Article

Energy balance modeling of an extensive green roof for the surface temperature mitigation of municipal buildings

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Abstract
In recent years, changing an urban environment, urban development and replacing no vegetated surface face to environmental challenges that can be the reasons for increasing urban temperatures and consequently causing urban heat island effects. These can be mitigated by environmental planning and building techniques, such as green roof that can moderate roof surface temperature and mitigate Urban Heat Island (UHI) phenomenon. In this context the present research deals with modeling of the surface temperature of green roofs located in Tehran, Iran. The surface temperature of both green and conventional roofs was modeled in ten years which months have the highest temperature in summer. Energy balance modeling carried out in conventional roof as a reference bituminous flat roof and extensive green roof with 85% vegetated surface and 50% accessible water. The modeling demonstrated the positive impact of green roof in decreasing the roof surface temperature. The modeling of green roofs in the summer determined that Q_H and Q_{net} values are lower and Q_E are higher than conventional roof. The results also showed that the conventional roof in Jun and August reached a peak of 48.69°C and 42.7°C whereas green roof were able to reach 44.47°C and 38.49°C respectively. In conclusion the reduced surface temperatures and increase in latent heat will be brought a decrease in sensible heat and hence a potential mitigation of the urban heat island effect via applying green roofs on existing buildings. The results indicated that green roofs can be beneficial on the environment and urban area such as improvement of air quality, biodiversity and noise reduction, green space increasing per capita.

Keywords extensive green roofs; roof surface temperature; urban heat island; energy balance modeling.

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1 Introduction

It is estimated more than half of the human population lives in cities and hence urbanization growth, water scarcity and climate change are current environmental problems in many cities around the world (United Nations, 2004; Hopkins and Goodwin, 2011; Razzaghmanesh, 2016). The development of cities causes climate change and the creation of urban heat island (Aghilinasab et al., 2013). Cities are known to be hotter than the rural areas that surround them; this phenomenon is called an ‘urban heat island’ (UHI) (Li et al., 2014). The urban heat island (UHI) effect is the changing climate consequence in the cities. It is attributed to higher urban temperatures in city districts compared to the rural areas or surrounding suburban (Razzaghmanesh, 2016). The temperature intensity of the heat islands in the cities has a significant negative effect on the environment, the quality of life, the amount of energy consumption for cooling, the emission of pollutants and greenhouse gases (Khosravi and Ghobadi, 2011). With the importance of the issue of urban heat island many studies have been conducted to identify the factors affecting its increase and decrease (Aghilinasab et al., 2013; Shamsaii Zafarghandi et al., 2017). In the main studies, vegetation has been evaluated as an important factor in controlling the ambient temperature and finally the urban heat islands (Aghilinasab et al., 2013). One of the possible solutions for the urbanization growth consequences is introducing green infrastructure to urban environments. The implementation of green infrastructure is a most effective climate change adaptation tool hence it is of considerable interest (Carter, 2011; Berardi et al., 2014; Li et al., 2014; Razzaghmanesh, 2016).

The use of urban green roofs and its development in the construction industry to improve the quality of the urban environment, the relative reduction of the urban heat island effects, improving air quality and establishing thermal balance in the indoors and outdoors of the building also have positive effects (Khosravi and Ghobadi, 2011). In fact, green roofs are one of the new approaches to architecture and urban planning and arise from the concepts of sustainable development, which can be used to increase the green space per capita, improve the quality of the environment and sustainable urban development (Yazdan Dad et al., 2010; Khosravi and Ghobadi, 2011). Green roofs are considered as an effective contribution to the resolution of environmental problems at the building and urban levels (Jaffal et al., 2012). Addressing this technology can be considered as one of the biggest positive environmental developments in cities.

Some studies have done experimental investigations to determine the thermal performance of green roofs (Coma et al., 2016; Bevilacqua et al., 2017).The results in showed that green roofs are effective in reducing heat fluxes through the roof in summer, thus lowering the energy demand for space conditioning in the building (Liu and Minor, 2005; Bevilacqua et al., 2017). The background study shows the direct solar radiation to the roof causes high roof and indoor temperatures in summer and low roof insulation can cause the heat loss and the indoor temperature reduction in winter. The indoor temperature will change by changing heat transfer from the roof. The usual methods for this purpose are green roofs, changing in roof color and insulation (Maiolo et al., 2020).

