Effect of high performance façades on heating/cooling loads in London UK office buildings

Wei Wang[1] and Chanakya Arya[2]

[1]Network Rail
[2]University College London, Department of Civil, Environmental and Geomatic Engineering, Gower Street, London WC1E 6BT

Abstract

Office buildings require a significant amount of energy for heating and cooling purposes. A possible strategy for reducing this energy in order to reduce carbon emissions and operational costs is to specify high performance facades. However, their benefits remain unclear for UK conditions with mild winters and cool summers. This paper reports on an investigation on energy demand in offices in London incorporating facades with U-values between 1.2-2.6 W/m^{2}K and g values between 0.3-0.5 using the dynamic simulation tool Tas. Other variable considered include climate change (using CIBSE future weather data files), low internal gains, long working hours and office orientation. It was found that apart from the case when internal gains are low, cooling is overwhelmingly necessary and energy usage increases with decreasing U-value and decreases with decreasing g-value. Low U-value facades act to reduce conduction heat losses thereby increasing energy use. Conversely, low g-value facades act to reduce solar heat gains thereby reducing the energy required for cooling. The results are used to highlight deficiencies in the Building Regulations and where more advice would be of benefit. The paper also discusses the merits of a number of strategies for reducing energy use in office buildings.

Keywords: Buildings, structures & design, Energy conservation

1.0 Introduction

The UK is aiming to achieve an 80% reduction in its carbon emissions from 1990 levels by 2050 because of climate change (DECC, 2013). It is widely believed that this can be accomplished by reducing energy use, much of which is currently derived from non-renewable sources such as coal, crude oil and natural gas. In Europe, buildings account for around 40% of total energy consumption and 36% of carbon dioxide emissions (European Commission, 2018) and would therefore seem to be an obvious sector to tackle. A large proportion of the effort to date in this area has been focused on domestic buildings whereas non-domestic buildings such as offices, which are also responsible for a sizable percentage of energy usage, seem to have received far less attention (Spyropoulos and Balaras, 2011; Boyano et al., 2013). This situation is only likely to get worse given the UK government's decision to drop the zero carbon target for non-domestic buildings in 2019 as part of the Productivity Plan published in 2015 (HM Treasury, 2015). Yet, office space dominates the land use in many major cities around the world. In London, office buildings account for the highest percentage of the total non-domestic building floor space provision, being of the order of 30% (Choudhary, 2012). A report by Ramidus Consulting Ltd (Harris, 2017) estimates, based on employment projections, that six million square metres of net additional office floor space will be required in London over the period 2016-2041, which is an increase of 23.2% from 2016 levels. This scale of development will no doubt further intensify the urban heat island (UHI) effect, currently responsible for temperatures in London being on average between 1-3ºC higher than the surrounding rural values (CIBSE, 2014; Levermore and Parkinson, 2019). The UHI effect is believed to be associated with changes in urban surfaces which have altered, among others, the radiative, thermal, evapotranspiration and aerodynamic properties of the environment (Kolokotroni and Giridharan, 2008; Priyadarsini, 2009). These conditions will be further exacerbated by the extreme temperatures experienced during recent heatwaves in the UK such as those in 2003, 2006 and 2018 which, according to some experts, will by 2040, constitute normal summer temperatures (Dunne, 2018; Temperton, 2018). The higher temperatures resulting from these effects are likely to increase the overall demand for air conditioning and hence electricity demand, which is mostly met by burning fossil fuel, and in turn further drives climate change, and emphasises the need to remain focused on non-domestic buildings in the UK and beyond.

The efficient use of energy in buildings is encouraged/enforced in the UK via the Building Regulations (DCLG 2016a) and voluntary initiatives such as BREEAM (BRE 2018). Building Regulations 2010: Approved Document L2A (DCLG, 2016b) includes minimum standards for fabric thermal efficiency e.g. curtain walling, as well as the efficiency of the equipment necessary for lighting, heating, ventilation and air conditioning of buildings. Of these two options, the former is favoured by some because it offers a number of advantages including better resilience to climate change, continuity to energy supplies and reduced whole life costs of buildings (CIBSE, 2015).

Fabric thermal efficiency is a function of its U-value. Lower U-values mean better thermal insulation. In locations with a temperate climate such as the UK where external temperatures are generally lower than those indoors it would seem reasonable to assume that the provision of well insulated facades and roofs would reduce energy use. Low U-value facades should stop heat from escaping during cold weather conditions but also prevent heat from entering buildings during hot spells. It is estimated that around 54% of the total energy consumed in office buildings is required for heating and cooling (Pérez-Lombard et al. 2008), and thus the provision of well insulated roofs/facades should have a substantial influence on total energy demand and hence carbon emissions from buildings. Accordingly, in recent years, much work has been focused on developing smart glazing technologies and controls (Kaluarachchi et al, 2005), high performance insulation materials and glazing products (Jelle et al. 2010). Use of the later technologies in office building envelops has enabled designers to provide thin and well insulated façades (curtain walls) with high window-to-wall ratios. Vacuum insulation panels are regarded as one of the most upcoming high performance thermal insulation solutions (Kalnæs and Jelle, 2014). During the last decade they have been used in building applications in increasing numbers in order to reduce energy use and carbon emissions. Vacuum insulation panels are able to achieve an overall *U*-value of 1.1 W/m^2K with a window-to-wall ratio of 0.7 (Kingspan, 2018). This is considerably better that the maximum allowed U-value for facades in Approved Document L2A, which is currently 2.2 W/m^2K.

Nevertheless, the studies that have been carried on office buildings in cold/cool climates appear to provide conflicting results. For instance, Pikas et al. (2014) investigations involving a generic single floor of an office building in Estonia where the climate is cold found that the most cost and energy efficient façade would be one with a small window to wall ratio, argon filled triple glazing and walls with 200 mm thick insulation with a U value of 0.16 W/m^2K. Grynning et al. (2013) investigated the energy performance of windows in a Norwegian office by varying both the U and g values of glass, the latter being the total solar energy transmittance, which indicates the share of the incoming solar energy converted into heat inside a building. It is expressed as a number between 0 and 1, where lower SHGC values mean less solar heat transmission and which generally account for the whole window including the effect of the frame. Grynning et al. (2013) found that despite the cold weather conditions, the cooling demand was high. Raji et al. (2016) explored through computer simulations the energy performance of a number of window types including single, double and triple glazing fitted to a typical high rise building in the Netherlands, which like the UK experiences a temperate climate. Their results showed that the energy required for heating and cooling reduced with reducing U-value. Similarly, Boyano et al. (2013) concluded that higher insulation values are recommended in office buildings located in cold and medium climate zones such as Tallinn in Estonia and London, respectively. A study conducted by AECOM (2011) for UK conditions, however, suggested that lowering the U-value from the currently recommended value of 2.2 W/m^2K for windows/curtains walls would have little benefit. The effects on energy consumption due to the use of high performance facades coupled with changes to parameters affecting building usage – for example, occupancy hours and occupancy density - as well as changes to the internal/external environment – for example, the use of more energy efficient lighting and equipment and future weather conditions - are also not clear from these studies.

Work by a number of authors has further shown that energy demand in buildings is also influenced by, among others, built form (Gratia and De Herde, 2003; Yang et al, 2008; AECOM, 2011), UHI effect (Magli et al; 2015; Gunawardena et al, 2017) and shading from adjacent buildings (Chan, 2012; Yu and Pan, 2018). However, currently there are no specific recommendations on these aspects in the Building Regulations and they are not discussed further. Nevertheless, the building model used in this work and the variables considered make it is possible to check the findings of some of these studies and, where necessary, to identify any anomalies that may exist.

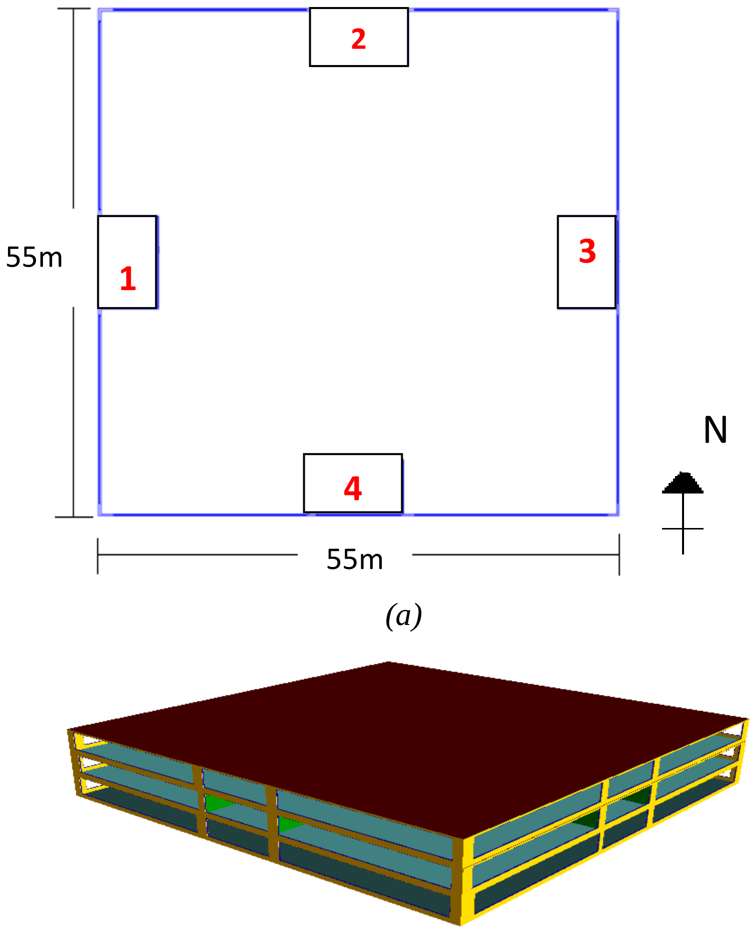
The two fold aims of the work reported in this paper are (a) to investigate the influence of high performance facades, specifically fabric parameters U in the range 1.2-2.6 W/m^{2}K and g-values in the range 0.3-0.5, on the energy required for heating and cooling of office buildings in London under a number of operating conditions including long working hours, low internal heat gains and future weather conditions and (b) to use the results to review the advice on these aspects in the UK Building Regulations 2010: Approved Document L2A (DCLG, 2016b) as well as to make recommendations for reducing energy use in office buildings. The energy required for heating and cooling in this work was estimated using a well-known dynamic simulation tool called Tas (EDSL 2012). Tas is a commercially available software, developed by EDSL. It is accredited by the UK government (Ward, 2018) and can be used to estimate the annual load due to heating, cooling, lighting and ventilation of buildings. Tas models hourly energy requirements and can be used to analyse the performance of whole structures (Gratia and De Herde, 2003; Abdullah and Wang, 2009). However, in this work only the performance of a number of single office spaces 6m deep × 3m high × 10m long was analysed (Kolokotroni et al, 2004; CIBSE, 2015)). The following provides further details of the building form analysed together with details of the simulations that were performed.

