panels would have an impact on total costs, in this analysis are included:

- Cost of offsets required
- Cost of the solar panels (for the refurbished and new building scenarios)
- Cost of the electricity acquired from the grid
- Revenue obtained by the electricity surplus sold to the grid (for the refurbished and new building scenarios)

The following values have been considered as a reference:

- **Autoconsumption:** Since storage systems have not been included, it is hypothesised that only 60% of the energy produced will be consumed by the building[4]. The remaining amount of energy needed will be purchased from the grid, and the surplus energy produced will be sold to the grid.
- **Electricity price:** The cost of the electricity acquired from the grid has been estimated based on Energy Brainpool's average baseload price projection for European countries **(Figure 4.33)**. Due to the current price instabilities, from 2023 to 2025, prices have been adopted from the "Tensions" scenario, while from 2026 the "Central" scenario has been considered. From 2060, the last value has been adopted as constant until 2073. These values were converted to the US Dollar currency using the current conversion (1 US Dollar= 1.08 Euro).
- **Price of electricity surplus sold to the grid:** The GSE pays a variable rate for all the energy that the photovoltaic system feeds into the grid and then re-powers, but it was hypothesised a value equal to 68% of the electricity price, approximated on the basis of current percentages.

[4]This value was approximated from the autoconsumption of a similar case study

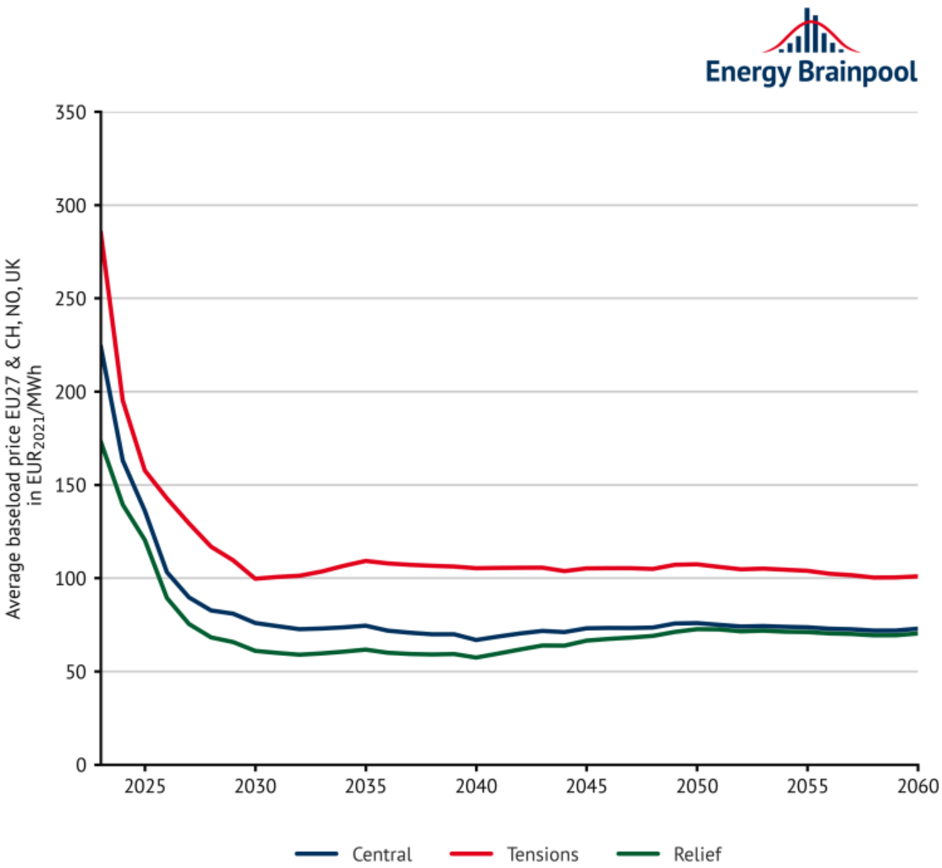


Figure 4.33: Projection of average baseload power price in EUR_{2020}/MWh (Source: Energy Brainpool, 2022) [221]

- **Cost of PV panels:** The current average solar panel cost of a system with a size of 6 kW in Italy is around $15,660 [222]. This value has been adopted to estimate the total cost of the solar PV installation.

In this analysis, two scenarios will be assessed:

➢ **PV Scenario I:** The photovoltaic system is designed to produce the amount of electricity required. The energy surplus and the energy requirements not covered by the PV system will be balanced with the grid network.

- **Office use:**

  Total electricity requirement: 598,702 kWh/year
  Total electricity produced by solar PV: 605,250 kWh/year
  Total energy auto-consumed: 363,150 kWh/year
  Total energy surplus sold to the grid: 242,100 kWh/year
  Energy acquired from the electricity grid: 235,552 kWh/year
  N° of PV panels of 400 V: 1,125
  Total area covered by the panels: 2,331.8 m^2

- **Residential use:**

  Total electricity requirement: 514,753 kWh/year
  Total electricity produced by solar PV: 516,480 kWh/year
  Total energy auto-consumed: 309,888 kWh/year
  Total energy surplus sold to the grid: 206,592 kWh/year
  Energy acquired from the electricity grid: 204,865 kWh/year
  N° of PV panels of 400 V: 960
  Total area covered by the panels: 1,989.8 m^2

➢ **PV Scenario II:** The photovoltaic system is designed to produce a third more than the energy required. The energy surplus and the energy requirements not covered by the PV system will be balanced with the grid network.

- **Office use:**

  Total electricity requirement: 598,702 kWh/year
  Total electricity produced by solar PV: 807,000 kWh/year
  Total energy auto-consumed: 484,200 kWh/year
  Total energy surplus sold to the grid: 322,800 kWh/year
  Energy acquired from the electricity grid: 114,502 kWh/year
  N° of PV panels of 400 V: 1,500
  Total area covered by the panels: 3,109.0 m^2

- **Residential use:**

  Total electricity requirement: 514,753 kWh/year
  Total electricity produced by solar PV: 694,020 kWh/year
  Total energy auto-consumed: 416,412 kWh/year
  Total energy surplus sold to the grid: 277,608 kWh/year
  Energy acquired from the electricity grid: 98,341 kWh/year
  N° of PV panels of 400 V: 1,290
  Total area covered by the panels: 2,673.7 m^2

4.1.4.1 Operational and embodied CO_2e emissions

Figures 4.34 to 4.37 illustrate total and operational emissions in the case of PV Scenario I, for the office and residential uses.

➢ **PV Scenario I (production of 100% electricity demand):**

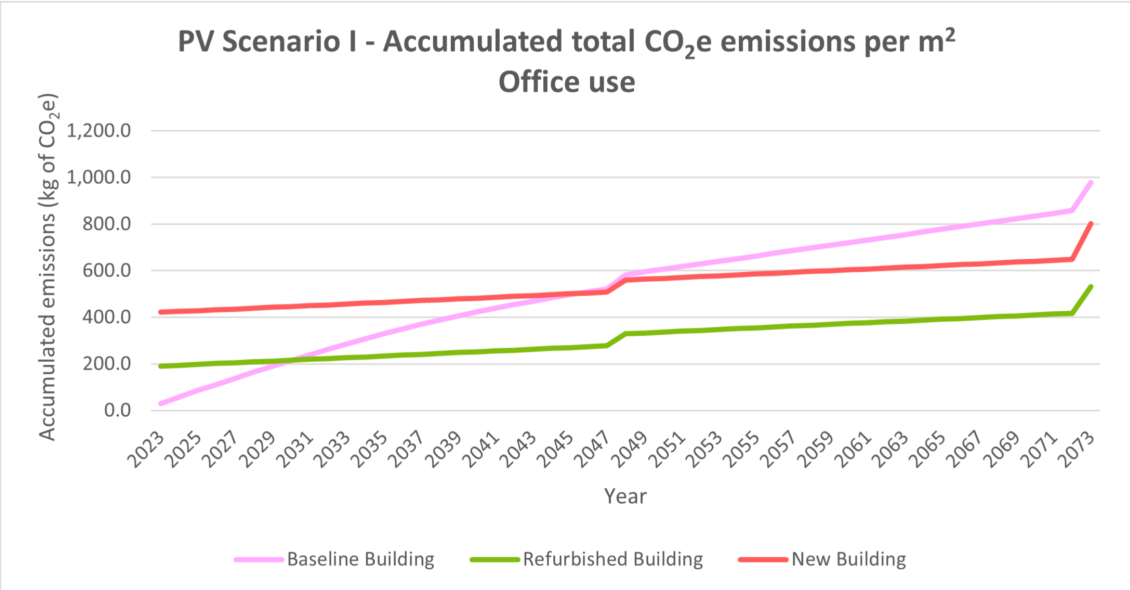


Figure 4.34: Total accumulated emissions, PV Scenario I, Office use

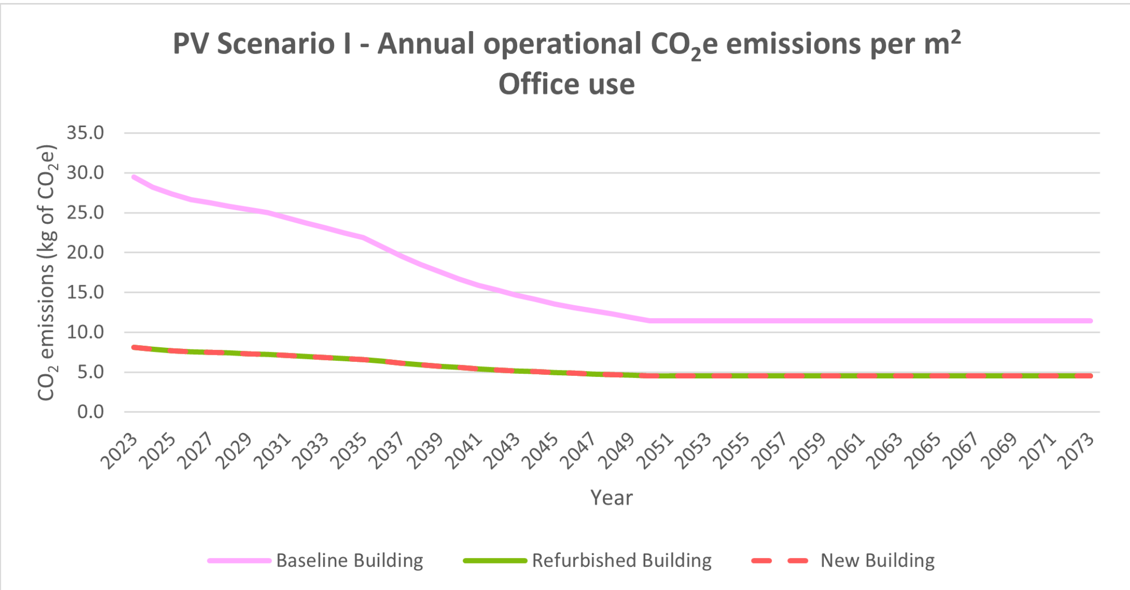


Figure 4.35: Annual operational emissions, PV Scenario I, Office use

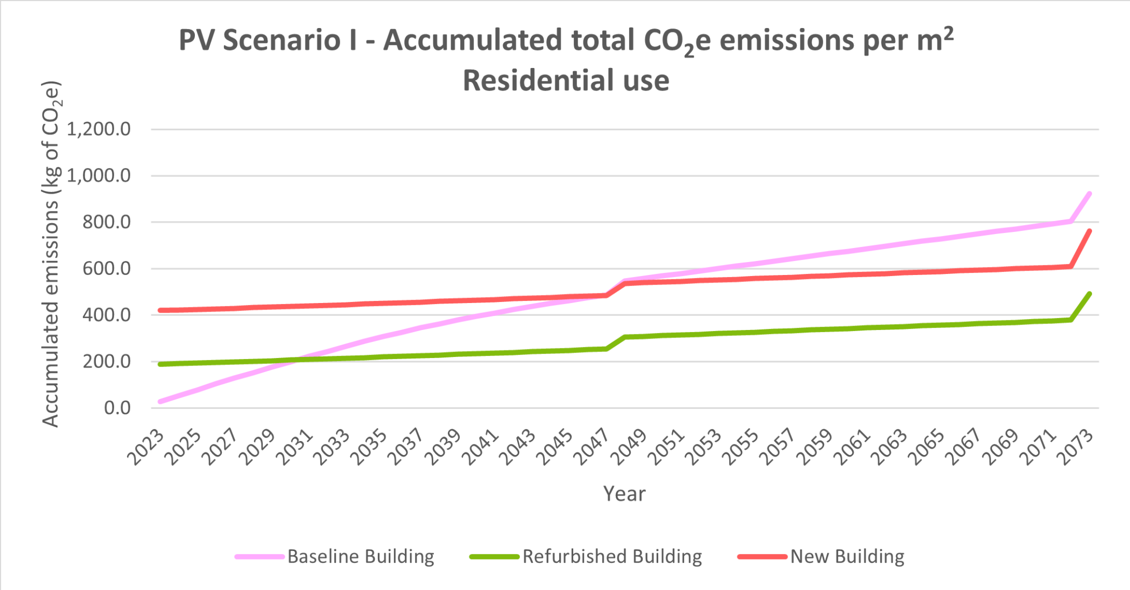


Figure 4.36: Total accumulated emissions, PV Scenario I, Residential use

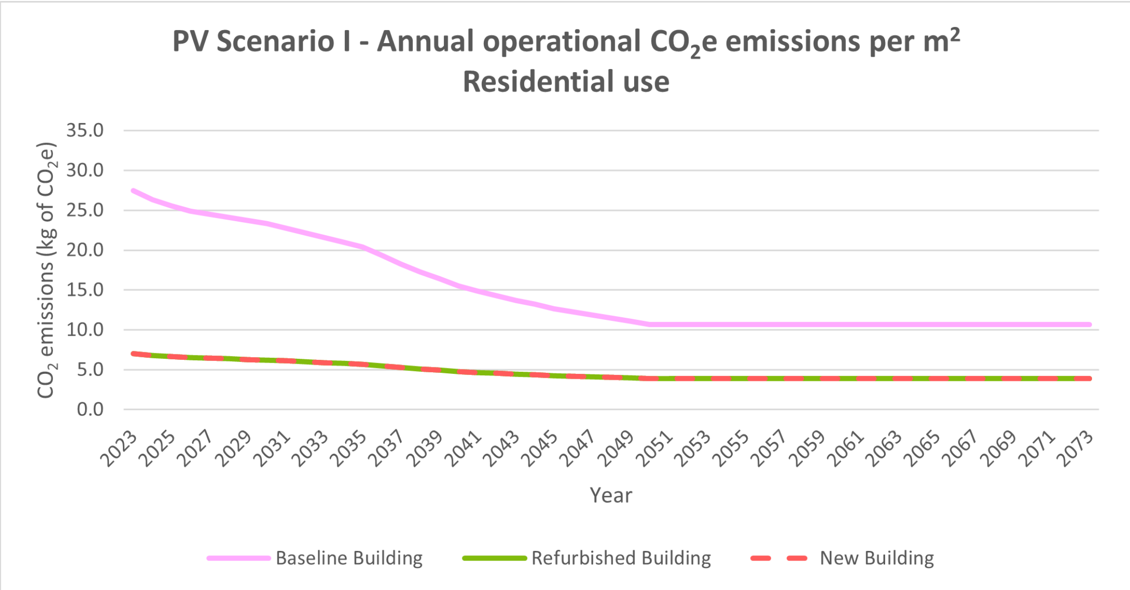


Figure 4.37: Annual operational emissions, PV Scenario I, Residential use

➢ **PV Scenario II (production of 133% electricity demand):**

Figures 4.38 to 4.41 illustrate total and operational emissions for PV Scenario II.

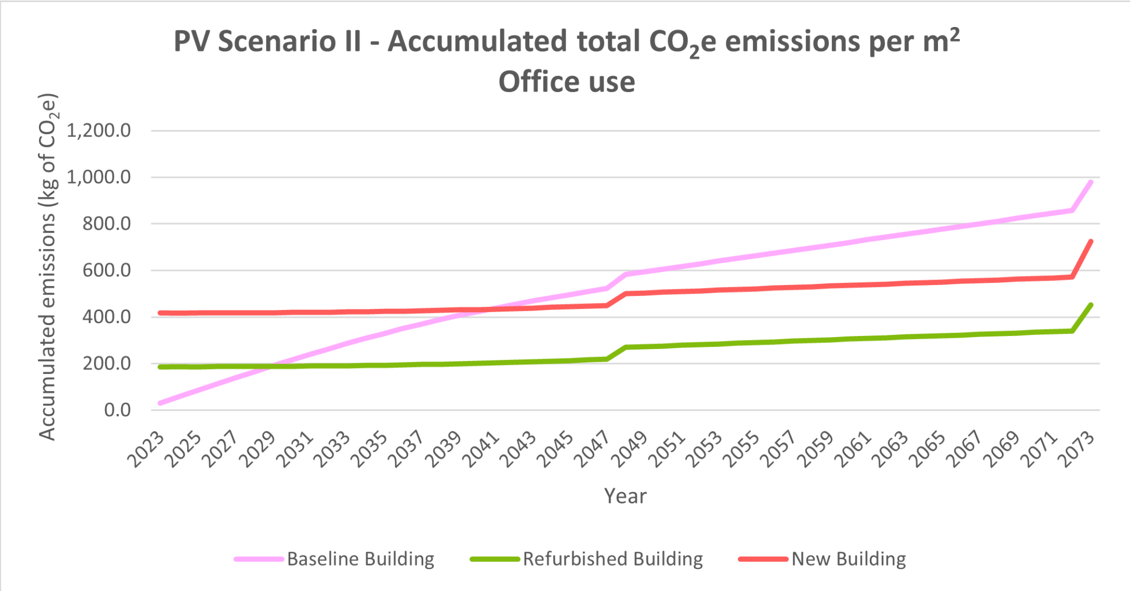


Figure 4.38: Total accumulated emissions per m^2, PV Scenario II, Office use

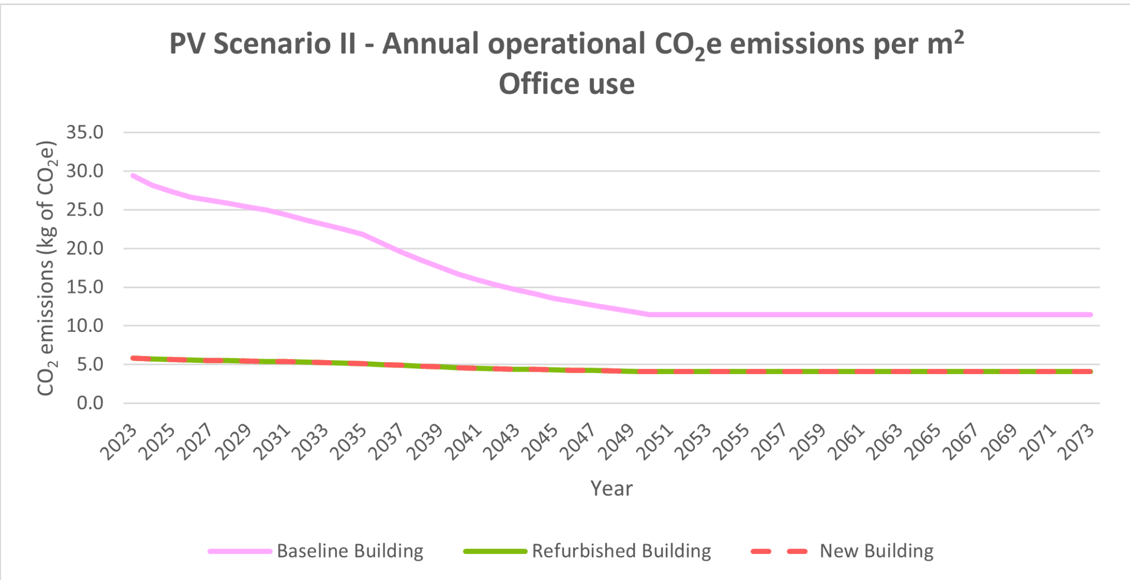


Figure 4.39: Annual operational emissions per m^2, PV Scenario II, Office use

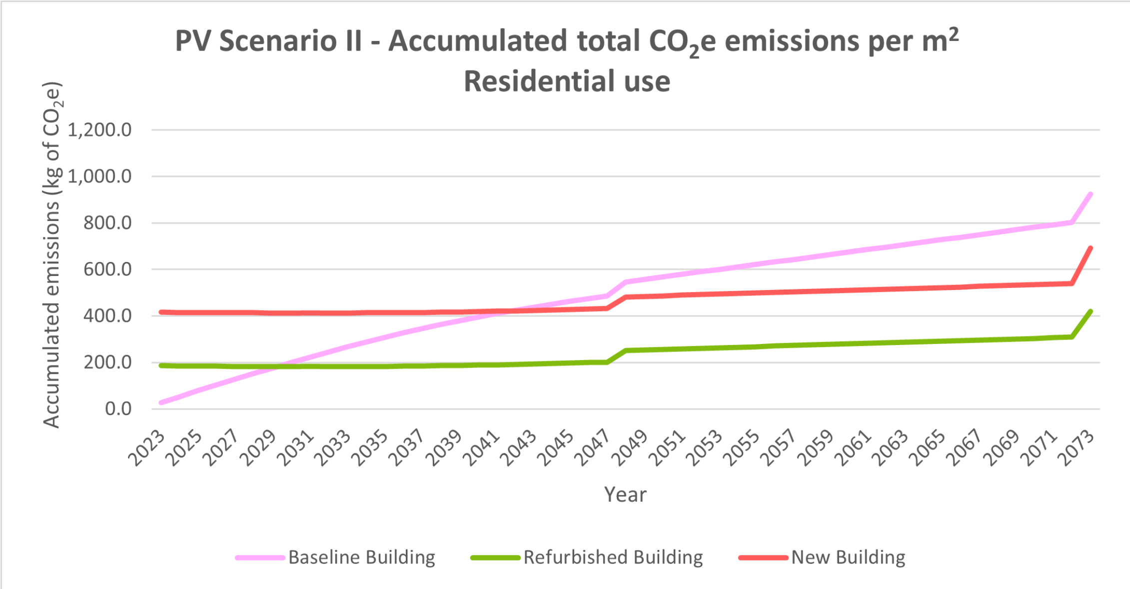


Figure 4.40: Total accumulated emissions per m^2, PV Scenario II, Residential use