The green roofs considered as a natural cooling system that have a potential in reducing energy consumption and mitigating the heat island effect through mechanisms such as solar radiation decrease which absorbed by the plants and decreasing roof temperature (Niachou et al., 2001; Maiolo et al., 2020). The impact of green roofs is for cooling in summer and heating performance in winter. The system using precipitation can also be useful in urban runoff management (Palermo et al., 2018; Piro et al., 2019; Palermo et al., 2019; Palermo et al., 2019; Pirouz et al., 2019; Maiolo et al., 2020).

In addition green roofs, despite having functions such as beautifying the city landscape and eliminating urban pollution; they are also very effective in exchanging energy and heat from outside to inside. Therefore green roof is one of the modern solutions to urban problems. This technology with many benefits such as reducing the load of cooling and heating, air purification, reducing noise pollution, storm water management and most importantly reducing energy consumption is an effort to stabilize cities (Mahmoudi et al., 2012).

The city of Tehran, Iran, has an area with a high concentration of municipal buildings. The intent of this study is to theoretically apply extensive green roofs to municipal buildings and simulate energy balance model. Therefore, simulation methods of the surface temperature of an extensive green roof located in Tehran is presented. The aim is to evaluate the impact of the installation of extensive green roof solutions on roof temperature and hence the urban heat island phenomenon through a comparison of the average building's roof temperature in conventional (a reference bituminous flat roof) and green roofs. Measurements carried out in highest month of ten years to determine the impact of extensive green roofs on average building's roof temperature. Therefore, this research simulates the effectiveness of extensive green roofs on current urban buildings of Tehran to manage roof surface temperature.

2 Green Roofs

Green roofs are generally categorized into three types: intensive, extensive, and semi-intensive. The vegetation in intensive green roofs includes trees, shrubs, and bushes. The medium depth of layers is 150-400 mm, which requires a high level of repair and maintenance. The weight of these roofs is 180-500 kg/m^2. The design of roof structures is of paramount significance and is more expensive due to their weight loads. In extensive green roofs the type of vegetation is limited to grass, permanent gramineous plants and plants resistant to drought due to the low depth and limitation in the rooting development. The extensive green roof bed is 60-200 mm. Based on the climate conditions; these roofs do not require significant irrigation. The weight of extensive green roofs is 60-150 kg/m^2, which is appropriate for large areas. A semi-intensive green roof is somewhere in between an extensive green roof and an intensive green roof. This roofing system contains drainage layers, deeper soil and plants, and more diverse plant species than that of an extensive green roof. The depth of layers is 120-250 mm, and their weights are between 120-200 kg/m^2 (Mahmoudi et al., 2012).

3 Study Area and Methodology

3.1 Study site

The study area is located inone sections of Tehran. The combination of different municipal buildings fulfills all the requirements of a statistical sample. Study area is of paramount importance due to its various compactness and usage, and after the investigation, the outcome can be extended to the entire district.

3.2 Separation of the study area

One case study from section was separated using the CAD map. These areas were important in terms of having a variety of densities and land uses. After examining case study, the results can be generalized to the entire area. Finally, the relevant roofs located in this case were extracted from maps of area.

3.3 Type of green roof

In this research, extensive green roofs with grass covering in the residential buildings of Tehran were analyzed. In this type of roof, plants with short roots requiring low maintenance, irrigation and are of low cost should be used. In addition, the depth of the soil layer of this roof was considered low; thus, the building contained a low dead load, which would not be influential in the strength calculations of the building. The long-term color of green grass in different seasons and easy maintenance were advantages considered in this research.

3.4 Energy balance

Energy balance model has been used to estimate the surface temperature that can be described as the energy flows into and out from the surface. Solar radiation is the dominant source of energy to the surface and received energy is channeled into sensible, latent and storage heat that is presented in Fig. 1 (Levallius, 2005).

