Impact of climate change on thermal comfort, heating and cooling energy demand in Europe

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Abstract
So far, in most European countries, the amount of energy required for heating is greater by far than the energy used for space cooling on a national basis– even in the service sector. But due to higher internal loads, the proliferation of fashionable glass facades, thermal insulation, and rising standards of comfort, the cooled floor area is steadily increasing. Events like the extraordinary hot summer of 2003 are accelerating this trend and steadily rising mean annual temperatures (1.3°C during the 20th century in Switzerland) are increasing the specific energy demand for space cooling. In this paper, we provide evidence regarding the increasing relevance of thermal discomfort in terms of overheating, due to both building retrofits and climate change. Further, possible changes in heating and cooling energy demand over the next 30 years are explored for two climate variants: mean annual temperatures remaining constant and a second case in which temperatures increase until 2035 by +1°C in winter and +2°C in summer. The possible impacts on the CO_2 emissions in different European locations are evaluated considering the CO_2 intensity of the heating fuels, the market penetration of electric heating, and the CO_2 intensity of electricity production.

For much of Europe, increases in cooling energy demand due to global warming will be outweighed by reductions in the need for heating energy. Depending on the generation mix in particular countries, the net effect on CO_2 emissions may be an increase even where overall demand for delivered energy is reduced. Strategies and measures in the building sector to minimize possible negative impacts of climate change on energy demand for heating and cooling are discussed.

Introduction
The short-term dependency of energy demand for space heating on winter temperature in the Swiss service sector is well understood. This provides a basis for estimating the effect on demand of longer term changes in temperature, such as those reported for the period 1970-2004 (Hofer, 2003) and the further warming of several degrees ˚C expected in the coming decades (Hohmann/Neu, 2004). Energy demand for space cooling is at present small and thus variations in summer temperature are yet hardly detectable in the national electricity demand pattern. But due to adverse impacts of higher internal loads, fashionable glass facades, and thermal insulation thermal comfort levels, the cooled floor area is steadily increasing. Increasing comfort expectations (in particular in the working environment) resulting from the diffusion of cooled trains, cars, and public space (shopping centres, cinemas) and events like the extraordinary hot summer of 2003 in Europe are accelerating this trend and the specific energy demand for cooling. In regions of the moderate climate zone such as the north of France, Germany, Switzerland, Austria etc., the impact of climate change could be particularly sensible due to a bascule effect. Indeed, under past weather conditions the number of days with uncomfortable indoor conditions in terms of overheating and the amount of cooling demand was relatively low. Thus, slightly higher outdoor temperatures could change this pattern drastically because a large number of hours and days which are currently only little below the cooling threshold could be moved above the threshold. It is important, therefore, to develop a better

Table 1. Indoor temperature limit as a function of daily outdoor temperature maximum

	Daily outdoor temperature maximum		
	<16.5°C	>16.5°C, <24.5°	>24.5°C
Indoor temperature limit	24.5°C	Linearly interpolated between 24.5°C and 26.5°C	26.5°C

Source: SIA (2006)

understanding of the relationship between changing summer weather conditions, thermal comfort and energy demand for cooling. Frank (2005) did very detailed simulation studies for individual buildings in Switzerland.

In this paper we explore possible changes in comfort levels, heating and cooling demand of individual office buildings and of the Swiss service sector as a whole. For a time horizon of 30 years, expected temperature increase and the evolution of the stock of buildings and their equipment is being taken into account. Two principal climate variants are evaluated: a reference case in which temperature remains constant and a second case in which temperature increases. For heating demand, changes in specific energy consumption are evaluated; for cooling demand, specific energy demand and floor area equipped with cooling equipment are varied.

The methodological approach to evaluate the impact of climate change was strongly inspired by a paper of Henderson (2005) presented at eceee'05. First results were presented at IEECB'06 (Aebischer et al., 2006).

The impact of climate change on the level of individual buildings

Indoor thermal comfort conditions and the energy requirements of buildings are influenced by a variety of factors such as internal loads from persons, appliances and lighting, thermal insulation levels, type of glazing and blinds, building technology and operation modes. In the mid and long term all of these factors are under lied more or less significant changes. Particularly insulation levels are being increased, occupation of persons will be denser and appliances, lighting and other building technology will become more efficient.

On the level of individual buildings the impact of climate change in terms of higher temperatures is twofold. Firstly, warmer temperatures affect indoor temperature and thermal comfort conditions. Secondly, specific heating energy requirements per unit of area are lowered and, if accordingly equipped, specific cooling energy requirements increased. Both factors impact on the aggregate energy demand of the buildings sector, either indirectly by a higher demand of cooled space of work and living or directly due to changed specific energy requirements.

In this section we estimate the impact of the above mentioned building related changes and of a climate change variant on both the thermal comfort and on specific energy requirements for different office building configurations, using a dynamic building simulation model (IDA-ICE, a follow-up generation of models such as DOE II). This is to provide some justification and evidence for the increasing relevance of cooling in buildings and for inputs of the later used bottom-up models.

Regarding thermal comfort we focus on the risks of overheating and its prevention, assuming that the research community, architects, planners and engineers have a good command of handling thermal comfort requirements during the cold season, last but not least due to the long tradition of heating buildings (although inadequate building configuration still might occur, in particular in relation with highly glazed buildings). However, thermal comfort in terms of overheating has often been neglected and it is becoming all the more relevant with increasing temperature.

The level of thermal comfort (or discomfort) can be characterised by different quantitative measures (e.g. number of hours or percentiles of either temperature or PPD-values[1]). Although percentile measures would bear some advantages we follow – for compatibility reasons – the current (2006) revision of the Swiss calculation norm SIA 382/1 (SN EN13779), where thermal discomfort in terms of overheating is characterized by the number of hours when the indoor temperature exceeds the so-called applicable upper temperature limit. Only hours during the building occupation periods are counted (see SIA 2006). The applicable daily temperature limit depends on the daily outdoor temperature maximum (Table 1). According to SIA (2006) the temperature limit should not be exceeded in more than 200 hours per year, if possible in less than 100 hours. Note that on the EU level, classification of buildings is in discussion according to which non-cooled buildings would be allowed to overpass the temperature limits in a higher number of hours than cooled ones.

INCREASING RELEVANCE OF THERMAL COMFORT AND COOLING UNDER CONSTANT WEATHER CONDITIONS

Due to the age structure of buildings and the lifetime of components a considerable part of the (office) building stock will be retrofitted and modernized in the coming decades. This retrofit includes both the external of the building such as window replacement and façade overhauling or retrofit and the renewal or retrofit of building technologies inside the buildings. These retrofit measures impact – needless to say – on the heating and electricity energy demand, but – less commonly discussed – also on the thermal comfort inside the buildings. As mentioned above the comfort discussion is focused on overheating risks.

