Analysis of Passive Architectural Roof Cooling Potential to Decrease the Cooling Demand for Northern European Office Buildings Based on Energy Modelling and Laboratory Tests

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Abstract: Passive architectural roof cooling or vegetated roofs, also called green roofs, have been shown to reduce rooftop heat transfer, offering enhancement to a building's thermal resistance or R-value in warm climate zones. However a comprehensive study of the magnitude of that effect has not been conducted previously, nor on the impact of green roof design variables and climatic effects in Northern European conditions at latitudes of 55° and higher. The objective of the research was to investigate the cooling potential of green roofs through building energy modelling and laboratory tests for Northern European conditions. The findings in this study show that unlike previous studies carried out in warmer climates, the main role in cooling the building is played by night-time cooling of the building enclosure. All measures, including green roofs, that decrease the thermal conductivity of the roof construction cause heat accumulation inside the building. In conclusion, green roofs do not have a significant cooling potential for office buildings in Nordic conditions.

Keywords: Green roofs, Energy efficiency, Energy simulation, Cooling Load

1. Introduction

Green roofs, eco-roofs or vegetated roofs are basically low maintenance gardens growing on the roofs of a range of building types from commercial and institutional blocks to residential homes. Many advantages are offered by green roofs: Storm Water Control – During rain the plants use the water and the soil absorbs the water, reducing or delaying storm water discharge. Aesthetics – The garden-like appearance of the roof is appealing to occupants of spaces adjacent to or in taller neighbouring buildings. Environmental – Rooftop gardens convert carbon dioxide to oxygen, reduce the "heat island" effect of massive horizontal reflective surfaces, and filter rain and irrigation water prior to discharge. Building Energy – Added layers of soil and plants insulate the roof and, coupled with evapotranspiration, act to reduce heat transmission through the building roof. Interest in, and installation of, green roofs is expanding rapidly. The reasons for each new green roof vary from case to case, but invariably one of the main reasons cited is the potential to reduce building energy usage. Even atop a roof with substantial insulation, the green roof adds yet more thermal resistance, or R-value, that could immediately begin to pay back the investment via reduced energy costs. The actual return on the investment thus depends directly upon the R-value that a given green roof design will yield once installed [1]. Investigations of installed green roofs [2 - 8] have included in situ measurements of temperature histories at different levels within the green roof, and have often been compared to similar measurements taken for control roofs without green roof cover that are exposed to similar weather and climatic conditions. In all cases, these studies have demonstrated that the green roof tempers the diurnal temperature swings, leading to the conclusion that the reduction in temperature fluctuation will extend the life of the roof membrane beneath the green roof, improving the life-long economic benefit of the green roof and decreasing the cooling demand. Too often, however, a concurrent conclusion is drawn that reduced temperature implies reduced heat flux; that conclusion is not necessarily true. An independent measure of heat transmission through a green roof is needed to document a green roof's energy conservation potential. The objective of the current research was to investigate the cooling potential of green roofs through building energy modelling and laboratory tests for Northern European conditions. Such a comprehensive study of either the magnitude of that effect, or the impact of green roof design variables and climatic effects in Northern European conditions, has never previously been performed.

2. Green Roof Construction

Green roof design varies widely, and so the following description of green roof construction should only be considered as a nominal guide. Green roofs typically have four layers of construction. A protection layer directly above the roof construction serves to protect the roof from moisture. This layer includes some combination of waterproof membranes and root barriers. A drainage layer, that may include small moisture-retention reservoirs and voids, resides directly above the protection layer to allow excess moisture to flow out of the green roof construction and either into downspouts or some form of storage. The growing media layer resides above the drainage layer, usually separated by a dense mesh fabric cloth. This media layer is typically a light-weight combination of sand, aggregate, and organic matter. The most important characteristics of the growing media are its thermal conductivity, specific heat capacity, and density. Depending upon the type of vegetation used, the media layer may be as thin as 5-10 cm or as thick as 1 m. The upper-most layer of green roof construction is the vegetation itself [9], [10].