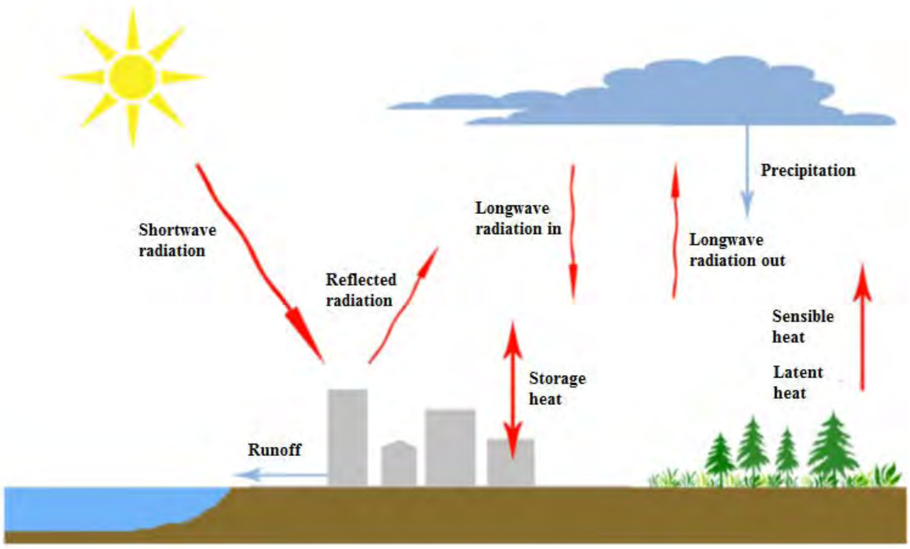

Fig. 1 The water, radiation and energy balance of a surface (Levallius, 2005).

3.5 Theoretical basis of energy balance equation

For a natural surface, the energy balance equation can be written as Eq. 1. All the necessary inputs for the surface temperature (T_s) equation can be estimated using functions (Eq. 2, 3, 4).

$K\uparrow + K\downarrow +$

$$L\uparrow = \varepsilon\sigma T_s^{\ 4} \quad (2)$$

$$Q_H = h_c(T_s - T_a) \quad (3)$$

$$K^* = K\downarrow + K\uparrow = K\downarrow(1-\alpha) \quad (4)$$

Finally surface temperature value (T_s) can be calculated using the energy balance equation (Eq. 5) that is modified from its original appearance.

$$K^* + L\downarrow = \varepsilon\,\sigma\,T_s^{\ 4} + h_C(T_s - T_a) + Q_E + Q_S \quad (5)$$

In Equations (1-5), variables are defined as shortwave radiation ($K\downarrow$), reflected radiation ($K\uparrow$) , longwave radiation in ($L\downarrow$), longwave radiation out ($L\uparrow$),properties of roof materials (albedo, emissivity; α, ε), latent heat (Q_E), sensible heat (Q_H) , storage heat (Q_S), surface temperature (T_s), air temperature (T_a), convection coefficient (h_C) and Stephan and Boltzman constant (σ). The chosen value for variables were considered as convection coefficient (h_c = 12 W m-2 K-1), albedo and emissivity (α, ε) for green roof (0.25, 0.95) and for bituminous roof (0.15, 0.9), roof slope (β=0), Stephan and Boltzman constant ($\sigma = 5.67\,E - 8\,\mathrm{W}\cdot\mathrm{m} - 2\cdot\mathrm{K} - 4$)(Levallius, 2005).

3.6 Energy balance modeling

In this study, roof surface consists dominantly of a conventional (a reference bituminous flat roof) that considered and green roof assuming 85% appropriate plant coverage with 50% accessible water. It must be determined which months of the year have the highest temperatures for a period of ten years. For this purpose, temperatures values related to the study years were obtained from Mehrabad Meteorological Stations in Tehran. The highest temperatures during these years are related to July and August. Raw input data was edited in

Microsoft Excel and the effective parameters in surface temperature were calculated, finally the surface temperature of conventional and green roof in July and August was obtained.

4 Results and Discussion

The Q_H, Q_E, Q_{net} and L_{net} values in conventional roof, as well as in green roof are presented in Table 1. Also the effects of conventional and green roof on the factors affecting roof surface temperature are shown in Fig. 2-5. In addition the surface temperature (T_s) of conventional and green roof in July and August is presented in Table 2. It is clear that the difference between their surface temperatures in July and August are 4.22°C and 4.21°C respectively.

Table 1 Conventional and green roof comparison.