2.0 Methodology

2.1 Building form and standard operating conditions

In general, high rise office buildings have simple shapes and large window to wall ratios. In this type of structure the perimeter zone is the most important with respect to energy use for heating and cooling because this is where the façade exerts the greatest influence and also where the largest amount of heat transfer occurs. Moreover, assuming similar occupancy/usage throughout, all the floors apart from the top and bottom will consume similar amounts of energy. Thus although it is possible to model the behavior of office buildings by examining the performance of an actual/entire structure it is also reasonable to consider only the behavior of a number of modules in the perimeter zone. It was felt that the latter approach offered a number of advantages including the fact that the results would be more generally applicable and that it would help highlight more clearly the influence of façades on heating and cooling loads in office buildings. It also allowed manual checks to be carried out on the results using the heat balance equation (Kreider et al, 1994), thereby preventing gross errors.

Fig. 1 shows the general arrangement of the building used in this work. It is three storey structure with an open-plan area 55m×55m and floor to ceiling heights of 3m. The structure is a simplified model of a multi-storey office building and assumes that all the floors apart from the top and the bottom consume similar amounts of energy (Korolija et al., 2013). Energy usage was assessed by considering the performance of four offices in the perimeter zone: 1, 2, 3 and 4, each 6m deep × 3m high × 10m long, presumed to be located on the middle floor and facing respectively West, North, East, and South. It was assumed that the façade is 10m long and 3m high and the window to wall ratio is 0.7 (Table 1). The remaining three sides of the room are internal walls and as such the effect of adjacent offices on the performance of the test offices would be minimal. The U-values of the floors and walls assumed in our work are the default values in Tas which are the same as those for the notional building as summarised in Table 5 of the UK Building Regulations 2010: Approved Document L2A (DCLG, 2016b). Here it can be seen that the U-value for walls is 0.26 W/m^{2}K and for floors is 0.22 W/m^{2}K.



(a)

(b)

Fig. 1. TAS building model (a) plan (b) isometric

Table 1 provides details of the normal operating conditions assumed in the simulations. The ventilation rate and values of internal gains due to people, lighting and equipment, based on an occupancy density of 12m^2 per person shown in Table 1 are taken from CIBSE Guide A (CIBSE 2015). It was further assumed that the building will normally be occupied between 8am and 6pm, seven days a week. The design set-point temperature was assumed to be 22ºC in both winter and summer. This was based on advice in CIBSE (2016) for open plan, air conditioned office buildings which recommends operating temperatures of between 21-23ºC in winter and 22-24ºC in summer. Neither relative humidity nor latent heat were considered in the simulations.

Office space	3m × 10m × 6m	
Facade	3m ×10m	
Window to wall ratio	0.7	
Internal gains (W/m2)	People	6.7
	Lighting	12
	Equipment	15
Ventilation rate	10 l/p/s	
Operating hours	0800-1800, 7 days a week	
Design indoor temperature	22ºC	

Table 1. Building form and operating conditions

						S (W/m²)			
Season	T_{min} (°C)	T_{max} (°C)	T_{out} (°C)	T_{in} (°C)	ΔT (°C)	N	E	S	W
Winter	0.5	14.5	6.8	22.0	-16.1	14.5	27.1	57.9	27.1
Mid-season	1.7	18.2	10.5	22.0	-11.5	49.4	80.8	100.7	80.8
Summer	9.3	25.7	16.7	22.0	-5.3	70.4	106.6	111.4	106.6

Table 2. London indoor and outdoor temperatures, solar irradiation, averaged by seasons

2.2 Climate data

Tas contains weather files which can be used to carry out the dynamic simulations but in fact the weather data given in the Test Reference Year (TRY) database (CIBSE 2016) was used as it is more representative of the weather conditions in the UK.

As previously noted, to check against gross errors in the dynamic simulations manual checks on both the annual and seasonal energy demands based on the heat balance equation were also carried out. This required access to values of both exterior temperatures as well as values of the incident solar irradiance on windows for London. For convenience the exterior temperatures were obtained from the Government's Standard Assessment Procedure (SAP) (BRE, 2012). These values show that London has a temperate climate with mild winters and cool summers. Fig. 2 shows the monthly average temperatures for London. The monthly values were used to calculate the average outdoor temperatures, T_{out}, by season shown in Tables 2. The table also includes figures for the minimum, T_{min}, and maximum, T_{max}, seasonal temperatures. Note that in this table, winter covers the period November-February and summer is the period between June-September. The remaining months are classed as mid-season.

The design indoor office temperature, T_{in}, was taken to be 22°C and used to calculate values of the average temperature difference between indoor and outdoor conditions, ΔT $(= T_{out} - T_{in})$, shown in Table 2. Note that the average outdoor temperature is always significantly lower than the design indoor temperature, as indicated by the negative ΔT values.

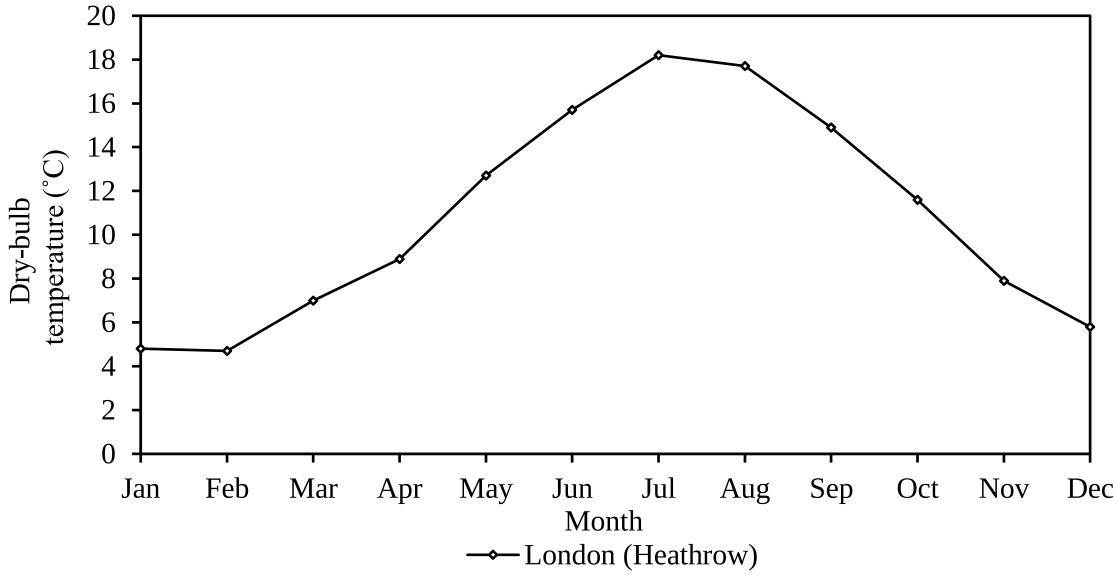


Fig. 2. Monthly average temperature profile for London

Scenario	Ref	Building model, window to wall ratio, ventilation rate	Hours of working	Internal gains (W/m2)	Weather (CIBSE)
1	SC1	Table 1	0800-1800, 7 days a week	33.7	current
2	SC2	Table 1	0700-2300, 7 days a week	33.7	current
3	SC3	Table 1	0800-1800, 7 days a week	25	current
4	SC4	Table 1	0800-1800, 7 days a week	33.7	Future: 2050

Table 3: Simulations performed

Table 2 also shows values of the monthly mean daily solar irradiance on vertical surfaces, *S*, averaged over 24 hours (W/m^2). The solar irradiance is a measure of the power per unit area on the Earth's surface produced by the sun in the form of electromagnetic radiation, perceived by humans as sunlight. These values were determined using the method in SAP (BRE 2012). Note that the weather data shown in Table 2 was not used in the dynamic simulations but has been included here to explain some of trends obtained.

2.3 Simulations performed

Four scenarios were investigated in this study as summarized in Table 3. Scenario 1 assumes the standard operating conditions and hours of occupation detailed in Table 1 apply. Scenario 2 assumes the same operating conditions as scenario 1 but that the building is occupied between 7am and 11pm, seven days a week. This is based on work by a number of authors including Azar and Menassa (2012) and Sun (2014) who found that there is a considerable difference between the predicted and actual energy use in buildings, often referred to as the energy gap. According to Korjenic and Bednar (2012) this can be particularly large for office buildings because the intended building use is unknown at the design stage. These authors attribute this discrepancy to the combined effect of building operation and maintenance, and occupants' activities and behaviour such as equipment and lights being left on during non-operating hours rather than any problems with the simulation software. Added to this is the fact that large size buildings tend to have longer average working hours which can vary between 60-80 hours, and building schedule and after-hours equipment use have been found to be very influential (Azar and Menassa, 2012). Menezes et al (2012) found that correct prediction of occupancy hours could greatly reduce performance gap.

Scenario 3 looks at the effect of lower internal gains due to a slightly lower occupancy density (16 rather than 12m^2/person) as well as the use of more energy efficient fluorescent lighting resulting in internal gains from people, lighting and equipment of 5, 8 and 12 W/m^2 respectively. Scenario 4 considers the impact of climate change on energy use and uses data provided in CIBSE (2016), which is the 2050 medium emission scenario, 50th percentile.