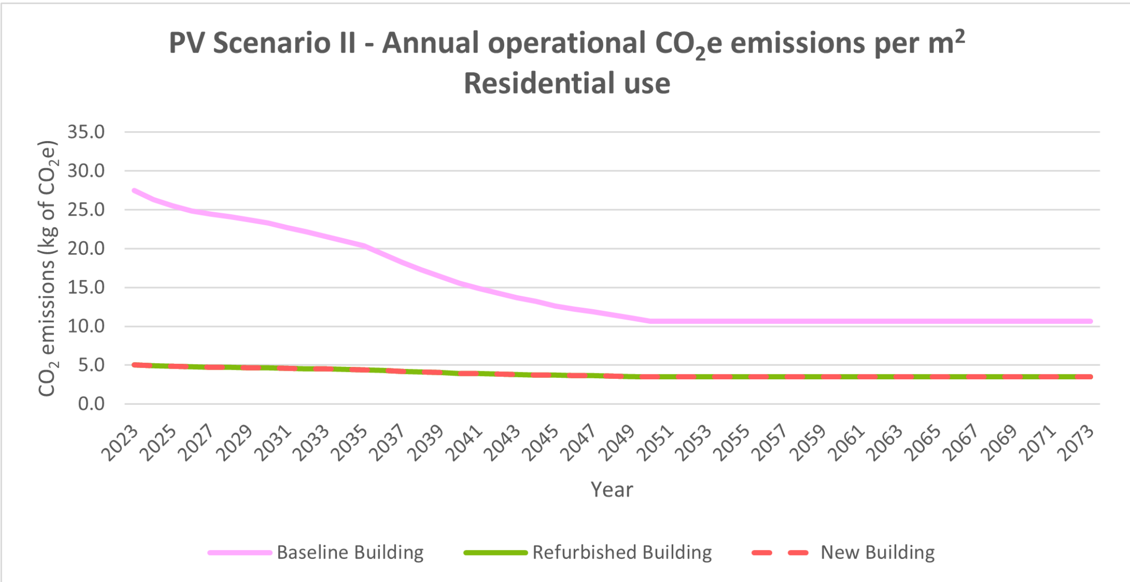


Figure 4.41: Annual operational emissions per m^2, PV Scenario II, Residential use

Tables 4.5 and 4.6 provide a comparison of the results obtained to better illustrate the impact of increasing the amount of PV panels.

	Min PV req		**PV Scenario I**		**PV Scenario II**	
Building type	**TAE**	**OAE**	**TAE**	**OAE**	**TAE**	**OAE**
Baseline Building	979	821	979	821	979	821
Refurbished Building	747	402	531 (-28.1%)	278 (-30.8%)	454 (-39.2%)	232 (-42.3%)
New Building	1,018	402	802 (-21.2%)	278 (-30.8%)	724 (-28.9%)	232 (-42.3%)

Table 4.5: Summary table of kg CO_2e per m^2 of the different scenarios analysed (Office use). TAE refers to Total Accumulated Emissions (operational+embodied), while OAE refers to Operational Accumulated Emissions. The percentage indicates the reduction with respect to the scenario of minimum PV required

	Min PV req		**PV Scenario I**		**PV Scenario II**	
Building type	**TAE**	**OAE**	**TAE**	**OAE**	**TAE**	**OAE**
Baseline Building	924	766	924	766	924	766
Refurbished Building	689	344	492 (-28.6%)	239 (-30.5%)	421 (-38.9%)	200 (-41.9%)
New Building	960	344	763 (-20.5%)	239 (-30.5%)	692 (-27.9%)	200 (-41.9%)

Table 4.6: Summary table of kg CO_2e per m^2 of the different scenarios analysed (Residential use). TAE refers to Total Accumulated Emissions (operational+embodied), while OAE refers to Operational Accumulated Emissions. The percentage indicates the reduction with respect to the scenario of minimum PV required

4.1.4.2 Offsets required to achieve Net Zero Carbon in PV Scenarios I & II

Figures 4.42 and 4.43 illustrate the total offsets needed to offset the embodied and operational emissions throughout the building's life cycle, for the PV Scenario I. Emissions are presented in tonnes of CO_2e (i.e. total values).

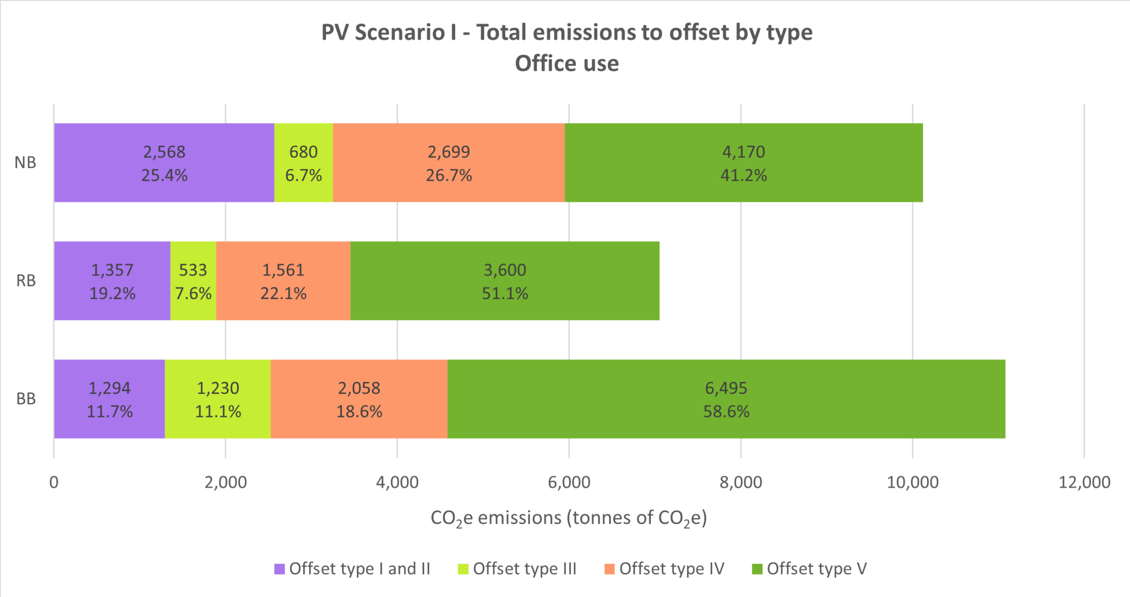


Figure 4.42: Total emissions (operational & embodied) for the case of PV Scenario I, classified by offset type (Office use)

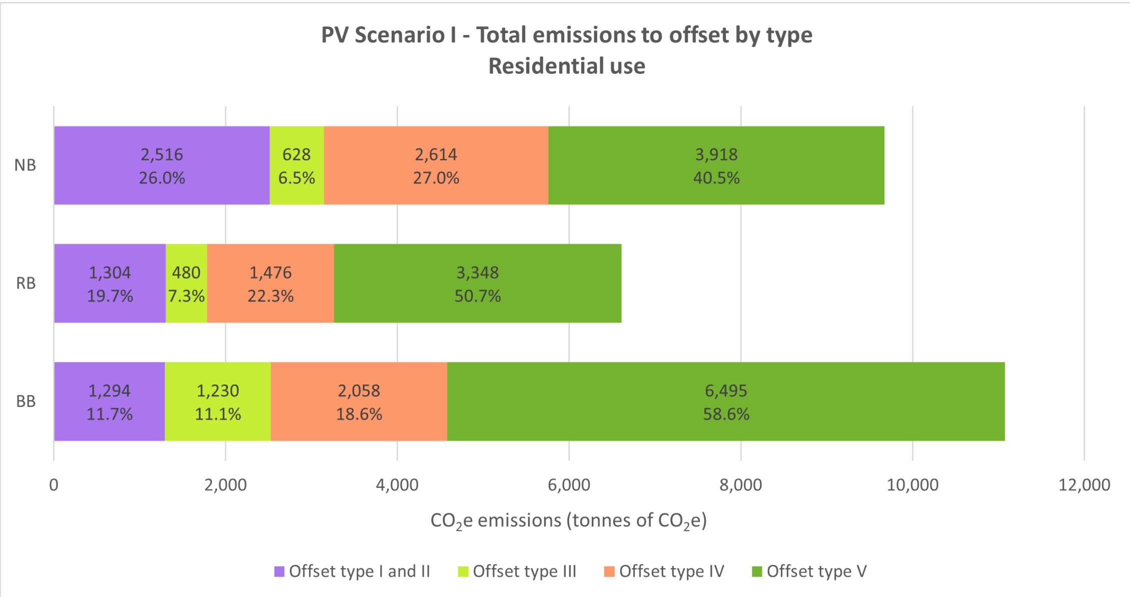


Figure 4.43: Total emissions (operational & embodied) for the case of PV Scenario I, classified by offset type (Residential use)

Figures 4.44 and 4.45 present these values for the case of PV Scenario II.

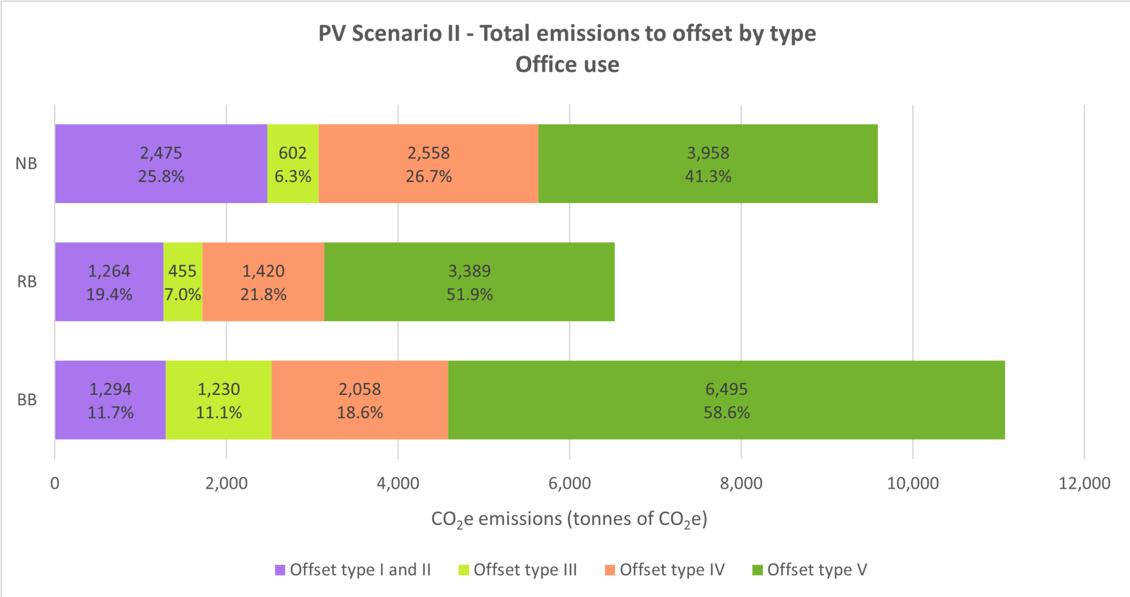


Figure 4.44: Total emissions (operational & embodied) for the case of PV Scenario II, classified by offset type (Office use)

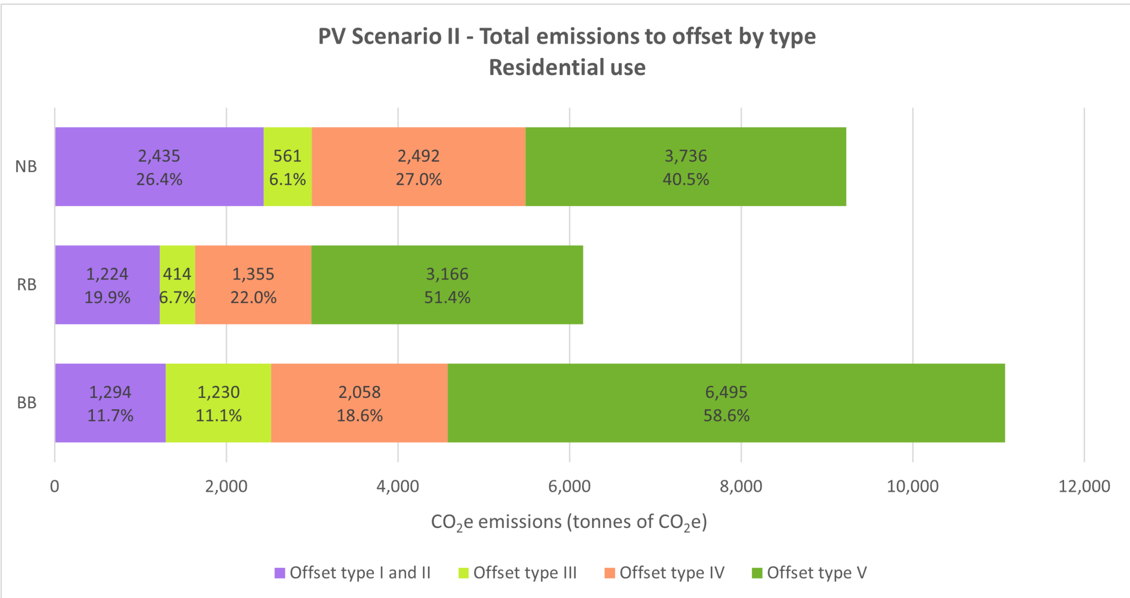


Figure 4.45: Total emissions (operational & embodied) for the case of PV Scenario II, classified by offset type (Residential use)

From these figures it can be determined that from all the scenarios presented, the case of a refurbished residential building with a surplus of PV solar panels requires the smallest amount of offsets to compensate for the embodied and operational emissions. **Table 4.7** presents a comparison of the total offsets needed for each scenario.

	Use	BB	RB	NB
PV Scenario I	Office	11,077	7,051 (-36%)	10,117 (-9%)
PV Scenario I	Residential	11,077	6,609 (-40%)	9,675 (-12.7%)
PV Scenario II	Office	11,077	6,527 (-41%)	9,593 (-13.4%)
PV Scenario II	Residential	11,077	6,159 (-44%)	9,224 (-17%)

Table 4.7: Comparison of offsets required in each scenario. Values are in tonnes of CO_2e. The reduction in percentage is with respect to the values obtained for the Baseline Building, which remain constant in the different scenarios

4.1.4.3 Cost projections

Figures 4.46, 4.47, and 4.48 present the costs projected for PV Scenario I. Costs are based on the three Price Scenarios introduced previously. Since graphs obtained for the residential and office uses are very similar, only the graphs correspondent to the office use will be presented.

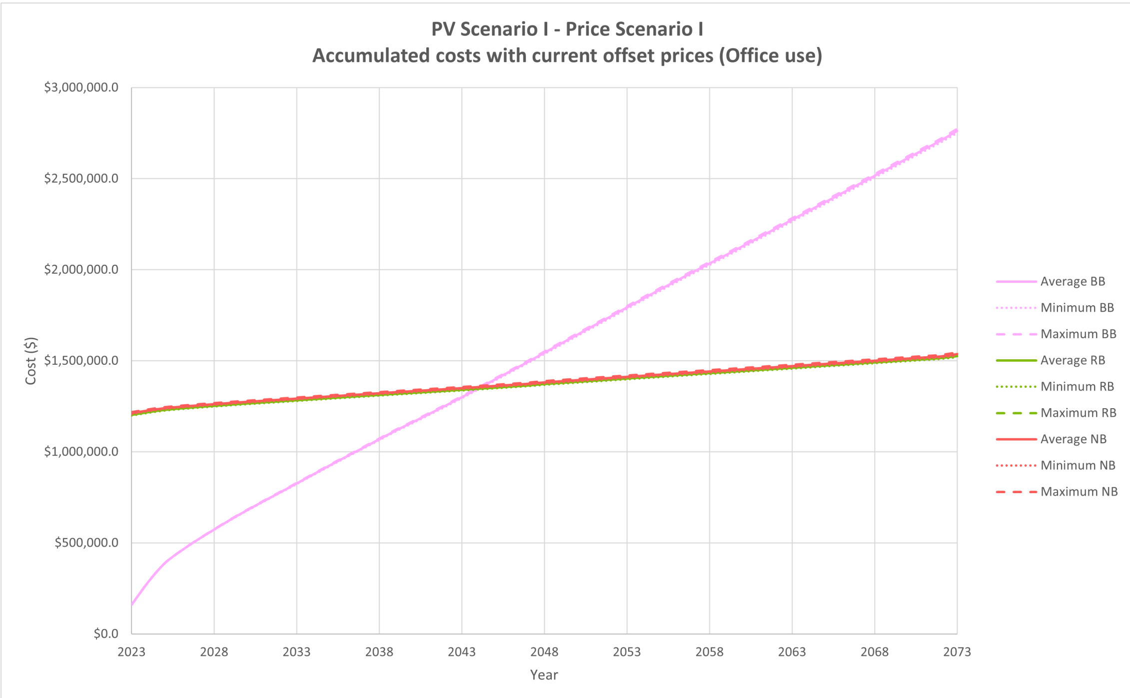


Figure 4.46: Projection of accumulated costs for PV Scenario I, Price Scenario I (Office use)

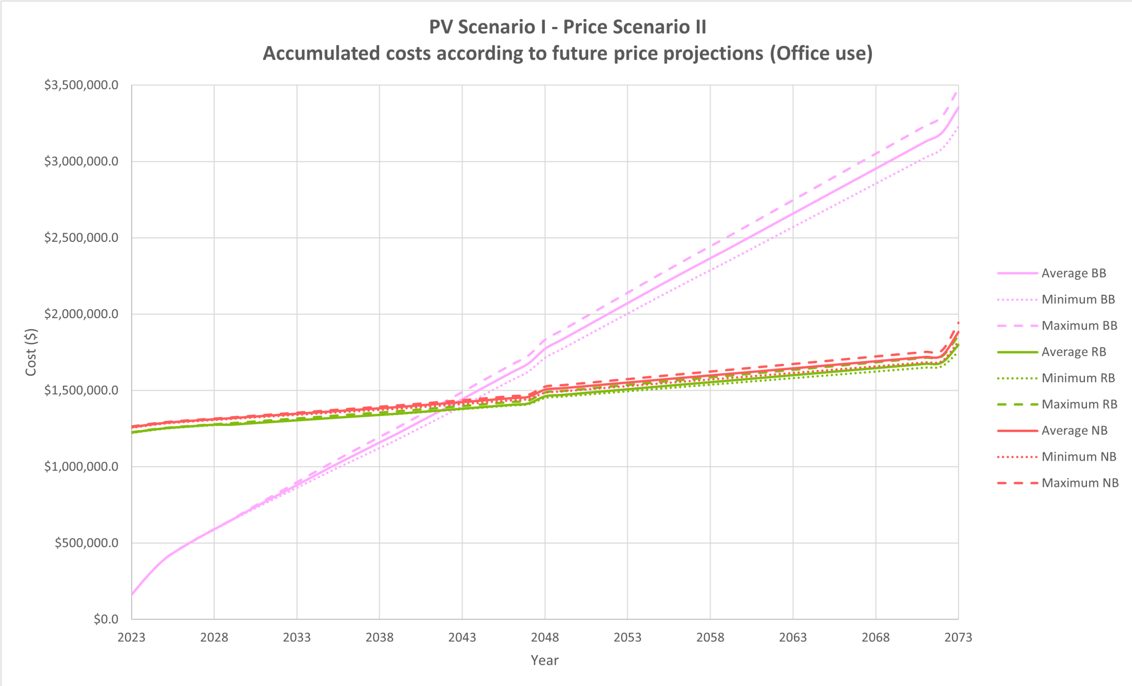


Figure 4.47: Projection of accumulated costs for PV Scenario I, Price Scenario II (Office use)

