

Enhancing Building Energy Efficiency with Green Roofs: Quantifying Non-renewable Primary Energy Benefits for Existing Buildings in the Mediterranean Region

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Abstract: This study analyzes the energy impact of applying green roofs on flat roofs of existing buildings, assessing their potential to reduce the demand for non-renewable primary energy for heating and cooling. Through dynamic numerical simulations conducted on two real buildings located near Florence, Italy, and modeled in 130 different European locations, with a particular focus on the Mediterranean climate, it was possible to quantify the energy benefits derived from the application of green roofs on existing structures. The results show that, while the effect on heating is limited, with an average reduction in energy demand of only a few percentage points, the impact on cooling is significantly more pronounced, with average savings of 20% in non-renewable primary energy, particularly in Mediterranean climates with high CDD (cooling degree days) values. The study confirms that green roofs can be an effective solution to improve the energy efficiency of existing buildings with flat roofs in the Mediterranean climate, in line with European goals for reducing CO₂ emissions and promoting renewable energy.

Key words: Green roof, flat roofs, renovation, energy efficiency, numerical simulation, Mediterranean climate, energy savings, summer cooling.

1. Introduction

Building energy efficiency is one of the keystones of global action against climate change [1] and of the EU (European Union) energy policy [2]. The EU's target to become a climate-neutral continent by 2050 requires a deep cut in CO₂ emissions from the building sector [3]. In 2024, the 2024/1275 Directive was launched [4], which requires that building roofs are solar-ready, i.e., designed for the installation of solar thermal and photovoltaic devices. Energy self-production is an active strategy to switch from fossil fuels to renewable energy sources. However, the first step is to reduce the building's energy demand, followed by the installation of renewable energy devices.

Passive design technologies applied to the building envelope allow for the reduction of the energy

requirement for HVAC (heating, ventilation, and air conditioning) without affecting indoor thermal comfort [5]. Among these, the use of vegetation to cover the building envelope is a reliable technique, though its widespread adoption is hindered by various factors [6, 7]. The grassy lawn is an eco-friendly application compatible with the 2024/1275 Directive, as it allows for the installation of solar devices on both roofs and facades [8, 9].

This paper analyses the application of grassy lawns on flat roofs through numerical transient simulations of two existing buildings. Climate inputs are varied across 130 different locations to represent the European area. The simulation assesses the energy savings for HVAC resulting from a comparison before and after the application of the grassy lawn. The assessment is

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expressed using common indicators such as non-renewable primary energy consumption and CO₂ emissions, in compliance with the recast Energy Performance of Building Directive (EPBD) [10].

2. Green Roofs in the Mediterranean Climate Context

2.1 Energy Benefits of Green Roofs in Hot and Temperate Climates

According to the Köppen [11, 12] climate classification, the Mediterranean climate is primarily designated by the codes “Csa” (hot Mediterranean climate) or “Csb” (temperate Mediterranean climate), depending on specific characteristics.

Numerous studies affirm that green roofs offer multiple energy benefits in hot and temperate climates, such as the Mediterranean. These benefits mainly stem from the ability of green roofs to enhance the thermal insulation of buildings, thereby reducing energy consumption for cooling and heating.

Green roofs reduce the summer thermal load due to their capacity to absorb less heat compared to conventional roofs. This effect is amplified by the presence of vegetation, which, through evapotranspiration, dissipates heat, keeping roof surfaces cooler and reducing the indoor temperature of buildings.

Studies conducted in Mediterranean cities like Valencia have shown that green roofs can lead to significant savings in annual energy consumption. Specifically, the activation of irrigation systems during the summer months can further increase these savings, reducing energy consumption for cooling by up to 36% compared to reference models with more traditional roofs [13].

In the Mediterranean context, characterized by high solar radiation and moderately high temperatures, green roofs are particularly effective in improving the energy efficiency of buildings. Water storage capacity and the choice of vegetation are crucial for maximizing energy benefits [14].

The choice between extensive and intensive green roofs affects the achievable energy benefits. Extensive roofs, which require less maintenance and have a lower dead load, are often preferred for renovations due to their lower cost and ability to provide energy savings similar to those of intensive roofs. In intensive roofs, slightly better results are generally obtained due to the thickness of the substrate and the types of vegetation used, which significantly influence the thermal performance of green roofs. A thicker substrate can improve thermal insulation, while the choice of plants with a high LAI (leaf area index) can increase shading and further reduce surface temperature.