If existing, previously non-insulated (office) buildings are insulated (façade, window or glazing) the number of hours with temperature above limit during occupation time is – everything else being equal – increasing significantly. The increase is typically up to 300 h in the summer half year, but may be more than 400 in a south-oriented room, assuming 11 h of occupation per day (Figure 1). The findings of this ceteris paribus comparisons are confirmed when plotting the number of hours with overheating against the specific heating energy demand (MJ/m^{2}a). In the case of non-cooled and non-ventilated (office) buildings the number with overheating increases as a function of lower heating energy demand (Jakob et al., 2006b, Figure 3, p. 10).

1. PPD: predicted percentage of dissatisfied persons

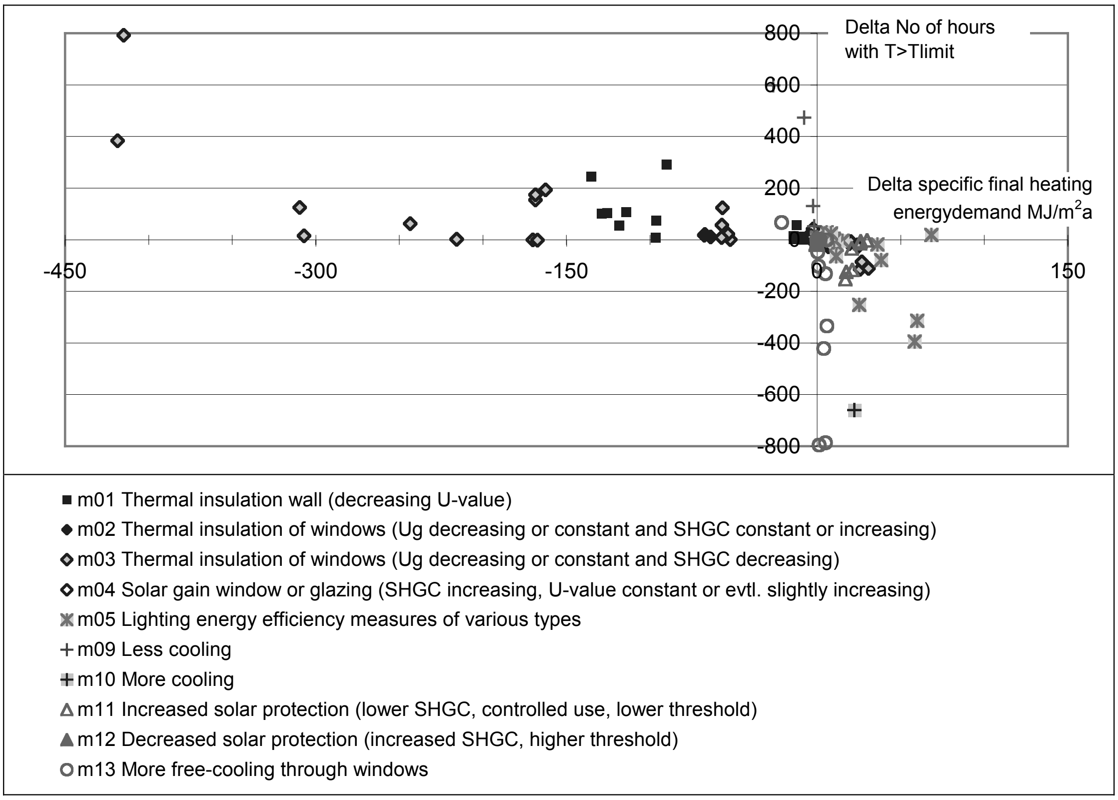

***Figure 1. Impact of energy efficiency measures on the number of hours with too high indoor temperature** (above limit according to Table 1) for south oriented rooms. Source: adopted from Jakob et al. (2006)*

These findings can be explained by the fact that solar energy gains and internal heat loads from persons, appliances and lighting are much less transmitted through the insulated envelope than through the non-insulated. Note heat from the outside is also less thermally transmitted to the inside, but for heat gains thermal transmittance is much less relevant as compared to the transparent part of the envelope and as compared to internal gains. Thus, heat is accumulated during periods of several sunny days, particularly in cases without cooling, night ventilation or aeration. With this respect buildings of the commercial sector behave fundamentally different than residential buildings where night ventilation is mostly assured.

On the other hand overheating can be reduced by (controlled) window opening or night ventilation, but also by reducing internal loads, for instance by renewing lighting and installing presence and daylight control. Improvements of up to 400 h per half-year can be achieved, in some cases even more. Conversely, overheating is increasing if internal loads are increasing. Internal loads increase due to more and larger appliances, but also due to a more dense occupation, a trend that is driven by the high cost of workspace. Hence the relevance of thermal discomfort in terms of overheating will increase even with constant climate.

Note however that the risk of overheating is not a plea to abandon building renewal and buildings insulation. Indeed energy gains from insulation are usually more than three times higher than electricity demand for additional cooling. Thus the primary energy balance is even positive if insulation is compensated by conventional cooling (assuming an electricity generation conversion factor of at least 0.33). This applies for new buildings (Frank 2005, Fig. 10 and Fig. 11 and Jakob et al., 2006b, Figure 2), but all the more for existing buildings (Figure 2). Efficiency gains on the primary energy levels are especially high in the case of lighting retrofit, particularly if combined with presence and daylight control. Indeed, electricity efficiency gains are more relevant than additional heating energy requirements. Inline with these gains is a considerable improvement of the thermal comfort (Figure 1).

The bottom-line of these considerations is that modernisation of (office) buildings should be carefully conceived to reduce risk of adverse effects on indoor climate (overheating) and to utilise synergy effects between energy efficiency and thermal comfort, in particular in the case of lighting.

IMPACT OF CLIMATE CHANGE ON THERMAL COMFORT AND ON SPECIFIC COOLING DEMAND

With higher outdoor temperature the risk of overheating is increasing, in particular in case of internal loads and an absence of (nocturnal) window aeration. Assuming meteorological data based on the summer of 2003 the indoor temperature of non-cooled office space is staying well above 26° even during morning hours and all the more during the course of the day (Brunner et al., 2006). A significant difference between 2003 and the design reference year was found (Brunner et al., 2006, Fig. 5 and 6). Significant overheating was also found by Frank (2005) for a climate change variant of +4.4°C for the period 2050 to 2100, in particular for the case without night ventilation, and this during a long period between June and September.