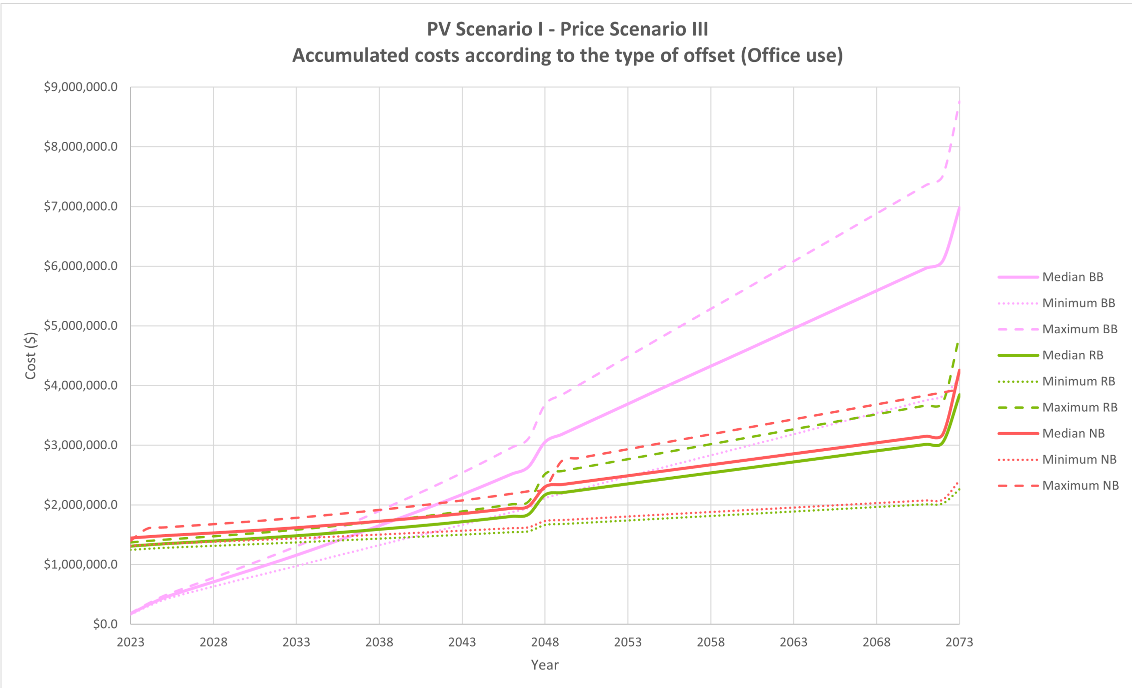


Figure 4.48: Projection of accumulated costs for PV Scenario I, Price Scenario III (Office use)

Figures 4.49, 4.50, and 4.51 illustrate the cost projections correspondent to PV Scenario II.

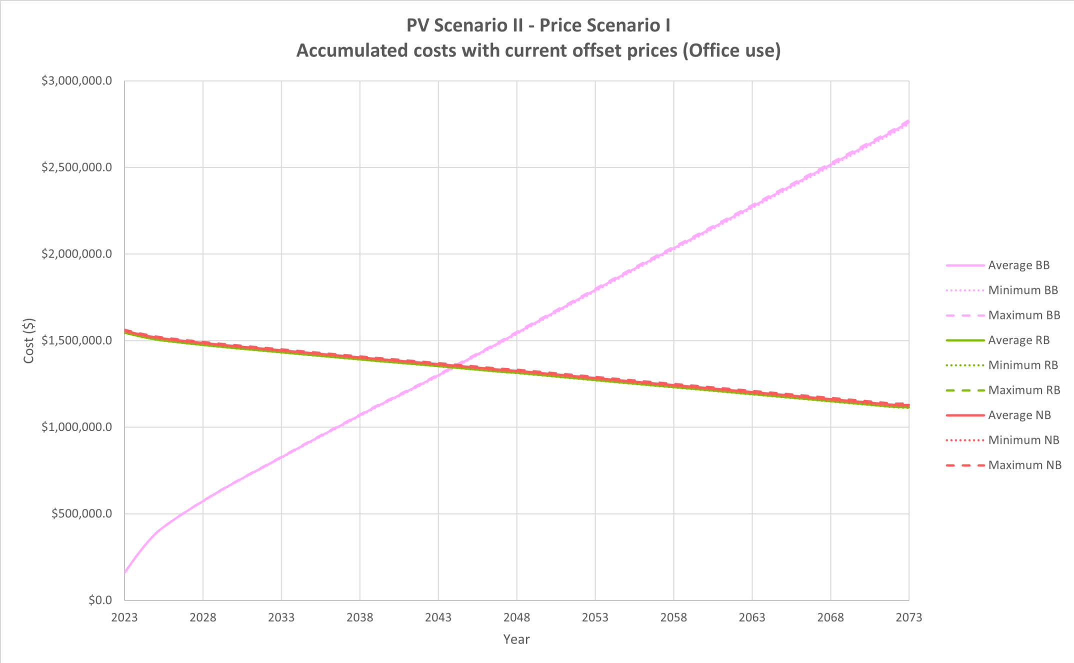


Figure 4.49: Projection of accumulated costs for PV Scenario II, Price Scenario I (Office use)

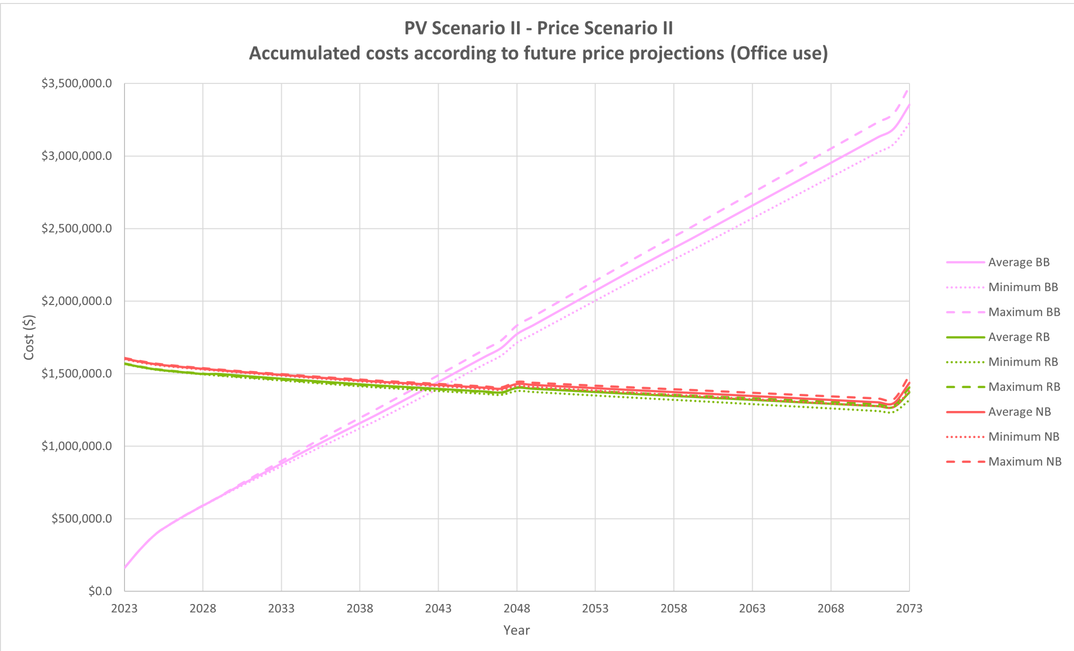


Figure 4.50: Projection of accumulated costs for PV Scenario II, Price Scenario II (Office use)

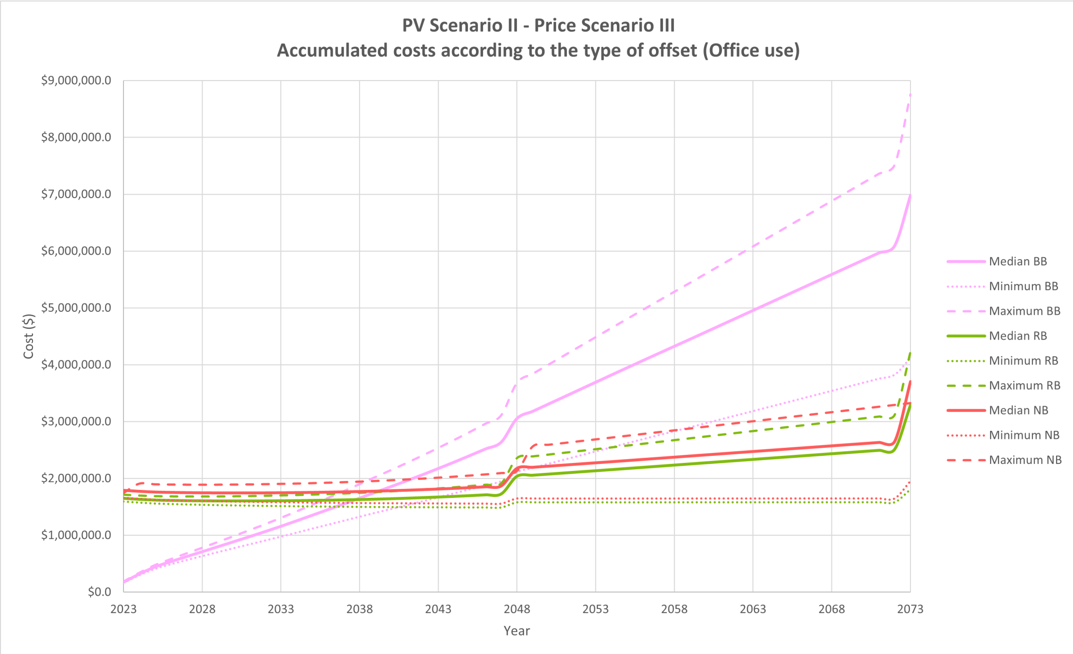


Figure 4.51: Projection of accumulated costs for PV Scenario II, Price Scenario III (Office use)

Tables 4.8 and 4.9 summarise the results obtained for each building case in PV Scenarios I and II.

	Projection of accumulated costs - Office use (average costs)					
	Price Scenario I		**Price Scenario II**		**Price Scenario III**	
	PV Sc I	**PV Sc II**	**PV Sc I**	**PV Sc II**	**PV Sc I**	**PV Sc II**
Baseline Building	$2.763 M	$2.763 M	$3.354 M	$3.354 M	$6.977 M	$6.977 M
Refurbished Building	$1.525 M	$1.116 M (-26.8%)	$1.801 M	$1.372 M (-23.8%)	$3.846 M	$3.292 M (-14.4%)
New Building	$1.538 M	$1.128 M (-26.6%)	$1.883 M	$1.438 M (-23.6%)	$4.260 M	$3.705 M (-13.0%)

Table 4.8: Summary table of cost projections for Price Scenarios I, II & III (Office use). The percentages refer to the change in PV Scenario II with respect to PV Scenario I

	Projection of accumulated costs - Residential use (average costs)					
	Price Scenario I		**Price Scenario II**		**Price Scenario III**	
	PV Sc I	**PV Sc II**	**PV Sc I**	**PV Sc II**	**PV Sc I**	**PV Sc II**
Baseline Building	$2.753 M	$2.753 M	$3.343 M	$3.343 M	$6.967 M	$6.967 M
Refurbished Building	$1.522 M	$1.116 M (-26.7%)	$1.774 M	$1.352 M (-23.8%)	$3.679 M	$3.148 M (-14.4%)
New Building	$1.535 M	$1.129 M (-26.5%)	$1.856 M	$1.418 M (-23.6%)	$4.092 M	$3.561 M (-13.0%)

Table 4.9: Summary table of cost projections for Price Scenarios I, II & III (Residential use). The percentages refer to the change in PV Scenario II with respect to PV Scenario I

4.1.4.4 Conclusions

As a result of examining several price scenarios and hypothesizing different amounts of PV panels installed, it has been determined that reducing the building's emissions to the absolute minimum is also convenient from an economic point of view. However, due to the high uncertainty that characterises offsets and electricity future prices, it is difficult to forecast exact costs in the long term.

4.2 Case B: Offsetting strategy for a new industrial plant

This case study was conducted on behalf of a private company that decided to build a new production plant with high energy and environmental performance. A Whole Life Cycle Assessment was performed to quantify the embodied and operational CO_2 emissions associated with the new building. Emissions were quantified for a "Baseline Building", in this case called "Standard Building (SB)" to avoid confusion with the previous case study, and a "Proposed Building (PB)", designed to have a higher performance.

The environmental impacts of the proposed building are lower than the impacts of the standard building mainly thanks to the use of product specific Environmental Product Declarations (EPDs) and the modification of:

- Envelope materials
- Roof insulation layers
- Wall plasterboard materials

More in detail, the following innovations were adopted in the proposed building as part of the design process:

- The use of a product specific EPD for the reinforcing steel and structural timber.
- The change of envelope insulation from polyurethane to mineral wool in the sandwich panels.
- The use of product specific EPDs for the sandwich panels of the envelope and the roof.
- The change of roof insulation from polyurethane to mineral wool.
- The use of product specific EPDs for the interior finishings.

4.2.1 Quantification of CO_2 emissions

The Life Cycle Assessment approach with cradle-to-grave boundaries was used to assess environmental impact values. The analysis was carried out in accordance with ISO 14044:2021 (Environmental management, Life cycle assessment, Requirements and Guidelines) [223], EN 15978:2011 (Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method) [224], and ISO 14040:2021 (Environmental management, Life cycle assessment, Principles and framework) [225].

The manufacturing facility plan is an industrial construction building with well-optimized structural and main design parameters. In order to obtain better environmental performance with respect to the standard construction approach, specific building products and materials were selected, which reduce the environmental impact of the proposed building.

The LCA of the baseline building was developed throughout the design phase to be representative of the conventional industry practice. The baseline building is an early iteration of the projected building, as recommended by the "Athena Guide to Whole Building LCA in Green Building Programs" [226]. The proposed LCA model was developed to support design decisions that utilize environmentally preferable assemblies and materials during the design phase by performing "what if" scenario evaluations. The selection of building materials and assemblies with better environmental profiles and fewer replacement cycles were the primary options analysed.

The calculation of the operational impacts was performed considering only stage B6.1, "Building-related operational energy use, regulated". Stages B6.2, B6.3, B7, B8, and D were not included in this analysis. The building's life span considered is of 50 years, and the functional unit examined in the LCA study is 1 m^2 of the building's Gross Floor Area (GFA).

4.2.1.1 Assumptions – Databases and System Boundary Scenarios for Embodied Carbon

Databases:

Ecoinvent 3.7 database - SimaPro software (version 9.3.0.3)
Characterisation method CML-IA baseline

A1-3: Production Phase

It begins with raw materials extraction, following with their transports to manufacturing site and manufacturing processes derived from secondary data, which are provided by international environmental database and product specific Environmental Product Declarations (EPDs).

A4: Transports

Average distances are assumed in the study:

- 100 km has been assumed for general construction products (Nemry et al, 2008 [227]; Lasvaux, 2010 [228]; Bribián et al, 2011 [229]; EeB guide B, 2012 [230]; Lavagna et al, 2018 [231]);
- 50 km have been assumed for products containing inert materials (Junnila et al, 2006 [232]; Ortiz et al., 2010 [233]; Asdrubali et al, 2013 [234]; Lavagna et al, 2018 [231]).

A5: Installation Process

Assumption: 4% of A1-A3 stage has been considered, based on LETI guide benchmark for commercial buildings [219].

B2: Maintenance

In the use phase, the maintenance cycles are accounted considering literature or EPDs data.

B4: Replacement

The building Reference Service Life (RSL) is 50 years. During those 50 years some materials shall be replaced, causing new environmental impacts. In the replacement phase, transport of replaced components and ancillary products, the waste of materials in the replacement actions, and the waste management of replaced and ancillary materials are included in the LCA analysis.

The Expected Reference Service Life of materials are based on EPDs indication or on average Austrian and Italian database IBO/CasaClima. Inert materials based on concrete have RSL between 100 and 50 years, as well as the materials based on plaster, bricks and metals. However, it is adopted a reference service life of 50 years, so, if the material has RSL equal to 100 years, 50 years are taken as maximum service life. Paper materials, mineral wool panels and wood materials have RSL of 50 years, at least they are used in windows and doors. A lower lifespan is assigned to bituminous and waterproof materials (between 10 and 35 years) and painting. Plastic insulations have RSL of 50 years, as well as the ceramics. Different lifespan is assigned to the windows, where frame (made by aluminium) and glass (double or triple) have a durability of 25 years. No replacements are accounted if the building technological systems service life exceeds the remaining service life of the building by 2/3rd. Moreover, no replacements are considered in the last 10 years of building's service life [235].

C2: Transports

Average distance are assumed in the study:

- 20 km have been assumed for transportation of non hazardous waste (Lavagna et al, 2018 [231]);
- 250 km have been assumed for transportation of hazardous waste (EeB guide B, 2012 [230]).

C3-4: End of life

The assumptions about end of life of building materials is based on construction practice in the Italian context. All the inert materials are sent to inert waste, waiting for a future recycle as road foundations or paving (module C4). The metals (aluminium and steel) will be recycled, so in this LCA study the preparation of metal scraps is included (module C3). Plastics will be send to incineration for energy recovery (module C3); other materials, such as gypsum, bitumen, etc. will be send to sanitary landfill (module C4) or to energy recovery (module C3).

4.2.1.2 Assumptions – Databases and Carbon factors for Operational Carbon

B6 stage assumptions:
The same emission factors as for Case A have been considered, which were indicated in **Table 4.1**.

Emission factors from Italian Grid Mix from CRREM, considering the study period of 50 years 2023-2073 and the progressive decarbonisation of electricity national mix over time. Since CRREM provides emission factors only until 2050, from 2051 to 2073 these factors were considered constant, which would be a conservative approach.

PV emission factor: 0.070 kg CO_2e/kWh (Ecoinvent 3.8).

4.2.1.3 Results

Total CO_2e emissions associated with 1 m^2 of the Baseline and Proposed Buildings are presented in **Figure 4.52**. There is a reduction of 20% in the emissions associated with the Proposed Building with respect to the Standard Building.

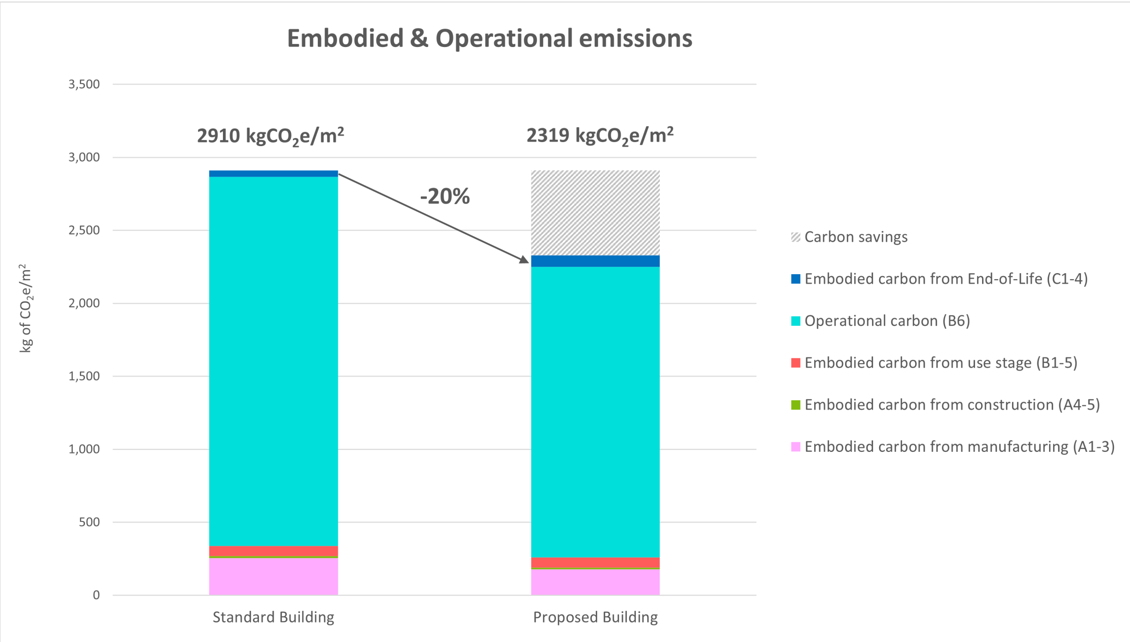


Figure 4.52: Comparison of CO_2e emissions associated with the Standard building and those associated with the Proposed building

Figures 4.53 and 4.54 illustrate the relative contributions of the LCA Stages to the total emissions per m^2 for the scenario of a Standard and a Proposed Building, respectively. The major contributor to the total emissions is operational energy use (B6) for both scenarios, which is responsible for 86.9% of the emissions in the SB scenario and 85.5% in the PB scenario. The second most emitting stage is the product stage (A1-3), which contributes to 8.8% for the SB and 7.6% for the PB.

