AIR CONDITIONING ENERGY USE IN HOUSES IN SOUTHERN ENGLAND

J. HE, A.N. YOUNG*, A. PATHAN, T. ORESZCZYN

Bartlett School of Graduate Studies
University College London
1-19 Torrington Place Site, Gower Street
London, WC1E 6BT, UK
*corresponding author, Tel: +44 (0) 207679 5905,
Fax: +44 (0) 207916 1887, email: alan.young@ucl.ac.uk

ABSTRACT

As a result of increasing summer temperatures in the UK, it is likely that more dwellings in the future will have air conditioning installed to meet the occupants' comfort requirements. This trend will inevitably increase the energy demand for cooling. This study, using computer simulation, estimates the likely increase in domestic cooling energy, under a number of scenarios. Three typical house types, detached, semi-detached and terrace were modelled and cooling energy consumption calculated based on information collected from a previous field study carried out by the authors and from the literature. The energy consumption data for the 3 dwelling types were then summed over the housing stock and adjusted for the level of air conditioning ownership to provide an estimate of the total cooling energy demand in southern England.

The study shows that the annual cooling energy needed for a typical sitting room of 18 m^2 is 100 kWh, and 180 kWh for a similarly sized bedroom. Simulations indicate that currently the total annual cooling energy needed by domestic air conditioners is around 50 GWh, with resulting emissions of 6 kilotonnes of carbon, for southern England, at current ownership levels, if units are installed in both the sitting room and main bedroom. This is estimated to be 0.012% of the total UK energy consumption of 402 TWh. However, this cooling energy could increase to 210 GWh per year (25 kilotonnes carbon), if ownership increases to 10%. Set-point temperatures also have a major impact, with a 2 ^oC decrease increasing consumption by 45%, while a 2 ^oC increase gives a 28% reduction. It was also found that using a "mixed mode" approach to cooling the bedroom, where windows were opened late at night and in the early morning, decreased the cooling required ten-fold. This would be a worthwhile mode of operation for use in climates, such as in southern England, where ambient temperatures at night often fall below the set-point of the air conditioners.

Keywords: domestic air conditioning, dwelling simulation, domestic cooling energy, domestic carbon emissions

1. INTRODUCTION

The UK is committed to reducing carbon emissions by 60% by 2050. This will require major improvements to the energy efficiency of the building stock as energy consumption in buildings accounts for around half of the total UK energy consumption of 402 TWh in 2004 [1]. Several studies have demonstrated how this 60% could be achieved for dwellings [2, 3], however, these have assumed zero domestic air conditioning use, due to the lack of robust data to estimate current and future cooling loads as summer temperatures increase due to climate change.

The UK Climate Impacts Programme (UKCIP) predicts that average annual temperatures in the UK are likely to increase by somewhere in the region of 2 to 3.5^{o}C over this century. Parts of southern England may even be 5^{o}C warmer in summer [4], and the number of cooling degree days will increase. This rise in temperature will increase the number of dwellings where air conditioning is installed, and increase the energy consumption in each air conditioned dwelling. Although the ownership of air conditioners is currently low in the UK, it could in the future rise to between 15 to 20% [5]. Some experts have even suggested that air conditioning should be a statutory obligation in all new UK housing [6]. Any such trend will inevitably compromise the carbon reduction target of the UK, and increase summer electricity loads. Quantifying and understanding the potential impact of domestic air conditioning is therefore important to help formulate future government policies and to help find alternative low energy cooling strategies.

Empirical data relating to domestic air conditioning energy consumption is currently unavailable in the UK. Computer modelling is therefore used in this study to estimate energy demand in houses in southern

England where mechanical cooling is predominately installed. As the results of computer modelling are critically dependent on assumptions about occupant behaviour, it is therefore important that any modelling is grounded with actual field data. In the summer of 2004 the authors monitored the usage patterns of 9 dwellings in the south of England. The results of this monitoring, which is described in detail in "UK Domestic Air Conditioning: A pilot study of occupant use and operational efficiency" [7], include the temperature at which people switch on their air conditioners, the length of time units are run once they are switched on and the temperatures achieved during operation, all of which are important input factors when modelling energy consumption. The data collected is summarised in Table 1.

This paper presents for the first time an estimate of the potential domestic energy consumption from air conditioning in the UK using this real field data of occupant usage patterns as input to thermal simulations of typical dwellings, and extrapolating these results under a number of different scenarios. Previous estimates have been based on extrapolating from the uptake and use patterns of the USA, correcting for cooling degree days [8, 9] and as such does not allow for different behavioural patterns that may occur in the U.K.

Table 1. Monitored air conditioning use patterns in 9 UK dwellings (Young at al., 2005).

		Average						
		Switch-on room temperature and RH		Maintained room temperature and RH		Outdoor temperature		Duration of single operation (hours)
Site and location	**Main usage time**	[ºC]	[%]	[ºC]	[%]	Day [ºC]	Night [ºC]	hh:mm
1. Loft study	Day/ Night	22.3	51	21.3	53	23	17	08:45
2. Bedroom	Night	23.8	50	22.1	46	21	14[Ë]	08:30
3. Bedroom	Night	24.2	48	18.8	46	21	14	10:00
4. Conservatory	Day	23.5	55	22.9	52	20	21	06:10
5. Bedroom	Night	25.0	48	21.2	52	20	18	08:15
6. Kitchen/dining	Day	22.8	61	22.1	55	20	15	04:20
7. Bedroom	Night	22.7	-	19.1	64	19	15	09:45
8. Sitting room	Day	27.9	50	27.8	54	23	17	04:30
9. Kitchen/dining	Day	25.9	43	25.5	40	15	22	00:45
Average	**-**	**24.2**	**51**	**22.3**	**51**	**20**	**17**	**07:00**

