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Carbon Removal from Green Roofs in Urban Communities: A Case Study in the City of Chania, Crete, Greece

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Abstract
Construction of green roofs on rooftop of buildings in urban areas has multiple environmental, economic and social benefits including the atmospheric carbon removal. Rooftops of buildings can be also used for the installation of solar photovoltaic and solar thermal systems generating green energy. The use of green roofs in buildings in Crete, Greece is very limited. The impact of green roofs and of solar-PV systems installed on rooftop of buildings located in the municipal unit of Chania, Crete, Greece has been examined. It has been estimated that green roofs remove atmospheric carbon through plants' photosynthesis and contribute in carbon emission savings due to lower energy consumption in buildings. Additionally, installation of solar-PV panels on rooftop of buildings contributes to green energy generation and to climate change mitigation. Apart from climate change mitigation green roofs have multiple external environmental, economic and social benefits. It has been indicated that the impacts of green roofs to climate change mitigation are lower than the impacts of solar photovoltaics' installation on rooftop of buildings. The multiple external benefits of green roofs indicate that their construction should be financially subsidized in Greece like in other EU countries. The findings could be useful to municipal authorities who should promote the construction of green roofs in urban buildings in their municipalities.

Keywords: Carbon Removal, Chania-Crete-Greece, Energy Generation, Green Roofs, Solar Photovoltaics, Urban Areas

1. Introduction
Mitigation of climate change requires the decrease of carbon emissions from several human activities. Construction of green roofs on rooftops of buildings particularly in urban communities has multiple environmental, economic and social benefits. The environmental and climate benefits of green roofs have been extensively studied [1, 2, 3, 4]. Vegetables can be cultivated in green roofs according to several researchers [5, 6, 7]. Green roofs can be used for rainwater harvesting [8]. Various studies have indicated that green roofs can mitigate the urban heat island (UHI) effect in cities [9, 10]. Green roofs can decrease the energy consumption in buildings with thermal insulation of their rooftops [11, 12]. Atmospheric carbon removal through plants' photosynthesis can be achieved with green roofs [13, 14, 15, 16].
The aims of the current work are:
a) The investigation of the possibility of carbon removal from rooftops of buildings with various ways,
b) The development of green roofs in the city of Chania, Crete, Greece and their impact on atmospheric carbon removal, and
c) The installation of solar photovoltaics on rooftop of buildings in the city of Chania, Crete, Greece and their impact on atmospheric carbon removal.

The text is structured as follows: After the literature survey the possibility of using the rooftop of buildings for atmospheric carbon removal is analyzed. Next, the development of green roofs in buildings in the city of Chania, Crete and their impact on carbon removal is analyzed. After that the installation of solar photovoltaics on rooftop of buildings in the city of Chania, Crete and their impact on carbon removal is examined followed by an analysis of the multiple benefits of green roofs. In the last two sections the discussion of the findings and the conclusions drawn are presented while the text ends with the citation of the references used.
The current work is innovative taking into account the absence of similar studies in urban communities in Greece while it covers an existing gap regarding the possibility of carbon removal in urban areas in Greece. The results could be useful to

policy makers, to municipal authorities, to architects, to energy companies and to municipal residents who are willing to reduce their carbon footprint and their climate change impacts.

