

Parametric simulation study for green roof retrofit over high performance solar house prototype “EFdeN Signature”

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Abstract. The advantages of green roofs are well documented, ranging from heat island reduction, thermal comfort, air quality, stormwater management and energy savings for buildings. However, it has been shown that green roof retrofits are more effective in old, low efficiency buildings. This paper studies the possibility of retrofitting a high efficiency solar house with a green roof system being partially shaded, optimising its characteristics by means of parametric simulation. The input variables of the green roof system are: growth medium thickness, LAI (leaf area index) and height of plants. The output variables by which the different green roof systems are compared are: annual energy demand for heating and for cooling. The study concluded that the average reductions of energy consumption when retrofitting an efficient building with an extensive green roof are of 1.01% for heating and 4.61% for cooling, but optimising parameters (low LAI in winter, high LAI and height of plants in summer) can get reductions to 1.55% for heating and 5.95% for cooling.

1 Introduction

1.1 Solar Decathlon competition

Solar Decathlon is the most important solar architecture and technologies competition worldwide, started by the U.S. Department of Energy in 2002. It challenges collegiate teams to design and build, at the site of the competition, solar house prototypes which are then monitored and juried by 10 contests, varying from architecture, engineering and construction, energy efficiency, comfort conditions to sustainability and innovation.

Solar Decathlon Middle East 2018 was the first competition of this kind to be taking place in the Middle East, with the intention of developing and promoting ideas, capacities and technologies that can be implemented for the benefit of the inhabitants of the Middle East region. The house prototypes had to be focused on solving the issues and needs for the sustainable living in this region, where high temperatures, high humidity and dust condition people's daily lives during most part of the year.

Romania was represented at Solar Decathlon three times in history. The first was team Prispa competing in Solar Decathlon Europe 2012 in Madrid, where they won second place in Energy Efficiency. The second was Team EFdeN in Solar Decathlon Europe 2014 in Versailles, winning an honourable mention in Sustainability.

1.2 EFdeN Signature prototype

House EFdeN Signature is the solar house prototype which represented Romania in the Solar Decathlon Middle East competition in 2018, the first to be taking place in an extreme hot and humid climate, Dubai. The main architectural and passive energy efficiency features are two raised volumes above the bedroom and kitchen, inspired by traditional Middle Eastern wind towers and an exterior facade, the “shell”, also inspired by the Middle Eastern “mashrabiya”, which shades the southern and eastern facades and provides an outdoor, semi-exterior space protected by weather phenomena such as intense solar radiation and sand/dust storms which take place in Dubai.



Fig. 1. House EFdeN Signature in Dubai.

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Fig. 2. House EFdeN Signature modular wooden structure

With a wooden structure, the main building construction feature of the house is modularity, designed to be assembled in 15 days time.

Designed for two people occupancy, the habitable surface area is 74 m². The conditioned space has a surface area of 66 m² and a volume of 205 m³. The area of the thermal envelope is 270 m².

Responding to Dubai's harsh climate was a challenge in designing a house that is both sustainable and comfortable. In order to adapt to the hot humid climate, multiple passive strategies were implemented in the design of the prototype to exploit natural means and depend less on mechanical systems. Local architecture acted as inspiration to use traditional elements in a modern way, which resulted in the multifunctional towers and the perforated facade. The elevated volumes follow basic principles from Middle Eastern wind towers to enhance natural ventilation by stimulating air circulation and hot air evacuation through the high-placed openings. The traditional mashrabiya inspired the patterns on the outer shell that filter light, while shading the outdoor private space.

With a median U-value of 0.13 W/m²K, walls are structured as follows: aluminium composite facade (4mm), ventilated air (10cm), rockwool insulation (20cm), wooden structural panel (11.5cm), cork tiles (3mm).

Based on timber frame construction system, the roof and floor slabs have an U-value of 0.19 W/m²K.

