Life cycle benefits and challenges of large – scale green roof implementation in a mediterranean compact city: the case of Thessaloniki

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Abstract. Green roof installation is considered to be an effective practice in restoring green spaces to high – density urban areas, in an effort to mitigate environmental problems that arise from their growing expansion. The present study attempts to further investigate this claim by assessing the environmental and economic life cycle benefits and challenges of two extensive green roof large – scale implementation scenarios (on existing or on well – insulated roofs) in the compact mediterranean city of Thessaloniki, Greece. In both scenarios green roofs provided energy savings (13-19%), greenhouse gas emissions (22-29%) and waste production (57-60%) reductions but also led to a significant increase in water consumption (279-291%), with performance being better in the latter case. They also accrued significant public economic benefits in both a low and high discount rate scenario, although they were not an efficient choice for private owners in the second one. These results seem to imply that green roofs could potentially be a viable urban green infrastructure solution, if their water use is minimized in a sustainable way and additional state incentives are considered.

1. Introduction
The increase of urbanization and the subsequent replacement of natural landscape by manmade infrastructure is a continuously growing worldwide trend, which challenges ecosystems and quality of life on both a local and global scale [1]. Compact cities, while considered to be a very good solution to combat urban sprawl and encourage mixed land use, may suffer from an accentuated loss of green space and other endemic problems such as increased traffic congestion, local air pollution, energy demand [2] or vulnerability to urban heat island phenomena [3]. Green roofs and green infrastructure in general are credited to be effective at alleviating these issues [4] and an increasing amount of life cycle analyses focus on estimating their environmental and economic performance [5].

In order to further investigate this topic, the present study aims to estimate the life cycle benefits or challenges that could spring from large – scale extensive green roof implementation efforts in compact cities under mediterranean climate conditions, using the city of Thessaloniki, Greece, as a case study. To this end, the results of a recently published comparative environmental and economic life cycle analysis of green and flat roofs conducted by the authors [6], that concluded that extensive green roofs might be a preferable option, are herein extrapolated to a citywide scale. The final target of this work is to improve the microclimate conditions in buildings and, as a consequence, decrease their energy
consumption. It should be noticed that other methods to decrease energy consumption of buildings as, for example, by a better use of energy from the inhabitants[7], are not studied here.

2. Methods and materials
The study from which the present work drew most of its life cycle data [6], carried out a comparison of a 40 years life cycle energy use, greenhouse gas (CO₂ equivalent) emissions, water consumption and waste production between a flat roof and all main types of green roofs (extensive, semi-intensive, intensive) and drainage layer compositions (synthetic or granular), under mediterranean climate conditions. The functional unit referred to a 100 m² roof along with the cooling and heating energy demand and respective CO₂ emissions of an underneath storey. Also included in the study was an economic life cycle analysis for the same time frame, estimating the Net Present Value of the choice of installing each of the green roof types instead of a flat one. Necessary data were drawn from a combination of a dynamic whole – building energy simulation conducted in its initial phase (whose results were used to calculate use stage energy consumption and CO₂ emissions), available literature, environmental product declarations and commercial or public sectors’ data for the other life cycle stages and the economic analysis. While focus was mainly directed to a 10 cm insulation scenario, the same analysis was performed in its context for a 5 and a 1 cm scenario too (initially in order to determine the extent of the insulation layer’s influence on energy use, but subsequently including all aforementioned aspects of the analysis). The study concluded that extensive green roofs performed better than the other green roof types, and that they could constitute a preferable choice over flat roofs in all environmental and economic perspectives, if their high water consumption is minimized through planning and innovation and some sort of financial support, justified by potential public benefits, is provided [6].