In each case, the heating/cooling load is calculated assuming that the U-value of the whole façade including frames, spandrel zone and glazing, varies between 1.2W/m^{2}K and 2.6W/m^{2}K. The higher value was selected based on recommendations in the Building Regulations: Part L2A (DCLG, 2016b) which states that the U-value of curtain walling should in general not exceed 2.2 W/m^{2}K but can be as high as 2.7 W/m^{2}K in buildings with high internal gains. The lower value was based on manufacturer's literature which shows that curtain walling with a U-value of 1.1 W/m^{2}K and lower is now commonly available (Cuce and Riffat, 2015). Three values of the total solar energy transmittance (*g*-value) namely 0.3, 0.4 and 0.5, were also investigated in this study. Selected results from this study are presented and discussed below.

3.0 Results and Discussion

3.1 Scenario 1

(i) Annual load

Fig. 3 show the effect of *U* and g-values on annual energy demand for offices at the four cardinal orientations. It can be seen that, irrespective of orientation, annual energy demand increases with decreasing *U*-value and that North facing offices have the lowest energy demand whereas South facing offices have the highest. The annual energy load was also found to decrease with decreasing g-value. These results were unexpected but were confirmed by hand calculations based on the energy balance equation which exhibited similar trends (Wang, 2018). In order to understand these trends the energy demand by season was considered.

(ii) Seasonal loads

Figs 4(i)-4(vi) show the energy required in winter, mid-season and summer for North and South facing offices. Here it can be seen that apart from winter (Fig. 4i, 4ii), where it appears that the least amount of energy is required when the facade has a *U*-value of around 1.8 W/m^{2}K for North facing office and 2.3 W/m^{2}K for South facing offices, energy demand increases with decreasing *U*-value. An examination of the nature of the energy usage in winter shows in fact that North and South facing offices require a mix of heating and cooling (Fig. 5) whereas at all other times of the year there is just a cooling demand. This is despite the fact that average outdoor temperatures in London are lower

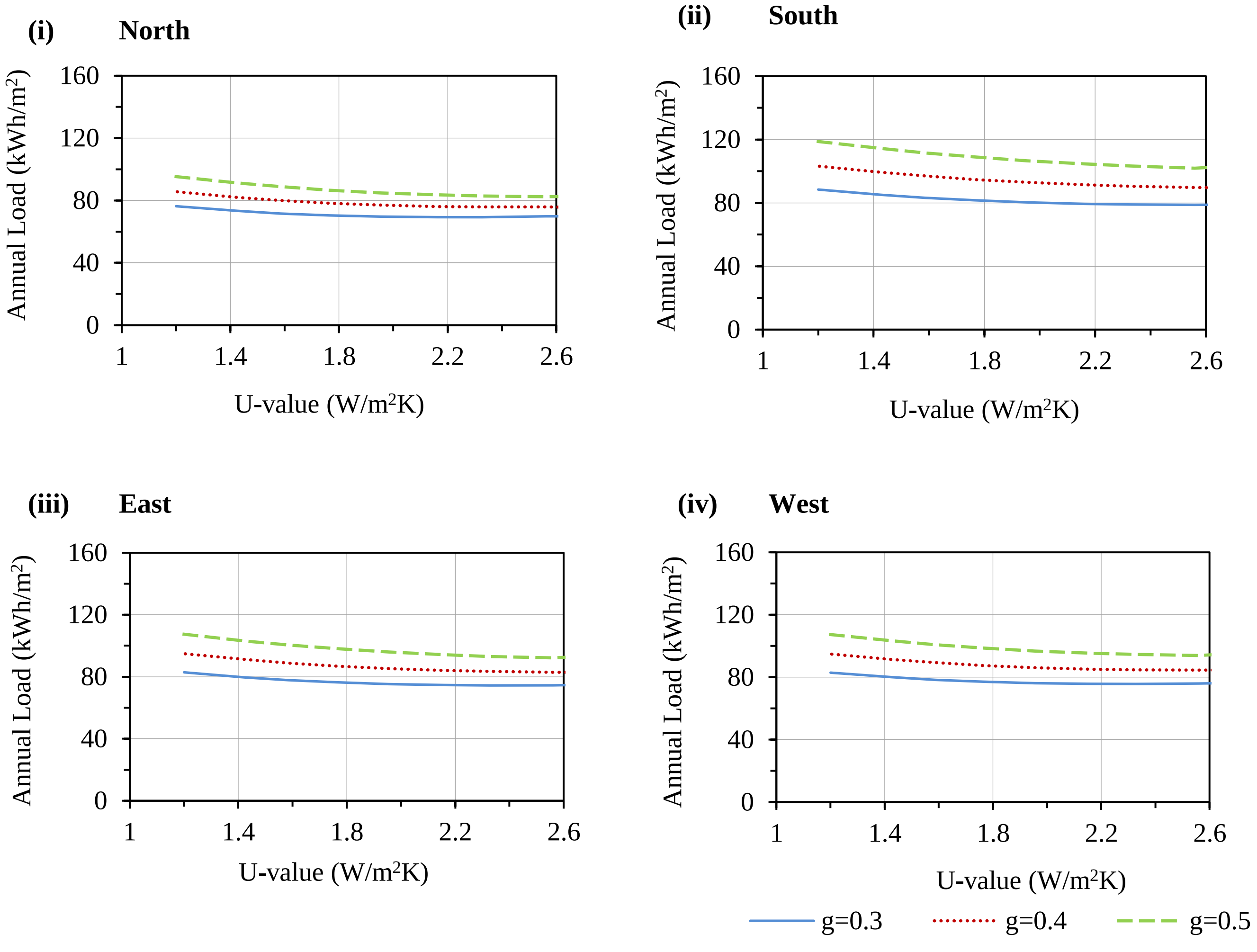


Fig. 3. Effect of U and g values on annual energy demand in North, South, East and West facing offices in London under the SC1 scenario

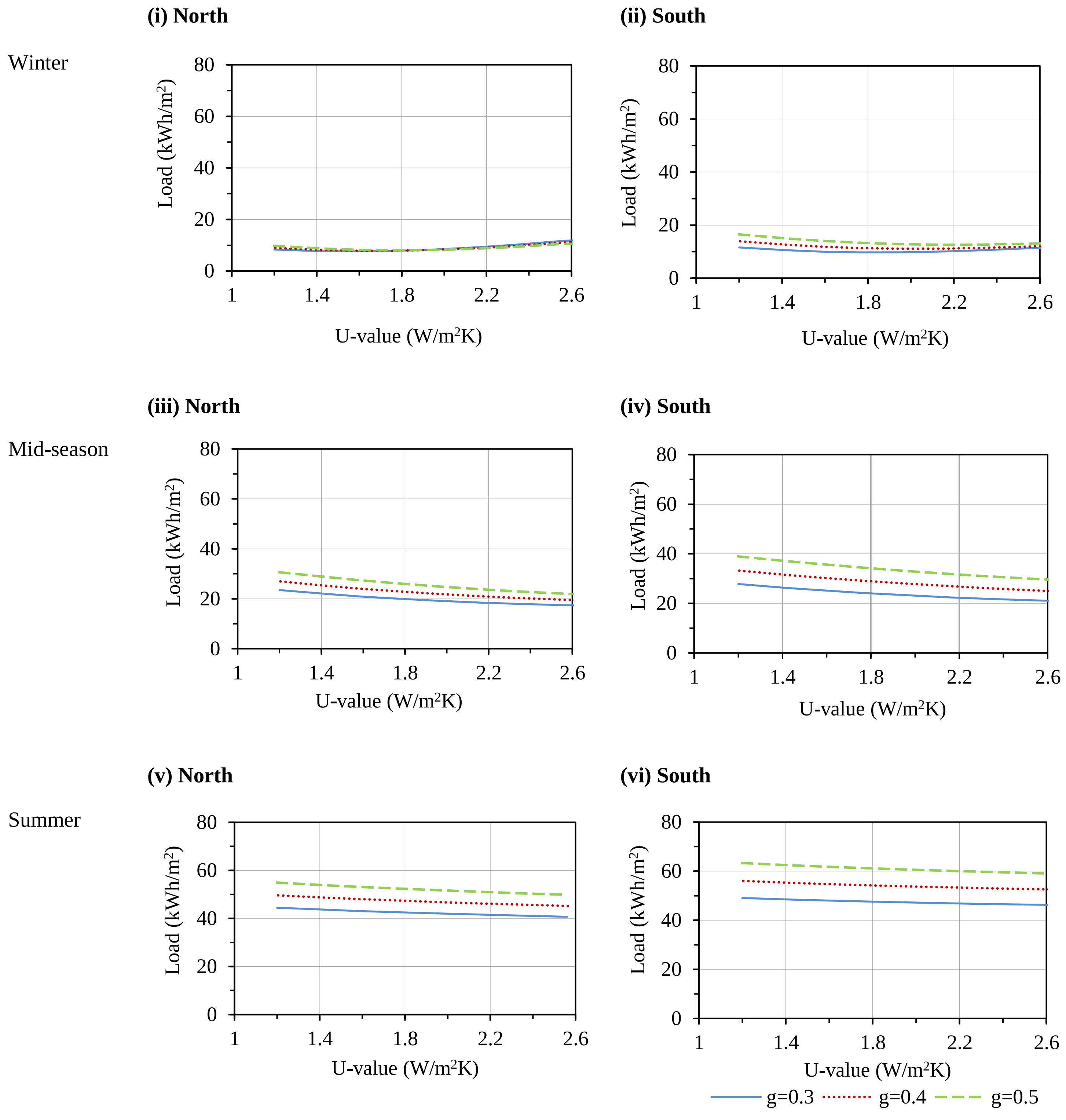


Fig. 4. Effect of U and g values on seasonal energy demand in North and South facing offices under the SC1 scenario

than those indoors throughout the year (Table 2). The results suggest that in London offices the problem faced by designers is not about keeping heat inside the building but predominantly about allowing it escape. Thus it appears low U-value facades trap heat inside the building, thereby increasing energy demand. This is consistent with the results for g-value. Lower g-value facades result in lower solar heat gains and hence reduced energy demand.