2. METHODOLOGY

2.1 Dwelling types modelled

The thermal simulation program used in the modelling was the commercially available software package, TAS [10, 11, 12]. The summer period, for which the modelling was carried out, was taken to be from 1 June to 30 September, in line with previous summer overheating research [13, 14]. Three types of typical English house were modelled using TAS: detached, semi-detached and terrace[1]. The age of the housing stock in England varies widely, and due to the changes in building technology over time and, more recently, the building regulations, differing building construction will impact on air conditioning energy consumption which needs to be accounted for in the computer modelling. The age distribution of the housing stock in this study was divided into pre-1919, 1919-1964 and post 1964, in line with published data [15, 16]. The geometric features, floor plan, building construction and internal conditions of the 3 dwelling types, in the 3 periods, were based on a combination of information from the authors' monitoring and field study (see above) and the literature [13, 14, 17]. In all a total of 9 dwelling types were modelled. To simplify the modelling process, the same geometric features and floor plan were used for each dwelling

[1] This study only considers houses and not flats.

type, and only the heat transfer properties of construction were changed to estimate the affect of the age of the property. Internal conditions, such as number of occupants, use of appliances and internal gains, were assumed identical in all 9 models. The weather condition used was the 2004 London area weather data obtained from the UK Meteorological Office. Table 2 summarises the model parameters.

Table 2. General dwelling modelling parameters.

Model parameters	Description	Source
Orientation	sitting room and main bedroom assumed to be facing south	
Total floor space	90 (±5) sq m	[15]
Total glazing area	20% of total floor space	
Sitting room space	detached: 22 sq m; semi-detached: 19 sq m; terrace: 12 sq m	[14] and field study
Main bedroom space	detached: 15 sq m; semi-detached: 14 sq m; terrace: 12 sq m	[14] and field study
Occupants	2.5	[14, 16]
Incidental gain	shown in figures 4 and 5	
Air tightness	background infiltration of 0.5 ac/h	
Weather condition	2004 London area weather data	

Dwelling size was derived from the English House Condition Survey [15]. This survey indicates that the average floor area in southern England is 90 m^2, slightly larger than the national average of 85 m^2. Nearly half of the southern England housing stock has 3 bedrooms. The dwelling models assumed 2 storeys with 3 bedrooms and a floor area of 90 (±5) m^2. The geometric features and floor plans of the detached and semi-detached dwellings were based on construction plans provided by a major UK house developer (as given in [14]), whereas, the floor plans of the terrace dwelling were based on the authors' field survey, since standard details were unavailable, and the surveyed dwelling closely matched the areas given in the English House Condition Survey [15]. Figures 1, 2 and 3 show the plans of the ground and first floor of the modelled detached, semi-detached and terrace houses, together with geometric layout used. All modelled dwellings were assumed to have the air conditioned living room and main bedroom facing south.

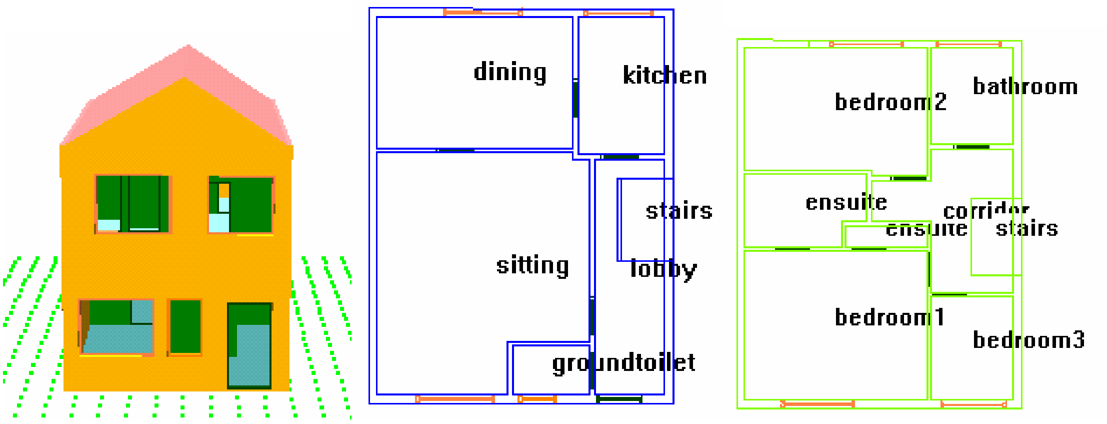


Figure 1. Geometric model and ground and first floor plans of the detached house.

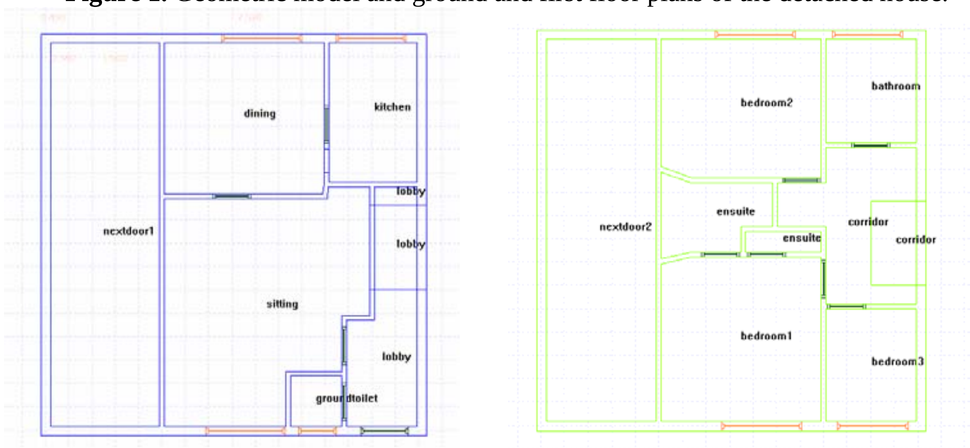


Figure 2. Ground and first floor plans of the semi-detached house.