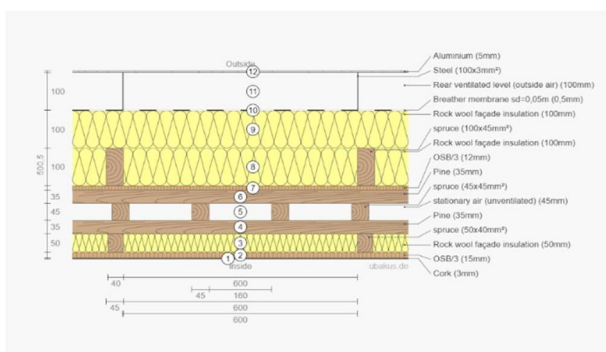


Fig. 3. Typical wall construction

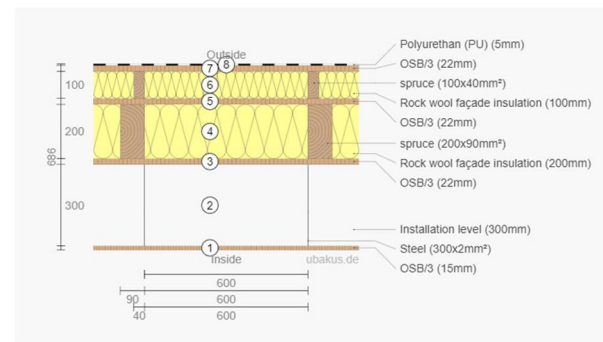


Fig. 4. Roof slab construction

Fresh air is supplied through a heat and humidity recovery unit. The mechanical ventilation is controlled by air quality sensors, which ensure that the CO₂ concentration is below 800 ppm and that humidity is between 30% and 60%. Unlike usual enthalpic recovery units, the model used in the prototype is not of the rotary type but plate heat exchanger made of desiccant fibres, thus reducing sound output. Other contaminants which might get indoors such as fine dust and small particles are filtered out by the advanced filtration integrated in the AC indoor units.

Cooling is done with a multi split system with two indoor units, this system combination having a cooling capacity of 8.5 kW, a SEER of 6.97 and a SCOP of 4.71. Features that improve both comfort and energy efficiency are the airflow distribution smart systems of the indoor units. These systems even out temperature distribution, while also avoiding direct airflow towards people.

The Building Automation System in house EFdeN Signature also play a part in its energy efficiency. One effective way to reduce the energy consumption is the 'stand-by' scenario which prepares the house for inactivity. The system turns off all the lights in the house, stops some of the appliances in use (TV, oven, stove, washing machine) and keeps turned on only the ones that must remain powered on (fridge) and reduce the power of the HVAC system to avoid the waste of energy.

2 Green roofs

2.1 Green roofs - overview

Benefits of green roofs are well documented and in certain countries the installation of green roofs is encouraged by state authorities.

Large scale installation of green roofs has been shown to decrease heat island effect in dense urban areas [1,2] by maximising reflection and cool exterior surfaces, also contributing to outdoor thermal comfort. It has been estimated that in developed urban areas, roof represent between 40 and 50% of outdoor surfaces [3], showing the great opportunity for reducing heat island effect by improving roofs.

Another benefit of green roof is improving stormwater management [4]. By retaining stormwater in the growth medium (soil) layer, green roofs reduce peak flow in the rainwater drainage systems and reduces site runoff.

During summer, green roofs reduce the cooling energy consumption by the combined effects of shading and evapotranspiration [5]. Plants reflect part of the solar radiation so that it does not get to the roof surface and water evaporation at leaf surface reduce superficial temperature thus reducing heat gains through the roof. In the case of green roof retrofits, the thermal resistance is also increased and this is why green roofs have been shown to have a greater energy consumption reduction impact on older, poorer insulated buildings [6].

A typical green roof construction consists of a waterproof membrane, a protection membrane to protect the waterproofing from root puncturing, a drainage layer usually made of gravel, a filter layer which separates drainage layer from upper soil, the growth medium (soil) and the plant canopy layer [7].

The thickness of the growth medium dictates what type of plants the canopy layer can contain so green roofs can be thus classified in intensive, semi-intensive, extensive and semi-extensive [8]. Intensive green roofs have a soil thickness of at least 30 cm and can accommodate a wide variety of plants, including small trees and shrubs. Because of the thick soil layer, intensive green roofs have a large water retention capacity but also pose structural limitations. Green roofs with soil thickness between 15-30 cm are called semi-intensive, they can accommodate small plants and shrubs but still require high maintenance and require structural considerations over the building [7].