(i) North **(ii) South**

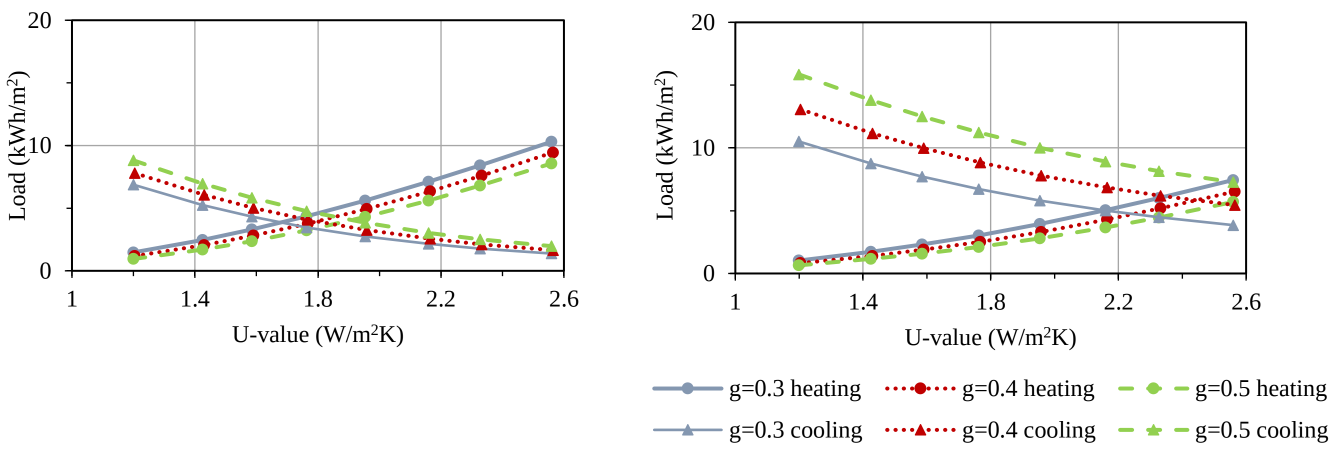


Fig. 5. Effect of U and g values on winter heating and cooling demand in North and South facing offices under the SC1 scenario

This can be more clearly appreciated by considering values of the principal factors influencing energy demand, namely

- Conduction heat gain/loss through façade (Q_{cond})
- Ventilation heat gain/loss (Q_{air})
- Internal heat gain (Q_{int})
- Solar heat gain (Q_{sol})
- Heat gain/loss due to building heat transfer (Q_b)

Table 4 shows summations of daily values of these parameters for South facing offices in winter, mid-season and summer assuming g = 0.5 and U is either 1.2 or 2.6 W/m^{2}K. Note that Q_h and Q_c represent respectively the heating and cooling load. Also, Q_b, which measures the heat gain/loss through internal walls is not discussed here because its value is small in comparison with other components of the heat balance and does not affect overall trends.

From Table 4 it can be seen that in winter when U = 2.6 Wm^2/K there is a requirement for both heating and cooling. But when U = 1.2 Wm^2/K there is just a cooling demand. The results for winter further show that there is an increase in energy demand when the U-value reduces from 2.6 to 1.2 W/m^{2}K. This is principally due to the conduction heat loss which reduces from -38 kWh/m^2 to -20 kWh/m^2, thereby eliminating the need for heating but significantly increasing the cooling load and hence the overall energy demand. The conduction heat losses as a percentage of the internal and solar

Season	U-value	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	1.2	0	17	-20	-19	39	22	-4
	2.6	5	8	-38	-19	39	22	0
Mid-season	1.2	0	41	-18	-13	40	37	-5
	2.6	0	31	-31	-13	40	37	-2
Summer	1.2	0	63	-13	-4	40	44	-4
	2.6	0	59	-19	-4	40	44	-1

Table 4. Effect of U-value on heating and cooling demand in South facing offices when g = 0.5 under the SC1 scenario

heat gains reduce from 62% (= 38/(39 + 22)) to 33% (= 20/(39 + 22)) when U is reduced from 2.6 Wm^2/K to 1.2 W/m^2/K. These results further suggest that South facing offices incorporating facades with a g-value of 0.5 and *U*-value of around 2 W/m^{2}K would require minimal heating and cooling during winter. Although this measure will increase energy demand at other times of the year, assuming much of this energy can be derived from various green sources such as photovoltaic modules installed in the spandrel area of the façade (Yu et al, 2017) and/or air source heat pumps, which is a realistic proposition given that irradiation levels and dry-bulb temperatures are higher during these periods, should help reduce CO_2 emissions (Wang and Arya, 2016).

In mid-season the average temperature difference between indoors and outdoors is smaller (Table 2) and this reduces the heat loss due to ventilation, Q_{air}, from -19 kWh/m^2 to -13 kWh/m^2. The conduction heat losses are also lower. Thus in the case of facades with a U-value of 2.6 W/m^{2}K the conduction heat loss reduces from -38 kWh/m^2 to -31 kWh/m^2. Moreover, because solar irradiance levels are higher during mid-season compared with winter (Table 2), the resulting heat gain, Q_{sol}, increases from 22 kWh/m^2 to 37 kWh/m^2. The net effect is that more energy is required for cooling despite the fact that the average outdoor temperature is still around 11°C lower than indoors.

In summer, the difference between the indoor and outdoor average temperature is lower still at around 5°C and therefore the heat losses due to ventilation, Q_{air}, and conduction (Q_{cond}) further reduce to, respectively, -4 kWh/m^2 and -19 kWh/m^2 assuming U = 2.6 W/m^{2}K. The sun is stronger during this period and this further increases irradiance levels and hence solar heat gains to 44 kWh/m^2, which in turn increases the energy required to regulate building temperatures, i.e. $Q_h + Q_c$, to 59 kWh/m^2. An interesting result which emerges from this analysis is that in office buildings the highest energy demand for heating and cooling occurs in the summer and the lowest in winter.

3.2 Scenario 2

(i) Annual loads

Scenario 2 looks at the effect of longer working hours on energy demand. As discussed in section 2.3 this scenario assumes that offices are occupied for 16 rather than 10 hours a day in order to take account of the energy performance gap. Figs 6(i) and 6(ii) show the effect of U and g values on annual energy demand of North and South facings offices respectively. Like scenario 1the results show that annual load increases with decreasing U-value irrespective of office orientation. It can also be seen that annual load decreases with decreasing g-value and that g-value has a larger effect on

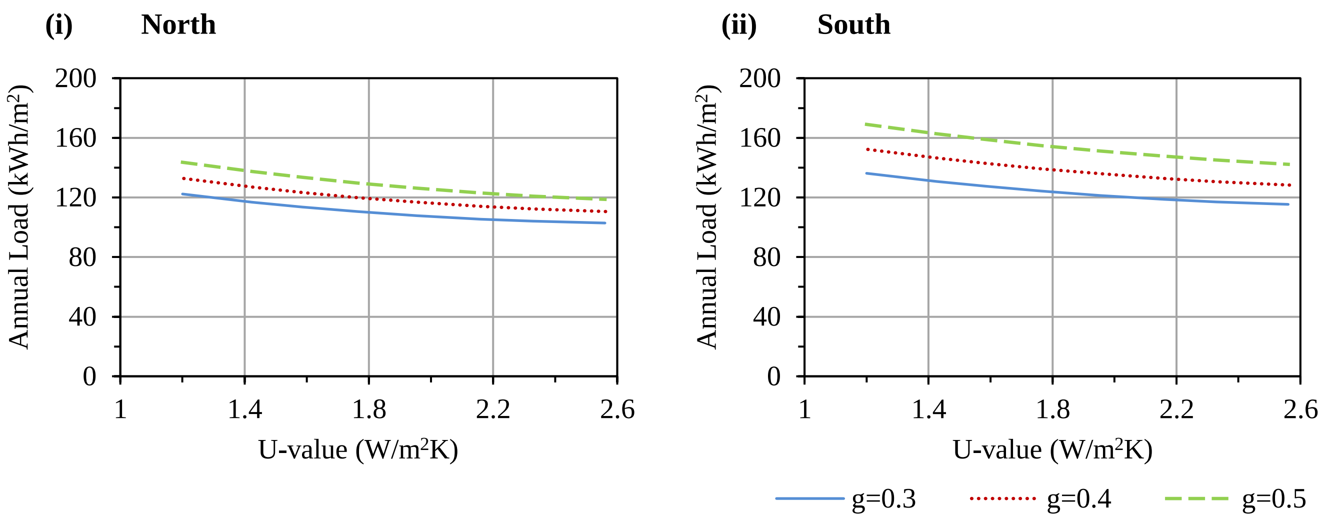


Fig. 6. Effect of U and g values on annual energy demand in North and South facing offices occupied for 16 hours (SC2)

South facing offices compared with North facing ones. As suspected, the annual loads obtained for scenario 2 are higher than those for scenario 1 presumably due to the more prolonged period of cooling.

(ii) Seasonal loads

The nature of the energy demand in winter and mid-season is shown in Figs. 7 and 8 respectively. From Fig. 7 it can be seen that offices in London require a mix of heating and cooling in winter. Decreasing the U-value decreases heating demand but increases cooling demand. For a given U-value, South facing offices have a higher cooling demand than North facing offices. From the results in Fig. 8 it can be seen there is minimal heating demand in mid-season, which is also true of summer. Comparing the results with scenario 1 (Fig. 5) shows that longer working hours results in similar heating loads but higher cooling loads.