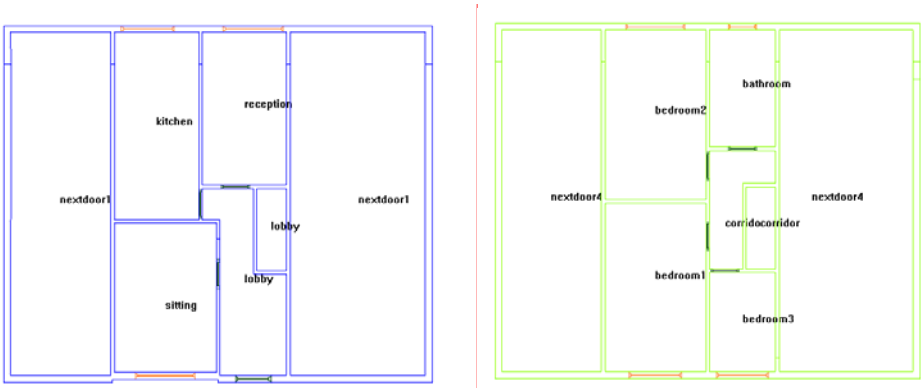


Figure 3. Ground and first floor plans of the terrace house.

Internal incidental heat gains, and their time profiles, which are based on the authors' field survey and used in the models, are shown in Figures 4 and 5. The number of occupants was taken as 2.5 as suggested by the General Household Survey [16].

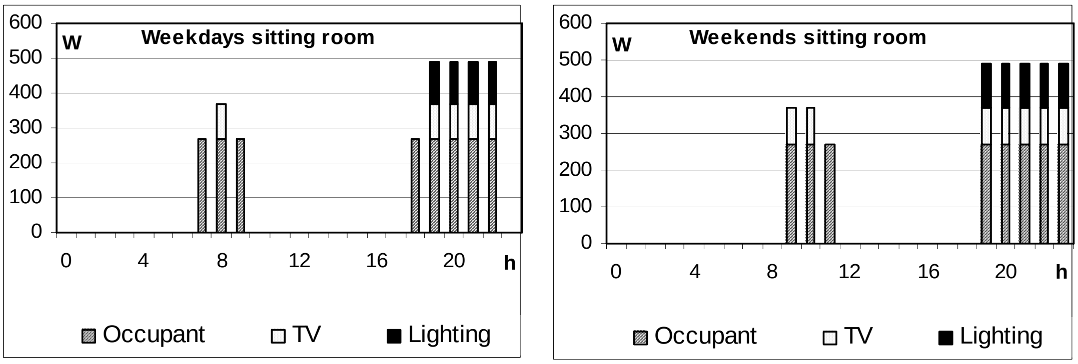


Figure 4. Assumed internal incidental heat gain patterns for sitting rooms.

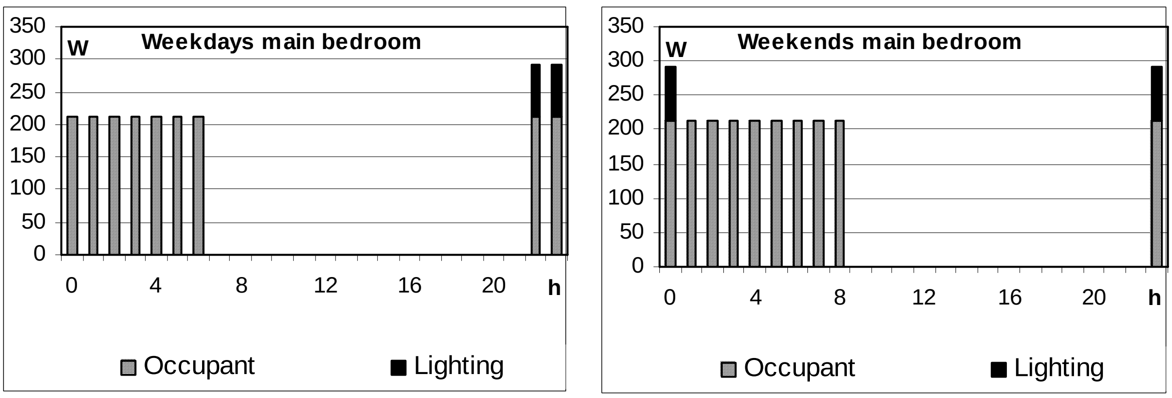


Figure 5. Assumed internal incidental heat gain patterns for bedrooms.

