4th International Conference on Countermeasures to Urban Heat Island, 30-31 May and 1 June 2016,
National University of Singapore, Singapore

Cool and green roofs to reduce cooling energy demand in storage buildings: simulation study for distinct climates

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ABSTRACT

Goods storage buildings surround urban areas and they usually have large areas of roof. In many climates such buildings require protection from external conditions for the goods and materials and for relative comfort of workers. These buildings may provide an excellent opportunity to use cool and green roofing construction techniques because they cover a large area exposed to solar radiation compared to residential dwellings and other commercial buildings and they are usually single-storey with the roof encompassing the entire internal volume. It is for this reason that any modifications to the U-values or solar reflectance properties of the building envelope are very influential towards the energy demand from the HVAC system of the building.

This paper presents a comprehensive computational analysis on the use of green and cool roofing techniques applied to a model that represents a typical steel goods storage building considering the local thermal building practice. The investigation is carried out using Energy Plus to compare the energy efficiency and related environmental impact in four distinct climates and six cities in Brazil with different climatic conditions; these are:

- hot and dry: Abu Dhabi UAE; Petrolina, Brazil, Brasília, Brazil
- hot and humid: Manaus, Brazil; Fortaleza, Brazil
- cold winter – hot summer: Wuhan, China; Santa Maria, Brazil
- mild winter and humid mild summer: London, UK; São Paulo, Brazil
- cold winter and mild summer: Stockholm, Sweden

For each location a parametric analysis is carried out through thermal simulations to calculate energy demand to provide heating and cooling to the structure with an analysis of the CO_2 equivalent (CO_2e) emissions due to these consumptions.

The green roof simulation results are shown to have a consistently positive impact on energy efficiency. Throughout all the simulation climates reductions of varying magnitude of both heating and cooling energy demand are recognised, which results in subsequent reductions in energy operational costs and CO_2e emissions.

The cool roof simulations provide both positive and negative results for the parameters that are explored in this paper. Case-studies in hot and dry climates (Abu Dhabi, Petrolina and Brasília) as well as hot and humid (Manaus, Fortaleza) experience a rejection of solar heat gain leading to a reduced cooling load and the resultant benefits. Conversely, cool roofs are shown to have a detrimental to energy efficiency and emissions in climates that predominantly require heating energy and well insulated external envelope which is confirmed within the cases of London and Stockholm. Cool roofs are shown to provide significant reductions in combined heating and cooling energy demands in cold winter and hot summer climates (Wuhan, Santa Maria). Despite this effect, higher emission rates might occur in these locations due to the increased heating energy consumption exceeding the corresponding reduction in cooling benefits when the structure is well insulated. A positive effect is observed for less well insulated cases indicating that in this case a cool roof may be a good cost effective strategy to reduce energy demand.

Key Words: Cool roof, green roof, storage buildings, heating, cooling, energy demand, environmental impact

1. INTRODUCTION

Many factors influence the energy demand of a building including its purpose, intended use and location. The thermal properties of the materials used for the external walls and roof can have a major influence on the surface temperature and in turn the amount of heat conducted through the surface of the building. A cool roof uses a coating with high thermal emissivity and solar reflectance properties and is recognised for decreasing the solar thermal load upon a building reducing its energy requirements for cooling (Pisello and Cotana, 2013). A green roof involves cultivating the surface of a roof with vegetation in addition to irrigation layers. This roofing technique lowers energy demand by reducing the thermal fluctuation of the roof surface and increases the roof's thermal insulation and capacity with many other beneficial impacts on the local environment (Niachou et al. 2001).

Many experimental and modelling studies have been published that compare building energy efficiency benefits of green and cool roofing techniques. (Coutts et al. 2013) studied this experimentally in Melbourne for 4 roofing variations suggesting that a cool roof with insulation would reduce the thermal energy transfer into building the most, at around 78% more than the vegetated roof. The results also emphasised the importance of irrigation for green roofs as it increases the effect of evapotranspiration. A simulation study into the impact of a green roof in comparison to conventional roofing has been carried out on warehouse-style buildings of various heights (Martens et al. 2008) for Toronto concluding that energy savings range from 18% for a 3-storey building, to 73% for a 1-storey building. Wong et al. (2002) investigated the effect of different types of green roofs on the energy consumption of 5-storey commercial buildings in Singapore. The results displayed energy savings of 14.6% in comparison to conventional roofing techniques and demonstrated that extensive green roofs were the most economically productive solutions for the Singapore climate. The study stresses the importance of the consideration of energy savings within life cycle cost analyses. Romeo et al. 2011 analysed the performance of a cool roof on a 700m^2 roof of an office/laboratory building in Sicily (Italy). The results were significant and displayed 54% reduction in cooling energy demand which is suggested, is due to the highly important ratio of the roof surface to the building volume. A study into the financial comparison of conventional roofing versus green and cool roof techniques in the US over a 50-year life cycle cost analysis (Sproul et al. 2013) suggested that cool roofs have the greatest economic net savings over this period. It highlights how this is mainly due to the high installation costs and maintenance of green roofs; the conclusion leans towards the idea that cool roofs are a more effective as a means to improve building thermal performance whereas green roofs are more beneficial to the local environment through biodiversity promotion, excess water management and counteracting air pollution. As a result, the choice should be based on the objectives of the building and its location. Whilst increasing the surface reflectance and infrared emittance of a material by adopting cool roofs can reduce energy consumption in hot climates, some research suggests that it may actually increase consumption of heating energy in cooler climates (Akbari et al. 2008).