2.2 Influence of Green Roofs on Seasonal Cooling/Heating

Green roofs, thanks to their ability to modulate surface temperatures, significantly influence the seasonal energy loads for cooling and heating buildings. Therefore, in a Mediterranean climate context, characterized by hot summers and mild winters, the adoption of vegetative covers can lead to notable energy benefits.

Studies conducted in southern Italy [15] have highlighted that green roofs can reduce surface temperatures compared to traditional roofs. During the summer months, the maximum surface temperature of a traditional roof reached 74.3 °C with a temperature fluctuation of 51.5 °C, while a green roof under the same conditions can reduce the surface temperature by up to 60%. Surface temperature peaks were reduced thanks to summer irrigation, demonstrating the importance of managing substrate moisture to optimize energy performance [15].

During winter, the same studies show that green roofs provide an additional insulating layer that helps limit heat loss to the outside. This effect is particularly evident on cold nights when the surface temperature of the green roof is more stable compared to that of traditional roofs. Green roofs can indeed reduce daily temperature fluctuations by up to 50% compared to

traditional roofs, helping to maintain more constant indoor temperatures and thus reducing the energy demand for winter heating.

2.3 Impact on the Urban Environment

Green roofs play a crucial role in mitigating the UHI (urban heat island) effect and improving urban comfort, especially in Mediterranean climate contexts. These benefits stem from their ability to regulate surface and air temperatures, thereby reducing the thermal load in densely built urban areas. Studies suggest that the benefits are maximized in urban contexts where other forms of urban greening, such as trees or ground-level green spaces, are difficult to implement due to high building density.

The effect of reducing air temperatures is more pronounced in compact, low-rise urban archetypes, where evapotranspiration, using a significant portion of the received solar radiation to cool the environment, reduces the heat flux transferred to the air [16]. This process also contributes to improving indoor thermal comfort in buildings.

In addition to thermal benefits, green roofs can contribute to mitigating air and noise pollution in urban areas. They act as natural filters for atmospheric pollutants and improve the acoustic insulation of buildings, reducing noise from urban traffic [17].

2.4 Relevant Case Studies in Mediterranean Contexts

In the literature, green roofs have already been the subject of numerous case studies in Mediterranean contexts, highlighting their effectiveness in improving energy efficiency and urban sustainability. These studies provide valuable data for understanding the performance of green roofs in climates characterized by high solar radiation and limited precipitation.

2.4.1 Relevant Case Studies in Italy

- Genoa, Italy: An economic and technical analysis of green roofs was conducted in Genoa using a Monte Carlo financial model. The study evaluated the feasibility of sustainable development, with significant

benefits in terms of energy savings and reduced flood risk [18].

- Milan, Italy: A case study in Milan identified the evapotranspiration rate as the main factor influencing green roof performance in the Mediterranean climate [18].

- Rome, Italy: In another study conducted in Rome, it was observed that green roofs can contribute to mitigating the urban heat island effect and achieve a reduction in building energy consumption of approximately 2.6 kWh per day [19].

2.4.2 Relevant Case Studies in Spain

- Valencia, Spain: The city of Valencia, characterized by low rainfall and a high risk of desertification, has seen the implementation of extensive and intensive green roof models to maximize energy benefits while managing water consumption. The simulation showed that irrigation can improve the energy performance of green roofs, but a balance must be found between energy savings and water consumption [13].

The studies cited above demonstrate that green roofs offer significant advantages in a Mediterranean climate, contributing to reduced energy consumption and improving the urban microclimate. However, their effectiveness strongly depends on water resource management and the choice of plant species suited to the local climate.

3. Renovation of Existing Buildings through Green Roofs

Buildings with flat roofs are particularly suitable for the application of a loam layer, as there is no problem of clod slippage, and irrigation and drainage of excess water are straightforward. A grassy lawn does not significantly overload the bearing structural capacity of a typical reinforced concrete roof slab. The overload can be estimated at approximately 100 kg/m² uniformly distributed for a loam thickness of 10 cm, considering also the other necessary layers such as separation fabric, drainage substrate, and so on [20].