Extensive and semi-extensive green roofs have a soil thickness of 7-15 cm and can only accommodate small plants such as grass or sedum. This type of green roof requires little maintenance, usually require no irrigation and are suitable for retrofit of old buildings, as they are lightweight [9].

2.2 Green roofs - parameters

An added green roof structure over an existing building increases the total thermal resistance of the roof construction, decreasing heat gains through the roof. However, this added insulation only limits conductive transfer and is no interest for the purpose of this study. Moreover, the resistance varies with the amount of water in the soil, phenomena which is currently not accounted in the numerical model.

The thickness of the growth medium (soil) and the gravel drainage layer mainly affects transient heat transfer through the roof, being thermally massive and adding thermal inertia to the building.

The height of the plants and the LAI (leaf area index) dictate how dense is the foliage layer in the canopy layer of the green roof, which affects the shading of the roof surface, as well as the radiative heat transfer between plants and the surface of the roof and convection at the surface. [10]

Minimum stomatal resistance of the plants affects evapotranspiration process which cools the adjacent media, by controlling water vapor transfer from the leaves surface into the atmosphere. [10]

3 Study methodology

3.1 Simulation engine

For simulation purposes, EnergyPlus building energy modelling engine has been used, with DesignBuilder graphical interface.

3.2 Green roof numerical model

The dynamic thermal behaviour of the studied green roof systems were evaluated using the Green Roof Model (EcoRoof) of EnergyPlus. The model allows the user to define the outermost layer of a roof construction as a green roof layer, specifying various aspects such as the depth and thermal properties of growth media and plant canopy variables such as LAI, plant height, stomatal resistance (ability to transpire moisture), spectral properties of leaves. [10].

The phenomena taken into consideration by the model are: long and short wave radiation within the plant canopy, plant canopy effects on convective heat transfer, evapotranspiration from the soil and plants and heat conduction and storage in the soil layer. The model does not account for moisture-dependent thermal properties [10].

3.3 Reference building energy model

Having an open space floor plan, house EFdeN Signature has been modelled with two thermal zones, a large one covering the living area, bedroom and kitchen and the second one which is the bathroom. The first zone also includes the elevated spaces, the two towers, one above the bedroom and one above the kitchen area. Also, there are two semi-exterior, unconditioned spaces - the wind-fang and the technical room.

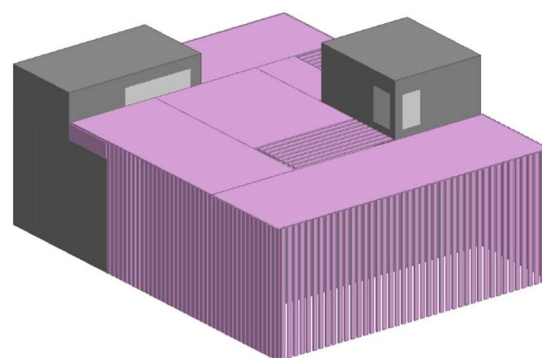


Fig. 3. House EFdeN Signature model in DesignBuilder

The extensive exterior shading has been modelled with component blocks which only affects solar radiation, having no thermal mass or resistance.

The building is occupied by two working people, weekends and holidays have been taken into consideration. The mechanical ventilation is controlled by CO₂ concentration, the limit being 800 ppm.

Heated gross-volume (V)	210 m ³
Thermal envelope surface (S)	270 m ²
Shape factor (S/V)	1.28 m ⁻¹
Net floor area	67 m ²
Roof Surface	91 m ²

Table. 1. Reference building geometric features

Wall type 1	0.127 W/m ² K
Wall type 2	0.117 W/m ² K
Floor slab	0.193 W/m ² K
Roof slab	0.126 W/m ² K
Windows	0.645 W/m ² K

Table. 2. Reference building envelope U-values

3.4 Parametric simulation methodology

First, the reference building has been modelled, taking into consideration its geometry and orientation, construction, occupancy patterns, internal heat gains, as well as ventilation and air-conditioning systems. These inputs have been chosen as to closely resemble its actual location and building characteristics. The hourly weather data used is from the ASHRAE IWE database, Bucharest INMH-BANE weather station. The building performance is assessed by evaluating its yearly heating and cooling energy consumption. These values are used as reference levels when comparing different green roof systems.