All current research suggests that the relative benefits of cool and green roofs depend on the type of building and its construction, climatic conditions, and the activity that occurs within it. This paper investigates numerically the application of cool and green roof technology to warehouse buildings in a variety of climatic locations considering local energy efficiency regulations.

2. CASE-STUDY BUILDING, CLIMATE AND ENERGY LEGISLATION

2.1 Warehouse Buildings

Warehouses (Figure 1) are structures that provide space for the storage of goods or material that requires adequate protection from external elements. The design of these industrial buildings depends entirely on storage contents and the business service requirements of the owners. Many varieties of warehouse exist depending on the material which is being stored. These include, but are not limited to; general warehouse for bulk storage that requires no special conditions, refrigerated warehouses for goods that require the contents to be kept below a certain temperature and controlled humidity warehouses that maintain a desired air humidity level (Acker, 2011).

Figure 1: *A typical steel warehouse structure exterior and interior [Havit (2012), Baofeng (2014)]*

Warehouses provide an excellent opportunity to use cool and green roofs. This is due to the buildings covering a large area exposed to solar radiation compared to residential dwellings and other commercial buildings. In addition to this large surface area, most warehouse buildings are single-storey, meaning that the roof encompasses the entire internal volume and has a more direct influence on the thermal load. It is for this reason that any modifications to the U-values or solar reflectance properties of the building envelope are very influential towards the energy demand from the HVAC system of the building. In addition to this, capital cost is also reduced because of the smaller plant size required for the heating and cooling demands. Due to their volume, the power required to provide the desired atmosphere of a warehouse building is often high and so design solutions that are able to manipulate the thermal properties of the building fabric, such as cool and green roofing strategies, are highly sought after.

2.2. Locations of Study

The concept behind this research project is to run simulations for locations with distinct climates and seasons in order to provide climate-related analysis and unique conclusions. Köppen climate classification is a widely recognised classification system that defines climates globally and is based on temperatures, precipitation and native vegetation within the region (Vindel et al. 2015) and is used to support definition of each location's climate. The locations are shown in Figure 2.

Figure 2: *Locations of the study. (1) Abu Dhabi, UAE; (2) Wuhan, China; (3) Stockholm, Sweden; (4) London, UK. Brazil: (5)* Brasília*, (6) Fortaleza, (7) Manaus, (8) Petrolina, (9) Santa Maria, (10)* São *Paulo[5].(Earth Chronicle, 2006)*

Abu Dhabi – UAE is characterised by a subtropical desert / low-latitude arid hot climate, low cloud cover and less than 250mm precipitation. Köppen climate classification is BWh.

Wuhan – China has a Köppen climate classification of 'humid subtropical' (Cfa) with large quantities of rainfall, four distinctive seasons and is characterised by humid summers. Its climate is often referred to as 'hot summer, cold winter' (Gao et al. 2014).

Stockholm – Sweden has a ‘humid continental’ (Dfb) Köppen climate classification which is characterised by a wide range in seasonal temperatures.

London – UK has a Köppen climate classification ‘oceanic climate’ (Cfb) which is characterised by a warm summer and cool winter.

Brazil is located in South America, its latitude varies by 39° and its geography allows various climates. Six cities were chosen for the analysis. Brasília has Köppen climate classification ‘Tropical with dry winter’ (Aw). Fortaleza is ‘Tropical with dry summer’ (As); it has a rainy season for half of the year and mostly sunny for the other half. Manaus (in the heart of the Amazon Rainforest) has Köppen climate classification ‘Tropical monsoon’ (Am). It is characterised by a highly humid and hot climate during the whole year. Petrolina is ‘Dry semiarid of low latitude and altitude’ (BSh). The climate is hot and dry with a rainy season in the first half of the year and dry in the second. Santa Maria has well defined seasons with Köppen climate classification ‘Humid, oceanic, subtropical, without dry season, with hot summer’ (Cfa). The summer is hot and the winter cold. São Paulo is ‘Subtropical humid with hot summer’ (Cfa/Cfw). Its climate is temperate, with some variation of temperature through the year with more rain during the summer.