2. Literature survey

The environmental benefits of green roofs have been analyzed [1]. The authors stated that green roofs have been proposed for sustainable buildings in many countries with different climate conditions. They also mentioned that their benefits include the lower energy consumption in the building, the mitigation of the urban heat island effect, the improvement of air pollution, the rain water management and the improvement of ecological preservation. The impacts of green roofs on air pollution and climate change have been reviewed [2]. The authors stated that green roofs recover green spaces in urban areas providing many environmental, ecological and economic benefits. They mentioned that green roofs reduce stormwater runoff, mitigate urban heat island effect, absorb dust and smog, sequester carbon dioxide, produce oxygen, create space for food production and provide habitats for animals and plants. The roof harvested rainwater usage in urban agriculture focusing in Australia and Kenya have been studied [5]. The authors stated that urban agriculture contributes to food and nutrition in developing countries while it receives increasing attention in developed countries. They also mentioned that urban agriculture and greening of cities require sufficient water quantities which can be partly provided by rainwater harvesting in green roofs. The vegetables' production in green roofs have been studied [6]. The authors stated that green roofs create spaces for production of vegetables in urban communities. They also mentioned that shallow-rooted vegetables (<15 cm depth) which include various green salads are the most suited in green roofs. Additionally, they stated that vegetables' production on green roofs can be conceived as a supplement to other sources of food production in urban areas. The sustainability of food production in buildings has been reviewed [7]. The authors stated that urban agriculture has multiple functions having positive impacts on urban life. It has environmental and social benefits while in economic terms it provides potential benefits. They also mentioned that food production on rooftop of buildings faces many challenges including the combination of several technologies, the high investment cost and the lack of acceptance. The use of green roofs for rainwater harvesting and sewage treatment has been studied [8]. The authors stated that both substrate and vegetation play an important role in influencing the sewage treatment of green roofs. They also mentioned that when designing green roofs priority should be given in the stability of the substrate as well as in the suitability and adaptability of the plants to cope with different temperatures and precipitation rates. The effectiveness of green roofs in the mitigation of urban heat island has been investigated [9]. The authors stated that the reduction of the temperature of the UHI by 1°C in Baltimore-Washington metropolitan area needs the coverage of about 30% of roof areas by green roofs, assuming that the soil moisture is satisfactory. The mitigation of UHI with green roofs in the city of Toronto, Canada using simulation techniques has been studied [10]. The authors stated that green roofs covering 5% of the total city area can reduce the temperature of the UHI by up to 0.5°C. The presence of bees in green roofs in Asia, Europe and North America has been examined [17]. The authors stated that according to various studies a lot of wild bee species have been recorded in green roofs while the percentage of cavity nesting bees on roofs is higher than that on nearby ground. The role of local communities in supporting green roofs in Indonesia has been examined [18]. The authors stated that the role of community is related with awareness, knowledge and active participation in maintaining and caring for green roofs. Additionally, the community can promote the productive use of buildings when green roofs are planted with productive species. The development of green roofs in European cities has been studied [3]. The authors stated that several incentives for the promotion of green roofs are used in several countries. In Austria the maintenance of green roofs is financially supported by 0.19 €/m^2/year. They also mentioned that according to the World Health Organization the minimum green areas in cities should be at 50 m^2 per inhabitant. The potential of roofs in city centers to be used for photovoltaic micro-installations in two districts in the city Opole, Poland has been analyzed [19]. Taking into account that the solar electricity generation in the two districts is 161.96 KWh/m^2/year the authors stated that there is a possibility of producing locally nearly 25% of the electricity consumed by residential buildings in the study area. The building integrated solar energy systems have been reviewed [20]. The authors stated that the solar energy systems integrated into buildings can be categorized as: a) solar thermal systems, b) solar-PV systems, and c) hybrid solar systems integrated into the facades. The role of green roofs on decreasing the energy consumption in buildings in Mediterranean climate has been studied [11]. The authors have experimented with three types of green roofs in Calabria, Italy. They stated that green roofs moderate the roof temperature in the summer and winter while the impacts in the summer are more remarkable. Their measurements have shown that the roof temperature under the roof surface was higher from 0.2°C-4.6°C in the winter and lower from 5°C to 11.3°C in the summer. The impact of green roofs on energy demand for cooling in Egyptian buildings has been studied [12]. The authors examined the impact of green roofs with different soil depth and thermal conductivity on energy consumption for cooling in Egyptian school buildings. They mentioned that the green roofs studied saved cooling energy in the buildings in the range of 31.61% to 39.74%. The experimental