Variable parameters	Soil thickness	7.5 cm 15 cm
	Height of plants	10 cm 20 cm 30 cm
	Leaf area index	1; 3; 5
Fixed parameters	Leaf reflectivity	0.220
	Leaf emissivity	0.950
	Minimum stomatal resistance	180 s/m

	Max. volumetric moisture content at saturation	0.500
	Min. residual volumetric moisture content	0.010
	Initial volumetric moisture content	0,150

Table.3 .Green roof simulation model parameters

By creating combinations of the variable parameters (soil thickness, height of plants and leaf area index), 18 green roof constructions have been created which are to be compared to each other and to the reference building model - without green roof.

The studied output parameters are total yearly electricity consumption for heating and cooling, as well as the yearly degree of overheating - the number of hours when indoor temperature is above 26°C, when air-conditioning is off.

4 Results and discussion

As expected the retrofit of the building with a green roof does influence its energy consumption for heating and cooling, but not significantly, in the case of an already highly efficient and well insulated building, as it is the case with the studied reference building.

	Heating kWh/yr	Heating reduction	Cooling kWh/yr	Cooling reduction
Reference building model	8092	-	560	-
SD = 7.5cm LAI = 1 PH = 10cm	7970	1.50%	582	-3.92%
SD = 7.5cm LAI = 1 PH = 20cm	7973	1.46%	580	-3.60%
SD = 7.5cm LAI = 1 PH = 30cm	7978	1.41%	577	-3.11%
SD = 7.5cm LAI = 3 PH = 10cm	8019	0.90%	541	3.41%
SD = 7.5cm LAI = 3 PH = 20cm	8021	0.87%	540	3.62%
SD = 7.5cm LAI = 3 PH = 30cm	8024	0.84%	537	4.08%
SD = 7.5cm LAI = 5 PH = 10cm	8038	0.66%	532	5.05%
SD = 7.5cm LAI = 5 PH = 20cm	8041	0.63%	530	5.31%

SD = 7.5cm LAI = 5 PH = 30cm	8043	0.60%	527	5.81%
SD = 15cm LAI = 1 PH = 10cm	7967	1.55%	580	-3.60%
SD = 15cm LAI = 1 PH = 20cm	7969	1.51%	578	-3.29%
SD = 15cm LAI = 1 PH = 30cm	7974	1.46%	576	-2.79%
SD = 15cm LAI = 3 PH = 10cm	8016	0.94%	540	3.49%
SD = 15cm LAI = 3 PH = 20cm	8018	0.91%	539	3.76%
SD = 15cm LAI = 3 PH = 30cm	8020	0.89%	536	4.21%
SD = 15cm LAI = 5 PH = 10cm	8034	0.71%	531	5.17%
SD = 15cm LAI = 5 PH = 20cm	8037	0.68%	529	5.43%
SD = 15cm LAI = 5 PH = 30cm	8040	0.64%	527	5.95%

Table.4. Parametric study results

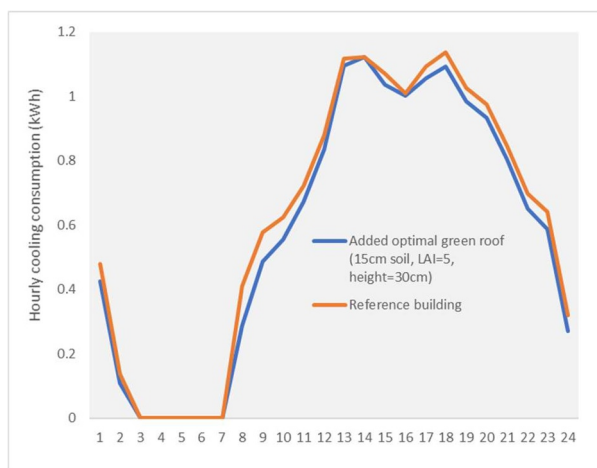


Fig. 6. Reference building vs. Optimal green roof for the cooling season – July 15