3. Cooling Demand in Northern European conditions

The modern design of office buildings in Northern Europe shows a tendency to increase the window share per facade to be more impressive with extensive visibility. An increased window share in general results in an increased use of energy and resulting costs for cooling [16]. When the heat from solar irradiation, people, office equipment and electrical lighting exceeds the heat loss at the highest accepted room temperature there is a heat surplus that has to be removed. In addition, modern office buildings are well insulated which conclusively causes the buildings to have cooling demand from April to the middle of September. There are multiple ways to decrease the cooling demand of office buildings. One of the methods, passive architectural cooling, including external overhangs, smart facades, etc., is becoming more popular and widely used. green roof technology is also one of the passive architectural cooling strategies. The aim of this study was to document a green roof's energy conservation potential to decrease the cooling load. Laboratory tests for green roof and energy modelling were carried out and comparisons made.

4. Experimental Methods

The laboratory tests were conducted at the Portland State University in Oregon, US. A laboratory facility has been designed and constructed that continuously exposes a green roof to constant temperature, wind speed, humidity, and sunlight. To achieve this control, full scale green roofs could not be accommodated. Instead, test roof sections were prepared that recreated green roofs in all respects except for the roof surface area. Those test sections were tested in a low speed wind tunnel, as illustrated in Figures 1 and 2.

The green roof plant trays were 0.6 m x 0.6 m each, and two were accommodated simultaneously to provide average data for two replications. Laboratory settings allow the analysis of any desired indoor and outdoor climatic condition.

Basic instrumentation included:

- Temperature – Type T thermocouples were used to measure air temperature on the hot side (green roof) and cold side. Hot side thermocouples were protected by radiation shields.
- Relative humidity – Thin film capacitance relative humidity sensors were suspended in two locations above the green roof.
- Heat flux – Thermopile heat flux meters were mounted on the surface between the hot side and cold side, located in the centre of each green roof tray to essentially measure one-dimensional heat transfer.
- Green roof weight – The green roof trays rested atop a platform supported at each corner by a strain gage load cell.
- Air flow – A hot film anemometer was used to measure the wind speed at an array of locations above the plant bed.

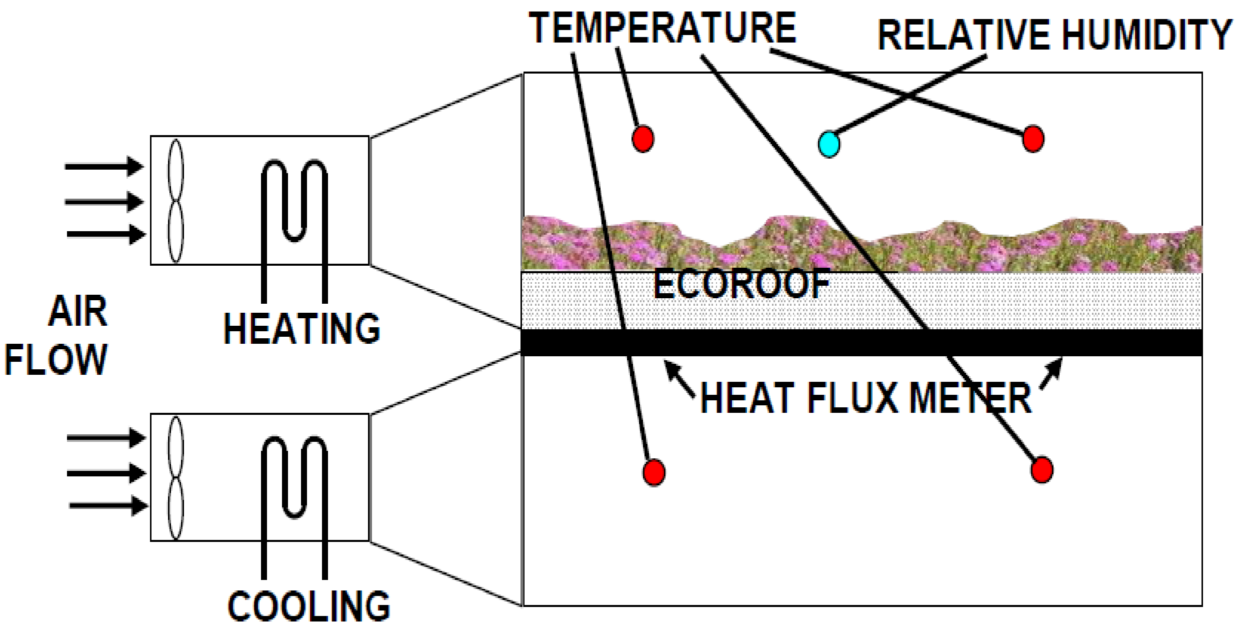

Figure 1. Schematic of the wind tunnel test facility for measuring heat transfer performance of green roof designs