A grassy lawn excludes the planting of shrubs and tall vegetation. It is therefore suitable for the renovation of existing buildings, whose load-bearing structures have limited overload capacity. However, a grassy lawn absorbs much less CO₂ than a plantation of shrubs. Adding a 10 cm layer of loam to an existing roof improves its thermal performance from multiple perspectives:

- Steady-state thermal transmittance: the loam layer increases the roof's overall thermal resistance, which depends on its humidity level. The thermal conductivity of clay soil is 0.76 W/(m²K) at a humidity content of 20% [21];
- Dynamic thermal parameters: the loam layer

increases the mass of the slab, resulting in an increase in the time shift of the thermal wave and an attenuation of its oscillation amplitude. The density of clay soil is 1,400-2,000 kg/m³ [21].

Considering the physical properties of loam, it can be concluded that the application of a grassy lawn is particularly suitable during the summer season and, therefore, in temperate or hot climates. In general, in buildings equipped with air conditioning devices, the energy demand of chillers is reduced, while in buildings without them, internal comfort improves under conditions of temperature drift.

The analysis focuses on two real buildings, shown in Fig. 1, for which the construction materials, energy

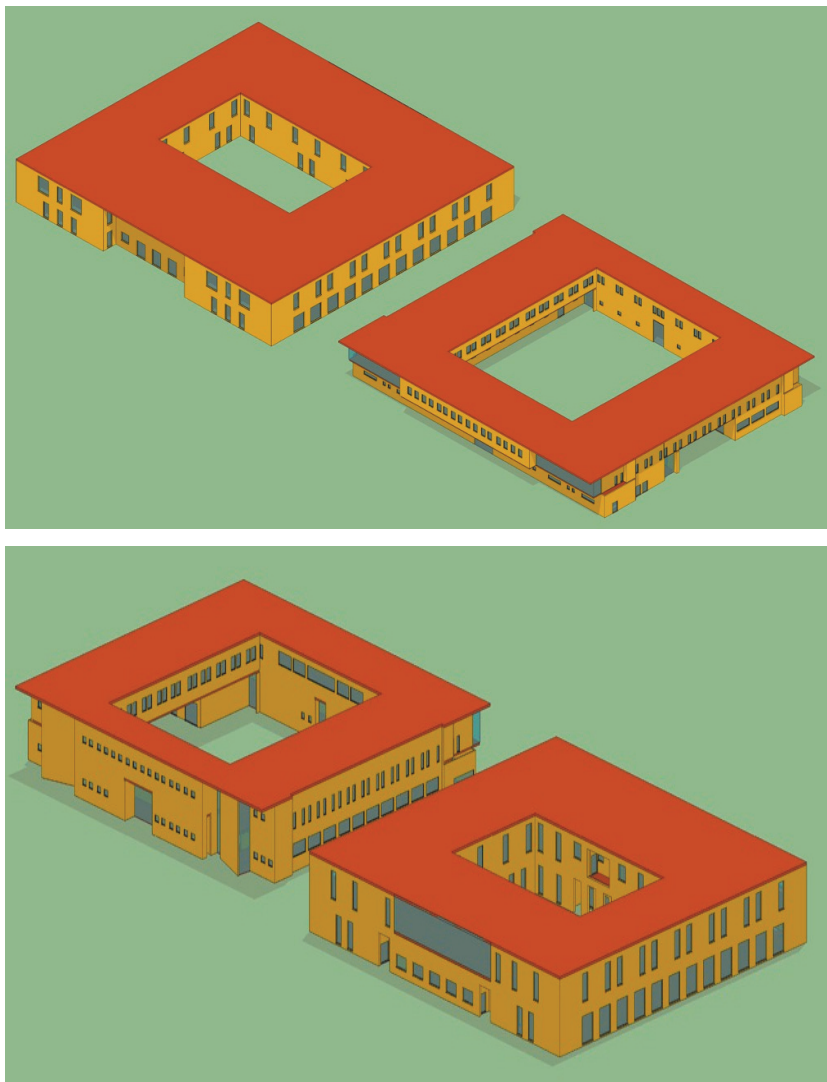


Fig. 1 Trnsys 3D model of the buildings.

systems, local weather data, and usage schedules are known. The analysis is performed in tailored rating mode. The second building serves to validate the results obtained for the first. Both buildings are located near the city of Florence, Italy, and are used as offices with continuous activity throughout the year.