2.3. Energy Efficiency Building Legislation of Locations

Most countries and regions have legislation in place by setting energy efficiency standards of practice for buildings to comply with. Incentive schemes, planning policies and reduced operating costs through lower energy use, are also methods implemented to lower building energy use.

In England and Wales, the regulations that buildings currently adhere to are ‘The Building Regulations’ (HM Government, 2010), of which part L2a gives details of conservation of fuel and power in new buildings other than dwellings (with part L1a relating to dwellings). The regulations are aligned with the Energy Performance in Buildings European Directive (EPBD), are supplemented by the national calculation method (SBEM) and voluntary assessment methods.

In Abu Dhabi, UAE, a mandatory program is used called ‘Estidama’, which is the Arabic word for ‘sustainability’. This incorporates a ‘Pearl Rating System’ to score buildings and industrial structures must achieve a minimum of a ‘1 Pearl rating’ and a ‘2 Pearl rating’ if the building is government funded. The aims of Estidama are incorporated into Urban Planning Council (UPC) policies such as the Development Code and ‘Plan 2030’, described as the drive towards building with innovative green standards (Estidama, 2010).

Swedish building regulations are published by the National Board of Housing, Building and Planning–Boverket. These documents include compulsory regulations as well as recommendations to provide building efficiency; the guidelines are very stringent in comparison to other countries due to the nature of the climate. The latest published legislation is BBR18 adopted in 2010 and covers residential, commercial and public buildings.

In China, the Ministry of Housing and Urban-Rural Development (MOHURD) implements an extensive building rating and labelling program, similar to Estidama in UAE. It has a 5 star rating system, which is applied to both residential and non-residential buildings and is determined by three categories; Basic, Required and Optional items. ‘Basic items’ include the simulated or measured energy usage per square metre, whereas ‘Required items’ refers to the performance requirements of the building enclosure and heating, ventilation and air conditioning systems. (Mo et al, 2010).

In Brazil, the mandatory legal Brazilian standards NBR 15220 and NBR 15575, the voluntary Brazilian Labelling Schemes for Residential Buildings (RTQ-R) launched in 2010 and the Brazilian Labelling Schemes for Commercial, Public and Services Buildings (RTQ-C) launched in 2009, are instruments in place to support energy efficient buildings (Tubelo et al, 2014).

These legislation documents provide guidelines for the thermal properties of building enclosure in order to obtain satisfactory U-values, infiltration rates, ventilation rates, and other design techniques in order to provide sustainable and energy efficient buildings. The regulations of each location were used to define the thermal characteristics of the model. The lower range of fabric thermal characteristics in NBR 15220 were used to determine U-values for Brazil.

3. DESCIRPTION OF THE PHYSICAL AND THERMAL MODEL

The shape of the building replicates an existing warehouse in the Khalifa Industrial Zone of Abu Dhabi. The design of the building can be seen in Figure 3. The total roof area is 2000 m² with an internal volume of 13500 m^3 and wall area 1140 m^2.

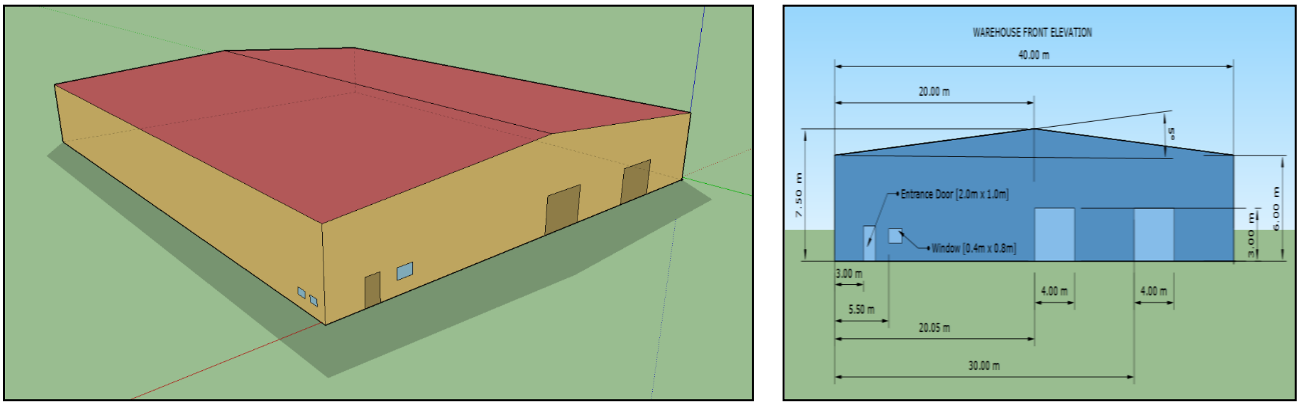


Figure 3: Axonometric and front elevation of the modelled warehouse.

