

Urban Greening and the UHI: Seasonal Trade-offs in Heating and Cooling Energy Consumption in Manchester, UK



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1 Introduction

In Northwest England, UK, climate change projections estimate that mean summer air temperature will rise by approximately 3.7 °C by the 2080's (medium emissions scenario, 50% probability level, 1961-1990 baseline). Previous research on the Urban Heat Island Intensity (UHII) in Manchester and Greater Manchester (Cheung 2011), found that the UHII can reach 8K and is also increasing over time.

For urban areas, increasing the proportion of greenspace is an adaptation strategy that is often suggested. While numerous studies have investigated the cooling effect of greenspace in terms of both air and surface temperatures, few studies have further investigated the links to building energy demand.

This research presents an interdisciplinary approach to model fine-scale microclimate changes due to greenspace additions, using the results to develop customised weather files for modelling building energy consumption in commercial buildings. This research builds on previous work presented on the summer microclimate and building energy changes presented at the Third International Conference on Countermeasures to the Urban Heat Island (IC2UHI3) (Skelhorn et al. 2014b).

2 Methods

Considering the large number of variables that influence microclimate interactions between buildings and greenspace, such as its location in the UHI, the building geometry, and surface characteristics surrounding it, coupled with a similar variability in energy usage data for different buildings (age, size, construction materials, HVAC characteristics and occupancy rates), modelling was determined to be a useful approach for assessing changes in building energy consumption due to different types and arrangements of greenspace.

Modelling occurred in two stages: microclimate modelling to determine changes in air temperature, relative humidity, and wind due to increases in greenspace; and building energy modelling, utilizing the microclimate results to inform weather file inputs and the related impacts to building energy.

In addition to modelling, this paper utilises analysis of the UHII in the City of Manchester and Greater Manchester local authority in the northwest of England, UK. Research by Cheung (2011) collected air temperature data using iButton temperature sensors that were attached to lampposts. The air temperature data were useful for: 1) calibrating and validating the microclimate element of the modelling; and 2) determining the seasonal daytime and nighttime averages of the Manchester UHII (Skelhorn et al. 2014b).

2.1 Urban Microclimate Modelling

The modelling process began by selecting a suitable energy balance model. While many models have been developed for fine-scale investigation of urban canyons and neighbourhoods (Ali-Toudert and Mayer 2006; Baklanov et al. 2009), most are either slab or single-layer and did not include canopy details. One model which met the objectives of the microclimate modelling is the model ENVI-met, (Bruse and Fleer 1998; Bruse 2004). It is specifically designed for modelling surface-plant-air interactions in the urban environment. Full reasoning for this selection, its benefits and limitations, are discussed in Skelhorn et al. (2014).

The Manchester CBD was selected for its mix of medium and tall retail and commercial buildings combined with low tree cover and relatively high surface temperatures. This area was selected as being most lacking in greenspace, and therefore, a useful modelling study for greenspace additions. Figure 1 shows an overhead view of the Manchester CBD area from Google Earth that was used for digitizing the area in ENVI-met. Percentages of buildings and tree canopy for the areas were estimated in ArcMap 9.3, while total greenspace for the area was estimated using colour pixel analysis in Adobe Photoshop®CS2.

Building and greenspace percentages for Manchester CBD are estimated as:

- Buildings – 36%;
- Greenspace – 3% (tree canopy cover is 1% of this);
- Roads, Pavements, Parking – 61%.



Figure 1 – Google Image of City Centre Study Area

Areas to be modelled are input on a rectangular grid which can range from small areas less than 20 x 20 cells up to a maximum of 250 x 250 cells, with each cell having a resolution of 0.5 m up to 10 m. Because larger model areas and/or higher resolution models require significantly longer running times, it was important to select a model size and resolution that was manageable, which was a resolution of 4m for this research.

2.2 Building Energy Modelling

In the UK, AECOM oversees a Building Energy Calculation Software Approval Scheme on behalf of Communities and Local Government (CLG) (Lim 2009). Only two software programmes, TAS and Virtual Environment (VE) by IES, are on the approved list for Dynamic Simulation Modelling (DSM), a method that can model the thermal dynamic response of buildings and demonstrate compliance with Part L of the Building Regulations (HM Government 2010).

IES-VE was chosen for a number of advantages. These include a user-friendly interface as well as low cost to students and academic researchers. Hourly weather data required for simulations are available for Manchester from CIBSE and custom weather files can be created for testing the effects of changing weather patterns. Importantly, for this research, the SunCast module is included for determining the effects of shading due to elements on or around the building.