These findings are confirmed with own building simulations. For this paper, about forty cases of buildings were selected from the set of simulations presented by Jakob et al. (2006a). These cases cover a wide range of potential factors that influence the

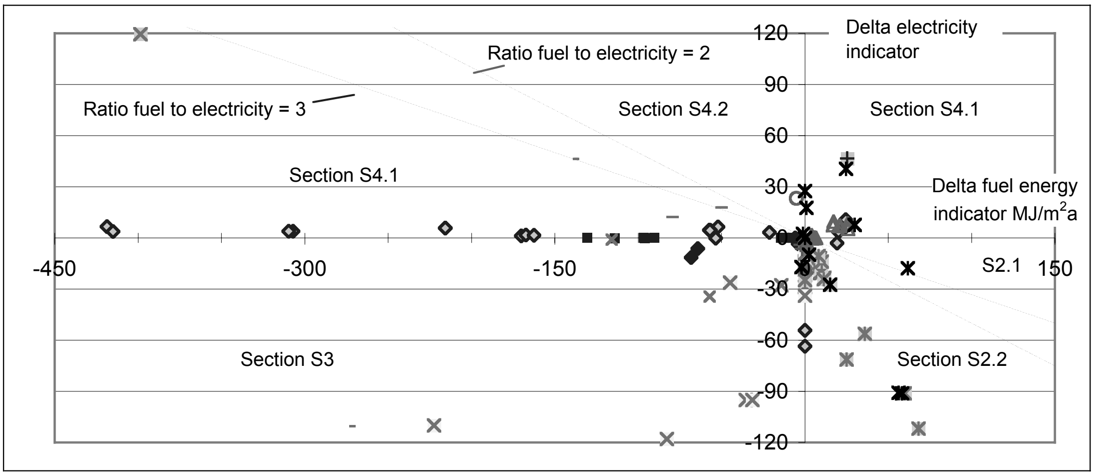

Figure 2. Impact of energy efficiency measures on electricity and fuel demand *(cf. Figure 1 for legend). Source: adopted from Jakob et al. (2006)*

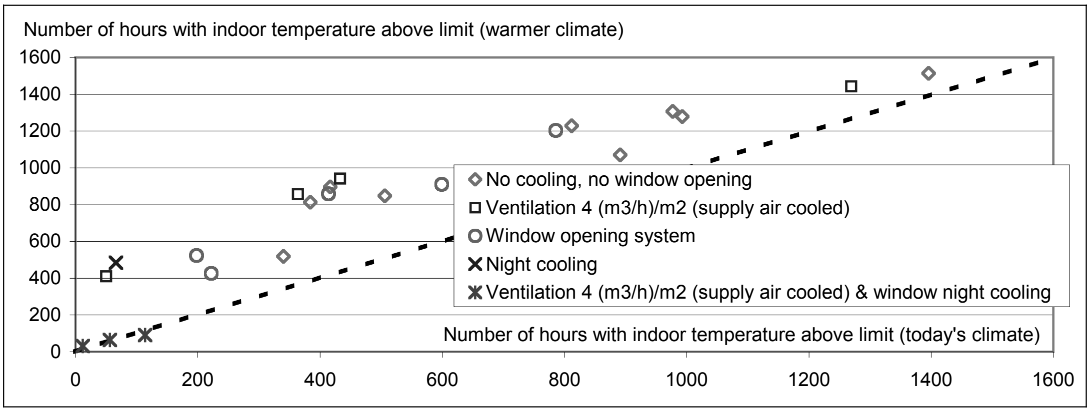

Figure 3. Number of hours with overheated rooms at warmer outdoor temperatures as a function of number of hours with overheated rooms at today's outdoor temperatures (*non-cooled or partially cooled buildings) Source: own calculations using simulation model IDA.*

cooling energy demand of buildings, including internal loads of persons and appliances, installed lighting load and lighting control concept, share of glazed building envelope, glazing quality, quality of sun protection and control concept, indoor temperature requirement, etc. Each case was run with a today's climate data set (DRY for Zurich, Switzerland) and with a data set of increased temperature (+2.5 K during the day and +3.5 K during the night).

The impact of this warmer climate is first discussed in terns of thermal discomfort for buildings without or with moderate cooling (only supply air cooling). This impact is considerable, particularly for buildings with more or less acceptable thermal indoor conditions (e.g. with up to 200 h of overheating in south oriented rooms during occupation as compared to the limit in Table 1) in the case of today's climate. In these cases the number of hours with overheating more than doubles and exceeds 400 h in the case of the warmer climate (Figure 3). In cases with 400 to 600 h of overheating in today's climate this discomfort indicator increases to 800 to 1000 hours. Hence, most buildings that can be operated with (controlled) window opening or ventilation with demand oriented air exchange (e.g. 4 $(m^3/h)/m^2$ in case of an occupation density of 10 m^2/person) do not satisfy thermal comfort requirements in the warmer climate case. Exceptions are buildings with a combination of ventilation with cooled supply air and night cooling through controlled window opening.

In terms of electricity demand for cooling due to warmer climate the estimated increase is between 10 and 30 MJ/m^2a (represented as error bars in Figure 4, left-hand side diagram) in the case of actively cooled buildings. Note that annual COP of cooling devices has been maintained constant and thus, these results represent the impact on the building only (excluding the impact on efficiency of the HVAC system). The relative increase of buildings with medium cooling energy demand (40 to some 100 MJ/m^2a) varies between 20 % and 50 % (Figure 4, right hand side diagram). For buildings with very low cooling demand (that include free cooling through windows, for instance), the relative change may be up to +100 %. To the upper end of the scale, i.e. for those with already high demand in the reference case, the relative increase due climate change is about 20 % (Figure 4). If compared with the total electricity demand of buildings, the impact of warmer climate varies mostly in a range 5 % and 10 % and reaches 15 % in one case.