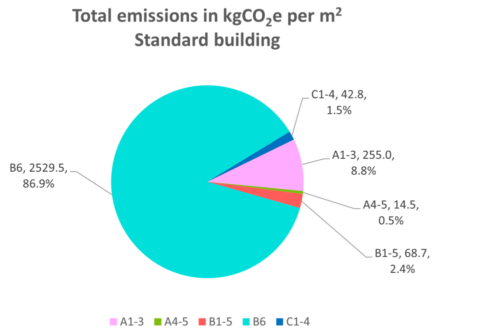


Figure 4.53: Embodied and operational emissions per m^2 associated with the Standard Building

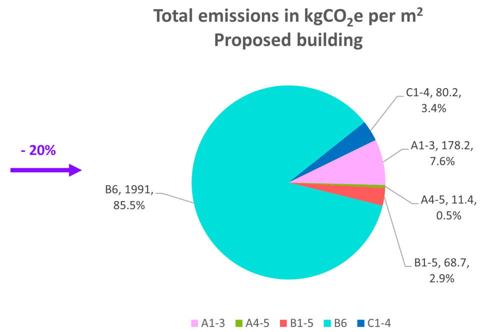


Figure 4.54: Embodied and operational emissions per m^2 associated with the Proposed Building

Figure 4.55 compares the accumulated total CO_2e emissions (embodied carbon + operational carbon) per m^2 of the Proposed Building with the Standard Building over a lifetime of 50 years.

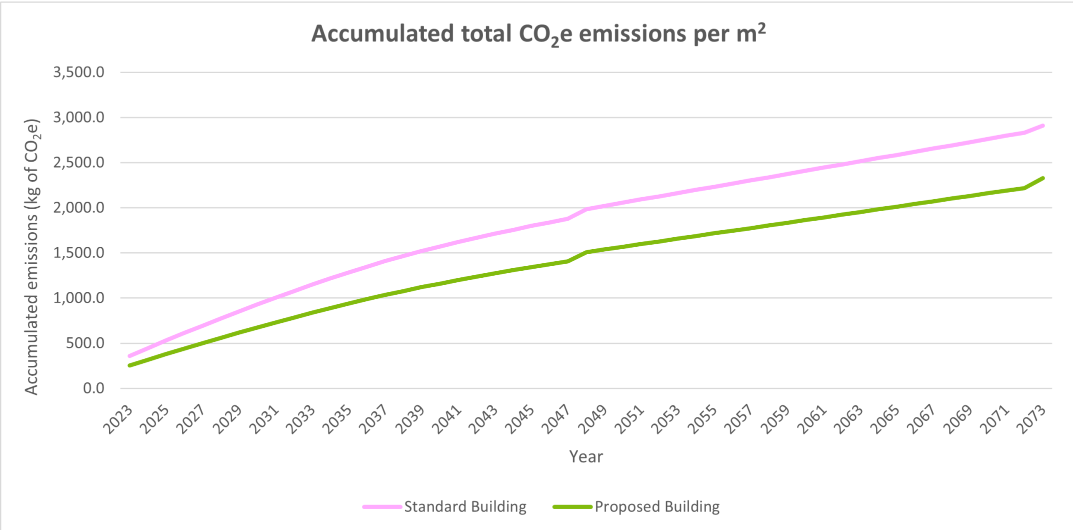


Figure 4.55: Comparison of CO_2e emissions associated with a Standard Building and those associated with the Proposed Building

With the aim of illustrating the development of operational emissions over time, **Figure 4.56** provides the annual operational results for both scenarios. For case B, just as for case A, the study was originally conducted based on the installation of the minimum renewable energy values required by Italian Legislative Decree n. 199 of 8 December 2021. For the Proposed Building, the Italian grid mix is used to supply the remaining energy requirements. In the scenario of the Standard Building, instead, the total energy requirement is supplied by the Italian grid mix. **Section 4.2.4** will provide the results of the same case study but with an increase in the amount of solar PV installed.

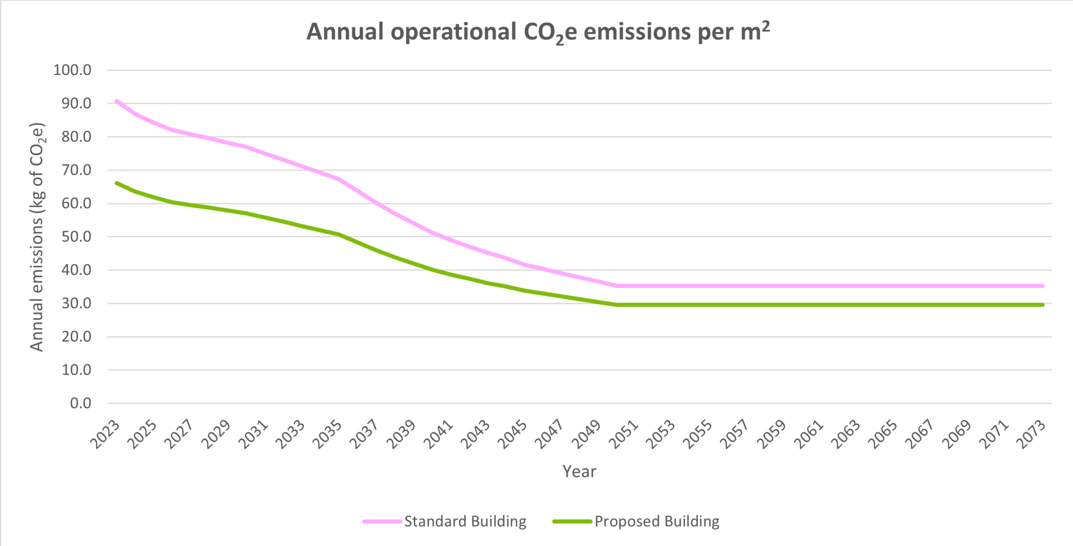


Figure 4.56: Annual operational CO_2e emissions per m^2 for the Standard and the Proposed Buildings

Figure 4.57 shows annual embodied CO_2e emissions per m^2. There is an increase in the embodied emissions at the end-of-life in the Proposed Building because of the use of specific EPDs: since the average Ecoinvent database for certain products is a mean value created from different production processes, from different countries, and with different production technologies, in this case it results in a lower value than the specific product EPD, which represents the selection of specific manufacturing processes.

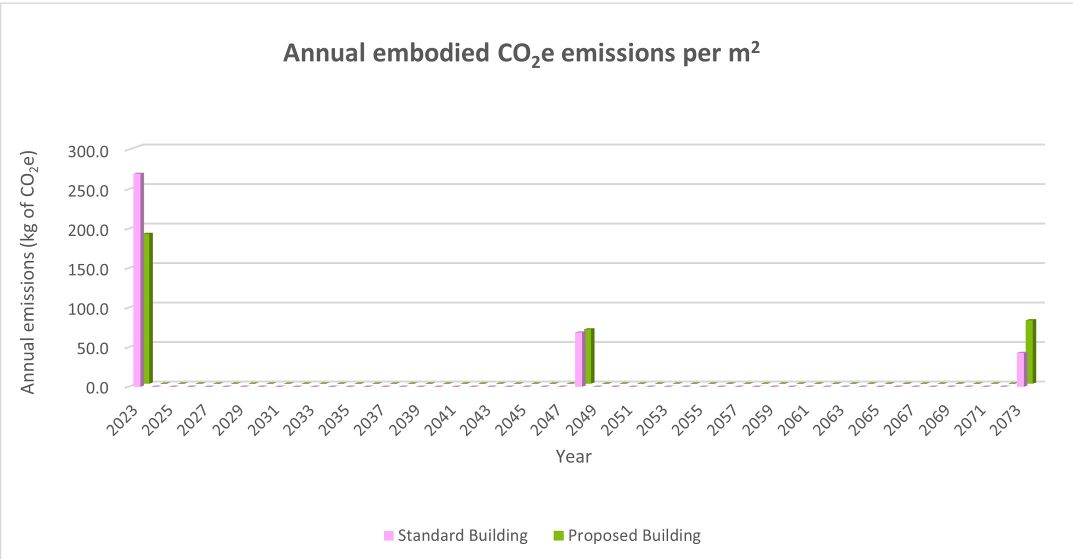


Figure 4.57: Annual embodied CO_2e emissions per m^2 for the Standard and the Proposed Buildings

4.2.1.4 Conclusions

With an overall reduction of 20% of the associated emissions, the Proposed Building has a much higher environmental performance with respect to a Standard Building. In contrast to Case A, where operational energy use (B6) contributed to a maximum of 54% in the case of an office renovated building, LCA results from Case B are considerably different from those obtained in Case A. The main factor that influences this difference is the energy consumption, as shown in **Table 4.10**.

Building Scenario	Unit	Case A Office use	Case A Residential use	Case B Industrial use
Baseline Building	kWh/m^2	104	97	321
Refurbished & New Building	kWh/m^2	53	45	303

Table 4.10: Comparison of the annual energy consumption between Case A and B in their different scenarios

Another factor contributing to these contrasting values is the type of construction: while Case A analyses a typical residential or office building, Case B analyses an industrial plant, which has a simpler design and structure. This is reflected in the contribution of the product stage (A1-3) to the total embodied emissions for each case, which is of 384 kg CO_2e/m^2 for Case A (New construction - office) and 178 kg CO_2e/m^2 (Proposed building - industrial).

The product stage (modules A1-3) is the largest contributor to embodied emissions, and its emissions are primarily a result of the production of concrete, steel, and different insulation layers. Module B4 (replacement stage) also has high impacts due to a one-time renovation of paint every ten years (in the interior finishing) and one-time replacement of completions (e.g. windows, skylight and sectional doors), which have a shorter lifespan than other building elements. Transport to the building site (module A4) and to the end of life facilities (module C2) have little impact on the outcomes.

4.2.2 Offsets required to achieve Net Zero Carbon

Figures 4.58 to 4.61 present the amount of offsets required to achieve carbon neutrality for both building scenarios following Oxford's offsetting trajectory presented in **Figure 4.1**.

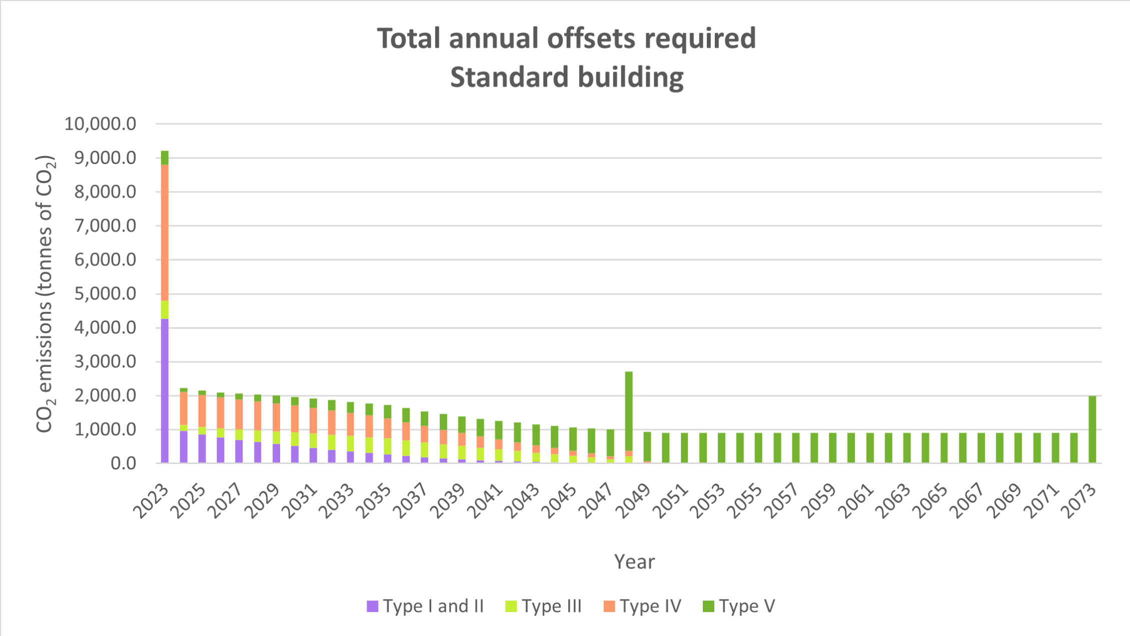


Figure 4.58: Annual offsets required to achieve carbon neutrality following Oxford's offsetting trajectory - Standard Building

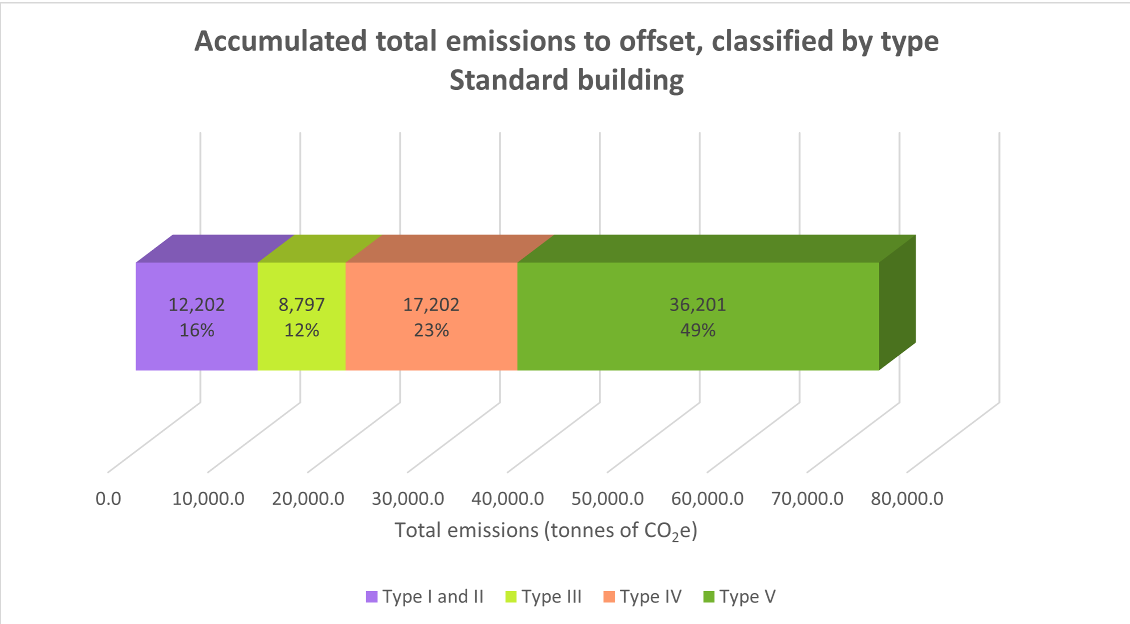


Figure 4.59: Accumulated total emissions to offset according to Oxford's offset classification - Standard Building

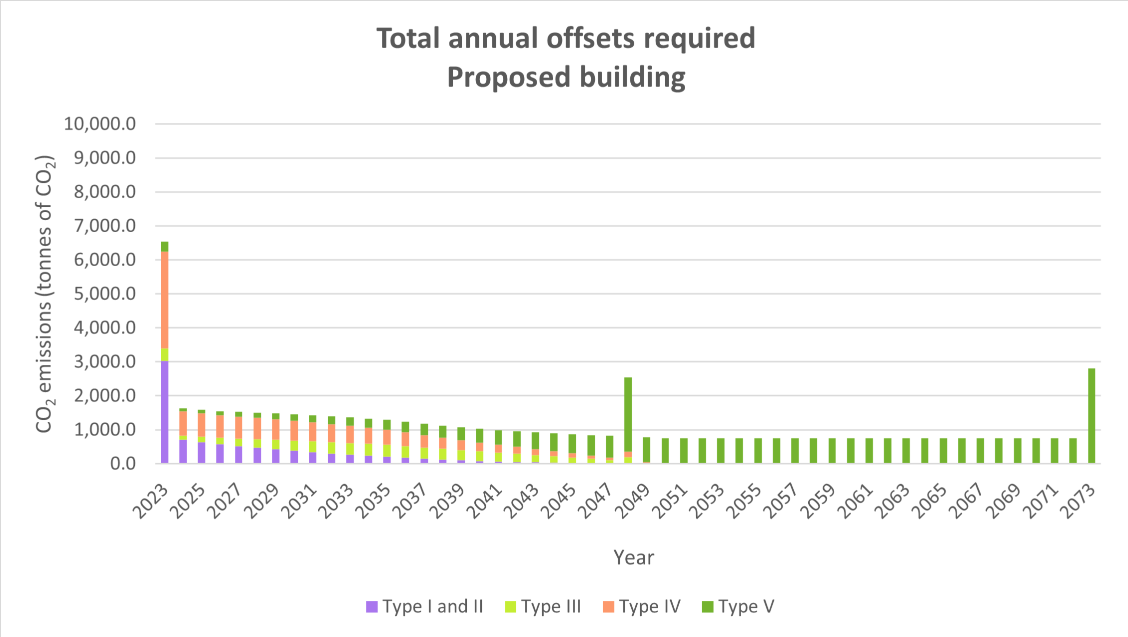


Figure 4.60: Annual offsets required to achieve carbon neutrality following Oxford's offsetting trajectory - Proposed Building

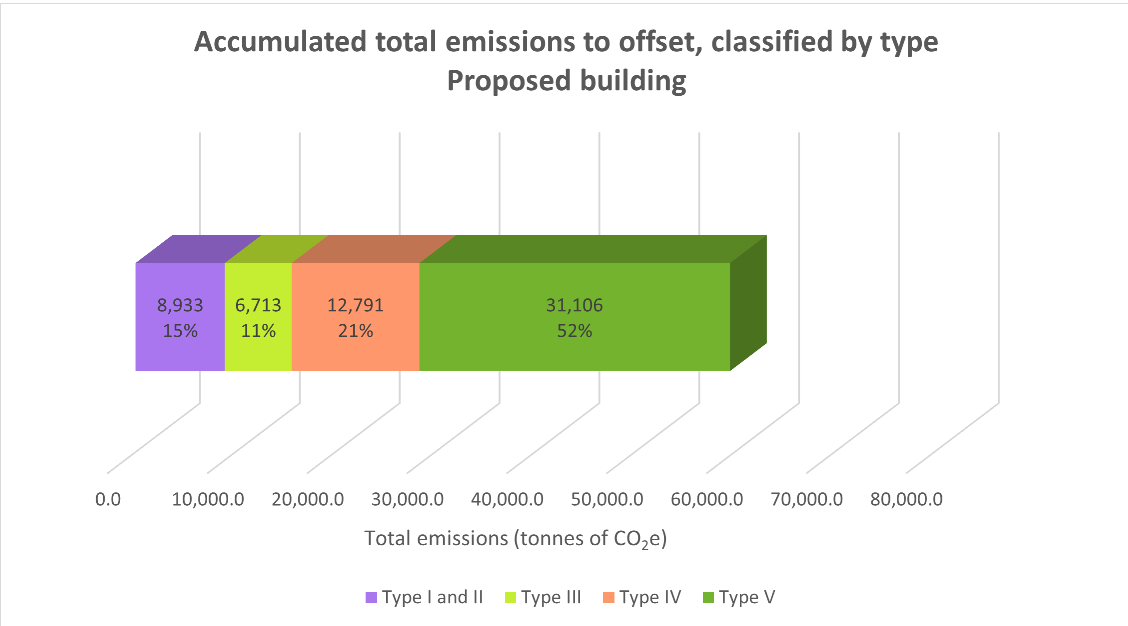


Figure 4.61: Accumulated total emissions to offset according to Oxford's offset classification - Proposed Building

The SB scenario, with a total amount of 74,401 tCO_2, requires the largest amount of offsets to achieve a Net Zero Emissions state[5]. In contrast, the PB scenario requires about 59,543 tCO_2 to achieve carbon neutrality, 20% less than in the SB scenario, in line with total emissions reductions. The peaks that can be appreciated correspond to emissions concentrated in the years 2023 (construction), 2048 (renovation of MEP components), and 2073 (end-of-life).