green roof had depth 0.1 m and thermal conductivity 0.9 W/m/K. The air pollution removal by green roofs in Chicago, USA has been estimated [4]. The authors estimated that 1,675 kg of air pollutants were removed by 19.8 ha of green roofs in one year with O_3 accounting for 52% of the total, NO_2 for 27%, PM_{10} for 14% and SO_2 for 7%. The use of green roofs for the mitigation of urban atmospheric pollution in semi-arid climates has been studied [21]. The authors were experimented with five plant species to quantify the deposition of particulate material on green roofs. Their results indicated that significant amounts of particles were deposited on green roofs while large differences in deposition were recorded among different species. The impacts of green roofs on carbon sequestration and on building carbon footprint in cold and dry climates have been studied [22]. The authors experimented with three plant species on a green roof in Mashhad, Iran. They estimated that the annual CO_2 absorption of three plants was 0.14, 2.07 and 0.61 Kg CO_2/m^2. They also mentioned that the green roof decreased the energy consumption of the building reducing the annual CO_2 emissions by 28.16, 26.48 and 23.44 kg CO_2/m^2 respectively. The use of moss on urban green roofs and the atmospheric CO_2 capture in South Korea has been studied [13]. The authors estimated that the annual CO_2 capture by green roofs was at 1.24 $KgCO_2/m^2$ - 2.66 $KgCO_2/m^2$. The reduction of CO_2 emissions and energy savings obtained by green roofs in Wuxi, China has been studied [14]. The authors stated that a green roof planted with Buddha grass can absorb annually 1.79 $kgCO_2/m^2$ and release 1.3 kgO_2/m^2. Additionally, the CO_2 reduction due to energy savings in the building was estimated at 9.35 $kgCO_2/m^2$. The carbon sequestration potential of 12 extensive green roofs in Michigan and in Maryland, USA has been estimated [15]. The authors stated that energy reduction in the building due to green roofs leads to annual carbon emission savings by 702 gC/m^2. They also mentioned that green roofs have stored 162 gC/m^2/year in above ground biomass. The CO_2 payoff of extensive green roofs with different vegetation species has been calculated [16]. The authors estimated the CO_2 emissions during the construction of the green roof at 25.2 $kgCO_2/m^2$ while the CO_2 emissions during the annual maintenance at 0.33 $kgCO_2/m^2$/year. They also evaluated the CO_2 sequestration at 2.5 $kgCO_2/m^2$/year and the reduction of CO_2 emissions due to saved energy in the range of 1,703-1,889 $kgCO_2/m^2$/year. The authors concluded that green roofs contribute to net atmospheric CO_2 reduction within their life span. The annual net uptake of carbon by urban green roofs in Berlin, Germany has been estimated [23]. The authors estimated the average net carbon uptake in a period of 5 years in the range of 125.6 gC/m^2/year - 156.6 gC/m^2/year. They stated that the annual carbon uptake varies between 189 gC/m^2/year for wet years to 95 gC/m^2/year for dry years. The green roof area in London using aerial imagery has been estimated [24]. The authors found that the proportion of green roofs' area to the total buildings' footprint area in various districts of London varies in the range of 0.5%-3.9%. They also mentioned that the proportion of green roofs' area to the geographical area in these districts varies in the range 0.1%-2.1 %. A report on green roofs in Basel, Switzerland has been released [25]. The report stated that the city of Basel has the largest area of green roofs per capita in the world at 5.71 m^2/inhabitant in 2019. The report stated that the city was providing in the past, when the construction cost was at around 100 CHF/m^2, subsidies for the installation of green roofs at 20-40 CHF/m^2 while their expected life time was around 50 years. The cost of constructing green roofs has been substantially reduced nowadays and it is estimated at around 23 CHF/m^2 while the thickness of the soil layer is at 12-15 cm. It is also mentioned that construction of hybrid rooftop systems consisted of solar-PV panels and green roofs in proportion 60% and 40% respectively have been investigated increasing the ecological value of buildings' rooftops. The average share of the build-up area of cities that is open space for public use for all, by sex, age and persons with disabilities has been evaluated [26]. The author stated that the share of build-up area occupied by streets in three European cities, Vienna, Antwerp and Madrid is 18%, 13% and 29% correspondingly. A United Nations' report regarding the Sustainable Development Goal 11 for making cities and human settlements inclusive, safe, resilient and sustainable has been issued [27]. The report stated that a sample of 911 cities from 114 countries shows that the share of urban area allocated to streets and open public spaces averages only 16% globally. It is also mentioned that the % of urban area in streets and open public spaces in Northern America and Europe is 18.4%. The use of solar energy, solid biomass and low enthalpy environmental heat, instead of fossil fuels, in residential buildings in Crete, Greece has been studied [28]. The author stated that these energy sources can eliminate all the life-cycle carbon emissions of residential buildings generating additionally the electricity required for re-charging the batteries of electric cars of the buildings' occupants. He also mentioned that the installation of the abovementioned green energy systems in residential buildings is economically affordable. The creation of net-zero carbon-emissions residential buildings due to energy use in Mediterranean region has been investigated [29]. The author analyzed a residential building with covered area 120 m^2 stating that it can zero its net-carbon emissions using a) a solar thermal system, b) a solar-PV system, and c) a ground-source heat pump covering all its energy demand.