Note that the impact of warmer climate in terms of cooling energy demand (in absolute values) is much smaller than the differences between the cases considered. This means that even with warmer climate, the cooling energy demand can be

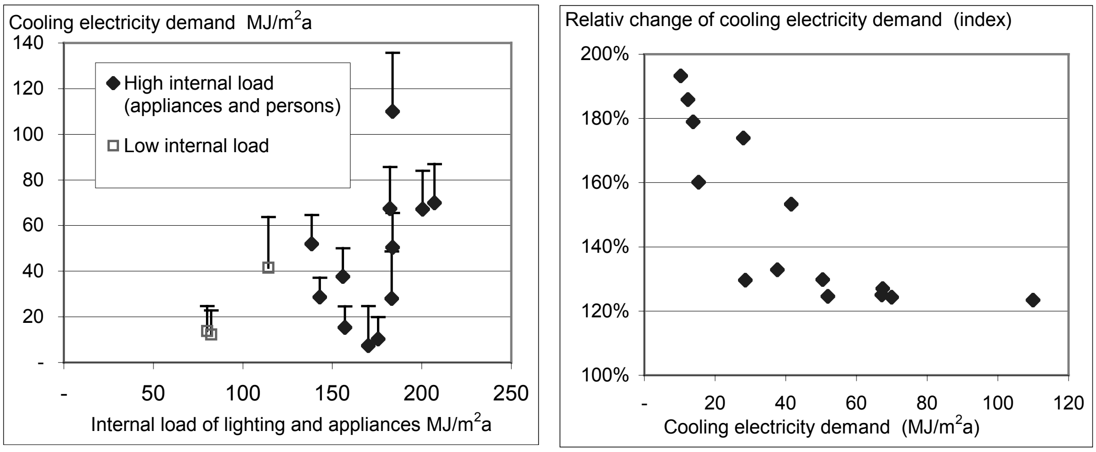

Figure 4. Sensitivity of cooling electricity demand regarding warmer outdoor temperatures *(absolute values, left-hand figure) and* ***Sensitivity of cooling electricity demand regarding warmer outdoor temperatures*** *(relative change, 100%=demand with today's climate, right-hand figure). Source: own calculations (simulation model IDA).*

reduced substantially, in particular below the demand of many cases with today's climate.

Having discussed the impact of increasing mean temperature on the electricity demand of individual office buildings, we look in the next section at the impact on energy demand of the entire service sector in Switzerland.

The impact of climate change on total energy demand of the Swiss service sector

The future energy demand of the Swiss service sector is evaluated with SERVE04, a bottom-up model developed in the 1990s and recently used by CEPE in the new energy scenarios for Switzerland (Aebischer /Catenazzi, 2007). The structure is mainly a widely used bottom-up approach:

Energy demand = Σ *(Floor area* $_{ij}$*) * (specific demand per unit of floor area* $_{ij}$*).*

For heat demand the calculations are done on the level of six economic sectors (denoted i) using a double cohort approach describing the dynamics of the demand of useful heat demand (building shell) and of the efficiency of the heating system (denoted j).

For the electricity demand this simple approach is extended to include the observed increase of electricity demand due to structural changes within the economic sub-sectors (Aebischer/Spreng, 1994; Aebischer et al., 1994). Wherever possible this observed increase in electricity demand of 1,5 % per year on average due to structural changes inside the sub-sectors is accounted for in the model by a relative increase of activities (floor area) characterised by higher specific electricity services. Examples of activities with higher electricity services are the modern retail stores with a large assortment of deep frozen food displacing more and more traditional corner shops ("Mom and Pop" stores) or large office buildings (with mechanical ventilation) including staff canteen and server room. In sub-sectors where this structural change could not be accounted for by changes in specific activities we assume an ongoing increase of electricity demand due to this structural change, but the increase of 1,5 % per year observed in the eighties/early nineties is adjusted in proportion to the ratio of the actual increase of value added to the increase of value added in the eighties/early nineties. The observed electricity demand 1990-2004 in the Swiss service sector is rather well described by this model.

The major assumptions and inputs for a scenario BAU (business as usual) are documented in Aebischer et al. (2006): moderate economic growth, low energy prices and "business as usual" regarding technological development and energy policy. Energy demand in this scenario BAU is evaluated first for the case "no change in mean yearly temperature" and then for the case "steadily mean temperature increase due to climate change". These two variants of the BAU-scenario are denominated "no climate change" and "with climate change".

VARIANT WITH NO CLIMATE CHANGE

In the variant with no climate change energy demand for space heating, warm water preparation and some process heat is steadily declining by about -0.2 % per year resulting in 2035 in a reduction of -6 % compared to 2005. On the contrary, electricity demand is growing at a rate of 0.9 %; the demand in 2035 is 32 % higher than in 2005 (Figure 7). The electricity produced in Switzerland is quasi CO_2 free. Under the assumption that this is still the case in 2035, then the CO_2 emissions of the service sector are declining faster than the heat demand, mainly due to the substitution of oil by gas and other energy carriers. In 2035 the reduction reaches -17 % with respect to 2005.

The electricity use for air conditioning is determined by the cooled area and the specific electricity demand for cooling. Table 2 shows our estimates of the floor area for different types of buildings and different economic sectors that are partially and fully air-conditioned (cooled).

In order to estimate the cooled areas, we postulate that "high tech" areas tend to be fully air conditioned, while "medium tech" spaces tend to be partially air-conditioned. This results in an estimate that of the total occupied floor area, 20 % is fully and another 20 % partially air-conditioned a plausible estimate when compared with those of other European countries. Offices show a significantly lower percentage of air-conditioned areas than in 100 office buildings examined in detail in 1990. Of those 100 buildings, 24 % (accounting for 40 % of the area) were fully air-conditioned, 28 % (32 % of energy-demanding space (EDS)) were partially air-conditioned, and the other 48 %

Table 2. Fraction of heated floor area for different types of buildings and different economic sectors that are partially and fully air-conditioned (cooled) in the variant no climate change. (Source: CEPE/Amstein+Walthert)

	2000	2005	2015	2025	2035
	Fraction of floor area				
Office buildings					
not cooled	47%	43%	33%	23%	14%
partially cooled	31%	35%	41%	48%	55%
fully cooled	22%	23%	26%	29%	32%
Retail stores					
not cooled	50%	47%	41%	35%	30%
fully cooled	50%	53%	59%	65%	70%
Hotels and restaurants					
not cooled	59%	55%	47%	39%	32%
partially cooled	30%	34%	40%	45%	51%
fully cooled	10%	11%	13%	15%	17%
Education					
not cooled	90%	89%	86%	83%	81%
partially cooled	6%	7%	9%	11%	13%
fully cooled	4%	4%	5%	6%	6%
Health care					
not cooled	65%	64%	62%	60%	58%
partially cooled	32%	33%	34%	35%	36%
fully cooled	3%	3%	4%	5%	6%
Other activities					
not cooled	50%	50%	50%	50%	50%
partially cooled	25%	25%	25%	25%	25%
fully cooled	25%	25%	25%	25%	25%
Total service sector					
not cooled	61%	59%	54%	49%	44%
partially cooled	20%	22%	25%	27%	30%
fully cooled	19%	19%	21%	23%	25%

(28 % of EDS) were not cooled at all (Aebischer, 2005). We expect significantly lower percentages for the entire office area within the service sector, since an unknown (but certainly large) number of office spaces are not situated within office buildings, but in other structures such as apartment buildings.

