Department of Mechanical Engineering

An Investigation into the Energy Consumption of Future Office Buildings around the world

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: **James Johnston** Date: **18th September 2009**

1 Acknowledgements

I would like to thanks my parents for taking care of me over the summer, my supervisor for his guidance and my girlfriend for her support and belief in me.

2 Abstract

Many of the studies into building energy consumption focus on optimizing a small detail rather than looking at the whole. This study was undertaken at a higher level and looked into a wide range of possible influences on the energy consumption – to build up a realistic profile for a future office.

The first element under investigation is the evolving flexible workplace strategy. The trend towards a more distributed and mobile workforce have implications on both occupancy gains in the space and IT equipment use. In order to fully appreciate the impact of a ubiquitous workforce, an occupancy profile generator tool was developed. This tool could be used for different proportions of office workers – fulltime onsite workers, telecommuters and mobile workers. Three workplace scenarios were developed to investigate a) business as normal b) increased teleworking and c) a future workplace. It was discovered that one of the most effective ways of reducing the energy consumption is simply encouraging the use of laptops instead of desktop computers.

A total energy simulation was then run on a 6 floor low-rise building in central London. A hybrid modelling approach was undertaken; using ESP-r for the thermal loads and developing excel spreadsheets for analysing the IT, lighting and HVAC loads. Scenarios were created, based on definitions from Carbon Trust typical and good practice benchmarks and compared with a theoretical future office. The results of the study show that energy consumption could be potentially reduced by 70% in 10 years time.

The potential for using photovoltaic solar power was then examined. An analysis into optimal tilt angles for roof based panels was undertaken to investigate the sensitivity of shading effects from adjacent panels. It was concluded that horizontal panels provided the maximum generation in a year.

Finally, a comparison of different worldwide locations, and the impact on the energy demands and PV supply was undertaken. The results show that the temperate maritime climate in north-west Europe is the least able to achieve carbon neutral, whilst offices in Mediterranean or desert locations can be 90% off-grid.

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6 Introduction

A major influence on the way offices will be used in the future is the increasing importance of sustainability – primarily with the need to reduce carbon emissions to mitigate the impact of anthropogenic climate change. Whilst an important factor now, by 2020 it will require more than awareness to meet the difficult carbon emission reduction targets set by our government and the EU [1].

The second trend is a behavioural change in how employees perceive their worksetting. Through the rapid progression of mobile communication devices, the era in which the office can be seen as a static place for individual work is over [2]. Employers and employees are finding that a more distributed approach to work can allow for a better work-life balance, and the increased independence actually increases productivity [3]. Reducing the number of hours travelling per week also reduces the carbon footprint of the commute [4].

6.1 Key trends and influences

This behavioural change is impacting the requirements of the office worksetting, in which fixed places for quiet work will be seen as auxiliary space, rather than the main purpose. Instead, offices will be seen as hubs for collaborative work and will require an extremely flexible and independent layout [5]. The technical challenges facing this new office environment are not insurmountable but do require some innovative solutions. The first challenge is with the “nervous system” of the building – the electrical network.

In the future office, almost all the electrical loads will be entirely unsuited to the high voltage alternating current (AC) network which is currently available. Instead all low-powered laptops, mobile devices, LED lighting and other office equipment will run on low voltage direct current (DC) power [6].

The intertwining nature of technology and behavioural trends are displayed in the diagrammatic in Figure 1.

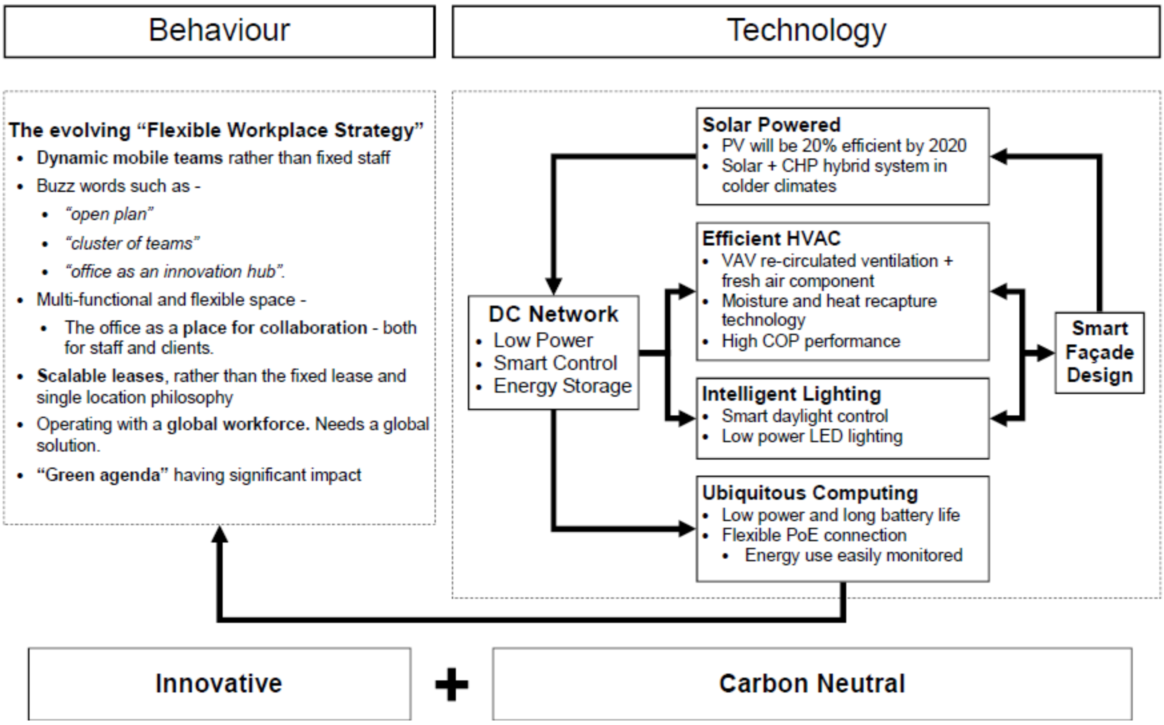


Figure 1: The intertwining nature of technology and behaviour

The figure demonstrates how the biggest electrical demands – cooling, lighting and computing can all be integrated using a DC network.

A central theme in the office of the future is generating electricity onsite using PV panels. To date, PV generation is seen as an inefficient and expensive method of electricity generation – however it is widely acknowledged that in a few decades, the cost effectiveness of installing and running PV could equal that of conventional means [8].

6.2 Summary and Scope

There are many elements of uncertainty in the design and operation of a future office, but most predominately;

- **Behaviour Trends:** how it is used by the occupants and how this is changing
- **Advances in technology:** the extent to which the building fabric and building systems will improve in the future
- **Environment:** the location in which the office is based.

7 Flexible Working Styles in the Future Office

Advances in communication, transportation and the trend towards a globalised and connected world are having a major impact in the office place. The three most influential trends are:

- the rapid expansion of the services industry, bringing ever more information work and the evolution of a creative economy [4]
- the development of a distributed work strategy with mobile and flexi-time workers [10]
- the increased awareness and sense of duty to mitigating environmental impact [11]

7.1 The "Flexible workforce Strategy"

7.1.1 Generation Y

The creative economy is the most dominant force in innovation and progress in the business world today. Whilst at the start of the 20th century, less than 10% of the working population focused on creative work such as the science and technology, cultural, and knowledge based industries such as law and medicine– in the last few decades this has risen to over 30% [12]. This has implications on our fundamental understanding of why we work in the first place. Davis et al. [3] argues that we have left behind the old-fashioned concept of work being as a form of punishment, and that now concepts such as work-life balance are becoming core requirements of the workforce.

In Post Fordist economies, effective communication networks are the pillars on which innovation and positive growth rely [2]. This need for effective communication is driven by Generation Y or Gen Y, defined as those who were born post 1980s and have all grown up with instant messaging, mobile phones and laptops. DEWG, a think-tank for the design of future offices, describes Gen Y as being independent, progressive, international and entrepreneurial [5]. Brought up in the age of Web 2.0 and open source, they are not accepting the strictly hierarchical and authoritarian rules of the traditional work place and instead are open to sharing ideas through mass collaboration [13].

We are entering a period where we have access to the sum of the world's knowledge and simultaneously are able to effectively communicate it to anyone in the world, anytime and anywhere [14]. There is a growing feeling amongst organisations that mass collaboration over the internet is not just a fad, and it is crucial that they can update their business plan to be more receptive to this new way of thinking. An essential component of this open approach is in how large organisations, which dominated the business world of the 20th century, will treat their employees in the future. Some have already adopted a far more open and flexible approach, such as IBM and Nokia with considerable success, encouraging others to follow in their footsteps [13, 15].

7.1.2 Alternative Working Styles

"Alternative working styles" [16] is one of the many ways of defining the new workplace strategies – amongst other words, such as "distributed working" and "flexi-working" [4]. It encompasses a range of *alternative* solutions for the workplace without focusing on one particular strategy – as summarised in the table below:

Type of AWS	**Typical Description [17]**
Part time	Increasingly popular - 2.2 million in 1970 to 7 million today (and mostly out of choice rather than necessity)
Job Share	Where one job is shared by 2 people. (Often 2 part-time workers are more productive than one full-time.)
Annualised Hours	Total number of annual hours is agreed, and then employee is free to complete them as they like. (Can do "two week, two off" etc)
Flexitime	Core hours – perhaps from 10am until 3pm or 4pm, then free to choose how to add hours either side.
Compressed working week	4 day week (10 hour days) 9 day fortnight (4 days, working 9 hours, on the 5th day 8hours one week, and free the next)
Teleworking	Defined as working from home, on the move or from telecentres or satellite offices – and requiring advanced telecoms to work

Table 1: Summary of Different AWS (Alternative Working Styles) options

The benefits of flexible working practices on the well-being of the worker are well documented [18]. The government fully supports these as an important aspect of the work-life balance: in a study (2007) they found that with better work-life balance, employers enjoyed better relations with their employees, received improved commitment and motivation and a lower staff turnover [19].

A CIB report carried out on a cross section of 5000 companies showed that in all aspects – the availability of these flexible work choices (both written and informal agreements) has been increasing over the last 4 years [20].

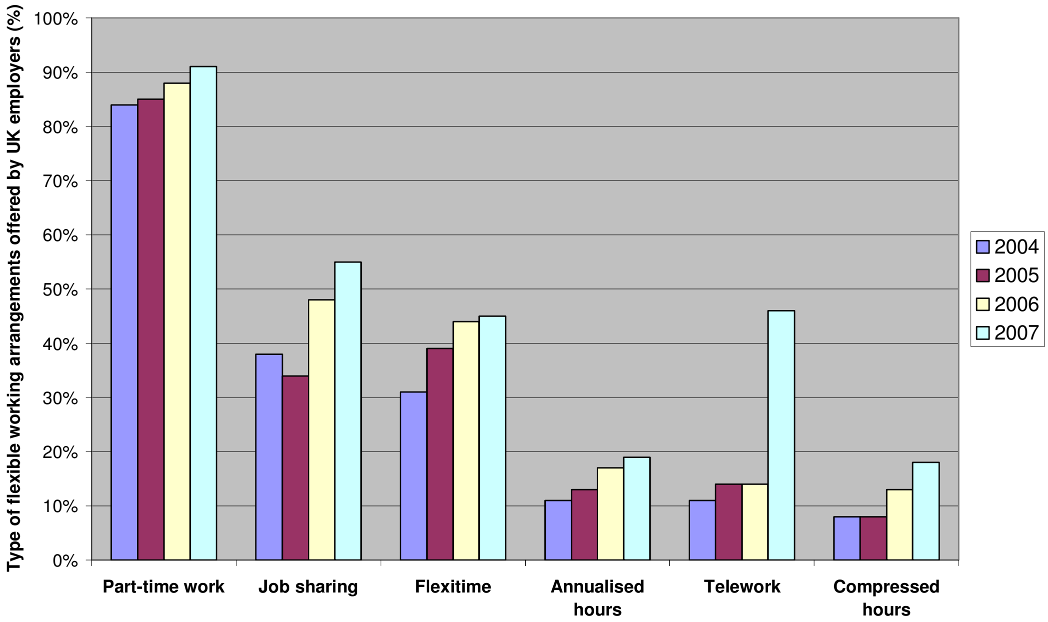


Figure 2: Summary of growth in alternative working styles in the UK, [20]

However, the Equal Opportunities Commission discovered in a study (2007), that there is an unmet need for flexible work styles in the UK, with key findings such as:

- 4.8 million feel their skills in their current job are underutilised but find it difficult to change jobs because of the lack of flexibility in the workplace
- Evolution of equal rights in the family: between 2000 and 2005, the number of fathers teleworking from home rose from 14% to 29%
- 50% of all working adults said they want more flexibility in their job
- But 60% said they had not been exposed to any information on flexible working options

The report uncovered that even though the availability of flexible working was increasing, the demand still greatly outweighs supply in flexible working practices [18]. In the future we will see more and more of these alternative approaches to working and with it, different requirements on the office environment.

7.1.3 Typical Workplace profiles

The cultural movement towards flexible working styles brings with it a more ubiquitous or mobile workforce. Some studies have been done on current levels of ubiquitous working practices in the office place.

A. Richman et al. [21] undertook a survey to define the real levels of mobility in modern US offices. They used a large sample size of 2057 full-time US employees from over 500 private companies. They defined workers into the different categories: "On-site worker", "Ad-hoc tele-worker", "Regular Tele-worker", "Mobile worker", "Remote worker" and "Customer Site worker". The proportion of each worker and an explanation of each category are explained in the chart and table below.

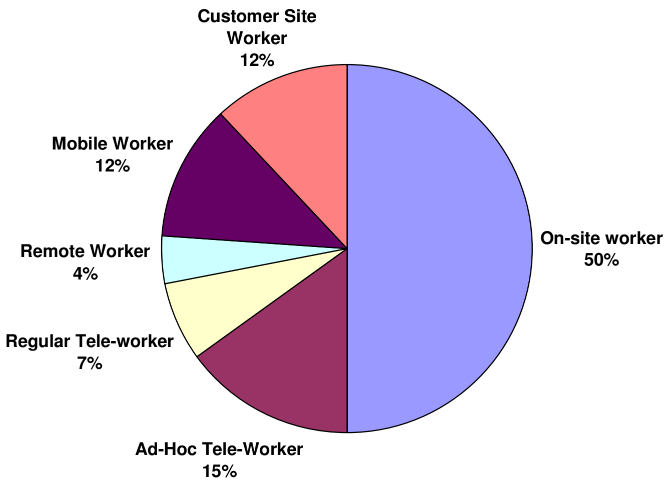


Figure 3: worker types as found in a survey across the US [21]

- **Onsite workers:** Traditional worker who does not work from home during regular office hours. Only occasionally leaves the office for meetings.
- **Ad-hoc tele-workers**: Similar to onsite workers, but work from home at least once a month
- **Regular tele-workers**: Work primarily in the office, but work from home at least 3 days a fortnight.
- **Remote workers**: Work based at home full-time, and only occasionally visit the office for administration purposes and meetings
- **Mobile workers**: perform their work in a number of locations, but do still spend a few days a week in the office.
- **Customer Site workers**: work full time at their project site, occasionally visiting the office

Table 2: worker types as found in a survey across the US

7.2 Occupancy Density and Building Utilisation

7.2.1 Benchmark data summary

Occupancy density (OD) is normally calculated by dividing the net internal floor area by the total number of employees allocated to the building [24].

An IPD report for the Office of Government Commerce looked at all available sources for benchmark data for occupancy density. There was a general consensus that around 14-16m^2/person was typical, and at most 12-20m^2/person [22]. This is displayed in graphical form in a report for the National Audit Office, as seen in Figure 4 [23].

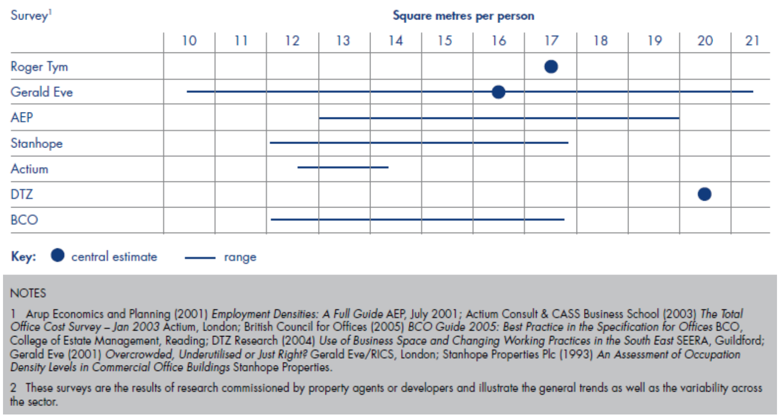


Figure 4: Benchmark data comparison displayed by NAO [23]

7.2.2 Seasonal and diurnal influence on occupancy density

Whilst these details on benchmark and good practice occupancy density (OD) are widespread, they are normally a calculation of workspace density rather than an actual account of how many occupants are in the office at one time. Real data on OD for offices in the UK, taking into account both seasonal and diurnal variations are difficult to find [16]. The author deemed it acceptable to use real OD data from an office from the US, as the most important variations in occupancy behaviour would occur between different office types and not from the office location [21]. Keith [25] took readings of the peak and average OD throughout a standard 9am-5pm workday, each month from October 1994 to September 1995 at the offices for the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. It is a research and academic institute consisting of a campus of three small buildings, a total of around 1200 rooms and an individual occupancy sensor in each room. Keith used a sample size of 97 rooms, and did not include rooms that were unallocated (permanently unoccupied). Each occupancy sensor had a binary output of either: “occupant detected” or “occupant not detected”.

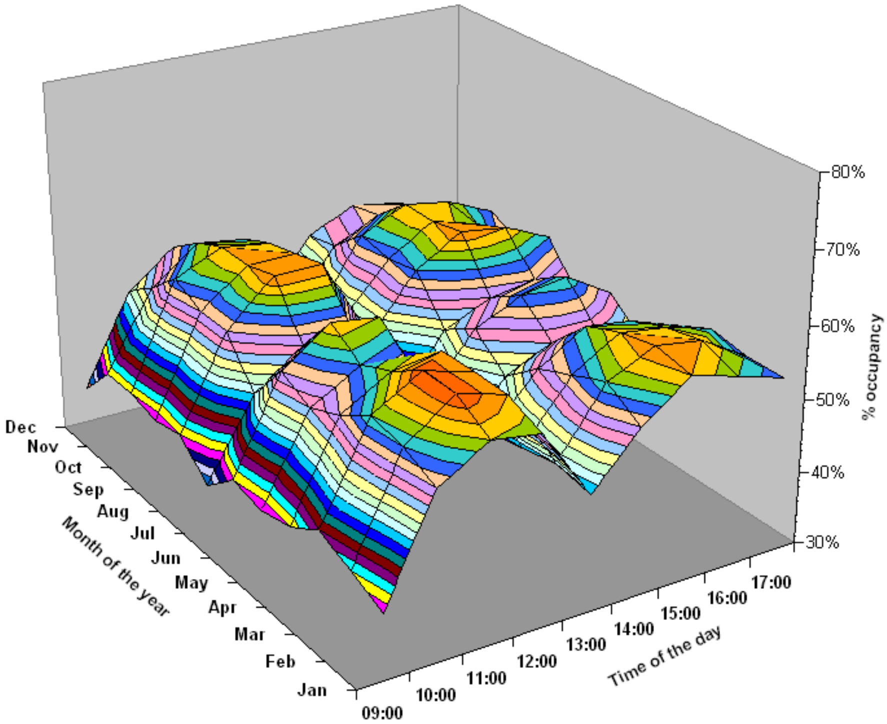


Figure 5: Graph showing diurnal and seasonal variations in average occupancy density for an office in Colorado in 1994/5 [25]

As seen in Figure 5 there is a clear diurnal and seasonal variation in OD, so that whilst the benchmark value will be useful in determining maximum conditions (used for design of the building services [26]) it is not appropriate for simulations on total annual energy consumption.

To simplify the data set, the average and peak OD were seasonally averaged. These are shown in Figure 6along with the widely recognised design OD from ASHRAE Standard 90.1-2007 [27]. It is immediately noticeable that the guideline values – at a nearly constant 95% occupancy are far away from the actual density. The average density only reaches a maximum of 57% with a peak of 65%.

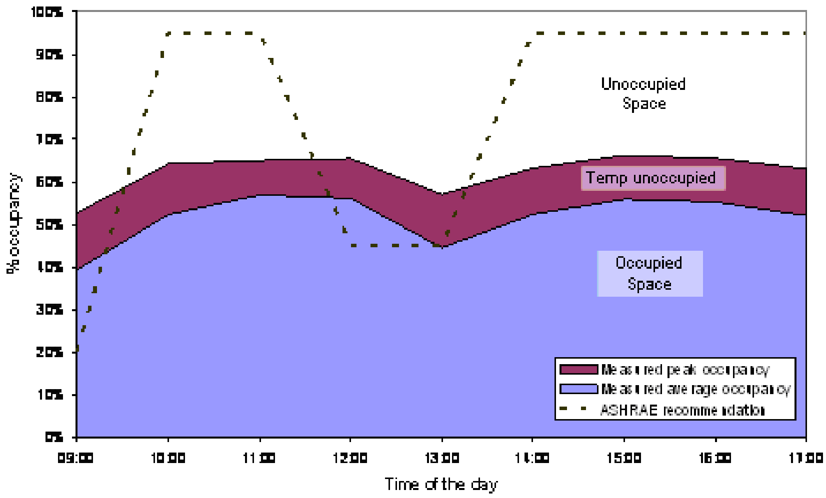


Figure 6: Seasonally averaged peak and average occupancy density [25, 27]

7.2.3 Sharing workspaces to increase building utilisation

Through a more ubiquitous workforce and with increasing alternative work styles, ever more office space is being left unused for long periods during the day. A solution to this problem is adopting desk-sharing or "hot-desking" practices [23]. The government has set a benchmark in its public administration buildings to achieve an average desk to user ratio of 1:1.25 (meaning: to increase the average OD by 25%). It is aiming to achieve an OD of 12m^2/person, with a desk arrangement of 15m^2/person. [22]

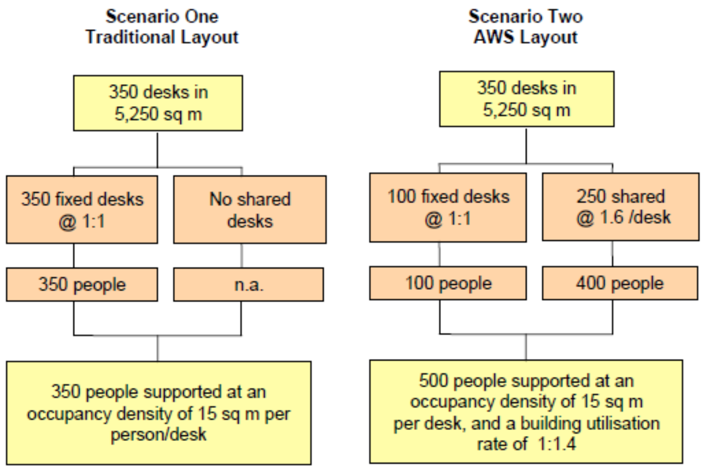


Figure 7: How a building can be utilised more effectively (as shown by Harris) [16]

There is growing evidence that organisations are adopting workspace sharing to increase the building utilisation. Examples can be seen in all industry sectors:

Organisation	Treated Floor Area (m²)	Number of Employees	% at 1:1	% sharing workspaces	Shared Workspace Ratio (Desk:employee)	Average Building Utilisation
Adult Learning Inspectorate	1,862	282	51%	49%	10:1	1.9
BAA	4,333	540	10%	90%	1.2:1	1.2
BP	41,209	4445	0%	100%	1.2:1	1.2
BT	26,500	4000	38%	63%	8.3:1	2.2
Cambridgeshire County Council	1,185	112	53%	47%	1.2:1	1.1
Dti	20,000	1600	0%	100%	1.3:1	1.3
Ernst & Young	37,800	4200	65%	35%	3:1	1.3
GCHQ	5,900	4900	0%	100%	1.5:1	1.2
Hertfordshire County Council	10,220	1000	0%	100%	3:1	1.3
IBM	15,525	1473	62%	38%	3.4:1	1.9
Norfolk county council	1,135	165	82%	18%	2.5:1	1.1
PricewaterhouseCoopers	9,316	1750	20%	80%	1.3:1	2.6
Suffolk County Council	13,286	1150	77%	23%	1.3:1	1.2
Sun Microsystems	25,220	1717	21%	79%	1.6:1	1.4

Table 3: Example organisations which are adopting workspace sharing [22]

7.2.4 Case Study: Shared workspaces at Ernst & Young LLP [23]

Figure 8: "More London – Ernst & Young HQ", www.flickr.com, Creative Commons

When Ernst & Young moved their headquarters in 2003, they downsized from 9 offices to just 2; halving the required floor area whilst retaining the same number of employees. They was achievable by actively encouraging tele-working and mobile working practices, and by implementing a 1:3 worker:desk ratio for 35% of their employees.

Along with this flexible work strategy, 80% of their staff use laptops and shelves were placed at a distance from the workstations to discourage "local nesting". To reduce the energy footprint of the office further, they have adopted highly efficient scanners, copiers and printers at a density of 1 machine per 50 staff.

Crucial to the success of their new head quarters is the concept of “spaceless growth” where a company does not have to acquire new space to house larger numbers of employees. The reported also discovered that 19% of workspaces in all government buildings remain unallocated because of the inflexible approach of being able to scale the lease. The new flexible work strategy relies on short term and scalable leases which can mean office space can be used far more effectively [28]. DEWG claim that 66% of their clients will not be renewing their leases after the current one runs out, suggesting that the idea of flexible leases will really become mainstream [29].

7.3 Simulating Daily Occupancy Behaviour

7.3.1 A framework for generating the profile

Occupancy behaviour plays an important role in calculating the casual gains and IT equipment demands in the space. As was discussed in section 7.2.2, there is limited quantitative understanding on actual occupancy density in offices. Hence it was necessary to develop a tool to generate a daily occupancy profiles which then could be varied depending on the number of mobile, semi-mobile and fixed workers.

As occupancy density is not yet a well defined science, there are many different descriptions of the same types of worker: so for the purposes of this study the definitions consistent with those written by Richman et al [21] will be used, but could be changed if necessary. The five types of worker are “Onsite worker”, “Ad-hoc teleworker”, “Regular teleworker”, “Remote worker”, “mobile worker” and “customer site worker” (please see section 7.1.3 for further description of each type). For simplification, the customer site workers have been combined with the data for remote workers, due to the small number of days each work on site.

To generate a total occupancy graph for a certain combination of workers – the characteristics of each type had to be defined in terms of:

- % of working year spent on holiday
- % of working days per year in the office. *(Source used: Richman et al [21])*
- Arrival time in the office. *(Source used: Lehmann et al [4])*
- Average length of working day. *(Source used: Richmann et al)*

Excluding bank holidays when the office would be shut anyway, an employee is entitled to 20days annual leave, which means only 92% of working year is spent working. This value was then multiplied by the % of total working hours that are spent in the office for each type of worker (93% for onsite workers down to 9% for remote workers) to find the overall % of working days spent onsite. Onsite workers spend actually only 86% of working days in the office, and this can be as low as 35% for mobile workers.

Employees of the Organisation				
Worker Type	**working days/ month onsite**	**working days in a year (total)**	**working days/ year onsite**	**% of working days onsite**
On-site worker	20.3	260	224	**86%**
Ad-Hoc Tele-Worker	19.3	260	214	**82%**
Regular Tele-worker	13.8	260	153	**59%**
Remote Worker	1.95	260	21	**8%**
Mobile Worker	8.1	260	90	**35%**

Table 4: % of working days in the office per year by employees

All of these workers types spend some of their off-site time at another company site. Assuming that this will be reciprocated by these other companies; it is necessary to model the impact of visitors that require workspaces too.

Visitors to the Organisation				
Visitor Type	**working days/ month onsite**	**working days in a year (total)**	**working days/ year onsite**	**% of working days onsite**
On-site worker	0.3	260	3	1%
Ad-Hoc Tele-Worker	0.6	260	7	3%
Regular Tele-worker	0.4	260	4	2%
Remote Workers	0.3	260	3	1%
Mobile Worker	2.6	260	31	12%
All Visitors	3.9	260	45	**18%**

Table 5: % of working days in the office per year by visitors

Worker Type	Daily Working hours [21]	Arrive time [4]	Departure time	% of working days onsite
On-site worker	9 hours	8am	5pm	93%
Ad-Hoc Tele-Worker	9.5 hours	8am	5:30pm	89%
Regular Tele-worker	10 hours	8am	6pm	63%
Remote workers	9 hours	9am	6pm	8%
Mobile Worker	10.5 hours	9am	7:30pm	37%
All Visitors	9 hours	9am	6pm	18%

Table 6: Summary of profile generation assumptions

7.3.2 Modelling Uncertainties

To model the affect of a distributed arrival time (employees will not arrive at exactly the same time), a time-offsetting variable was randomly allocated to each worker: -30mins, 0mins or +30mins. This does not affect the overall time spent at the office for each worker, but achieves a more realistic smoothing-off of occupancy levels at the start and end of the day.

To model occupants leaving the office at lunchtime, a 30% decrease in occupancy density is implemented between the hours of 12pm-1pm. The distributed arrival time algorithm means that this dip at lunchtime is also slightly more distributed.

7.3.3 Profile Verification

Using the above assumptions, the occupancy density profile was created as seen in Figure 9. For validation it was compared against the maximum values of occupancy (between the hours of 9am and 5pm) as was measured by Keith [25] in the office in Colorado. There seems to be a good match between the levels, again underlining the fact that 25% of the office is empty even during peak hours.

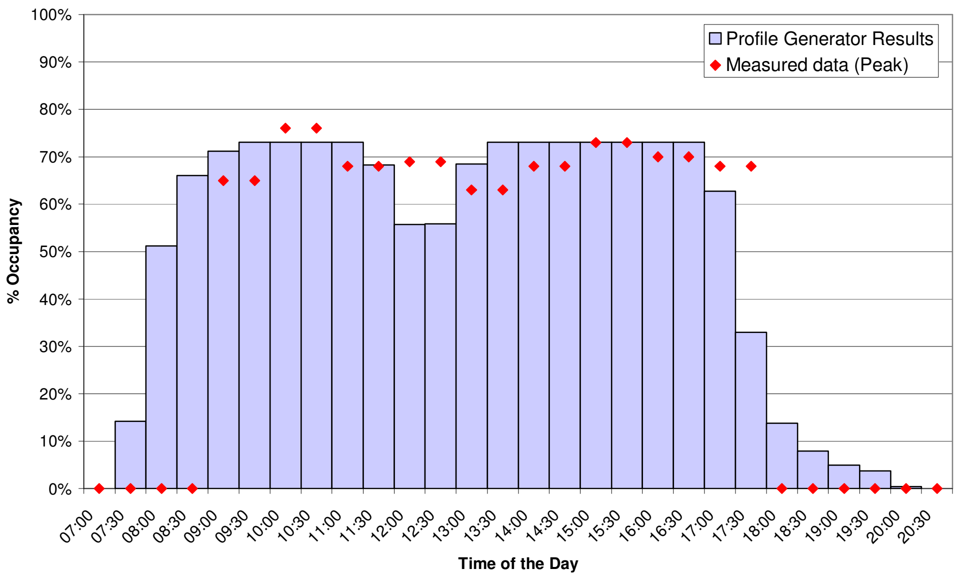


Figure 9: Design condition and maximum measured data

7.4 Flexible Workplace Study

Three different profiles were generated to simulate different scenarios of flexible and ubiquitous working styles. A base of 100 work stations was used.

1. **Business as usual:** the base case. 95 employees at fixed desks, and 5 "hot-desks" for the occasional remote workers and visitors.
2. **Tele-working workforce:** working from is actively encouraged as a company policy. 40 employees at fixed desks, and 60 desks at a desk: worker ratio of 2.5 to 1.
3. **Mobile workforce:** a future scenario where mobility is key, and the office is seen as mainly a place for collaborative work. 23 fixed desks and 77 flexible desks at a desk: worker ratio of 3.1 to 1.

	Business as usual		Scenario 1: Tele-working workforce		Scenario 2: Mobile workforce	
	Quantity	Ratio	Quantity	Ratio	Quantity	Ratio
Permanent- desks	95	@ 1:1	40	@ 1:1	23	@ 1:1
Flexi- desks	5	@ 8.3:1	60	@ 2.5:1	77	@ 3.1:1
Total	100	@ 1.3:1	100	@ 1.9:1	100	@ 2.5:1

Table 7: Summary of office layout scenarios

The table holds a detailed overview of the number of workers at each type of desk.