The construction of the building envelope vary depending on the location with differences mainly in the thickness of the insulation to satisfy building regulations of the region being analysed. These are presented summarised in Table 1. The Green Roof module within EnergyPlus was used to define the green roof variations of the base model while the cool roof variation was modelled by changing the solar reflectance properties of the most external roof layer. The solar reflectance value for the base model is 0.30; the solar reflectance values for the cool roof are varied at 0.55, 0.70 and 0.90 in order to serve as a representation of the performance of different cool roofs as they age and become dirty/weathered, resulting in decreasing solar reflectance.

Table 1: U-values of the warehouse model for the different locations

Location:	London	Stockholm	Abu Dhabi	Wuhan	Brazil
Roof U-Value (W/m^2·K)	0.25	0.13	0.33	0.70	2.00
Wall U-Value (W/m^2·K)	0.35	0.18	0.48	1.00	2.20
Floor U-Value (W/m^2·K)	0.25	0.15	1.65	n/a	2.00

Three sources of internal heat gains were considered. **Lighting:** In the most recent and relevant ASHRAE energy standard concerning lighting in industrial buildings (ASHRAE/IES 90.1-2013), the maximum power densities based on building area are suggested to be 0.66 W/ft^2 or 7.1 W/m2 for warehouse buildings (Dilouie, 2013). The lighting internal gain is consistent across all countries with relation to their respective operation schedules. **Equipment**: A value of 5 W/m^2 is assigned to the models of each location to represent the use of storage equipment such as stock computer systems and storage equipment. The use of equipment will be dictated by a schedule based on the percentage of occupancy within the building. **People:** 20 occupants (which equates to 100 m^2 per person) to be representative of the workforce of the building.

The legislation for each location were used for infiltration rates for the base model; 10m^3/hr/facade @ 50 Pa for London, 0.61 L/s @ 50Pa for Stockholm, 3.64 L/s @ 75 Pa for Abu Dhabi and 0.75 ACH @ 50 Pa for Wuhan. For Brazil 1 ACH was assigned to the base model.

ASHRAE Standard 62 states that the required minimum ventilation rates in the breathing zone for warehouse buildings is 0.3 L/s·m^2. In practice however, it is suggested that 2 – 6 ACH are required to provide acceptable indoor air quality for the occupants for the type of building based on 'extensive experience' of ventilation equipment manufacturers (Vent-Axia, 2012). For the simulations reported in this paper, ventilation rate was fixed to 2 ACH.

The HVAC system employed for the EnergyPlus model is an 'Ideal Load Air System' operating on thermostat set points for heating and cooling of 16°C and 26°C respectively. These set points are wider when compared to systems commonly found in residential buildings or offices as in industrial workforces are expected to be provided with more suitable clothing for the climate.

Open source weather files of Solar and Wind Energy Resource Assessment (SWERA) are used for the locations in Brazil while International Weather for Energy Calculation (IWEC) are used for all other locations.

4. SIMULATION RESULTS

Hot and dry climate locations: Simulation results for Abu Dhabi are presented in Figure 4. It shows noticeable positive benefits for cool and green roof compared to base model with most savings achieved by a cool roof with SR = 0.90. Similar results were obtained for Petrolina and Brasília (see Table 2) but the green roof has the lowest energy demand. No heating demand is predicted in these locations too; however because of the lower U-value of the roof, additional insulation provided by the green roof has a noticeable impact on heat transfer. Monthly profiles for Abu Dhabi and Petrolina are presented in Figure 5.