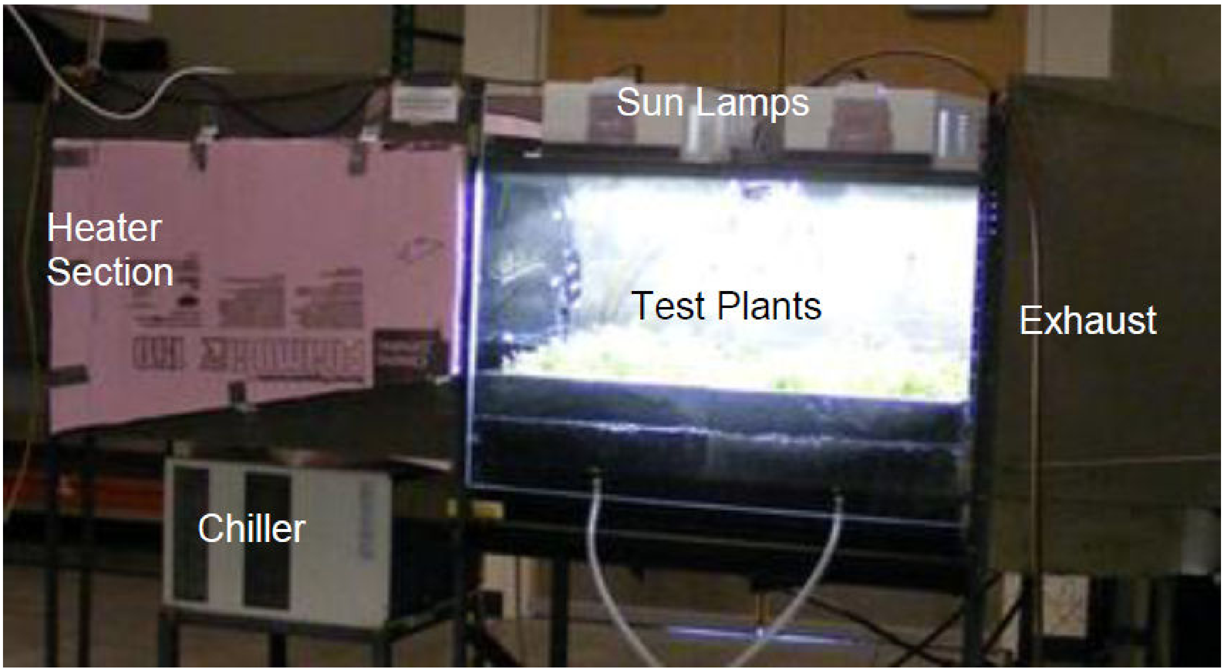

Figure 2. Photograph of the wind tunnel test facility for measuring heat transfer performance of green roof designs.

Green roof sections were created in special-purpose trays designed to fit the wind tunnel. Each tray allowed for easy and repeatable measurement of heat flux, while allowing the use of conventional green roof construction materials. Ryegrass (*Lolium perenne*) was used in the laboratory tests.

All plants were grown in a commercial greenhouse, moved to the laboratory during testing, and were then returned to the greenhouse. An image of *Lolium perenne* ready for testing is shown in Figure 3.

Figure 3. Ryegrass (*Lolium perenne*) was used in the laboratory test

5. Energy Modelling

A five story office building was designed for the energy simulations. The roof area of the building was 800 m^2. Figure 4 illustrates the building that was used for the calculations. Table 1 provides the more detailed input data used in the simulations. Information not indicated in Table 1 was taken according to the Estonian Government decree nr. 258 "The Minimum Requirements for Energy Efficiency", see also chapter seven for more detail. The basic parameters of the building were 40 m length, 20 m width and 17.5 m height.