Business as usual		Scenario 1: Tele-working workforce		Scenario 2: Mobile workforce	
Permanent - desk		**Permanent - desk**		**Permanent - desk**	
Onsite workers	57	Onsite workers	11	Onsite workers	11
Ad-hoc tele-workers	17	Ad-hoc tele-workers	28	Ad-hoc tele-workers	11
Regular tele-workers	8				
Mobile workers	14				
Subtotal	**95**	**Subtotal**	**40**	**Subtotal**	**23**
Flexi-desk		**Flexi-desk**		**Flexi-desk**	
Remote workers	18	Regular tele-workers	74	Regular tele-workers	53
Visitors	17	Mobile workers	30	Mobile workers	93
		Remote workers	18	Remote workers	18
		Visitors	32	Visitors	72
Subtotal	**35**	**Subtotal**	**153**	**Subtotal**	**236**
Total	131	**Total**	193	**Total**	259
Increase	0%	**Increase**	48%	**Increase**	98%

Table 8: Detailed overview of worker profiles for each scenario

7.4.1 Scenario 1: Business as normal

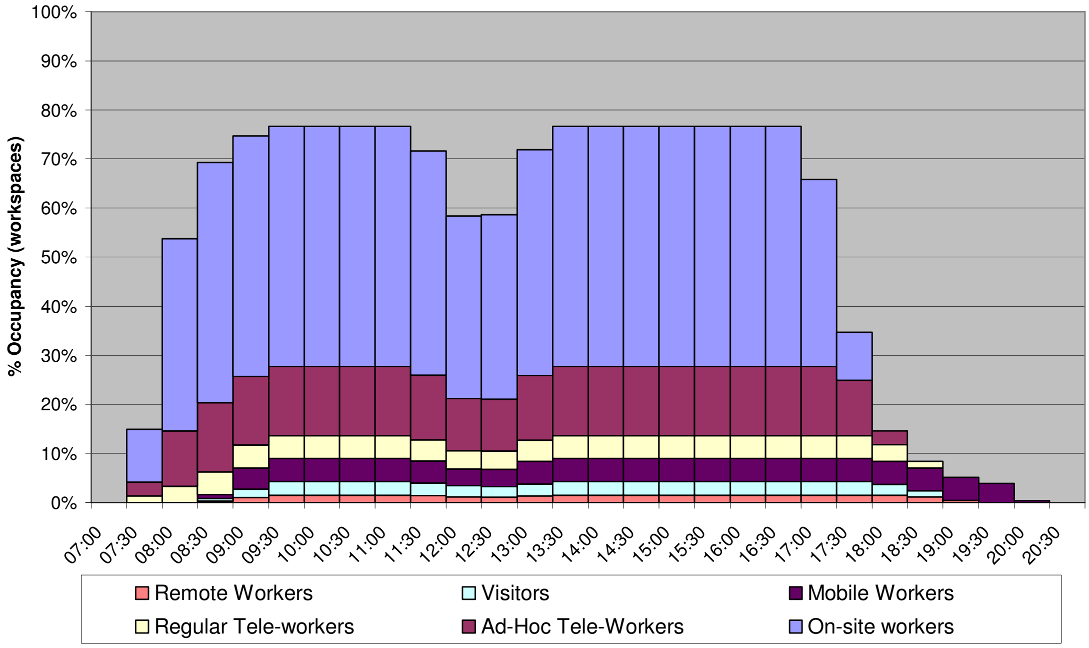


Figure 10: Business as Usual occupancy density

7.4.2 Scenario 2: Encouraged tele-working and shared workspaces

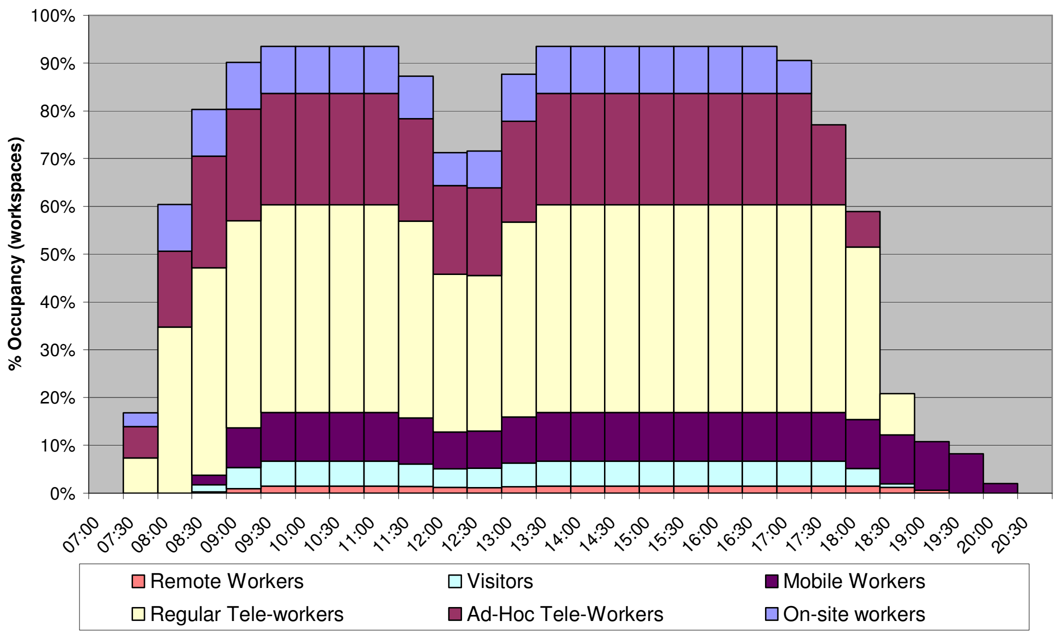


Figure 11: Encouraged teleworking and shared workspaces

7.4.3 Scenario 3: The future office and a mobile society

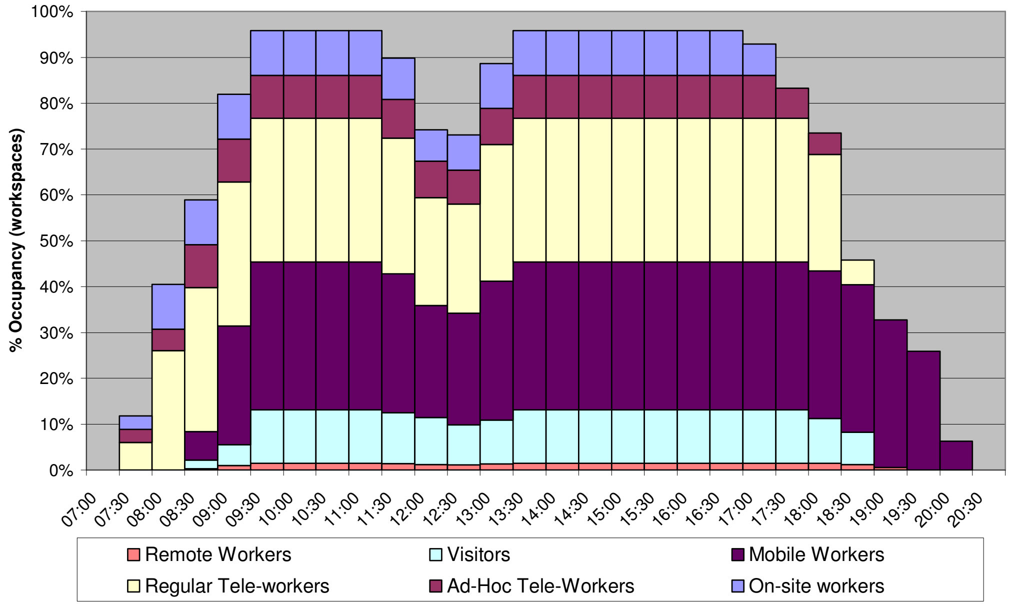


Figure 12: Future mobile society and shared workspaces

7.5 Analysis

Increasing the number of shared workspaces and encouraging more mobile and tele-workers is a very easy way to increase the building utilisation and achieve spaceless growth. The case studies show that it is not only possible, but is becoming a widespread practice amongst organisations around the world.

As seen in scenario 2; by encouraging more regular tele-working, which is only 3 days at home a fortnight, and using more shared workspaces – a 48% increase in building utilisation is possible.

In the future scenario, with 93 mobile workers – who all use the office only 2 days a week – a 98% increase in building occupancy is possible.

8 The Impact on IT in the Future Office

8.1 Overview

IT consumption in modern offices is often very large – accounting for 16% of the total electrical consumption. It can rise as high as 40% if there are dedicated computer rooms in the office [38]. This does not even take into account the impact on the cooling requirement; as all the electrical energy put into a computer ultimately convects and radiates into the space as heat.

There have been many studies on the energy consumption of office equipment, especially by the Lawrence Berkeley National Laboratory in the US [30, 31, 32, 33]. A summary of these studies can be seen in appendix 17.

8.2 Influence on energy-use

One of the biggest challenges lies with improving the energy efficiency of desktop computers. All the studies which have investigated actual power consumption, usage patterns and night-time switch-off rates in typical offices show that desktop PCs perform the poorest relative to all the other technologies.

In addition, 50- 60% of desktop computers were found to be left in a high power state over night, compared with only 20-30% of monitors and 25% of laptops. What accentuates this problem more is the fact that desktop computers use the most power; and whilst trends in laptops and monitors are showing that power is reducing with time, the opposite is true with PCs. They are certainly getting more efficient in how they use their power, but the continually growing hardware demands from applications overrides this positive influence.

Perhaps the biggest influence on the energy consumption of IT equipment is with managerial policy. In the Ernst & Young case study, it was clear that a policy of giving out laptops to 80% of staff– will eradicate all the challenges associated with improving the energy efficiency of PCs. Laptops are inherently low-power, and the trends are still towards reducing this; to maximise the battery life and hence mobility of the device.

8.3 Simulating office equipment energy use

The energy consumption of office equipment has been simulated for the three different scenarios as defined in the flexible workplace strategy.

- **Scenario 1:** "business as normal" – representing an office with poor building utilisation, with high power consumption and poor energy management
- **Scenario 2**: "flexible workforce" – representing a company that has adopted a shared workspace strategy, along with using more laptops
- **Scenario 3**: "Future workforce" – representing a future, far more mobile workforce. Power management is optimal and power levels are much lower. Most employees use low power notebooks

8.3.1 Summary of equipment density assumptions

In the studies on equipment density for typical offices, there seems to be little correlation between laptop use, suggesting that it is very dependent on the country and type of application of the office. The most conservative estimate is that 10% of all computers are laptops [37], and the most wild is 50% [21]. Other estimates are in between at 15% for the US and 42% for Japan [35]. A middle value of 25% was assumed. Richmann et al [21] have shown that laptop and desktop ownership depends on the role of the employee in the company, as seen in Figure 13 and Figure 14.

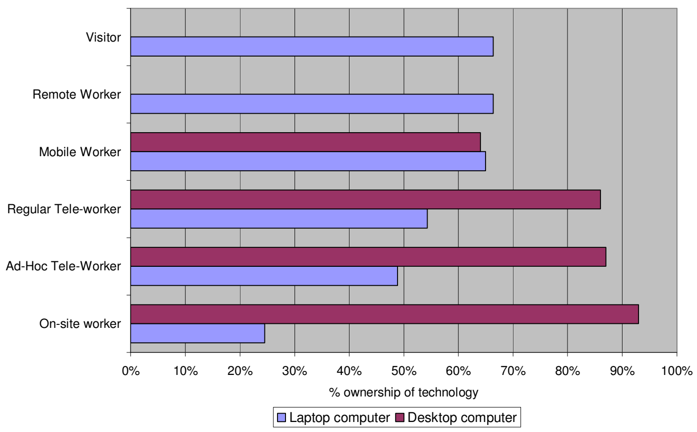


Figure 13: Scenario 1: Comparison of computer use between different workers

For the future scenario, it is assumed that 80% of employees have ownership of laptops [23] and do not require the use of a desktop computer.

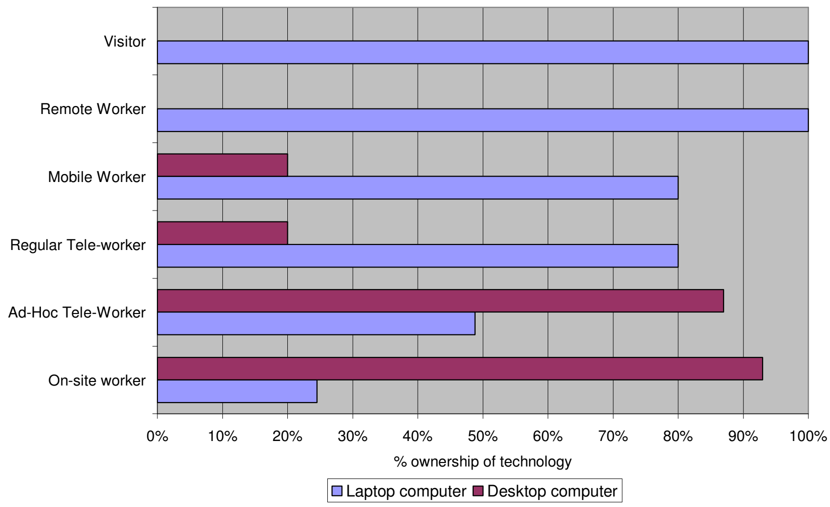


Figure 14: Scenario 2: Comparison of computer use between different workers

In scenario 1, auxiliary equipment density has been taken from the study by Kawamoto et al [35], where laser printers are shared by 6 employees and Fax, Scanner and Photocopier machines are shared by 16 employees on average. In 2nd scenario, as adopted in Ernst & Young, it is assumed that each machine is shared by 50 employees [23].

8.3.2 Power levels of office equipment

Power levels of equipment for the first two scenarios (current technology) and the third scenario (future technology) have been catalogued in the following table [30, 32and 37].

Scenario	Equipment Description	On (W)	Idle (W)	Off (W)
Current	**Laptop**	19	3	2
	Desktop	70	9	3
	CRT screen	63	2	1
	Printer	278	27	11
	Copier	1354	396	34
	Fax	30	15	15
	Scanner	150	15	0
Future	**Laptop**	15	3	2
	Desktop	60	9	3
	LCD screen	17	2	2
	Multifunctional machine	720	48	0

Table 9: Summary of Power Consumption of IT equipment

8.3.3 Power management of office equipment

The final aspect of simulating office equipment behaviour is looking into the typical power management of each device. It can be seen that desktop computers in the current scenarios are the worst performers – in which 55% of machines are left in high power state overnight. During the daytime they also are the worst performers –whilst laptops and screens often employ an efficient level of power management, very little is done in desktop computers [30, 33 34]. In the future scenario, it is assumed that power management in desktops has been improved and effective organisational policy has been implemented.

Scenario	Equipment Description	Daytime (10 hours)			Night time (remaining 14 hours)		
		High	Low	Off	High	Low	Off
Current	Laptop	55%	22%	23%	10%	0%	90%
	Desktop	77%	0%	23%	55%	3%	42%
	CRT screen	55%	22%	23%	30%	40%	30%
	Printer	7%	93%	0%	0%	100%	0%
	Copier	10%	90%	0%	0%	100%	0%
	Fax	2%	98%	0%	0%	100%	0%
	Scanner	2%	98%	0%	0%	100%	0%
Future	Laptop	55%	22%	23%	0%	0%	100%
	Desktop	55%	22%	23%	0%	0%	100%
	LCD screen	55%	22%	23%	0%	0%	100%
	Multifunctional machine	17%	83%	0%	0%	0%	100%

Table 10: Summary of power management in IT equipment

8.4 Comparison and Analysis

Given a workspace density of 15m²/workspace, the three different scenarios were compared.

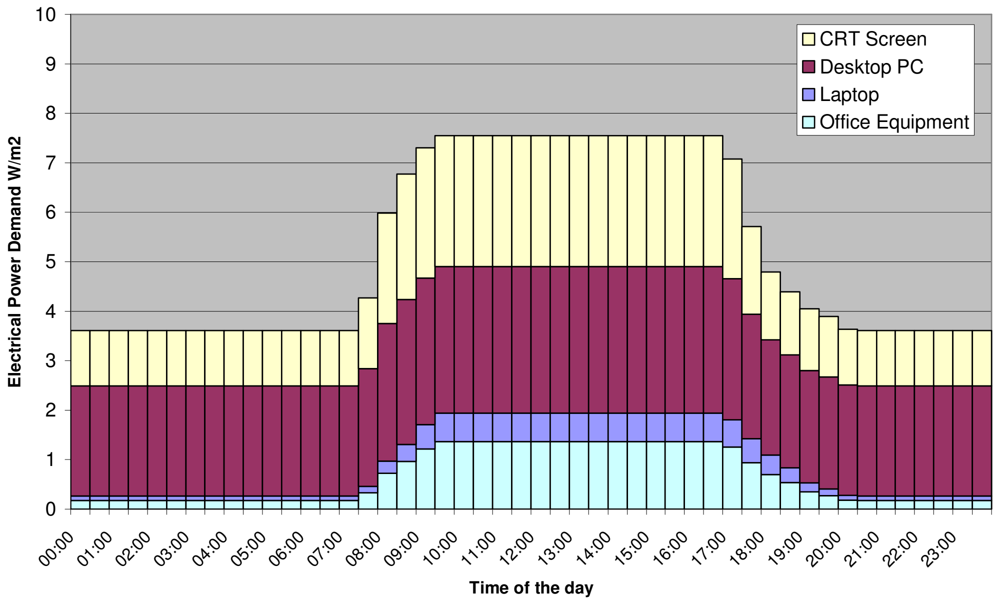


Figure 15: Business as normal scenario electrical IT demand

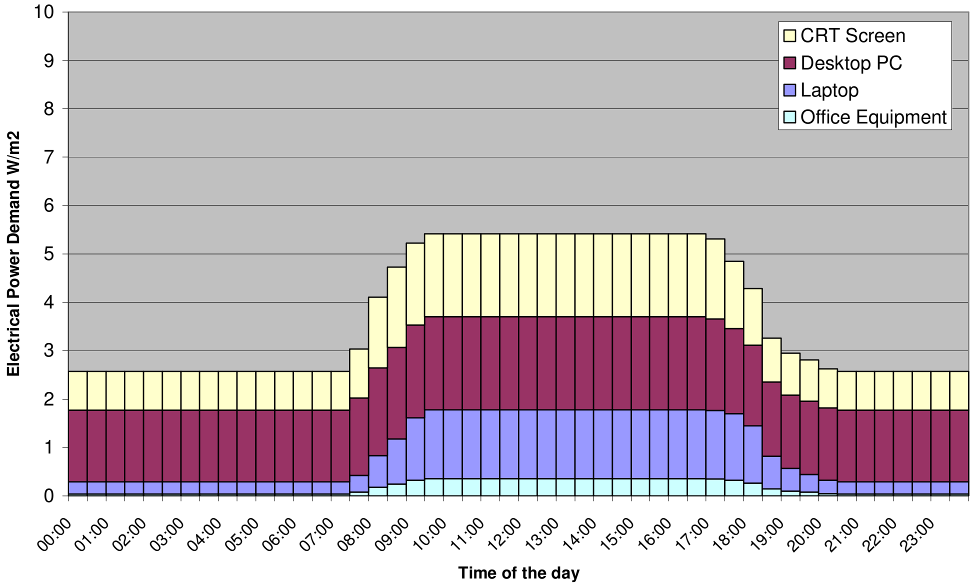


Figure 16: Flexible workforce scenario electrical IT demand

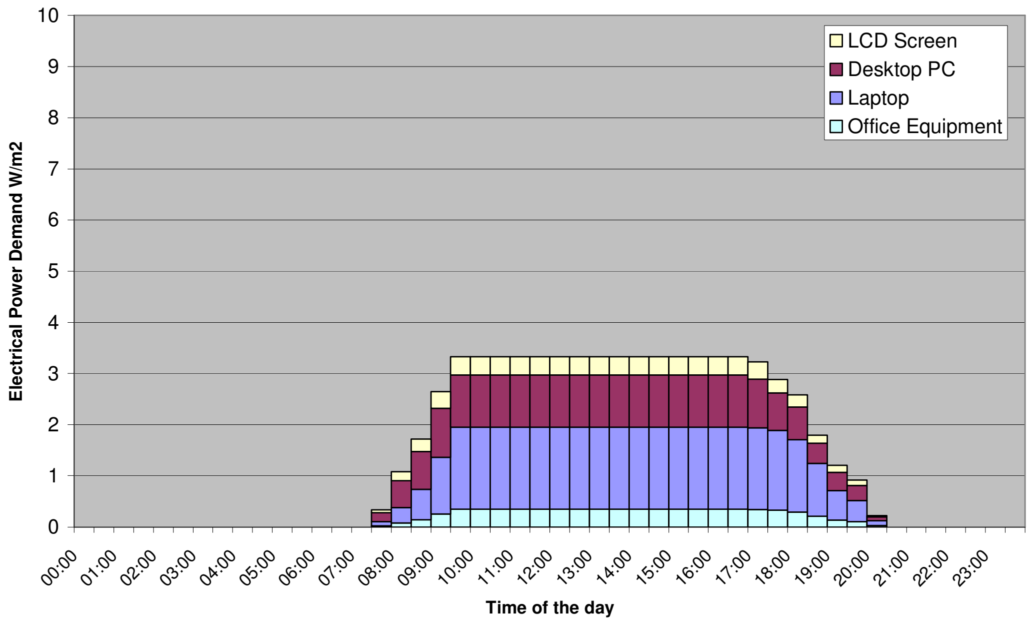


Figure 17: Future scenario electrical IT demand

A summary of the three scenarios is shown in the figure below. It is immediately apparent that the energy consumption of IT in the future can be dramatically less than it is currently. An 80% reduction is possible, even with the increased building utilisation. This accounts for saving 320tonnes of carbon a year, for a typical 6 floor office.

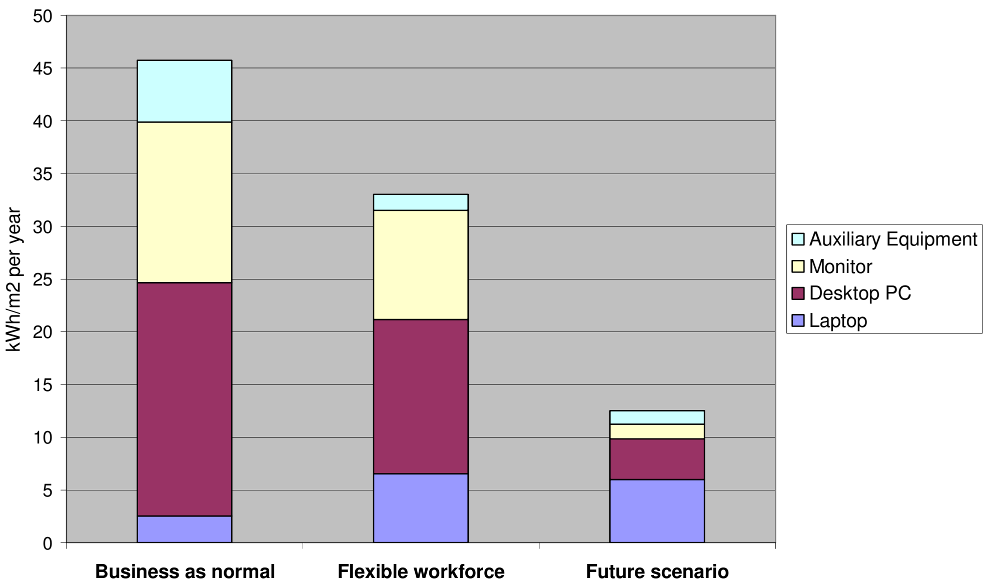


Figure 18: EUI comparison of IT scenarios

Perhaps a more consistent way to compare the performance of each office is to use show the energy consumption per employee rather than per m^2. This will show that the future scenario actually consumes much less energy whilst having double the employees.

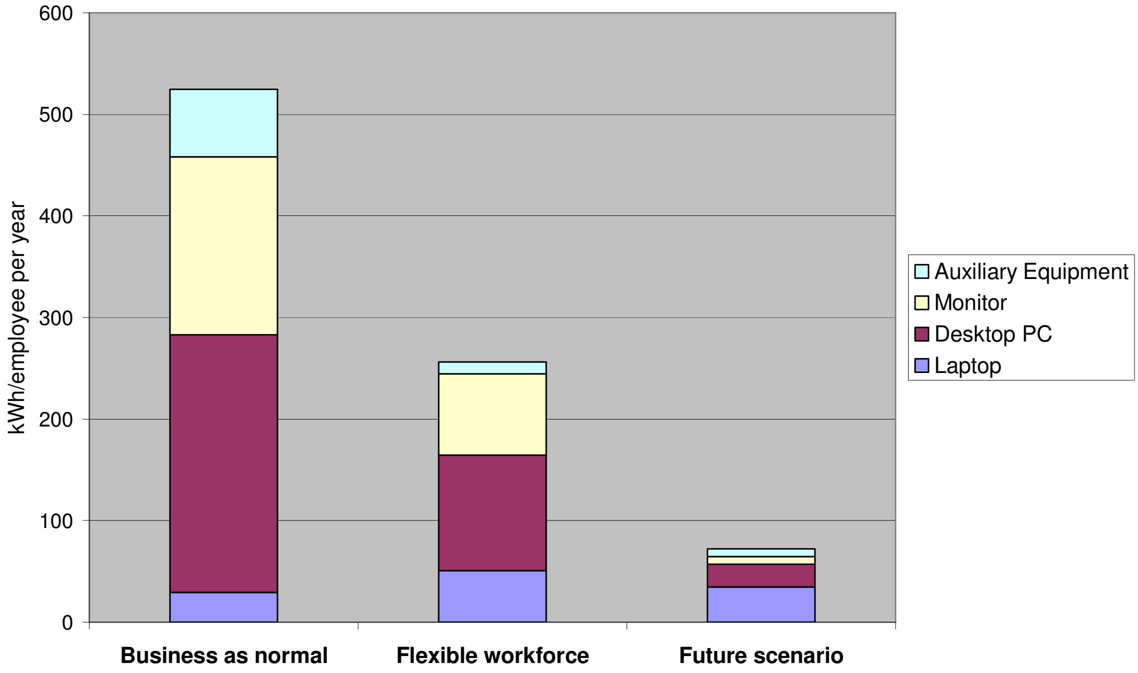


Figure 19: Employee Energy Use Index for IT

This underlines the importance of moving towards lower powered and more efficiently controlled computers and screens.

One of the biggest influences is night-time state of computers. Many studies have been undertaken on the subject, and there is a general consensus that most offices perform poorly.

To improve this requires a combination of improved power management and more effective behavioural policy. In the business as normal scenario – a typical onsite worker is in the office for 9.5hours a day, meaning that they are away for 14.5 hours. If they one of the 55% of workers who leave the computer in an active state when departing in the evening, this means that more energy is consumed when they are not actually present in the office.

9 Lighting in the Future Office

9.1 Overview

Electric lighting accounts for 24% of the electrical load of typical offices in the UK [38]. In large offices, even when effectively laid out, they are often inefficiently controlled and on average they are running for 85% of the working year. With careful consideration, this electric lighting load could be dramatically reduced, with:

- High efficacy LED lamps
- Effective use of daylight during the day through better controls
- Better practice standards of "out of hours" lighting for security/cleaning etc.

This section investigates what the lowest feasible level that lighting energy consumption could be reduced to in the future, and will compare this with current typical and good practice scenarios.

9.2 Daylight Design

Daylight design covers a wide range of subjects, and only an overview of the main topics will be presented here.

There are many different conditions of natural light conditions throughout the world and throughout the year. The UK, with its maritime climate, and northerly location, has much lower external illuminance, and more diffuse light – compared with a location at the equator.

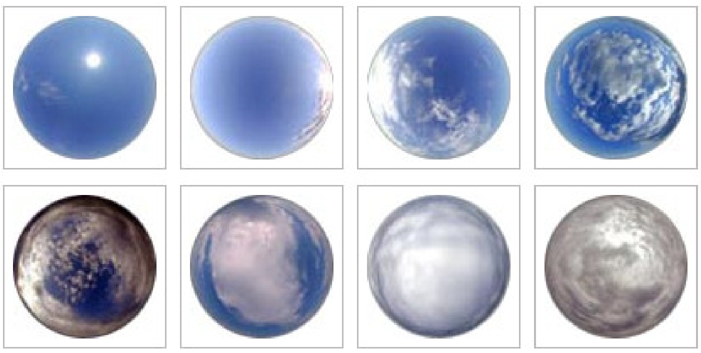


Figure 20: Examples of different sky types (from Sq1 research) [48]

Commission International de l'Eclairage (CIE) developed a number of standard sky types which are used as design constraints when investigating brightness levels and glare potential of a daylit room [49].The most common models are the CIE standard overcast sky, CIE uniform sky and CIE clear sky. BRE have also developed the UK Average Sky - one specifically suited for use in the UK [48].

The design sky is defined as the level of horizontal diffuse illuminance value that is exceeded 85% of time in the standard working day for a certain location. They are used as a worst-case scenario, in which the building will have better lighting conditions for 85% for the time. Seen the figure below; this 85% exceedance level for London falls at around 5500lux.

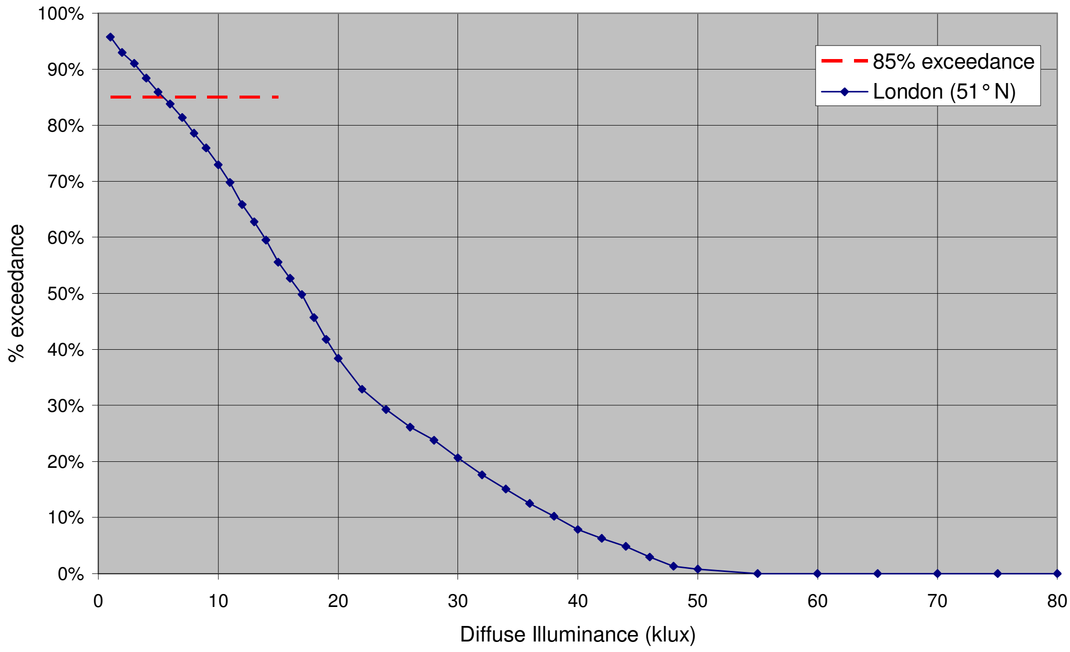


Figure 21: Design sky exceedance curve for London

The daylight luminance in the space is calculated using a concept known as daylight factor – which is simply understood as the fraction of the external horizontal diffuse illuminance that has entered the room. There are various ways of calculating this daylight factor and to varying levels of accuracy. The most realistic is with backwards ray-tracing software such as Radiance; and gives a physically accurate impression of all the lighting behaviour in the space. Whilst very powerful, it is not suitable for high-level and conceptual lighting energy studies as it requires many parameters for each "snapshot" in time [41]. Similarly, geometrical based daylight protractors are commonly used in industry to quickly find the daylight factor at a specific point in a room, but are not adaptable for dynamic simulations.

BRE and CIBSE instead developed some equations to find the average daylight factor in a room, as a function of some easily defined parameters [42, 43]:

$$DF = \frac{C_G A_G \theta O \tau}{A_{IS}\left(1-\rho^2\right)}$$ **Equation 1**

Where:

DF	=	daylight factor
C_G	=	Glazing obstruction coefficient *(0.9 for a vertical office window*) [43]
A_G	=	Area of glazing
θ	=	Angle of visible sky = *60° taking into account adjacent buildings*
O	=	Orientation factor *(0.97 to 1.55 depending on orientation)* [47]
τ	=	glazing transmission factor (*Clearfloat = 0.79)*
ρ	=	area weighted average reflectance of room surfaces *(0.5 average)* [39]
A_{IS}	=	Total internal surface area

This average daylight factor can be used in conjunction with the design sky, to find the average illuminance in the room which will be exceeded 85% of the time.

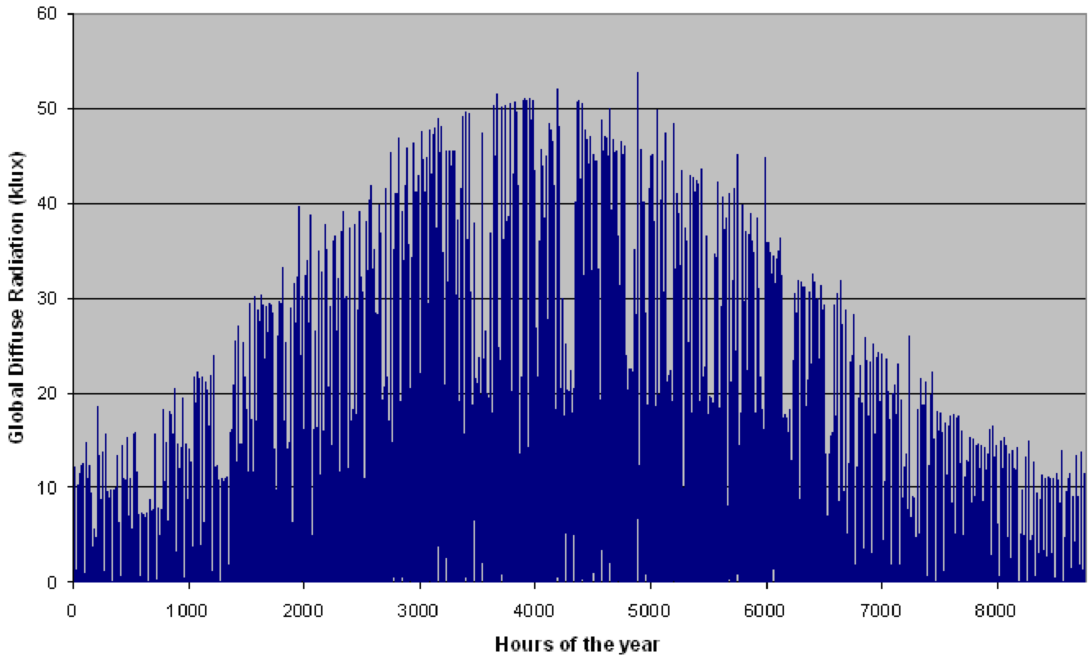
$$E_i = E_{Dei\,\mathrm{sgn}\,Sky} \times DF(\%)$$ **Equation 2**

Where E_i = internal illuminance, and $E_{DesignSky}$ = design sky illuminance (5500lux)

9.3 Procedure

9.3.1 Hour by hour average daylight factor analysis

To investigate the required electric lighting levels on a seasonal basis, Jenkins et al [39] improved on the design sky method by suggesting an approach which used the data on the average daylight illuminance for each month. A further improvement is possible by modelling the daylight illuminance available in the space for every hour of the year, by using the US department of Energy's directory of climate data [50]. This can allow for a more accurate prediction of the lighting demand over the full year and at any given time during the year. Whilst it is more accurate than the Jenkins approach, it does not lose any of the flexibility and ease of changing input conditions.



9.3.2 Control Strategies

A standard lamp set point of 500lux was used [42].

Operating modes:

- ON: When the daylight luminance contribution falls below 500lux, the artificial lighting is activated.
- OFF: When the daylight luminance contribution increases above 500lux, the artificial lighting is turned off.

Blinds: When more than 2000 lux (average) is received on the working plane, it is assumed that blinds would be activated to reduce the Visual Transmission of the glass from 0.7 to 0.2.

9.3.3 Electric Lighting Power Density

The total luminous flux required from the electric lighting for a room is calculated using the following equation:

$$\phi = \frac{E_i A_S}{UF \cdot MF} \qquad \textbf{Equation 3}$$

Where, A_S = surface area of the room

E_i = design working illuminance (500lux)

UF = Utilisation Factor, a measure of how much light from the source will land on the working plane. Standard value of 0.7 is used [39].
MF = Maintenance factor, depends on the age and condition of the lamp. A value of 0.9 is taken for an office place.

The total lighting power for the room is calculated using the following equation:

$$P = \frac{\phi}{BF\varepsilon} \quad \textbf{Equation 4}$$

Where, BF = Ballast factor *(a measure of efficiency of ballast: 0.9 is assumed)* [39]
ε = luminous efficacy of the lamp

The luminous efficacy of a lamp is the measure of how much light is produced relative to the power demand. The higher the efficacy, the less electrical energy and correspondingly less heat is produced for the same amount of brightness. For the three scenarios, the different lamp choices are shown:

	Typical [38]	**Best Practice [38]**	**Future [40]**
Lamp type	Fluorescent tube	High efficacy Fluorescent tube	LED
Efficacy (lumens/W)	45	70	150
Power Density	12	20	6
Assumptions	*UF = 0.7, MF = 0.9 and BF = 0.9 for each scenario.*		

9.3.4 Modelling Uncertainties

To accurately represent a real-life office environment extra elements of uncertainty had to be included. The three elements of uncertainty are:

- **Night-time lighting level**. For security, cleaners and irresponsible behaviour from staff [39,51]
- **Full-time lighting requirements** – auxiliary areas without windows, such as corridors, lifts and toilets.
- **Minimum daylight lighting level**. For areas with poor lighting during the day and different lighting level requirements for some workers [45].