The specific electricity use for cooling (including chilling, control of humidity and pumps and fans used in distribution) in office buildings is based on the above-mentioned 100 office buildings. A special analysis (Aebischer, 2005) produced the following values:

- 23 MJ/m^2.year (6.3 kWh/m^2.year) for partially air conditioned office buildings,
- 96 MJ/m^2.year (26.7 kWh/m^2.year) for fully air-conditioned office buildings.

These results correspond well to simulation calculations (Adnot et. al., 2003) for office buildings under similar climatic conditions (Figure 5). As with the other technologies, we are assuming an “autonomous” annual reduction of the specific energy requirements by -0.5 %.

For calculating the specific electricity use in the other building types and economic sectors, we apply Adnot’s (2003) simulation calculations. This leads to the following values (relative to the office buildings): trade = 129 %, hospitality sector = 68 %, schools = 100 %, health sector = 116 %, other sectors = 100 %.

Based on these assumptions, electricity demand for indoor cooling in the Swiss service sector is increasing from 3.8 PJ/year in 2005 to 5.4 PJ/year in 2035 (+40 %). The percentage of the estimated electricity requirement for air conditioning relative to the overall electricity use is 5.9 % in 2000 and 6.5 % in 2035. Relative to the electricity use for climate and ventilation according to SIA 380/4, it comes to 24 % in 2000 and 26 % in 2035.

VARIANT WITH CLIMATE CHANGE

Weather characteristics

Temperature and radiation are used to describe the weather under continuous global warming conditions. We assume the following increases of the average daytime temperature and radiation (Hohmann/Neu, 2004):

- +1°C in the months from September to May,.
- +2°C from June through August,
- +5 % solar radiation (less clouds, more sunny days).

For the years between 2005 and 2035 we apply a linear inter-/extrapolation.

We investigate the energy effects of continuous global warming, defined by the climate change variant. The various political and socio-economic reactions that accompany continuous global warming over the next thirty years are beyond the scope of this sensitivity analysis. We assume that the societal, economic and technical circumstances and developments remain unchanged from the variant no climate change. It is also not feasible to investigate the effects on the many end uses of energy and electricity. For the purposes of this paper, we focus on the two most obvious and likely most sensitive areas, heating and cooling.

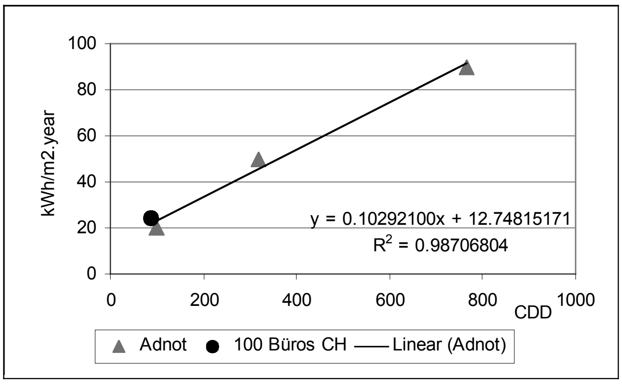

***Figure 5. Electricity demand for cooling, in kWh/m²**.year, of office buildings in function of the Cooling Degree Days (CDD) in London Milano and Sevilla** (depicted Adnot). For comparison we show also the measured value of fully air-conditioned office buildings in Switzerland (depicted 100 Büros CH). (Source: Adnot, Henderson, CEPE)*

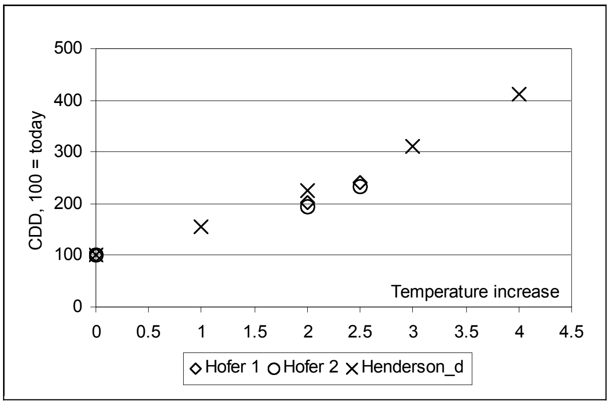

***Figure 6. Relative change of Cooling Degree Days** (100 = mean temperature today in Switzerland) in the case that temperature increases in summer (June–August) between 1 and 4 °C. (Source: Hofer, Henderson, CEPE)*

Demand for heating energy

We use the correction factors calculated by Hofer (2006) to quantify the effects of these new weather data on the demand for heating energy. These factors are based on building simulation models using monthly degree days and radiation values. This method is the same as correcting for the average of observed historical energy demand under variable weather conditions. Hofer produces correction factors for twelve building types.

The increase of the average daytime temperature by 1°C from September to May and by 2°C from June through August leads to a reduction of average heating degree days of 11 %, comparable to the very warm winter months in 1994. The demand for heating decreases continuously compared to the variant no climate change and by 2035 it is 13 % lower than without temperature increase (Figure 7), and the CO_2 emissions are accordingly lower as well. In this calculation, the inventory of buildings remains unchanged relative to the trend development.

Electricity demand for cooling

In order to arrive at a value for the electricity requirements for cooling under the climate change variant, two factors must be taken into consideration:

1. higher specific electricity use (in cooled buildings) due to higher average temperature, and
2. faster increase of partially and fully air conditioned spaces.

The impact of the first factor is evaluated using the correlation between electricity demand for cooling and the corresponding Cooling Degree Days (CDD). The correlation is determined by using results of simulations of energy demand for cooling office buildings in London, Milan, and Seville, as simulated by Adnot (2003). The corresponding Cooling Degree Days (CDD) were calculated by Henderson (2005) for this study. The fit of Adnot's energy data to Henderson's CDD results in a very good linear dependence (equation 1). The empirical energy usage for the already mentioned sample of 100 office buildings in Switzerland lies very close to this line as well (Figure 5).

Specific electricity demand for cooling =
*12.7 + 0.103 * CDD , in kWh/* $m_c^2.a$ *(1)*
where m_c^2 *is the fully cooled floor area*

We apply this linear dependence (equation 1) when calculating the higher electricity usage under the climate change variant. Depending on the method used, it is possible to arrive at two different results when the Cooling Degree Days are calculated for a temperature increase of 1°C from September to May, and of 2°C from June to August (Figure 6). For 2035 we use the average of the two values computed by Hofer (2006): an increase of CDD by 199 % between now and 2035. Based on equation 1, specific electricity consumption due to higher temperatures is 46 % higher in 2035. The increase in specific demand – relative to the variant no climate change – is computed by a linear interpolation between 0 in 2005 and 46 % in 2035.