2.2.1 Building Models

The simulation focuses on two (out of four) types of office buildings identified in the UK by BRE and CIBSE (CIBSE 2000). Those selected are:

- Air-conditioned, standard; and
- Air-conditioned, prestige.

A total of three buildings were examined:

- Two versions of the standard building, one shallow-plan three-storey, and one shallow-plan ten-storey; and
- One prestige, deep-plan three-storey.

The buildings were sketched in IES-VE. Table 1 provides the building details while Figures 2, 3, and 4 show the three buildings as sketched in IES-VE (Skelhorn et al. 2014b). All buildings were modelled as a General Office with 20% glazing and building constructions applied were to the 2002 Building Regulations for England and Wales (HM Government 2002). Key thermal template settings (ibid.) were:

- Timing – Office 8:00-6:00;
- Cooling Temperature – 23.0 °C;
- Heating Temperature – 19.0 °C;
- RH – 70% maximum;
- ACH – 0.250 Infiltration; and
- Internal Gains – Fluorescent lighting, 12 W/m²; Occupancy 14 m²/person; Equipment, 12 W/m².

Table 1 – Building Types and Descriptions (Skelhorn et al. 2014b)

Building Designation	Plan Type	Floor Area and Layout	Height
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A	Shallow	972 m ² - 9 (6 m x 6 m) rooms per floor	3 Floors
B	Shallow	3240 m ² – same layout as building A	10 Floors
C	Deep	5418 m ² - 84 (3 m x 3m) rooms, 4 central open plan areas (10 m x15 m), 18 larger offices (5 m x 5 m)	3 Floors



Figure 2 – Building A - Three-Storey Shallow Plan

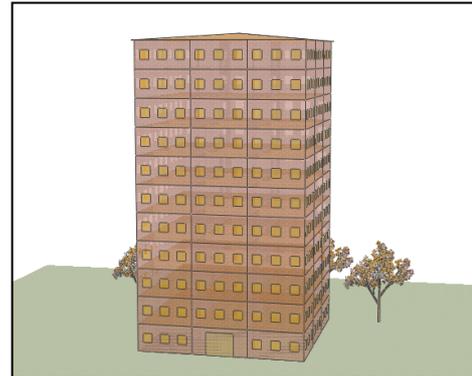


Figure 3 – Building B - Ten-Storey Shallow Plan

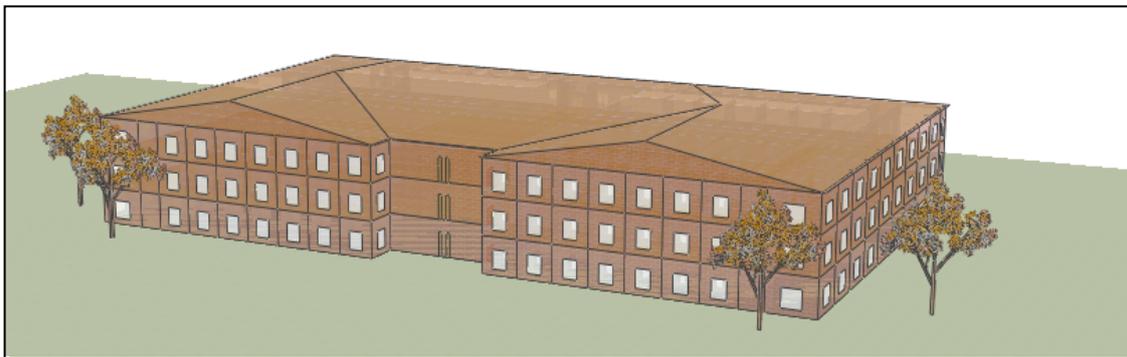


Figure 4 – Building C - Three-Storey Deep Plan

2.2.2 Summer Energy Scenarios

Each building was first modelled without tree shading, using the July Test Reference Year (TRY) weather data for Manchester Airport. Trees of approximately 10 m were selected as the shading element given that mature trees were found to have the most effect in the microclimate modelling (Skelhorn et al. 2014b). This base case was then compared with the following:

- **Shade – North** Four trees added as Topographic Shade, shading approximately 20% of the North side of the building; and **South** - Four trees added as Topographic Shade, shading 20% of the South side of the building;
- **Urb_UHI** - To simulate each building's energy increase due to the UHI (i.e., a building placed in urban conditions), a new weather file (UHI+6) was created in IES-VE. In the UHI+6 file, daytime temperatures were increased by 1.5 °C, and nighttime by 3 °C. These values are based on Manchester research (Cheung 2011) showing average summer daytime/nighttime UHI. Also, in the TRY dataset, nearly two full days in July (16th-18th) are clear, calm and warm days, which are conditions for an intense UHI, so temperatures were increased strongly, +3 °C for daytime and + °6 for nighttime;
- **Urb_UHI_green** - To test the effect of greening (shading plus reduced UHI peak hours), a new weather file (UHI+6_green) was created based on the TRY_UHI+6 file. The UHI on the peak days (16th-18th July) was reduced by 1 °C, resulting in +2 °C for daytime and +5 °C for nighttime. This reduction in UHI due to greening is based on the negative summer correlation between UHI and area of tree canopy from an analysis as part of a Manchester thesis (Skelhorn 2013). The regression equation indicates a potential reduction of 10 cooling degree hours for each 5% increase in greenspace. These results are scaled up, allowing for a total of 40 cooling degree hours due to the 20% shading around the shallow-plan three-storey building.

2.2.3 Winter Energy Scenarios

For the winter investigation, a model using the December TRY weather data and a model under UHI conditions are compared. In winter, the daytime UHI average is 1.6 °C, while the nocturnal UHI is 3.1 °C. Under clear and calm, peak UHI, conditions, the UHI daytime mean is 2.0 °C and nighttime mean is 6.0 °C. The clear and calm conditions (defined as <3 m/s wind speed and <2 oktas of cloud cover) occurred on portions of several days (7th-9th, 12th and 14th December), totalling 39 hours in the month.

Analysis of air temperature data collected with iButtons did not find any correlations between area of tree canopy and the air temperature indices investigated for the month of December. Therefore, the modelling assumes a neutral air temperature effect from greening for winter months.

3 Results

3.1 Summer Building Energy Modelling

Results from the summer energy modelling (Table 2) show a maximum of 1.6% reduction in chiller energy as a combined result of four trees shading the south side of the building and the reduction of UHI peak hours on a shallow plan three-storey building. Total reductions for this same building with the combined effects of 4 trees on the north and 4 trees on the south are estimated at 2.7%.

Table 2 - Summer Results, Chiller Energy Usage (MWh) (Extract from Skelhorn et al. 2014b)

Building	Tree Location	Base Energy, Chillers	Shade		Urb_UHI		Urb_UHI_green	
		Amount (MWh)	Amount (MWh)	% Change	Amount (MWh)	% Change (from Base)	Amount (MWh)	% Change (from Urb_UHI)
A	North	3.6168	3.5833	-0.9%	4.0555	12.1%	4.0126	-1.1%
	South		3.5628	-1.5%			3.9921	-1.6%
B	North	11.2775	11.2494	-0.3%	12.6552	12.2%	12.6001	-0.4%
	South		11.2380	-0.4%			11.209	-0.6%
C	North	22.5894	22.4979	-0.4%	24.8123	9.8%	24.677	-0.6%
	South		22.4652	-0.6%			24.6441	-0.7%

The percentage savings is reduced for a deep plan building (0.7% for four trees on the south side and a reduction in number of UHI peak hours), primarily due to the fact that the same four trees in this scenario will not be shading an equivalent surface area (only 10% of the building's surface in this model). However, if the model had achieved the 20% shading of the shallow-plan building and assuming a linear relationship, this would lead to 1.4% savings, a slightly lower reduction than achieved in the shallow plan building. This is reasonable due to the larger internal building volume for a deep-plan building that would be unaffected by shading measures.

Savings would likely be greater in air-conditioned buildings that are occupied during the nighttime, when UHI is greatest. As these buildings are modelled as office buildings, the air conditioning is switched off at night, potentially masking the potential savings for buildings that are occupied at this time.

3.1.1 Summer Carbon Emissions

Table 3 shows the changes in carbon emissions (for the set of buildings with 20% glazing) due to the average summer UHI (+1.5 °C daytime and +3.0 °C nighttime). The results show the greatest increase for the 10-storey shallow plan building and the least increase for the deep plan building. While the deep plan building shows a higher overall usage and higher usage per square metre, the energy consumption increased by a lower percentage than buildings A and B under the UHI conditions.