Details of construction of the pre-1919 dwellings were based on the 3 pre-1919 dwellings monitored during the authors' field study, while for the 1919-1964 models, the construction was based on the typical structure of dwellings built in the 1930s [17]. The construction used for the post-1964 dwellings was again based on 4 houses from the authors' survey built in the 1980s and 90s and the appropriate building regulations current at the time. Table 3 shows the composition of the main building elements used in the models for the different ages. Although insulation measures such as loft insulation and double glazing were not required by the Building Regulations then, by 2001, 93.5% and 74.5% of the dwelling stock nation-wide had loft insulation and double glazing [16]. This study therefore assumed roof insulation and double glazing in all modelled dwellings. A background infiltration of 0.5 air changes per hour has been assumed. The largest investigation into air leakage in UK dwellings suggests that the mean air leakage is 13.1 air changes per hour at 50 Pascal's [18]. This would normally equate to a winter air infiltration rate of about 0.75 air changes per hour. However a lower summer time air infiltration rate has been assumed because of the different weather conditions that would prevail during the summer. The lower wind speeds typical of hot spells and the reduced indoor/outdoor temperature differential would be expected to produce a lower air infiltration rate in the summer.

Table 3. Composition of the main building elements used in the dwelling models.

Type of element	Age	Description	U-value (W/m2 K)	Y-value (W/m2 K)
Walls	Pre-1919	Solid brick with 13 mm plaster finish	1.3	2.8
	1919-1964	50mm cavity brick with 13 mm plaster finish	1.2	2.7
	Post-1964	Cavity bricks with 55 mm glass fibre insulation	0.36	1.7
Floors	Pre-1919	Suspended timber floor with 500 mm cavity on ground floor, wood floors on upper storey	0.5*	2.1*
	1919-1964	Suspended timber floor with 500 mm cavity on ground floor, wood floors on upper storey	0.3*	1.2*
	Post-1964	Concrete floors on ground floor, wood floors on upper storey	0.28*	3.1*
Roofs	Pre-1919	Slated roof with 70 mm glass fibre insulation	0.46	1.3
	1919-1964	Slated roof with 100 mm mineral wool insulation	0.32	0.68
	Post-1964	Slated roof with 140 mm glass fibre insulation	0.25	1.3

*Ground floor U- and Y-value

Cooling control was assigned to the sitting room and main bedroom only as these are the two main locations where domestic air conditioning is installed. Table 4 lists the temperature settings assumed for these spaces.

Table 4. Hours of operation and temperature set-point of air conditioning.

	Air conditioning operation hours between 1 June to 30 September	Temperature maintained
Sitting Room	Weekdays: 5:00pm - 11:00 pm; 7:00 am - 9:00 am Weekends: 5:00pm - 12:00 pm; 10:00 am - 2:00 pm	22 ± 2 C
Bedroom	Weekdays: 9:00 pm - 8:00 am Weekends: 10:00 pm - 9:00 am	22 ± 2 C

2.2 Dwelling stock profile

There were approximately 21 million dwellings in England in 2001, of which 41% (or 8.6 million) were located in London, the southeast and southwest of England [15], which this study has taken as a definition of southern England. Table 5 shows the distribution of national and regional housing stock by dwelling type and age. However, there is no data available on the distribution of types at different time periods. This paper therefore assumes that the distribution of dwelling type for each period is the same as that for all dwellings in southern England.

Table 5. Distribution of dwelling type and age in southern England (ODPM, 2003).

		London	South East	South West	Total (Southern England)	
					All dwellings (,000s)	%
	Number of dwellings [,000s)	3,076	3,428	2,119	8,623	
Distribution by dwelling type	**Terrace [%]**	31.2	25.0	28.4	2,419	28.0
	Semi-detached [%]	17.5	27.8	28.1	2,087	24.2
	Detached [%]	5.3	29.0	29.5	1,782	20.7
	Flat [%]	46.1	18.1	14.0	2,335	27.1
Distribution by age	**Pre-1919 [%]**	25.6	17.9	22.5	1,878	21.8
	1919-1964 [%]	45.7	36.3	31.7	3,322	38.5
	Post-1964 [%]	28.7	45.8	45.8	3,423	39.7

2.3 The profile of future ownership

Future levels of ownership of air conditioning in dwellings will depend on such factors as market penetration, price and the severity of summers. In marketing literature, statistical models have been developed to estimate product market penetration [19]. However, there are limited historic statistics on the number of air-conditioning systems in UK homes due to the small market size (as distinct form commercial systems) [20], and so modelling of future ownership using historical trends is likely to be unreliable. It is believed that the current number of air conditioning units in use in the domestic sector in the UK is of the order of half a million [21]. Assuming ownership of one unit per dwelling, this indicates that 2.4% of the 21 million housing stock in England have a unit currently installed. Future projections state that this stock will increase to around 0.7 million by 2010, 1.1 million by 2020 and 2.3 million by 2050 [21]. It is also estimated that the number of UK dwellings will increase from 21 to around 29 million by 2050 depending on different future social, economic and environmental scenarios [3, 22]. However, this study assumes a similar housing stock level in the future as of today, which is 21 million, in line with the UK government's sustainability scenario to limit the number of dwellings in the future [3, 22]. This means that future dwelling ownership of air conditioning units will be about 3.3% by 2010, 5.2% by 2020 and 11% by 2050 in the UK. This future ownership projection is assumed across the whole country including southern England.

Market surveys indicate that of the half million air conditioners in dwellings, most are portable units sold "over the counter". The latest sales analysis indicates that of the units sold to the residential market in 2002, 80-90% were of the portable type [20]. As no historic figures are available to understand past and future trends, this study assumed that 85% of the half million units currently in the UK are portable units, with the reminding 15% being domestic scale single-split vapour compression systems, and that the same distribution of types will hold in the future. The numbers of other types are negligible in the context of this study.