9.3.5 <u>Sensitivity Analysis</u>

A sensitivity study was undertaken to look into the influence of these three elements of uncertainty. The first scenario (optimum) shows the annual electricity requirements when there is optimum control and no night-time lighting requirements. The second scenario (bad practice) attempts to show the impact of bad practice behaviour in the office – when the only half of the lights are dimmed during the day, and 30% of lights are left on at night. The analysis compares the impact of varying the glazing area from 0% to 100% for the two cases.

Optimum

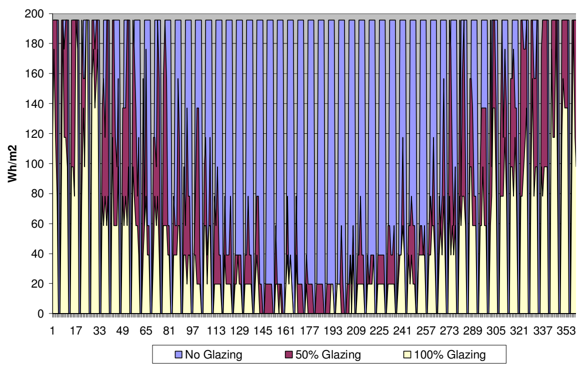


Figure 22: Optimum daily energy consumption

Bad Practice

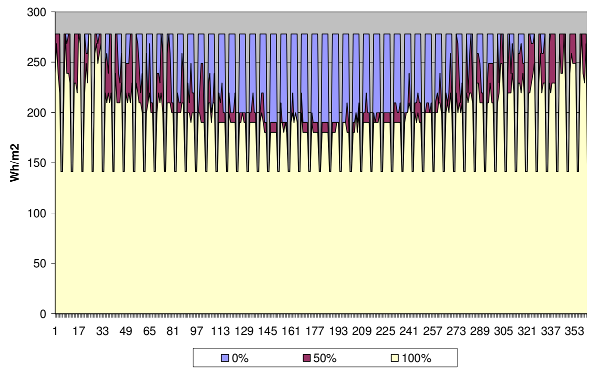


Figure 23: Bad Practice daily energy consumption

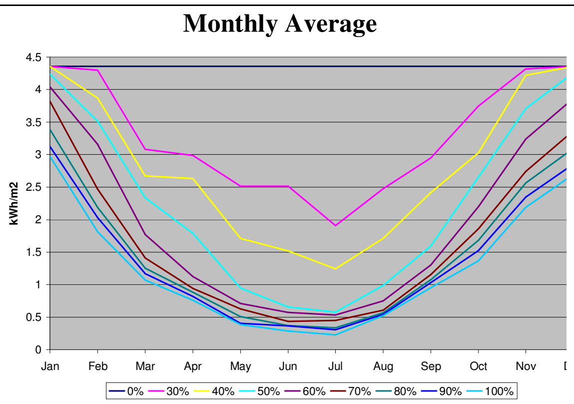


Figure 24: Theoretical monthly average

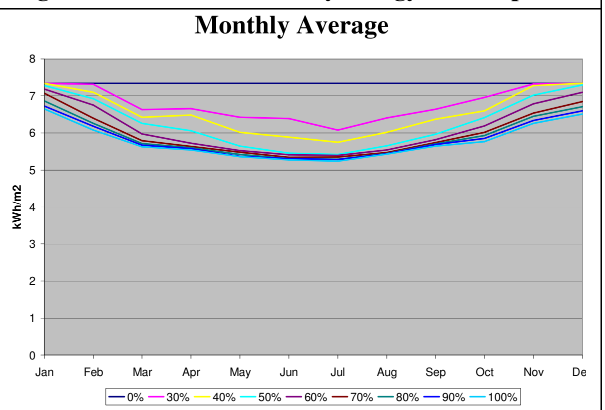


Figure 25: Bad Practice monthly average

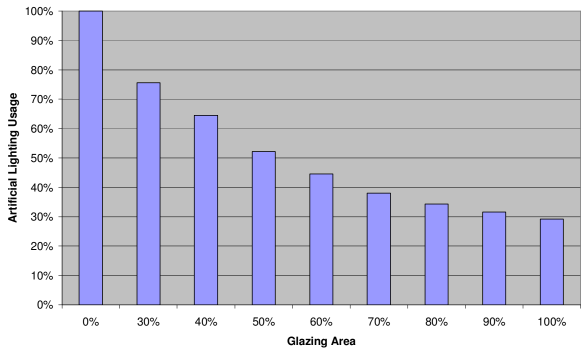


Figure 26: Theoretical % electric lighting

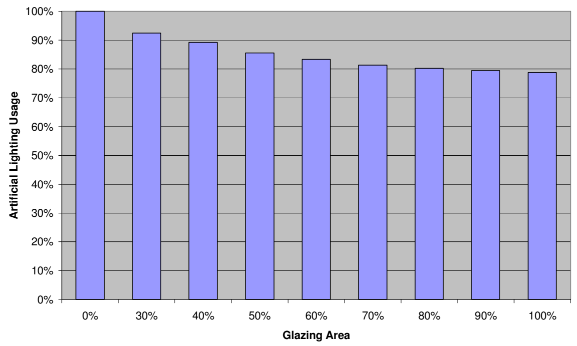


Figure 27: Bad Practice % electric lighting

In conclusion, the lighting level is very much dependent on the level of control and behaviour patterns by the employees. As expected, there is a strong correlation between glazing area and artificial lighting load when the perfect conditions are set. However, this relationship is weakened considerably – almost to the degree that glazing area does not make much difference in the overall energy consumption when bad practice effects are added.

Much research has looked into the optimal glazing area to maximise the use of natural daylight whilst not producing too much solar heat gain [52]. However, it is clear that whilst this can be optimised during the design stage; how the building is used has much more of an effect on the total energy requirements of the building.

Assumptions for % of total lighting use in the office for each scenario are shown in the table below:

	Typical	Good Practice	Future
Full-time lighting			
Lighting the auxiliary areas	10%	10%	10%
Bad Practice/poor light availability	20%	15%	10%
Security/cleaners/bad practice	20%	10%	5%
Total Occupied	30%	25%	20%
Total Unoccupied	30%	20%	15%

Table 11: Summary of lighting use assumptions

9.4 Results and Analysis

The electric lighting requirements were calculated for a room with the dimensions of 45m length by 15m depth, and a height of 2.7m (assuming 100% glazing on the façade to simulate a curtain wall).

	Typical	**Good Practice**	**Future Scenario**
Lamp	Fluorescent Tube	Fluorescent Tube	LED
Efficacy	45	70	150
Power Density	20W/m^2	12W/m^2	6W/m^2
Min Occupied usage	30%	25%	20%
Unoccupied usage	30%	20%	15%
Overall usage	76%	70%	60%
EUI kWh/m^2	66	34	13.5
(ECON-19EUI kWh/m^2)	*(60)*	*(29)*	

Table 12: Summary of results for each office scenario

The figures below show the average luminous flux of natural and electric light for a typical winter and summer day. In the summer condition, it can be seen that between the hours of 12 and 3pm, the blinds are activated to reduce the daylight contribution.

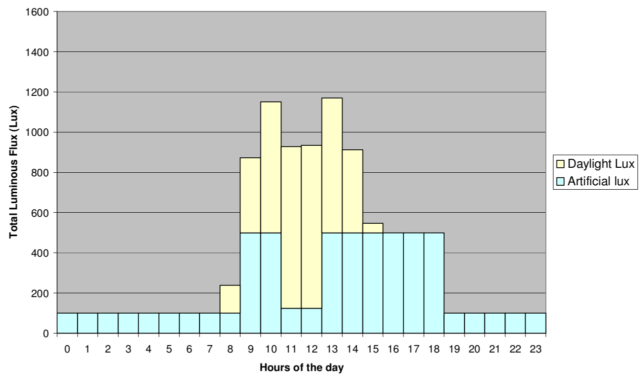


Figure 28: Winter illuminance daily profile

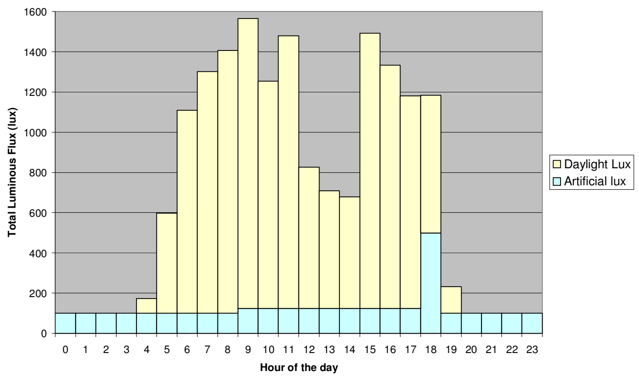


Figure 29: Summer illuminance daily profile

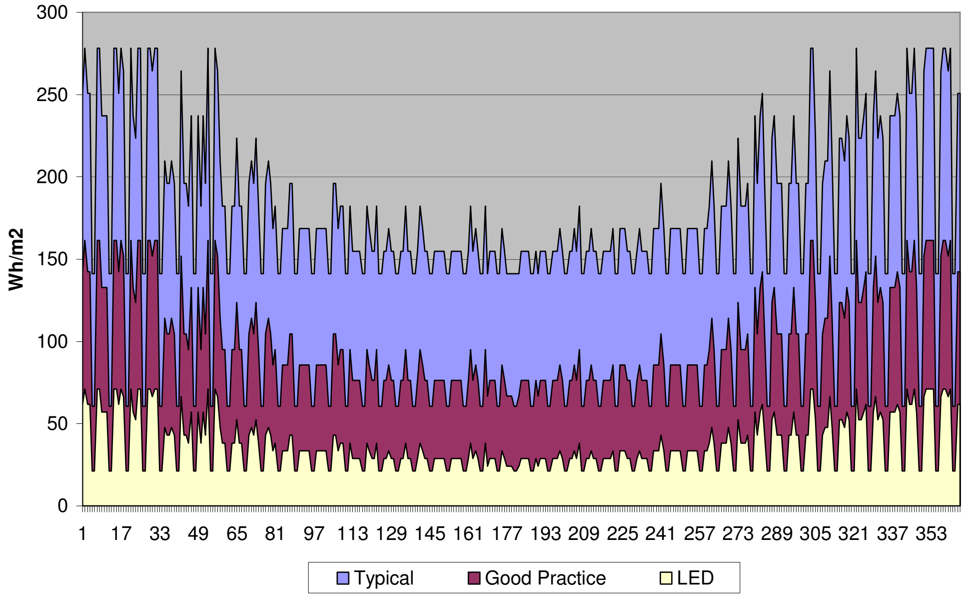


Figure 30: Comparison between typical and best practice daily lighting demand

It is clear that by installing LED lights, and with advanced controls then an overall 81% reduction can be achieved.

10 Modelling the HVAC requirements

10.1 Building a Speculative Office

10.1.1 Introduction

The heating, ventilation and air-conditioning (HVAC) demand is the largest source of energy use in the office environment [38]. The HVAC requirements of any building are dependent on a large number of variables, uncertainties and sensitivities:

1. Building aspect, dimensions and location
2. The construction quality of the fabric
3. The internal heat gains from occupants, lighting and equipment
4. The type and quality of the HVAC systems

Three different office scenarios were investigated. The scenarios are described as “Typical”, “Good Practice” and “Future”. The first two scenarios have been previously defined by Carbon Trust for energy management benchmarking processes [38].

10.1.2 Building aspect and dimensions

A number of parameters have been held constant in comparing the performance of the typical, good practice and future offices.

Building Dimensions

Office assumed to have a 45m x 45m floor area, with a 15m x 15m core in the centre.

It will be 6 floors (24.6m) tall to simulate a typical low-rise office building in a UK city.

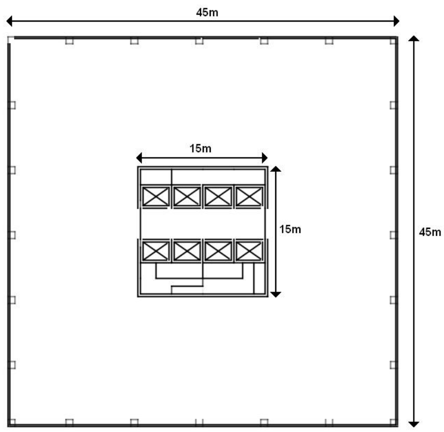


Figure 31: Plan of office floor

Floor to Floor Height

The floor to floor height is 2.7m.

Ceiling void depth is 1.4m.

The intended finished floor to ceiling height is recommended to be around 2.7m for an office environment. This allows a reasonable sense of openness for effective natural and artificial lighting [53].

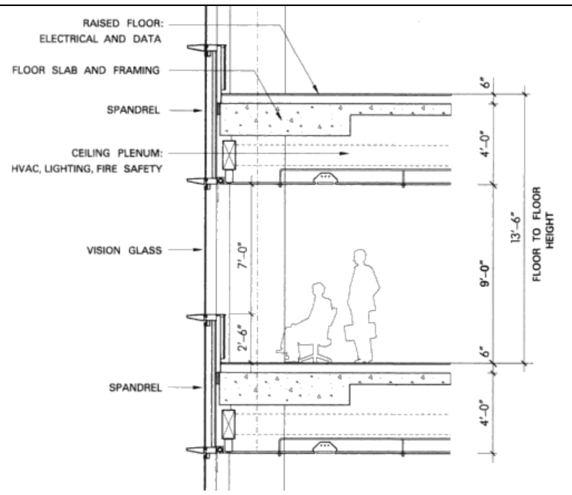


Figure 32: Office section (E. Kohn et al) [53]

Urban Environment

Assumed to be in a busy urban area, with buildings almost the same height on all four sides at a distance of 20m.

The surrounding buildings have strong implications on the amount of shading on the façade of the building.

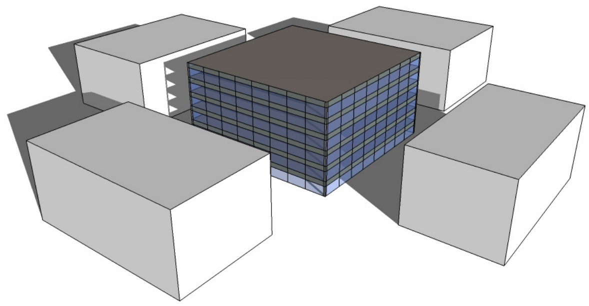


Figure 33: Perspective drawing of office

10.1.3 Fabric Construction

The building is assumed to have a curtain wall, of which 100% of the area is glazing. The glazing area has been fixed in this analysis – as it assumes that all the functional and aesthetic benefits of a curtain wall will mean it will still be desirable in the future [54]. Instead, the three office scenarios will have different qualities of glazing and shading.

Glazing Constructions			
	Typical	**Best Practice [55]**	**Future [56]**
Name	Standard	PPG Sungate 100 Clear	Solarscreen 2000 VEI-2M
Glazing	Double Glazed	Double Glazed	Triple Glazed
Enhancements	None	Argon filled, low-e coating, e = 0.2	Argon filled, low-e coatin, e = 0.05
U value (W/m^2K)	2.8	1.76	1.0
VT	0.79	0.73	0.7
SHGC	0.7	0.57	0.37

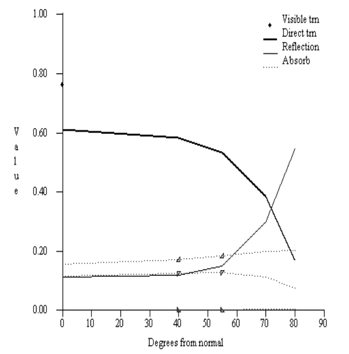
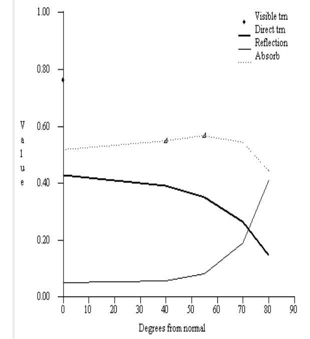
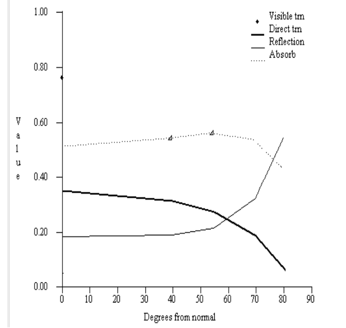
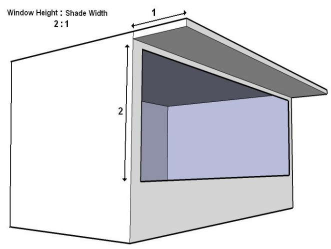
Performance Graph			
Shading	No	No	Yes, 2:1 (ratio is window height : shade length) 

Table 13: Summary of glazing assumptions

- The U value is a measure of how much heat is transferred through the material through conduction – which is preferable to keep to a minimum during winter months to minimise the heating load. The smaller the U-value, the better the material performs.
- A low-emissivity layer prevents heat loss through infrared radiation in winter months, when the outside surfaces are much colder than the internal surfaces.
- The Solar Heat Gain Coefficient (SHGC) is a measure of the proportion of direct solar beam that will enter the building – ideally kept to a minimum to reduce the summer cooling load.
- VT is the visual transmission, whilst not directly coupled with the heating gain, as high as VT as possible is desired to maximise the natural daylight and minimise electric lighting.

The other constructions of the building are assumed to be constant between the different scenarios. For completeness their details are listed below:

Other Constructions			
Surface	**Material**	**Thickness (mm)**	**U value (W/m^2K)**
Ground	Earth, Gravel, Heavy mix concrete, Air, Chipboard, Wilton	250 150 150 50 19 6	0.86
Room Ceiling	Gypsum plaster	13	4.98
Room floor	Wilton Chipboard Air Heavy mix concrete steel	6 19 50 140 4	1.50
Roof	Aluminium Air Glass fibre quilt Aluminium	3 25 80 3	0.427
Internal Wall (Core)	Heavy mix concrete Perlite plasterboard	150 12	1.73

Table 14: Constructions Summary

Infiltration is the measure of the leakiness of a building. Whilst the infiltration of the building varies throughout the year, depending on the temperature and wind speed and direction; for the purposes of modelling an average value was taken. The values for typical, best practice and future buildings were taken from "Turner et al [57]" – associated with the recommendations for leaky (1.1ac/h), above average (0.33ac/h) and tight (0.18ac/h) for the three respective buildings.

Infiltration			
	Typical	**Best Practice**	**Future**
Build quality	Leaky	Above average	Tight
Average infiltration rate [57]	1.1 ac/h	0.33ac/h	0.18ac/h

Table 15: Infiltration Summary

10.2 Modelling Procedure

10.2.1 Modelling using ESP-r

The transient energy simulation package ESP-r was used to model the heating and cooling requirements of the space. It is an open-source program and can be downloaded from the University of Strathclyde's Energy Systems Research Unit (ESRU) website [58]. ESP-r calculates the sensible and latent energy requirement to keep a space at a set temperature and humidity while it is being influenced by 8 interrelated parameters: lighting gain, IT equipment gain, occupancy gain, solar heat gain, infiltration losses, long-wave radiative losses, conductive and convective losses. The external influences can come from outside the building, or from an adjacent zone.

	Time	Heating setpoint	Cooling setpoint	Relative Humidity setpoint
Weekday occupied	7am to 8pm	21	23	50%
Night-time setback	8pm to 7am	18	26	40-60%
Weekend	All day	18	26	40-60%

Table 16: ESP-r zone temperature and humidity set-points

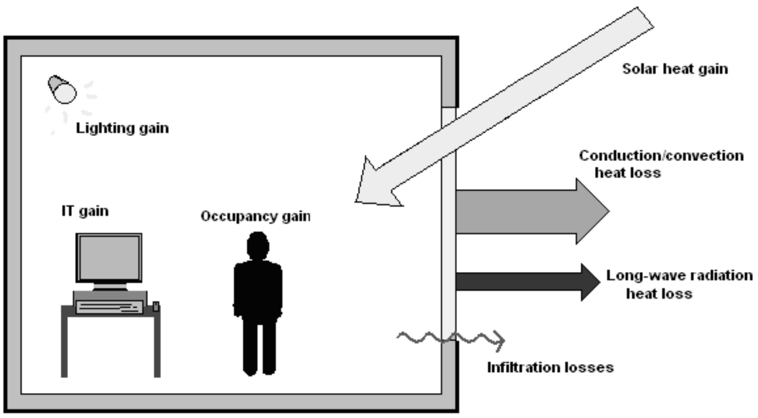


Figure 34: ESP-r heat flux balance in each zone

All of the parameters include a sensible heat component, and the occupancy and infiltration also have a latent heat component (affecting the relative humidity). The level of heat produced by a person varies from what type of activity they are undertaking: typical values in an office are 73W sensible and 59W latent heat [26].

10.2.2 Model Detail

A fundamental decision is the level of detail that the thermal simulation will represent. A comprehensive model of all the zones, surfaces and energy flows of the entire building will provide the most realistic conclusion; however it comes at a time and complexity penalty. At the conceptual stage, it is crucial to have a simpler and adaptable model that can efficiently model and test a wide range of design parameters.

A sensitivity analysis was carried out to compare the results from a comprehensive and a simple model. The ESP-r diagram of the comprehensive model (12 zones: 6 office spaces, 6 ceiling voids) and the simple model (2 zones: office space and ceiling void) are compared in Figure 35 and Figure 36 below. The adjacent zones in the simple model are assumed to be at a similar temperature.

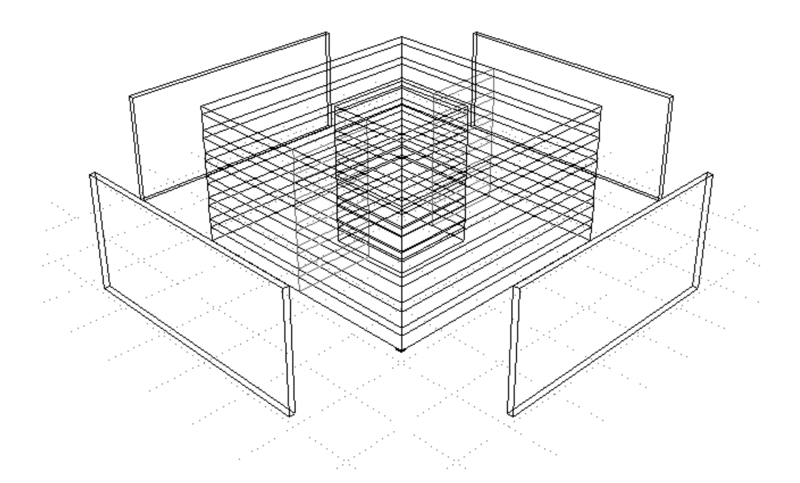


Figure 35 Comprehensive ESPr building model

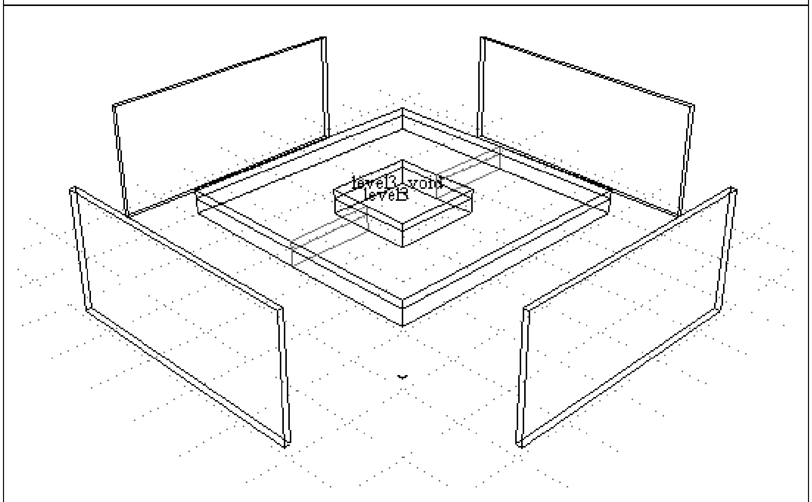


Figure 36: Simple ESPr building model

Climate data was sourced from the US department of Energy's online database [50]. Hourly data for a full year (1991) at Gatwick Airport in London was used for this analysis. The building parameters defined for a "typical" building in the previous sections were used.

The results show a correlation between the height of the zone and extent of the heating and cooling load. The bottom floor is connected to the ground which acts as a sink for heat and is also more shaded. The top floors are more exposed to the sun and therefore have a greater cooling load.

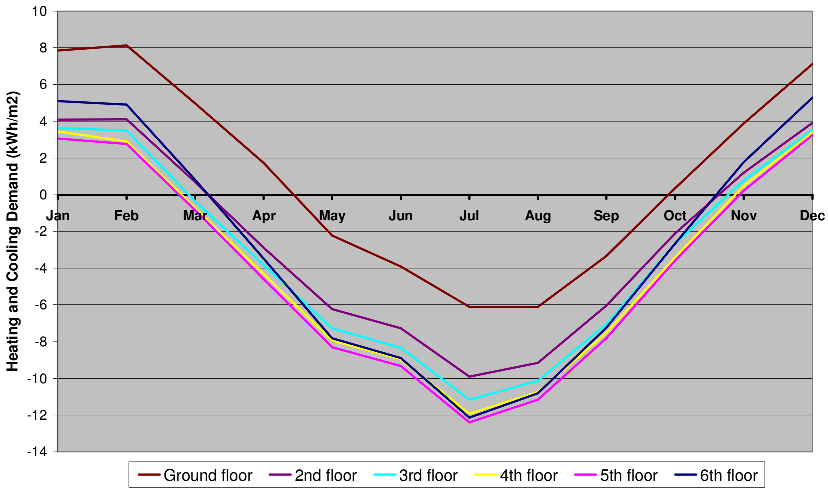


Figure 37: Monthly averaged heating and cooling loads of the building

As seen in the comparison between the two models in Figure 38; the impact from ground floor distorts the full building model in having an overall greater heating requirement and reduced cooling requirement. However, it is also very apparent that these values are very much dependent on the shading from adjacent buildings specific for each individual site.

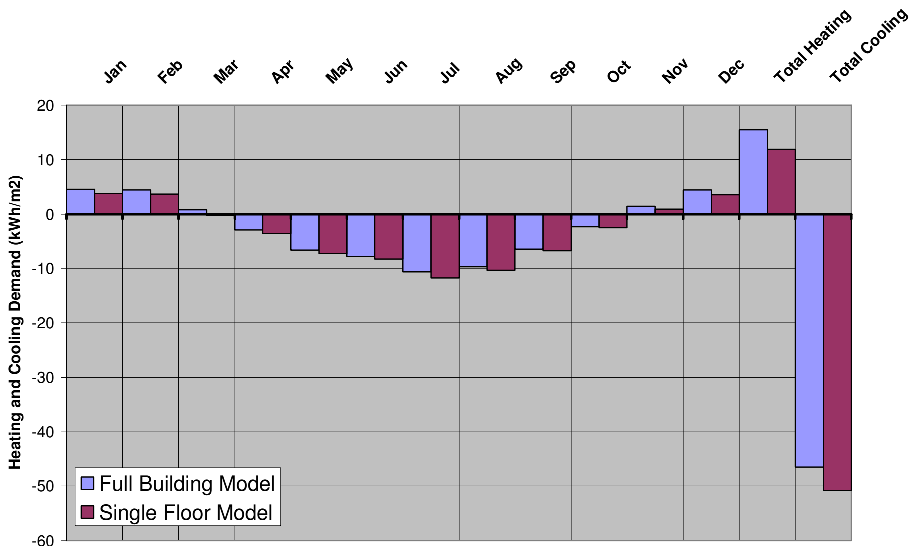


Figure 38: Verification of single floor model

10.3 HVAC system Design

HVAC system performance is not only dependent on the heating and cooling fluxes in the spaces but on the type of ventilation strategy, ambient air temperature, relative humidity (RH), zone supply temperature, zone exhaust temperature (which are not necessarily the same as room conditions) and the varying equipment efficiencies. Whilst ESP-r can be used to tackle all of these elements – it was decided that a hybrid approach of ESP-r and excel spreadsheets would provide greatest control over the calculations.

10.3.1 Overview

	Typical	**Good Practice**	**Future**
Ventilation System	Constant Air Volume (CAV)	Variable Air Volume (VAV)	Variable Air Volume (VAV)
Fan SFP (W/l/s)	2	2	1.5
Heat wheel	No	Yes	No
Hygroscopic wheel	No	No	Yes
Humidification	Dew-point wet coil	Ultrasonic	Ultrasonic
Boiler Type	Conventional	Condensing	Condensing
Maximum chiller COP	3 - 3.5	3 - 3.5	3 - 6

Table 17: HVAC systems overview

10.3.2 Ventilation Strategy

There are many different ways to ventilate a building, commonly divided into three categories – natural ventilation, mechanical ventilation and air-conditioning. Natural ventilation is mostly achieved in small scale office buildings as it is difficult to control. However, it is sometimes used as hybrid system in buildings such as 30 St Mary's Axe in London; where in viable wind conditions, air is drawn up inside the building and with the natural pressure differentials, naturally ventilates the office. In this way, natural ventilation can be achieved for 40% of the year [62]. Mechanical ventilation is the next level up, in which air is mechanically drawn around the building but is not actively treated before it enters the space.

Within air-conditioning, there are again many different possible strategies; most popular are Constant Air Volume (CAV) and Variable Air Volume (VAV), but other options include fan coil units, chilled beams and displacement ventilation [59]. CAV and VAV systems are often desired in large commercial buildings because they are centralised solutions, meaning all the plant can go in a centralised location, making it easier to design and maintain. It was assumed that the less expensive but less efficient CAV system is used in typical offices and the more efficient VAV system for good practice offices.

For a future office, it is difficult to choose one particular type of system as there is likely to be an ever wider range of options. In north-west Europe, the biggest argument is whether we need air-conditioning at all and if a cleverly designed "free-cooling" mechanical ventilation system will suffice [26]. However this dissertation is looking at solutions for a worldwide market; and only in Northern Europe, with its temperate maritime climate can a building not require cooling in the summer. In addition, the biggest argument countering the installation of air-conditioning is the problem it creates for the electricity grid during hot summer days. If in the future, chillers can be designed to be connected to solar panels on the roof – the peaks in chiller load will match exactly with peaks in PV supply [8]. In conclusion, a VAV air-conditioning system is assumed – a trade-off between the higher costs of systems such as displacement ventilation, whilst still maintaining high efficiency [59].

For both the CAV and VAV systems it is assumed that a fresh air unit (FAU) is connected to a recirculation unit (RU). In both systems the FAU only operates during the occupied hours of 7:30am to 6:30pm – delivering 10l/s/person [26]. See Figure 39.

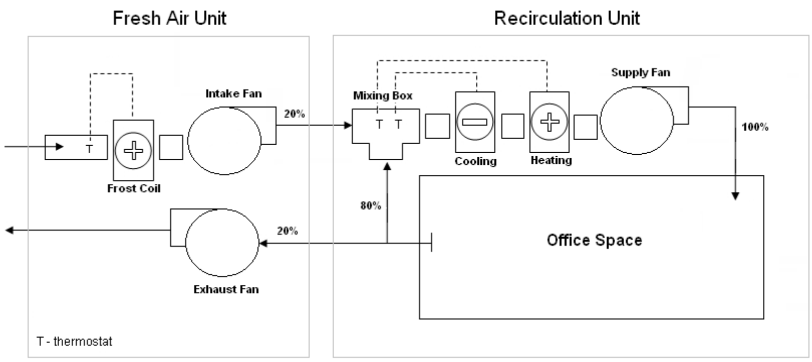


Figure 39: VAV and CAV system diagram

The operation of the RU varies between the CAV and VAV systems. In the CAV the air is recirculated at a constant rate regardless of the heating or cooling requirement in the space. The rate of the volume flow is set so the supply air temperature can vary between 10^{o}C and 30^{o}C [60]. During the night, at low demand the ventilation rate is set back to 30%.

When the VAV system is in cooling mode, the supply air is delivered at a constant 14°C and the volume flow rate is varied. In this way, the amount of fan power is reduced to only what is necessary to cool the space. In heating mode it operates the same as the CAV system; at a constant volume whilst increasing the temperature of the heating coil. In this respect, VAV systems are reported to work best when there is a year round cooling load [59]. Figure 40 shows the volume flowrate requirement a CAV and VAV system.

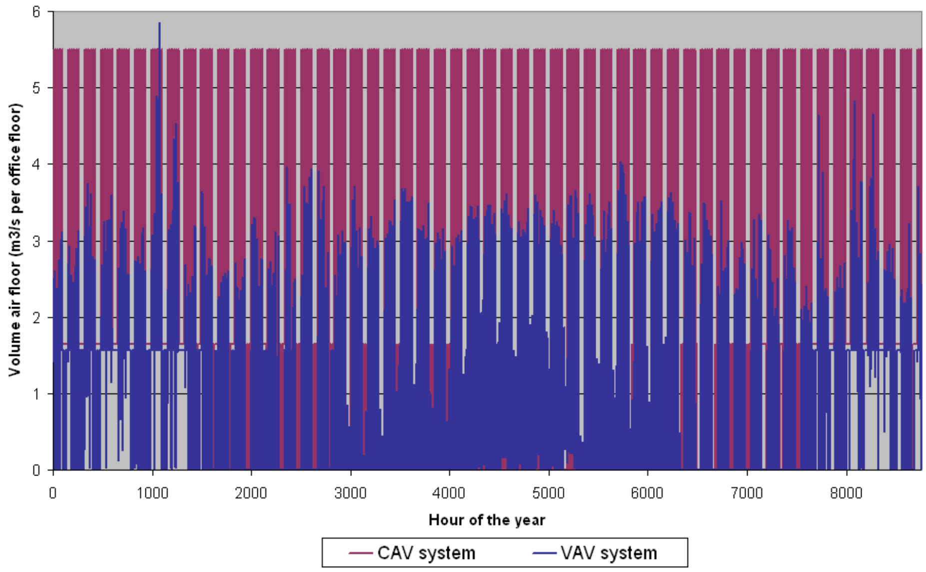


Figure 40: Volume flow rate for CAV and VAV systems

10.3.3 Fan Power

Specific fan power (SFP) is a function of the efficiency of the fan impeller and the static pressure against which it has to work. For this reason, the SFP is very much dependent on a particular HVAC unit design, length of duct and air-tightness of the zone so is therefore is difficult to predict for each office scenario [61]. The Carbon Trust has associated values of $3W/m^3/s$ and $2W/m^3/s$ for typical and best practice offices respectively [38]. For the future office, it is assumed that the design of the air-con unit will have been improved to lower the static head and hence a SFP of $1.5W/m^3/s$ could be possible. Figure 41 shows the daily energy requirement of the fans for each office scenario.