4.2.3 Cost projections

Adopting the price scenarios for carbon offsets presented in **Section 2.4.1**, three cost projections were performed, which are presented in **Figures 4.62, 4.63, and 4.64**.

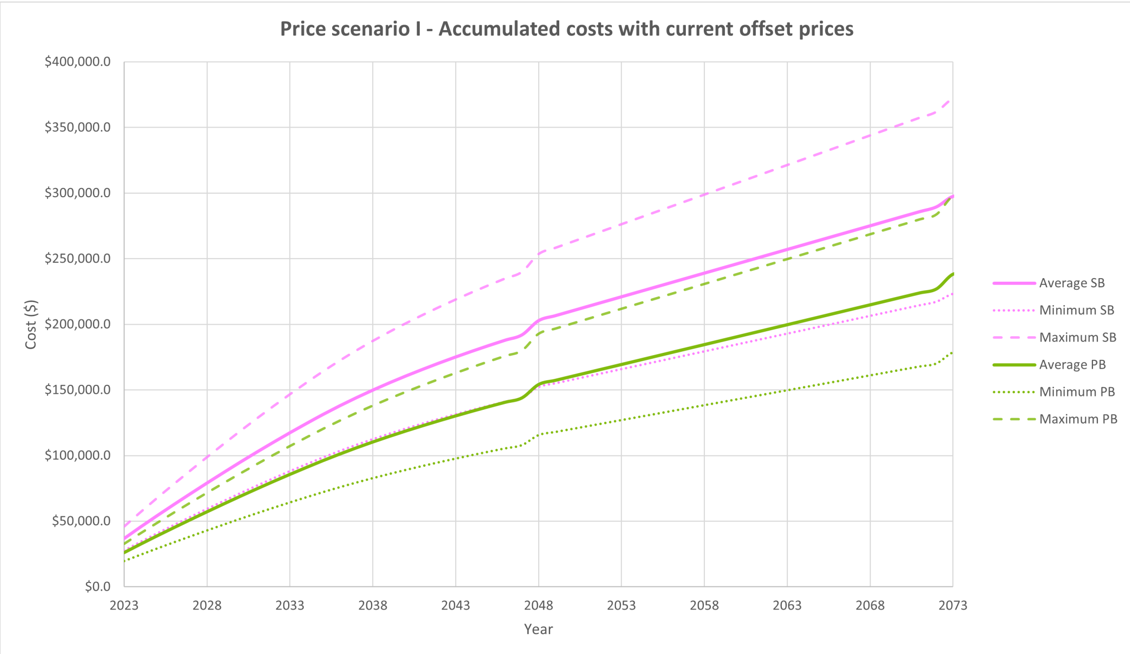


Figure 4.62: Projection of accumulated costs for Price Scenario I

The results obtained with Price Scenario I, which correspond to a scenario with current offset prices on average (i.e. not taking into account the share of each offset type), are excessively low if compared with the other two price scenarios, in accordance with the low quality that characterises offsets sold at these prices.

The accumulated cost projection with Price Scenario II, which reflects average future price projections, it is most likely to represent real future costs. As a result, this scenario should help to understand the importance of reducing emissions to the minimum possible, not only because it should be the standard practice to make a

[5]It is important to take into account that these values correspond to total emissions for a building with a Gross Floor Area of 25,568 m^2. A comparison between offsets required per m^2 in Case A and B will be provided in Chapter 5

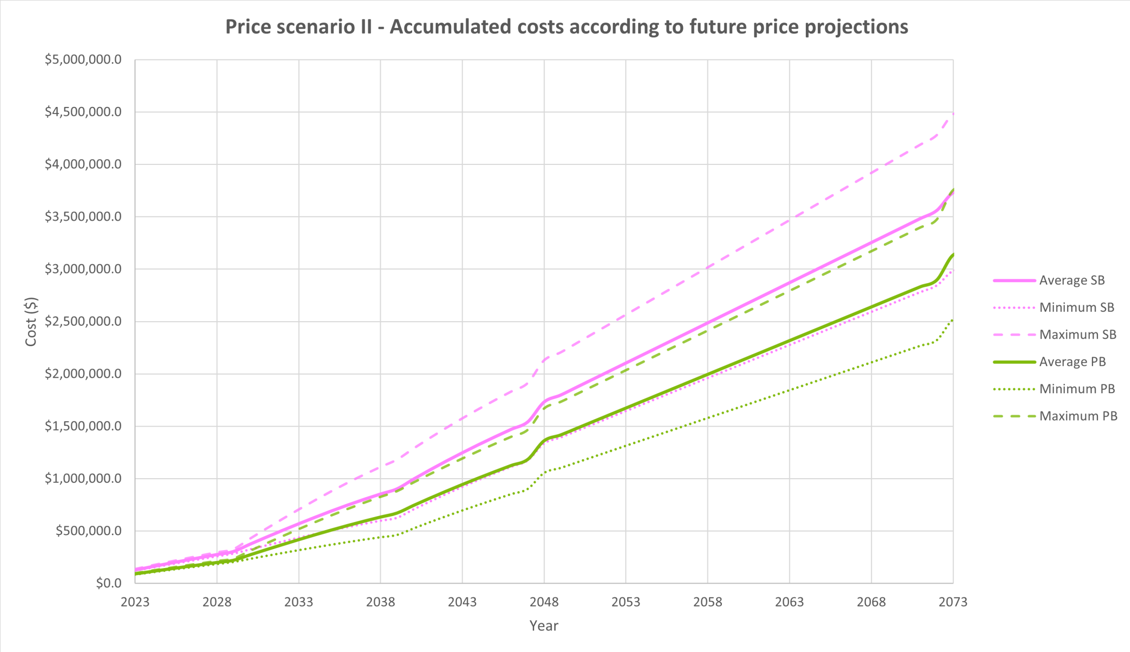


Figure 4.63: Projection of accumulated costs for Price Scenario II

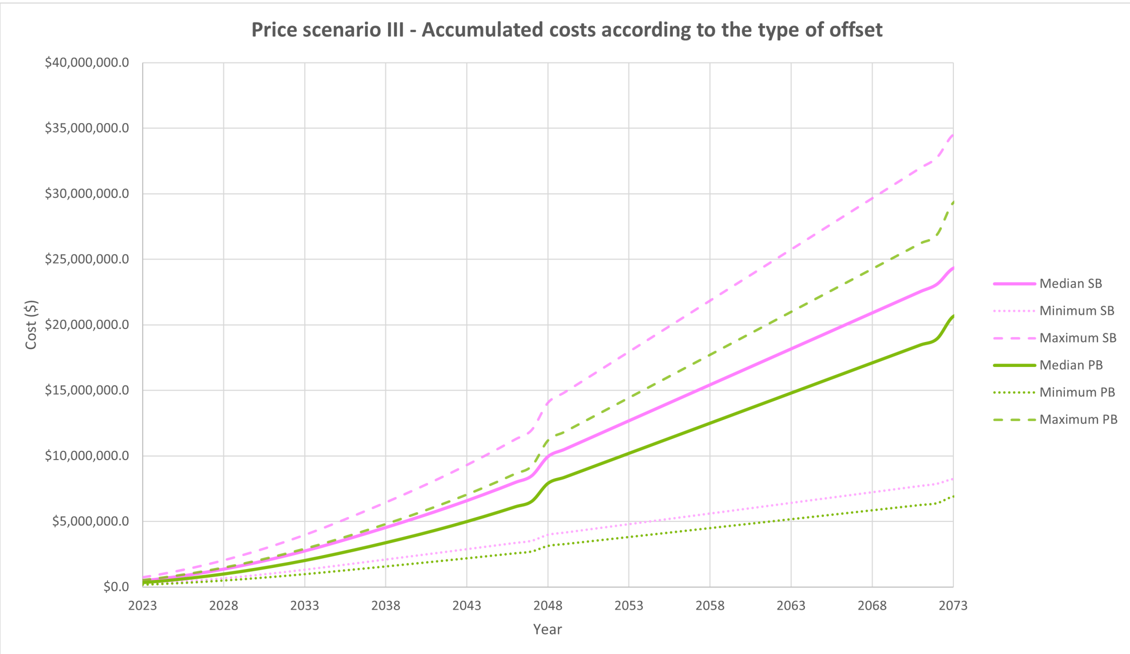


Figure 4.64: Projection of accumulated costs for Price Scenario III

credible Net Zero claim, but also because it will be most surely needed to reduce costs.

Cost projections obtained with Price Scenario III, which represents average prices in 2022 for each type of offset, show that Net Zero state following Oxford's trajectory would be totally out of reach from an economic point of view with current offset prices. This emphasises the need to reduce type V offsets costs if offsetting is to be performed following Oxford's offsetting principles.

Table 4.11 provides a summary of costs for the Standard and Proposed Building scenarios according to the three different offset's price scenarios.

	Projection of accumulated costs								
	Price Scenario I			Price Scenario II			Price Scenario III		
	Avg	Min	Max	Avg	Min	Max	Median	Min	Max
Standard Building	$0.298 M	$0.223 M	$0.372 M	$3.731 M (+1,154%)	$2.984 M	$4.478 M	$24.312 M (+8,069%)	$8.245 M	$34.506 M
Proposed Building	$0.238 M	$0.179 M	$0.298 M	$3.136 M (+1,217%)	$2.517 M	$3.755 M	$20.656 M (+8,573%)	$6.912 M	$29.320 M

Table 4.11: Summary table of cost projections for Price Scenarios I, II & III for the Standard and Proposed Building scenarios. The percentages added to the average and median columns of scenario II and III refer to the increase in percentage with respect to scenario I

4.2.4 Increase in the number of PV panels

In contrast with past analyses that considered only the minimum amount of PV, this section hypothesizes an increase in the total amount of solar panels installed. The goal of this analysis is to assess how operational emissions can be reduced and the cost savings associated with this reduction.

Since the amount of solar PV panels would have an impact on costs, in this analysis was included:

- Cost of offsets required
- Cost of the solar panels
- Cost of the electricity acquired from the grid
- Revenue obtained by the electricity surplus sold to the grid

The same values of “Autoconsumption”, “Electricity price”, “Price of electricity surplus sold to the grid”, and “Cost of PV panels” as for Case A (**Section 4.1.4**) have been considered as a reference.

The following PV Scenarios will be assessed in this section:

➢ **PV Scenario I:** The photovoltaic system is designed to produce the amount of electricity required. The energy surplus and the energy requirements not covered by the PV system will be balanced with the grid network.

  - **Standard Building:**
    Total electricity requirement: 8,199,081 kWh/year
    Total electricity produced by solar PV: 0 kWh/year
    Total energy auto-consumed: 0 kWh/year
    Total energy surplus sold to the grid: 0 kWh/year
    Energy acquired from the electricity grid: 8,199,081 kWh/year

N° of PV panels of 400 V: 0

- **Proposed Building:**

  Total electricity requirement: 7,742,583 kWh/year
  Total electricity produced by solar PV: 7,743,044 kWh/year
  Total energy auto-consumed: 4,645,827 kWh/year
  Total energy surplus sold to the grid: 3,097,218 kWh/year
  Energy acquired from the electricity grid: 3,096,756 kWh/year
  N° of PV panels of 400 V: 13,368
  Total area covered by the panels: 27,707 m^2

➢ **PV Scenario II:** The solar power system is designed to produce a third more than the energy required, which will be then sold to the grid. The energy surplus and the energy requirements not covered by the PV system will be balanced with the grid network.

- **Standard Building:**

  Total electricity requirement: 8,199,081 kWh/year
  Total electricity produced by solar PV: 0 kWh/year
  Total energy auto-consumed: 0 kWh/year
  Total energy surplus sold to the grid: 0 kWh/year
  Energy acquired from the electricity grid: 8,199,081 kWh/year
  N° of PV panels of 400 V: 0

- **Proposed Building:**

  Total electricity requirement: 7,742,583 kWh/year
  Total electricity produced by solar PV: 10,323,576 kWh/year
  Total energy auto-consumed: 6,194,146 kWh/year
  Total energy surplus sold to the grid: 4,129,430 kWh/year
  Energy acquired from the electricity grid: 1,548,437 kWh/year
  N° of PV panels of 400 V: 17,823
  Total area covered by the panels: 36,941 m^2

4.2.4.1 Operational and embodied CO_2e emissions

Figures 4.65 to 4.68 illustrate total and operational emissions in the case of PV Scenario I.

➢ **PV Scenario I (production of 100% electricity demand):**

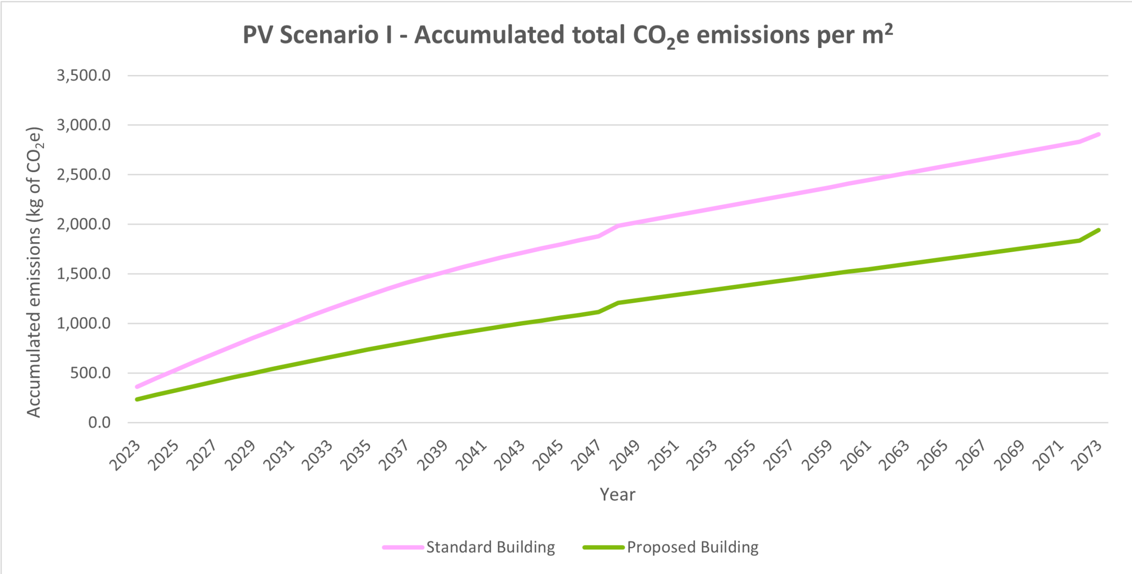


Figure 4.65: Total accumulated emissions per m^2, PV Scenario I

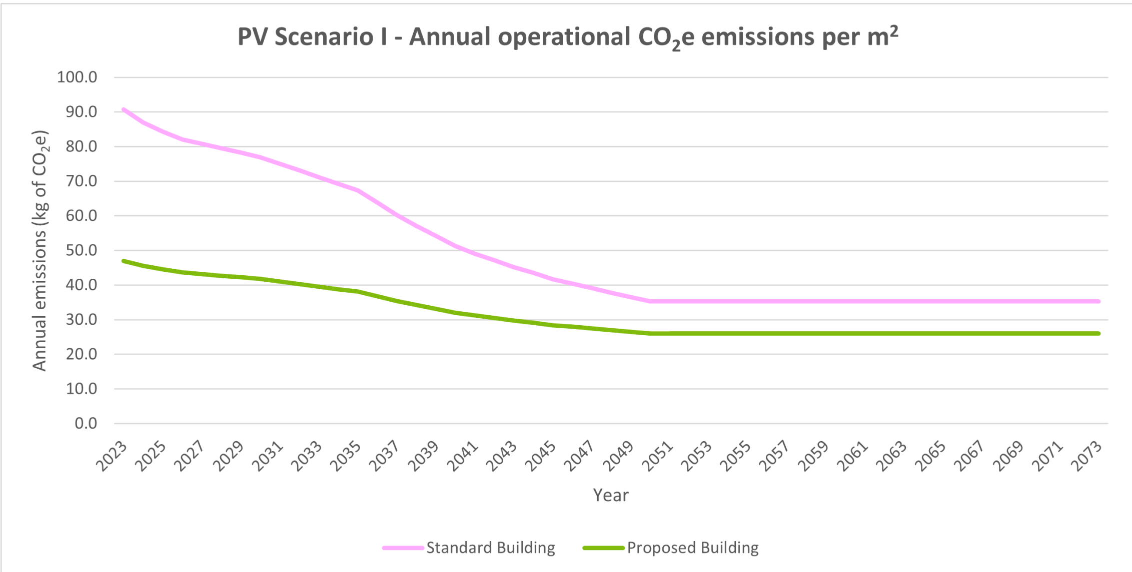


Figure 4.66: Annual operational emissions per m^2, PV Scenario I

➢ PV Scenario II (production of 133% electricity demand):

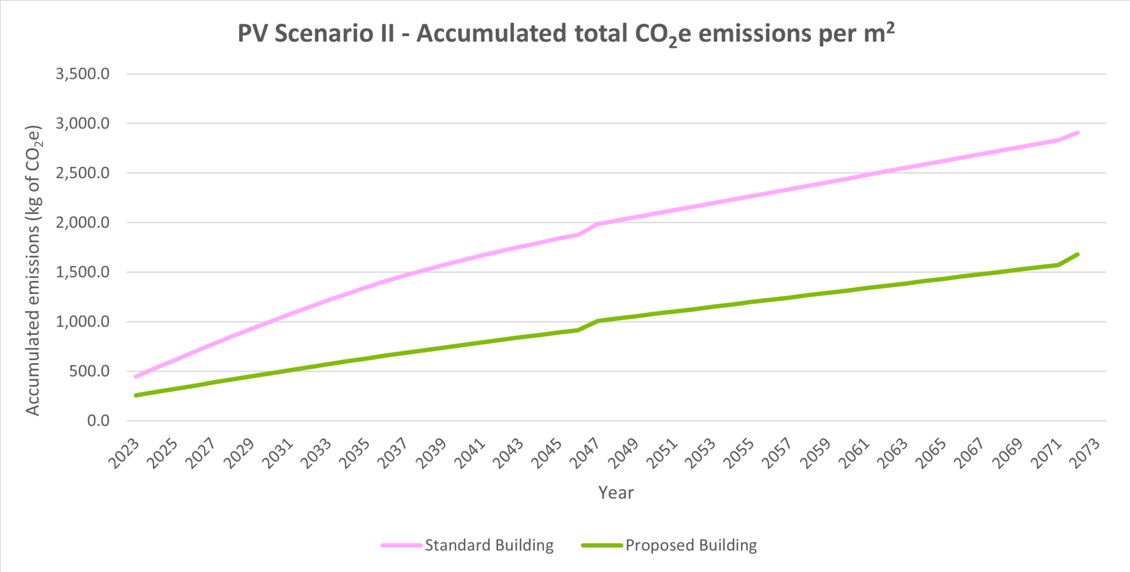


Figure 4.67: Total accumulated emissions per m², PV Scenario II

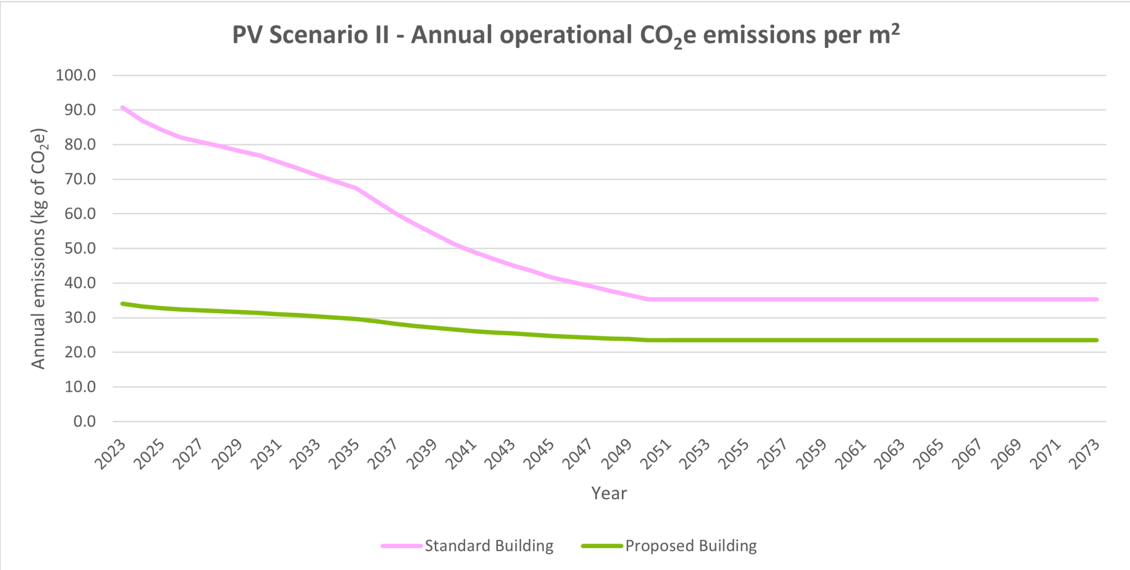


Figure 4.68: Annual operational emissions per m², PV Scenario II

Table 4.12 provides a comparison of the results obtained to better illustrate the emissions reductions achieved by increasing the amount of PV panels.