2.4 Energy Efficiency Ratio (EER)

The nominal energy performance, obtained under standard conditions [23, 24], of individual air conditioning units (the EER) are available from manufacturers. The latest energy label directives define air-cooled air conditioners with an EER above 3.2 as energy efficiency class A [23]. Most portable units available on the market belong to classes E and F with an average EER less than 2.6, whilst most split systems belong to class D, E and F with an average EER of 2.8 [20, 25]. In this study, an EER of 2.8 for the split system has therefore been used. However, as part of the authors' previous work, laboratory tests were carried out to evaluate approximately the EER of a portable unit (bought at random from a DIY supermarket). The study, carried out under real use conditions [7], produced an average EER of around 0.8, and this value is used here.

Table 6 summarises the data used in the modelling relating to the percentage of dwellings that own air conditioning systems and the EER.

Table 6. Air conditioning ownership in dwellings in southern England and their EER.

	2005	2010	2020	2050
Air conditioning unit ownership (%)	2.4	3.3	5.2	11
Ownership distribution by type (%)	Split system		Portable unit	
	15		85	
EER (split system)	2.8			
EER (portable unit)	0.8			

2.5 Housing stock cooling demand calculation

The electrical energy needed to meet the cooling demand in dwellings in southern England is calculated as follows,

$$E = \sum_{m=1}^{2} \left(\sum_{i=1}^{3} \sum_{j=1}^{3} (CE_{i,j} \times HS_{i,j} \times OW) \times AC_m \div EER_m \right) \quad (1)$$

where i = 1 to 3 (for the 3 house type); j = 1 to 3 (for the 3 construction periods) and m = 1 to 2 (for the 2 air conditioning unit types), and

E is the annual energy requirement for cooling in southern England [kWh]

$CE_{i,j}$ is the simulated cooling energy for dwelling type *i*, built in period *j* [kWh]
$HS_{i,j}$ is the number of dwellings, type *i*, built in period *j*
OW is the ownership of air conditioning [%]
AC_m is the distribution of air conditioning unit type, *m* [%]
EER_m is the average seasonal energy efficiency rating, in use, of air conditioning unit type *m*
and

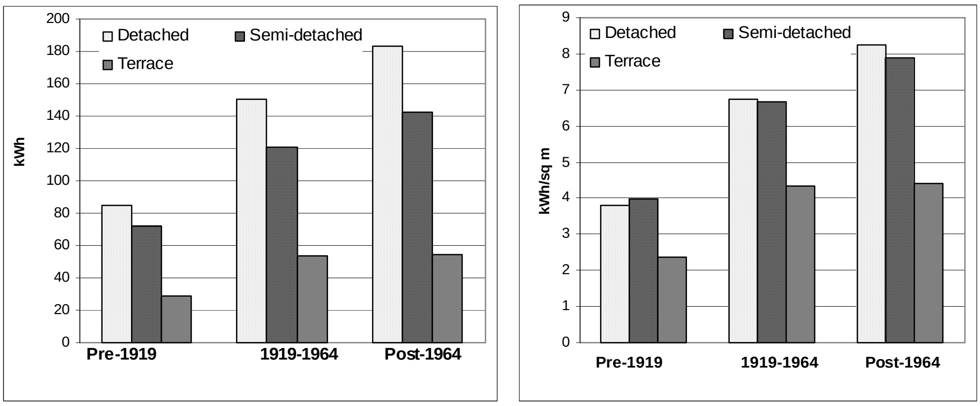
$$HS_{i,j} = Stock \times T_i \times P_j \qquad (2)$$

where
Stock is the total number of dwellings in southern England
T_i is the number of type *i* dwellings, as a percentage of the total number of dwellings, and
P_j is the number of dwellings, built in period *j*, as a percentage of the total number of dwellings.

3. RESULTS

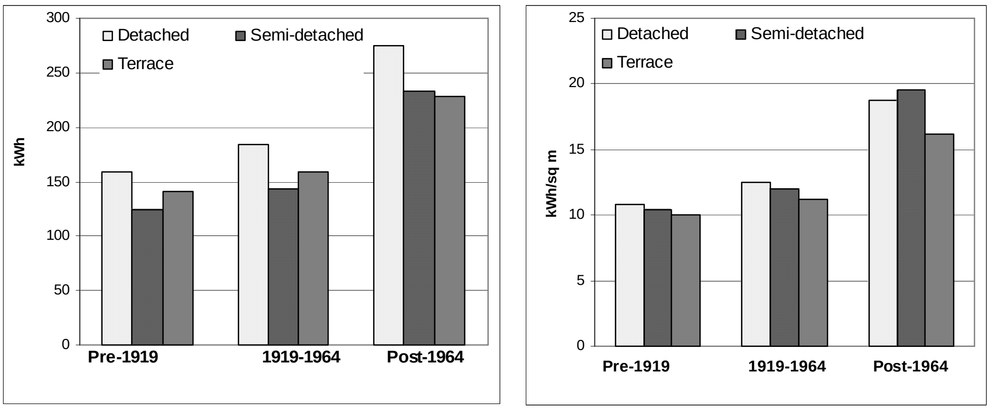
3.1 Energy consumption for summer cooling of individual dwellings

Figures 6 and 7 show the TAS simulated summer cooling energy (kWh) and cooling energy per square metre (kWh/m^2) for the sitting room and main bedroom in the 9 modelled dwellings. Post-1964 dwellings need the most cooling in the sitting room, while pre-1919 the least. Sitting rooms in the detached dwellings require more cooling than those in semi-detached and terrace types, while semi-detached dwellings need more than terrace houses. The cooling energy per unit floor area in sitting rooms, however, is similar to the detached and semi-detached models. On average, 100 kWh of cooling are needed to keep a sitting room with an average size of 18 m^2 cool in summer, which results in 6 kWh/m^2 cooling energy for each sitting room.
Nearly double the amount of cooling is need in the main bedrooms compared to sitting rooms. On average, 180 kWh of cooling are needed for bedrooms with an average size of 19 m^2 (or 15 kWh/m^2). The relationship between dwelling age and cooling energy for the bedrooms is similar to that for sitting rooms.