The second factor, namely the rapid increase of partially and fully air conditioned spaces, leads us to the ad-hoc assumption that by 2035 half of the spaces that appear as non-cooled under the variant no climate change will be partially air-conditioned. Further, we estimate that half of the partially air conditioned spaces under the variant no climate change will be fully so by 2035.

After determining these two factors, it is now possible to calculate the electricity demand for cooling under the variant with warmer climate. Compared to the variant no climate change, an increase of 115 % is calculated. Roughly 40 % result from the higher specific requirements of the spaces that are already air-conditioned under the variant no climate change. 20 % are due to an increase of partially, 40 % are due to an increase of fully air-conditioned areas and the higher specific consumption for cooling these spaces relative to the variant no climate change.

Total energy demand under the climate change variant

The total demand is therefore 7.5 % higher in 2035 (Figure 7). In 2035, the percentage of electricity requirements for cooling as a part of overall electricity demand of the service sector grows from 6.5 % without climate change to 13.1 % under climate change. Relative to the electricity consumption for climatisation and ventilation according to SIA 380/4, the percent-

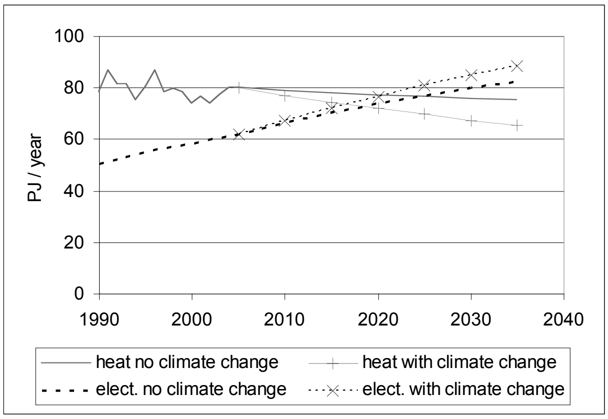

Figure 7. Heating energy demand and electricity demand for two climate variants *(variant with constant mean temperatures and climate change variant with continuous increasing mean temperature and irradiation), in PJ per year (Source: CEPE, own calculations)*

age grows from 26 % under no climate change to 44 % under climate change.

Implications of climate change for energy demand and CO_2 emissions for heating and cooling purposes of the service sector in Europe

The approach used to evaluate impacts of climate change on energy demand for heating and cooling, described in detail the sections 3 for Switzerland, was applied to different climate zones in Europe. In this section we present the resulting impact on CO_2 emissions due to the climate change induced changes in heating and cooling demand in this different climate zones in function of two parameters:

- the fuel-mix for heating purpose and
- the CO_2 content of electricity.

Heating degree days (HDD) and cooling degree days (CDD) for mean climate conditions for the period 1961 to 1990 ("$HDD_{\_mean}$" and "$CDD_{\_mean}$") were calculated using temperatures obtained from Meteonorm for 8 European locations and for Florida, which is noted for its high cooling loads. HDD were calculated according to the standard Swiss definition, using a base of 20°C with a cut-off temperature of 12°C. CCD were calculated to the ASHRAE definition, using a base of 18.3°C with no cut-off. Heating and cooling degree days for warming climate conditions ("$HDD_{\_warmer\_climate}$" and "$CDD_{\_warmer\_climate}$") were calculated with the following simplified assumptions for all locations:

1. temperature increase of +1°C in the months from September to May
2. temperature increase of +2°C in the months from June to August.

The relative variations of heating degree days are highest for warm climates and the variations of cooling degree days are largest for cold climate zones (Table 3, first part)

Specific final energy demand per m² of heated area "$H_{\_location}$" for room heating and for preparation of sanitary water and process heat in these 9 locations was determined by the very rough approximation shown as formula (2), where $H_{\_CH}$ and $HDD_{\_CH}$ are the specific energy demand in Switzerland of 153 kWh/m².a and the mean heating degree days in Switzerland of 3514 degree days and the parameter "$a_{\_CH}$" is the fraction of heat demand in Switzerland that varies proportionally to the number of heating degree days, approximated by the fraction of total heat demand which is not used for sanitary water and process heat. The specific heat demand for sanitary water and process heat is supposed to be equal to 16 kWh/m².a - independent of climatic conditions.

$$H_{\_location} = H_{\_CH} + H_{\_CH} * a_{\_CH} * (HDD_{\_location} / HDD_{\_CH} - 1) \quad (2)$$

The heat demand in the case of higher mean temperatures is calculated analogously by formula (2).

Electricity demand for cooling per unit of cooled floor area (m_c^2) in the different locations was either taken from Adnot et al. (2003) or calculated with formula (3) determined by a linear fit to Adnot's simulation results for locations in temperate and Mediterranean cities (Figure 5). The same formula (1) was used in the precedent section to evaluate increase of electricity use due to higher temperature.

$$El_{\_location} = 12.7 + 0.103 * CDD_{\_location}, \text{ in } kWh/m_c^2.a \quad (3)$$

The calculated specific energy demand for heating (including preparation of sanitary warm water and process heat) and cooling of commercial buildings in the 9 locations and the relative variations in the case that temperatures increase vary considerably (Table 3, second part).

In order to determine the total variation of electricity for cooling we have to evaluate the increase of cooled floor area due to climate change. We assume that in 2030 100 % of the floor area is using heat (heating and/or sanitary water and process heat), but that with no climate change only a fraction is cooled. With increasing temperature this fraction of cooled floor area is increasing and the variation of electricity demand for cooling shown in the second part of Table 3 is also increasing. The fraction of cooled floor area (partially cooled is taken as half the area is cooled) in Zurich is assumed to be the same as in Switzerland altogether (section 3): 40 % in the case of no climate change and 59 % if the temperature increases by 2°C in summer. These fractions for the other locations are rough guesses (Table 3, third part). The specific energy demand for cooling per unit of total floor area (m²) of the commercial sector (and not just per unit of cooled floor area, m_c^2) is of course lower – except for Florida, where we assume that all the floor area is cooled) - and the relative increase of electricity for cooling is higher due to the increase of cooled floor area (Table 3, third part).