The buildings are of the central courtyard type, with flat roofs, and consist of two floors. The choice is due to:

- (1) ease of applying a grassy lawn, since the roof is flat and predominantly free from technical plant devices;
- (2) high impact of the roof on the energy demand for air conditioning, given the geometry of the building envelope and the size of its surfaces;
- (3) low impact of orientation, since the buildings are isolated on all sides and there are no other buildings nearby.

4. Numerical Model

Both buildings were modelled in a transient state with an hourly timestep using the software Trnsys-Simulation Studio [22]. The geometric and thermophysical calculations of the buildings were carried out using the Trnbuild plugin. The models are multi-zone with thermally coupled zones. The energy performance of the buildings was assessed in a before- and after-comparison mode. The only difference between the ante- and post-configurations is the application of a grassy lawn on the roof. The calculation data of the main building are reported in Table 1. Those of the other building are very similar.

The numerical models were validated using real weather data collected near the buildings by the LaMMA weather station [23] over the period 2000-2010 and statistically aggregated using the UNI EN ISO 15927-4 methodology [24]. The buildings were modelled in 130 different locations to represent the European area and its climate variability. The hourly weather data were obtained from the Energy Plus global database [25].

Table 1 Key parameters of the main building.

	Before renovation	After renovation
Conditioned floor area	5,000 m ²	
Overall conditioned volume	20,000 m ³	
Roof thermal transmittance	1.063 W/(m ² K)	0.795 W/(m ² K)
Roof time shift	-11.88 h	-20.31 h
Roof decrement factor	0.155	0.03

The building's central heating is powered by gas boilers, and the heating system is hydronic. The heaters are fan-coils with temperature control for each room. The average seasonal efficiency is estimated at 0.73. The building's cooling system is powered by air-cooled electric chillers, and the cooling system is hydronic. The coolers are fan-coils with temperature and relative humidity control for each room. The average seasonal efficiency is estimated at 2.57. The necessary air change rate is managed by a mechanical ventilation system that controls both temperature and relative humidity. The system operates Monday through Friday, from 07:00 to 19:00, with intermittent activation.

The amounts of energy carriers (gas and electricity) were converted into non-renewable primary energy consumption and CO₂ emissions using the Italian national standard UNI/TS 11300-5 [26]. The conversion factors are 1.05 for gas and 1.95 for electricity. The CO₂ emission factors are 0.21 kg/kWh for gas and 0.46 kg/kWh for electricity. These values are characteristic of European countries where the electricity mix is dominated by fossil fuel-based generation, with limited contribution from renewable energy sources.

5. Results Analysis

The numerical model was tested in 130 different locations across Europe, particularly in Mediterranean climate countries such as Italy (26 cities) and Spain (45 cities). Each location is characterized by the number of HDD (heating degree days) for the winter season and CDD (cooling degree days) for the summer season.

Regarding heating, the effect of the green roof is minimal. Applying the grassy lawn reduces the steady-

state thermal transmittance, which is the main thermal factor in winter, by 25%. However, the energy demand for heating decreases by only a few percentage points because the roof accounts for only 25% of the total building envelope. The effect is consistent regardless of the number of HDD in the city considered.

Regarding cooling, the effect of the green roof is significant in all locations. From an absolute perspective, the cooling energy demand decreases in direct proportion to the number of CDD. The trend is linear.

The observed effect confirms that the main thermal factor in summer is the roof mass. Applying the loam layer increases the roof mass, consequently increasing the roof's thermal time shift, as shown in Fig. 2.

From a relative perspective, high percentages—up to 60%—are observed for Nordic cities with low CDD values, as shown in Fig. 3. As the CDD values increase, the percentages tend to stabilize around 20%, which can be considered an average value representing the effect of the green roof, particularly in Mediterranean climates.