In order to extrapolate these results to a large-scale green roof implementation hypothesis, the findings of an existing study regarding the total available roof area suitable for green roof installation in the Municipality of Thessaloniki (of the eponymous compact mediterranean city) were used, estimating it to potentially be able to reach 2.29 km² of roof space [8]. This surface refers to buildings with non-sloped roofs, built after 1960. For the present study, as can be seen in Table 1, using data from the 2011 Buildings Census [9], this area is divided between three construction date categories of the building stock of the municipality, namely: 1960 – 1980, 1981 – 2011 and buildings built after 2011 (which were under construction at the time of the census). The reason behind the adoption of these subcategories is that the first Greek Regulation on Thermal Insulation of Buildings started to apply after 1980 (and as such most buildings built prior to this date are expected to be uninsulated), and was replaced by the Greek Regulation on Energy Efficiency of Buildings (KENAK) in 2010, setting forth stricter rules for buildings’ insulation.

Table 1. Categorization of the building stock of the municipality of Thessaloniki, as recorded in 2011, per construction date. Percentages and totals of suitable surface for green roof installation.

| Before 1960 | 1960 - 1970 | 1970 - 1980 | 1980 - 1990 | 1990 - 2000 | 2000 - 2005 | 2005 - 2011 | Under constr. |
|-------------|-------------|-------------|-------------|-------------|-------------|-------------|---------------|
| Number of buildings | 291 | 1,218 | 2,398 | 5,513 | 6,557 | 2,022 | 1,785 | 1,428 | 1,173 | 939 | 750 | 99 |
| Percentage of suitable surface | 2.29% | 5.04% | 9.92% | 22.81% | 27.13% | 8.36% | 7.38% | 5.91% | 4.85% | 3.88% | 3.10% | 0.41% |

| Subtotals | 16.16% | 49.93% | 33.50% | 0.41% |
| Percentage of suitable surface | 0.00% | 59.56% | 39.95% | 0.49% |
| Suitable surface [m²] | 0.00 | 1,363,875.46 | 914,937.83 | 11,186.72 |

The environmental and economic life cycle data of the three insulation cases (1, 5 and 10 cm) of [6] were afterwards respectively assigned to these categories in the context of the large-scale
analysis, and two separate scenarios were examined: one where extensive green roofs are installed on the existing building infrastructure (and thus insulation distribution) of the municipality and one where the green roofs are installed over a 10 cm insulation layer on every roof. This choice of scenarios is based on the fact that, as was also recorded in [6], green roof installation cannot adequately substitute roof insulation and thus the first one may not be recommended. In addition, the same study found that green roofs’ energy savings potential is reduced when strong insulation is adopted. Thus, although the 10 cm layer could be slightly reduced and still abide by the latest update of the KENAK regulation (2017), its adoption could be useful in order to examine whether green roofs remain sustainable even when their energy savings potential is reduced. Moreover, since in the last decade large-scale state and European Union-funded programs aim to the enhancement of buildings’ energy performance, subsidizing among other tasks the replacement of existing insulation under strict regulations, it might be interesting to investigate whether green roofs could be of sufficient environmental and economic benefit to be included in similar initiatives.

The life cycle duration for this analysis too was set at 40 years (including a full replacement of the flat roof after 20 years of life) and it was hypothesized that in both scenarios, all roofs are replaced simultaneously. The economic analysis was conducted both for the private owner and the public sector, using the Net Present Value method for two discount rate scenarios (2.5 and 0.16%) with the latter referring to current (March 2021) rate levels in Greece, as recorded by the National Bank of Greece. All cost and benefit parameters remained the same as in [6], with the exception of the mean total annual rainfall, which was adapted to better reflect conditions in Thessaloniki at 450 mm, based on data from the Hellenic Climatic Atlas [10]. It was used in a stormwater retention subsidization hypothesis where 75% of the water retained yearly by green roofs is deducted from the owner’s annual water bills. For the present study, the stormwater retention findings of an irrigated green roof installation under similar climate conditions [11] were used and were conservatively adapted to a 20% of the total annual rainfall volume, since that roof featured a slightly deeper substrate layer (7.5 cm instead of 6 cm), which amounts to a total of 206.1 dam³ of water retained annually if all roofs in the municipality become green. It should be noted though, that the total rainfall in that study was significantly higher (807.6 mm) and since in addition the time interval between storm incidents plays a vital role in green roof retention ability, the actual percentage withheld in our case could be different.