In the heating season, predominant in the studied climate, the added thermal insulation and thermal mass added by a green roof retrofit reduce the energy demand for heating by an average 1.01%. We observe that the soil thickness and height of plants are not decisive factors, but the leaf area index. The largest improvements take place when studying low leaf area index green roofs, as the additional shading provided by a

dense foliage layer (high LAI) reflects solar radiation so the solar heat gains, beneficial in the heating season are reduced. The largest reduction in energy demand is achieved when installing a green roof with 15 cm of soil, as to be an extensive green roof, a low LAI, the studied case is LAI=1 and low height plants. We thus conclude that during the heating season, the thermal mass of the soil is decisive in reducing heating energy demand, with scarce or inexistent foliage layer wanted.

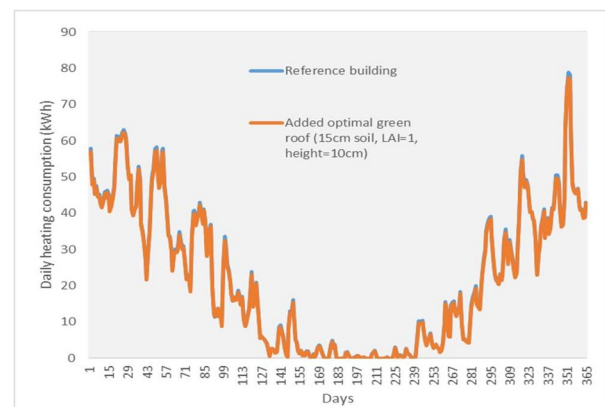


Fig. 4. Reference building vs. Optimal green roof for the heating season – whole year

On the other hand, during the cooling season, the shading and evapotranspiration prove to be important, in addition to the added thermal insulation and thermal mass. The reducing in energy demand for cooling is higher than that for heating, to an average of 4.61%. However, the installation of low-LAI green roof increases the consumption for cooling, as the highly thermally absorbent soil is directly exposed to solar radiation, increasing solar heat gains. The highest reduction is achieved when studying a green roof with 15 cm of soil, dense foliage layer with LAI=5 and 30 cm tall plants, which is about the tallest achievable height with extensive type green roof.

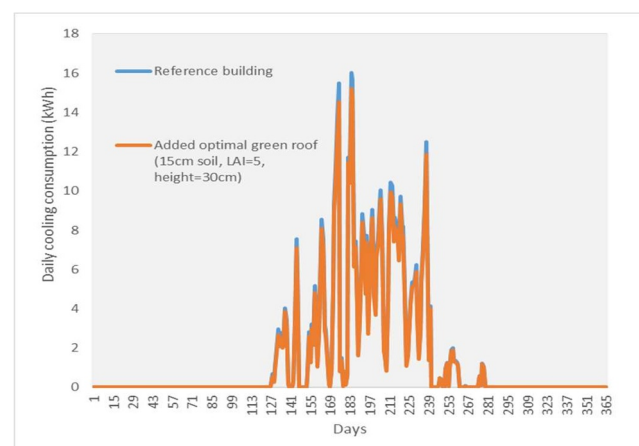


Fig. 5. Reference building vs. Optimal green roof for the cooling season – whole year

5 Conclusions

We can conclude that even in the case of an already very efficient building, very well insulated and having added passive strategies for lower the energy consumption for air conditioning and with an already partially shaded roof, the retrofit with a green roof is still beneficial, lowering the energy consumption for cooling with up to 5.95%, with an optimised green roof construction for the hot months.

The study shows that the average reductions of energy consumption when retrofitting an efficient building with an extensive green roof are of 1.01% for heating and 4.61% for cooling, but optimising parameters (low LAI in winter, high LAI and height of plants in summer) can get reductions to 1.55% for cooling and 5.95% for cooling.

While retrofitting such a building with a green roof might be rational from an energy consumption standpoint, the economical point of view is yet to be studied, considering the overall reduction in cost with electricity and the investment required for installing a green roof on such an existing building.

6 References

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