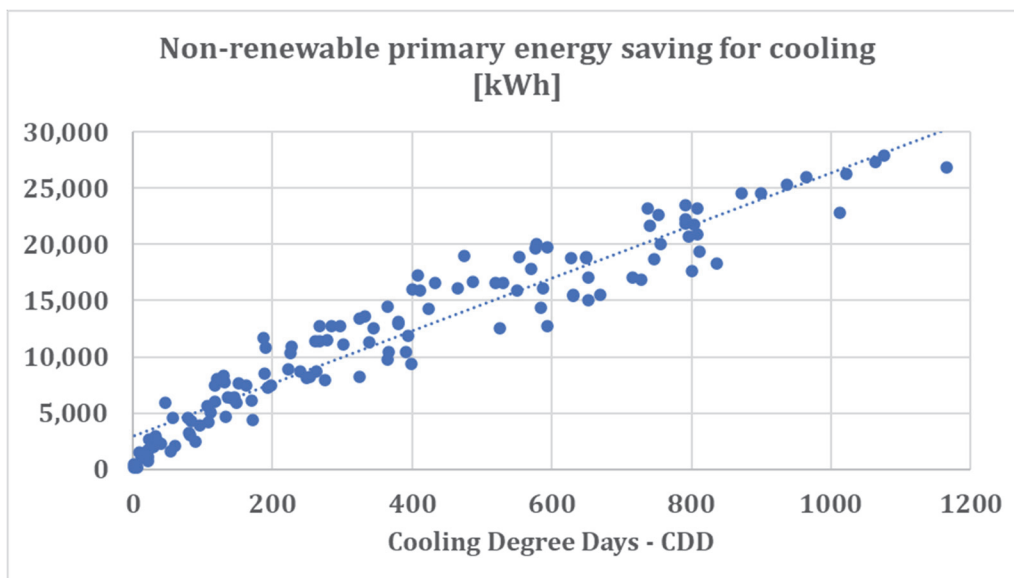


Fig. 2 Absolute cooling energy savings plotted against CDD values.

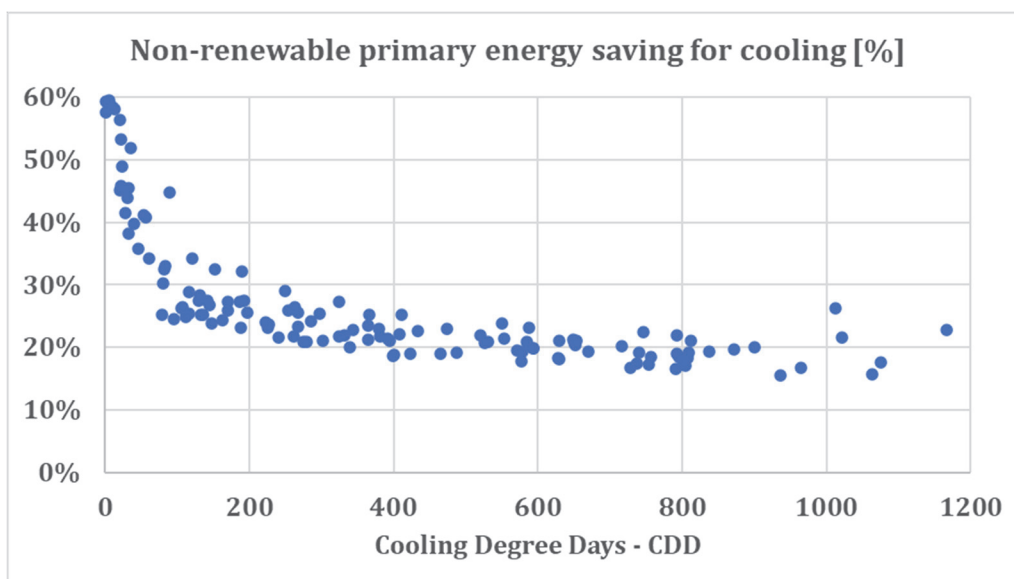


Fig. 3 Relative cooling energy savings plotted against CDD values.

The calculation results for the main building are very similar to those for the comparison building, except for a scale factor. The reliability of the analysis method is corroborated, as well as that of the outlined trends. The results in terms of CO₂ emissions are equivalent to those in terms of non-renewable primary energy, as graphically represented, because thermoelectric production still dominates the European electricity mix.

6. Conclusions

The analysis carried out highlights the excellent performance of a “green roof” in reducing the energy demand for heating during the summer season. This has been verified for all European locations considered, particularly those located in a Mediterranean climate (high CDD values). The savings in terms of non-renewable primary energy, considering electricity as the energy carrier for powering the chillers, amount to an average of 20%. A subsequent phase of in-depth study could involve assessing the performance of the green roof from a cost-benefit perspective.

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