Direct (by the substrate and plants) carbon sequestration data were also included in the life cycle analysis, expanding on the results of the aforementioned study, which only focused on the CO₂ emissions reduction due to the building’s use and the materials’ life cycle energy savings. These data were based on the findings of [12], which used a substrate mix (CSB: compost – soil – crushed bricks mix of 5 cm depth) very similar to the one adopted in [6] and two plant species commonly found throughout Greece (S: Silene vulgaris, L: Lagurus ovatus). The mean value of the results of both plants for this substrate mix was adopted and extrapolated to a 100 m² functional unit for a 40-year period, as can be seen in Table 2, in order to be subtracted from the green roof CO₂ emissions values of the aforementioned life cycle analysis.

### Table 2. Direct carbon sequestration values.

| Total carbon sequestration (kg/m²) in 2 years | Substrate type | CSB5-S | CSB5-L |
|--------------------------------------------|----------------|--------|--------|
| Total carbon sequestration (kg) in 40 years | 100 m² unit    | 883.32 | 767.79 |
| Mean value                                 |                | 825.55 |        |
3. Results – Discussion

3.1. Life cycle results of large – scale implementation on existing roof infrastructure

The results concerning the total life cycle energy and water consumption, greenhouse gas (CO₂ equivalent) emissions and waste production of the large – scale green roof implementation on the municipality’s current roof infrastructure (with most buildings being moderately or not at all insulated), can be seen in Figures 1 - 4. Green roofs provide total life cycle energy savings (13 – 17 %), greenhouse gas emissions (22 – 26 %) and waste production (57 – 60 %) reduction but also quite significantly increase the total life cycle water consumption (291%) when compared to flat roofs. Green roofs with a granular drainage layer provided higher energy savings (27%) and emissions reduction (13%) than those with a synthetic one, but also produced slightly more waste (5%). Differences in water consumption were minimal, but this was to be expected since irrigation needs were assumed to be the same for both types.

![Figure 1. Total life cycle energy consumption of flat and green roofs in the implementation on current roof infrastructure scenario. Green roofs provide energy savings.](image1)

![Figure 2. Total life cycle CO₂ emissions of flat and green roofs in the implementation on current roof infrastructure scenario. Green roofs provide emissions reduction.](image2)

![Figure 3. Total life cycle water consumption of flat and green roofs in the implementation on current roof infrastructure scenario. Green roofs require significantly higher amounts of water.](image3)
3.2. Life cycle results of large – scale implementation on universally well – insulated roof infrastructure

The life cycle results of the large – scale green roof implementation in a scenario where all roofs of the municipality feature a 10 cm insulation layer, are depicted in Figures 5 – 8. Green roofs provided in this case as well energy savings (18 – 19%), emissions (29%) and waste production (57 – 60%) reductions, while again producing a big increase in life cycle water consumption (279%). The differences between synthetic and granular green roofs however were less important, with the granular type recording slightly higher energy savings (6%) and emissions reduction (1.4%), and of course the same increase in waste production (5%) as in the previous scenario.
The Net Present Value estimations over the 40-year life cycle of the large – scale green roof implementation on well insulated roofs are presented in Table 3. As can be seen, flat roofs are a better economic option for the private owners in the high discount rate scenario, but in the lower discount rate case, which is representative of current rate levels in Greece, green roofs become a preferable and economically sustainable choice, although not by a large margin. They also produce however, in both rate scenarios, significant public benefits, which are approximately two to three times greater than the difference of the total installation costs between green and flat roofs.

Table 3. Private owners and public Net Present Value of the choice of large - scale installation of extensive green roof types instead of flat roofs, for two discount rate scenarios.

| Discount rates | Large - scale private NPV |   | Large - scale public NPV |
|----------------|---------------------------|---|--------------------------|
|                | Flat                      | Extensive - Synthetic | Extensive - Granular |
| 0.16%          | 0.00 €                    | 4,230,102.24 €         | 6,086,970.70 €      |
| 2.50%          | 0.00 €                    | -25,049,182.70 €       | -23,743,291.98 €    |
| Installation costs | 105,340,000.00 €         | 178,620,000.00 €       | 178,620,000.00 €    |

3.3. Implications – limitations

As was shown in the previous subsections, green roofs provide total life cycle energy savings and reduction in greenhouse gases emissions and waste production. However, they also produce a very important increase in life cycle water consumption, which could prove to be a quite significant limiting factor for their implementation, especially in regions where water shortages are to be expected.
both in the near or more long-term future. It is thus crucial that efficient irrigation, water reuse or harvesting systems [13,14] are incorporated both in green roof construction practices and examined in future green roof life cycle studies.