		Min PV req		PV Scenario I		PV Scenario II	
Building type	**Unit**	**TAE**	**OAE**	**TAE**	**OAE**	**TAE**	**OAE**
Standard Building	kg CO_2e/m^2	2,910	2,530	2,910	2,530	2,910	2,530
Proposed Building	kg CO_2e/m^2	2,329	1,991	1,941 (-16.7%)	1,602 (-19.5%)	1,679 (-27.9%)	1,340 (-32.7%)

Table 4.12: Summary table of the different scenarios analysed. TAE refers to Total Accumulated Emissions (embodied+operational), while OAE refers to Operational Accumulated Emissions. The percentage indicates the reduction with respect to the scenario of minimum PV required

4.2.4.2 Offsets required to achieve Net Zero Carbon in PV Scenarios I & II

Figure 4.69 illustrates the total offsets needed to offset the embodied and operational emissions throughout the building's life cycle for PV Scenario I. **Figure 4.70** presents values obtained for PV Scenario II. Emissions are presented in tonnes of CO_2e, therefore, they consider the emissions associated with the total surface of the building.

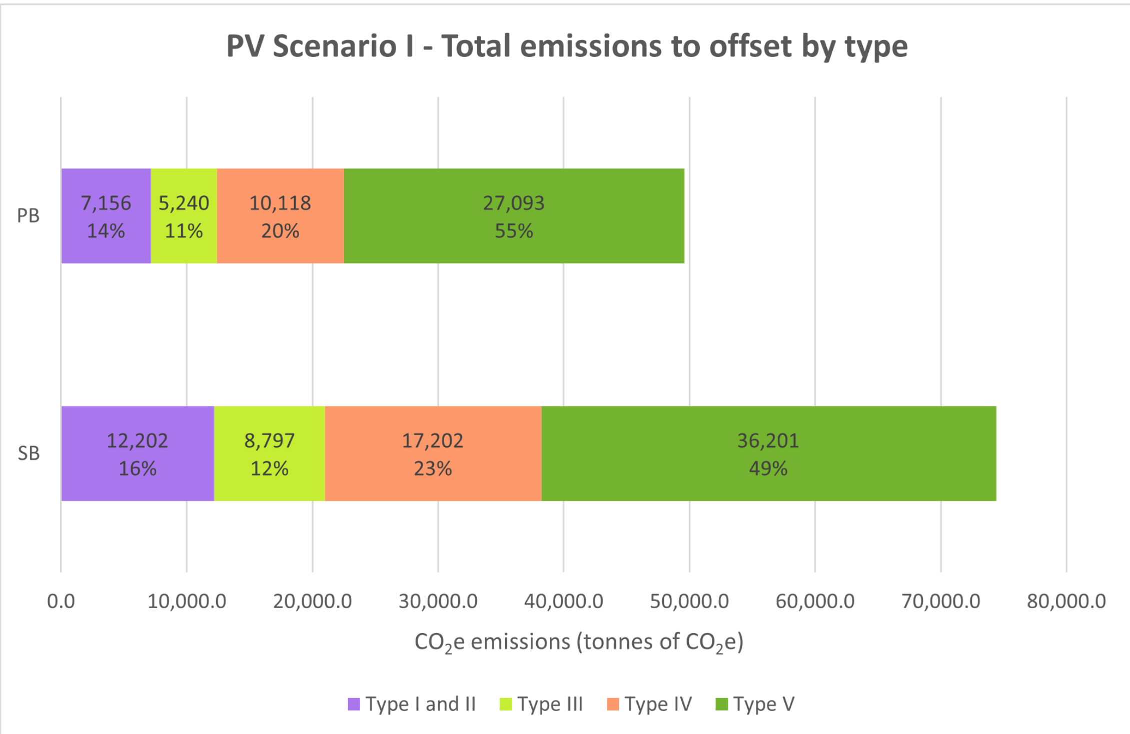


Figure 4.69: Total emissions (operational & embodied) for the case of PV Scenario I, classified by offset type

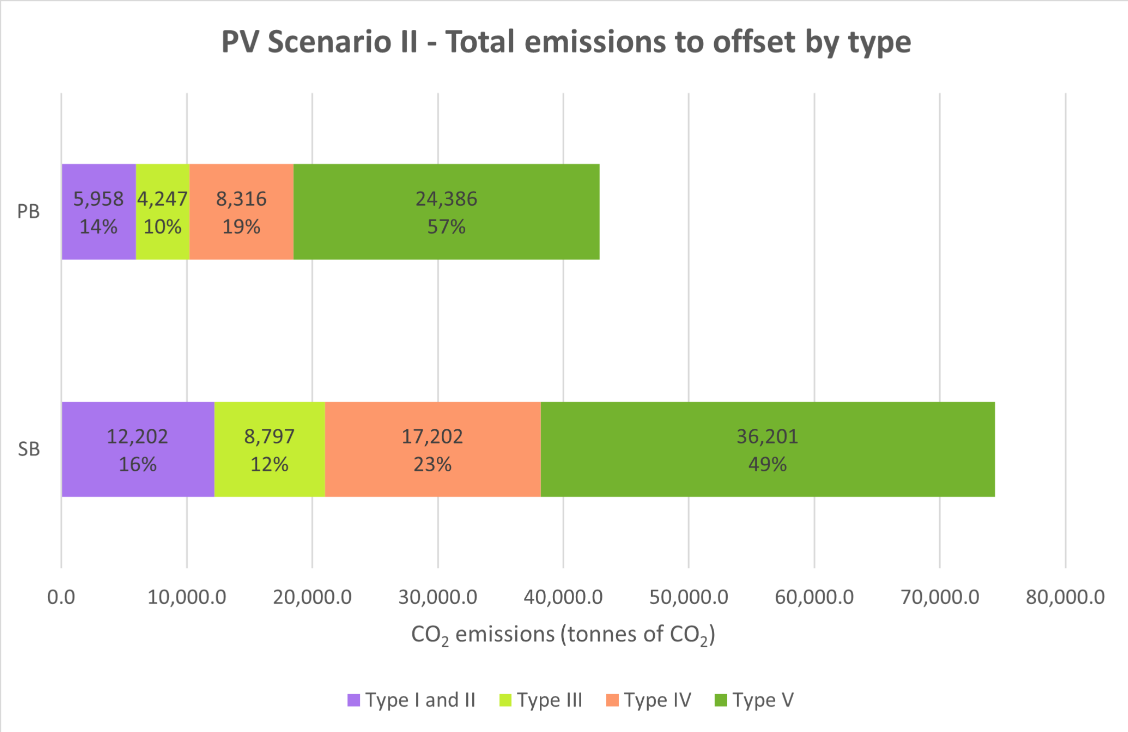


Figure 4.70: Total emissions (operational & embodied) for the case of PV Scenario II, classified by offset type

According to these figures, the proposed building of PV Scenario II requires the least amount of offsets to compensate for its embodied and operational emissions. The total emissions needed for each scenario are shown in **Table 4.13**.

	Unit	Standard Building	Proposed Building
PV Scenario I	tCO_2e	74,401	49,607 (-33%)
PV Scenario II	tCO_2e	74,401	42,906 (-42%)

Table 4.13: Comparison of offsets requires in each scenario. The reduction in percentage is with respect to the Standard Building case, which remains constant in the different scenarios

4.2.4.3 Cost projections

Figures 4.71, 4.72, and 4.73 present the cost forecasts for PV Scenario I for the different Price Scenarios introduced in **Section 2.4.1**.

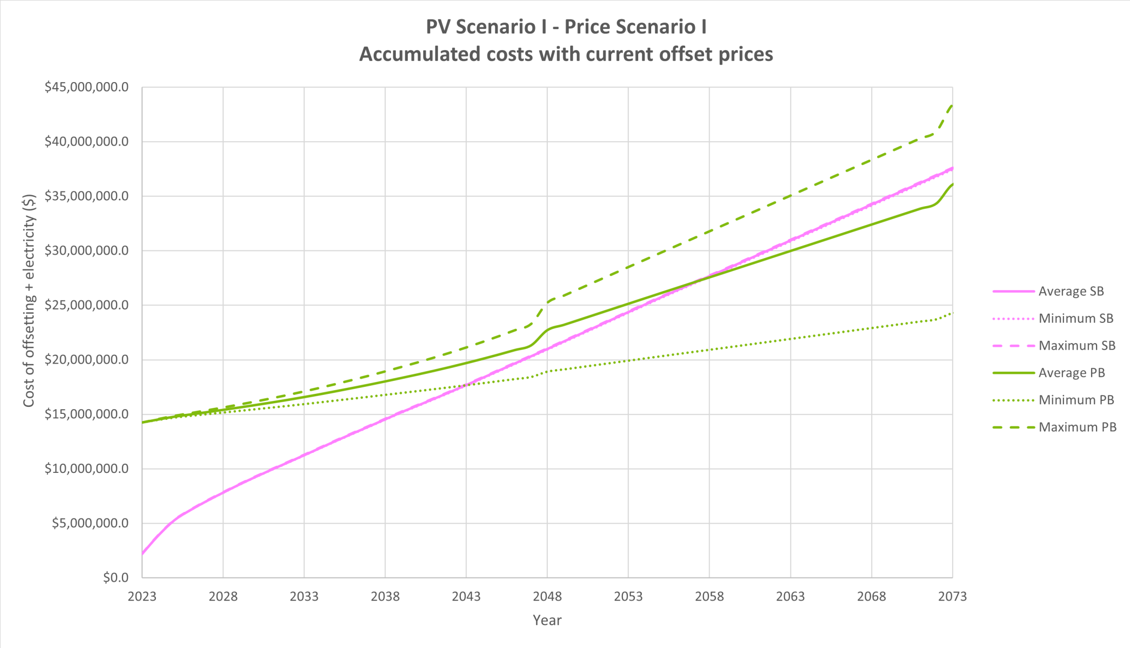


Figure 4.71: Projection of accumulated costs for PV Scenario I, Price Scenario I

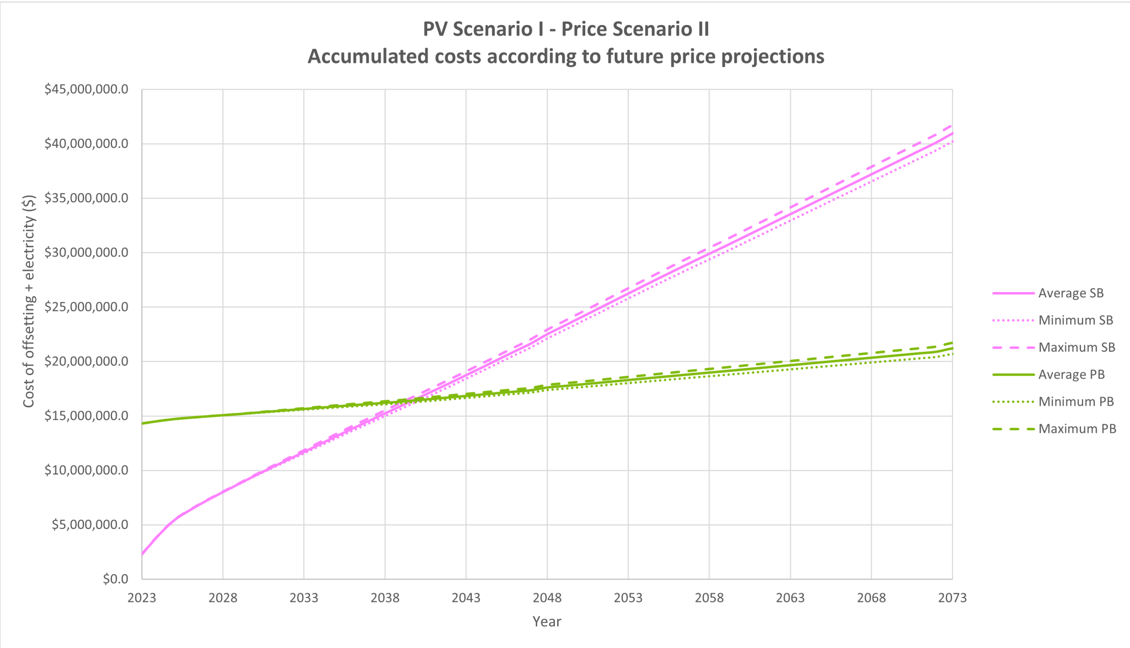


Figure 4.72: Projection of accumulated costs for PV Scenario I, Price Scenario II

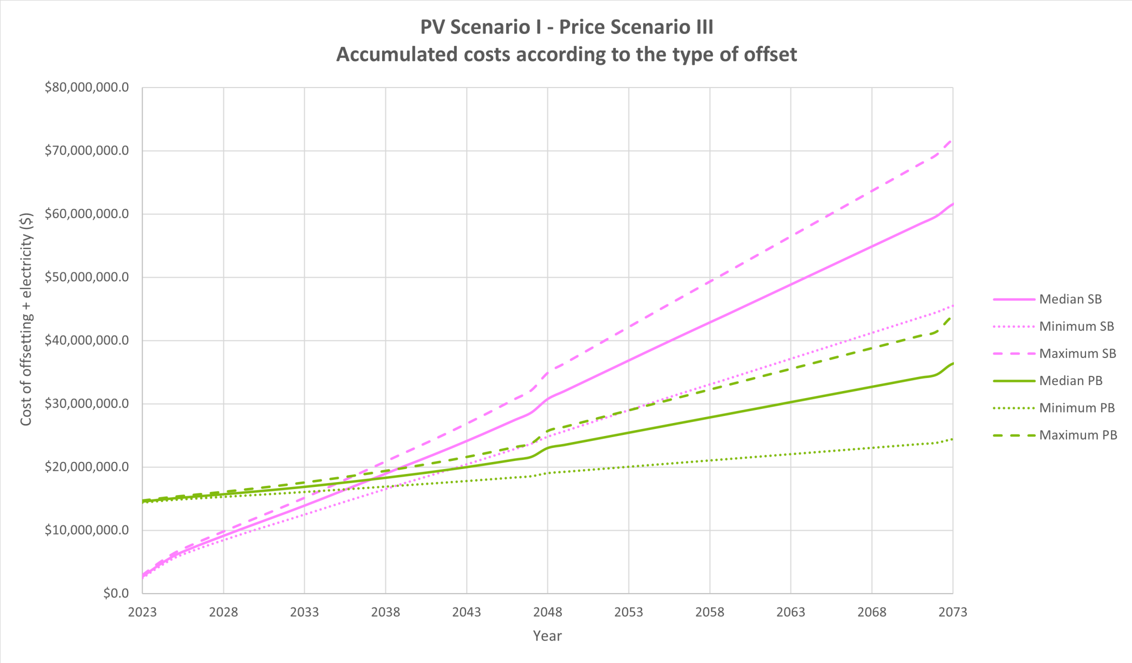


Figure 4.73: Projection of accumulated costs for PV Scenario I, Price Scenario III

Figures 4.74, 4.75, and 4.76 illustrate the cost projections for PV Scenario II, in which energy production is increased up to 133% of the energy requirement.

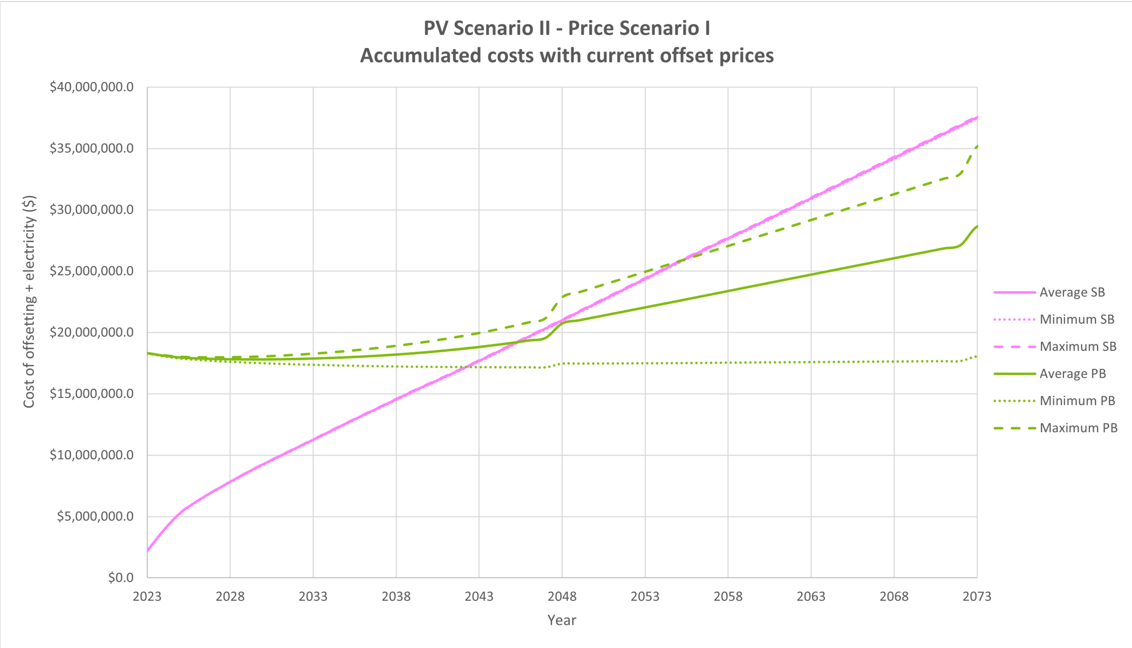


Figure 4.74: Projection of accumulated costs for PV Scenario II, Price Scenario I

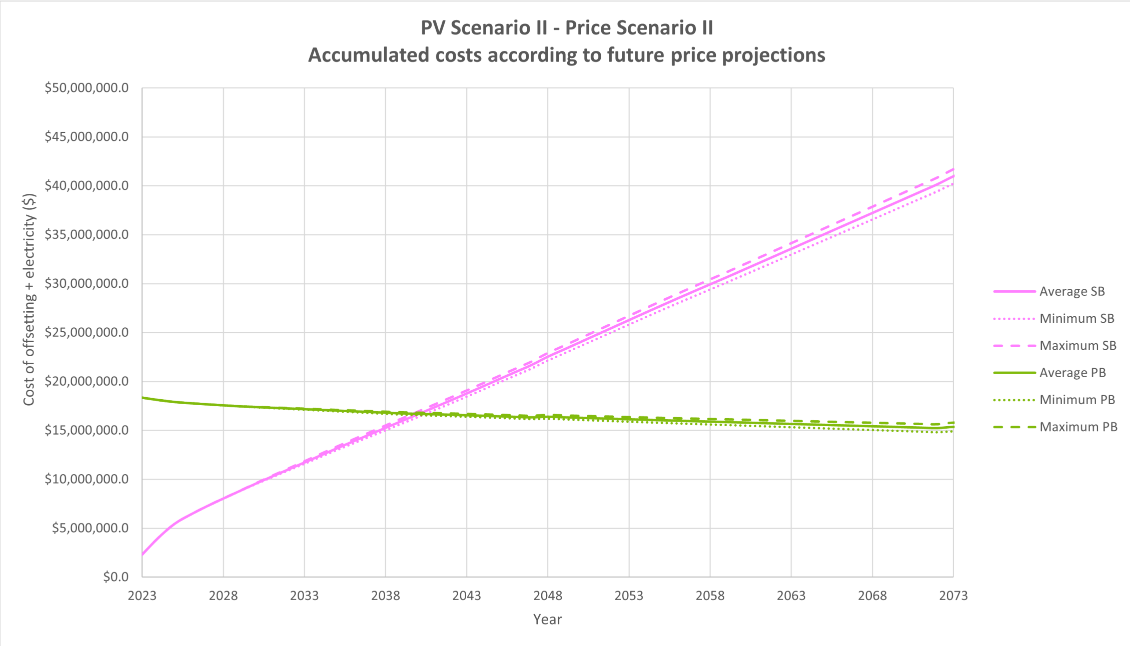


Figure 4.75: Projection of accumulated costs for PV Scenario II, Price Scenario II

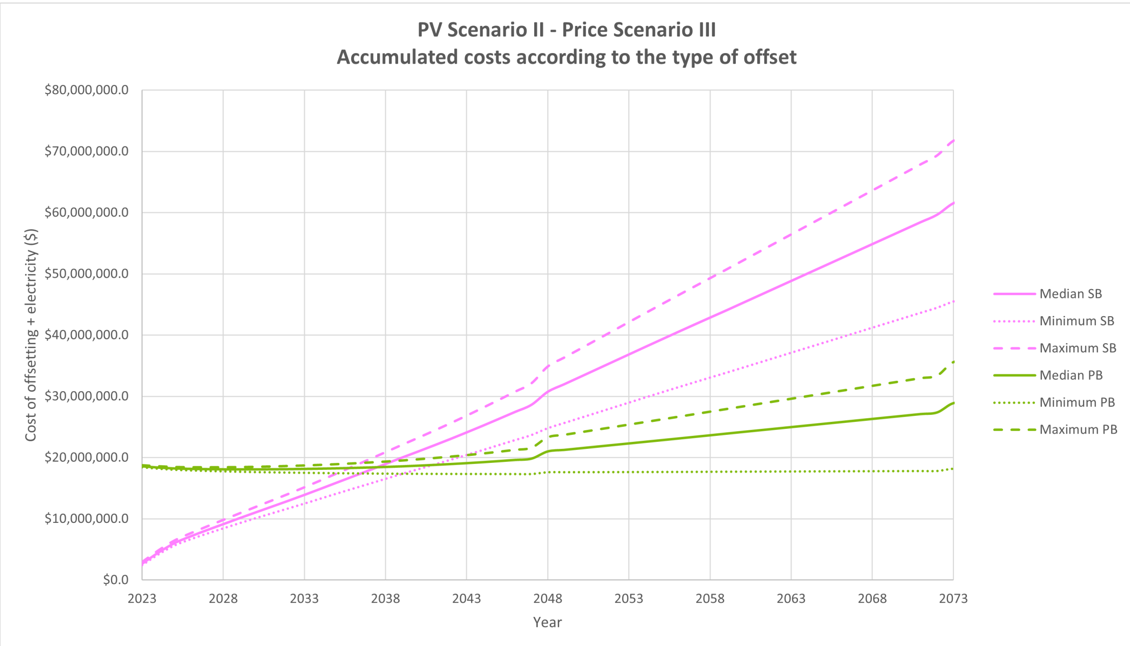


Figure 4.76: Projection of accumulated costs for PV Scenario II, Price Scenario III

Table 4.14 summarises the results obtained in each scenario.