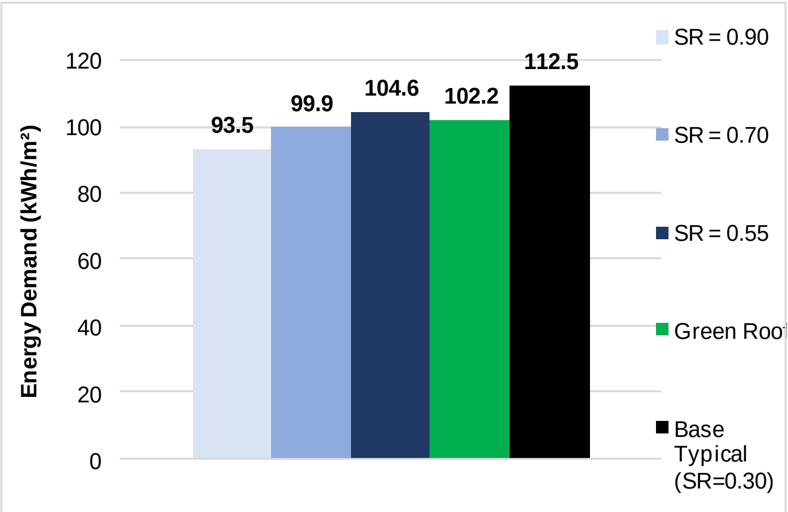
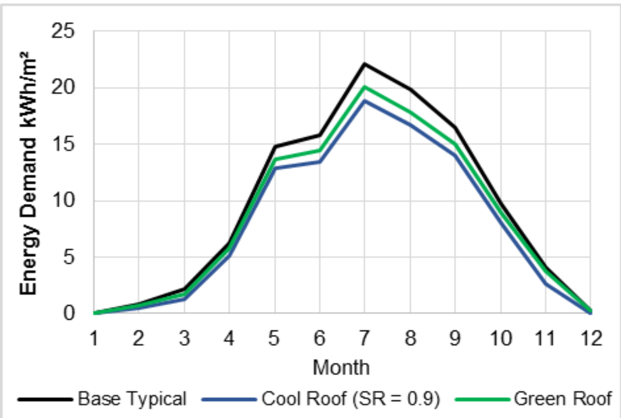


Figure 4: Simulation results for Abu Dhabi



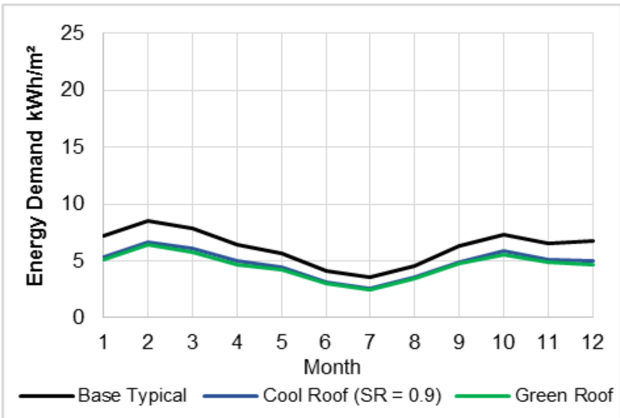


Figure 5: Abu Dhabi (Left) and Petrolina (Right) monthly energy demand.

In **hot and humid climates**, similar beneficial impact has been predicted mainly because of the absence of heating demand. Therefore, cooling demand is reduced by the function of the cool roof and insulation value of green roof. Results for the cities of Manaus and Fortaleza in Brazil are presented in Table 2.

'Hot summer-cold winter' climate locations: simulations results for Wuhan are presented in Figure 6. In this case, green roof yields maximum energy demand reduction as it offsets both cooling and heating demand. It can be seen that an SR=0.9 cool roof achieves highest cooling benefit but with a corresponding increase of heating demand. This can be seen in more detail in monthly values in Figure 6. Similar results were obtained for Santa Maria in Brazil.

Table 2: Simulation results for the locations in Brazil

kWh/m^2	Base	0.55 SR	0.7 SR	0.9 SR	GR
Hot and Dry					
Petrolina	503.8	454.9	426.0	389.1	370.9
Brasilia	184.1	148.4	128.4	104.1	96.2
Hot and Humid					
Manaus	788.6	715.3	668.3	602.5	579.4
Fortaleza	745.1	687.7	652.9	607.0	580.3
Cold Winter – Hot Summer					
Santa Maria	208.6	183.9	170.1	153.6	140.1
Mild Winter and Humid Mild Summer					
São Paulo	142.3	117.2	103.7	87.9	79.5

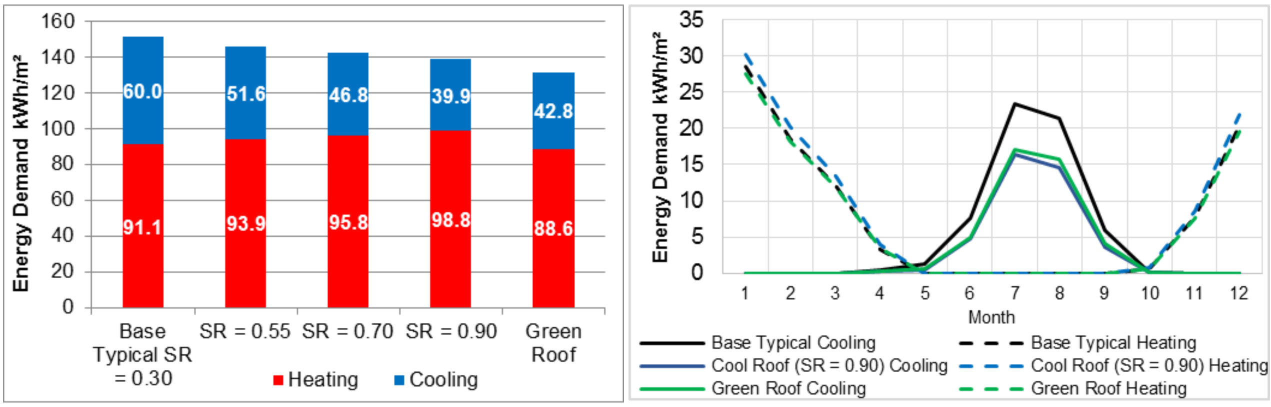


Figure 6: Simulation results for Wuhan.