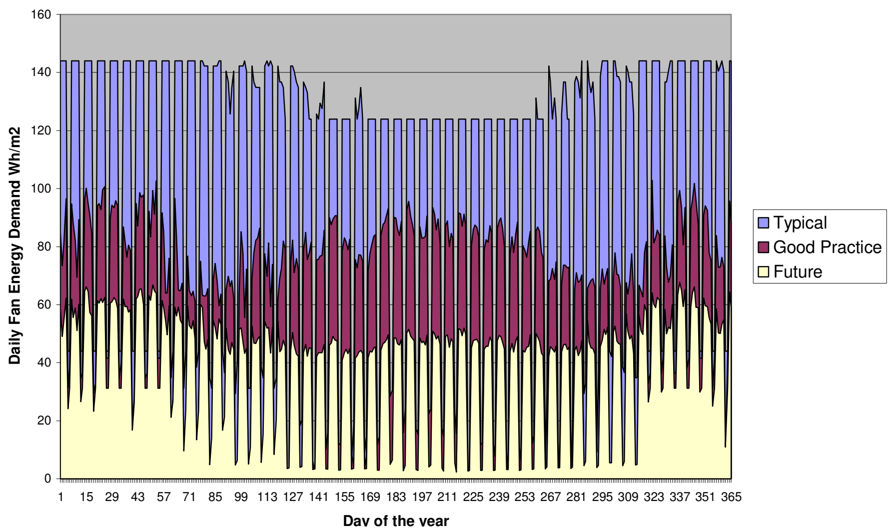


Figure 41: Fan energy requirement comparison between the different office scenarios

10.3.4 Heat Recovery

A good practice way to reduce the heat requirement in cold winter days is to recover the lost heat when the warm air is exhausted from the building. During occupied hours 20% of the ventilated air is removed from the building – and using the conventional system, all the associated heat in this air is lost too. The heat recovery wheel is an air-to-air heat exchanger transferring the heat from the hot exhaust air to the intake air at a small energy cost. The newly warmed fresh air component mixes with the rest of the exhaust air in the mixing box, reducing the amount of reheating required in the recirculation unit. The good practice office scenario has a heat recovery wheel installed in the fresh air unit, shown in Figure 42.

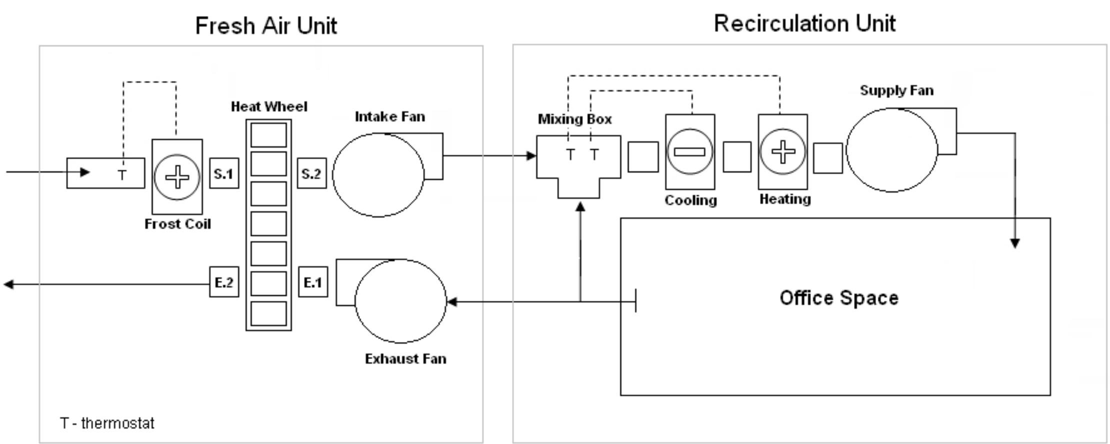


Figure 42: HVAC system with Heat recovery wheel in the Fresh Air Unit

The heat exchanger is assumed to have a good effectiveness of 80% [64]. Assuming the same volume flow in the intake and exhaust flows – the performance of the heat exchanger is given by the following equation:

$$\varepsilon = \frac{q}{q_{\max}} = \frac{(t_{S2} - t_{S1})}{(t_{E1} - t_{S1})}$$ **Equation 5**

Where, ε = effectiveness, q = actual heat transfer and q_{max} = maximum heat transfer

The future office is assumed to have a hygroscopic thermal wheel – which can transfer moisture as well as heat. This can reduce the humidification and dehumidification load to save even more energy. A hygroscopic wheel uses the concept of total effectiveness which takes into account both latent and sensible heat transfer [64].

$$q_T = m(h_{in} - h_{out})\varepsilon_T$$
$$q_S = mC_P(t_{in} - t_{out})\varepsilon_S$$ **Equation 6**

Where, $q_T = q_S + q_L$ = Total energy transfer (kW), m = mass flow (kg/s), Cp= specific heat = (1.00kJ/kg.K), t_{in} = dry bulb temperature entering exchanger (^oC), t_{out} = dry bulb temperature leaving exchanger (^oC), h_{in} = enthalpy of air entering exchanger (kJ/kg), h_{out} = enthalpy of air leaving exchanger (kJ/kg), ε_T = Total Effectiveness, ε_S = Sensible Effectiveness.

It is assumed that a total effectiveness of 70% will be possible in the future scenario.

10.3.5 Humidity control

To achieve the humidity setpoint of 50% relative humidity in the summer, the fresh air input will have to be dehumidified. This is achieved by cooling the air down past its dew-point temperature and forcing the moisture out of the air. This requires an in-depth controls analysis into the amount of air which will be cooled down at any given point, including an analysis of the contact ratio of the coils, airflow speed and coil temperature. As an approximation, the latent cooling as derived by ESP-r will be used and simply added on to the total cooling requirement to be met by the chiller.

In the same way, humidification can be achieved in a number of ways including dew-point wet coil, ultrasonic and steam injection. As a simplification, it is assumed that the latent heating as derived by ESP-r will approximate this additional heating requirement by the boiler.

10.3.6 Boiler Performance

Boiler performance is dependent on the part load conditions in which it is operating. The efficiency at different part load levels are taken from CIBSE guide B [60] for both conventional and condensing boilers. A further reduction of 20% is taken to account for pumps and other losses in the system.

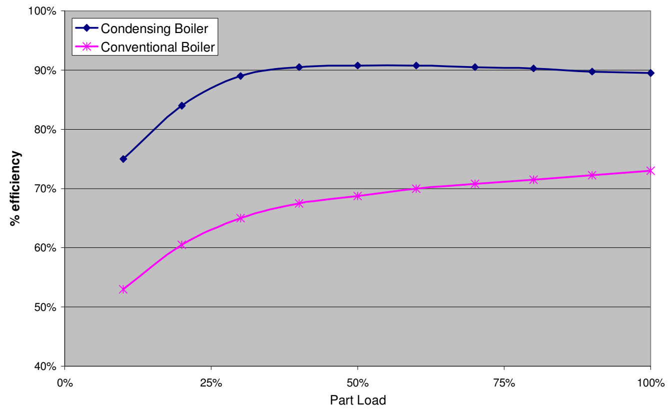


Figure 43: Boiler Part-load performance

10.3.7 Chiller Performance

The cooling performance is dependent on part load conditions of the chiller and also ambient temperature which affects the efficiency of the condenser. The coefficient of performance (COP) of a chiller with conventional condenser performance is shown in Figure 44 [63]. It can be seen that at higher ambient temperatures the less effective the condenser is at exhausting heat and hence gives a lower COP.

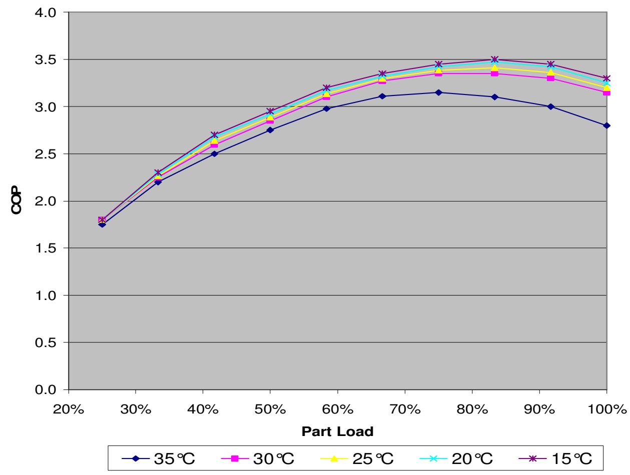


Figure 44: Conventional chiller system COP

A future scenario is shown in Figure 45, in which the chiller and condenser performance is maximised in all operating conditions [63]. At lower ambient temperatures, this has a big impact and the COP can increase to 7 at 70% part load; whilst at 35°C, there is little difference from the conventional system.

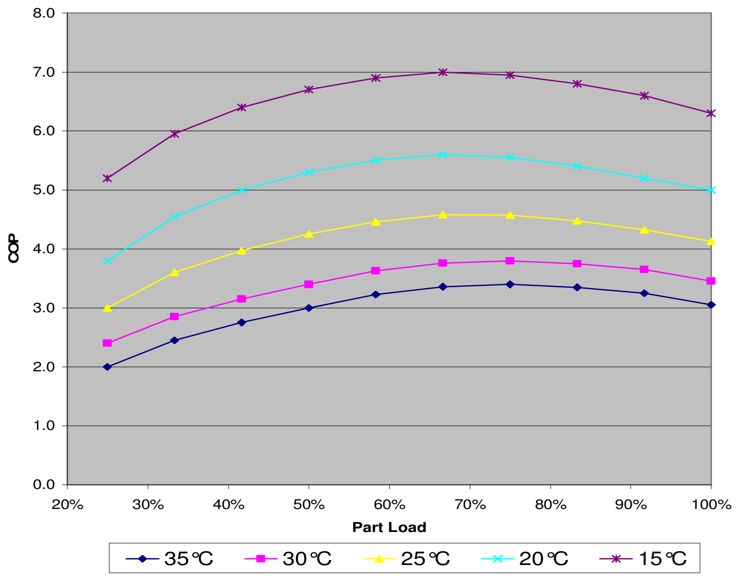


Figure 45: Future chiller system COP

Running through an annual simulation, a comparison between the levels of COP reached by different office scenario chillers is seen below:

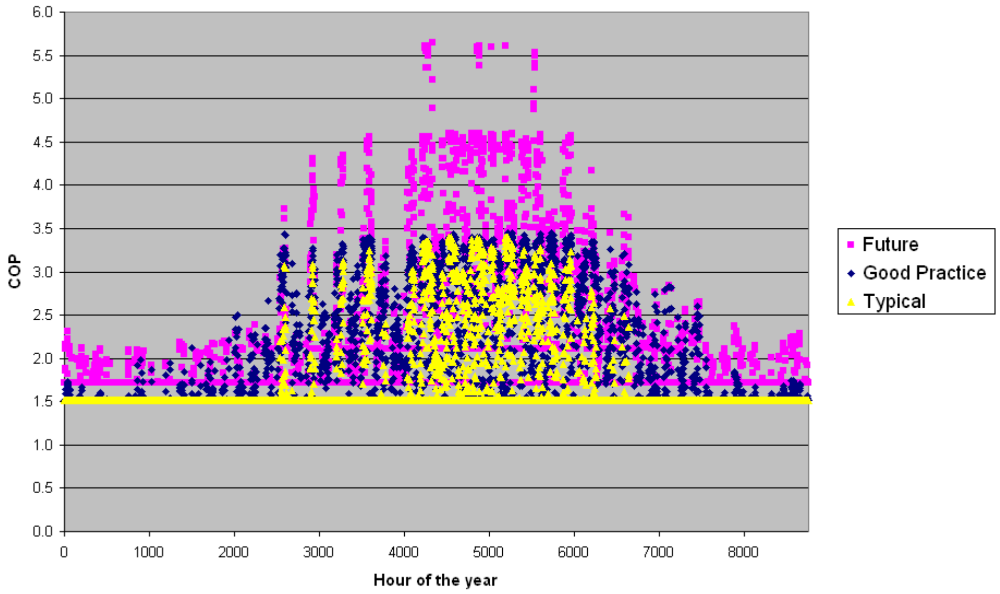


Figure 46: COP variation throughout the year for the different office scenarios

11 Total Energy End-use Review

11.1 Auxiliary Loads

11.1.1 Hot Water Energy Consumption

Hot water consumption values have been taken from the ECON-19 office benchmark data [38].

End-use	System type	Good Practice	Typical
Hand Washing	local electric	4 kWh/m^2	7 kWh/m^2
Hand Washing	central gas boiler	7 kWh/m^2	10 kWh/m^2
Hand Washing and catering kitchen	central gas boiler	12 kWh/m^2	20 kWh/m^2

Table 18: Hot Water Energy Consumption

11.1.2 Lift Energy Consumption

Lift energy consumption is reported to represent 5% of electrical consumption per year [66]. Using values extrapolated from a case study by Peters [65], values for typical and good practice in both high and low-rise buildings can be calculated.

	Daily		**EUI**	
	High-rise	Low-rise	High-rise	Low-rise
	kWh/day/building		kWh/m2/year	
Typical	745	112	5	4
Good Practice	459	69	3	2
Future	459	69	3	2

11.1.3 Catering

Catering has been ignored for this study.

11.2 Results and Analysis

An overall energy use index taking into account the 8 loads in the office are presented here.

11.2.1 Typical Office

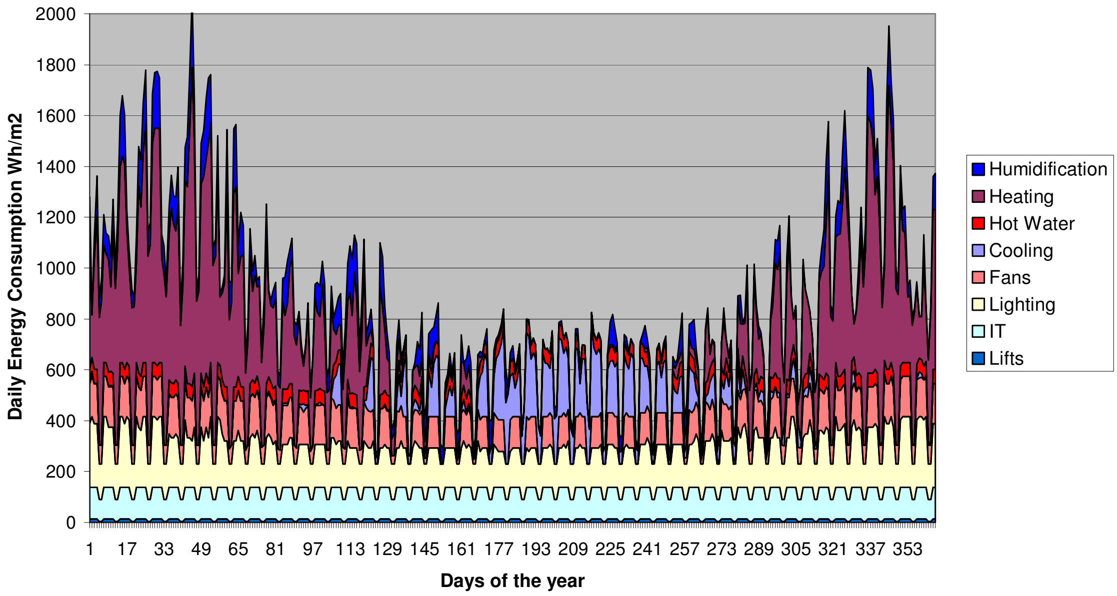


Figure 47: Typical office annual energy use

11.2.2 Good Practice

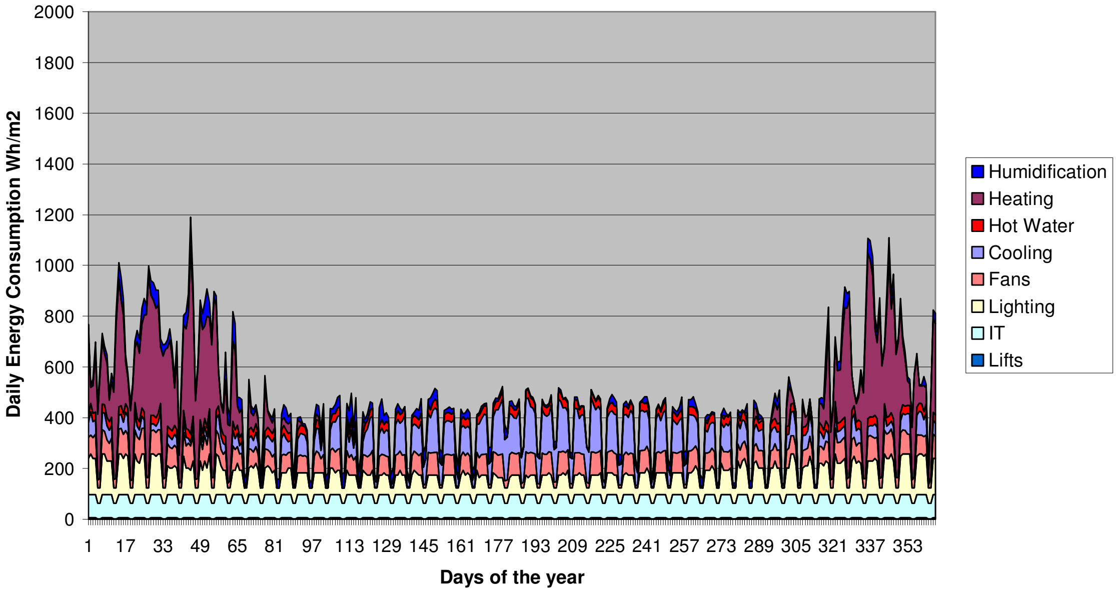


Figure 48: Good Practice annual energy use

11.2.3 Future

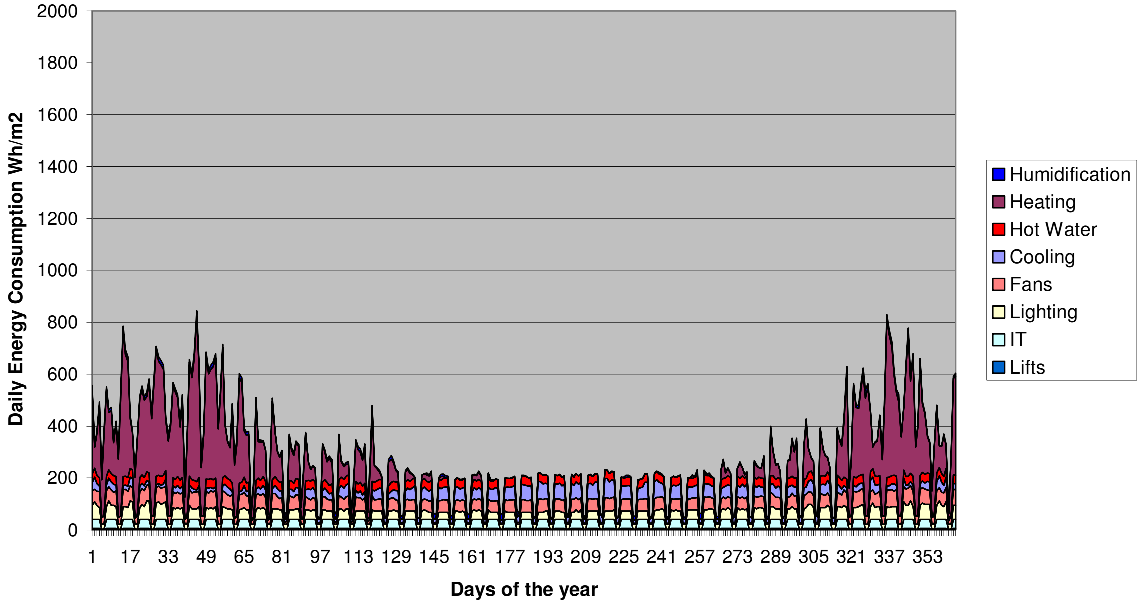


Figure: Future office annual energy use

11.2.4 Summary

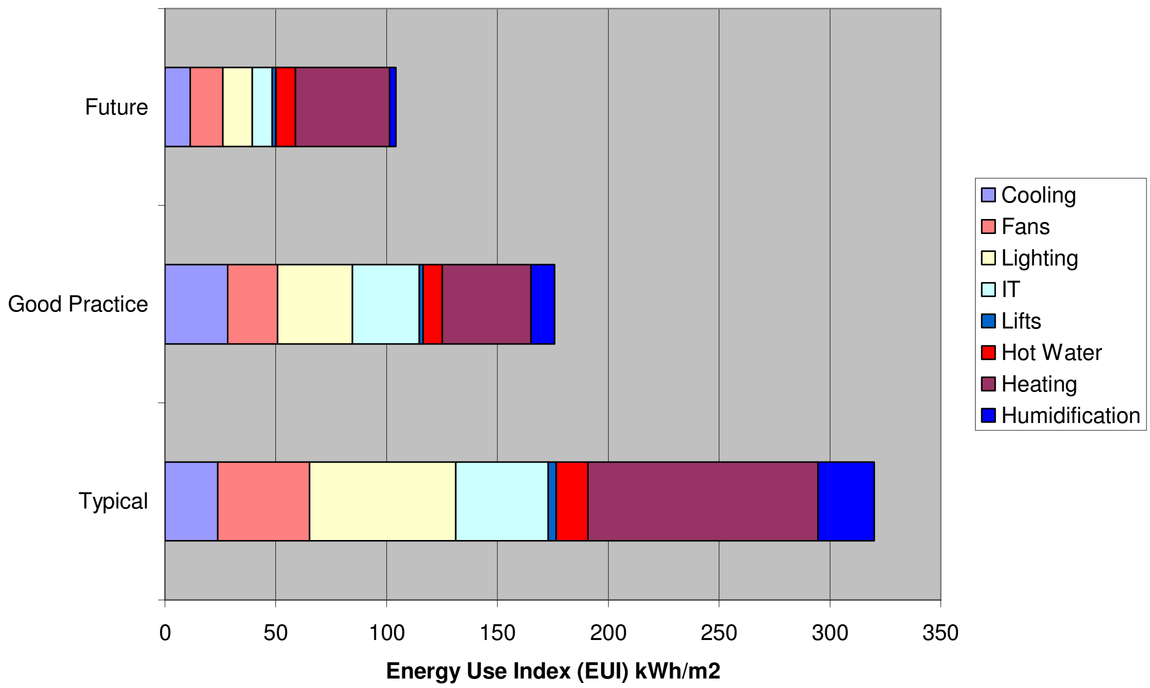


Figure 49: The three office scenarios annual energy use comparison

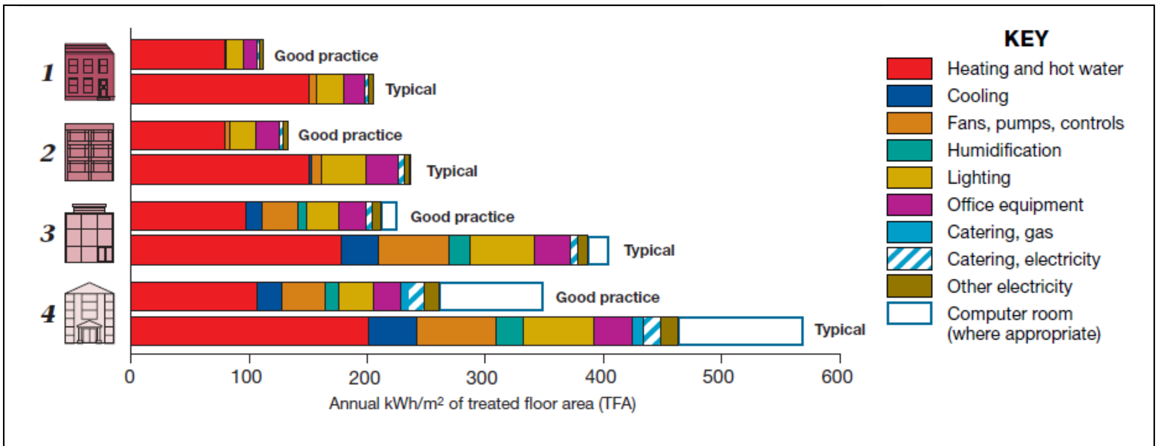
11.3 Summary

A future office could have a EUI reduction of 67% from current standard.

	Typical		Good Practice		Future	
	EUI (kWh/m^2)	CEI (kgC/m^2)	EUI (kWh/m^2)	CEI (kgC/m^2)	EUI (kWh/m^2)	CEI (kgC/m^2)
Cooling	24	13	28	16	11	6
Fans	41	23	23	13	15	8
Lighting	66	37	34	19	13	7
IT	42	23	30	17	9	5
Lifts	4	2	2	1	2	1
Hot Water	14	3	9	2	9	2
Heating	104	20	40	8	44	9
Humidification	26	5	11	2	3	1
Total	**320**	**127**	**176**	**77**	**105**	**38**
Reduction	**0%**	**0%**	**45%**	**39%**	**67%**	**70%**

11.4 Verification and discussion

The results of the study seem to correlate quite well to those from the carbon trust. In both the typical and best practice offices – the heating load is underestimated compared with the Carbon Trust values. This could be from added inefficiencies in perimeter heating systems and convection current losses.



Key: 1 = naturally ventilated cellular, 2 = naturally ventilated open-plan, 3 = air-conditioned standard and 4 = air-conditioned prestige

Figure 50: Carbon Trust Econ-19 office energy consumption benchmarks[38]

12 PV Resource

12.1 Overview

Solar energy is the most abundant source of energy in the world. To power the entire UK, only 1.7% of the country would need to be covered in photovoltaic cells [67]. This can be compared with figures of 12-15% for wind energy [76]. This is surprising, considering that the UK is renowned for its windy weather and not its sunshine.

Countries in the south of the EU, such as Spain could generate double the amount of PV electricity compared with the UK. See Figure 51 for a comparison between the maximum potential in different EU countries.

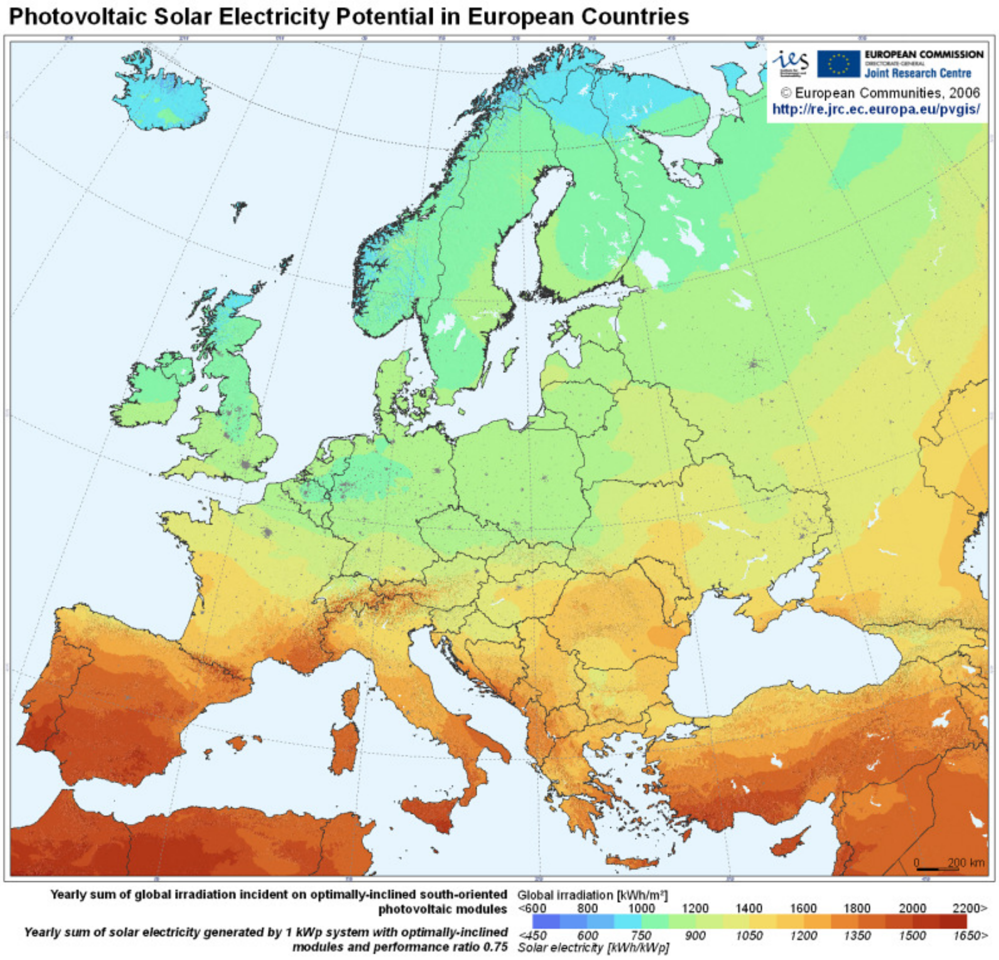


Figure 51: Photovoltaic Solar Electricity Potential in European Countries [67]

12.2 Photovoltaic Panels and Efficiency

PV panels traditionally convert sunlight into electricity by harnessing the effect that the photons have on bumping electrons across a doped silicon layer. When this can be achieved on a mass scale (hence the large flat surface) an electric current is formed [75]. To date this has occurred at a massive efficiency cost – and the best commercially available crystalline-Si cells only convert a maximum of 13% of the available solar radiation. The first assumption to challenge is that future PV technology will remain in the same condition.

In a paper analysing the policy of the R&D and deployment of PV, 18 experts in the field were asked their opinion on the cost and efficiency of the PV in the future [68]. As PV does not cover just one type of technology but a family of concepts, the first big question is: is there a clear favourite technology choice that we want to adopt? The answer was unanimously no, and that the current approach of designing a multitude of concepts, with no biases on the different maturity level of each technology is valuable to the progress of the industry.

Estimations of efficiencies for the year 2030 varied wildly even in within one PV type. The table below catalogues the key predictions from the paper; whilst mature technology such as Crystalline-silicon could only achieve a high best efficiency of 25% by 2030, "novel, high-efficiency" technology such as the hot carrier, plasmonics or thermophotovoltaic concepts could achieve a high-best efficiency of 45%.

Extremes in estimated efficiencies (2030)							
Technology*	Crystalline-Si	Thin film 2a+b	Thin film 2c+d	Thin film 2d+e+ composite	Concentrator	Excitonic	Novel, high-efficiency
high max. value (%)	30	35	29	30	65	25	52
high best estimate (%)	25	30	24	25	53	19	45
low best estimate (%)	14	10	10	13	25	7	14
low min. value (%)	13	7	8	9	20	3	8

Table 19: Summary of expected PV efficiencies in 2030 [68]

It is clear from this information it would be difficult to associate a single value of efficiency for PV technology available in 10 years time. However, PV efficiency was needed to be set to run the simulations, so a value of 20% was chosen. Falling between most high and low best estimates for 2030, it was deemed neither too conservative nor overly optimistic.

12.3 Geometry of Building and PV Panels

The amount of solar power generated by a building depends on three geometric considerations; how many of the surfaces of the building are covered in PV, how much of each surface is covered and what tilt angle the panel is at.

Solar radiation is made up of two components: direct and diffuse light. Direct beam comes directly from the sun, whilst diffuse radiation as the name suggests is diffused on something first – such as a cloud. Diffuse radiation is always present even if it is not noticed because of the larger presence of direct sunlight (except on overcast days when 100% of light it diffuse). Solar panels are normally never positioned on the north side of the building (in the northern hemisphere) as it would see very little or no sun all year round and would make little sense as an investment.

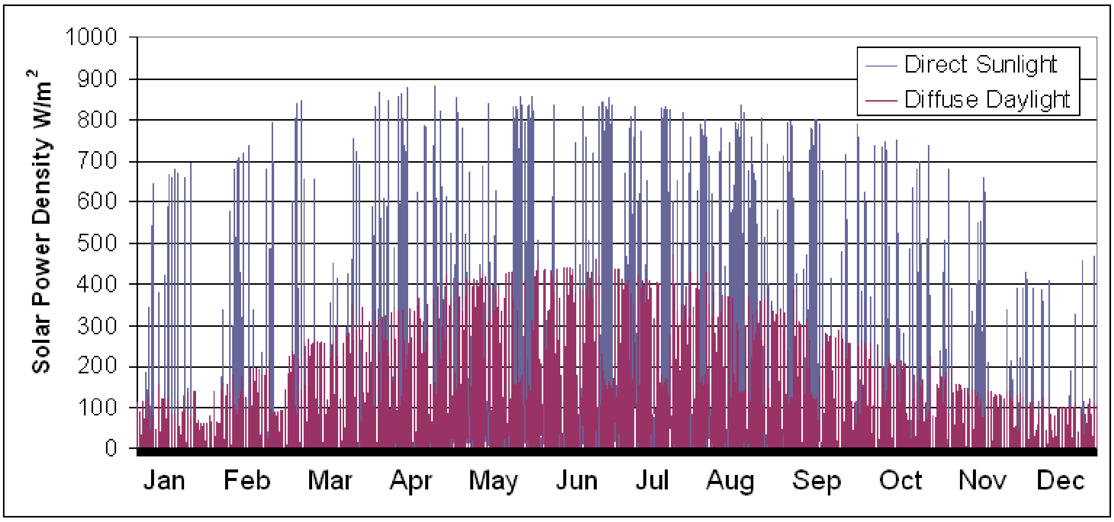


Figure 52: Direct and Diffuse solar radiation components for London

The angle that the PV panel makes with the sun is an important factor to how much energy can be delivered to the panel in a year. It has been assumed in this study that the façade panels are fixed vertically to the walls (South, West and East façades only). The complex relationship between PV tilt angle, and the shading effect on the winds (which effects lighting and cooling loads) requires further analysis outside the scope of this thesis.

The roof panels are assumed to be facing south and the tilt angle can be varied. This optimal tilt angle is a function of many different parameters including the latitude of the site (macro-climate effects), cloud cover patterns (micro-climate effects) and local shading effects.

The energy modelling software ESP-r created by the university of Strathclyde has an inbuilt function to calculate the PV energy generation of any surface. However, to calculate the optimum tilt angle meant that 10 different models would required for every location (ultimately 60 simulations in total). A more efficient approach was to model the interaction from the sun and panels from equations derived from first principles. An Excel spreadsheet was created where it was much more straightforward to manipulate the tilt angle and hence the maximum possible PV generation could be found for each location.

12.4 Optimum Tilt angle from first principles

Weather stations record the data on the average diffuse and direct beam components of solar radiation for every hour of the year and the US department of Energy has a directory of data files for locations all over the world [50].

The diffuse component is only dependent on the amount of sky that the panel can "see", and therefore is dependent only on the tilt angle of the panel. The direct component varies during the day depending on the angle that the direct beam makes on the panel – which is always changing depending on the time of day and year, the location and the orientation and tilt of the collector. Formulas for calculating the various solar angles are well defined and can be found in numerous sources [70, 71, 72, 73, 74]. Due to the large number of variables involved, there does not seem to be a consistent range of mathematical symbols between the different sources. To avoid confusion, a list of the mathematical symbols for each variable is listed in the table below:

Altitude	β
Solar azimuth angle	γ_s
Incident angle	θ
The surface azimuth angle	γ
The surface solar azimuth angle	α
The tilt angle (measured from horizontal)	Φ
Declination	δ
Hour Angle	**h**
Latitude	ζ
Masking angle	ψ

Table 20: Symbols used in solar angle calculations

12.4.1 Modelling the Sun

The path of the sun can be tracked using only the angles of altitude and azimuth.