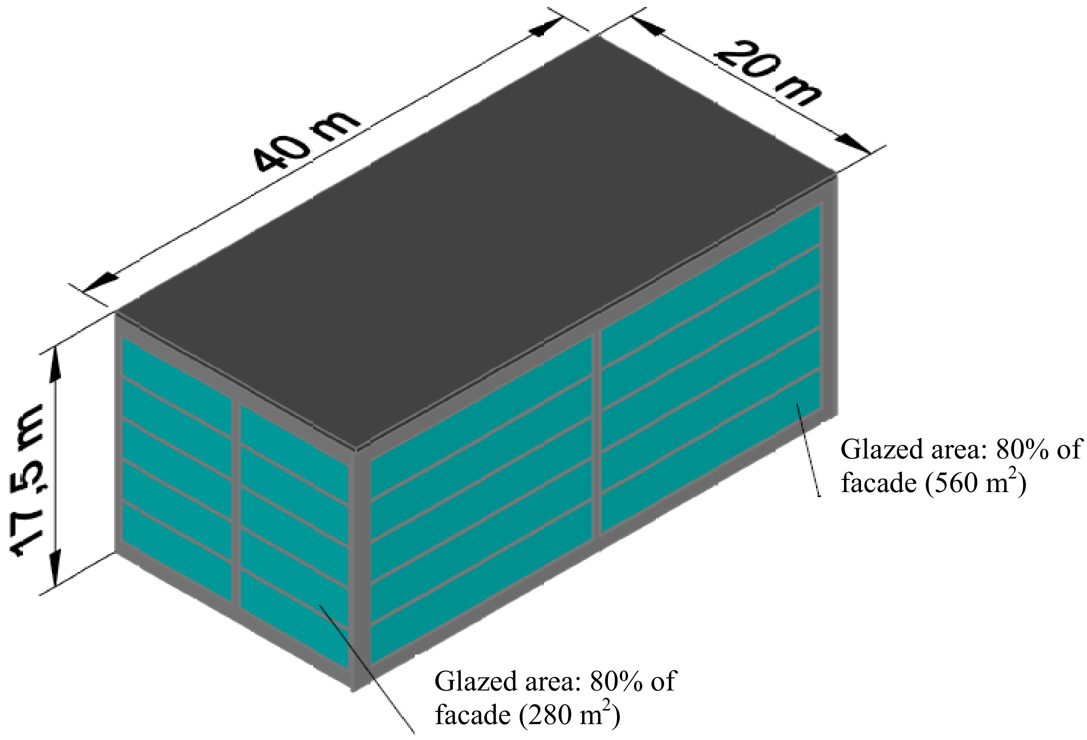

Figure 4. Office building used for calculations

Table 1. Office building input data used for calculations

Room temperatures:

Lowest acceptable indoor air temperature	21 °C
Highest acceptable indoor air temperature	25 °C

Ventilation:

Ventilation supply air temperature	18°C
Ventilation heat exchange efficiency	80%
Ventilation operation hours	06:00 – 19:00, 5 days a week. During the weekend the system is not in operation.
Ventilation air flow	2 l/s*m^2 (7006 l/s)

Free heat

Time when free heat is considered	07:00-18:00; 5 days a week
Simulatanety factor	0.55
Lighting	15 W/m^2
Equipment	18 W/m^2
People	5 W/m^2
Specified area	Heated area

U-values:

Wall	0.22 W/K*m^2
Roof	0.17 W/K*m^2 (the highest insulation level specified in regulation was used)
Floor on soil (Soil temperature +7°C, 1 m below the surface).	0.15 W/K*m^2
Window (including the frame)	1.70 W/K*m^2

Building parameters:

Area	3503 m^2
Window area	50% per facade
Infiltration	0.056 l/s, m^2 (196 l/s)

Cold bridges:

Wall- floor	0.09 W/K*m
Wall- roof	0.07 W/K*m
Window perimeter	0.07 W/K*m

The simulation was carried out using an EnergyPlus building simulation tool. EnergyPlus software was chosen based on the study by [11]. Besides which it is one of the newest and most advanced building energy simulation programs available on the market. EnergyPlus is stand-alone building energy simulation model capable of modelling the hourly energy consumption of a building subject to user specified construction, internal loads, schedules and weather. As its core, EnergyPlus relies on key elements of both BLAST and DOE2 programs. EnergyPlus was first released in April 2001, and is updated twice a year. The key features of EnergyPlus include: sub-hourly user defined solution time steps, text based weather-input files, simulation solutions of internal and external heat balance and loads, transient heat conduction through building elements, thermal comfort models, advanced fenestration features, daylight controls, and atmospheric pollution calculation for on site and remote energy conservation. A detailed description of the features of EnergyPlus, and its parent programs DOE-2 and BLAST, is beyond the scope of this paper, therefore the interested reader is referred to the corresponding Department of Energy publications [8], [12]. EnergyPlus is a complicated tool, and it should be pointed out that the author of the paper has had six years of experience using the EnergyPlus software.