Left: room cooling loads; Right: room cooling loads per m^2

Figure 6. Cooling loads for sitting room in the 9 dwellings modelled using TAS.



Left: room cooling loads; Right: room cooling loads per m^2

Figure 7. Cooling loads for the main bedroom in the 9 dwellings modelled using TAS.

3.2 Cooling demand for the housing stock

Table 7 shows the predicted electrical energy used for cooling the housing stock in southern England for 2005, 2010, 2020 and 2050 using Eq (1). The corresponding carbon emissions are calculated using the conversion factors given by the National Energy Foundation [26]. The data includes the increase of ownership from the current level to 2050, and shows that three times more electricity is needed for summer cooling. In this analysis, the weather file used was for 2004. The effect of climate change is dealt with below. If both the sitting room and one bedroom are air conditioned by 2050 in 10% of dwellings in southern England, the cooling energy demand will amount to 210 GWh with carbon emissions of 25 kilotonnes.

Table 7. Predicted present and future energy demand and carbon emissions from air conditioning systems in dwellings in southern England.

	To cool sitting rooms		To cool main bedrooms		To cool sitting and main bedrooms	
	Energy [GWh]	Carbon emissions [kilo tonne]	Energy [GWh]	Carbon emissions [kilotonne]	Energy [GWh]	Carbon emissions [kilotonne]
2005	18	2	32	4	50	6
2010	25	3	44	5	69	8
2020	40	5	70	8	110	13
2050	77	9	133	16	210	25

Conversion factors: 0.43 kg CO_2/kWh or 0.117 kg C / kWh (= 0.117 kilotonne carbon / GWh) (National Energy Foundation [26]).

3.3 The effect of changing the set-point temperature of the air conditioning unit

Table 8 compares the energy consumption of the main bedroom of the post-1964 detached house for a number of temperature set-points. Lowering the set-point to 20^{o}C increases the energy demand by 45%, while raising it by 2 ^{o}C to 24 ^{o}C causes a 28% decrease.

Table 8. Effect of changing temperature set-point on cooling energy demand of the main bedroom of the post-1964 detached dwelling.

Description	Result	
	Cooling energy [kWh]	Change [%]
Set-point temperature: 22 (±2) ^{o}C	275	-
Set-point temperature: 20 (±2) ^{o}C	398	45
Set-point temperature: 24 (±2) ^{o}C	199	-28

3.4 The effect of passive cooling techniques on the energy demand

To estimate the effect of some passive cooling techniques, such as solar shading and window opening on the energy demand, further simulations were carried out. Table 9 shows how the cooling energy demand for the main bedroom of the post-1964 detached dwelling changed as a result. The provision of window blinds and a very window large overhang (of 5 m) produced a very modest reduction of 2% in the cooling energy. Clearly, a more practically sized overhang would produce an even smaller reduction.

Although occupants are unlikely to open windows when running their air conditioning units, there are times when the outdoor temperature will be below the temperature set on their units, for example, late at night and early in the morning. Simulations were carried out to investigate the effect of two window opening regimes on the cooling energy required. The first used a regime reported by occupants during the authors' field survey, which included daytime opening, while the second allowed window opening only during the late evening and early morning. The first gives an almost negligible 1% increase, while the second gives a large 90% reduction. The issue of window opening is complex, as this type of passive cooling involves the dwelling's thermal storage effects, where the daytime heat stored in the structure can leak into the bedroom at night, and the associated time lag can mean that the previous day's ventilation regime affects the cooling loads for the following day. Clearly if the outdoor temperature is above the indoor, windows should be kept shut, whether the air conditioning unit is running or not. It is recognised that occupants are unlikely to keep windows open in bedrooms while they sleep if the bedroom feels hot when they first go to bed, so the reduction suggested here is unlikely to be realised. Nevertheless, the simulation shows that considerable savings can be made using a "hybrid" or "mixed mode" arrangement combining natural night-time ventilation with air conditioning, and that further research should be undertaken into this method of operation.

Table 9. Effect of passive cooling methods on cooling energy demand of the main bedroom of the post-1964 detached dwelling.