The atmospheric carbon sequestration from green roofs and carbon emission savings due to reduced energy consumption in buildings with green roofs is presented in Table 1 while the share of urban area allocated to streets and open public spaces in European cities in Table 2.

Table 1: Carbon sequestration from green roofs and carbon emission savings due to reduced energy consumption in buildings with green roofs

Author, year, country	CO_2 sequestration from green roofs ($kgCO_2/m^2$/year)	Carbon emission savings due to reduced energy consumption in buildings with green roofs ($kgCO_2/m^2$/year)
Reza Segedabadi, 2021, Iran	0.14-2.07	23.44-28.16
Seo et al, 2023, South Korea	1.24-2.66	
Cai et al, 2019, China	1.79	9.35
Getter et al, 2009, USA	0.59	2.57
Kuronuma, 2018, Japan	2.5	1,703-1,889
Konopka, 2020, Germany	0.46-0.57	

Source: Various authors

Table 2: Share of urban area allocated to streets and open public spaces in European cities

City	Urban area allocated to streets and open public spaces (%)	Author, year
Vienna	18	Ndugwa, R.P., 2008
Antwerp	13	Ndugwa, R.P., 2008
Madrid	29	Ndugwa, R.P., 2008
Several EU cities	18.4	The Sustainable Development Goals Report 2021

Source: [26, 27]

3. Using the rooftop of buildings for atmospheric carbon removal

Urban environments contribute significantly to carbon emissions, largely due to energy consumption in buildings and transport activities. Rooftop spaces present a largely untapped resource for carbon reduction with a) the installation of solar photovoltaic panels, b) the promotion of photosynthesis via green roofs, c) the installation of solar thermal systems, and d) the reduction of energy consumption in buildings through green roofs.

3.1 Installation of solar photovoltaic panels

Solar photovoltaic panels convert sunlight directly into electricity, offering a significant opportunity for buildings to reduce their reliance on carbon-emitting energy sources. Rooftop solar installations can play a major role in carbon reduction by decreasing the demand for electricity generated from fossil fuels such as coal, oil, and natural gas. For instance, every kWh of electricity generated by a rooftop solar-PV system directly displaces a kWh that would have been generated by a carbon-intensive source. The adoption of rooftop solar-PV systems is becoming more prevalent as the cost of solar technology decreases and government incentives become more widely available. By utilizing unused rooftop spaces for solar-PV installations, urban buildings can significantly reduce their carbon emissions and contribute to global climate goals.

3.2 Photosynthesis from plants in green roofs

Green roofs, also known as vegetated roofs, provide another valuable mechanism for carbon sequestration by harnessing the natural process of photosynthesis. Plants absorb carbon dioxide from the atmosphere and convert it into organic matter, storing carbon in their biomass and the surrounding soil. This process not only removes carbon from the air but also improves the local air quality and mitigates the urban heat island effect. The effectiveness of green roofs in carbon sequestration depends on factors such as the type of plants, soil depth, and climate conditions. While the amount of carbon sequestered per square meter may be modest compared to forest ecosystems, the cumulative impact across a city can be substantial, particularly in densely populated areas with limited green space.

3.3 Installation of Solar Thermal Systems

Solar thermal systems, which use the sun's energy to generate heat rather than electricity, offer another opportunity for carbon reduction on rooftops. These systems typically involve the installation of solar collectors, which absorb solar radiation and convert it into heat that can be used for water heating, space heating, or even cooling through absorption chillers. The use of solar thermal systems reduces the need for conventional heating methods, which often rely on natural gas, oil, or electricity produced from fossil fuels. By displacing these carbon-intensive energy sources, solar thermal systems directly reduce greenhouse gas emissions. Moreover, solar thermal systems have high efficiency rates, converting a significant portion of the solar energy they capture into usable heat. The integration of solar thermal systems into urban buildings, particularly in regions with abundant sunlight, can lead to significant reductions in carbon emissions. These systems are particularly effective in reducing emissions associated with heating, which accounts for a substantial portion of building energy consumption.