Month	Conventional roof				Green roof			
	Q_H	Q_E	L_{net}	Q_{net}	Q_H	Q_E	L_{net}	Q_{net}
July	213.2	3.26e-17	175.43	242.35	162.59	75.5	175	207.03
August	158.64	2.54e-17	152.153	194.9	108.11	65.5	151.56	169.13

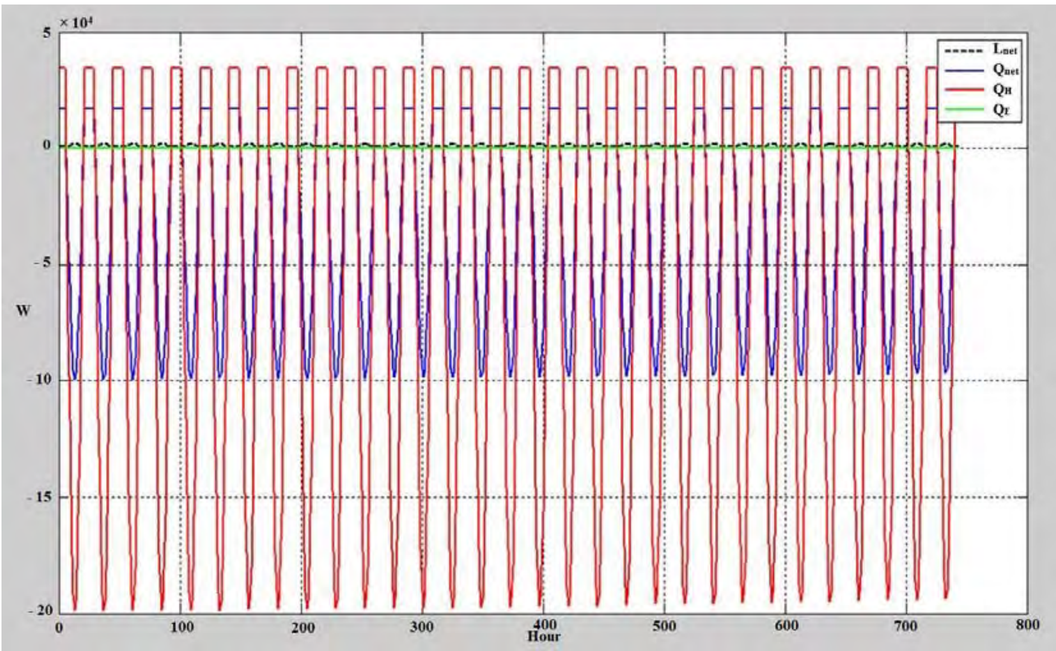

Fig. 2 The effect of conventional roof on the factors affecting roof surface temperature on July without green roof.

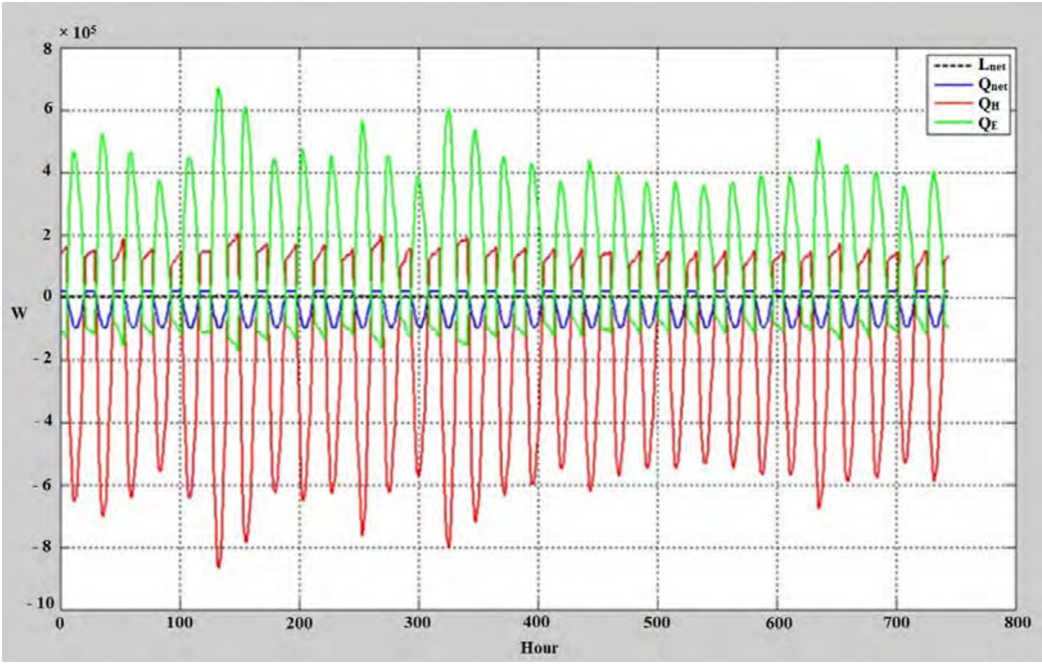

Fig. 3 The effect of green roof on the factors affecting roof surface temperature on July.