Table 3 – Changes in Summer (July) Carbon Emissions due to UHI

Building	Chiller CE Base (Electricity, kg CO ₂)	Chiller CE Urb_UHI	
		Amount	% Change
A	6714	7020	4.6%
B	20323	21284	4.7%
C	46517	48068	3.3%

If also considering the direct reduction in CO₂ emissions due to the carbon sequestered by each tree, the carbon savings due to tree planting in urban areas is marginally higher. Akbari (2002) estimated that each urban tree can reduce an average of 4.6-11.4 kg CO₂ per year (with older trees sequestering more carbon). This leads to an estimate of at least 1 kg CO₂ per tree for the month of July, considering that the most tree growth in the UK is during spring and summer. With four trees around each building, the reduction is 4kg CO₂ for July

3.2 Winter Building Energy Modelling

In comparing the energy changes for winter (Table 4) large percentage reductions in boiler energy are found for all buildings located in the urban area under UHI conditions, as compared to the base case (suburban) location. However, while chiller usage is smaller in absolute terms, this shows substantial increases for the urban location. This is explained by the fact that, depending on the building construction and thermal profile, chillers may be required in winter to offset internal gains.

Table 4 – Winter (December) Table of Results, Boiler and Chiller Energy Usage

Building	Base Energy, Boilers	Boiler Energy with Avg UHI		Base Energy, Chillers	Chiller Energy with Avg UHI	
	MWh	MWh	% Change	MWh	MWh	% Change
A	1.6262	0.726	-55.4%	0.6631	0.8734	31.7%
B	4.4010	1.7875	-59.4%	1.1761	1.8536	57.6%
C	2.3309	0.8453	-63.7%	7.7157	9.824	27.3%

3.2.1 Winter Carbon Emissions

Following on from the changes to boiler and chiller energy discussed in the previous section, Table 5 summarises the changes in carbon emissions from these same scenarios. This was important to investigate as it is often argued that the benefit of a winter UHI is more important for energy savings than the detriment of a summer UHI. While it might be true that, in absolute terms, the reduction in boiler energy outweighs the increase in chiller energy, the results shown in Table 5 indicate only a very slight advantage to carbon emissions when investigating the trade-offs in boiler and chiller energy for December. The results show that carbon emissions due to chiller usage are far higher than that for boilers. Building A, for example, only has carbon emissions of 322 kg (suburban), and although reduced to 144 kg for the average UHI conditions, the relatively small amount of chiller energy leads to 4652 kg CO₂ for the suburban and increases to 4799 kg for the urban UHI.

While it could be argued that a UK building is unlikely to use chiller energy in winter, the same comparison could also be made for summer to winter trade-offs. Even if chillers were completely turned off in winter, the case is more apparent for carbon emissions due to summer air conditioning usage. On balance, in terms of carbon emissions, any increase in summer air conditioning will outweigh the reductions in winter heating for buildings using gas boilers for heating and electricity for air conditioning.

Table 5 – Changes in Winter (December) Carbon Emissions

Building	Boiler CE (Natural Gas, kg CO ₂)	Boiler CE with Avg UHI		Chiller CE (Electricity, kg CO ₂)	Chiller CE with Avg UHI		Total System CE (Electricity, kg CO ₂)	Total System CE with Avg UHI	
		kg	% Change		kg	% Change		kg	% Change
A	322	144	-55.3%	4652	4799	3.2%	4974	4943	-0.6%
B	871	354	-59.4%	13272	13745	3.6%	14144	14099	-0.3%
C	462	167	-63.9%	36136	37607	4.1%	36597	37775	3.2%

4 Conclusions

While it may appear that the benefits of a winter UHI far outweigh the summer detriment, it is worthwhile to further examine some of the causes for the large differences estimated here. One explanation is possibly in the methods used to develop the summer and winter UHI weather files. During the summer, the UHI analysis is more weighted to the daytime average of 1.5 °C because sunrise is typically around 5 am and sunset around 9 pm (16 daytime hours). During the winter, the UHI analysis is weighted toward the nighttime average of 3.1 °C because sunset is, on average, at 4 pm, and sunrise is not until 8 am (16 nighttime hours). In reality, this

daytime/nighttime differentiation is likely to be less straightforward and more of a gradual increase or decrease in temperature differences than estimated here.

Also, the exact causes of a higher winter UHI require further investigation. Undoubtedly, some portion of the UHI is due to greater thermal mass and heat storage/release in urban areas, but it might be argued that an anthropogenic component enhances this (Smith et al., 2009). Another cause may be warm air leakage due to poorly sealed buildings, which would represent an excess of boiler energy in any initial calculation of energy consumption.

Using mature trees of 10m height, the building energy modelling estimated a reduction of 2.7% in July chiller energy due to the combination of reduced UHI peak hours and eight additional trees (four on the north side and four on the south side) surrounding a three-storey shallow plan building, with savings increasing to 4.8% under a three-day period of peak UHI conditions. While winter boiler energy usage is substantially reduced for a building in an urban location with a low proportion (approximately 3%) of greenspace, the wintertime benefit is marginal when analysed in terms of carbon trade-offs between summer cooling and winter heating requirements.

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