	Projection of accumulated costs (average costs)					
	Price Scenario I		**Price Scenario II**		**Price Scenario III**	
	PV Sc I	**PV Sc II**	**PV Sc I**	**PV Sc II**	**PV Sc I**	**PV Sc II**
Standard Building	$44.086 M	$44.086 M	$47.519 M	$47.519 M	$68.100 M	$68.100 M
Proposed Building	$41.027 M	$27.634 M (-32.6%)	$22.600 M	$14.364 M (-36.4%)	$41.320 M	$27.910 M (-32.5%)

Table 4.14: Summary table of cost projections for Price Scenarios I, II & III. The percentages refer to the change in PV Scenario II with respect to PV Scenario I

4.2.4.4 Conclusions

The results obtained in Case B are consistent with those obtained in Case A, and therefore they further support the conclusion that reducing the emissions associated with the operation and construction phases to the minimum possible is also convenient from an economic point of view.

Chapter 5

Conclusions, limitations, and future perspectives

Chapter 4 introduced two different case studies that analysed how an offsetting strategy could be applied to different types of buildings by following Oxford's offsetting principles. For the purpose of providing a straightforward comparison and enabling the extrapolation of these results to other cases, **Section 5.1 and 5.2** summarise the main results obtained for a new construction of each building type analysed. **Section 5.3** provides an overview of existing frameworks and future perspectives regarding offsetting in the building sector, while **Section 5.4** highlights the limitations of the study and the main conclusions.

5.1 Comparison of offsets required per m^2 according to the type of building

In order to provide an overview of the total emissions per m^2 to be offset in the case of a new construction designed to have lower environmental impacts, the results for three different building types are provided in **Table 5.1**.

		Offsets required per m^2		
PV Scenario	**Unit**	**Office**	**Residential**	**Industrial**
Min required PV	kg CO_2e/m^2	1,018	960	2,329
PV Scenario I	kg CO_2e/m^2	802 (-21.2%)	763 (-20.5%)	1,941 (-16.7%)
PV Scenario II	kg CO_2e/m^2	724 (-28.8%)	692 (-27.9%)	1,679 (-27.1%)

Table 5.1: Summary table of total offsets required for a building of new construction. The percentages refer to the change in PV Scenario I and PV Scenario II with respect to the scenario of minimum required PV

Since the energy requirements are much larger for the industrial building, there is a larger opportunity to reduce emissions by increasing the production of renewable energy. This is reflected in terms of total reductions in kg CO_2e/m^2, which for an office building correspond to a maximum of 294 kg CO_2e/m^2 and for a residential building up to 268 kg CO_2e/m^2, while for an industrial building this reduction can scale up to 650 kg CO_2e/m^2. However, the large surface requirements needed for the installation of solar panels represents a huge challenge. The use of off-site renewable procurement presented in **Section 3.3.1** should be considered as an important means to reduce operational emissions if the production of renewable electricity is challenged by a lack of surface available.

Regarding off-site renewable procurement solutions, an analysis of the options available for the specific location should be carried out. High-quality green tariffs, for example, may not be available in every region, and information regarding Power Purchase Agreements (PPAs) may not be very diffused or of common knowledge. In that case, it could be wise to seek advice from a consultant to explore off-site solutions locally available.

5.2 Comparison of offsetting costs per m^2 according to the building use and the price scenario adopted

Table 5.2 compares the costs per m^2 required to compensate for a building of new construction according to the building's use correspondent to the scenario of minimum required PV.

	Cost of offsets required per m^2		
	Office	**Residential**	**Industrial**
Price Scenario I (average)	\$4.1	\$3.8	\$9.3
Price Scenario II (average)	\$43.4 (+965%)	\$40.3 (+949%)	\$122.7 (+1,217%)
Price Scenario III (median)	\$278.9 (+6,748%)	\$258.9 (+6,633%)	\$807.9 (+8,573%)

Table 5.2: Summary table of costs required to offset emissions per m^2 for a building of new construction according to the building's use. The percentages refer to the change in Price Scenario II and III with respect to Price Scenario I. Values are in US dollars

These results correspond to the costs associated with the total building's emissions throughout its 50-years life-span. The aim of presenting these results is to highlight the great contrast between the three different price scenarios analysed. This wide variability remarks the need of more specific frameworks on how to approach offsetting and the necessity of consistent price projections, which would lead to more accurate forecasts.

5.2.1 Medium-term projections

Since it is not possible to make accurate long-term projections of offsetting costs, the results of a 20-year forecast will be presented in this section. The cost projection in this case will be performed only for Price Scenario III, which represents the offsetting strategy developed by Oxford with current offset prices.

Figures 5.1, 5.2, and 5.3 illustrate the annual emissions (embodied + operational) per m^2 to be offset by 2043, for the case of minimum required PV installed.

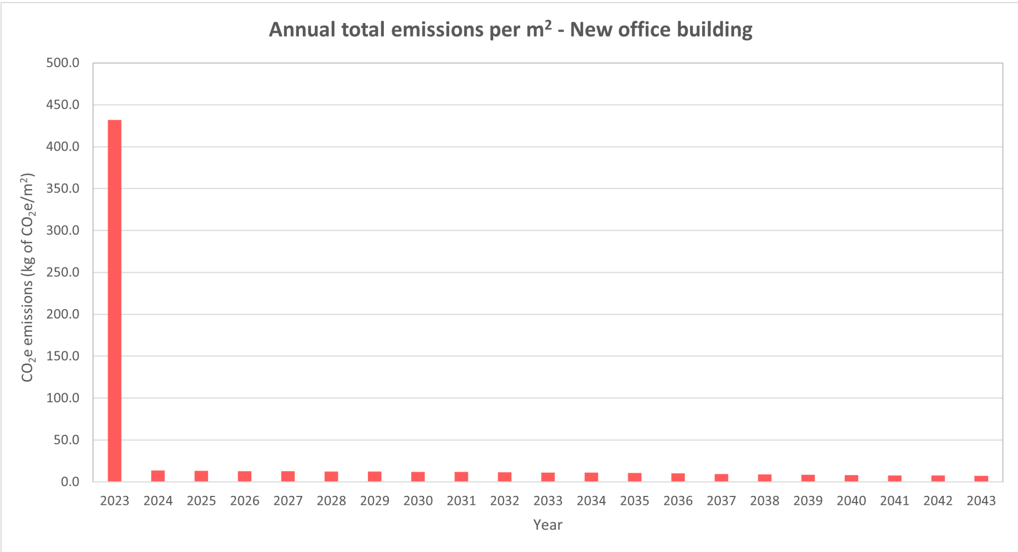


Figure 5.1: Annual embodied and operational emissions for a new office building

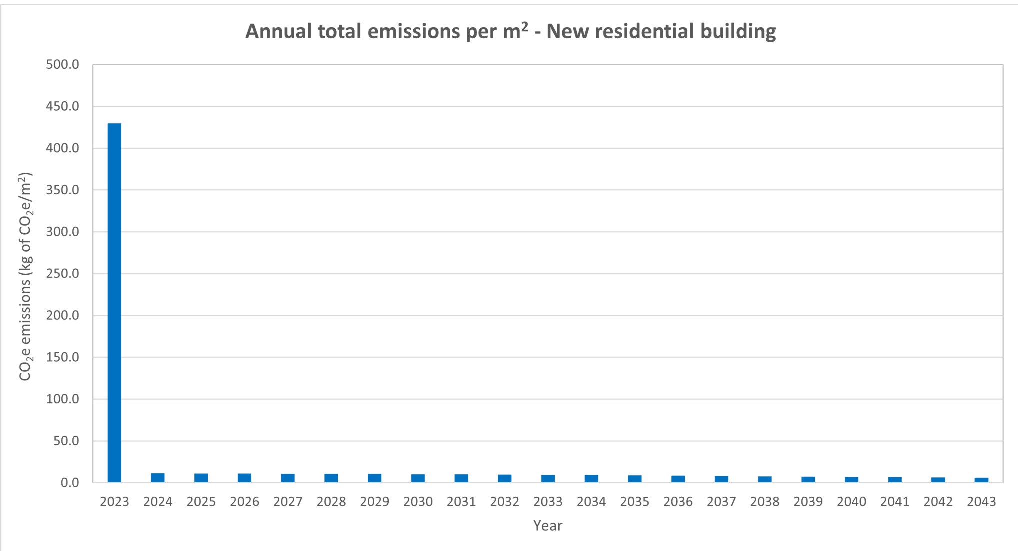


Figure 5.2: Annual embodied and operational emissions for a new residential building

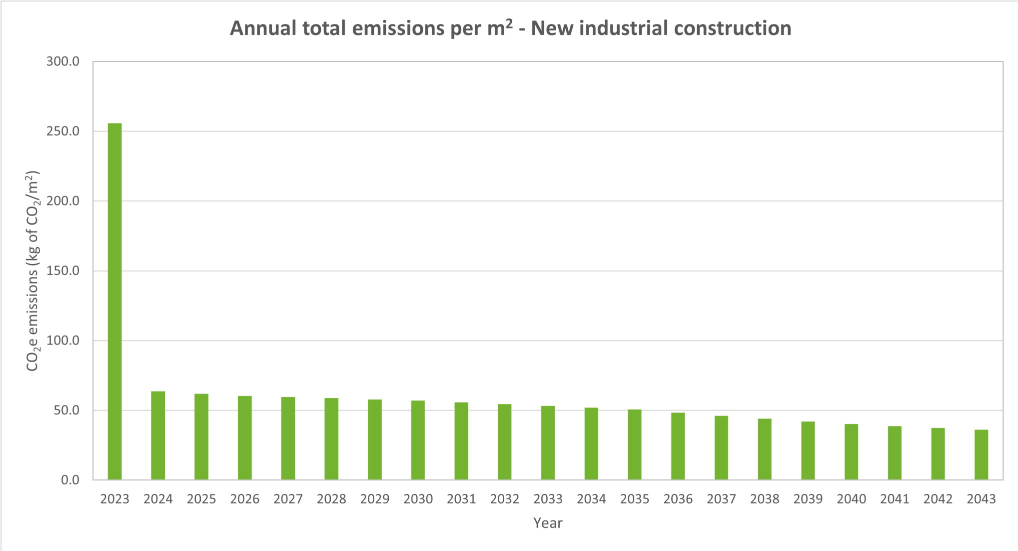


Figure 5.3: Annual embodied and operational emissions for a new industrial building

As it can be appreciated in the figures, the share of embodied emissions is much larger for the residential and office buildings due to the enormous energy requirements of the industrial building. By 2043, the accumulated emissions for the new office building are 645 kg CO_2e/m^2, 612 kg CO_2e/m^2 for the residential, and 1,274 kg CO_2e/m^2 for the industrial new construction.

In order to provide results of annual costs per m^2 for each case, **Figures 5.4, 5.5, and 5.6** provide both annual and accumulated offsetting costs per m^2.

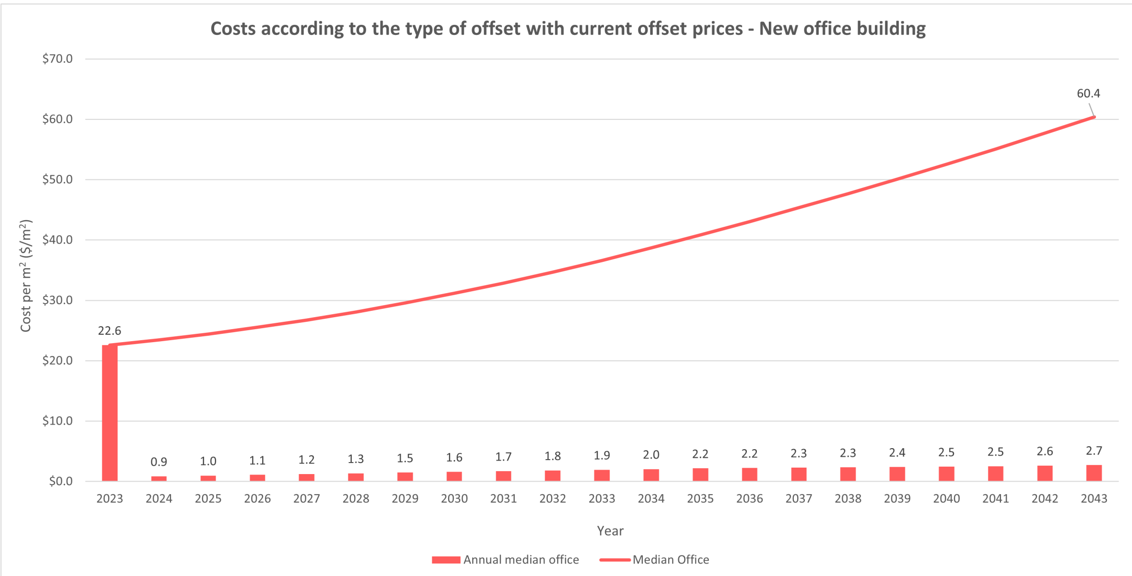


Figure 5.4: Annual and accumulated offsetting costs per m^2 for a new office building, for Price Scenario III

Figure 5.5: Annual and accumulated offsetting costs per m^2 for a new residential building, for Price Scenario III

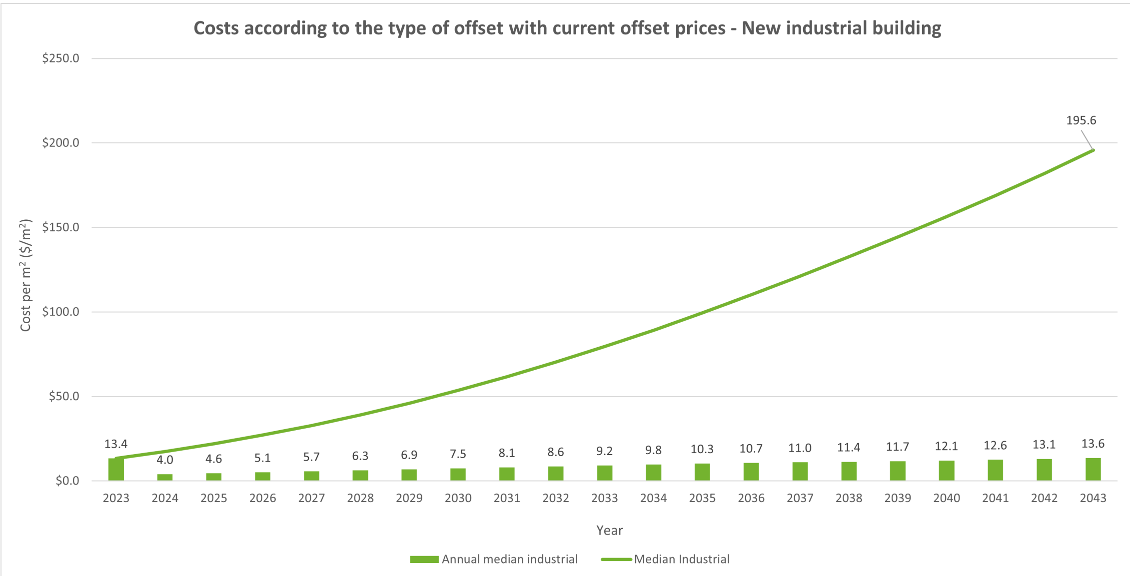


Figure 5.6: Annual and accumulated offsetting costs per m^2 for a new industrial building, for Price Scenario III

A comparison of offsetting costs per m^2 for the three building scenarios is presented in **Figure 5.7**. As it can be observed, the initial costs per m^2 for the industrial building are lower than for the other two cases. This is because the embodied emissions per m^2 from the construction phase in the industrial building are less than for the office and residential buildings. However, the industrial building is associated with higher operational emissions, which leads to a rapid cost increase over time. For the residential and office buildings, costs per m^2 are very similar during all their life-span, mostly at the beginning. This is due to the fact that they have associated the same embodied emissions and only their energy requirements differ.

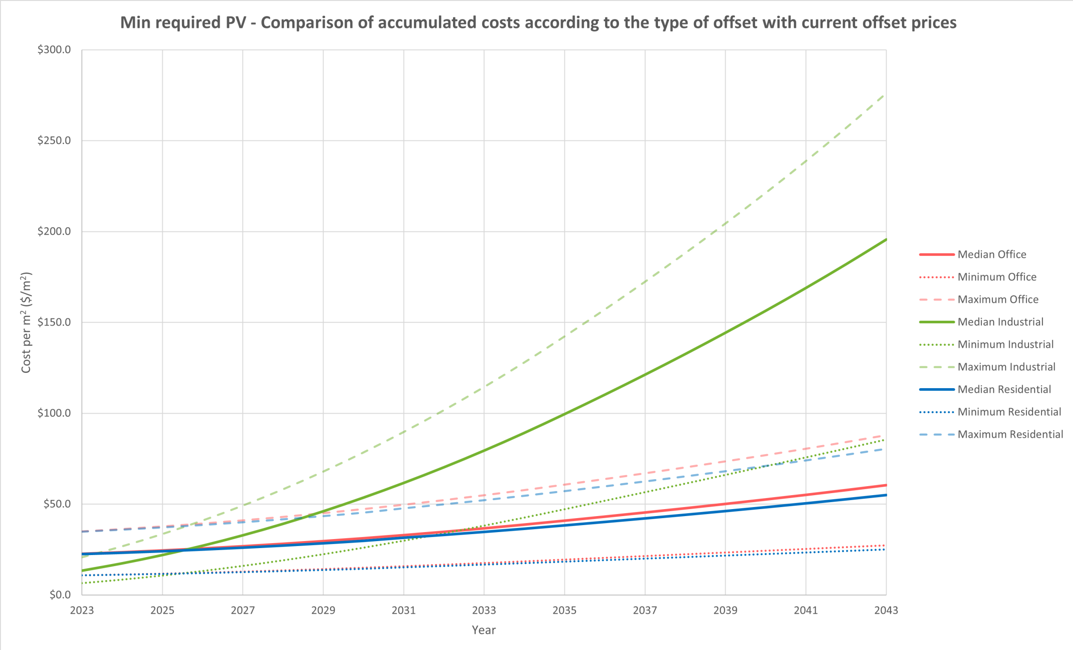


Figure 5.7: Comparison of accumulated offsetting costs for three different building types. The results were obtained with Price Scenario III, which represents current offset prices and follows Oxford's offsetting strategy

In order to see which are the impacts of increasing the amount of PV production in terms of costs, a comparison of the results obtained for PV Scenario I and PV Scenario II are illustrated in **Figures 5.8 and 5.9**. In PV Scenario I, the amount of PV installed is increased up to 7,743,044 kWh/year (production equal to 100% of energy requirements), and in PV Scenario II up to 10,323,576 kWh/year (production equal to 133% of energy requirements).