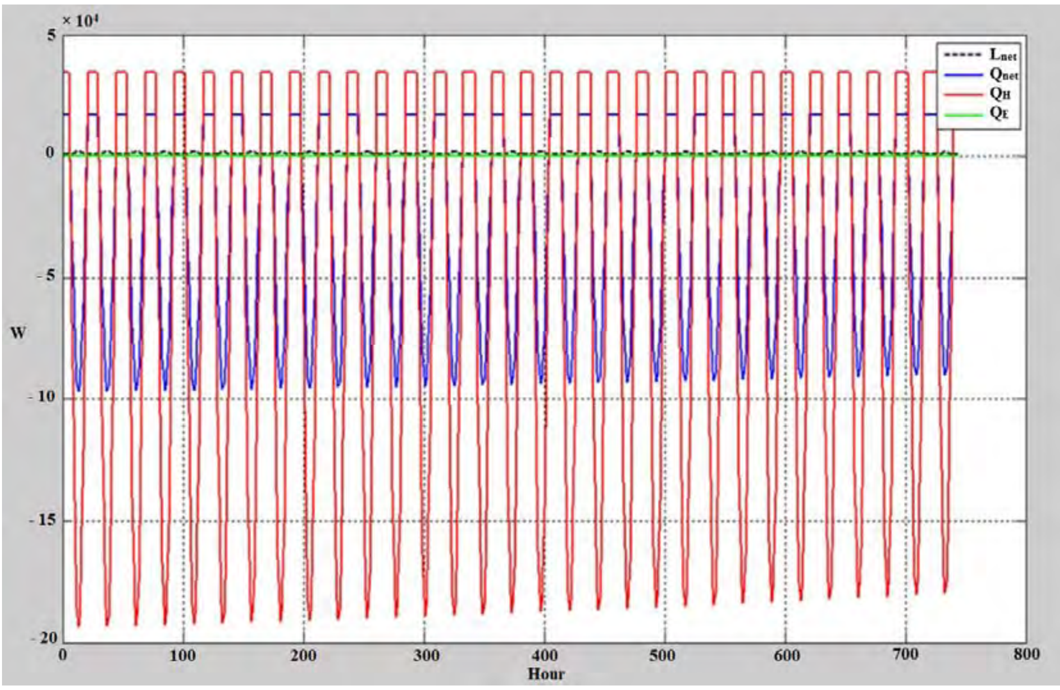

Fig. 4 The effect of conventional roof on the factors affecting roof surface temperature on August.