Further insights are provided by considering values of the principal factors influencing energy demand. Table 5 shows the results for South facing offices in winter, mid-season and summer assuming g = 0.5 and U-values of 1.2W/m^{2}K and 2.6W/m^{2}K. The values in the table are summations

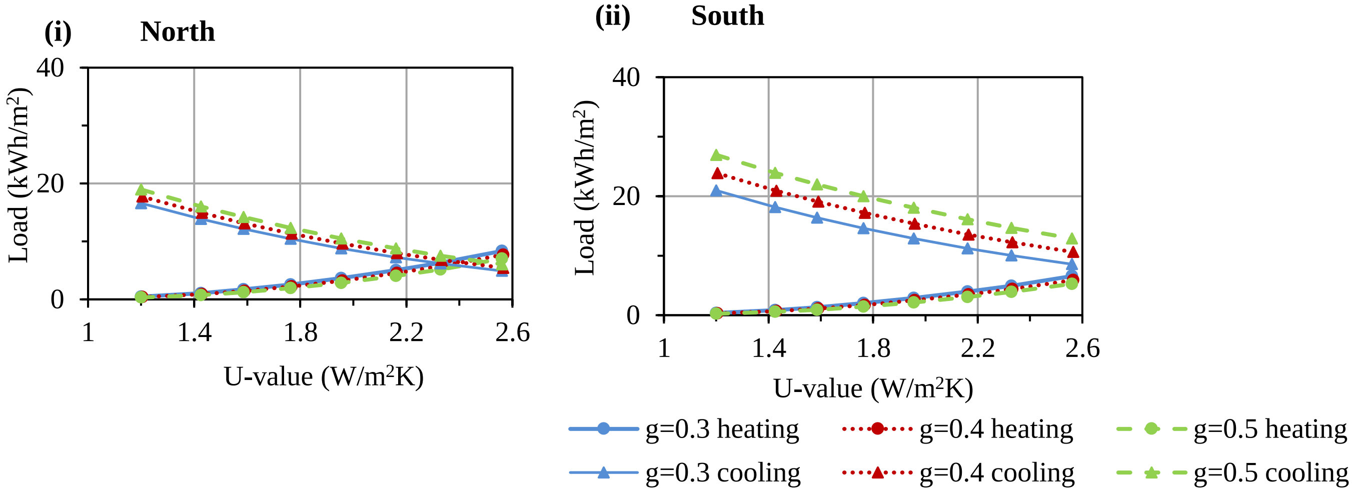


Fig. 7. Effect of U and g values on winter heating and cooling demand in North and South facing offices occupied for 16 hours (SC2)

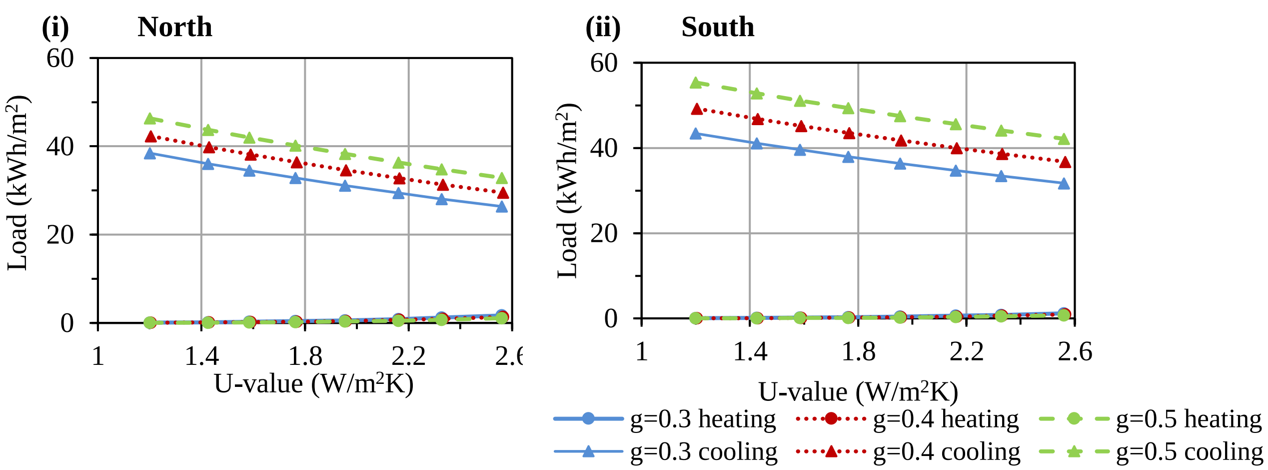


Fig. 8. Effect of U and g values on mid-season heating and cooling loads in North and South facing offices occupied for 16 hours (SC2)

Season	U-value	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	1.2	0	26	-26	-32	62	21	0
	2.6	5	12	-46	-32	62	21	2
Mid-season	1.2	0	54	-22	-22	64	36	-2
	2.6	1	42	-36	-22	64	36	0
Summer	1.2	0	83	-14	-8	64	43	-1
	2.6	0	78	-20	-8	64	43	0

Table 5: Effect of U-value on energy demand of South facing offices in London assuming g = 0.5, SC2

of the hourly energy demand of individual terms for each season. Comparison with the results for scenario 1 (Table 4) shows that both the conduction heat losses and the ventilation heat losses are higher at all times of the year. The internal heat gains are significantly higher but the solar heat gains remain the same. Longer working hours result in higher cooling loads essentially because internal heat gains persist over a longer period of time and although conduction and ventilation heat losses both increase, these increases are insufficient to offset the increase in internal heat gains. Lowering the U-value of façades further increases office cooling loads because it unfavourably reduces conduction heat losses. From the results in Tables 4 and 5 it will be appreciated that longer working hours increase energy usage and the use of lower U-value facades exacerbates this condition.

These results further indicate that sometimes during winter and mid-season there may be a need for cooling in south facing offices and heating in north facing ones. This would suggests there is potential to effect further savings in heating energy in London's office building by installing a heat recovery system such as variable refrigerant flow (Kani-Sanchez and Richman, 2017).

Table 6 shows the effect of g-value on annual and seasonal energy demand for South facing offices. As in the case of scenario 1, lowering the g-value reduces energy demand in all seasons. The reduction in cooling load achieved by decreasing the g-value from 0.5 to 0.3 in scenarios 1 and 2 is similar. This is because lowering the g-value only affects solar heat gains which is the same in both cases. The extended working hours occur either early in the morning or late evening when solar heat gains are low.

From these results is appears that lower U-value facades still perform poorly if buildings are occupied for longer hours because they trap unwanted heat.

Season	g-value	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	0.3	0	20	-24	-32	62	11	2
	0.4	0	23	-25	-32	62	16	1
	0.5	0	26	-26	-32	62	21	0
Mid-season	0.3	0	43	-18	-22	64	19	1
	0.4	0	48	-20	-22	64	27	0
	0.5	0	54	-22	-22	64	36	-2
Summer	0.3	0	69	-10	-8	64	22	1
	0.4	0	76	-12	-8	64	32	0
	0.5	0	83	-14	-8	64	43	-1

Table 6. Effect of g-value on heating and cooling demand in South facing offices when U = 1.2 W/m^2K under the SC2 scenario

3.3 Scenario 3

This scenario considers the impact of using equipment and lighting with lower internal gains.

(i) Annual results

Figs 9(i) and 9(ii) show, respectively, the effect on energy demand in North and South facing offices if internal gains from lighting, equipment and occupants is 25 W/m^2 rather than 33.7 W/m^2 as

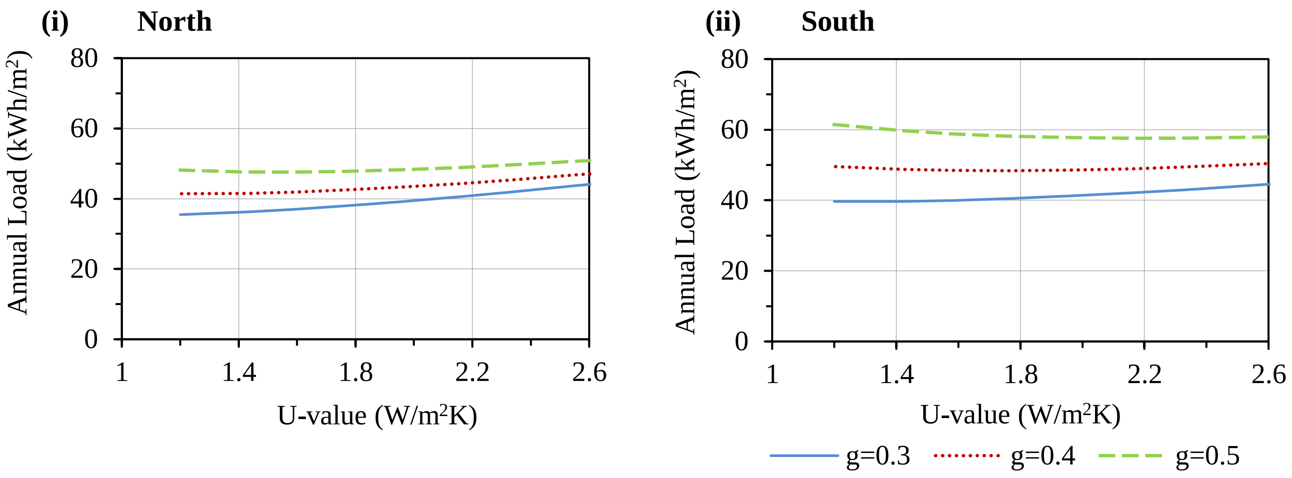


Fig. 9. Effect of U and g values on annual energy demand in North and South facing office with internal heat gains of 25 W/m^2 (SC3)

Season	U-value	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	1.2	3	1 12	-23	-23	28	21	-5
	2.6	0		-37	-22	28	21	-1
Mid-season	1.2	0	16	-23	-19	28	36	-7
	2.6	2	10	-35	-18	28	36	-3
Summer	1.2	0	39	-18	-10	28	43	-4
	2.6	0	33	-26	-10	28	43	-2

Table 7. Effect of U-value on heating and cooling demand in South facing offices when g = 0.5 under the SC3 scenario

assumed for scenarios 1 and 2. It can be seen in the case of North facing offices that the annual energy load decreases with decreasing U-value for all g-values. This is also true of South facing facades when g = 0.3 but becomes more marginal when g = 0.4. When g = 0.5 the trend reverses and energy usage increases with decreasing U-value.

Comparing the results in Fig. 9 with the corresponding results in Fig. 3 shows that there is almost a 50% reduction in overall energy demand if internal gains are 25 W/m^2 rather than 33.7 W/m^2.

(ii) Seasonal results

Table 7 shows a breakdown of the results for South facing offices in winter, mid-season and summer assuming g = 0.5 and U is either 1.2W/m^2K or 2.6W/m^2K. The values in the table are summations of hourly energy demand for these seasons.