The following aspects have been considered to estimate the costs:

- Cost of the PV installation;
- Cost of offsetting remaining emissions;
- Cost savings due to the production of electricity:
  - Cost savings in electricity, which otherwise would have been acquired from the grid. It is considered a 60% of autoconsumption and electricity costs presented in **Section 4.1.4**
  - Revenues from the energy surplus sold to the grid, considering electricity prices presented in **Section 4.1.4**

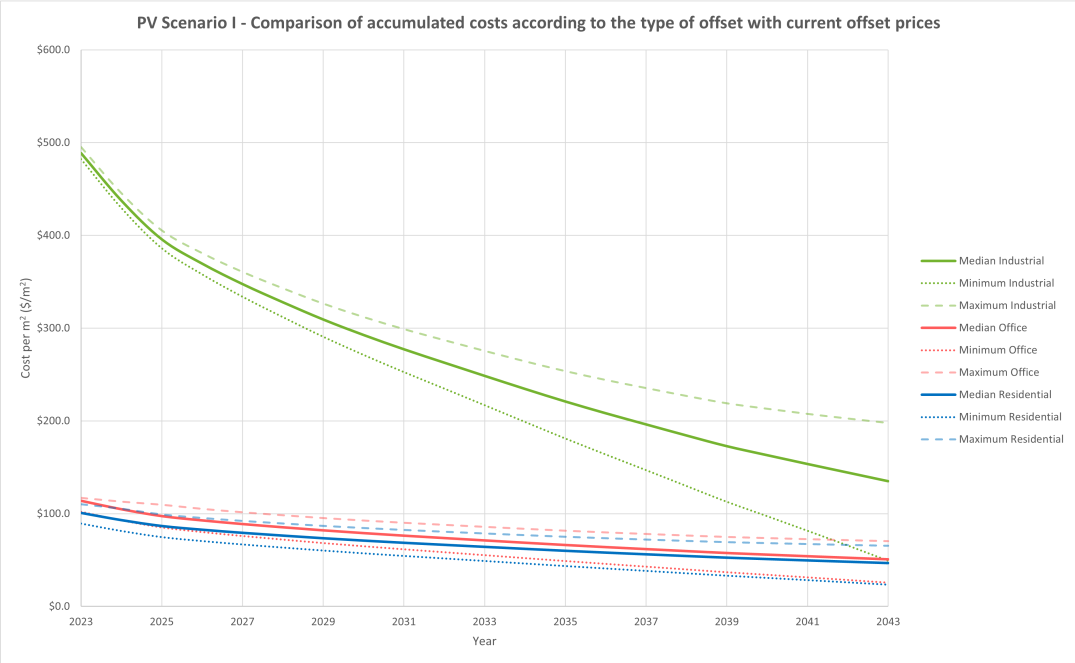


Figure 5.8: Comparison of accumulated offsetting costs for three different building types for PV Scenario I. The results were obtained with Price Scenario III, which represents current offset prices and follows Oxford's offsetting strategy

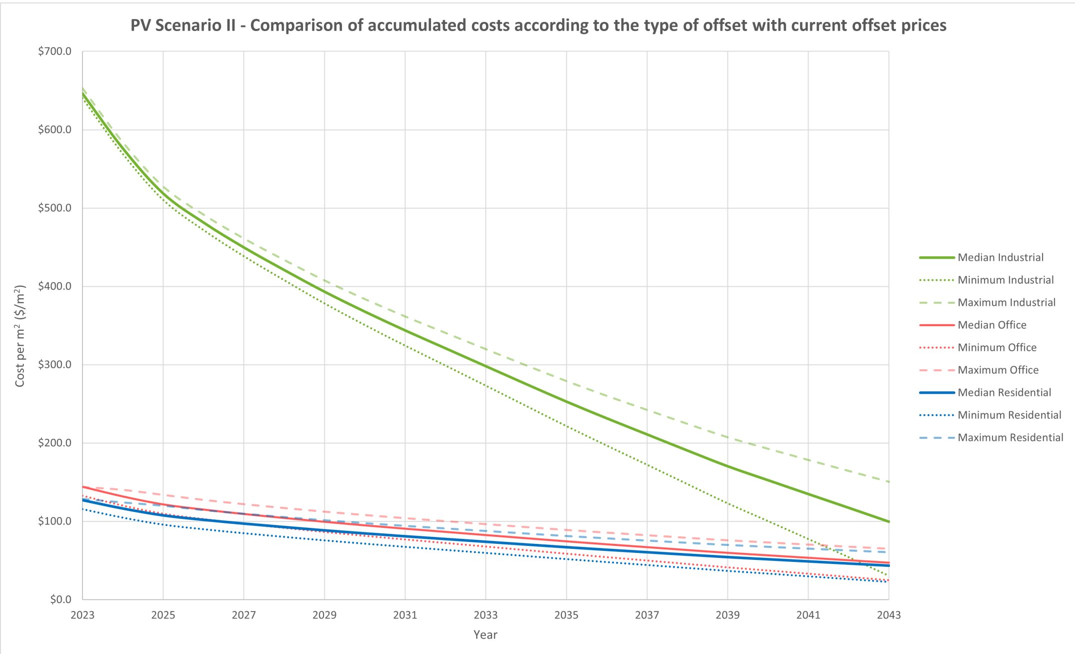


Figure 5.9: Comparison of accumulated offsetting costs for three different building types for PV Scenario II. The results were obtained with Price Scenario III, which represents current offset prices and follows Oxford's offsetting strategy

It can be observed that when cost savings in the scenarios of increased PV are analysed, the trend obtained is opposed to the trend shown in **Figure 5.7**. This change is due to the fact that the yearly costs savings in electricity are considerably high, and at the same time the emissions to be offset are reduced because of the use of renewable electricity.

As a result of the opposite trends, it is possible to obtain the year in which the costs of the PV installation are compensated by the cost savings in electricity. **Figure 5.10, 5.11, and 5.12** illustrate this scenario for each building case. For the industrial building, the investment made to install the PV panels is paid off in 2040, while for the other two cases is paid off in 2041.

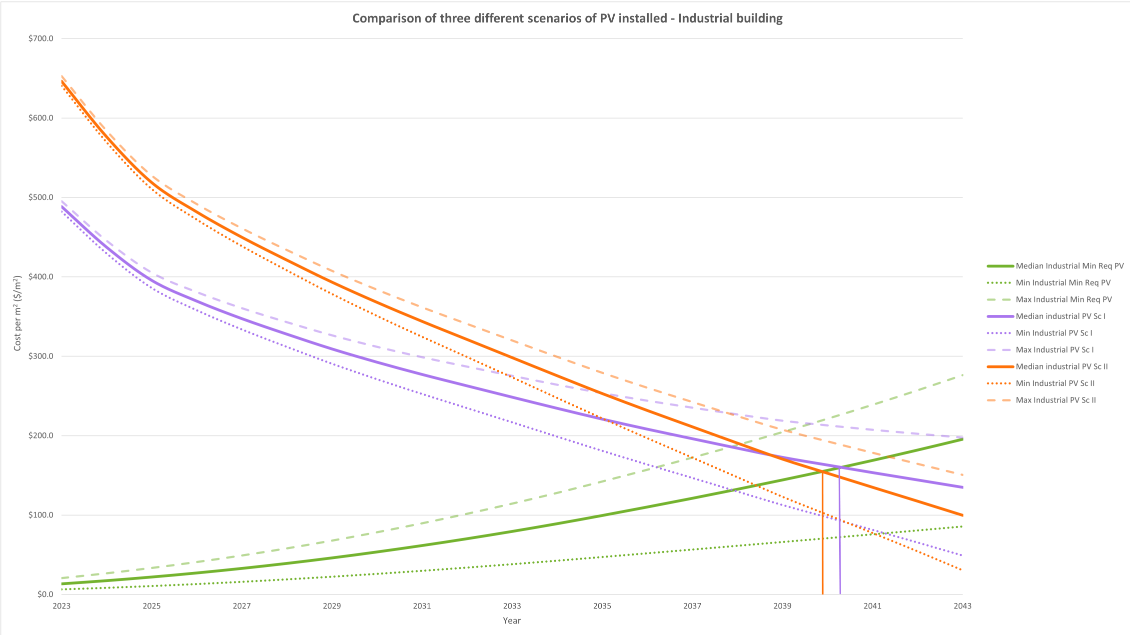


Figure 5.10: Comparison of accumulated costs per m^2 for the three PV scenarios analysed for the Industrial building

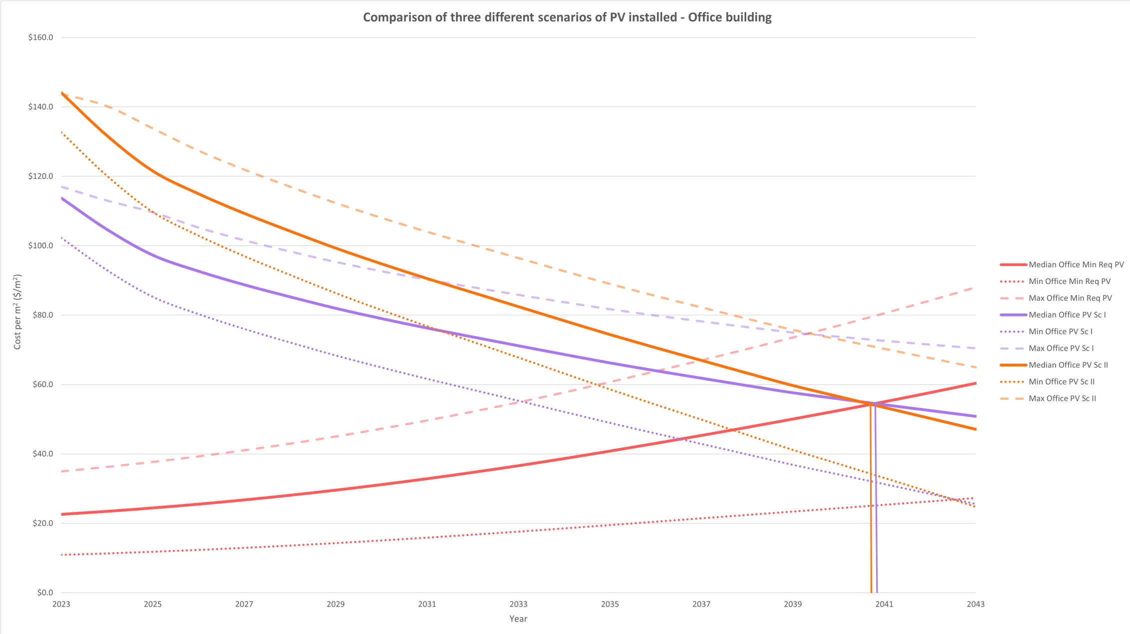


Figure 5.11: Comparison of accumulated costs per m^2 for the three PV scenarios analysed for the Office building

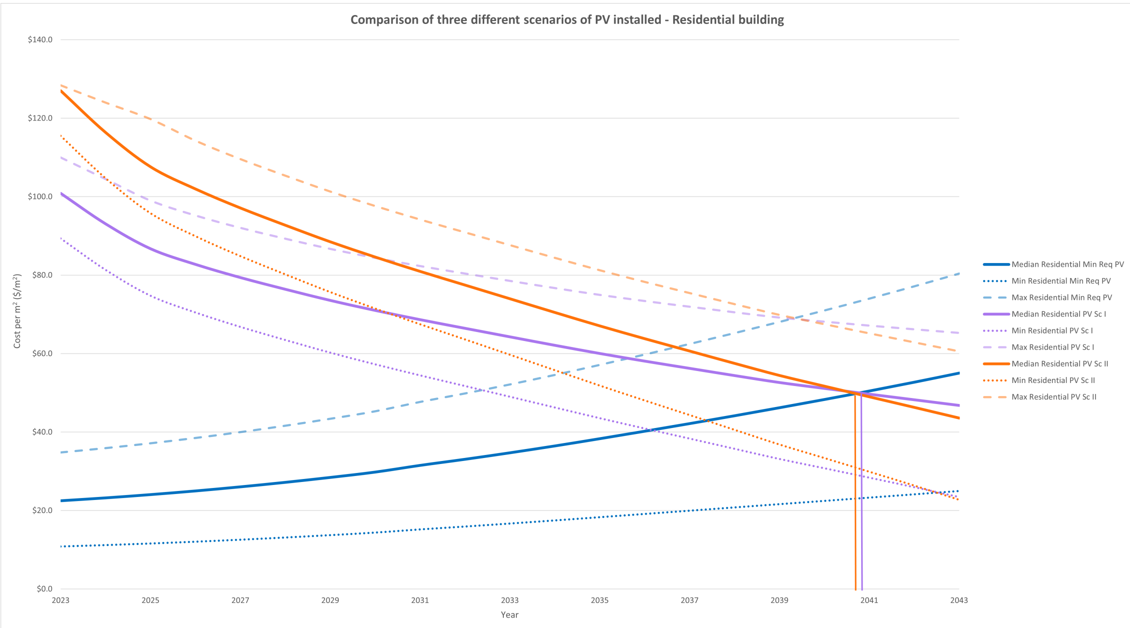


Figure 5.12: Comparison of accumulated costs per m^2 for the three PV scenarios analysed for the Residential building

With the aim of summarising the final values obtained for each building type and scenario, **Table 5.3** provides the costs per m^2 by 2043. However, it should be considered that if a different period is analysed, the results will be different due to the variation in prices and emissions over the years.

		Unit	Industrial	Office	Residential
General information	**Area**	m^2	25,568	11,317	11,317
	Electricity needed	MWh/year	7,746	599	515
Min required PV	**Emissions**	kg CO_2e/m^2	2,329	1,018	960
	Costs by 2043	$/m^2$	195.6	60.4	55.0
PV Increase I	**Emissions**	kg CO_2e/m^2	1,941	802	763
	Costs by 2043	$/m^2$	134.9 (-31.0%)	50.9 (-15.7%)	47.1 (-14.4%)
PV Increase II	**Emissions**	kg CO_2e/m^2	1,679	724	692
	Costs by 2043	$/m^2$	99.8 (-49.0%)	47.1 (-22.0%)	43.6 (-20.7%)

Table 5.3: Summary table of median costs required to offset emissions per m^2 for a new construction in three different scenarios. The percentages refer to the change with respect to the scenario of minimum required PV. Values are in US dollars

The yerar 2043 was chosen as reference instead of the 50-years of life-span to consider that current offset values will most likely change over time. In addition, this time frame considers the year in which the investments are paid-off, which could be of interest to stakeholders.

From this table it can be easily recognised that there is a huge opportunity to reduce costs for large energy consumers by increasing the production of renewable energy (represented by the industrial building). The economic benefits of increasing the production of renewable electricity extend to buildings with lower energy needs, but on a smaller scale (represented by the office and residential buildings). This is due to the fact that the share of operational emissions for industries or organisms with large energy requirements is much bigger than for cases in which the energy requirement is smaller.

5.3 Current and future perspectives regarding offsetting frameworks in the building sector

UKGBC's "Renewable Energy Procurement & Carbon Offsetting" [14] is among the most detailed frameworks released on carbon offsetting in the building sector. According to this guidance, organisations and consumers are expected to make a transition aligned with the net zero path and with Oxford's Offsetting Principles. One important aspect regarding this framework is that it has no specific requirements regarding the type of carbon offset projects that can be funded. However, they anticipate reviewing this as the market develops.

While this framework provides a very comprehensive analysis of how offsetting should be approached, it should require a disclosure of the offset projects supported and how the entity or organism plans to design its offsetting strategy. This information could be very valuable when analysing the impacts of different Net Zero Carbon Buildings (NZCB) and could be used as a reference for organisms seeking to achieve a NZCB.

As part of the World Green Building Council's (WGBC) "Advancing Net Zero" initiative, the council aims to promote the development of NZCB around the globe. A key aspect of this initiative is the development of the framework "Net Zero Carbon Buildings: A Framework Definition", which was introduced in **Section 3.3** [236].

This framework has been developed by the UKGBC's Advancing Net Zero programme, motivated and in line with the "Advancing Net Zero" initiative from the WGBC [236].

In addition to the framework, the "Advancing Net Zero" initiative also provides other resources and tools to support the development and implementation of NZCBs. Among these resources are included guidance on energy efficiency, renewable energy technologies, building design, and case studies of other NZCB projects [215]. This initiative is expanding around the world through other Green Building Councils, which are developing Net Zero programmes and tools specific to their local market [215]. These GBCs are also advocating for national legislation to encourage the decarbonisation of the construction sector [215]. The GBCs around the world and the participants of this initiative are presented in **Figure 5.13** [215].

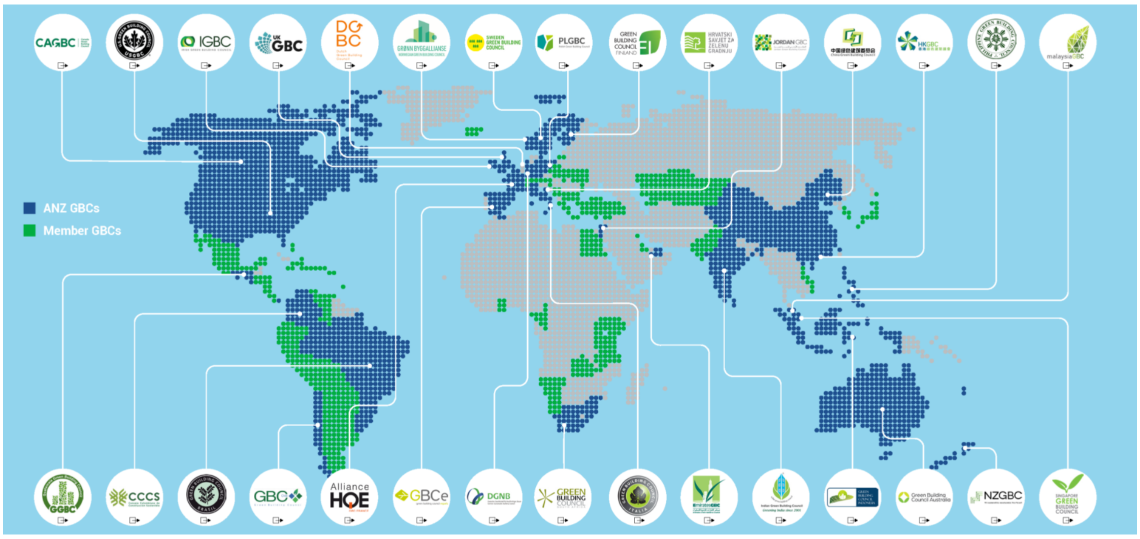


Figure 5.13: Green Building Councils and participants in the "Advancing Net Zero" initiative. Source: World Green Building Council [215]

While a number of frameworks and initiatives have been developed to support the advancement of Net Zero Carbon Buildings, concerns remain regarding the consistency and rigor of the offsetting approach employed. Despite efforts to establish best practices and provide guidance, it is still difficult to apply offsetting uniformly across different projects. In this context, the development of detailed offsetting frameworks in the building sector is essential, primarily at national level.

5.4 Conclusions and limitations of the study

From the results presented in **Table 5.3**, it can be concluded that reducing emissions during the operational and construction stages is not only required to make a credible environmental claim, but also reduces the costs of offsetting. There is a large opportunity for intensive energy consumers to reduce costs by increasing the amount of renewable energy installed.

By increasing renewable energy supply, the entity or organism claiming Net Zero can also improve its brand image and reduce reputational risk. Furthermore, the site can reduce its vulnerability to uncertain offset and electricity prices by reducing the number of offsets required and its dependence on non-renewable energy. Considering that these results were obtained for three different building types of different sizes and emissions per m^2, this outcome could be extrapolated to other cases. However, because results were only available for a single building for each use typology, it is possible that factors specific to that building influenced the final results. Therefore, in order to eliminate possible trends or errors, it would be interesting to conduct a similar study on a larger scale by increasing the amount of input data. In addition, since future offset and electricity prices are uncertain, this study should be revised regularly to ensure its validity.

Regarding available frameworks, if more stringent and standardised approaches to offset remaining emissions are not developed, it will still be a challenge to consistently compare different Net Zero Carbon Buildings. A more precise description on how offsetting should be approached in the building sector to ensure consistency and comparability is required. In addition, information regarding off-site renewable electricity procurement should be developed at regional and local level to take into account national policies and available solutions.

As this study has shown, the issue of offsetting in the building sector is complex and should not be underestimated. Nevertheless, available best practices, such as Oxford's Offsetting Principles and current frameworks on Net Zero Carbon Buildings, can be used as a reference while guidance is developed at national level.

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