Solar Altitude, $\beta = \sin^{-1}(\cos\zeta \cos(h)\cos\delta + \sin\zeta \sin\delta)$ **Equation 7**

Solar azimuth, $\gamma_s = \cos^{-1}\left(\frac{\sin\zeta \cos(h)\cos\delta - \cos\zeta \sin\delta}{\cos\beta}\right)$ **Equation 8**

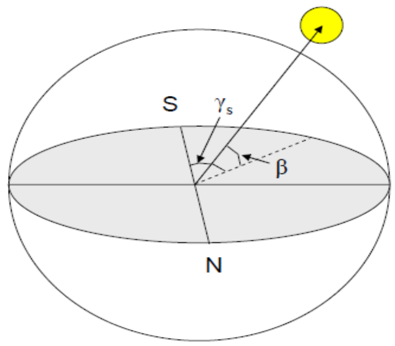


Figure 53: Explanation of solar azimuth and elevation [75]

These two solar angles are dependent on three factors (δ, *h* and *l*) which are specific to each location and time on earth.

- **Declination: (δ)** the variability of the seasonal angle from the 23.5° declination angle from the earth/sun normal orbit.

$\delta = \delta_0 \times \sin\left(\frac{360 \times (284+n)}{365}\right)$, ***where*** δ_o ***=23.5°*** ***and n = day of the year*** **Equation 9**

- **Hour Angle: (*h*)** converts the sun path "time" into angular notation. Dependent on the real solar time: which differs from the unadjusted reference time around the world, by taking into account extra correction factors which characterise the earth's annual revolution patterns.

Where $h = 15(12 - t_{sol})$ [am] and $h = 15(t_{sol} - 12)$ [pm] **Equation 10**

And $t_{sol} = t_{ref} + \left[\frac{4(L_{ref} - L) + E}{60}\right]$ **Equation 11**

Where L = longitude of site (London = -0.18°), L_{ref}*=Longitudinal reference (UK is 0°)*

And $E = 9.87\sin(2\beta) - 7.35\cos\beta - 1.5\sin\beta$ *and* $B = \frac{360(n-81)}{364}$ **Equation 12**

- **Latitude: (ζ)** the distance the site is from the equator: London is 51.51° N.

12.4.2 Direct Radiation on Horizontal and Vertical Surfaces

The component of the measured direct beam falling on a horizontal surface is:

$I_{bH} = I_b \sin\beta$ **Equation 13**

The component of the measured direct beam falling on a vertical surface is:

$I_{bV} = I_b \cos\beta \cos\alpha$ **Equation 14**

α = *wall solar azimuth (which is adjusted to take into account the orientation of the wall relative to south;* $\alpha = \gamma - \gamma_s$. *As the wall is south facing*, $\gamma=0$ *and* $\alpha = -\gamma s$ (*-solar azimuth angle))*

12.4.3 Direct Radiation on Tilted Panels

The direct component received by a tilted panel is calculated by combining the horizontal and vertical vectors shown in equations 1 and 2.

$$I_{b\Phi} = I_b(\cos\beta\cos\alpha\sin\Phi + \sin\beta\cos\Phi)$$ **Equation 15**

Φ= *tilt angle, measured from horizontal.*

Where $I_{b\Phi} \geq 0$ for non-negative values of both expressions in the parenthesis, otherwise $I_{b\Phi}$= 0.

12.4.4 Diffuse Radiation

The diffuse radiation is calculated as a fraction of the hemisphere the panel can "see". A flat panel without any obstruction will see the entire amount as recorded in the weather file. As the plate is tilted, the fraction seen is decreased, as shown in the diagram below.

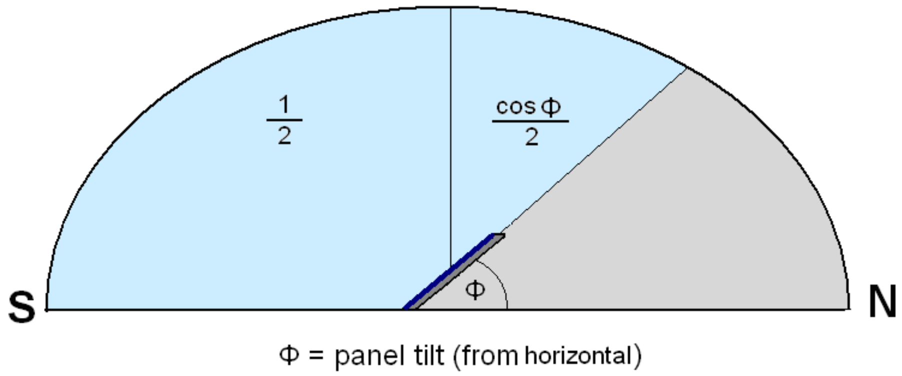


Figure 54: North-south section explaining diffuse radiation on tilted panels

Diffuse radiation on a tilted panel on the roof:

$$I_{d\Phi} = I_{dh}\left(\frac{1+\cos\Phi}{2}\right)$$ **Equation 16**

A panel placed vertically on the wall will only "see" half of the hemisphere, so this equation is simplified to:

$$I_{d\Phi} = I_{dh}\left(\frac{1}{2}\right)$$ **Equation 17**

12.5 Optimum tilt for panels with local shading

The equations for the direct and diffuse components are only valid if there is only one PV panel per surface. In reality, the PV panels will likely be organised in rows, in which by increasing the tilt of each panel increases the shading on the adjacent panel. This will reduce the effectiveness of the panels at greater tilt angles, and produce a more realistic maximum PV resource for each surface. As seen in the figure below, the rooftop shading is most evident at low sun angles – early morning or evening. As discussed before, the wall based panels are assumed to be fixed vertically to the wall and are not included in this analysis.

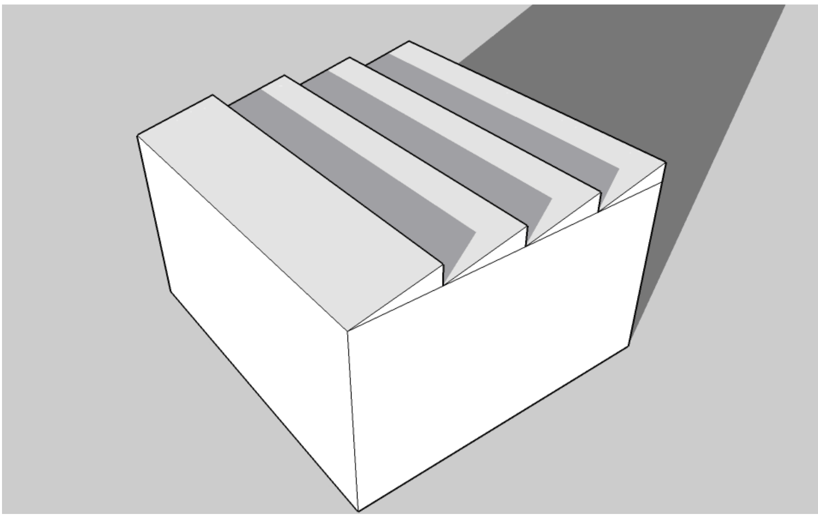


Figure 55: Shading occurring on rooftop PV panels

12.5.1 Direct Beam Shading Coefficient

Using first principles, this requires finding a diffuse and direct beam shading coefficient for the different panel configurations. J. Appelbaum et al 1979 [73] and D. Passias et al 1983 [72] have shown that the direct beam shading coefficient (C_{SD}) as a % of the total panel area is:

$$C_{SD} = \left[1 - \left\{\frac{\sin\beta}{\cos\theta} \times \frac{D + A\cos\phi}{A}\right\}\right] \times \left[1 - \left\{\frac{\sin\phi\cos\delta\sin(h)}{\cos\theta} \times \frac{D + A\cos\phi}{L}\right\}\right] \qquad \textbf{Equation 18}$$

Where, β = solar altitude as defined above, and θ = incidence angle. For a south facing panel,

$$\cos\theta = \sin(\zeta - \phi)\sin\delta + \cos(\zeta - \phi)\cos\delta\cos(h)$$ **Equation 19**

Where the parameters refer to Figure 56:

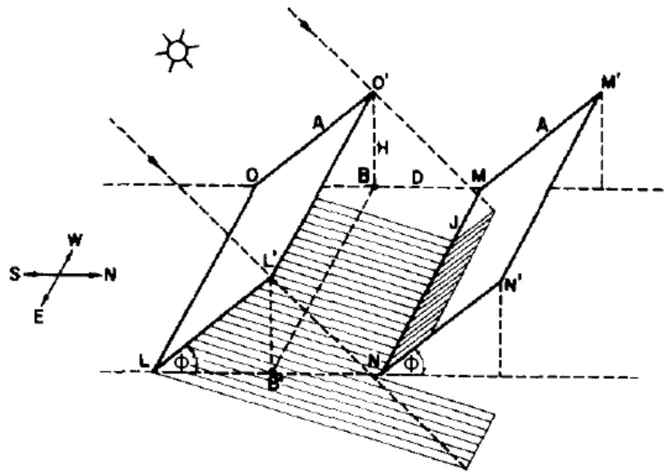


Figure 56: Direct beam shading from adjacent panels (from Appelbaum et al. [73])

The shaded direct beam (I_{BS}) is then calculated from:

$$I_{BS} = I_B C_{SD}$$ **Equation 20**

12.5.2 Diffuse Shading Coefficient

In the same way, shading from the adjacent panel will reduce how much a panel can "see" the hemisphere. The adjacent panel causes a "masking effect" and will reduce the total level of diffuse irradiance hitting the surface. This is particularly important in climates where diffuse radiation is predominant. The level of this "masking effect" is defined by the masking angle ψ and depends on the position along the surface (z) of panel – as is shown in Figure 57 [72].

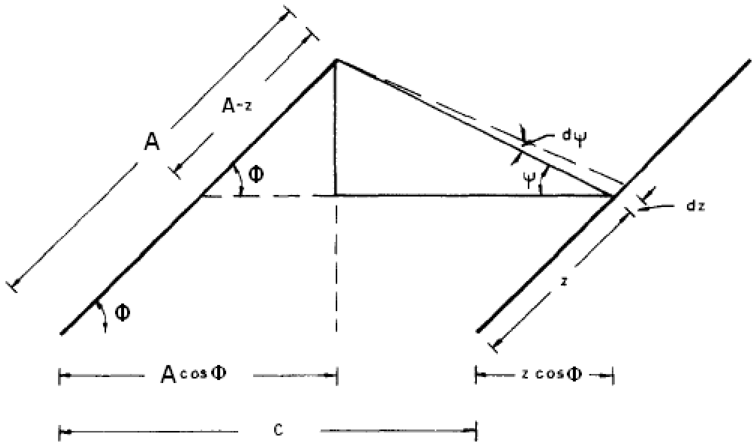


Figure 57: Diffuse beam shading impact from adjacent panels (from Passias et al. [72])

Where $\psi(z) = \arctan\left[\dfrac{(A - z)\sin\phi}{C - A\cos\phi + z\cos\phi}\right]$ **Equation 21**

To find the overall diffuse shading coefficient, it is necessary to find the average masking angle, with respect to z:

$$\overline{\psi} = \frac{1}{A}\int_0^A \psi(z)dz$$ **Equation 22**

This average masking angle varies depending on the inclination of the panel, and on the closeness of the adjacent panel. With k = C/A = 1, (adjacent panel one panel length away), the maximum masking angle is 32^{o} and with k = 3 (adjacent panel three panel lengths away), the maximum masking angle is under 10^{o}. These results correspond with the study done by D. Passias et al [72].

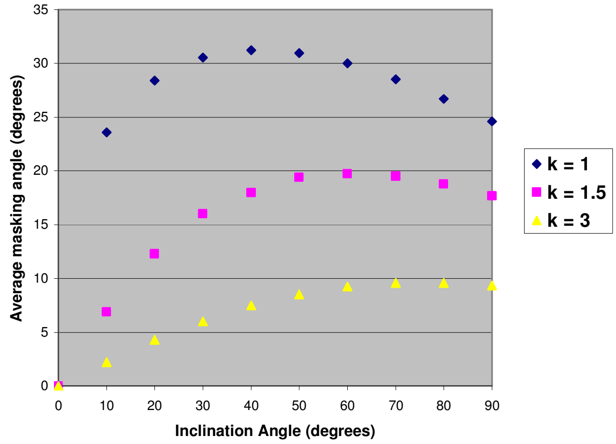


Figure 58: Average masking angles vs. inclination angle for various values of C/A (=k)

Overall diffuse irradiance is recalculated taking into account this average masking angle:

$$I_{DS} = I_D\left[\cos^2\left(\frac{\phi}{2}\right) + \cos^2\left(\frac{\overline{\psi}}{2}\right) - 1\right] \qquad \textbf{Equation 23}$$

12.5.3 Verification with ESP-r

The panels are assumed to be in rows across the entire width of the speculative building (45m), and assuming PV panels of 1.5m in length means 30 rows of panels can fit on the roof.

Verification study
• row width (L) = 45m • panel length (A) = 1.5m, • tilt angle of 30^o and facing south

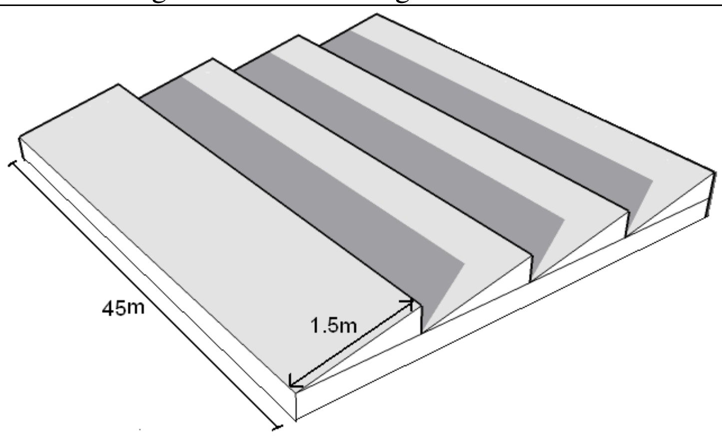


Figure 59: Roof PV layout

As seen in Figure 60 and Figure 61, there is a close correlation between the monthly direct beam shading coefficients between the ESP-r model and excel spreadsheet. The excel sheet tends to slightly underestimate the shading coefficients during the summer, but overall the shape and magnitude is the same.

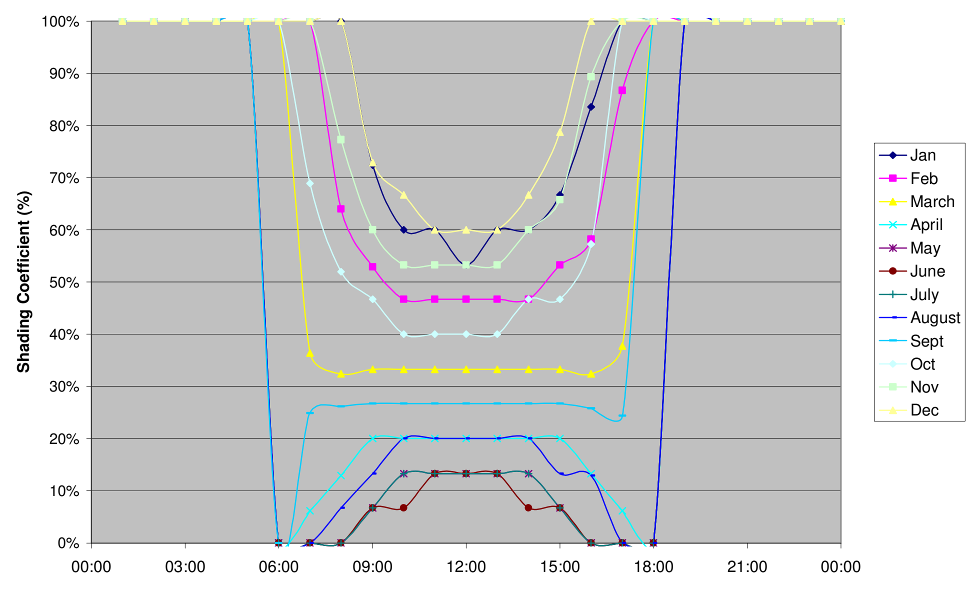


Figure 60: Monthly direct beam shading coefficients using Excel

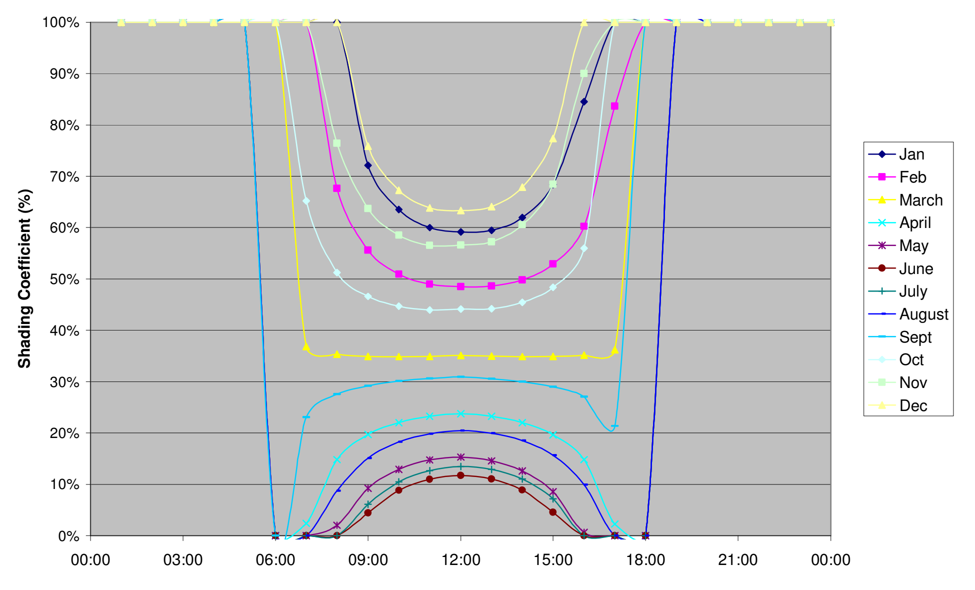


Figure 61: Monthly direct beam shading coefficients using ESP-r

Using the climate data for Gatwick Airport, the energy generated from the Excel and ESP-r models were compared.

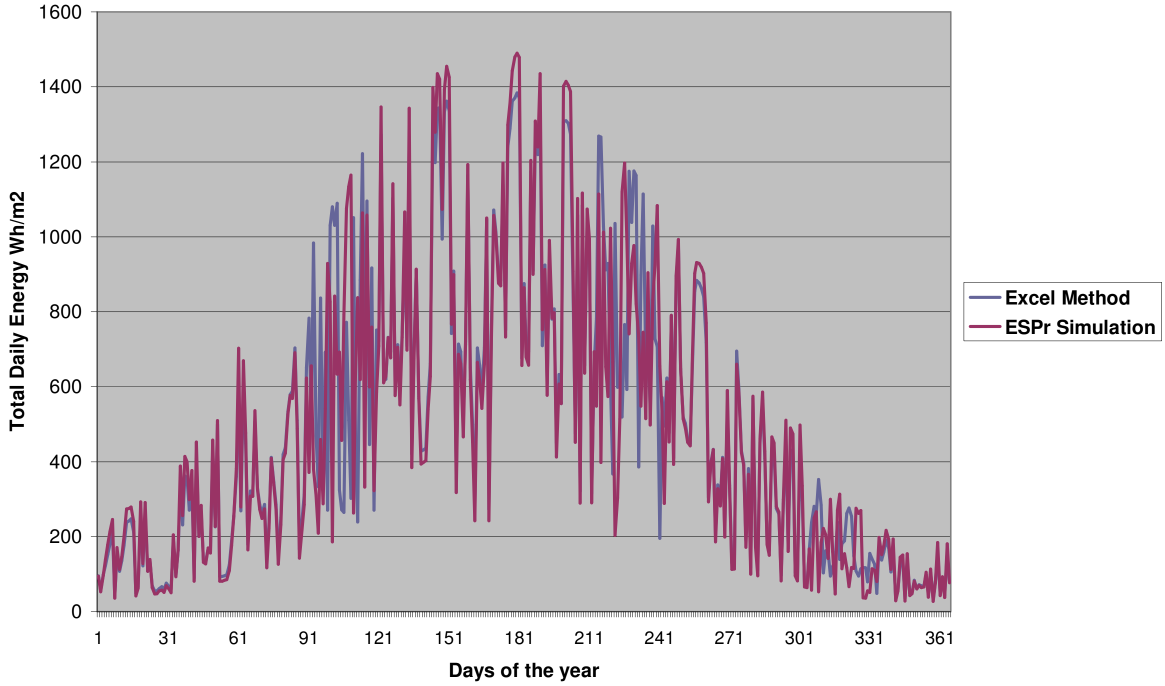


Figure 62: PV generation comparison between ESP-r and Excel for a London climate

Overall there is a very good correlation. There seems to be a slight unexplainable disparity in the months of April and August and in the summer the model tends to slightly underestimate the peaks in PV generation; perhaps explained with the small discrepancy between the direct beam shading coefficients.

Energy Delivered kWh/m2			
	Excel	**ESPr**	**% Difference**
1st Quarter	22.6	22.6	0.0%
2nd Quarter	73.1	73.3	-0.2%
3rd Quarter	67.7	66.6	1.5%
4th Quarter	16.6	16.5	0.6%
Annual Total	**179.9**	**179.0**	**0.5%**

Table 21: PV generation comparison between ESP-r and Excel for a London climate

12.6 Optimum Tilt Angle

Some interesting conclusions were found: whilst the optimum angle for an unshaded PV panel in London is around 30° from horizontal; when the panels are arranged in south facing rows along the roof, the shading affect from the adjacent panel means that the optimum position is actually horizontal.

The slight increase in shading from tilting the panel immediately cancels off any benefit from tilting the panel towards the sun. The global irradiation for different tilt angles is shown in Figure 63; which can be seen to correlate with the values predicted by Šúri et al. [67] in their solar map of Europe.

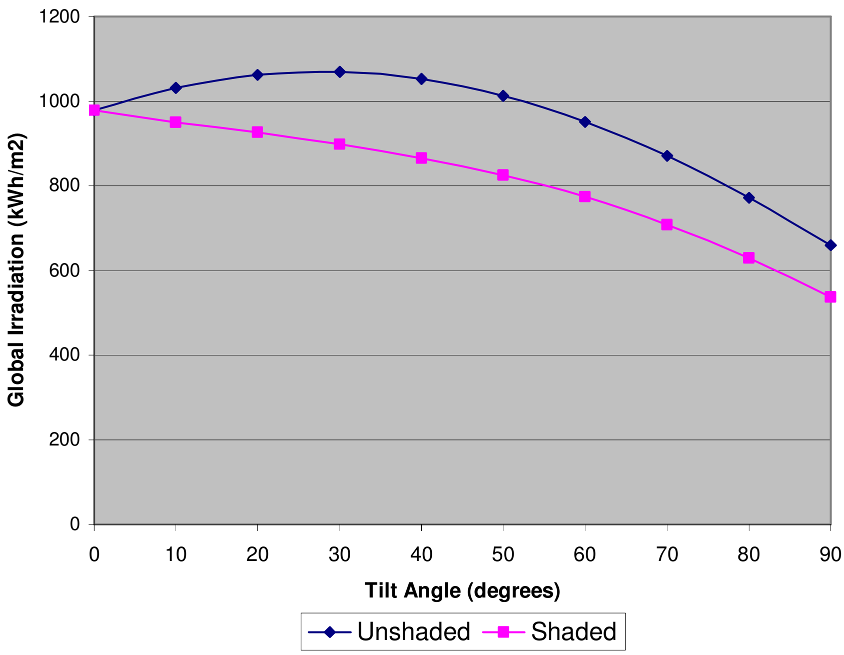


Figure 63: Global irradiation for panels at different tilt angles in London

13 International Case Studies

13.1 Rationale for choosing location

In this dissertation a number of locations have been simulated to discover the potential opportunities and drawbacks of different climates. The challenge was to choose a sample range of cities that balances the following three criteria:

- Are seen as hotspots for trade and commerce
- Represent a wide range of climatic conditions

13.1.1 Worldwide Trade and Commerce

The first criterion was examined using the MasterCard Worldwide Centers of Commerce Index 2008 [78]. The Index is a list of the top 75 cities in the world to do commerce in. It ranks each city based on 7 different criteria; appraising their legal and political framework, the economic stability, ease of doing business, financial flow, business centre, knowledge creation and information flow and finally livability.

From the pie chart, it can be seen that the majority of the split is between Europe, Asia and North America, with little impact from Latin America.

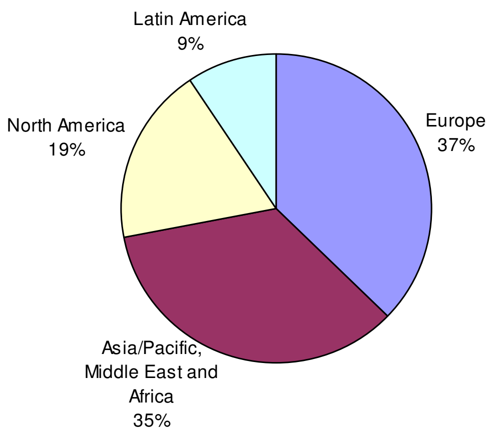


Figure 64: MasterCard Centers of Commerce: Continental split

Top 10 Cities

Rank	City	Country	Region
1	London	UK	Europe
2	New York	United States	North America
3	Tokyo	Japan	Asia/Pacific
4	Singapore	Singapore	Asia/Pacific
5	Chicago	United States	North America
6	Hong Kong	Hong Kong	Asia/Pacific
7	Paris	France	Europe
8	Frankfurt	Germany	Europe
9	Seoul	South Korea	Asia/Pacific
10	Amsterdam	Netherlands	Europe

Table 22: MasterCard Centers of Commerce: Top ten cities

In the top 10 places there are 4 European cities, 4 Asian cities and 2 North American cities. However, these 10 do not entirely represent the wide range of climate conditions in the world – especially because of the vicinity of the European countries to each other.

13.1.2 Worldwide Climate zones

The Köppen climate classification is the most widely respected system for dividing the world into discreet zones of similar climate [79]. It was developed by Wladimir Köppen around 1900, and categorises the world into different climate zones through vegetation distribution, temperature, precipitation and the seasonality of the precipitation [80, 81]. Global climate is divided into 5 classes and then subdivided further into different groups.

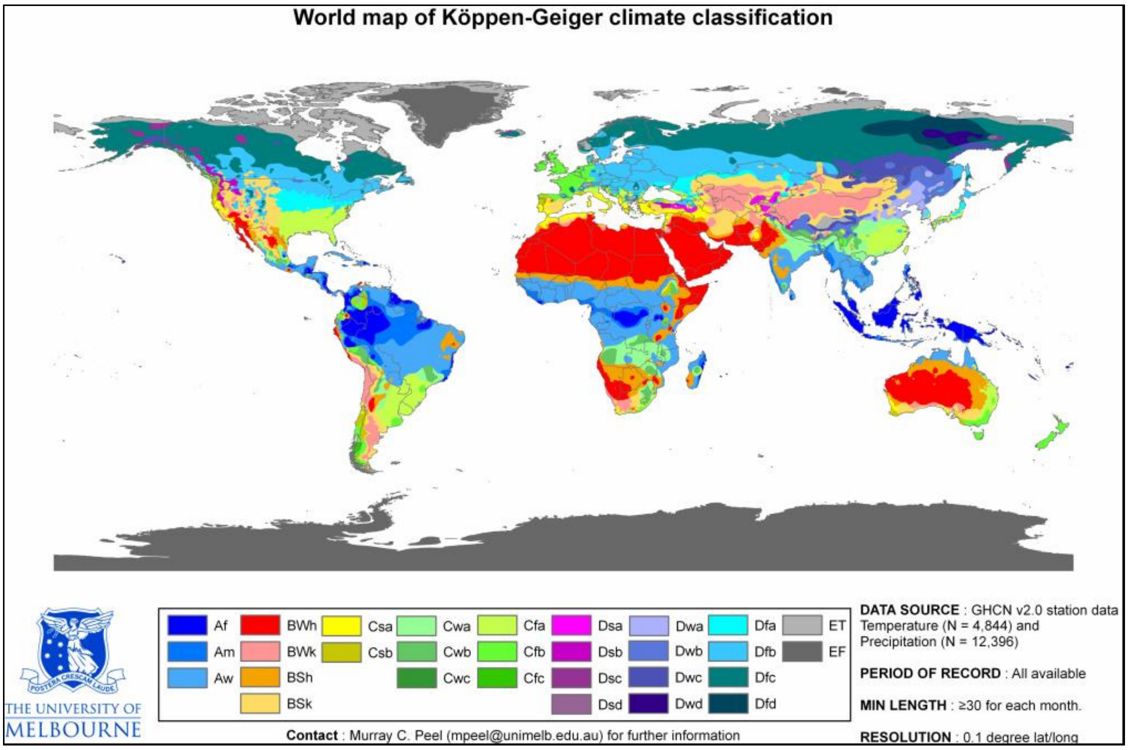


Figure 65: World map of the Köppen-Geiger climate classification [81]

- **Class A: Tropical Climate** *(Subclasses: Equatorial, Monsoon and Savanna)*
  - Tropical climates are defined as having a constant high temperature above 18^{o}C throughout the year and large annual rainfall.
  - Equatorial climates are found between 5-10^{o} of the equator and whilst there are no real seasons, rainfall of at least 60mm is expected every month.
  - Monsoon climates are found adjacent to the equatorial climates, which with the seasonal winds (especially in South-east Asia) means there is a distinct wet and dry season.
- **Class B: Dry** *(Subclasses: Desert and Semi-arid)*

- Desert regions are defined as receiving less than 250mm precipitation per year, whilst semi-arid is between 250-500mm. The lack of cloud cover means there is a lot of solar energy available during the day, but also extreme cooling requirements.

- **Class C: Temperate** *(Subclasses: Humid Subtropical, Maritime, Mediterranean)*
  - Mediterranean climates are found on western coasts between 30-45^o of latitude; in winter they have changeable and rainy weather but have hot and dry summers.
  - Maritime climates are also found on western coasts, immediately poleward of Mediterranean climates and reaching as far 60^o in Western Europe. The weather is dominated by polar fronts giving changeable and overcast weather all year round. Summers are cool because of cloud cover and winters are mild compared with similar latitudes.
  - Humid subtropical weather occurs on eastern coasts from 25-40^o of latitude; unlike Mediterranean weather, the summers are humid and wet.
- **Class D: Continental** *(Subclasses: Humid Continental, Subarctic and Continental Mediterranean)*
  - Found in the interior of continents where the average summer temperature is above 10^{o}C and winter averages above -3^{o}C. There is often a conflict between polar and tropical air masses and hence huge seasonal variability.
- **Class E: Polar** *(Subclasses: Polar and Alpine)*
  - Defined as areas where the temperature is below 10^{o}C average all year. There are no major cities in this climate and is therefore not considered.

13.2 Selecting the Sample Range

It was decided that a sample size of 6 was possible to cover the most important climate zones: including – Equatorial (Tropical), Desert (Dry), Humid Subtropical, Maritime and Mediterranean (Temperate) and Humid Continental (Continental). To help in the decision process, a table was created to compare the choices of the cities found in each zone, their latitude and longitude and their MasterCard ranking.

6 sample cities								
Class	Name	Subclasses	Symbol	Cities	Latitude	Longtitude		Mastercard City Rating
A	Tropical	Equatorial	Af	Singapore	1.23	103.92		4
				Kuala Lumpur	3.13	101.70		50
		Monsoon	Am	Mumbai	18.98	72.83		48
				Miami	25.79	-80.22		
				Rio de Janeiro	-22.90	-43.23		65
		Savanna	Aw,As	Bangalore	12.97	77.57		66
B	Dry	Desert	BWh,BWk	Dubai	25.20	55.30		44
		Semi-arid	BSh,BSk	Denver	39.74	-104.98		
C	Temperate	Humid subtropical	Cfa, Cwa	Shanghai	31.20	121.50		24
				Hong Kong	22.30	114.20		6
				Tokyo	35.68	139.77		3
				Houston	29.76	-95.38		34
				New York	40.72	-74.00		2
				Milan	45.46	9.19		20
		Maritime	Cfb,Cwb,Cfc	London	51.51	-0.13		1
				Frankfurt	50.11	8.68		8
				Amsterdam	52.37	4.89		10
				Dublin	53.35	-6.26		31
		Mediterranean	Csa,Csb	Barcelona	41.38	2.18		38
				Rome	41.90	12.50		47
				Los Angeles	34.05	-118.25		17
				San Francisco	37.78	-122.42		28
D	Continental	Humid continental	Dfa,Dwa,Dfb,Dwb	Toronto	43.67	-79.38		13
				Chicago	41.89	-87.62		5
				Beijing	39.90	116.40		57
				Seoul	37.55	126.98		9
		Subartic	Dfc,Dwc,Dfd,Dwd					
		Continental Mediterranean	Dsa,Dsb,Dsc	Madrid	40.40	-3.68		11
E	Polar	Polar	ET,EF					
		Alpine	ET/H					

Table 23: Comparison between the climates of world cities

The 6 final cities chosen were: Singapore, Chicago, Hong Kong, London, Los Angeles and Dubai. The first four are in the top ten ranking, whilst the remaining two are 17th and 44th respectively. Although the highest MasterCard rankings were not always chosen, the sample provided the largest variation in latitudes of the possible choices.

13.3 Building Scenarios

13.3.1 Scenario 1: Sheltered urban low-rise

Central London is a good example of a densely urbanised, low-rise environment. Using data from the IKONOS-2 satellite; it can be seen in Figure 66 that most of the buildings, which are shown in dark blue or pink, vary between 16 and 26 metres.

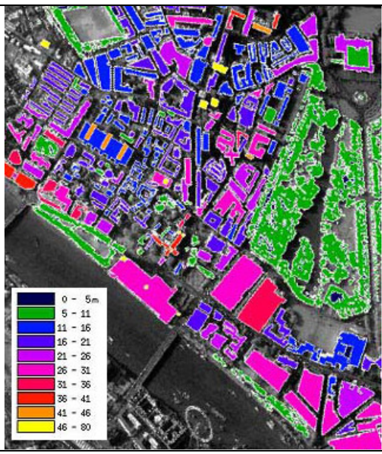
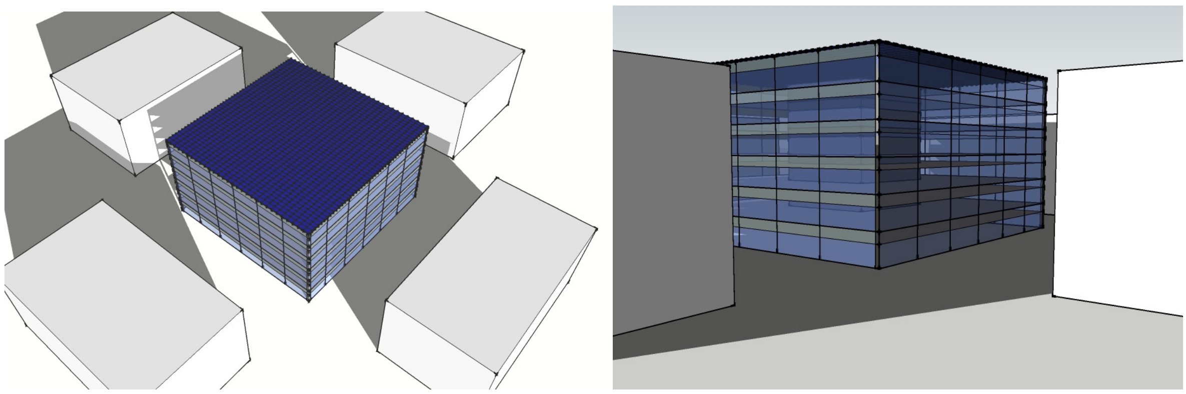
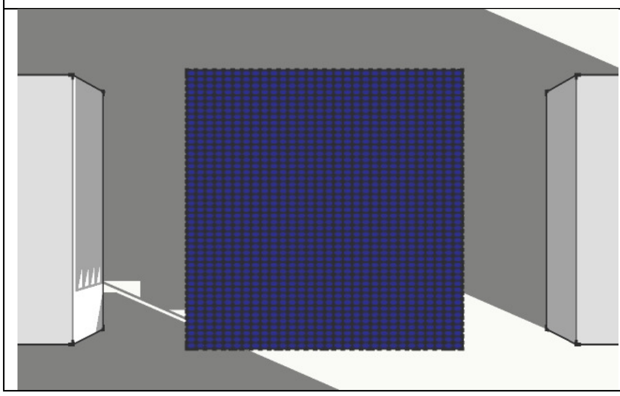


Figure 66: Building Height in Central London using IKONOS data [77]

Figure 67: Fitzroy Street in London shading from trees and adjacent buildings [82]

Scenario 1 is loosely based on Arup's new Fitzrovia office, shown in Figure 67 (above); assumed to be in a dense urban area with shading from trees and adjacent buildings. With these high levels of shading throughout the day, PV generation is only possible on the roof, as shown in the models below.