3.4 Reduction of energy consumption in buildings due to creation of green roofs

In addition to their role in carbon sequestration, green roofs offer a passive means of reducing energy consumption in buildings, thereby contributing indirectly to carbon reduction. Green roofs provide insulation to buildings, reducing the need for heating in the winter and cooling in the summer. This thermal regulation results in lower energy demand, particularly in cities where air conditioning is a major source of energy consumption. The insulating properties of green roofs come from both the plant layer and the soil substrate. These layers help regulate temperature by absorbing heat during the day and releasing it at night, thereby reducing the heat flux into the building. In the summer, green roofs can significantly lower rooftop temperatures, mitigating the need for air conditioning and, in turn, reducing electricity consumption. In winter, the insulation provided by green roofs helps retain heat within the building, reducing the need for fossil fuel-based heating systems. Energy savings from green roofs can vary depending on climate conditions, building type, and roof design. However, studies show that energy savings can range from 15% to 45% in terms of cooling load reduction during the summer. By reducing the demand for energy from fossil fuels, green roofs contribute indirectly to carbon removal through energy conservation.

4. The development of green roofs in the city of Chania, Crete, Greece and their impact of atmospheric carbon removal

Chania is located in the western part of the island Crete and it is the capital of the prefecture of Chania one of the four Prefectures of the island. It is the second largest city in the island with population at 111,375 inhabitants [30] while its area is 351.3 km^2. The municipal unit of Chania has 54,559 inhabitants [30] while its area is 11 km^2. Considering the development of green roofs in the municipal unit of Chania and their impact in atmospheric carbon removal the following assumptions are made:

a) In the municipal unit of Chania 20% of the urban area is allocated to streets and open public spaces while the rest 80% is allocated to buildings,
b) 5% of the buildings' rooftop area in the municipal unit of Chania is going to be covered by green roofs,
c) The CO_2 sequestration from the plants in the green roofs is going to be 2kgCO_2/m^2/year,
d) The CO_2 emissions savings due to lower energy consumption in the buildings covered by green roofs is going to be 10 kgCO_2/m^2/year,
e) The life span of green roofs is 30 years, and
f) The construction cost of green roofs is 30 €/m^2.

The results of our estimations are presented in Table 3.

Table 3: Development of green roofs in the municipal unit of Chania, Crete, Greece and their impact on atmospheric carbon removal

Parameter	Value
Building area in the municipal unit of Chania	8,800,000 m^2
Rooftop area covered by green roofs (5% of total)	440,000 m^2
Green roof area per resident	8.06 m^2/resident
Atmospheric CO_2 sequestration from the plants	880 tnCO_2/year
Atmospheric CO_2 sequestration from the plants per resident	16.13 kgCO_2/year/resident
Atmospheric CO_2 emissions savings due to lower energy consumption in the buildings covered by green roofs	4,400 tnCO_2/year
CO_2 emission savings due to lower energy consumption in the building per resident	80.65 kgCO_2/year/resident
Total CO_2 removal and CO_2 emission savings from green roofs	5,280 tnCO_2/year
Total CO_2 removal and CO_2 emission savings from green roofs per resident	96.78 kgCO_2/year/resident
Total CO_2 removal and CO_2 emission savings from green roofs during their life span of 30 years	158,400 tnCO_2
Construction cost of green roofs (without subsidies)	13.2 mil. €
Cost of CO_2 removal and emission savings from green roofs during their life span of 30 years (without subsidies)	83.3 €/tnCO_2
Construction cost of green roofs (subsidizing the construction cost by 20%)	10.56 mil. €
Cost of CO_2 removal from green roofs during their life span of 30 years (subsidizing the construction cost by 20%)	66.7 €/tnCO_2

Source: Own estimations

5. Installation of solar photovoltaics on rooftop of buildings in the city of Chania, Crete, Greece and their impact of atmospheric carbon removal

Considering the installation of solar photovoltaics on the rooftops of buildings in the municipal unit of Chania and their impact on carbon emissions savings the following assumptions are made:

a) 5% of the buildings' rooftop area in the municipal unit of Chania is going to be covered by green roofs,
b) The required installation surface of a solar-PV module with nominal power 1kW_p is 10 m^2,
c) The annual electricity yield of solar-PV modules in Crete, Greece is 1,400 kWh/kW_p,
d) The life span of solar-PV modules is 25 years,
e) The installation cost of solar-PV modules on rooftops of buildings in Crete is 1,200 €/kW_p, and
f) The CO_2 emissions related to generation of 1 kWh in Greece is 0.6 kgCO_2.

The results of the estimations are presented in Table 4 while the carbon removal with different methods from rooftop of buildings in the city of Chania, Crete, Greece are presented in Table 5.