Green roofs were also found to be more efficient in each of these aspects when installed on a well – insulated roof substructure. Although this outcome might seem counter – intuitive, it is based on the fact that they cannot adequately replace roof insulation, but also to the fact that the greatest portion of their life cycle benefits, especially those regarding energy use and greenhouse gas emissions reduction, are connected to their production and manufacturing of material and not their maintenance/use life cycle stage. This finding can be attributed to the protection that green roofs provide to the materials underneath, doubling their service life and rendering their replacement after 15 – 20 years (as is the case with common roofs) unnecessary [6].

On the basis of these factors, the large – scale implementation on well – insulated roofs may be deemed preferable when compared to the scenario where green roofs are installed on the existing roof infrastructure of the area, since it corresponds to increased energy savings (31 – 34%) and emissions reduction (26 – 29%). It also produced an increased amount of waste (1%) and water consumption (0.5%), these differences however are minimal when compared to the previous ones.

Although green roofs were not the best choice in the high discount rate case of the economic life cycle analysis of the second implementation scenario, they produced significant public benefits in both discount rate levels calculations, which could even exceed by two to three times the difference in installation costs between green and flat roofs. This finding, combined with the ones of the environmental analysis, could imply that their large – scale implementation could be supported by state subsidies, especially along the lines of existing state-led programs concerning the upgrade of the energy efficiency of the building sector, that in most cases include the replacement of roof insulation.

Existing green roof policies in Greece mainly focus on urban planning regulation incentives, increasing the vertical built – surface ratio of a property in the case of green roof implementation. Such measures however could perhaps fail to encourage their installation where it is mostly needed, namely in densely-built urban areas with no or sparse green space access, that are most vulnerable to urban heat islands effects, stormwater flooding and traffic noise [15] (since the increase in built-surface ratio may not produce adequately exploitable space for the owners), but could also fail to support marginalized low – income communities that may be most exposed to these conditions [16]. A combination of direct financial support and socio - spatial analyses of urban areas to prioritize green roof implementation based on population vulnerability [16] and ecosystem services potential [15,17] may thus be the most efficient solution.

It should be noted though that a series of potential limitations may apply to green roof life cycle studies, both in general but also concerning the outcomes of the present study a well. Both the environmental and economic performance of green roofs are dependent on local conditions that can vary even in a national context. Hence an attempt to use local data whenever possible is instrumental to the accuracy of their life cycle evaluation. In addition, although data concerning them are not always available, efforts must be made to include all materials and life cycle stages. However, not all environmental and economic data used in the life cycle analyses on which the present study is based, were possible to be collected locally, while there was data shortage regarding the construction stage of green roofs’ life cycle and of other stages for some of their individual materials [6]. Finally, benefits and challenges that may still be hard to quantify environmentally or economically, such as the eutrophication potential, health and leisure services or sound insulation properties of green roofs were not included in the analyses, but could have an important effect on their life cycle evaluation.

4. Conclusions
Large – scale green roof implementation in the Municipality of Thessaloniki proved to be preferable on a well – insulated roof substructure scenario rather on an existing infrastructure one, providing life cycle energy savings (18-19%), greenhouse gas emissions (29%) and waste production (57 – 60%) reductions, but also a big increase in water consumption (279%). While not a preferable economic
option for private owners in a high discount rate scenario, they were found to produce significant public benefits in both a high and low-rate level, a fact that could be used to justify their state subsidization. Since most of their life cycle benefits spring from the roof materials’ longevity they provide, this support could be incorporated in buildings’ energy performance upgrade programs that usually include roof insulation replacement, and could in general become more efficient by targeting areas and populations most vulnerable and in need of urban ecosystem services.

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