In order to make a realistic balance of decreasing CO_2 emissions for heating purposes and increasing CO_2 emissions for cooling we would not only need detailed information about the CO_2 content of heating energy and of the electricity used for cooling in the year 2030, but also about the CO_2 content of the avoided heating energy and of the additional electricity used

Table 3. Heating and cooling degree days for today's weather conditions ($HDD_{\_mean}$ and $CDD_{\_mean}$) and in the case of a climate change with mean temperature increase of +2°C in summer and +1°C in winter ($HDD_{\_warmer\_climate}$ and $CDD_{\_warmer\_climate}$); and **specific heating ($H_{\_mean}$) and cooling ($El_{\_mean}$) energy demand** per unit of **heated** (m_h^2) **and cooled (m_c^2) floor area** (2005) for today's weather conditions and variations for increasing temperatures; fraction of cooled floor area in 2030 without ($\%cooled_{\_mean}$) and with ($\%cooled_{\_climate\_warmer}$) temperature increase and **specific heating ($H_{\_mean}$) and cooling ($El_{\_mean}$) energy demand** per unit of **total floor area** (m^2) for today's weather conditions and variations for increasing temperatures. (Source. Meteonorm, CEPE)

	Florida	Athens	Murcia	Milan	London	Berlin	Zurich	Copen-hagen	Stock-holm
$HDD_{\_mean}$	28	696	1035	2797	2904	3436	3571	3847	4406
$HDD_{\_climate\_warmer}$	10	502	797	2526	2561	3126	3200	3459	4036
Variation	-64%	-28%	-23%	-10%	-12%	-9%	-10%	-10%	-8%
$CDD_{\_mean}$	2219	1061	766	319	63	119	88	26	52
$CDD_{\_climate\_warmer}$	2644	1337	1021	504	147	229	190	81	122
Variation	19%	26%	33%	58%	133%	92%	115%	212%	135%
$H_{\_mean}$, $kWh/m_h^2.a$	17	43	56	125	129	150	155	166	187
Variation	-4%	-18%	-16%	-8%	-10%	-8%	-9%	-9%	-8%
$El_{\_mean}$, $kWh/m_c^2.a$	241	122	90	50	20	25	22	15	18
Variation	18%	23%	29%	38%	43%	45%	48%	37%	40%
$\%cooled_{\_mean}$	100%	90%	80%	60%	40%	40%	40%	40%	40%
$\%cooled_{\_climate\_warmer}$	100%	95%	90%	75%	59%	59%	59%	59%	59%
$H_{\_mean}$, $kWh/m^2.a$	17	43	56	125	129	150	155	166	187
Variation	-4%	-18%	-16%	-8%	-10%	-8%	-9%	-9%	-8%
$El_{\_mean}$, $kWh/m^2.a$	241	110	72	30	8	10	9	6	7
Variation	18%	30%	45%	73%	109%	112%	116%	100%	104%

for cooling due to higher temperatures. This will be done in the framework of the ADAM project (www.adamproject.eu). Here, we do a simple sensitivity analysis in order to get a feeling about the possible variation due to different fuel choices. In order not to confuse the reader, we do not use any geographic names, but characterise the different locations by their CDD only.

The fuel mix for heating is characterised:

1. by the fraction of electricity in the total final energy demand for heating ("**little**" = 10 %; "**much**" = 50 %) and
2. by the CO_2 content of the remaining (non-electric) fuel mix used for heating (0.2 Mt CO_2 per TWh corresponding approximately to the CO_2 content of natural gas; 0.3 Mt CO_2 per TWh corresponding to CO_2 content slightly above the one for light fuel oil)

For the CO_2 content of electricity we use the two extremes:

1. **high** CO_2 content (1 Mt CO_2 per TWh corresponding to electricity produced by coal fired power plants)
2. **low** CO_2 content (0.1 Mt CO_2 per TWh corresponding to electricity produced 90 % CO_2 free)

The main outcomes can be summarized as follows (Figure 8):

- The results depend only weakly on the CO_2 content of the non-electric fuels for heating. We present the results of the fuel mix with 0.2 Mt CO_2 per TWh corresponding approximately to the CO_2 content of natural gas.
- In warm climates, there is a large increase in terms of relative CO_2 emissions in the case **low** and very large increase in the case **high**. The fraction of electricity used for heating has a significant effect, except for the warmest locations. In absolute terms the increase is, not surprisingly, much higher in the case of **high**.
- In cold climates, the variations are in relative and in absolute terms significantly lower than in warm climates. Except in the case of **high** and **little**, the CO_2 emissions are always reduced by a temperature increase. The fraction of electricity used for heating has a significant influence in the case of **high**.
- In temperate climates, the situation is qualitatively very similar to the situation in cold climates, except in the case **high** and **much**, where the reduction of CO_2 emissions in the cold climate is changed into an increase of CO_2 emissions. In particular, there is:
  – a substantial reduction of CO_2 emissions in the case **low** almost independent of the fraction of electric heating;
  – a substantial (slight) increase of CO_2 emissions in the case **little** (much) and **high**
- The large differences between the locations HDD=2797 and HDD=2904 with rather similar heating degree days is due to the large differences in the cooling degree days.

The impact of increasing temperature due to climate change on energy induced CO_2 emissions differs from one location to an other and depends on today's energy system. For a country like France, characterized by its moderate climate, by a low CO_2 content of the electricity and by much electric heating, the impact in the service sector is small (±5 %), whereas in a southern country with a fossil fuel based electricity system the increase of CO_2 emissions due to increasing mean temperature may reach for the service sector as much as 30 %. These differences may become important in future burden sharing discussions of European and global CO_2 reduction targets.

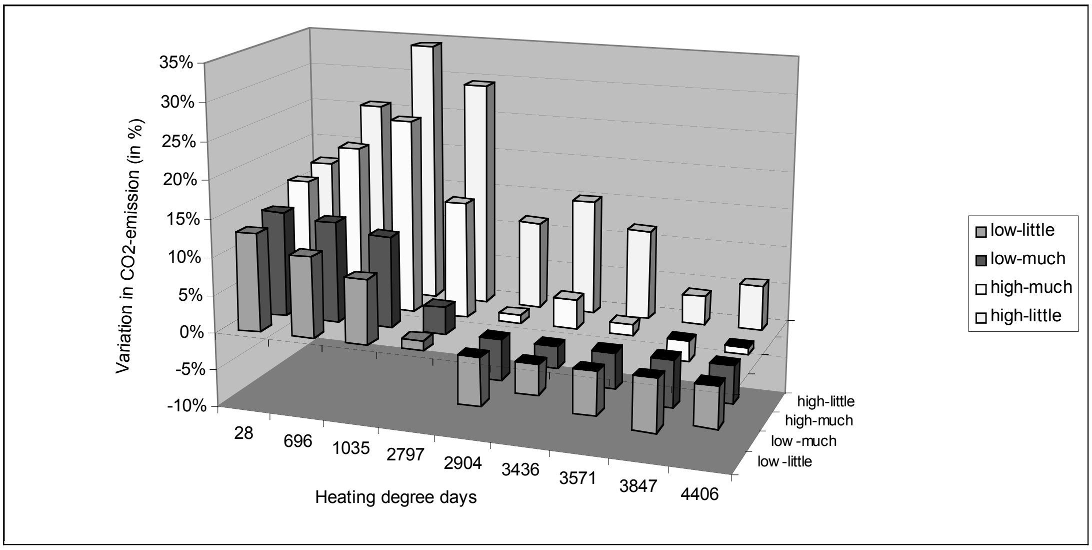

Figure 8. Changes in relative CO_2 emission from heating and cooling *due to climate change in different locations (characterised by their heating degree days), in percent. The denotation is explained in the text. (Source: CEPE, own calculations)*