Table 4: Installation of solar photovoltaics on rooftop of buildings in the city of Chania, Crete, Greece and their impact of atmospheric carbon removal

Parameter	Value
Rooftop area covered by solar-PV panels (5% of total)	440,000 m^2
Nominal power of the installed solar-PV modules	44 MW_p
Annual solar electricity generation	61,600 MWh
Annual CO_2 emission savings due to solar electricity generation	36,900 tonCO_2/year
CO_2 emission savings due to the installation of solar-PV systems per resident	676.33 kgCO_2/year/resident
Total CO_2 emission savings due to solar electricity generation in 25 years	922,500 tonCO_2
Total installation cost of solar-PV modules on rooftop of buildings	52.8 mil. €
Cost of CO_2 emission savings due to solar photovoltaics during their life span of 25 years	57.2 €/tnCO_2

Source: own estimations

Table 5: Carbon removal with different methods from rooftop of buildings in Chania, Crete, Greece

Carbon removal method	Quantity
Atmospheric CO_2 sequestration from the plants per resident	16.13 kgCO_2/year/resident
CO_2 emission savings due to lower energy consumption in the building per resident	80.65 kgCO_2/year/resident
Total CO_2 removal and emission savings from green roofs per resident	96.78 kgCO_2/year/resident
CO_2 emission savings due to the installation of solar-PV systems per resident	676.33 kgCO_2/year/resident

Source: Own estimations

6. The multiple environmental, economic, energy, and social benefits of green roofs

Green roofs, also known as vegetative or living roofs, are increasingly recognized for their wide-ranging benefits, which extend across environmental, economic, energy, and social domains. A green roof is a building's roof partially or completely covered with vegetation, growing on a waterproof membrane. These roofs not only enhance urban aesthetics but also address several critical challenges, making them an attractive option for sustainable urban development.

6.1 Environmental benefits

Green roofs play a significant role in mitigating the urban heat island effect. By adding vegetation to rooftops, green roofs reduce ambient temperatures and lower energy consumption. They also improve air quality by absorbing pollutants and carbon dioxide, releasing oxygen in the process. Furthermore, green roofs help manage stormwater. In urban settings, rainwater runoff often overwhelms sewer systems, leading to flooding and pollution. Green roofs absorb and filter rainwater, reducing runoff and helping cities manage heavy rainfall more effectively. This can also lead to less pollution entering waterways, contributing to healthier ecosystems.

6.2 Economic benefits

Green roofs offer long-term economic benefits by extending the lifespan of a roof structure. The vegetation and soil layers shield the waterproofing membrane from harmful ultraviolet (UV) radiation, extreme temperature fluctuations, and physical damage, thus reducing maintenance and replacement costs. Additionally, green roofs can increase property values. The aesthetic appeal of a building with a green roof can attract potential buyers or renters, boosting real estate prices. Commercial buildings with green roofs may also see increased leasing potential, as businesses and tenants increasingly value sustainability. Green roofs offer the opportunity for cultivation of various vegetables including green salads as well as for honey production generating a small income.

6.3 Energy benefits

One of the most immediate benefits of green roofs is energy efficiency. Green roofs provide insulation, reducing the need for heating in winter and cooling in summer. The energy savings achieved in buildings result in lower CO_2 emissions due to energy use. The vegetative layer acts as a thermal barrier, keeping buildings cooler by absorbing sunlight and reducing heat transfer. This lowers air conditioning demand, which translates to significant reductions in energy consumption and costs. For buildings in colder climates, the additional insulation can also reduce heating needs, providing year-round energy savings.

6.4 Social benefits

Beyond their tangible environmental and economic benefits, green roofs enhance social well-being. They contribute to the creation of green spaces in urban areas, where access to nature is often limited. Green roofs offer opportunities for gardening, relaxation, and even urban agriculture, fostering a sense of community and improving mental health by providing spaces for interaction and stress relief. Green roofs can also contribute to biodiversity by creating habitats for birds, insects, and other wildlife, even in densely built-up areas. This promotes ecological balance and brings nature closer to urban residents, raising environmental awareness and fostering a connection with the natural world. The benefits of green roofs are presented in Table 6.