Mild winter and humid mild summer climate locations: simulations results for London are presented in Figure 7. It can be seen that cool roof savings are marginal for the well insulted structure while green rood provides some benefits because of the additional insulation. However for São Paulo, Brazil (see Table 2) because of the less severe winter and milder summer and the lower insulation of the structure a cool roof provides some net benefit of almost 40% energy savings compared to the base case. On the contrary, in the case of **cold winter and mild summer** of Stockholm with very well insulated structure (Figure 7) a cool roof results to a penalty of 1% increased energy demand. These results point to possible energy benefits if optimization is applied and this is discussed briefly in the next section.

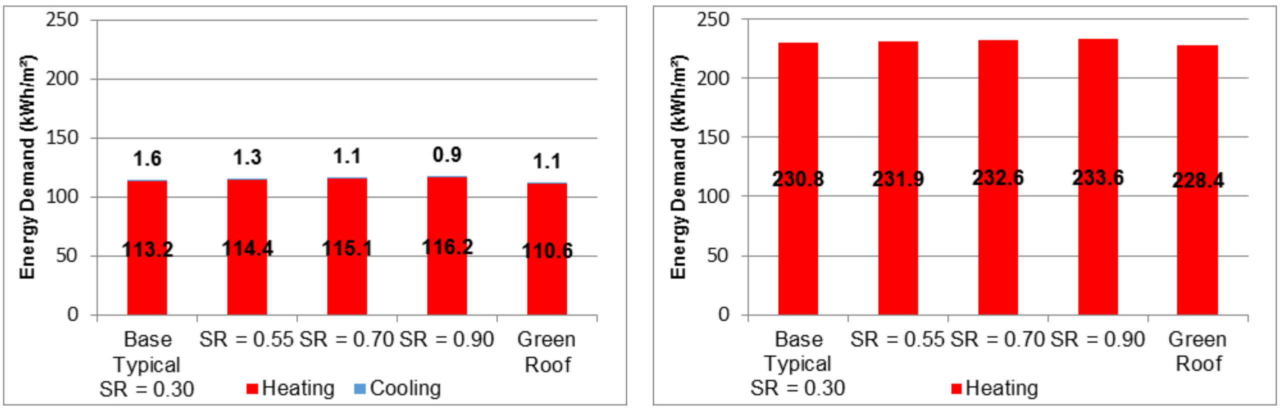


Figure 7: Simulation results for London (left) and Stockholm (right).

4. DISCUSSION

The simulations presented in section 3 indicate the energy demand required to keep the structure at temperatures within the thermostat set points. In order to quantify the amount of fuel consumed by the system, an electric air-cooled chiller is assumed for cooling which is a common system for industrial applications (Daikin, 2015). A coefficient of performance (COP) is introduced to ascertain the quantity of electricity consumed as defined by the following equation:

$$Coefficient\ of\ Performance\ (COP) = \frac{Cooling\ Power\ Output}{Electrical\ Power\ Input}$$

For air-cooled heat rejection the COP typically falls into the range of 2.8 – 3.2 (Tymkow et al. 2013). A value of 3.0 is used in this paper. For the heating requirements of the structure, an electric heating system is assumed able to provide 100% efficiency at the point of use.

The calculation of electricity needed to provide the simulated energy demand was used to calculate Carbon dioxide emissions. CO_2e (Equivalent CO_2) is a term for describing multiple greenhouse gases in a common unit that determines the amount of CO_2 that would have the equivalent global warming impact. The analysis of the CO_2e quantities that the building emits, provides an informative perspective on the environmental efficiencies that the case studies have. CO_2e produced from the models were calculated (see Figure 9 and Table 3) by applying distinct CO_2e emission factors of each location which are dependent on how energy is produced in that region (Table 4). This information provide a comparison of the emission intensity of each location with a case study application and shows the impact that green and cool roofs have on the total emissions of the building. It also provides information on the impact of electricity production fuels of the studied locations.