Comparing with Table 4 shows that the value of internal heat gains, Q_{int}, are significantly lower and both the conduction heat losses, Q_{cond}, and ventilation losses, Q_{air}, are generally somewhat higher. The net effect of these changes are

(a) cooling loads are lower in summer but heating loads are higher in winter.

(b) the heating and cooling requirement in mid-season and winter now exhibit similar trends in that with high U-value facades some heating may be necessary whereas in the case of low U-value facades this need is significantly reduced or even eliminated.

Season	U-value	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	1.2	5	0	-22	-22	28	6	5
	2.6	17	0	-37	-21	28	6	8
Mid-season	1.2	0	8	-22	-19	28	17	3
	2.6	3	4	-35	-17	28	17	8
Summer	1.2	0	32	-17	-10	28	29	1
	2.6	0	25	-27	-10	28	29	4

Table 8. Effect of U-value on heating and cooling demand in North facing offices when g = 0.5 under the SC3 scenario

Season	g-value	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	0.3	5	0	-20	-22	28	11	-1
	0.4	4	0	-22	-23	28	16	-3
	0.5	3	1	-23	-23	28	21	-5
Mid-season	0.3	1	7	-19	-18	28	19	-3
	0.4	0	11	-21	-19	28	27	-5
	0.5	0	16	-23	-19	28	36	-7
Summer	0.3	0	26	-13	-10	28	22	-1
	0.4	0	32	-15	-10	28	32	-3
	0.5	0	39	-18	-10	28	43	-4

Table 9. Effect of g-value on heating and cooling demand in South facing offices when U = 1.2 W/m^2K under the SC3 scenario

Table 8 shows a similar set of results for North facing offices. The biggest difference between these two sets of results are the values of solar heat gains, Q_{sol}. This is due to the difference in diffuse and direct components of the total solar irradiation received by North and South facing offices. Although this does change overall trends, North facing offices require more heating in winter but less cooling in summer. The reduction in heating load due to the reduction in U-value is greater in North facing offices than South facing ones. Moreover, in mid-season the increase in cooling load is less in North facing offices than South facing offices. The net effect of these changes is that whereas a reduction in U-value reduces energy demand in North facing offices the opposite is true in South facing ones.

(iii) The effect of g-value

The results in Fig. 9 show that lowering the g-value reduces the energy demand, irrespective of office orientation. This measure results in greater savings in energy use than achieved by reducing U-value. This is probably because offices in London generally require cooling and methods which reduce internal heat gains appear to be more efficient at reducing energy usage. For example, Table 9 shows the effect of g-value on seasonal energy demand in South facing offices assuming U = 1.2W/m^2K. Here it can be seen that there is a heating element in winter but at all other times there is only a cooling requirement. Reducing the g-value reduces Q_{sol} and hence cooling demand. In summer, for instance, this was found to be as much as 20kWh/m^2 for South facing offices. But it should be remembered that any potential savings in cost should be offset against the higher cost of providing low g-value glazing.

3.4 Scenario 4

This scenario investigates the effect of climate change on energy use in London office buildings featuring high performance facades. The climate data used is the 2050 medium emission scenario, 50th percentile, mentioned in CIBSE (2016). See Table 3 for further details of the assumed operating conditions assumed in scenario 4.

London	T_{max}(˚C)	T_{min}(˚C)	T_{av}(˚C)	S_o (kWh/m^2)
Winter	14.7	1.3	7.9	1467
Mid-season	19.2	3.2	12.2	4069
Summer	27.7	11.1	19.9	5932

Table 10. Seasonally averaged temperatures and solar irradiation values for London in 2050 (CIBSE, 2016)

Season	U-value	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	1.2	0	18	-22	-18	39	20	-2
	2.6	4	9	-37	-18	39	20	1
Mid-season	1.2	0	45	-19	-10	40	39	-4
	2.6	0	37	-29	-10	40	39	-2
Summer	1.2	0	69	-12	-1	40	45	-3
	2.6	0	67	-16	-1	40	45	-1

Table 11. Effect of U-value on heating and cooling demand in South facing offices when g = 0.5 under the SC4 scenario

(i) London future climate data, 2050

Table 10 shows the outdoor seasonal maximum, T_{max}, minimum, T_{min}, and average temperatures, T_{av}, together with the total daily solar irradiation values, S_o, for London in 2050. The seasonally averaged temperatures are predicted to increase by 1.1˚C, 1.7˚C and 3.1˚C in winter, mid-season and summer respectively. The solar irradiation is projected to be 22kWh/m^2 lower in winter, but 289kWh/m^2 and 531kWh/m^2 higher in mid-season and summer respectively.

(ii) Annual trends

Fig. 10(i) and 10(ii) show the effect of U and g-values on annual energy demand for North and South facing offices in London respectively. It can be seen that the trends are similar to those for scenarios 1 and 2, namely energy demand increases with decreasing U-value but decreases with decreasing g-value. In general, the annual loads found in scenario 4 are higher than those in scenario 1.

(ii) Seasonal loads

A breakdown of the results for South facing offices assuming g = 0.5 and the U-value is either 1.2W/m^{2}K or 2.6W/m^{2}K is presented in Table 11. Here it can be seen that except in winter when U = 2.6Wm^2/K there is generally only a cooling demand, despite the fact that the average outdoor temperatures are lower than those indoors throughout the year (Table 10). Thus reducing the U-value increases energy demand.

Table 11 also show that there is an increase in energy demand from 13kWh/m^2 to 18kWh/m^2 in winter when the U-value reduces from 2.6 to 1.2W/m^{2}K. This is because of the reduction in heat loss due to conduction via the façade, which eliminates the need for heating but significantly increases the need for cooling and hence increases overall energy demand. This finding is similar to that for winter in scenario 1. The higher outdoor dry-bulb temperatures in mid-season and summer increase energy loads because of the greater need for cooling.

Table 12 shows the effect of g-value on annual energy demand for South facing offices. Here it can be seen that lowering the g-value reduces energy load largely because of the reduction in solar heat gains.

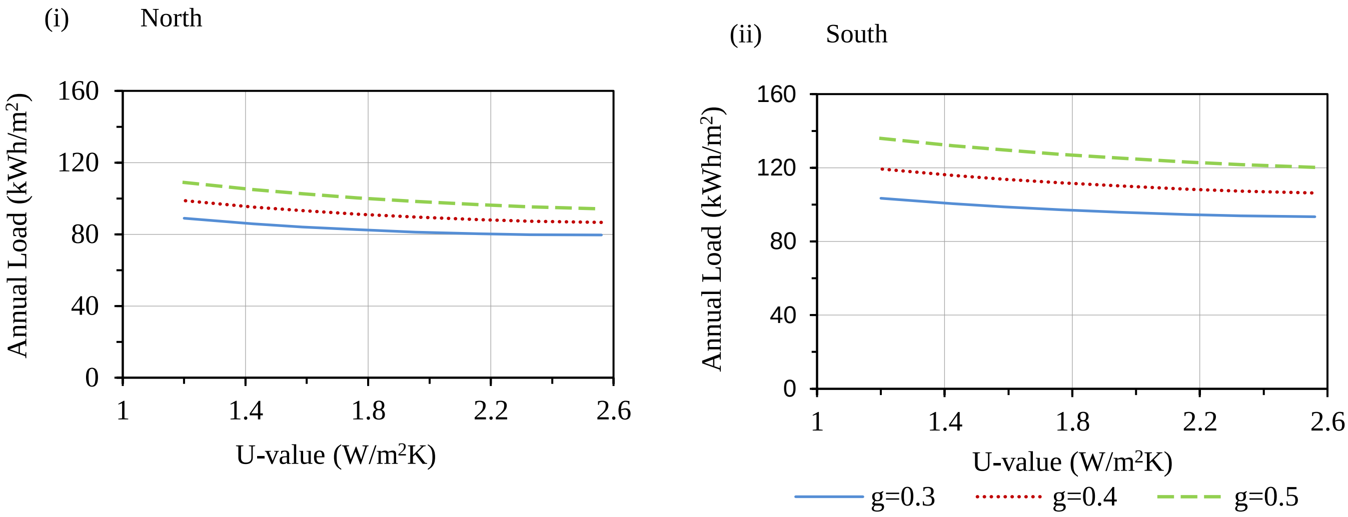


Fig. 10. Effect of U and g values on annual energy demand in North and South facing office under the SC4 scenario

Season	g-value	Q_h	Q_c	Q_{cond}	Q_{air}	Q_{int}	Q_{sol}	Q_b
Winter	0.3	1	13	-20	-18	39	11	0
	0.4	0	15	-21	-18	39	16	-1
	0.5	0	18	-22	-18	39	20	-2
Mid-season	0.3	0	33	-15	-10	40	20	-1
	0.4	0	39	-17	-10	40	29	-3
	0.5	0	45	-19	-10	40	39	-4
Summer	0.3	0	54	-7	-1	40	23	0
	0.4	0	62	-10	-1	40	34	-2
	0.5	0	69	-12	-1	40	45	-3

Table 12. Effect of g-value on heating and cooling demand in South facing offices when U = 1.2 W/m^{2}K under the SC4 scenario

4.0 Implications for Building Regulations and strategies for reducing energy use in offices

The results of this study show that the energy required for heating/cooling of office buildings is not simply a function of U-value but is also related to a number of other factors including external temperatures as well as solar and internal heat gains. The results further show that despite the fact that average outdoor temperatures in the UK are always below design indoor values, cooling is predominantly necessary in office buildings because of high internal gains. The provision of lower U-value facades reduces conduction heat losses which in turn increases cooling demand and hence overall energy demand. This agrees with the findings of the AECOM (2011) study which concluded that U-values should not be reduced from the currently recommended value of 2.2 W/m^{2}K in the UK Building Regulations: Approved Document L2A (2016b). This would not appear to be true, however, if internal heat gains are low. This finding may not also be true of countries or regions of the world where outdoor temperatures are significantly lower than design indoor values for prolonged periods of the year such as Estonia and Norway and/or regions which experience lower solar heat gains. This was confirmed by carrying out similar simulations to those described for the UK but using the climate