6. Green Roof Energy Balance Model

To analyse the green roof, a green roof model for building energy simulation programs was created. The physically based model of the energy balance of a vegetated rooftop has been developed and integrated into the EnergyPlus building energy simulation program [8]. The green roof module allows the energy modeller to explore green roof design options, including growing media thermal properties and depth, and vegetation characteristics such as plant type, height and leaf area index. The model has been tested successfully using observations from green roofs monitored in Florida. A preliminary set of parametric tests has been conducted on a prototypical 4000 m^2 office building in Chicago, Ilinois, and Houston, Texas. The green roof model accounts for long-wave and short-wave radiative exchanges within the plant canopy, plant canopy effects on convective heat transfer, evapotranspiration from the soil and plants, heat conduction (and storage) in the soil layer, and moisture dependent thermal properties. The model formulation is based on the Army Corps of Engineers' FASST vegetation models [13], drawing heavily from two models used extensively in the Biosphere-Atmosphere Transfer Scheme (BATS) [14] and the Simple Biosphere model (SiB) [15]. The model simultaneously solves for soil surface and foliage temperature at each time step. As implemented in EnergyPlus, the green roof module allows the user to specify a green roof as the outer layer of a rooftop construction. The user then can either accept default values or specify various parameters of the green roof construction, including growing media depth, thermal properties, plant canopy density, plant height, stomatal conductance (ability to transpire moisture), and soil moisture conditions (including irrigation and precipitation).

Prior to using green roof construction the user of the software must first define (or accept defaults for) the characteristics of the green roof material. In addition to supplying a unique name for the material, the user must also specify the following fields [9]:

- Height of plants – the height of plants is limited to values in the range 0.01 < height < 1.0m.
- Leaf area – the projected leaf area per unit area of soil surface.
- Leaf reflectivity – the fraction of incident solar radiation reflected by the individual leaf surfaces. Solar radiation includes the visible spectrum as well as infrared and ultraviolet wavelengths.
- Leaf emissivity – the ratio of thermal radiation emitted from leaf surfaces to that emitted by an ideal black body at same temperature. This parameter is used when calculating the long-wavelength radiantion exchange at the leaf surfaces.
- Minimum stomatal resistance - the resistance of the plant to moisture transport in units of s/m. Plants with low values of stomatal resistance will result in higher evapotranspiration rates than plants with high resistance.
- Roughness – a character string that defines the relative roughness of a particular material layer. This parameter only influences the exterior convection coefficient.
- Thickness – the depth of the growing media layer in metres.
- Conductivity – the thermal conductivity of the (dry) growing media in W/(m-K).

- Density – the density of the (dry) growing media in kg/m^3.
- Specific heat – the specific heat of the (dry) growing media layer in J/(kg-K).
- Absorptance: thermal – the fraction of incident long wavelength radiation that is absorbed by the growing media.
- Absorptance: solar – the fraction of incident solar radiation that is absorbed by the (dry) growing media.
- Absorptance: visible – the fraction of incident visible wavelength radiation that is absorbed by growing media.

Once the green roof material is defined, the user can apply it as the outermost construction layer on any roof element. As desired, various green roof construction membranes can be included using existing EnergyPlus capabilities. While the code can currently handle multiple definitions of green roof materials, only one such material can be applied within any individual simulation. When the EnergyPlus software encounters an outermost construction layer it checks whether this material is of the green roof type. If it is then the software uses the equation set described above to track the vegetation and soil temperatures as well as the heat flux through the green roof.

7. Regulation 258

The input data used for the calculations was taken from the Estonian Government decree nr. 258, "The Minimum Requirements for Energy Efficiency". Since July 2009 it is compulsory for a new or major renovation building project to meet the requirements set by this decree. Regulation 258 establishes minimum requirements for the energy performance of buildings and the primary data and calculation methods required to verify that it conforms.