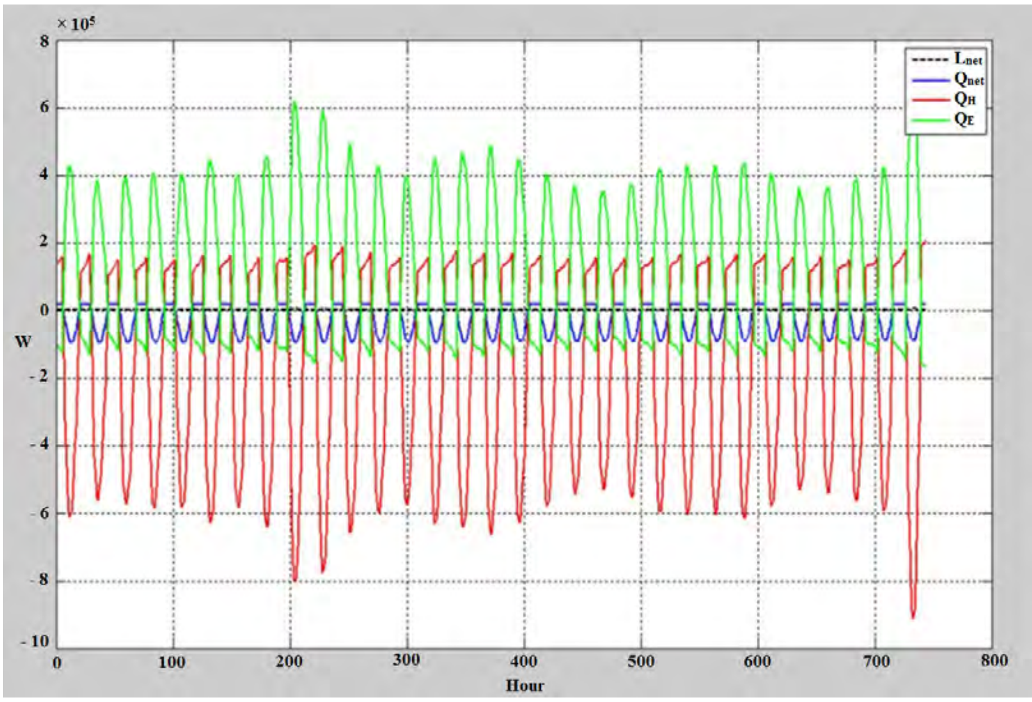

Fig. 5 The effect of green roof on the factors affecting roof surface temperature on August.

Table 2 Surface temperature of conventional roof and green roof.

Month	Average temperature (°C)		
	Air	T_s	
		Conventional roof	Green roof
July	30.92	48.69	44.47
August	29.43	42.7	38.49

5 Conclusions

The study of innovative solutions in the building sector has led to the research of green roofs as energy saving and medium of temperature moderation with other benefits (Li et al., 2014). In this study, mitigation of the roof surface temperature at city scales via green roof technologies is investigated using the energy balance model. The impact of extensive green roofs in Tehran climate considering summer in July and August was presented. Results of the modeling demonstrated the positive performance of green roofs in generating a lower surface temperature in summer comparing to the conventional roof as reference roof. For this, a series calculation are performed to investigate values of sensible heat (Q_H), latent heat (Q_E), net radiation (Q_{net}), Long wave radiation net (L_{net}) and surface temperature (T_S) values. The modeling of green roofs in the summer shows that Q_H and Q_{net} values are lower and Q_E are higher than conventional roof. Moreover, the surface temperature T_S of the traditional roof was considerably higher than the green roof. The performances of green roofs will be lead to decrease surface temperature via available water by decreasing Q_H and Q_{net} and increasing Q_E. The percentages of surface temperature reduction in green roof with 85% vegetation compared with the conventional roof are presented in Table 3 and Fig. 6. Furthermore the outcomes clearly indicated that the surface temperature values had been reduced in the green roofs compared with the conventional roofs.

Table 3 Comparison between percentage reduction of Q_H, Q_{net} , Q_{net} and T_s in green and conventional roofs.

Month	Q_H	Q_E	L_{net}	Q_{net}	T_s
July	23.74	-2.32e20	0.25	14.57	8.67
August	31.85	-2.58e18	0.39	13.22	9.86

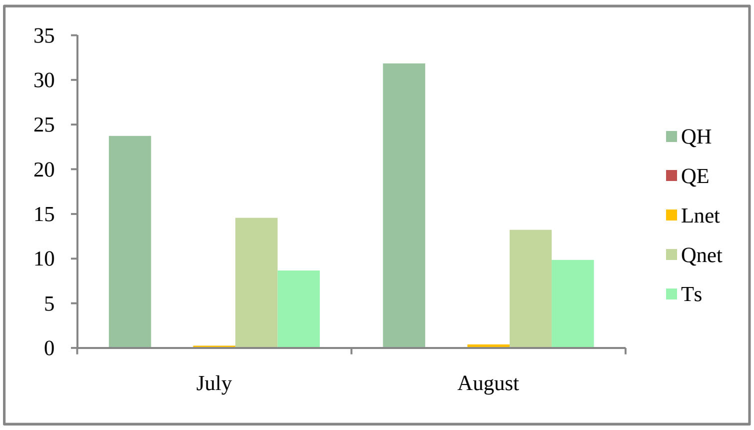

Fig. 6 Comparison between percentage reduction of Q_H, Q_{net} ,Q_{net} and T_s in green and conventional roofs.

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