Discussion and conclusions

Buildings with internal loads and no or limited night aeration or ventilation bare a risk of overheating. This risk is increased by add-on insulation of these buildings leading to a significant increase of hours with uncomfortable room conditions already under current climate. Although a reduction of internal heat loads, in particular the renewal of lighting and the use of presence and daylight control, may compensate partly the overheating risk, the relevance of building cooling will increase in the future. Economic benefits of comfortable workspace in terms of increased productivity and satisfaction of staff will – along with higher expectations due to more and more cooling in the traffic sector – increase the demand for cooled space. Indeed already lower estimates of these benefits exceed the costs of providing cooling.

The increase in mean outdoor temperature is the second factor leading to a considerable increase of the number of hours with overheating. Compensating measures such as mechanical cooling, controlled window opening or night cooling will be necessary to maintain minimal comfort requirements. We present simulation results showing that the specific energy demand for cooling is notably affected in actively cooled buildings.

Detailed studies of long-term temperature records show that temperatures in Switzerland rose by around 1.3 K during the 20th century, approximately twice as fast as mean global temperature, with most of the increase occurring in the last three decades. The trend towards higher temperatures is expected to continue, and may be expected to lead to a reduction in the need for heating in winter and increased thermal discomfort and thus increased need for cooling in summer.

In this paper we provide evidence regarding the above mentioned trends and explore the impact of a temperature increase of 1 K in winter and 2 K in summer on energy demand for heating and cooling and the induced CO_2 emissions. A change of this magnitude reduces HDD by about 10% for most locations in Europe. For CDD, the change is much more dramatic in relative terms, in many cases leading to more than double the present levels.

The reduction in HDD and the increase in CDD will tend to have opposing effects on energy use and CO_2 emissions. Increases in CDD are likely to cause an increase in both energy use in buildings that already have cooling and in the fraction of total floor area that has mechanical cooling. Even a relatively modest increase in summer temperature may therefore lead to a doubling of cooling energy requirements compared to what would be needed if there is no temperature increase.

The net effect on energy use and CO_2 emissions depends on the balance between the effects on heating and cooling needs. For Switzerland, heating accounts for vastly greater energy use and CO_2 emissions than does cooling, as it does throughout North West Europe. Consequently, the effect of large percentage increases in cooling demand can be outweighed by much smaller percentage changes in heating demand. Another important factor affecting this balance is the relative CO_2 intensity of the electricity and heating fuels supplied to buildings. We found, therefore, a very large increase in CO_2 emissions where both summer temperatures and the CO_2 intensity of electricity are high.

Policy measures to reduce cooling energy demand may be aimed both at reducing the number of installations and at reducing energy use in buildings that have cooling capacity installed. The former is arguably the more effective in countries with cooler summers, and is most applicable for new buildings and major refurbishments, where intervention is possible at the design stage. Minimisation of summer cooling requirements is already encouraged by building regulations in some countries, including Switzerland and the UK. Our results suggest, however, that for Switzerland the present focus on avoiding mechanical cooling may need to be supplemented by emphasis on the design and effective operation of cooling systems. The avoidance strategy will remain viable, however, for the northerly maritime areas (including Ireland, the UK and Scandinavia).

Improvements to the efficiency of air conditioning equipment have been the subject of two EU SAVE projects – EERAC and EECAC – which have provided a basis for further intervention, including labelling and minimum efficiency standards. Legislation arising from Article 9 of the Energy Performance of Buildings Directive, which will to come into force in EU countries in 2006, is expected to lead to better maintenance and more appropriate installations of air conditioning equipment in future.

Rising peak demand in summer is an area of particular concern for policy makers. In Switzerland and other countries with moderate summer temperatures, this will not be significant unless the use of air conditioning increases by a very large factor. In the Mediterranean countries, however, it is a problem that needs immediate consideration both for generation and distribution capacity. The EERAC study found that, in countries with summer peaking, additional investment in generation, transmission and distribution might be needed as a result of growing air conditioning loads. The difficulties experienced in recent years in meeting peak loads in California are of interest and may offer lessons for Europe. Wilson et al, 2002, gave estimates of the contribution of air conditioning to the peak demand experienced in 2002. Commercial sector air conditioning was estimated to account for 15 % (7000 MW) of the total peak load, with residential air conditioning contribution a further 14 %.

In all European countries, it is clear that the design of buildings should no longer be based on past climatic data but should instead take account of expected changes during the planned life of the building. Frank (2005) and Jakob et al. (2006) show how energy simulation can be used to assess impacts on particular building types and the benefits of particular technical measures, such as night ventilation. More use of building energy simulation should be made for individual buildings and simplified tools based on simulation results should be used in order to take best advantage of opportunities for minimising cooling load through design features. Building retrofit should be carefully conceived to reduce risk of adverse effects on indoor climate conditions (overheating) and to utilise synergy effects between energy efficiency and thermal comfort, in particular in the case of lighting.

While becoming more conscious of the need to avoid (where possible) and minimise cooling demand, it is important that policy makers do not lose sight of the continuing need to reduce heating demand, especially in Central and Northern Europe. Indeed, on the primary energy level the balance of building insulation is positive for Swiss-like climate conditions even if additional cooling is being installed. Even for Southern Europe, where awareness of cooling demand is already strong, heating demand is likely to remain significant and should not be forgotten, especially if it is covered by electricity to a significant extent.

Energy statistics in many European countries fail to distinguish energy used for cooling. While this may have been justified in the past by the relative insignificance of cooling in terms of total energy delivered, it is no longer the case. Bodies responsible for the collection of energy statistics should be encouraged to develop methods for collecting and presenting the relevant data.

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