Table 6: Benefits of green roofs

Environmental	Remove atmospheric CO_2
	Remove various atmospheric pollutants
	Release oxygen
	Mitigate the urban heat island effect
	Reduce the noise in the building
	Improve the management of water runoff
	Create a healthy ecosystem attracting birds, insects et cetera increasing the biodiversity in urban areas
Economic	Increase the life span of the building roof
	Increase the value of the property
	Create the opportunity for cultivation of vegetables and production of honey resulting in economic benefits
	Reduce the energy consumption and the energy bill in the building
Energy	Reduce the heat and cooling requirements in the building
Social	Offer the opportunity for gardening and relaxation
	Improve mental health and stress relief
	Promote ecological balance and bring nature closer to urban residents

Source: Own estimations

7. Discussion

The possibility of mitigating climate change in urban environment using the rooftop of buildings in Chania, Crete, Greece has been investigated. Rooftop spaces present an underutilized asset in the fight against climate change. By implementing a combination of technologies and nature-based solutions, such as solar photovoltaic panels, green roofs and solar thermal systems, we can significantly reduce carbon emissions from urban environments. Each of these solutions contributes uniquely to the overall goal of carbon reduction, whether through direct carbon sequestration, displacement of fossil fuel energy, or passive energy savings. As cities continue to grow and face mounting environmental pressures, maximizing the potential of rooftops for carbon removal will be a crucial strategy in mitigating climate change and creating more sustainable urban ecosystems. The possibilities of carbon removal with green roofs and installation of solar photovoltaics on rooftop of buildings have been studied but not the possibility of installing solar thermal systems for domestic hot water production.

Our results indicate that green roofs can contribute in climate change mitigation having also many environmental, economic and social benefits. They should be considered as an additional method for climate change mitigation in cities. However, they are not commercially profitable so far. Since green roofs have many external benefits, increasing the quality of life at city level their construction should be subsidized in Greece like in other countries. Taken into account that green roofs are very rare in the city of Chania, which is characterized by lack of public green spaces, the municipal authorities should try to construct some pilot green roofs in public buildings. Taken into account that Mediterranean cities are characterized by high solar irradiance and low annual precipitation the construction of green roofs should be complementary to the installation of solar photovoltaics and solar thermal systems on rooftops of buildings. In our case study the green roof area in the city of Chania at 8.06 m^2/resident is higher than the largest green roof area in Basel, Switzerland at 5.71 m^2/resident [25]. In our case study, in the municipal unit of Chania, the 5% of buildings' rooftop area covered with green roofs is comparable with the % of green roofs recorded in several neighborhoods in London at 0.5%-3.9% [24]. The results indicate that the CO_2 emission savings due to lower energy consumption in buildings with green roofs are significantly higher than the CO_2 sequestration from the plants of green roofs. Additionally, the CO_2 emission savings due to a solar photovoltaic installation on rooftop of a building are substantially higher than the total CO_2 removal and emission savings achieved by a green roof in the same building.

The accuracy of our estimations depends on our assumptions, taken from published results, regarding the carbon sequestration rate from the green roofs' plants and the carbon emission savings due to lower energy consumption in buildings with green roof installations.

Future work should study the CO_2 emission savings due to installation of solar thermal systems on rooftops of buildings as well as the use of hybrid systems consisted of green roofs, solar thermal and solar-PV systems.

8. Conclusions

The use of rooftops of buildings in urban areas for climate change mitigation has been studied. Two different approaches have been examined focused in the city of Chania, Crete, Greece. The first examines the construction of green roofs and the second the installation of solar-PV panels on rooftops of buildings in Chania.

Our findings indicate that:

a) Green roofs contribute in climate change mitigation due to atmospheric carbon sequestration from the planted species and in carbon emission savings due to lower energy consumption in buildings,
b) Installation of solar photovoltaics on rooftop of buildings for solar electricity generation contributes to climate change mitigation,
c) The impact of solar photovoltaic installation on rooftops of buildings to climate change mitigation is significantly larger than the impact of green roofs,
d) Construction of green roofs on rooftops of buildings has multiple environmental, energy, economic and social benefits, and
e) The cost of carbon removal for green roofs is 83.3 €/tnCO_2 while for the installation of solar photovoltaics 57.2 €/tnCO_2.

The adoption of green roofs represents a multifunctional solution that addresses critical environmental, economic, energy, and social challenges. By cooling urban environments, improving energy efficiency, extending the lifespan of roofing materials, and offering community spaces, green roofs provide a sustainable path forward for urban development. Their widespread implementation could transform cities into greener, more resilient, and healthier spaces. Due to multiple external benefits of green roofs their construction cost should be financially subsidized.

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