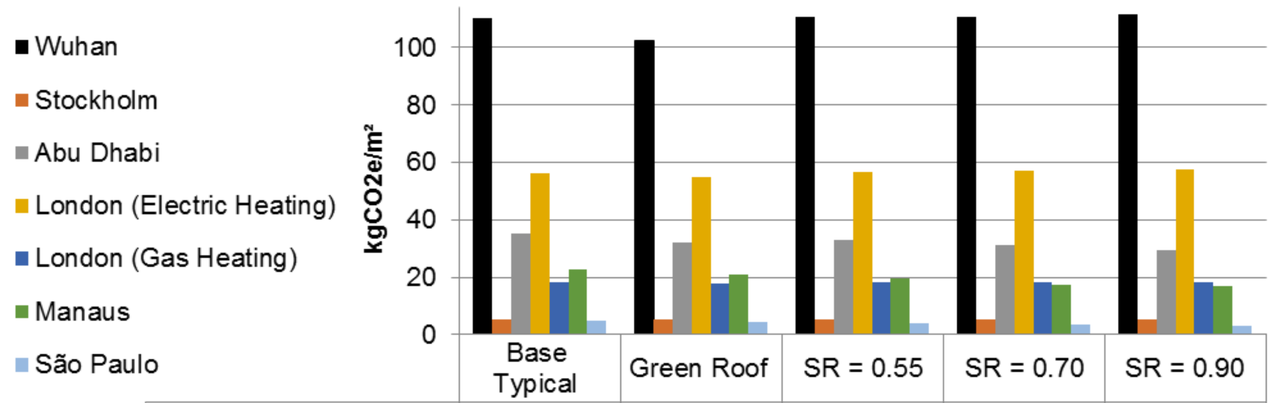
Wuhan creates a substantial amount more CO_2e emissions than other locations due to its high emission factor caused by coal derived electricity. The cool roofs lead to a rise in CO_2e emissions despite the decrease in total energy demand. Although the cooling load of the building is decreased substantially, the heating demand increases which consumes larger amounts of energy and therefore fuel to operate. The Wuhan green roof module however provides a saving of 8.12 $kgCO_2e/m^2$ annually (7.35%), the largest reduction of any original case study roof due to the reduction of both heating and cooling loads. Experimental research conducted in Wuhan (Gao et al. 2014) on the application of cool roofs on office buildings shows that increasing the roof solar reflectance from 0.2 to 0.6 resulted in maximum net savings in air conditioning consumption and CO_2 emissions of 5.55 kWh/m^2 and 2.06 kg/m2, respectively. This is likely to be attributed to the higher internal heat gains and narrower thermostat set points of the office building compared to the warehouse, resulting in a smaller heating load and larger cooling load to obtain the benefits from the increased solar reflectance.

The six locations in Brazil (Table 3) emit the least CO_2e than other locations due to the low emission factor caused by mainly hydro and wind electric plants. Because of the high U-values in the roof and walls of the base model, a cool roof achieves CO_2e reductions in all locations in proportion with their energy demand profiles.

The results for London (Electric Heating) and Stockholm remain in proportion with their energy demand relative to their CO_2e emission factors. However for London (Gas Heating), reductions of CO_2e emissions are registered due to the lower conversion factor of gas production. Stockholm provides very low carbon emissions driven by the low conversion factor from Sweden's high use of renewable energy resources to produce fuel.

Abu Dhabi and all locations in Brazil have benefits from both green and cool roofs; it is worth noting that Abu Dhabi has a similar conversion factor and simulation energy demands to Wuhan. The reason there is a significant difference in emissions is due to the fact that Abu Dhabi exclusively relies on cooling which requires less fuel to operate, whilst Wuhan has a cooling load in addition to a considerable heating demand that consumes more fuel in its operation, leading to a higher rate of CO_2e emissions. The four locations in Brazil with hot and dry/humid climate (and without heating demand) also display benefits although to less quantities because of the conversion factors.

It is necessary to acknowledge the subsequent costs of installation and maintenance for green and cool roofs as the analysis omits these factors and focuses on operational savings of heating and cooling energy consumption. For cool roofs, cleaning and recoating is a requirement that will ensure optimum performance of the roof as when it accumulates dirt or becomes weathered the solar reflectance properties can be reduced. Green roofs require a substantial investment in there installation due to the complexity and materials of the system ranging from £20-£50 per m^2 in the UK depending on their design, whilst maintenance costs are usually high within the first 2 years as the system beds in (CIBSE, 2007). In addition to this, the structural integrity of the roof must be fully evaluated before a green roof is implemented due to the significant weight increase, which may incur supplementary financial input. The return on investment of any roofing system aimed to provide financial benefits should be fully evaluated before implementation.



	Base Typical	Green Roof	SR = 0.55	SR = 0.70	SR = 0.90
Wuhan	110.4	102.3	110.5	110.8	111.5
Stockholm	5.3	5.3	5.3	5.4	5.4
Abu Dhabi	35.3	32.0	32.8	31.4	29.4
London (Electric Heating)	56.2	54.9	56.7	57.1	57.6
London (Gas Heating)	18.1	17.6	18.2	18.3	18.4
Manaus	22.9	20.7	19.4	17.5	16.8
São Paulo	4.9	4.2	3.9	3.5	3.1

Figure 9: *CO_2e* Emissions of study locations with roofing techniques.