Change	Description	Result	
		Cooling energy [kWh]	Change [%]
No change	-	275	-
Use of solar shading	Window blind and 3 m roof overhang	269	-2
Occupant opening regime	Windows scheduled to open as described by the occupants in the field study: Weekdays: 8:00 - 9:00 am; 6:00 - 9:00 pm Weekends: 10:00 am - 10:00 pm	278	1
Window open only at night	Windows scheduled to open late at night and in the early morning: Weekdays: 10:00 pm - 8:00am Weekends: 10:00 pm -10:00 am	27	-90

3.5 The effect of adopting different future scenarios on the cooling energy demand

The main factors that may affect the modelled future amount of total cooling energy demand in southern England are total housing stock level and profile, the EERs of the air conditioning units, levels of ownership, market share of each air conditioning type and climate change or increase in number of cooling degree days. Many scenarios can be formed based on different combinations of changes in these factors. Table 10 examines the effects of changing some of the factors on the total main bedroom cooling energy demand in southern England in 2050. Doubling the current EER for both split systems and portable units causes this cooling demand in 2050 to reduce by 67%, while increasing the share of split systems to 50% decreases it by 28%. The ownership of air conditioning is likely to vary greatly between regions in the UK as many areas would still remain relatively cool in summer, even if summer temperatures rise as suggested by UKCIP climate change scenarios [8]. Ownership in southern England is believed to be higher than the national average, in fact between 30-40% higher [8]. Arbitrarily increasing ownership to 30% will increase the cooling energy demand to 400 GWh. The UK government's foresight programme predicted that the worst future scenario, or "world market" scenario [3, 22], would lead to 29 million houses by 2050. Assuming 41% of this stock is located in southern England, this would increase dwelling numbers in this region by 40% to 11.9 million. Changing the housing stock to this level results in a similar 40% increase in cooling energy demand.

Table 10. Effect of adopting different scenarios for EER, market profile, ownership, housing stock and number of cooling degree days on main bedroom cooling energy demand in 2050 in southern England.

Scenario	Description	Result	
		Cooling energy [GWh]	Change rate [%]
Original scenario	Original main bedroom cooling energy demand in southern England in 2050	134	0
1: EER	EER of split systems improved to 5 EER of portable units increased to 2.5	44	-67
2: Market profile	Split system market share increased to 50% with portable unit share decreased to 50%	96	-28
3: Ownership	Air conditioning ownership increased to 30%	401	199
4: Housing stock	Housing stock in southern England increased to 11.9 million	184	37
5: Cooling degree days	Cooling degree days increased from present value of 68 to 218	430	220

The UK Climate Impact Programme has suggested a number of scenarios for future climate trends in the UK. Their latest study [4] has produced data (for future years) for use in building design and assessment purposes. This work took the predicted trends and "morphed" them with the current CIBSE/Met Office weather data files, to produce data for use in predicting building thermal performance, and energy needs, in the future [13]. Their work suggests that the number of summer cooling degree days will increase from the current value of 68, by 150 to 200 degree days in the future, for the London area, with a base temperature of 22°C [13]. If it is assumed that the number of cooling degree days increases by 150 by 2050, and that the cooling energy increases proportionally to the number of degree days, the cooling energy required for the bedroom will more than double to 430 GWh.

4. DISCUSSION

The factors which determine the level of overheating in dwellings are well known. They include solar gains, ventilation regime, thermal mass, casual heat gains and ambient temperature. Recommended measures used to address these factors to limit overheating and therefore to achieve passive and/or low energy cooling include natural ventilation at night and solar shading [14, 27, 28]. The simulations show that both window opening (at appropriate times) and solar shading reduce cooling energy. In particular, the analysis shows that night time and early morning window opening can decrease cooling energy in the main bedroom by a factor of 10. Cooling temperature control (the temperature set-point) is also important in limiting cooling energy. If the cooling expectation of the occupants can be adjusted from the current 22 ºC to 24 ºC, space cooling energy consumption can be lowered by 20-30%.

It should be noted that this study did not investigate other types of recommended measures, such as dwelling orientation, providing additional thermal mass with night cooling, control of incidental gains and evaporative cooling through external water features and trees [14, 27, 28]. Further study is recommended to quantify the effects of those low energy cooling measures.

5. CONCLUSION

This study has shown that post-1964 dwellings need more cooling than dwellings built before 1919, or during 1919-1964. Generally, detached dwellings require more cooling energy for sitting rooms and/or bedrooms, than semi-detached and terrace houses. On average 100 kWh of cooling energy is needed, annually, for an 18 m^2 sitting room and 180 kWh for a similarly sized bedroom. If this level of cooling is achieved by portable air conditioning units, it would lead to CO_2 emissions of 50 and 80 kg in these two spaces respectively. As a comparison, the current average annual CO_2 emissions from heating are 900 kg [9]. The sensitivity analysis of the simulation study reveals that the cooling load in the main bedroom could be reduced ten-fold with appropriate natural ventilation using window opening from around midnight to early morning. As there is little data available on the cooling of dwellings, it is difficult to verify the simulation result. However, it is possible to compare the predictions presented in this study with those based on extrapolation from the experience in the USA [8, 29]. Henderson [8], taking the weather data for 2003 in the UK, estimates that the whole house cooling of an 85 m^2 dwelling will need 32 kWh electricity, or 0.4 kWh/m^2. Henderson[8] also states that if the summer temperatures were 2 K greater than in 2003, the cooling load would increase to 260 kWh (3.1 kWh/m^2). If the average US air conditioning system, with an EER of 3[30] is input to the simulated models in this study, 30 and 60 kWh electricity (1.7 and 3.2 kWh/m^2) is needed to operate the air conditioning systems in the sitting and main bedroom respectively. Considering that UK dwellings are more compact and so incidental gains will be more concentrated, more cooling would be expected to be required [8]. This suggests that the simulated results are of a similar order to that estimated by Henderson [8].