Building Dimensions	
Length x width	45m x 45m
Floor to ceiling height	2.7m
Ceiling void	1.4m
Total height	25m
Floors	6
Floor area per level	1800m^2
Total office floor area	10800m^2
PV Dimensions	
Number of panels on roof	1350
Total PV area	2025m^2

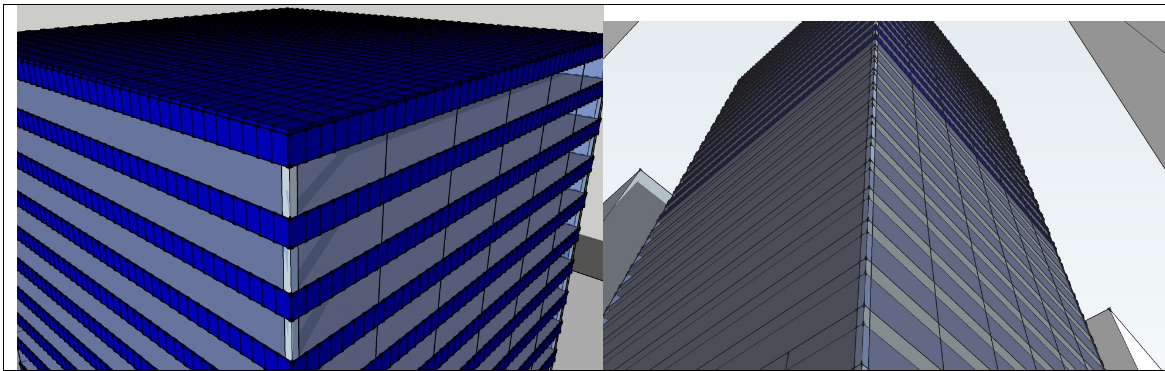
Figure 68: Details of urban low-rise scenario

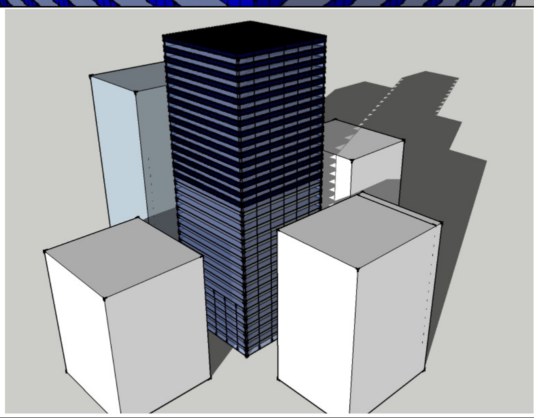
13.3.2 Scenario 2: Semi-exposed downtown high-rise

The second scenario is a semi-exposed high-rise building in the downtown area of a city.

Figure 69: View of Toronto downtown area

As can be seen in the typically dense downtown skyline of Toronto, most high-rise buildings are neither fully exposed, nor fully sheltered but have at least 1 side uncovered. Hence, it is assumed PV generation is possible on the south, east and west façades of the top half of the building.





Building Dimensions	
Length x width	45m x 45m
Floor to ceiling height	2.7m
Ceiling void	1.4m
Total height	140m
Floors	32
Floor area per level	$1800m^2$
Total office floor area	$57600m^2$
PV Dimensions	
Number of panels on roof	1350
Number of panels on façade	2025
Total number of panels	3375
Total PV area	$5078m^2$

Figure 70: Downtown High-rise scenario details

13.4 PV Generation Potential

13.4.1 Optimal Tilt Angle

The optimum tilt angle for shaded and unshaded PV panels positioned on the roof of the building were compared in the 6 worldwide locations.

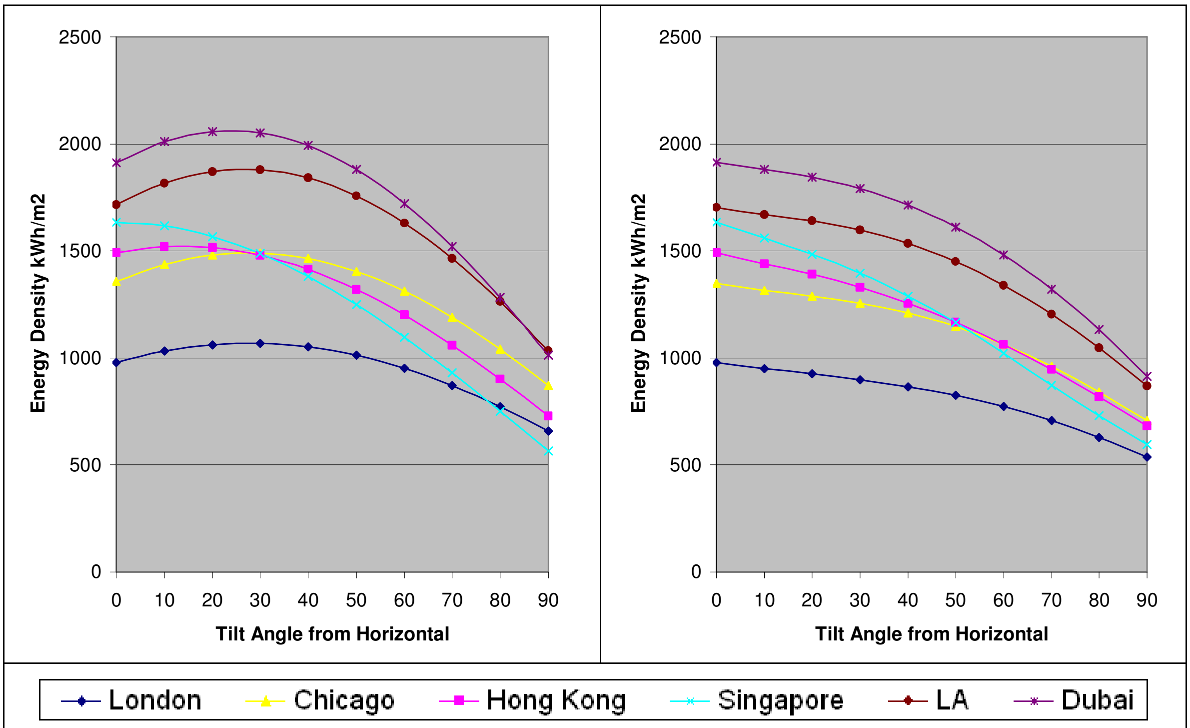


Figure 71: Global irradiation for shaded panels in different world locations

Figure 72: Global irradiation for unshaded panels in different world locations

As expected in the unshaded PV panels – the optimum tilt is most heavily influenced by the latitude at which the site is at. The closer the site to the equator the higher the altitude of the sun at midday – which means a tilt angle closer to horizontal, is desired.

There are some surprising results when shading effects are included – the optimum level is horizontal irrespective of the latitude or climate of the site.

Optimal PV Tilt Angle			
	Latitude	**Unshaded**	**Shaded**
London	51.51°	28°	0°
Chicago	41.89°	28°	0°
LA	34.05°	27°	0°
Dubai	25.2°	24°	0°
Hong Kong	22.3°	14°	0°
Singapore	1.23°	0°	0°

Table 24: Optimal PV tilt angle in different worldwide locations

Shading effects from adjacent terrain, including other buildings, trees and nearby hills have not been included in this analysis. However it is clear from this study that shading is a major influence on the global irradiance potential of a particular site – and a thorough, site-specific study is required at the design stage.

13.4.2 PV Generation per building type

A key difference between the low-rise and high-rise scenarios is with the PV generation opportunity.

	Low Rise	High Rise
PV area on walls (m^2)	0	3053
PV area on roof (m^2)	2025	2025
Total PV area (m^2)	2025	5078
Gross Floor area (GFA) (m^2)	10800	57600
PV panel area : GFA	≈ 1:5	≈ 1:11

Table 25: PV opportunity per building type

High rise buildings have a high energy density, with a poor surface area to floor area ratio – unsuitable for renewable generation. This can be seen in Figure 73; a comparison between the different worldwide locations.

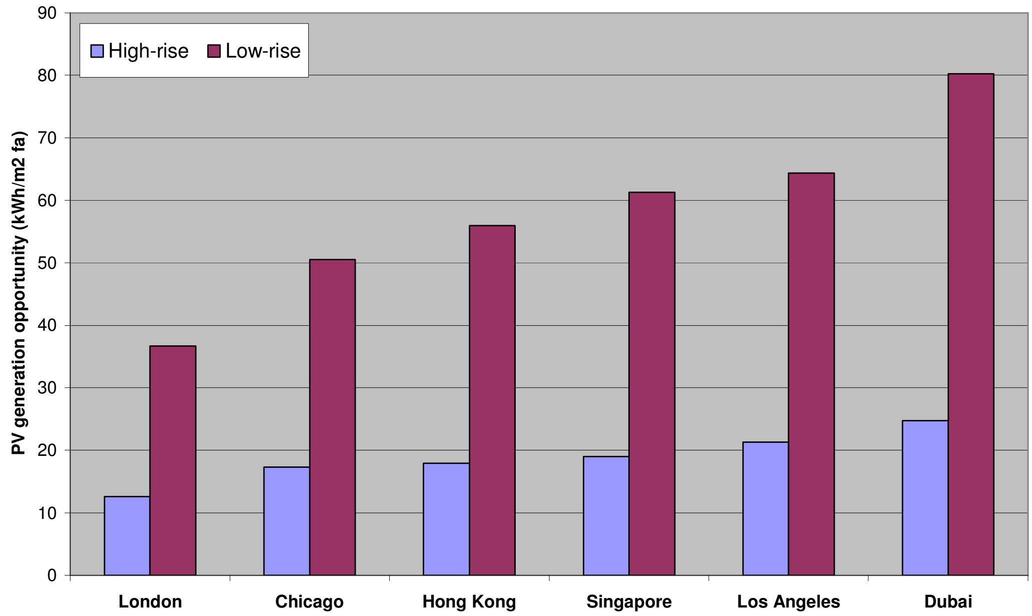


Figure 73: PV Generation opportunity for different building types around the world

13.5 Energy Demand Comparison

13.5.1 Lighting

Using the same statistical analysis of external diffuse illuminance – the 85% exceedance, or "design sky" can be compared in the different locations. It can be seen in Figure 74 that the design sky varies considerably between the locations – up to around 20klux on the equator – four times greater than in the UK.

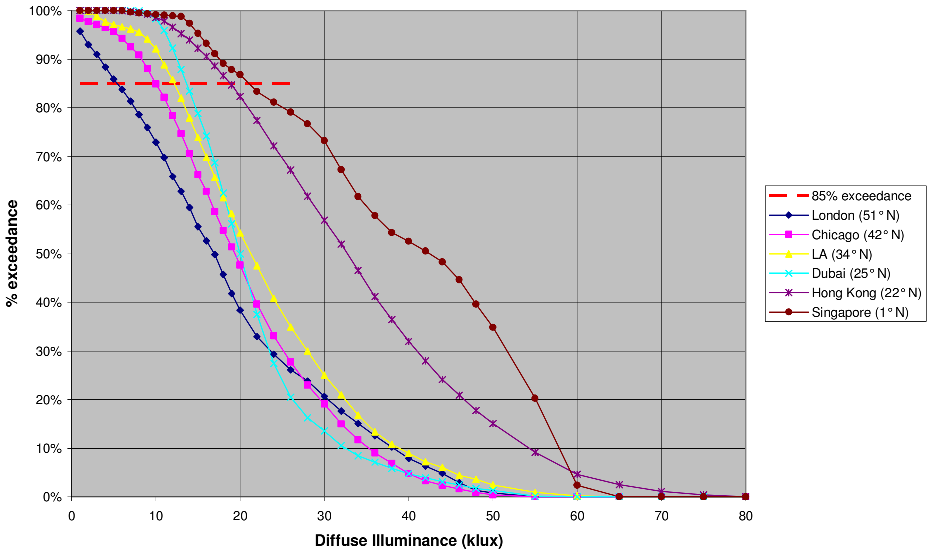


Figure 74: External Diffuse Illuminance availability around the world

The associated energy load for lighting is calculated for a future office scenario – with LED lighting, and same assumptions and procedure as defined in section 9.3.

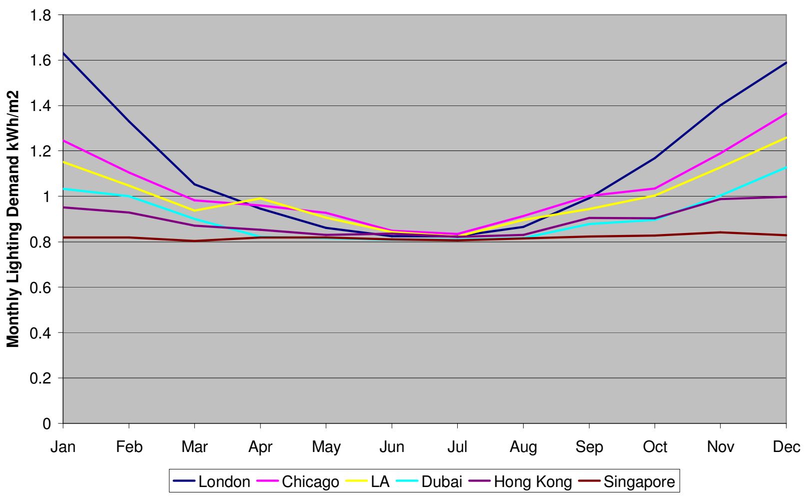


Figure 75: Monthly lighting energy demand comparison around the world

The amount of electric light required varies proportionally to the latitude of the site – with locations on the equator having the least energy consumption.

	Latitude	Electric Light Usage	Total Energy Demand (kWh/m^2)
London	51.5°	65%	13.5
Chicago	41.89°	60%	12.4
Los Angeles	34.05°	58%	11.9
Dubai	25.2°	53%	10.9
Hong Kong	22.3°	52%	10.7
Singapore	1.23°	47%	9.8

Table 26: Summary of electric lighting requirement around the world

13.5.2 Demand Summary

A comparison between the energy demand of both building scenarios – broken down into the heating and electrical components are shown in Figure 76 and Figure 77.

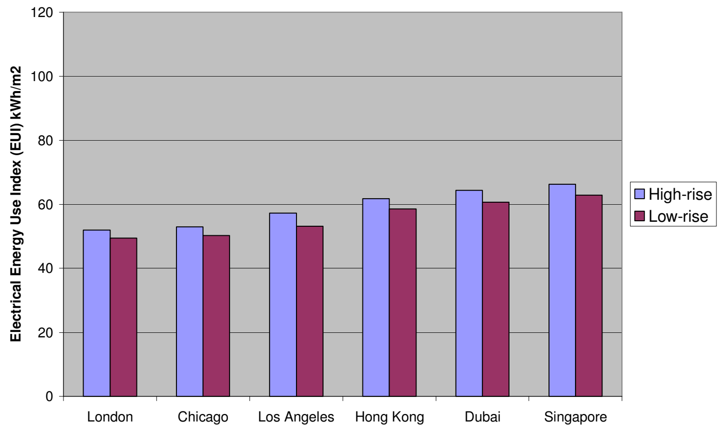


Figure 76: Electrical Demand per building type in each location

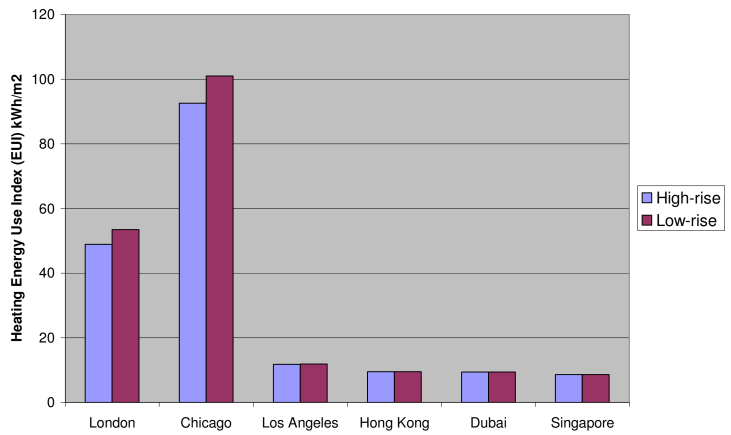


Figure 77: Heating Demand per building type in each location

Overall, there is not a significant difference in the minimum level of demand each scenario could potentially reach. Whilst in practice, bigger offices use more energy because they are harder to design well and the operation cannot be as closely controlled. The energy use index for both scenarios can be further broken down into the 8 main energy end uses: cooling, fans, lighting, IT equipment, lifts, hot water, heating and humidification.

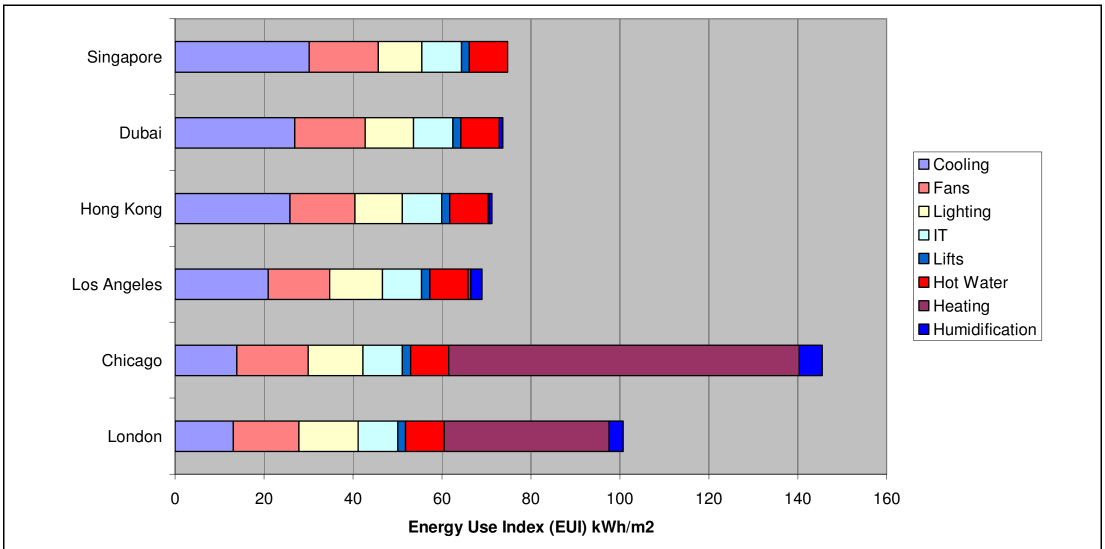


Figure 78: High-rise Energy Use Index for each worldwide location

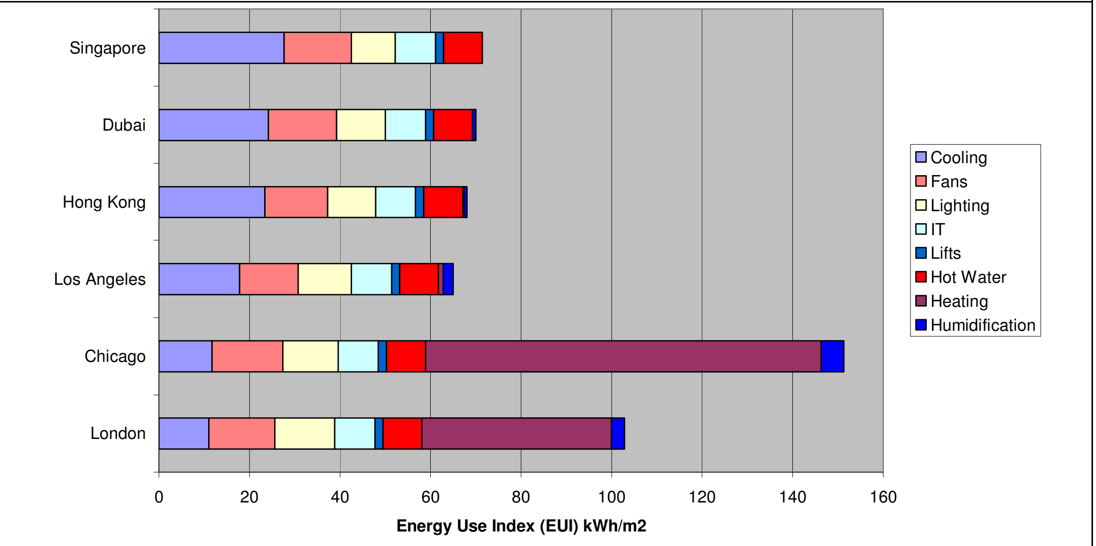


Figure 79: Low-rise Energy Use Index for each worldwide location

As expected, there is a greater cooling and lesser heating load in the high-rise building as it is more exposed. The individual daily demand profiles for each city, broken down into each end use can be viewed in the Appendix 17.2.

13.6 Supply and Demand Matching

The variable nature of renewable energy requires an analysis of the suitability of how the supply matches with the demands of the building. For example, in high latitudes the PV resource is very large during the summer but almost non-existent during the winter. This would match very well with the cooling demands of the building, which are also high in the summer and low in winter; but not very well with lighting demand which peaks in the winter.

There are also the supply and matching variations throughout a 24hour period. Whilst some loads, such as the HVAC or lighting loads could be in operation at night-time, solar energy is only available during office hours.

13.6.1 Battery Storage Assumptions

In order to use the solar energy received in the summer for lighting in the winter an impossibly large number of batteries would be required. A way round this is to think of the national electricity grid as like a battery. Electricity can be sold to the grid during peak times, and bought back when required.

Ideally, the future low powered office will only require selling and buying electricity from the grid when it really needs to – so that most of the electricity generated onsite can be used locally. This requires a trade-off between the two extremes of a strong grid connection with no battery storage and no grid connection with infinite battery storage. As a simplification of a detailed analysis into the optimum level of batteries (which would have to take into account the capital cost of batteries and transformers and potential grid electricity costs in the future), it is assumed that up to 24hours storage is possible onsite. Whilst quite optimistic by today's standards – energy storage technology is constantly improving [83], and as it has been made quite clear in this dissertation, there are opportunities in considerably reducing the demand typical and even good practice offices.

13.6.2 CHP analysis

Instead of using a traditional boiler to cover the hot water and heating requirements, a combined heat and power (CHP) unit could be employed. CHP units generate electricity locally and so can make use of the waste heat which is normally lost in conventional power stations [86].

Whilst they can run at over 90% efficiency, they are also more expensive than boilers, so cost effectiveness depends on how much of year they are needed to operate. Often they are designed to cover the baseload of heat throughout the year, and coupled with boilers which can be operated to cover the peak loads in winter. An industry rule of thumb is that they should be sized to run for around 5000hours per year [85].

13.6.2.1 CHP for hot water

Assuming that in the future, the hot water load will not change from good practice levels today; it can be seen in Figure 79 that hot water could account for almost 15% of the annual energy consumption in an office. As this is a heating load which will be ran throughout the entire working year (6258 hours/year); this is a good candidate for a dedicated CHP system. The hot water CHP unit chosen for the two buildings are summarised in the table below.

Scenario	Daily hot water consumption	Average power (running 24h)	CHP model [84]	Heat : Power Ratio
Low-rise	356 kWh/day	14.9kW	ENER·G 10y	1.7:1
High-rise	1901 kWh/day	79kW	ENER·G 50M	1.5:1

Table 27: CHP for Hot Water summary

It is assumed that a hot water tank would smooth out the hot water supply and demand variations throughout each working day.

13.6.2.2 CHP for heating

Both London and Chicago have large space heating requirements in the winter, so are investigated for suitability for CHP. Shown in Figure 80 is the number of running hours per year for different CHP system sizes.

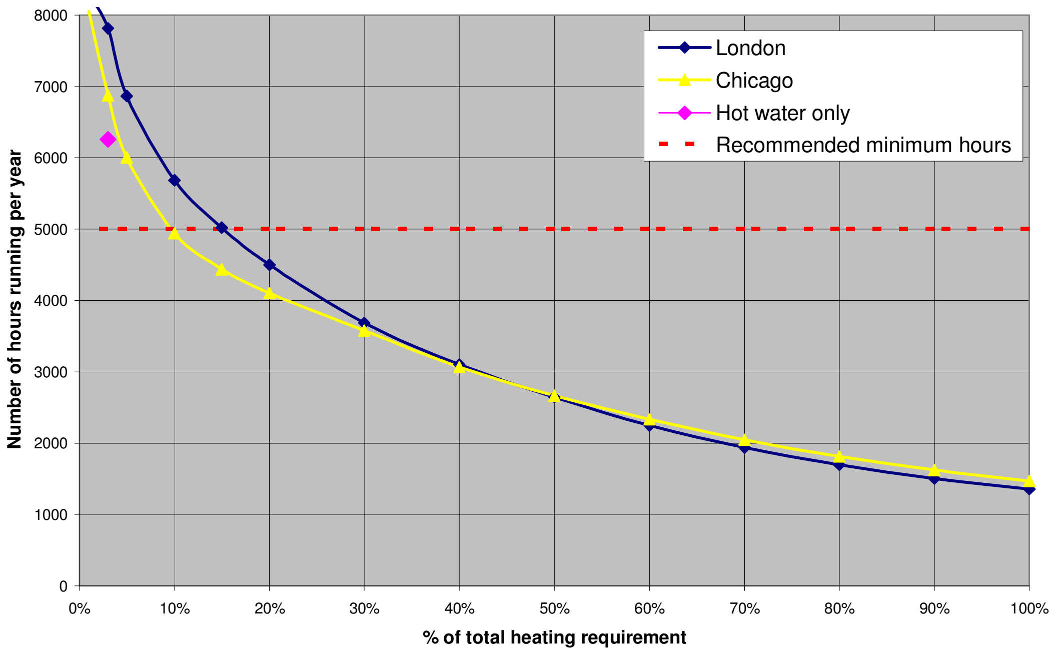


Figure 80: CHP for Space Heating Suitability

Assuming that it will not be cost effective to run the CHP below 50% part load, it can be seen that if the unit is designed to cover the peak loads – it will only be running for 1500 hours per year. To achieve the minimum recommended hours per year, the CHP unit could only be sized to cover a baseload of 10-15% total requirement. At this level, it is basically only covering the hot water demand.

In conclusion, assuming the recommended minimum hours required to make CHP a sound investment does not change dramatically in the next 10 years (it is a function of capital cost of the CHP, fuel costs and grid electricity cost), it seems unrealistic that CHP would be installed to cover the winter heating load.

13.7 Results and Analysis

The electrical supply from the PV and CHP (for hot water) was compared with the electrical demand in each location. The net energy demand for each 24 hour period was calculated (takes into account 24 hour battery capabilities). In Figure 81 and Figure 82, the fraction of demand which is met by the PV source each month is compared between the two offices. It is clear that the low-rise office performs much better than the high-rise building: and in some cases can almost be fully grid independent.

13.7.1 <u>% of met demand with PV supply</u>

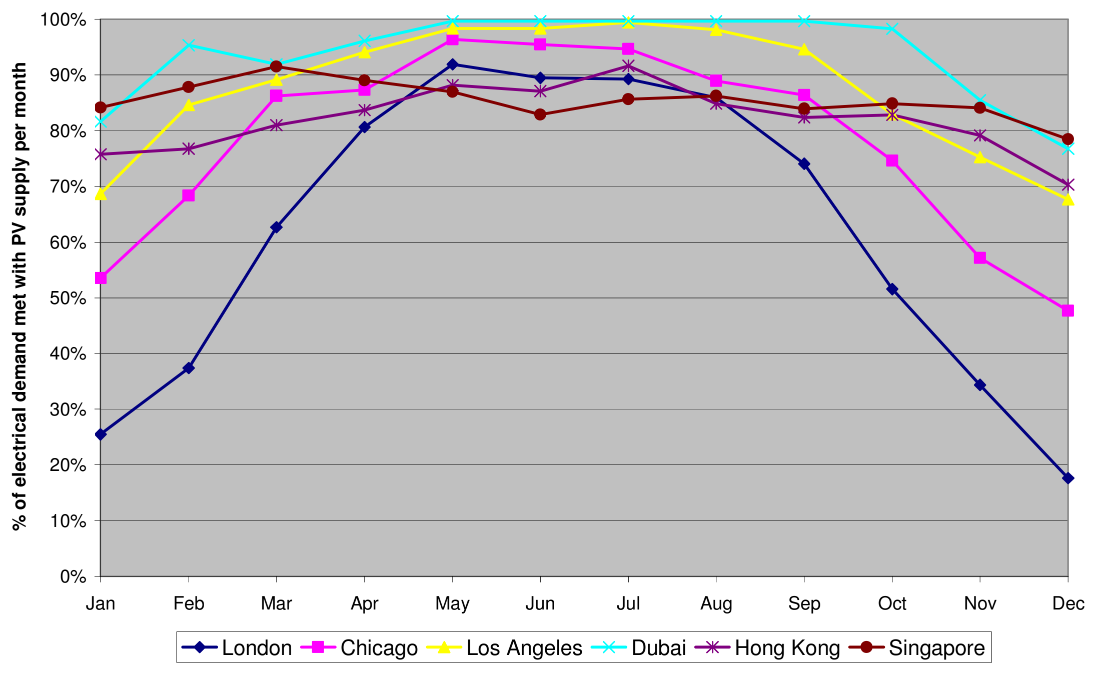


Figure 81: Low rise Building: % of electrical demand met with PV supply per month

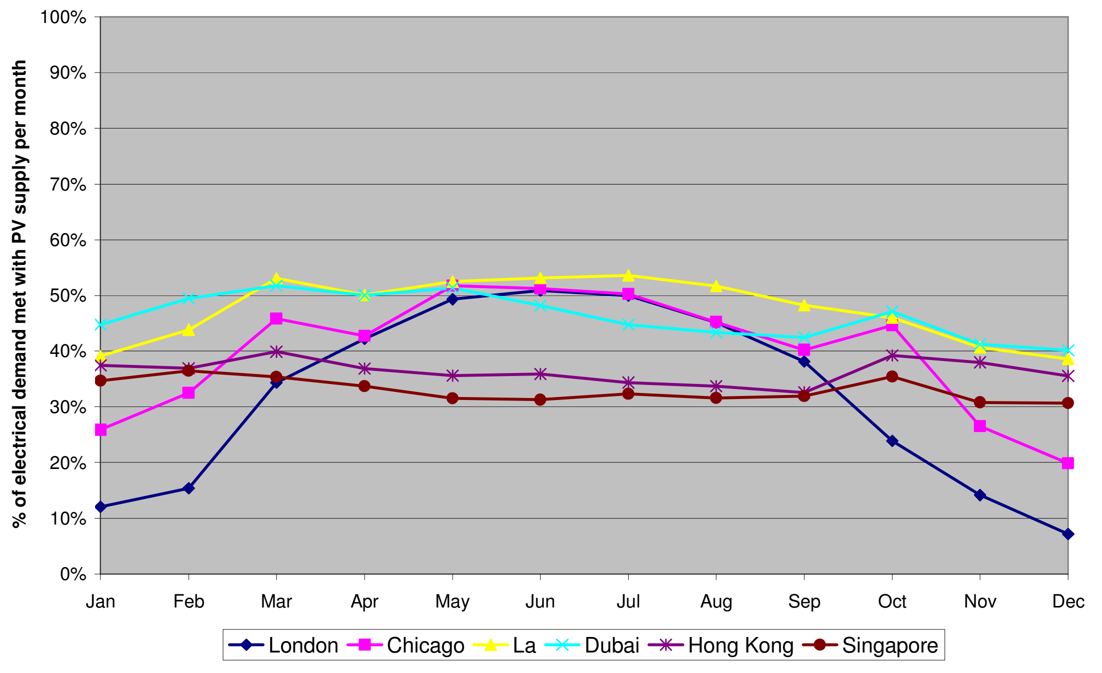


Figure 82: High rise Building: % of electrical demand met with PV supply per month

13.7.2 Average electrical demand met by Renewable Source

The average annual demand which is met by these renewable sources gives an indication of the relative performance of each location. In Figure 83, it is can be seen that Dubai – with the desert climate performs the best, whilst Los Angeles with the Mediterranean climate is second best. As expected, the UK with its cloudy skies is the worst performer.