According to the purpose of buildings, requirements shall be imposed on the following buildings:
1) residential buildings: small houses (residential buildings with one or two apartments, terraced houses with three or more apartments; apartment buildings (residential buildings with three or more apartments, facilities of social welfare institutions and hostels;
2) other non-residential buildings: office and administrative buildings; commercial buildings (hotels, other accommodation and catering facilities, trading and service facilities, with the exception of office buildings); public buildings (recreational, educational and other public buildings, with the exception of health care facilities and indoor swimming pools) and transport facilities (with the exception of garages); health care facilities (hospitals and other medical buildings).

8. Results

The results of the study showed that heat fluxes through the roof were variable and heavily dependent on the intensity of solar radiation. The mean heat flux was mainly negative, indicating that the roof contributes to cooling of the building. Green roof configurations lowered the positive heat flux throughout the day, and functioned as an additional insulation layer at night and reduced the night time cooling at the roof surface. The lab tests and simulation results showed that due to this the heat generation inside the building accumulated over sequential days when green roof layers were present, and the overall cooling demand increased.

Figure 5 shows the total heat flow dynamics comparing the ordinary roof indicated by a dark blue line with a green roof indicated with a pink line. The yellow line represents the direct solar radiation.

The figure summarises the test results and represents the time period from 1st June until 31st August for an ordinary year. It can be seen from the figure that an ordinary roof has remarkably higher heat exchange characteristics between the indoor environment to outdoor environment compared to a green roof.

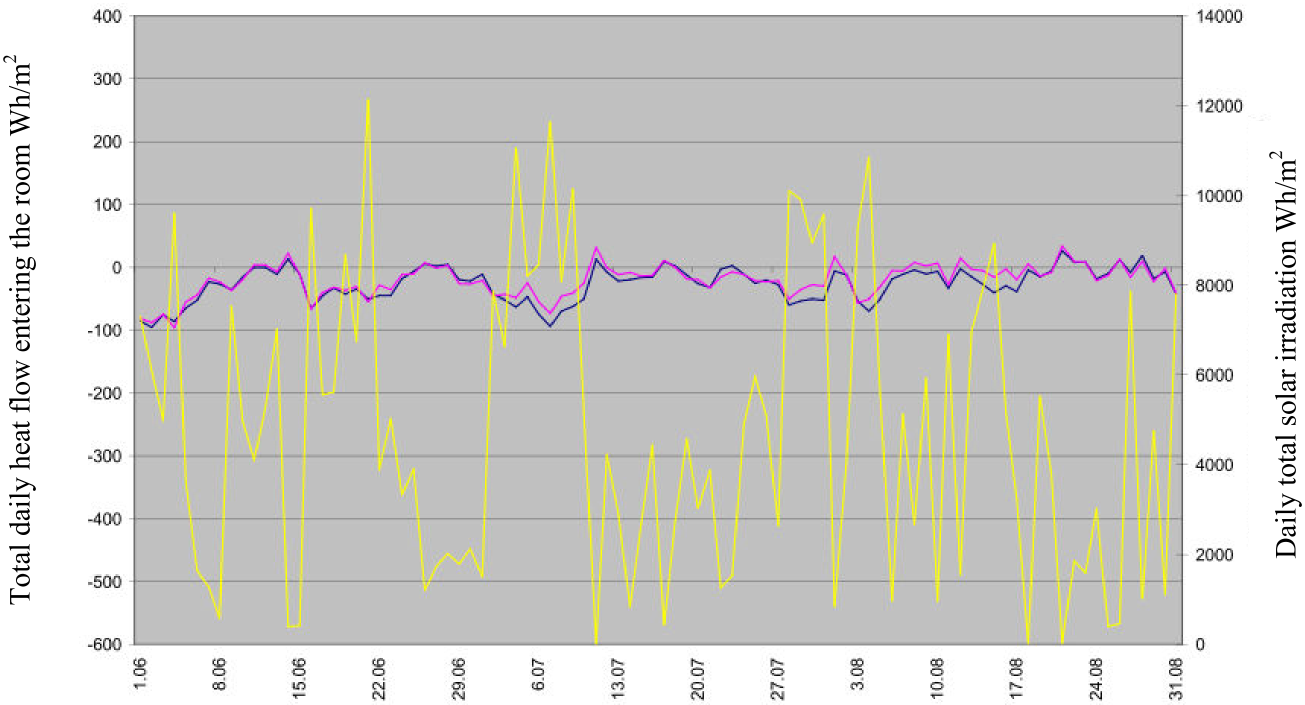

Figure 5. Total heat flow dynamics of an ordinary roof indicated by a dark blue line and a green roof indicated with a pink line. The yellow line represents the direct solar radiation.