Assuming the ownership of air conditioning is 2.4% in the current housing stock, it is estimated that respectively 18 and 32 GWh of electricity would have been needed to cool the sitting rooms and main bedrooms in southern England in the summer of 2004. Together this is 0.012% of the total energy consumption of the UK in 2004 (402 TWh). If a similar housing stock level, 10% ownership and installation of air conditioning in both the sitting room and main bedroom is assumed for 2050, the cooling energy demand will amount to 210 GWh with 25 kilotonnes of carbon emissions. A number of different scenarios for 2050 have also been modelled. These show that cooling energy demand increases dramatically when ownership levels, as predicted in the literature, are reached. Cooling energy demand triples by 2050 when unit ownership rises to 30%. Climate change also has a major impact, with the energy required more than doubling with an increase in cooling degree days of 150.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge financial support from the Engineering and Physical Sciences Research Council (EPSRC) for the work carried out in this study. The authors are also grateful for invaluable and extensive guidance and expertise from the project's Steering Committee members and to the many householders who contributed to the study. However, the opinions expressed in this paper are those of the authors and not necessarily those of the organisations and individual mentioned.

REFERENCES

[1] DTI. Digest of United Kingdom Energy Statistics 2005. HM Stationery Office; 2005.

[2] Johnson D. A Physically-based Energy and Carbon Dioxide Emission Model of the UK Housing Stock. PhD Thesis. Leeds Metropolitan University; 2003.

[3] Boardman B, Darby S, Killip G, Hinnells M, Hardine CN, Palmer J and Sinden G. 40% House. Environmental Change Institute University of Oxford; 2005.

[4] Hulme M, Jenkins GJ, Lu X, Turnpenny JR, Mitchell TD, Jones RG, Lowe J, Murphy JM, Hassell D, Boorman P, McDonald R and Hill S. Climate change scenarios for the United Kingdom: The UKCIP02 Scientific Report. Norwich: Tynadall Centre for Climate Change Research, School of Environmental Science, University of East Anglia; 2002.

[5] Anon. Residential AC - not if, but when Refrigeration and Air Conditioning 1999; 101 (1217): 46-48.

[6] Shackley S. Centre for Climate Change, UMIST. Quoted in an article by M Townsend, the Observer; 11 August 2002.

[7] Young AN, He J, Pathan A and Oreszczyn T. UK Domestic Air Conditioning: A pilot study of occupant use and energy efficiency. Submitted to the International Journal of Building Services Engineering Research & Technology; 2005.

[8] Henderson G. Electricity use for air conditioning by households in the USA. Part L review report; 2003.

[9] ODPM. Proposals for amending Part L of the Building Regulations and Implementing the Energy Performance of Buildings Directive. HM Stationary Office; 2004.

[10] Environmental Design Solutions Ltd. www.edsl.net, 2005

[11] Crawley DB, Hand GW, Kummert M, Griffith BT. Contrasting the Capabilities of Building Energy Performance Simulation Programs. A joint report by US Department of Energy, University of Strathclyde, University of Wisconsin; 2005 (available at http://www.eere.energy.gov/buildings/tools_directory/pdfs/contrasting_the_capabilities_of_building_energy_performance_simulation_programs_v1.0.pdf).

[12] Panayi P. Prioritising energy investment in new dwellings constructed in Cyprus. Renewable Energy 2004; 29: 789-819.

[13] CIBSE. Climate change and the indoor environment: impacts and adaptation. CIBSE TM36; 2005.

[14] Orme M and Palmer J. Control of overheating in future housing-design guidance for low energy strategy. Birmingham: Fabermaunsell Ltd.; 2004.

[15] ODPM. English House Condition Survey 2001. The Office of the Deputy Prime Minister. HM Stationery Office; 2003.

[16] Shorrock JD and Utley JI. Domestic Energy Fact File 2003. Watford: BRE; 2003.

[17] BRE. Thermal mass and overheating-providing modelling support to guidance on overheating in dwellings. Birmingham: Fabermaunsell Ltd.; 2005

[18] Stephen RK. Airtightness in UK dwellings: BRE's test results and their significance. Building Research Establishment, BRE 359. UK; 1998.

[19] Bass FM. A new product growth model for consumer durables. Management Science 1969; 15: 215-227.

[20] BSRIA. Western European Market for Air Conditioning: room, packaged and close control air conditioning UK. BSRIA report 17544/4; 2003.

[21] House of Common. Hansard (House of Commons Daily Debates) of 7 June 2005. http://www.parliament.the-stationery-office.co.uk/pa/cm200506/cmhansrd/cm050607/text/50607w05.htm, 2005.

[22] SPRU. Foresight future 2020-revised scenarios and guidance. Science Policy and Research Unit, University of Sussex, 2002.

[23] Enrovent. http://www.eurovent-certification.com, 2005.

[24] Market Transformation. http://www.mtprog.com/approvedbriefingnotes/BriefingNoteTemplate.aspx?intBriefingNoteID=88, 2005.

[25] Adnot J, Becirspahic S, Rivière P and Waide P. Four years after: a RAC story (RAC: Room Air conditioners). Proceeding of the 3rd International Conference on Energy Efficiency in Domestic Appliances and Lighting 2003(EEDAL'03) ; Italy: Turnin.

[26] National Energy Foundation. http://www.nef.org.uk/energyadvice/co2calculator.htm, 2005.

[27] Action Energy. Low Energy Design. UK: Interface Publishing; 2002.

[28] Smith PF. Eco-refurbishment-a guide to saving and producing energy in the home. Elsevier Architectural Press; 2004.

[29] Sailor DJ and Pavlova AA. Air conditioning market saturation and long-term response of residential cooling energy demand to climate change. Energy 2003, 28: 941-951.

[30] LBNL. Room Air Conditioners Rulemaking-Technical Support Document for Energy Conservation Standards for Room Air Conditioners. Lawrence Berkeley National Laboratory;1997.