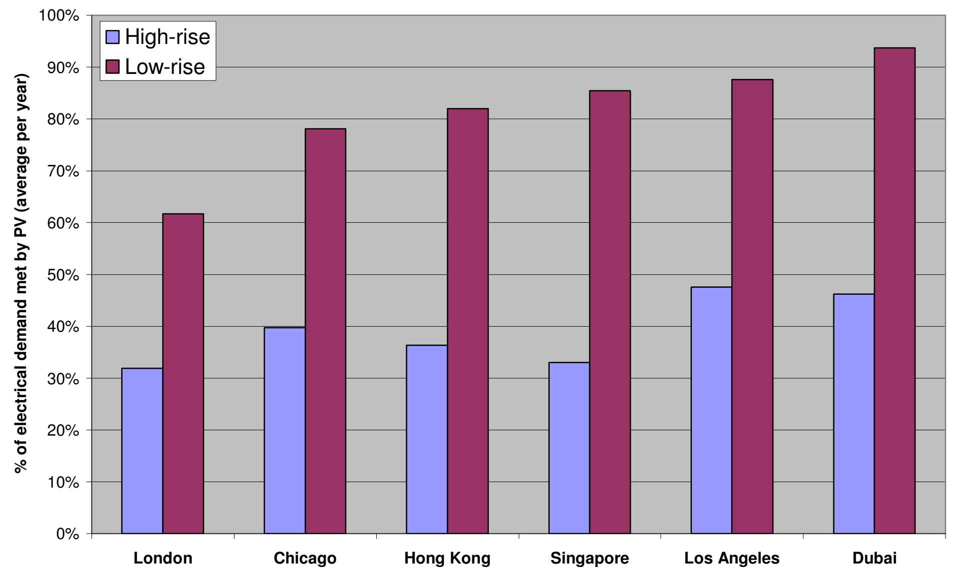


Figure 83: Electrical demand met by PV supply (alone) per year

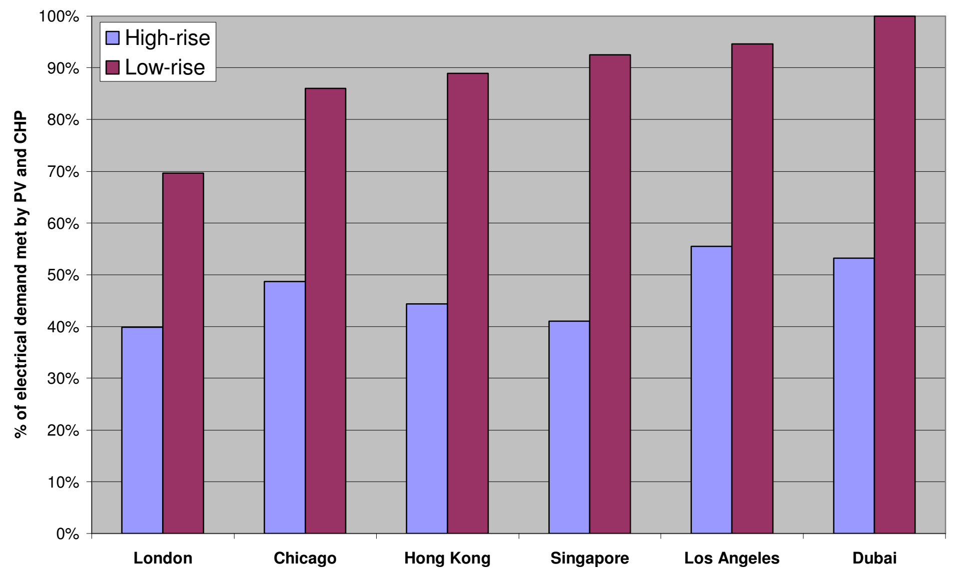


Figure 84: Electrical demand met by PV and CHP per year

13.7.3 Excess sold back to the grid

A second metric of performance is to compare how much electricity is surplus per year – i.e. when the total daily PV supply exceeds the demand. Again, Dubai and LA are the best performers. As expected, high-rise buildings in all the locations do not have much opportunity to sell back electricity to the grid.

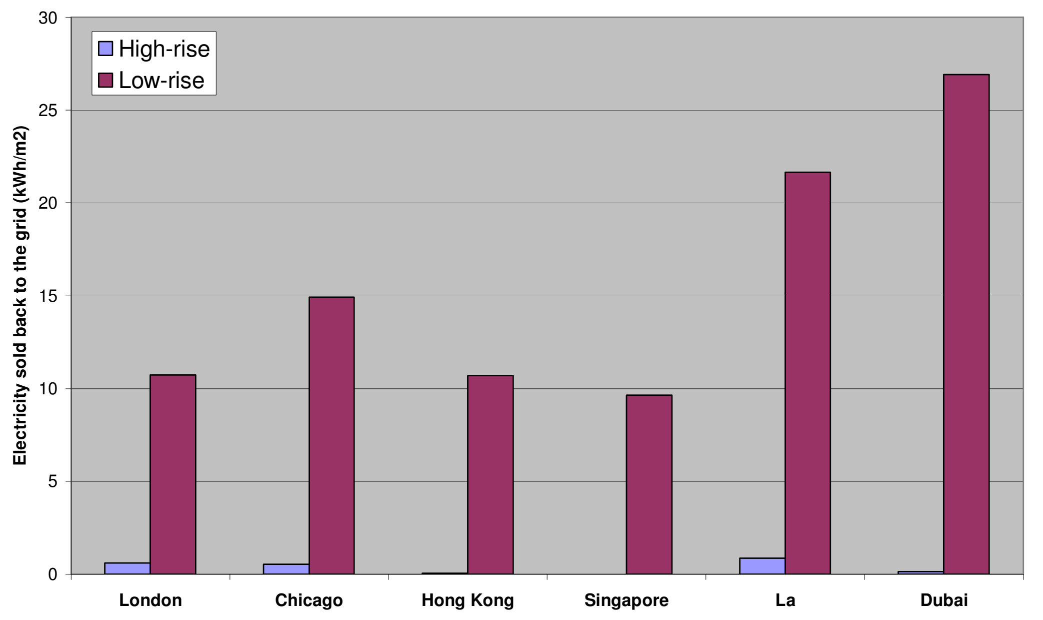


Figure: Excess electricity sold back to the grid

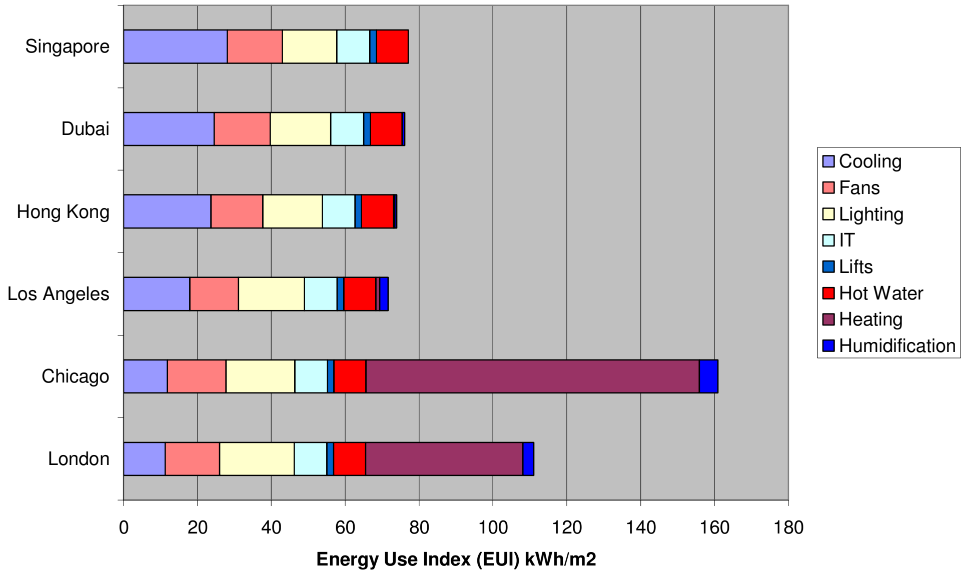
13.8 Sensitivities

The high number of different parameters required to undertake this analysis means it is important to ascertain which of the parameters are highly sensitive to result of the study. The three parameters which are dependent on location are:

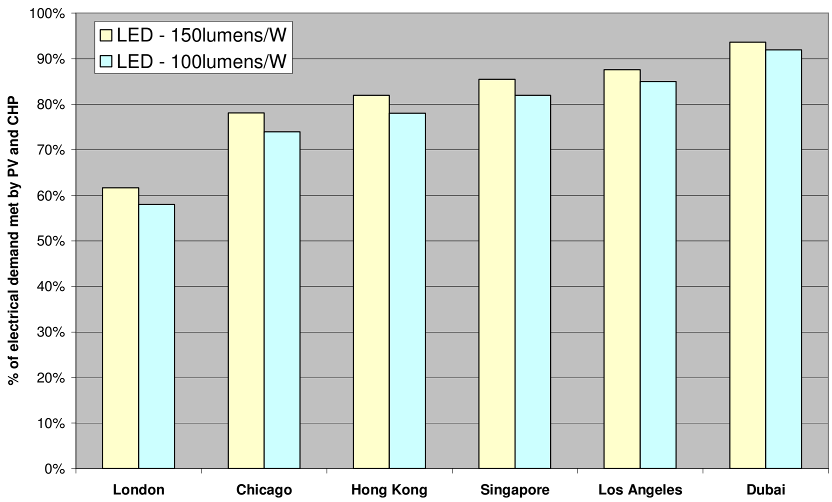
- **Lighting** *(sensitivity: efficacy of future LED lamps)*
- **Cooling** *(sensitivity: performance of future chillers)*
- **Solar energy** *(sensitivity: efficiency of future PV panels)*

13.8.1 Sensitivity 1: LED Efficacy

LED lamps are estimated to be able to achieve an efficacy of 150lumens/W in the next decade [40]. This study looks into the impact if 100lumens/W is only realistic on a commercial scale.



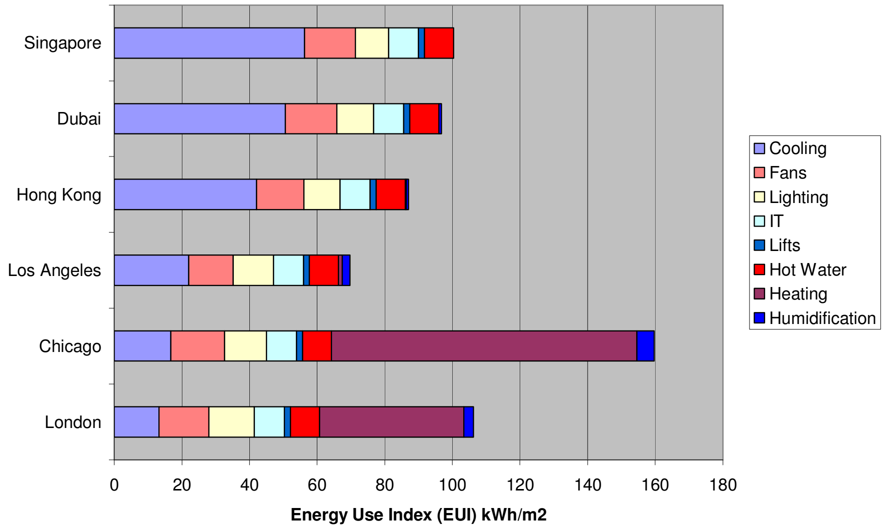
The increase in lighting energy is slightly more apparent in northern locations, but overall it does not dramatically change the relative shape of the EUI.



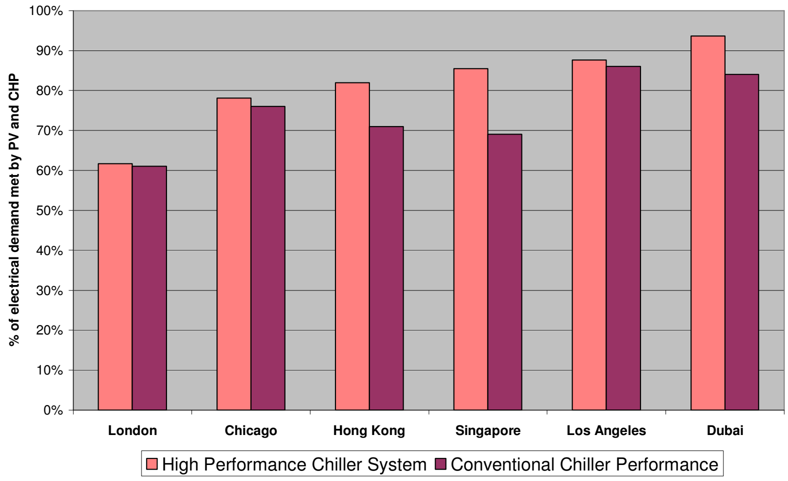
There is only a slight decrease in the level of electrical demand which can be met per day, and not much difference between locations.

13.8.2 Sensitivity 2: Chiller Performance

An important assumption is that in the future, the chiller and condenser technology will be able to perform much nearer to optimum conditions and temperature set points. This sensitivity study looks into the impact if the current scenario COP for cooling *cannot* be improved on in the future (see section 10.3.7 for more details).



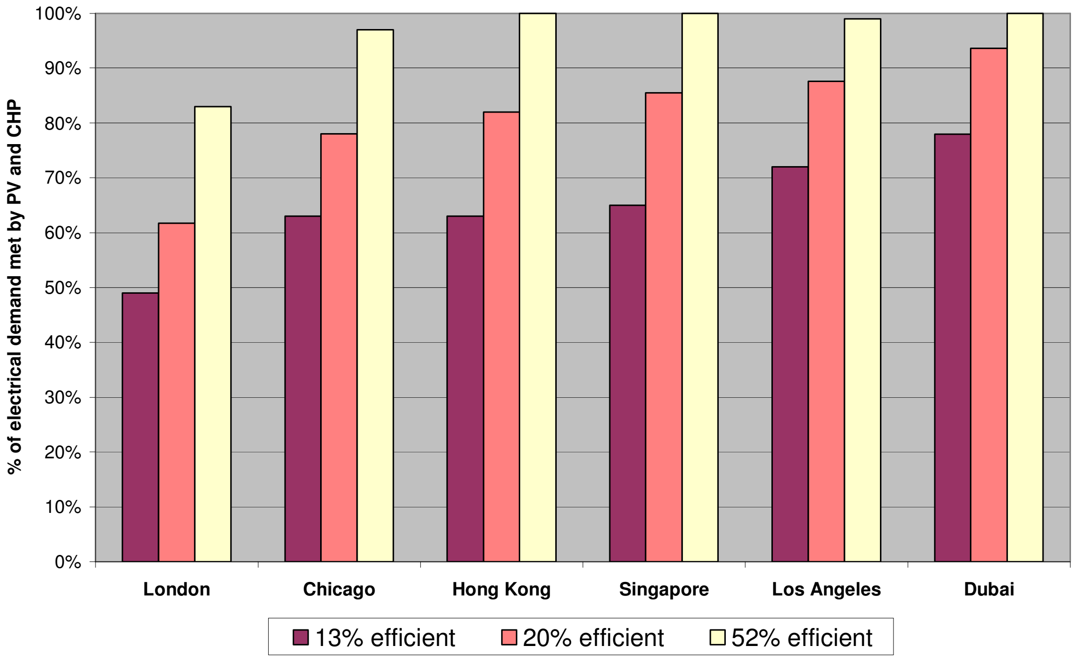
It is clear that in the desert and tropical climates, the decrease in COP has a major impact. The electrical load in Dubai has increased by 30%, whilst in London it remains unchanged.



Dubai, Hong Kong and Singapore both lose the top positions; but LA which is relatively cooler in comparison, does not suffer – and becomes the top location.

13.8.3 Sensitivity 3: PV efficiency

The PV efficiency has been set at 20% throughout the study. Whilst considered realistic, the potential range is much wider: from "no change from current" at 13%, to "best estimate for novel-high efficiency" at 52% [68]. These two extremes are modelled to find the extreme potential for onsite PV generation.



Even with current standards of 13% efficiency, the PV supply can match 50% of the demand in London. With novel-high efficiency PV – most locations can easily become carbon neutral.

14 Discussions

14.1 The Flexible Workforce

14.1.1 Discussion

Workforces are becoming more distributed, workers more mobile and communication more virtual. Currently, on average only 50% of workers actually work full time on site, with increasing numbers opting to telecommute; 15% telecommute around once per month and 7% regularly. Mobility is also increasing; 12% of the workforce describe themselves as "mobile workers", who spend most of the working week at different locations; client bases, at home or on the move.

In addition to increased mobility, the level of alternative working styles is also increasing. Job sharing, annualised hours, flexitime and compressed working weeks are all growing in popularity with the greater recognition of having a work-life balance.

Offices can no longer be seen as static places for individual work – instead, time spent in the office will mostly be for meeting colleagues and clients.

14.1.2 Summary of Contributions

In order to simulate the occupancy profile of a future office, it was necessary to develop a tool which used information on the different types of worker and the amount of time each spent in the office to generate a daily profile. The profile generator is flexible and different inputs or assumptions can be added.

14.1.3 Analysis of Sensitivities

Definitions for the different type of workers vary between sources, organisations and countries. Tele-commuting in the US means mainly working onsite and sometimes working from home. In the UK, most sources describe tele-commuting as working mainly working from home and only contacting work virtually. In this dissertation, it was decided that the US model was clearer – as the category description "home-workers" was more simpler and clearer.

14.1.4 Results and Conclusions

Three different scenarios were created: business as usual, increased tele-working and a future, more mobile workforce.

With a baseline of 100desks; in the business as usual scenario, it was assumed there were 95desks and 5 flexi-desks for visitors and remote workers. A total of 131 employees and potential visitors were associated with this space, with a maximum occupancy density of 75% during the day.

With the increased tele-working scenario, to simulate using the office space more effectively, the occupancy density was increased to 95% peak, by using 40 fixed desks and 60 flexi-desks. A total of 193 employees and potential visitors were then able to use this space.

With the future, more mobile office, again the occupancy density was increased to match 95% peak – but with 77 flexi-desks and 23 fixed. Only a core team of 11 full time workers and 12 ad-hoc teleworkers would have full-time desk – whilst the rest would share desks at a ratio of 3.1:1 (people per desk). A total of 259 workers and potential visitors would use this future workplace – a 98% increase from the business as usual case.

14.2 Ubiquitous Computing

14.2.1 Discussion

The biggest challenge lies with improving the energy efficiency of desktop computers. The many studies that have been undertaken on measure the power consumption, usage patterns and night-time switch-off – show that they by far perform the poorest relative to all the other technologies. Most shocking of all, in some studies 50- 60% of desktop computers were found to be left in a high power state over night, compared with only 20-30% of monitors and 25% of laptops. What accentuates this problem the most, is the fact that desktop computers use the most power too, and whilst trends in laptops and monitors are showing that power is reducing with time, the opposite is true with PCs. They are certainly getting more efficient in how they use their power, but the continually growing hardware demands from applications overrides this positive influence and the overall level of power consumption is still increasing.

Perhaps the biggest influence on the energy consumption of IT equipment in offices is with managerial policy. In the Ernst & Young case study, it was clear that a policy of giving 80% of staff laptops – will eradicate all the challenges associated with improving the energy efficiency and poor operational behaviour with PCs. Laptops are inherently low-power, and the trends are still towards reducing this; to maximise the battery life and hence mobility of the device.

Fundamentally, encouraging ubiquitous computing is inline with the increasing requirements of a flexible workforce. The situation then occurs where simultaneously; technology is driving new trends in behaviour which reciprocate by advancing the technology. In short, it is a clear and effective way in which natural innovation will drive progress in sustainability.

14.2.2 Summary of Contributions

As an extension on the occupancy profile generator, a tool which could create different IT equipment usage scenarios was developed. Each occupant, depending on the type of worker they were, was associated with either a PC and screen or a laptop. Information on the current ownership of PCs and laptops was taken from a combination of sources, and if there was a wide discrepancy between values a middle value was taken. Again, all the inputs used in this study are adaptable, and with new information, the profile generator can be updated accordingly. Auxiliary equipment densities were added on using typical values for current offices, or best practice values for future offices

This ownership profile was then mixed with typical or future values of power level for each device, including high, low and off states. Several sources agreed that computers were only actively used for 9% of the week, or 3 hours a day. The rest is spent in idle mode or in low power or switched off. Finally different power management capabilities were associated with each device, which could be changed for each scenario to simulate improvements in the future.

14.2.3 Results and Conclusions

The scenarios as defined before, business as normal, increased teleworking and a future, more mobile office were simulated.

The business as normal assumed that most employees with their fixed desks would use a desktop PC and CRT monitor. Typically bad night-time switch-off rates, poor power management and high power consumption levels characterise this profile. An annual IT equipment consumption of $46kWh/m^2$ compared quite well with carbon trust benchmark data. During a weekday, $125Wh/m^2$ of energy was consumed, and during the weekend, this only fell to 87 Wh/m^2 per day, demonstrating the incredible wastage of energy by not switching off the computer.

The encouraged tele-working scenario assumed that all those that used shared workspaces (regular tele-workers, mobile workers, remote workers and visitors) would use laptops. Those who remained in fixed places retained desktop PCs and CRT screens. An annual IT equipment consumption of $33kWh/m^2$ was possible; a reduction of 28%. For a 6 floor building, this would account for 77 tonnes of saved carbon a year.

The future mobile office similarly assumed that all those that used shared workspaces would own laptops. The only other difference was reduced power demand of each type of equipment, improvement power management and strongly implemented energy efficiency policy. This meant that no computers were left on at night. An annual IT equipment consumption of $12.5kWh/m^2$ was possible; a reduction of 72%. For a 6 floor building, this would account for 201 tonnes of saved carbon a year.

14.3 Future Lighting Systems

14.3.1 Discussion

Lighting accounts for 24% of the electrical load in typical buildings – around $60kWh/m^2$. By introducing low-power LED bulbs and improving the control of the lighting, this can be realistically reduced to between $10\text{-}15kWh/m^2$ depending on location.

In addition to the trends with increasing efficiency of electric lighting, three other parameters can be seen as influential in the lighting energy demand.

First of all, is with the design of the building and façade to make effective use of natural daylight as much as possible. The benefits of natural light in productivity, health and happiness of workers are well documented. In addition, the efficacy of natural light is very high – up to 150lumens/W for sunlight; which if solar gains are minimised by good façade design, a very efficient form of light can be taken advantage of.

The second influential parameter is the amount of lighting which is not met entirely with natural daylight:

- At night-time normally a minimum area has to lit for security reasons.
- Certain areas in the building might not receive enough daylight, such lift vestibule areas, toilets and corridors.
- Different lighting needs between occupants is well documented; where often workers require more than the standard 500lux of luminance.
- Desktop lighting is widespread, and serves to increase the brightness locally at on the work station.

Finally, there is a major influence from the operational controls of the lighting. There are many different solutions; from fully manual control, fully automatic and hybrid systems. Crucial to the effective control of lighting is how it responds to occupancy levels in the space. There are challenges in every approach. A fully manual system leaves wide margins for bad practice, whilst surveys have shown that in hybrid systems, users are less likely to switch lights off when leaving a space; reducing most of the benefits. A fully automatic system can likely become irritating for occupants if it does not perform as they would like.

14.3.2 Summary of Contributions

A modified version of the "design sky" daylight factor analysis was created. Instead of using a single value of 5000lux to represent the minimum conditions seen for 85% of the year, diffuse illuminance values for every hour of the year were taken. Using the average daylight factor equation, developed by BRE, the illuminance in the zone could be calculated for every hour of the year – and used to decide how much of the year electric lighting was required.

Three scenarios were modelled: typical, best practice and future offices. Each had different assumptions on lamp efficacy and level of usage during the day and night.

14.3.3 Analysis of Sensitivities

In the modelling process, a key sensitivity was in the assumptions on the night-time lighting and minimum daytime lighting. Due to lack of access to real data, the lighting energy demand had to be calibrated with benchmark data from the Carbon Trust.

In the typical office scenario; to simulate bad practice effects of unnecessarily leaving on lights at night-time, excessive lighting for security and cleaning – a value of 30% of all lights left on was taken. In the good practice office, this was reduced to 20% and assuming a baseline for security of 15% in the future office.

Similarly, it is difficult to predict the minimum number of lights that will be left on during occupied hours. A value of 30% in typical, 25% in good practice and 20% in the future office scenario were chosen.

Clearly, these assumptions are very sensitive to the overall energy consumption in the offices. To validate them, they were compared to benchmarks defined by the carbon Trust.

14.3.4 Results and Conclusions

A typical office with average quality fluorescent tube lighting will consume 66kWh/m^2.

A good practice office with high quality fluorescent tube lighting will consume 34kWh/m^2, a reduction of 50% from the typical office scenario and for a 6 story building this means a reduction of 194 tonnes of carbon dioxide per year.

A future office with LED lighting will consume 13.5kWh/m^2, a reduction of 80% from the typical office and for a 6 story building this means a reduction of 318 tonnes of carbon dioxide per year.

14.4 HVAC systems

14.4.1 Discussion

HVAC system demand is highly sensitive to all the heating and cooling requirements of the office space as well as the design of the system.

In the future office, it was shown that the net casual gains in the space will be less than current offices. Even though there could be a 25% increase in occupancy, it does not compete with the benefits of reducing the lighting and IT equipment loads.

Decisions on the ventilation strategy employed in the building will affect the chiller and fan power requirements. A constant air volume (CAV) air-conditioning system is inefficient as it cannot reduce the volume flow, even during low conditions. In addition, the varying supply temperature requirements mean that the chiller cannot work at optimum condition. A variable air volume system works at constant outputs, and varies the fan demand when necessary. This means the chiller can work most of the year at peak conditions and fan power energy consumption is minimised.

An argument to whether air-conditioning is needed at all should be had in most north-west European cities. During most of the year, with appropriate controls the space could be naturally or mechanically ventilated and take advantage of free cooling. The temperature requirements of a naturally ventilated space actually are wider than in an air-conditioned space – as the user and the user is much more likely to accept more extreme conditions.

Heat recovery is essential in minimising the heating requirement in colder climates, and cooling requirements in hotter climates. A thermal wheel positioned in the fresh-air unit could transfer 80% of the heat from exhaust into the intake air- increasing the temperature before it enters the mixing box. In the future office, hygroscopic wheels – which transfer latent as well as sensible heat, could be employed to also reduce the humidification and dehumidification load in the HVAC unit.

14.4.2 Summary of Contributions

Using the heating and cooling requirements for the building as calculated by ESP-r, an Excel based model was created to simulate the different HVAC plant components. Algorithms to simulate both the CAV and VAV ventilation strategies – including chiller, boiler, fan and heat exchanger components were created and ran for every hour of the year to find the annual energy consumption for different scenarios. Humidification plant was not simulated and approximated to the values of latent heat gain as calculated by ESP-r.

14.4.3 Analysis of Sensitivities

A number of parameters were influential in computing the overall energy use, and where assumptions had to be held to undertake the analysis.

Fan power is derived from the specific fan power (SFP) in a particular HVAC unit design. SFP is dependent not only on the efficiency of the fan impellor, but on the pressure drops inherent in the system, again dependent on the characteristics of the building in question. In absence of this real data, values for typical and good practice buildings were taken from benchmark data taken from the Carbon Trust.

The coefficient of performance of the chiller and condenser were equally influential. Typical values of COP from conventional and optimal configurations, dependant on part load conditions and ambient temperature were used in the study. It was assumed that the future office would employ a cooling system in which the components could be controlled to near optimal conditions.

14.4.4 Results and Conclusions

Three office scenarios; typical, good practice and future were simulated to compare their energy use index (EUI) and carbon dioxide emissions index CEI).

The first scenario, typical – which used the business as normal occupancy and IT loads, and the typical lighting and CAV ventilation strategy as described above had a EUI of 320kWh/m^2, and correspondingly a CEI of 127kg/m^2.

The second scenario, good practice – which used the encouraged tele-working occupancy and IT loads, and the good practice lighting and conventional VAV ventilation strategy had a EUI of 176kWh/m^2, and correspondingly a CEI of 77kg/m^2. This was a 45% reduction in overall energy use and a 39% reduction in the carbon footprint.

The final scenario, future – which assumed predictions on a ubiquitous computing and a mobile workforce, as well as LED lighting and highly efficient VAV ventilation and optimised chiller solution, had a EUI of 105kWh/m^2, and correspondingly a CEI of 38kg/m^2. This was a 67% reduction in overall energy use and a 70% reduction in the carbon footprint.

14.5 PV Resource

14.5.1 Discussion

Onsite solar resource goes hand in hand with the vision for a DC gird reconfigurable office. Without having to convert to AC before reaching the appliance end-use, higher efficiencies can be achieved.

The amount of solar power generated by a building depends on three geometric considerations; how many of the surfaces of the building are covered in PV, how much of each surface is covered and what tilt angle the panel is at. In this study, it was assumed as a simplification that the panels on the walls were fixed vertically. The roof panels were assumed to be facing south and the tilt angle can be varied. Optimal tilt angle is widely documented, and are most heavily influenced by the latitude of the site. However, little study since the early 1980's seem to be concerned about the design of panel rows and the impact of shading effects from adjacent panels.

In the future, PV panels could potentially become more dynamic, and the tilt angle could be varied throughout the day and year to maximise the amount of available solar power at every moment.

14.5.2 Summary of Contributions

The optimum tilt angle was desired to be found in order to discover the maximum PV resource available at each location. In order to complete this task efficiently, it was decided to create an Excel spreadsheet using the well documented equations for solar angles. The option to use the inbuilt PV energy generation capability in ESP-r was ruled out as there would have had to be 60 different simulations to calculate the total energy generation for tilt angles 0 – 90 in the 6 different locations.

Further calculations which took into account the shading effect (in both direct and diffuse irradiance) caused by adjacent panels were undertaken.

14.5.3 Analysis of Sensitivities

Estimations of PV efficiency in the future vary wildly even within one family type of PV. Whilst mature technology such as Crystalline-silicon could only achieve a high best efficiency of 25% by 2030, "novel, high-efficiency" technology such as the hot carrier, plasmonics or thermophotovoltaic concepts could achieve a high-best efficiency of 45%. An in-between value of 20% was assumed as it was deemed neither too conservative nor overly optimistic.

14.5.4 Results and Conclusions

The optimum tilt angle for unshaded panels decreases from 28^o in London to 0^o (horizontal) at the equator. When shading is taken into account, the optimum tilt angle is horizontal for all locations. In any case, the difference between the maximum generation potential in shaded and unshaded is less than 10%.

14.6 Building Type

14.6.1 Discussion

There are two main influences of the building type on the energy calculations. First of all is the size and aspect ratio of the building, the second is with the quality of the fabric.

The aspect ratio difference between a high and low rise building is crucial. Due to the sheer number of floors in a high-rise, its overall surface area to floor area is much smaller than that of the low-rise building. This has significant implications on the maximum PV generation in each building. Whilst low-rise buildings are likely to be shaded on all four walls, they have a much larger relative roof size compared to high-rise buildings and hence can generate more PV power per m^2.

A second key influence is the quality of fabric. It is assumed that the fabric of current "good practice" office can still be improved upon – especially with regards to glazing and infiltration. The idea is to reduce solar heat gain during the summer, whilst not allowing long-wave radiation and convection losses in the winter. Shading should be applied to the glazing to cut down on the peak solar gains in the summer, whilst benefiting from the heating effect from the solar rays in the winter.

Regarding air-tightness, most buildings in the UK perform quite poorly when compared with those in countries with more extreme environments – such as the US. It is assuming that buildings in the future will be built to the tightest standard that is possible currently.

14.6.2 Summary of Contributions

ESP-r models were created to simulate the improvements in the façade of a typical “semi-exposed downtown high-rise” and a “sheltered urban low-rise” building.

A comprehensive model of all the zones, surfaces and energy flows of the entire building will provide the most realistic conclusion; however it comes at a time and complexity penalty. At the conceptual stage, it is crucial to have a simpler and adaptable model that can efficiently model and test a wide range of design parameters.

14.6.3 Analysis of Sensitivities

A fundamental decision is the level of detail that the thermal simulation will represent. A comprehensive model of all the zones, surfaces and energy flows of the entire building will provide the most realistic conclusion; however it comes at a time and complexity penalty. A sensitivity analysis was carried out and showed that there was accurate correlation between the models.

A further sensitivity is in the level of infiltration in the building. For the purposes of modelling it was assumed to be constant, whilst in reality it would vary according to wind speed, direction and temperature gradients.

14.6.4 Results and Conclusions

The results of changing the fabric parameters were compared with Carbon Trust benchmark data for typical and good practice offices. Whilst the simulated model underestimated the heating by 15%, the relative magnitude of each scenario was very similar.

As it was more exposed, the high-rise office had 10% more cooling requirement compared with the low-rise building, and conversely had a 10% less heating.

High-rise buildings could only achieve around a third of the PV generation possible in low-rise buildings.

14.7 Worldwide Locations

14.7.1 Demand Summary

The IT, lifts and hot water demands were assumed to be the same in each location. When comparing the lighting power use around the world, it is clear to see that there is a relationship between lighting use and latitude; the further away from the equator, more lighting is required in the winter. However, the minimum lighting level; which is set by factors unrelated to daylight availability, limit the extent of which lighting demand varies with location. While lighting would be used for 65% of the working year in London, this will only reduce to 47% in Singapore.

As expected the cooling load increases the further south the location. Overall, the best climate is the Mediterranean; which does not have any substantial heating requirement in the winter, whilst has the minimal cooling requirement.

14.7.2 PV Supply

The results prove that intuitively a desert climate can provide the best conditions for solar generation. A Mediterranean climate is the second best location – beating both equatorial and subtropical climates. As expected, the UK climate – with its northerly latitude performs the poorest.

14.7.3 Supply and Demand Matching

Ideally, the future low powered office will only require selling and buying electricity from the grid when it really needs to – so that most of the electricity generated onsite can be used locally. In this analysis, 24hour battery storage capability was assumed.

The results show that it would be very difficult for an office in the UK to become completely disconnected from the grid relying on solar power along. Only in the summer will the office perform almost at off-grid conditions, whilst in winter only 25% of the electrical demand can be met with PV.

In counties nearer the equator there is not so much of a seasonal variation – and in Singapore there is no variation throughout the year. Overall the best location is Dubai, which can be on average 93% off-grid throughout the year, and the secondly – Los Angeles which can be 88% off-grid.

There is further potential with integrating a dedicated hot water CHP system. This could allow a further 8% of the demand to be matched by local generation – meaning that in the UK – 70% off-grid is possible, above 90% in Singapore and LA and fully off-grid in Dubai.

14.7.4 Sensitivities

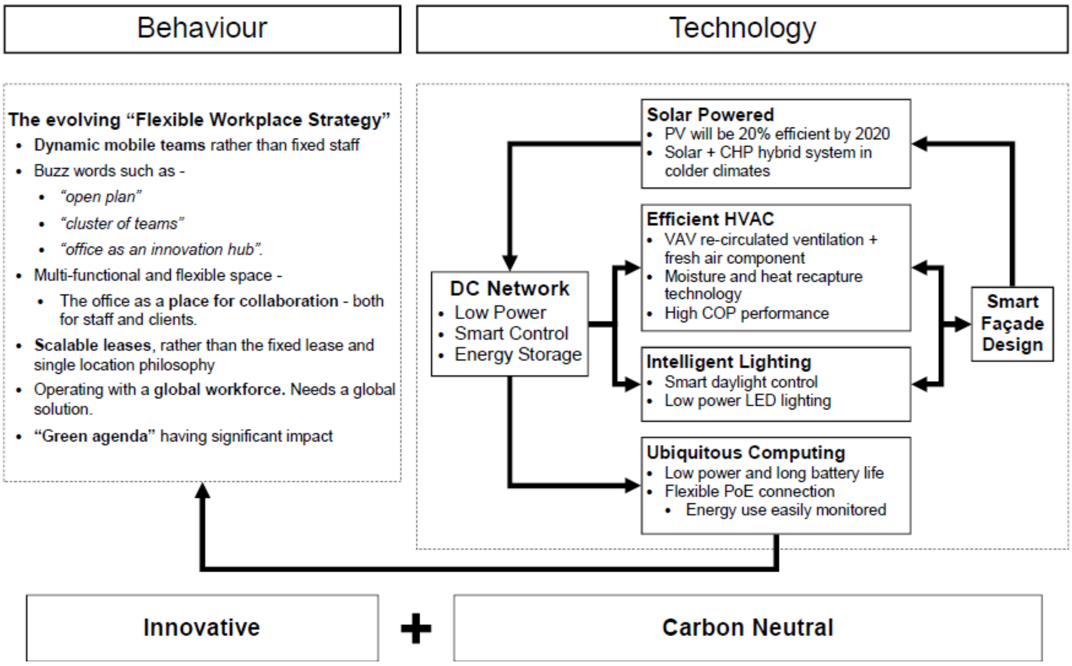
The first study took a reduced LED efficacy of 100lumens/W. The results showed that this only reduced the match between demand and supply by 5% and there was not much variation between locations.