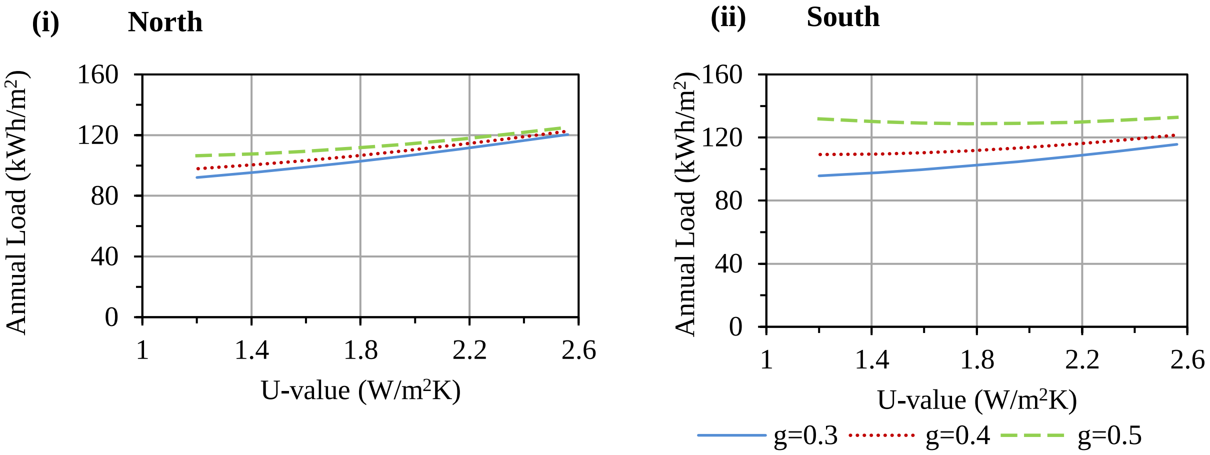


Fig. 11. Effect of U and g values on annual energy demand in North and South facing offices in Caribou (Wang, 2018)

data for Caribou, USA. The results are shown in Fig. 11. Here it can be seen that in the case of north facing offices, lowering the U-value reduces annual energy demand. In south facing offices this is true only of facades with a g-value of 0.4 or lower. Facades with higher g-values will increase solar gains which coupled with low U-values actually increases overall demand as indicated by the results for facades with a g-value of 0.5.

While the decision to not lower the existing U-value for curtain walling in Approved Document L2A would appear to be reasonable, the advice in Clause 2.39 suggests that the U-values in Table 3 should be regarded as an upper limit and in reality facades with better fabric performance i.e. lower U-values, will be necessary in order to achieve the target CO_2 emission rate (TER) as set out in the National Calculation Methodology (NCM) modelling guide (BRE, 2016) and summarised in Table 5 of Approved Document L2A. However, this appears unlikely given that this measure is liable to increase energy demand rather than to reduce it.

Note 4 of Table 3 of LA2 states that in buildings with high internal gains the U-values can be relaxed but should be no greater than 2.7 W/m^{2}K. The results of this study suggest a similar trend. But unfortunately the Regulations do not define the term high internal gains and more information on this point would be helpful to designers.

The work presented in this paper suggests three possible strategies for reducing energy use in office buildings, namely

- Reduce internal heat gains
- Specify low g-value facades
- Increase design indoor temperatures in winter.

As noted in Table 1 of the paper, the main sources of internal gains are occupants, office equipment and lighting. Work by Jenkins (2009) suggests that the most effective way of reducing internal gains in office buildings is via the provision of

- low-energy office equipment such as more efficient PC’s, low energy LCD screens, multi-function machines for all printing/copying/scanning needs
- low energy (LED) lighting.

The author presented data which shows that such equipment could result in savings of peak internal gains of around 60% by 2030. This compares with the 25% reduction in internal gains assumed in scenario 3, and suggests that if the levels of reduction in internal gains indicated by Jenkins could be assured the use of low U-value facades should reduce the energy required for heating and cooling.

But it is worth remembering that the provision of low energy office equipment and lighting will increase the upfront cost of commissioning and, if the experience of the Hong Kong Government is typical, voluntary compliance is likely to prove challenging despite the promise of (future) reduction in energy bills (Environment Bureau, 2007). It is also worth remembering that the reduction in internal gains from these sources is likely to diminish over time as a result of improvements to infiltration rates in office buildings as well as the effect of climate change.

The results of these simulations show that the use of low g-value glazing invariably reduces the energy required for heating/cooling (Figs 3, 6, 9 and 10). But this study has not consider the effect of g-value on lighting load, which can be comparable with the energy required for space heating/cooling load for office buildings (Boyano et al (2013). Thus, although the use of low g-value glazing will reduce solar heat gains it may well reduce the level of daylight entering the building, thereby increasing the energy required for lighting. This is confirmed in a study by Fasi and Budaiwi (2015) of a typical office building in Dhahran, Saudi Arabia who found that clear-glass double glazed windows (U = 2.8 W/m^2 K and g = 0.7) required less lighting energy at all times of the year than bronze tinted glazed (U = 2.6 W/m^2 K and g = 0.5) which in turn required less energy that low-E double glazing (U = 1.9 W/m^2 K and g = 0.4). According to Hee et al (2015) the daylight penetration is heavily dependent on the visible light transmission (VLT) properties of glass, which for the glazing types investigated by Fasi and Badaiwi were, respectively, 74%, 47% and 44% and explains the results obtained. Nevertheless, development in glazing technology mean that it is now possible to specify glazing which has low g-values and high VLT values (Cuce and Riffat, 2015). But such glazing is more expensive and will again increase upfront costs. In general, the UK Building Regulations recommends a g-value of 0.68 for occupied spaces (Cl. 2.53), which would appear to be conservative. In order to comply with the target CO_2 emission rate, however, the notional building requirements is for glazing with a g value of 0.4 which is more reasonable. The results of this study and indeed others (AECOM, 2011; Grynning et al., 2013) suggest that Building Regulations should place more emphasis on this fabric parameter than perhaps is currently the case for office buildings and similar.

The recommended design temperature for UK offices in winter is between 21-23ºC and in summer between 22-24ºC (CIBSE, 2015). The fact that design temperatures are lower in winter than in summer is somewhat surprising, especially given that energy use played no part in arriving at these values (Nicol and Roaf, 2017), and appears to be partly related to the practice of wearing heavier clothing during winter. Determining suitable values of design temperatures for thermal comfort in buildings is a complex task as it requires consideration of a large number of factors including outdoor climate, humidity, air movement, clothing insulation as well as the activity, age, gender and culture of the occupants to the building (Nicol and Humphreys, 2002; CIBSE, 2013). Suitable values of design temperature have been derived by carrying out comfort surveys on subjects in climate chambers and analysing the results in accordance with either the ASHRAE or Bedford scales (Humphreys et al, 2016). However, this practice has been criticized in recent years by various authors on a number of grounds including the range of conditions which subjects find comfortable in field surveys is much wider than these indices predict (Nicol and Roaf, 2017). For example, work by Humphreys (1978) suggests that European office workers are comfortable with temperatures in the range 17-28ºC. The results of the present study suggest that if the design temperature in winter was raised to the same value as for summer this would reduce energy use in office buildings. The proposed change in design temperature is well within the human comfort zone and, unlike reducing internal gains, would help reduce energy usage and pollution at no cost.

5.0 Conclusions

The paper elucidates the effect of fabric parameters U and g, office orientation, long working hours, low internal heat gains and future weather conditions on energy use for heating and cooling of office buildings in London. Relevant guidance in the UK Building Regulations is reviewed and the merits of a number of strategies for reducing energy use in office buildings are discussed.

For U-values in the range 1.2-2.6 W/m^{2}K and g-values in the range 0.3-0.5 it was found that:

> Offices with internal gains of 33.7 W/m^2 experience an increase in annual energy demand with decreasing U-value and increasing g-value, irrespective of office orientation, extended working hours and future weather conditions.
>
> Offices with internal gains of 25 W/m^2 experience almost a 50% reduction in annual energy demand compared with offices with internal gains of 33.7 W/m^2. Moreover, the annual energy demand decreases with decreasing U value for all values of g in the case of north facing offices but only when g = 0.3 in the case of south facing offices.
>
> Despite the fact that average outdoor temperatures in London in winter are significantly lower than the design indoor value, there is a cooling demand in office buildings with internal gains of 33.7 W/m^2, which increases with reducing U-value and decreases with decreasing g-value.
>
> In all cases the annual cooling load is significantly greater than the annual heating load with the result that (i) energy demand is highest in summer and lowest in winter (ii) lowering the U-value increases energy demand because of reduced conduction heat losses.
>
> Longer occupancy hours increase annual energy demand because internal heat gains persist for a longer period of time which increases the needed for more sustained cooling.
>
> Climate change will result in higher outdoor temperatures and solar irradiation levels which respectively reduces conduction heat losses and increases solar heat gains, thereby giving rise to higher cooling loads and hence higher annual energy demand.
>
> The energy required for space heating/cooling can be reduced by lowering internal gains and/or by specifying low g-value facades but these measures are likely to increase the upfront cost of construction.

Increasing the design set point temperature of office buildings in winter to say 24ºC is another way of reducing energy usage and could be achieved at no cost.

Aspects of the UK Building Regulations where more guidance/information would be of benefit includes (i) minimum recommended U-values in office buildings with high internal gains (ii) clear definitions of low, medium and high internal gains (iii) greater emphasis on the influence of g-value and the visible light transmission factor of glass on energy usage in office buildings.

References

Abdulah, A.H. and Wang, F. (2009). Modelling thermal environmental performance in top-light Malaysian atrium using computational fluid dynamics (EFD). *International Journal of Integrated Engineering*, 1(2), 79-93.

AECOM (2011). *Zero carbon non-domestic buildings Phase 3 final report*. London, UK: Department for Communitities and Local Government. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/6329/1940106.pdf

Aktacir, M. A., Büyükalaca, O. and Yılmaz, T. (2010). A case study for influence of building thermal insulation on cooling load and air-conditioning system in the hot and humid regions. *Applied Energy*, 87(2), 599-607.