The next table nr 2 shows the degree hours the cooling set point temperature 25 °C was exeeded for ordinary roof compared to green roof. Also the degree hours above 30 °C are shown.

Table 2 Total heat flow dynamics

	Ordinary roof	**Green Roof**
Degree hours above 25 °C	1980	2692
Degree hours above 30 °C	4	0

As indicated in table 2 the calculated degree hour over 25 °C showed 36% increase in cooling demand for ordinary roof compared to green roof. Finally it should be mentioned that the laboratory tests and simulation results matched relatively well having just 6% discrepency in results.

9. Discussion and Conclusion

The objective of the research was to investigate the cooling potential of green roofs through building energy modelling and laboratory tests for Northern European conditions. The findings in this study show that unlike previous studies carried out in warmer climates, the main role in cooling the building is played by night-time cooling of the building enclosure. All measures, including green roofs, that decrease the thermal conductivity of the roof construction cause heat accumulation inside the building. The results showed even as high as showed remarkable increase in cooling demand for ordinary roof compared to green roof. In conclusion, green roofs do not have a significant cooling potential in Northern European conditions.

Acknowledgements
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References

[1] H. Bell, & G. Spolek, 2009, Measured Energy Performance of Greenroofs, *Greening Rooftops for Sustainable Communities Conference Award and Trade Show*, Atlanta, GA

[2] R. Kumar, & S. Kaushik, 2005, Performance evaluation of green roof and shading for thermal protection of buildings, *Building and Environment* 40(11): 1505-1511.

[3] K. Liu, & B. Baskaran, 2003, Thermal performance of green roofs through field evaluation, *Proc. of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Chicago*. The Cardinal Group, Toronto.

[4] A. Niachou, K. Papakonstantinou, 2001, *Analysis of the green roof thermal properties and investigation of its energy performance,* Energy and Buildings 33(7):719-729.

[5] S. Onmura, M. Matsumoto, & S. Hokoi, 2001, Study on evaporative cooling effect of roof lawn gardens, *Energy and Buildings* 33(7):653-666.

[6] J. Sonne, 2006, Evaluating green roof energy performance. *ASHRAE Journal* 48:59-61

[7] T. Takakura, 2000, Cooling effect of greenery cover over a building, *Energy and Buildings* 31(1):1-6.

[8] T. Theodosiou, 2003, Summer period analysis of the performance of a planted roof as a passive cooling technique, *Energy and Buildings* 35(9):909-917.

[9] D. Sailor, 2008, A green roof module for building energy simulation programs. *Energy and Buildings* 40(8):1466-1478.

[10] H. Voll, 2011, Comparison of Modeling and Laboratory Tests on Green Roof. *13th WSEAS International Conference on Modelling and Simulation*, Lanzarote, Canary Islands, 27-29 May 2011.

[11] T.Tark, 2010, Comparisson of Alternative Simulation Softwares, Tallinn University of Technology,

[12] D. Grawley, 2005, *Contrasting the Capabilities of Building Energy Performance Simulation Programs*, US Department of Energy, WA DC.

[13] S. Frankenstein, 2004, *FASST Vegetation Model*, U.S. Army Engineering Research and Development Center, Cold Regions Research and Engineering Laboratory, Technical Report. WSEAS press 82-89

[14] R.Dickinson, 2009, *Biosphere-Atmosphere Transfer Scheme (BATS) for the NCAR Community Climate Model*, In: Selected Topics on Energy and Development-Environment-Biomedicine 2009: Proceedings of the 3rd International Conference on Energy and Development-Environment-Biomedicine (EDEB 09).

[15] P. Sellers, 1986, *A Simple biosphere model (SiB) for use within general circulation models,* Journal of Atmospheric Sciences 43:505-531.

[16] T-A Kõiv, 2009, Energy Efficient Assessment -The Influence of Facade Design. *In: Selected Topics on Energy and Development-Environment-Biomedicine 2009: Proceedings of the 3rd International Conference on Energy and Development-Environment-Biomedicine (EDEB 09).* WSEAS Press, 2009, 47 - 52.