The second study looked into the scenario if the COP of a chiller system could not be improved on from current technology and control. The results showed that this had a much bigger influence on countries with hotter ambient temperatures. Whilst making little difference in the UK, Chicago and Los Angeles, there was significant impact on the performance of buildings in Hong Kong, Singapore and Dubai. Los Angeles is now the best location as it still can maintain 85% off-grid.

The final study looked into the prediction of PV efficiency in the future. The results showed that even with today's standards of 13% efficiency, a PV array on the roof of a low-rise building in London could still meet 50% of the demand. With novel, high-efficiency PV technology, and a dedicated CHP for hot water system, 90% of the electrical loads in an office in London could be met.

15 Summary

The technical problems for the future office are difficult but not insurmountable. One of the biggest drivers towards this vision of a PV powered office is the trend towards ubiquitous working practices. This need for an office to act as a reconfigurable space, either for collaboration or quiet work will drive the use of mobile computing and encourage the development of a low-powered DC network.



This could provide the incentive towards the design of an office which is far more energy efficient – with intelligent lighting solutions, smart controlled HVAC systems and an optimized façade with inbuilt PV generation.

By 2020, low-rise offices in any location in the world could reduce their energy demand by around 70%; and by installing PV panels, offices could be at least 60% carbon neutral in the UK or above 90% in a Mediterranean or desert climate.

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17 Appendices

17.1 Appendix 1: Office equipment energy use

17.1.1.1 Climatic and internal factors affecting future UK office heating and cooling energy consumption

Jenkins et al [30] compared the energy consumption of IT equipment now (2005) and in the future (2030), and the impact on the heating and cooling. In their analysis they included the variations in power levels and the variations in idle time.

Table 2
Equipment characteristics for current (2005) and future (2030) scenario

Year	Machine	On		Standby		Suspend		Off		Total (kWh/year)
		Power	h/year	Power	h/year	Power	h/year	Power	h/year	
2005	PC	70	5131	9	376	0	0	3	3255	372.3
	Monitor	61	3281	2	2980	0	0	1	2505	208.6
	Printer	278	263	27	2190	11	2978	11	2978	
	PhotoCop.	1354	313	396	1408	68	1408	0.6	5631	
	Fax	30	62.4	15	8674	0	0	0	0	1415.7
	Scanner	150	104	15	1508	0	7124	0	0	
2030	PC	60	988	9	4472	0	0	3	3224	109.2
	Monitor	7	988	2	4472	0	0	2	3224	22.3
	MF	720	576	48	2553	0	0	0	5631	537.3

Jenkins et al [30] – Equipment characteristics for current (2005) and future (2030) scenarios

17.1.1.2 Review of computer energy consumption and potential savings [31]

Bray [31] undertook a literary review of computer energy consumption for Dragons Systems Software Ltd, a company specialising in power management software. The review looked over the studies undertaken on computer and monitor use during the occupied and unoccupied hours.

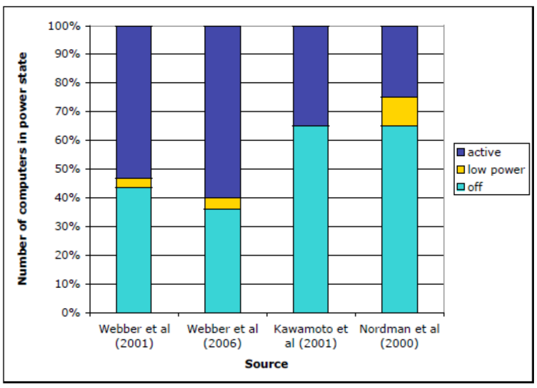


Figure 4: Nighttime power state of computers

Figure: Night time power state of computers

Estimates ranged from 30% to 60% of desktop computers that were left on full power. Of the rest, most were off, and hardly any were in low power mode.

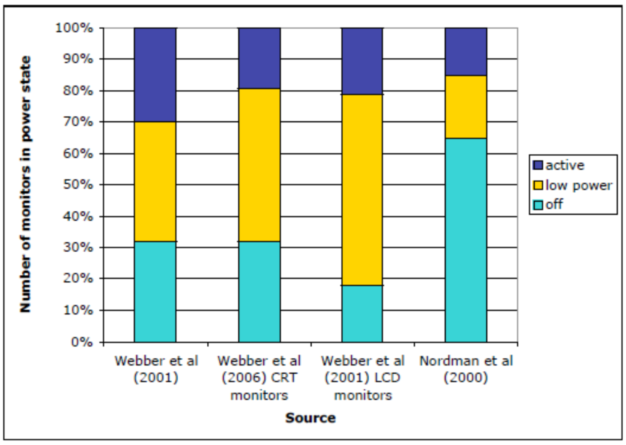


Figure 5: Nighttime power state of monitors

Figure: Night time power state of computers

Monitors performed better, with a maximum of 30% of screens left on at full power. In 3 out 4 studies, most monitors were left in a low power mode, and not switched off entirely.

17.1.1.3 <u>After-hours power status of office equipment and inventory of miscellaneous plug-load equipment [37]</u>

As part of a night-time survey of the quantity of office equipment that was left on at night, this study discovered that approximately 10% of all computers were laptops. This was described as a conservative figure, as it did not take into account laptops and cables that were taken home, or were locked in a drawer. Of the laptops that they found: 25% of the laptops were clearly running and 95% were plugged in.

17.1.1.4 Energy use and power levels in new monitors and personal computers [37]

A study done in 2002 by Roberson et al, looked at the average power levels of office equipment in a sample of offices in the US.

Table 8. Variation in Monitor *On* Power (W), for Selected Monitors

		Monitor *On* Power (W)								
Display		Desktop	Application	Black	White	Desktop		Black	White	**Ratio of max to**
Resolution		As-found				Min	Max	Min	Max	**min *On* W (%)**
CRT	15"	63	66	62	66	58		57	67	118
	15"	56		48	57					119
	17"	86	97	75	93	82	86	74	96	131
	17"	96	104	74	104					140
	19"	90		86	103					120
	19"	91	99	69	97	82	99	59	111	188
	21"	118	123	103	128	116	125			124
	21"	99		93	111					119
LCD	15"	17		16	16					106
	15"	33		32	33	33				103
	18"	59		57	59					104
	18"	40		37	40	40		37		108

Table 9. Statistical Analysis of Desktop Computer Power Levels

Count (n)	14	14	13	7	7	14
All Desktop Computers	*Off* (W)	*Sleep* (W)	**Wake from** *Sleep* **(sec)**	*Light Sleep* (W)	**Wake from** *Light Sleep* **(sec)**	*On* (W)
Minimum	1	2	5	29	2	28
25th percentile	2	3	9	34	3	50
50th percentile/Median	3	4	12	52	4	63
Average/Mean	3	9	13	49	5	70
75th percentile	4	5	14	54	6	94
Maximum	4	48	24	90	11	117

Table 11. Statistical Analysis of Laptop Computer Power Levels

Count (n)	9	9	7	8	7	9
Laptop Computers	*Off* (W)	*Sleep* (W)	**Wake from** *Sleep* **(sec)**	*Light Sleep* (W)	**Wake from** *Light Sleep* **(seconds)**	*On* (W)
Minimum	1	1	2	2	1	14
25th percentile	1	2	5	8	1	15
50th percentile/Median	2	3	14	11	1	19
Average/Mean	2	3	10	11	2	19
75th percentile	2	3	16	14	2	20
Maximum	3	8	16	19	4	25

Tables: Variation and statistical analysis of Monitor, desktop and laptop computer power levels according to Roberson

17.1.1.5 Energy Saving Potential of Office Equipment Power Management [32]

This can be compared with Kawamoto et al [35], who took lower average power levels.

		On (W)	Low-power (W)	Off (W)
PC	Desktop	55	25	1.5
	Portable	15	3	2
Display	CRT	85	5	0.5
	LCD	15	1.5	0.5
Copier (monochrome)		185	76	8.7
Laser printer		77	25	1

Table: Monitor, desktop and laptop computer power levels according to Kawamoto

Some information on the density of ownership of different types of office equipment

		Density (units per worker)		Manual-off rate (%)	
		Japan	US	Japan	US
PC	Portable	0.42	0.15	97	44
	Desktop	0.62	0.94	82	44
Display	CRT	0.54	0.92	60	32
	LCD	0.086	0.025	60	32
Copier		0.047	0.060	55	18
Laser printer		0.14	0.17	55	24

Table: Office Equipment density in Japanese and US offices

Kawamoto et al 2004 discovered that on average a computer is operated for 6.9 hours a working day. From these 6.9 hours, 3.9 hours the computer is left idle. 3 hours per day at 5 days per week, is a total of 9% of the week in use.

	Power-on time (hours per day)	Idling time (hours per day)
PC	6.9	3.9
Display	6.9	3.9
Copier	12.0	11.5
Laser printer	9.9	9.8

Table: Average length of computer operation per day

Kawamoto also studied the impact of a delay before a computer goes into idle. If it is set to only 5mins, then 76% of the daytime idle time is in low power mode. If the idle time delay is an hour, then only 20% of the daytime will be in low power mode. There is an obvious trade-off between a system which is too sensitive (turning off all the time and causing annoyance) and a system which does not have any impact on saving energy.

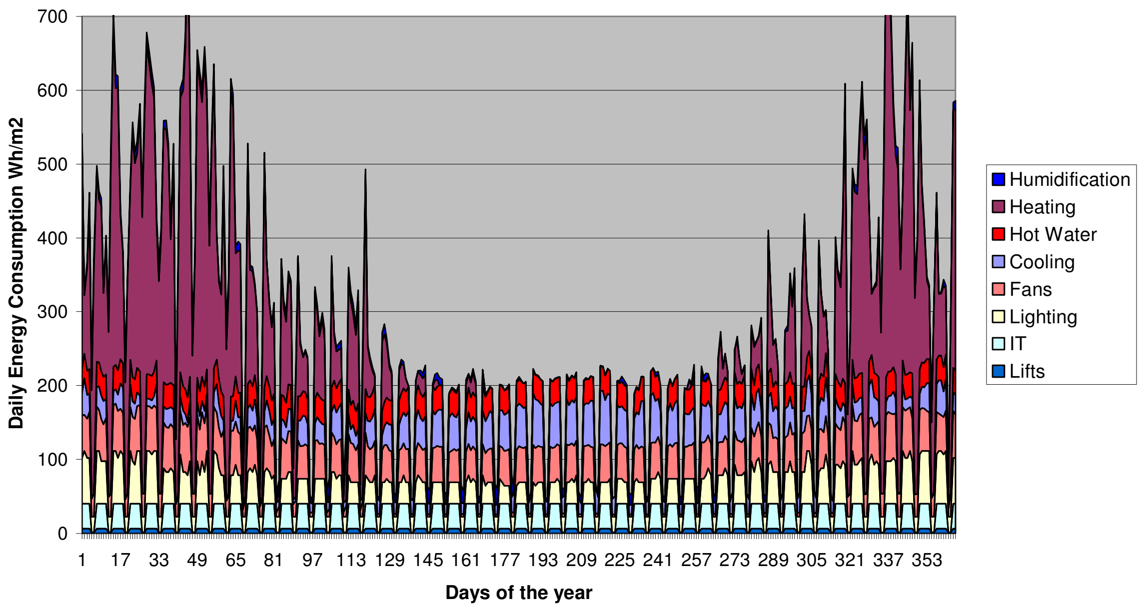
Total idle time = 3.9 hours per day			
Idle time delay (minutes)	Idle time in active mode (hours)	Idle time in low power mode (hours)	Time in low power mode (%)
5	0.9	3	76
15	1.9	2	51
30	2.6	1.3	34
60	3.1	0.8	20

Table: Effect of idle time delay on power state

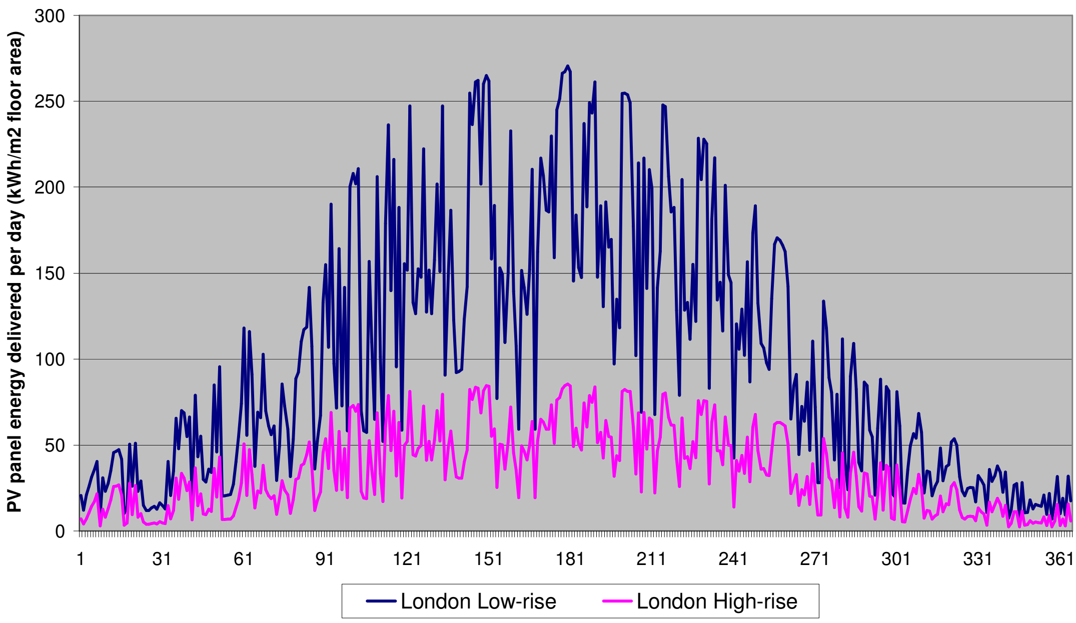
17.2 Appendix 2: Energy breakdown for each city

17.2.1 London

17.2.1.1 Energy Demands

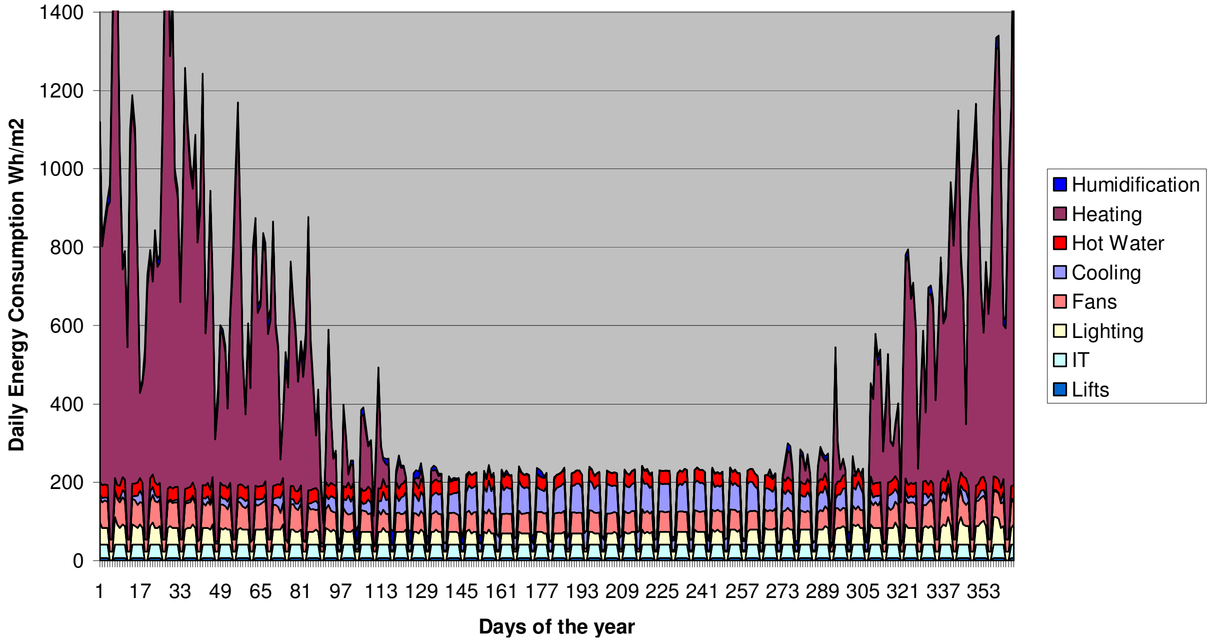


17.2.1.2 PV Supply

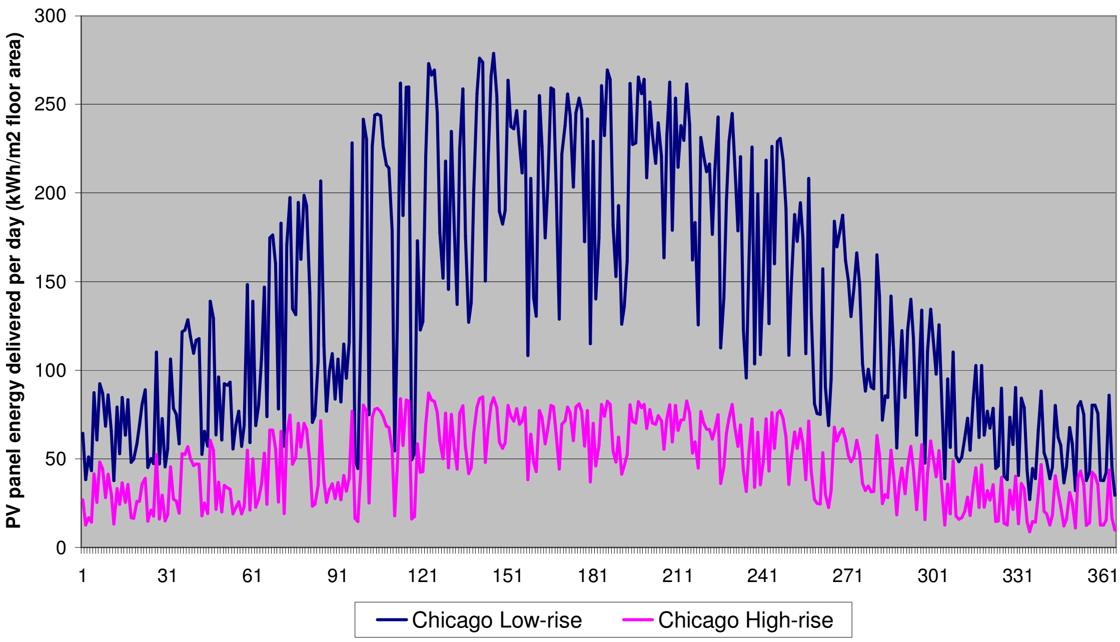


17.2.2 Chicago

17.2.2.1 Energy Demands

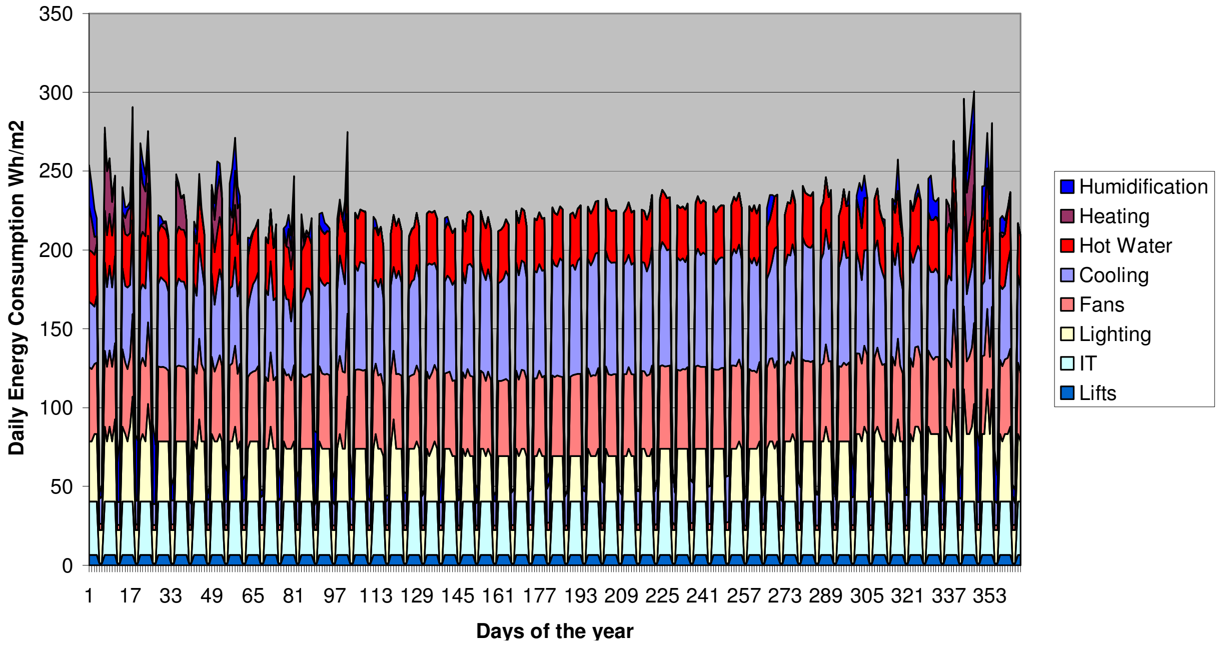


17.2.2.2 PV Supply

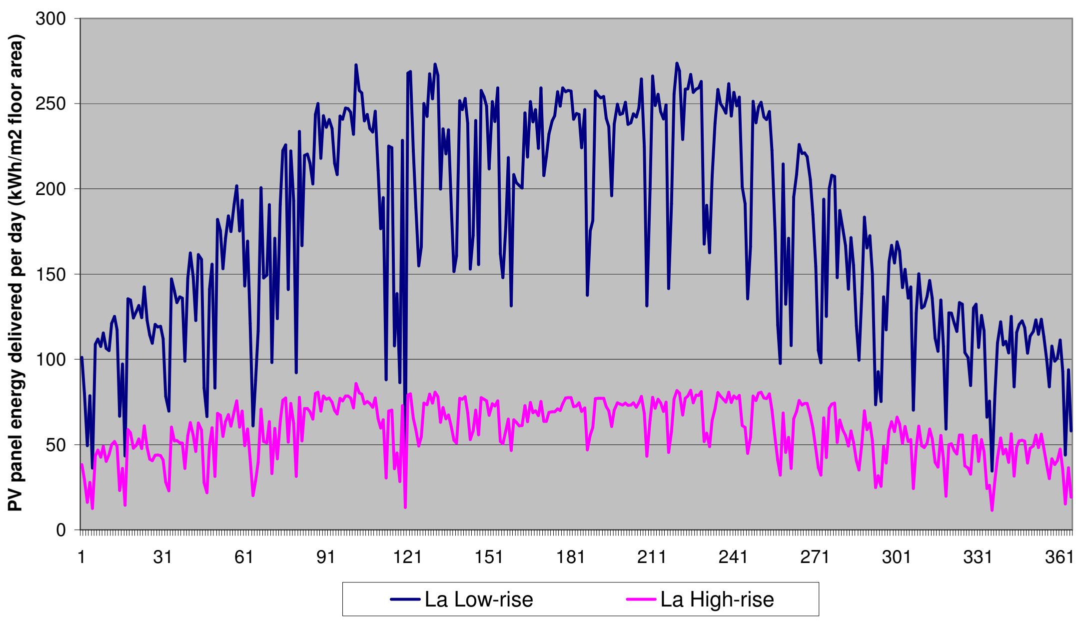


17.2.3 Los Angeles

17.2.3.1 Energy Demands

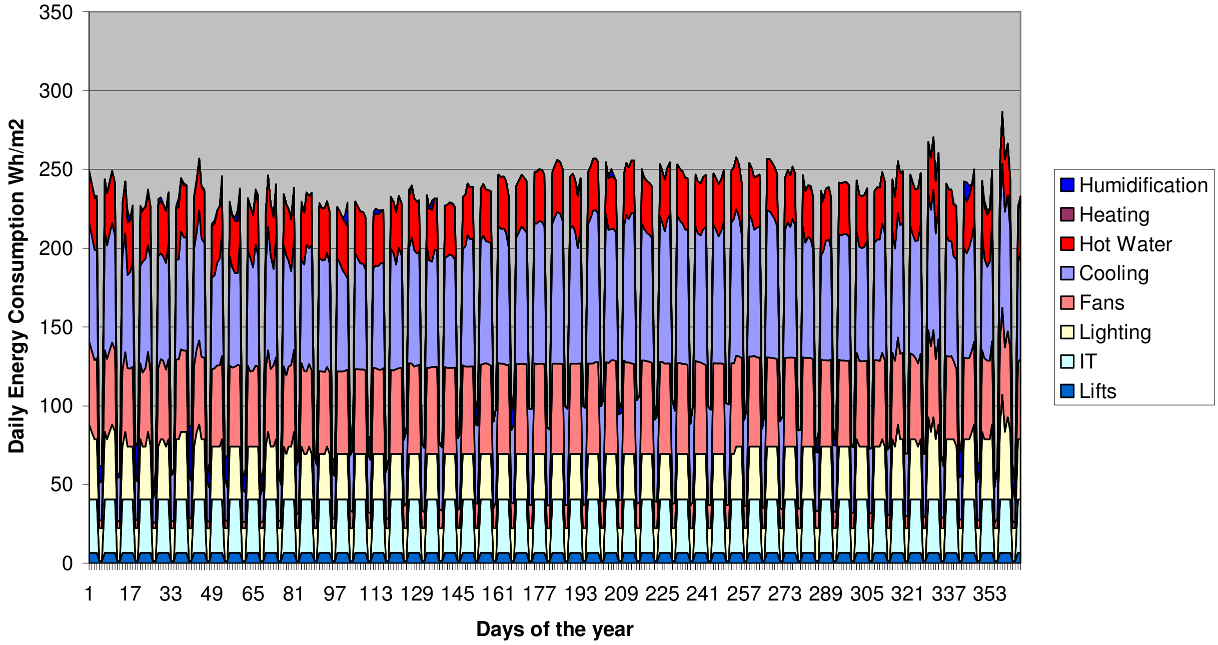


17.2.3.2 PV Supply

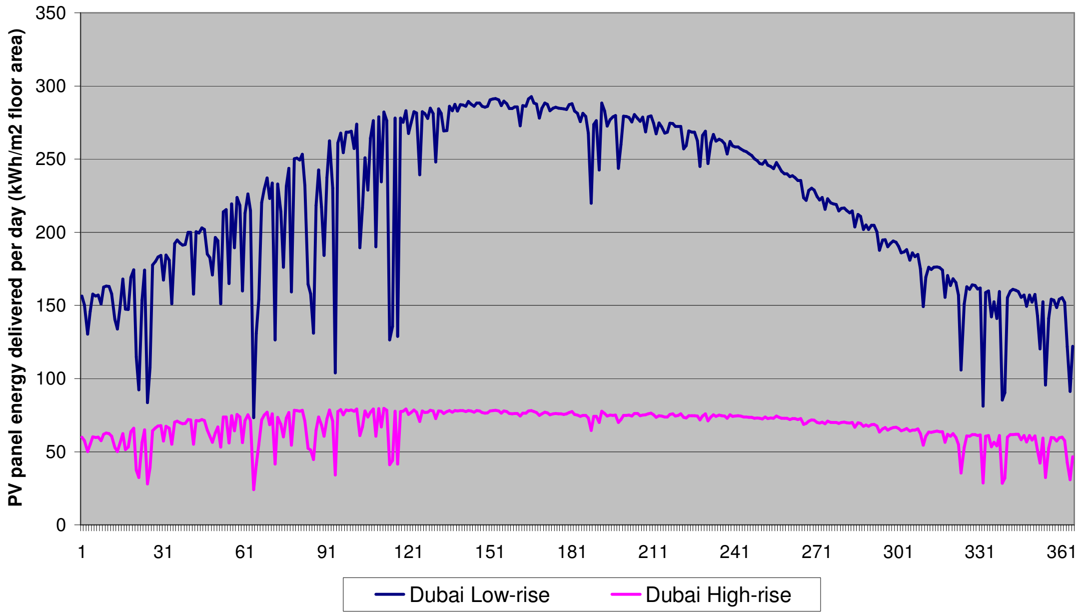


17.2.4 Dubai

17.2.4.1 Energy Demands

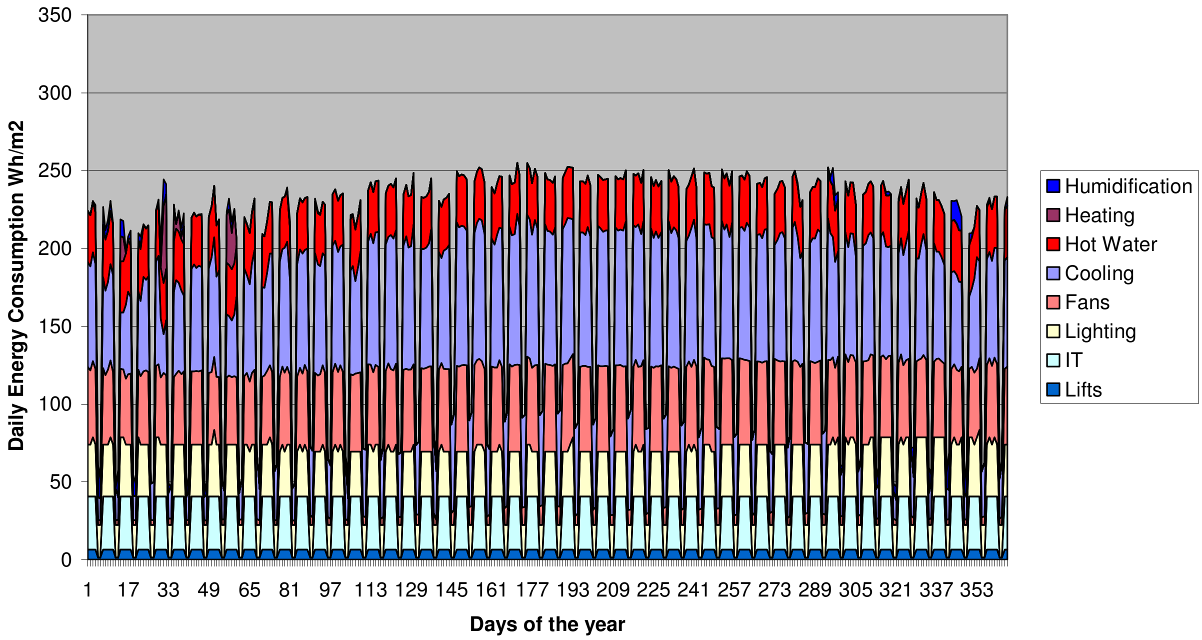


17.2.4.2 PV Supply

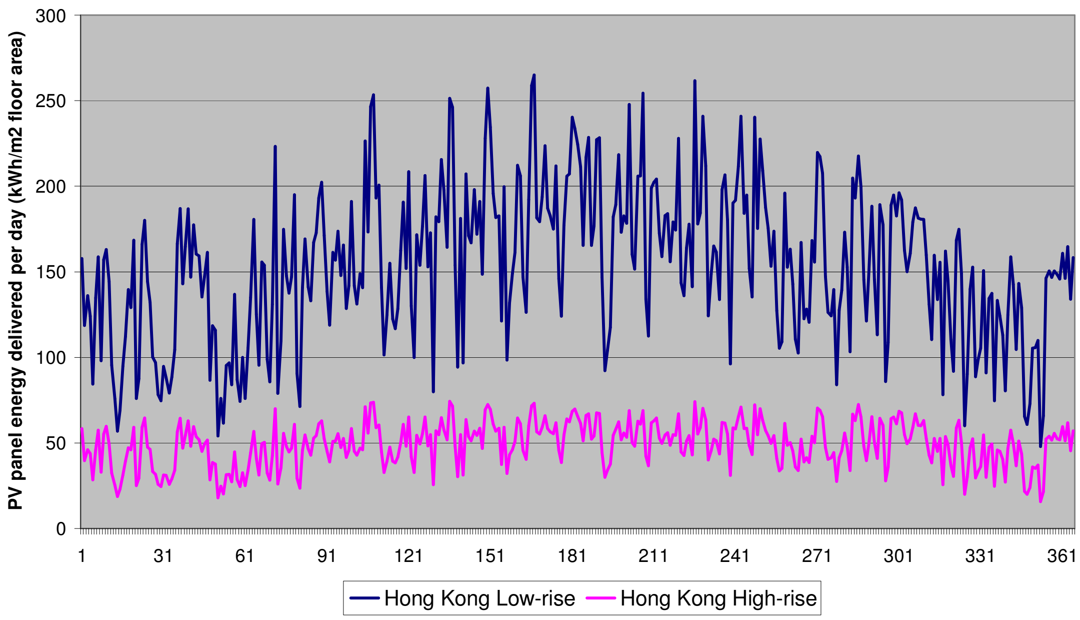


17.2.4.3 Hong Kong

17.2.4.4 Energy Demands

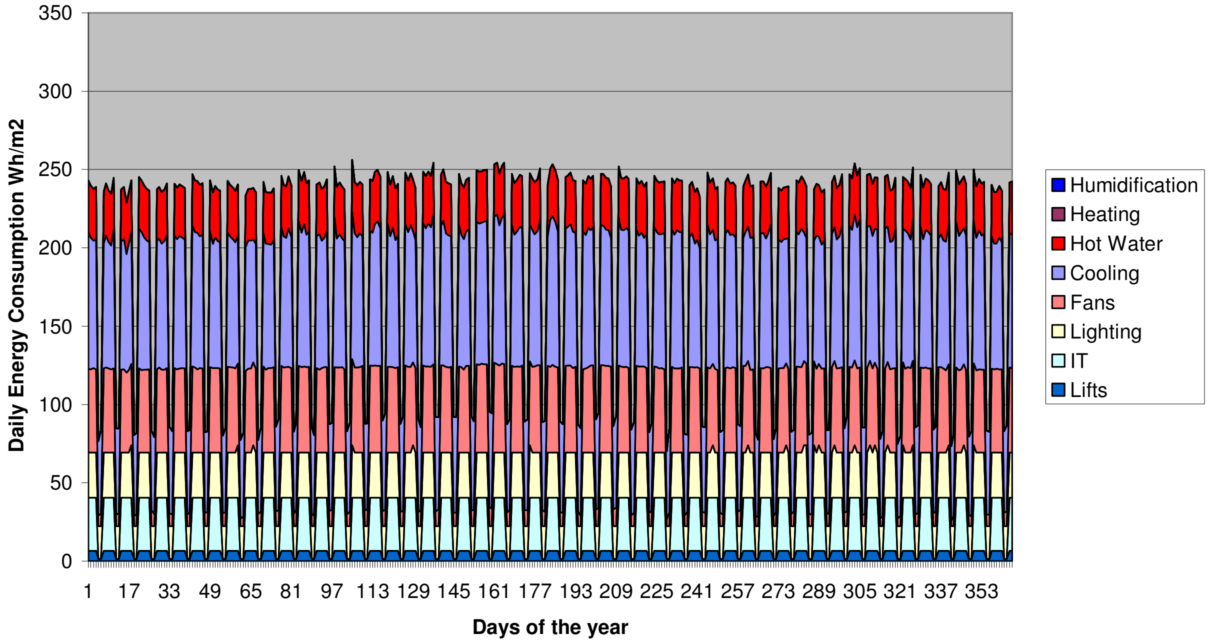


17.2.4.5 PV Supply



17.2.5 Singapore

17.2.5.1 Energy Demands



17.2.5.2 PV Supply