Azar, E. and Menassa, C. C. (2012). A comprehensive analysis of the impact of occupancy parameters in energy simulation of office buildings. *Energy and Buildings*, 55, 841-853.

Boyano, A., Hernandez, P. and Wolf, O. (2013). Energy demands and potential savings in European office buildings: Case studies based on Energy Plus simulations. *Energy and Buildings*, 65, 19-28.

BRE (2012). *The Government's Standard Assessment Procedure for Energy Rating of Dwellings (SAP)*. London, UK: Department of Energy and Climate Change.

BRE (2013). *National Calculation Methodology (NCM) modelling guide for buildings other than dwellings in England*. Retrieved from https://www.uk-ncm.org.uk/filelibrary/NCM_Modelling_Guide_2013_Edition_20November2017.pdf

BRE (2018). *What is BREEAM* ? Retrieved from https://www.breeam.com

Chan, A.L.S. (2012). Effect of shading on the thermal performance of residential buildings in a subtropical region. *Applied Energy*, 92, 516-522.

CIBSE (2013). *The limits of thermal comfort: avoiding overheating in European buildings* (Report TM52). London, UK: The Chartered Institution of Building Services Engineers.

CIBSE (2014). Design Summer Years for London (Report TM 49). London, UK: The Chartered Institution of Building Services Engineers.

CIBSE (2015). *CIBSE Guide A: Environmental Design*. London, UK: The Chartered Institution of Building Services Engineers.

CIBSE (2016). *CIBSE Weather Data Sets*. Retrieved from http://www.cibse.org/weatherdata

Cuce, E. and Riffat, S.B. (2015). A state of the art review on innovative glazing technologies. *Renewable and sustainable energy reviews*, 41, 695-714.

Choudhary, R. (2012). Energy analysis of the non-domestic building stock of Greater London. *Building and Environment*, 51, 243-254.

DCLG (2016a). *The Building Regulations 2010*. London, UK: Department for Communities and Local Government.

DCLG (2016b). *The Building Regulations 2010: Approved Document L2A Conservation of fuel and power in new buildings other than dwellings - 2013 edition incorporating 2016 amendments-for use in England, UK*. London, UK: Department for Communities and Local Government.

DECC (2011). *The Carbon Plan: Delivering our low carbon future*. London, UK: Department of Energy and Climate Change.

Kingspan (2018). *OPTIM-R External wall systems*. Retreved from https://www.kingspan.com/gb/en-gb/products/insulation/insulation-boards/optim-r/optim-r-external-wall-system

Dunne, D. (2018). Met Office: Climate change made 2018 UK summer heatwave '30 times more likely'. Retrieved from https://www.carbonbrief.org/met-office-climate-change-made-2018-uk-summer-heatwave-30-times-more-likely

EDSL (2018). *EDSL Tas: A complete solution for the thermal simulation of new or existing buildings*. Retrieved from http://www.edsl.net

Environment Bureau (2007). *Consultation Paper: A proposal on the mandatory implementation of the building energy code*. Retrieved from https://www.gov.hk/en/residents/government/publication/consultation/docs/2008/building_energy_codes.pdf

European Commission (2018). *Factsheet: The revised Energy Performance Building Directive*. Retrieved from https://ec.europa.eu/info/sites/info/files/epbd_factsheet_20180503_dc_v03e_final.pdf

Fasi, M.A. and Badaiwi, I.M. (2015). Energy performance of windows in office buldings considering daylight integration and visual comfort in hot climates. *Energy and Buildngs*, 108, 307-316.

Gratia, E. and De Herde, A. (2003). Design of low energy office buildings. *Energy and Buildings*, 35, 473-491.

Grynning, S., Gustavsen, A., Time, B. and Jelle, B. P. (2013). Windows in the buildings of tomorrow: Energy losers or energy gainers? *Energy and Buildings*, 61, 185-192.

Gunawardena, K.R., McCullen, N. and Kershaw, T. (2017). Heat island influence on space-conditioning loads of urban and suburban office buildings. Cities and Climate Conference 2017, Potsdam, Germany.

Harris, R. (2017). *London Office policy review 2017*. London, UK: Report by Ramidus Consulting Ltd in association with CAG Consulting.

HM Treasury (2015). *Fixing the foundations: Creating a more prosperous nation*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/443897/Productivity_Plan_print.pdf

Humphreys, M.A. (1978). Outdoor temperatures and comfort indoors. *Building Research and Practice (Journal of CIB)*, 6(2), 92-105.

Humphreys, M., Nicol, F. and Roaf, S. (2016). *Adaptive thermal comfort, foundations and analysis*. London, UK: Earthscan/Routledge.

Jelle, B. P., Gustavsen, A. and Baetens, R. (2010). The path to the high performance thermal building insulation materials and solutions of tomorrow. *Journal of Building Physics*, 34(2), 99-123.

Jenkins, D.P. (2009). The importance of office internal heat gains in reducing cooling loads in a changing environment. *International Journal of Low-carbon Technologies*, 4, 134-140.

Kalnæs, S. E. and Jelle, B. P. (2014). Vacuum insulation panel products: A state-of-the-art review and future research pathways. *Applied Energy*, 116, 355-375.

Kani-Sanchez, C. and Richman, R. (2017). Incorporating variable refrigerant flow (VRF) heat pump systems in whole building energy simulation – Detailed case study using measured data. *Journal of Building Engineering*, 12, 314-324.

Kolokotroni, M., Robinson-Gayle, S., Tanno, S. and Cripps, A. (2004) Environmental impact analysis for typical office facades. *Building Research & Information*, 32(1), 2-16.

Kolokotroni, M. and Grindharan, R. (2008). Urban heat island intensity in London: An investigation of the impact of physical characteristics in changes in outdoor temperatures during summer. *Solar Energy*, 82, 986-998.

Korjenic, A. and Bednar, T. (2012). Validation and evaluation of total energy use in office buildings: A case study. *Automation in Construction*, 23, 64-70.

Korolija, I., Marjanovic-Halburd, L., Zhang, Y. and Hanby, V.I. (2013). UK office buildings archetypal model as methodological approach in development of regression models for predicting building energy consumption from heating and cooling demands. *Energy and Buildings*, 60, 152-162.

Kreider, J. F. and Rabl, A. (1994). Heating and Cooling of Buildings, Design for Efficiency. London, UK: McGraw-Hill series in mechanical engineering.

Levermore, G and Parkinson, J. (2019). The urban heat island of London, an empirical model. *Building Services Engineering Research and Technology*, 40(3), 290-295.

Li, D. H. W., Lam, J. C. and Lau, C. C. S. (2002). A Study of Solar Radiation Daylight Illuminance and Sky Luminance Data Measurements for Hong Kong. *Architectural Science Review*, 45(1), 21-30.

Magli, S., Lodi, C., Lombroso, L., Muscio, A. and Teggi, S. (2015). Analysis of the urban heat island effects on building energy consumption. *International Journal of Energy and Environmental Engineering*, 6(1), 91-99.

Masoso, O. T. and Grobler, L. J. (2008). A new and innovative look at anti-insulation behaviour in building energy consumption. *Energy and Buildings*, 40(10), 1889-1894.

Menezes, A.C., Cripps, A., Bouchloghem, D. and Buswell, R. (2012). Predicted vs actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Applied Energy*, 97, 355-364.

Nicol, J.F. and Roaf, S. (2017). Rethinking thermal comfort. *Building Research and Information*, 45(7), 711-716.

Nicol, J.F. and Humphreys, M.A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, 34, 563-572.

Pérez-Lombard, L., Ortiz, J. and Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings*, 40(3), 394-398.

Pikas, E., Thalfeldt, M. and Kurnitski, J. (2014). Cost optimal and nearly zero energy building solutions for office buildings. *Energy and Buildings*, 74, 30-42.

Raji, B., Tenpierik, M. J. and van den Dobbelsteen, A. (2016). An assessment of energy-saving solutions for the envelope design of high-rise buildings in temperate climates: A case study in the Netherlands. *Energy and Buildings*,124, 210-221.

Priyadarsini, R. (2009). Urban heat island and its impact on building energy consumption. *Advances in Building Energy Research*, 3, 261-270.

Spyropoulos, G.N. and Balaras, C. A. (2011). Energy consumption and the potential of energy savings in Hellenic office buildings used as bank branches – A case study. *Energy and Buildings*, 43, 770-778.

Sun, Y. (2014). *Closing the building energy performance gap by improving our predictions* (Doctoral dissertation). College of Architecture, Georgia Institute of Technology, USA.

Temperton, J. (2018). London's sizzling heat island is bad news for your sweaty office. Retrieved from https://www.wired.co.uk/article/uk-heatwave-london-urban-heat-islands

Wang, W. (2018). *Merits of using low U and g-value facades on heating/cooling demand and CO_2 emissions from office buildings* (Unpublished doctoral dissertation). University College London, UK.

Wang, W. and Arya, C. (2016). *Influence of high performance facades on heating/cooling load in office buildings in London and Hong Kong*. Newcastle (Great North Museum), UK: Proceedings of the 3rd IBPSA-England Conference Building Simulation and Optimization 2016 (BSO 2016).

Ward, J. (2018). *9.4.2 Approval letter*. Retrieved from http://edsl.myzen.co.uk/downloads/misc/approval/Tasv9.4.2Approval.pdf

Yang, L., Lam, J.C. and Tsang, C.L. (2008). Energy performance of building envelopes in different climate zones in China. *Applied Energy*, 85, 9, 800-817.

Yu, C. and Pan, W. (2018). Effects of shading on the energy consumption of high rise office buildings in Hong Kong. 2018 Building Performance Analysis Conference and SimBuild. Chicago, USA. Retrieved from https://www.ashrae.org/File%20Library/Conferences/Specialty%20Conferences/2018%20Building%20Performance%20Analysis%20Conference%20and%20SimBuild/Papers/C067.pdf

Yu, J.S., Kim, J.H., Kim, S.M. and Kim J.T. (2017). Thermal and energy performance of a building with PV-applied double-skin façade. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, 170:6, 345-353