With comparison to this paper, a similar one month simulation study was carried out concerning green roofing used on warehouse-style buildings of various heights in Toronto, USA (Martens et al. 2008). The study also used an ideal HVAC system, although used a constant thermostat set point of 22°C which yielded maximum savings of 73%. Comparison of this research to the results in this paper and other research confirms that the internal requirements, in particular how far they differ from the external climate, dictate the quantity of savings. As the case study building in this paper has comparatively manageable parameters (such as a relatively wide range of internal temperature requirements due to its proposed purpose), the savings in energy demand, operational costs and CO_2e emissions are all lower what is commonly found in research for office and residential buildings.

Previous research has indicated that savings for cool roofs provide maximum energy savings for buildings located in climates with long cooling seasons and short heating seasons and this is ideally exemplified in the results of the Abu Dhabi case study as increasing solar reflectance of the roofing material leads to savings in energy demand, fuel consumption and CO_2e emissions.

Whilst the impact of cool roofs can reduce energy consumption in hotter climates, research has been identified that suggests it can increase consumption of heating energy in colder climates (Akbari et al. 2008). The simulation results have identified this effect within the case studies of London and Stockholm and as a result are only detrimental to energy demand as they are heating dominated climates.

Table 3: CO_2e Emissions for the locations in Brazil and Stockholm

	Base	Green roof	SR=0.55	SR=0.70	SR=0.90
Brasilia	5.5	4.5	3.9	3.2	2.9
Fortaleza	21.6	19.9	18.9	17.6	16.8
Manaus	22.9	20.7	19.4	17.5	16.8
Petrolina	14.6	13.2	12.4	11.3	10.8
Santa Maria	8.2	7.7	7.4	7.2	6.3
São Paulo	4.9	4.2	3.9	3.5	3.1
Stockholm	5.3	5.3	5.3	5.4	5.4

Table 4: CO_2e Emissions Factors for the studied locations

Location	CO_2e Emissions Factors (kg CO_2e/kWh)	Source
Wuhan	0.9944	Gao et al. 2014
Stockholm	0.023034	Brander et al. 2011
Abu Dhabi	0.938297	Brander et al. 2011
London	0.49426 (Electricity), 0.184973 (Gas)	DEFRA, 2015
Brazil	0.087	IPCC, 2005

5. CONCLUSIONS

The results presented in this paper have determined the energy efficiency of operational performance when green and cool roofing techniques are applied to an EnergyPlus model based on a typical warehouse building in five distinct climates. The EnergyPlus simulation results were used to quantify the energy demand and CO_2e emissions for each case study for each location.

Creation of the base typical models obtained bespoke parameters relevant to a variety of building regulations and can provide an insight into the influence of U-values giving perspective to the limits suggested by the corresponding legislation. Green roofs are shown to produce positive reductions ranging in magnitude for both heating and cooling energy demand for all the models. This created subsequent reductions in CO_2e emission rates. The most notable energy benefits of the application of green roofs relative to the respective base typical models were identified in the results of the Wuhan case study which took full advantage of the insulation properties of the roofing technique. Application of the green roof parameters to the Stockholm case study gave only modest savings caused by minimal impact on the highly insulated base typical roofing.

Cool roofs only provided positive results for energy efficiency for the case studies without heating demand due to the higher surface reflectance of the roof resulting in the rejection of significant solar heat gains. This effect only increases the energy consumption in the locations that predominantly (Wuhan and London) or exclusively (Stockholm) require heating. The cool roof applied to the Wuhan model did produce considerable savings to the energy demand but as this significantly increased the quantity of heating required with respect to cooling, the CO_2e emissions were greater than the values of the base typical. Positive results were predicted in all locations in Brazil. High U-values of the base model are a contributory factor in the cool roofs achieving reduction of energy demand even in locations requiring heating (Santa Maria and São Paolo). Substantial savings in energy demand are predicted in the four locations with hot and dry/humid climates.

Based on the climates and parameters that were investigated, the use of cool roofs on steel warehouse buildings is only likely to produce benefits for energy consumption, operational costs and reduced CO_2e emissions when located in a climate that has a predominant cooling load or less well insulated external envelope. For any potential application, it must be assessed whether the effect of the cool roof increasing heating demand does not cancel out the potential savings. The results also suggest the application of green roofs will have a positive reduction on heating and cooling loads. However, a full cost analysis including a return on investment for each roofing technique is necessary prior to making an ultimate recommendation of energy, environmental impact and financial performance that the roofs produce.

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