Energy Conservation in Buildings and Community Systems Programme

Energy Impact of Ventilation

Estimates for the Service and Residential Sectors

Malcolm Orme

International Energy Agency

AIVC Air Infiltration and Ventilation Centre

This report is part of the work of the IEA Energy Conservation in Buildings & Community Systems Programme.

Publication prepared by
Annex V Air Infiltration and Ventilation Centre

Document AIC-TN-49-1998
ISBN 1 946075 97 2

Participating countries:

Annex V
Belgium, Canada, Denmark, Germany, Greece, Finland, France, Netherlands, New Zealand, Norway, Sweden, United Kingdom, and United States of America

Additional copies of this report may be obtained from:

The Air Infiltration and Ventilation Centre
University of Warwick Science Park
Sovereign Court
Sir William Lyons Road
Coventry CV4 7EZ
Great Britain

Energy Impact of Ventilation

Estimates for the Service and Residential Sectors

Malcolm Orme

About the author:

Malcolm Orme is a Scientist at the Air Infiltration and Ventilation Centre, with a background in mathematics. His work at the Centre has included the compilation and analysis of building airtightness and wind pressure coefficient data, and, in addition, he has been actively involved in numerical air flow modelling.

Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster co-operation among the twenty-four IEA Participating Countries to increase energy security through energy conservation, development of alternative energy sources and energy research development and demonstration (RD&D).

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, as well as air quality and studies of occupancy.

The Executive Committee

Overall control of the programme is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial.

To date the following have been initiated by the Executive Committee (completed projects are identified by *):

I	Load Energy Determination of Buildings*
II	Ekistics and Advanced Community Energy Systems*
III	Energy Conservation in Residential Buildings*
IV	Glasgow Commercial Building Monitoring*
V	Air Infiltration and Ventilation Centre
VI	Energy Systems and Design of Communities*
VII	Local Government Energy Planning*
VIII	Inhabitant Behaviour with Regard to Ventilation*
IX	Minimum Ventilation Rates*
X	Building HVAC Systems Simulation*
XI	Energy Auditing*
XII	Windows and Fenestration*
XIII	Energy Management in Hospitals*
XIV	Condensation*
XV	Energy Efficiency in Schools*

XVI BEMS - 1: Energy Management Procedures*
XVII BEMS - 2: Evaluation and Emulation Techniques*
XVIII Demand Controlled Ventilating Systems*
XIX Low Slope Roof Systems*
XX Air Flow Patterns within Buildings*
XXI Thermal Modelling*
XXII Energy Efficient Communities*
XXIII Multizone Air Flow Modelling (COMIS)*
XXIV Heat Air and Moisture Transfer in Envelopes*
XXV Real Time HEVAC Simulation*
XXVI Energy Efficient Ventilation of Large Enclosures*
XXVII Evaluation and Demonstration of Domestic Ventilation Systems
XXVIII Low Energy Cooling Systems
XXIX Daylight in Buildings
XXX Bringing Simulation to Application
XXXI Energy Related Environmental Impact of Buildings
XXXII Integral Building Envelope Performance Assessment
XXXIII Advanced Local Energy Planning
XXXIV Computer-aided Evaluation of HVAC System Performance
XXXV Design of Energy Efficient Hybrid Ventilation (HYBVENT)

Annex V Air Infiltration and Ventilation Centre

The Air Infiltration and Ventilation Centre was established by the Executive Committee following unanimous agreement that more needed to be understood about the impact of air change on energy use and indoor air quality. The purpose of the Centre is to promote an understanding of the complex behaviour of air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

The Participants in this task are Belgium, Canada, Denmark, Finland, France, Germany, Greece, Netherlands, New Zealand, Norway, Sweden, United Kingdom and the United States of America.

Contents

Executive Summary

Air change energy use in 13 major industrialised countries is considered here. The countries included are Belgium, Canada, Denmark, Finland, France, Germany, Netherlands, New Zealand, Norway, Sweden, Switzerland, UK, and the USA. Also discussed is the effect that air change energy use has on carbon dioxide emissions due to the use of fossil fuels, both directly in combustion appliances, and indirectly as electricity.

An examination of the relative importance of non-industrial (dwellings, offices, etc.) building energy use in these countries as compared to other energy sectors demonstrates that total building energy demand is of comparable significance to the transport sector and more than twice that of industrial demand. Therefore it is important to understand why the building sector uses such a significant quantity of energy, and, in particular, the impact of ventilation and air infiltration (i.e. air change) on this demand.

Ventilation is essential for the maintenance of good indoor air quality. However, despite its necessity, there is much evidence to suggest that energy loss through uncontrolled or unnecessary air infiltration is excessive and that much can be done to minimise such loss. Considerable losses may also be associated with ventilating pollutants that can be more effectively controlled by their elimination at source. Air infiltration exacerbated by poor building airtightness adds further to lack of control and energy waste.

In order to quantify the energy impact of air change on total energy use, the AIVC has been undertaking a study of current estimates for non-industrial buildings. The potential for reduced energy use by improved ventilation control is also briefly reviewed. It is found that air infiltration and ventilation together account for a significant proportion of energy use in buildings. This report outlines the findings from a study into estimating the full impact of air change on building energy use. Considering the non-industrial building stock of the 13 countries collectively, the total annual loss of heating energy due to air change is estimated to amount to 48% of delivered space conditioning energy (including heating equipment losses). Stated in terms of delivered space heating energy alone (i.e. excluding space cooling), this rises to 53%. If the outdoor air supply rate per occupant were to be universally reduced to a minimum level, taking into account metabolic needs and pollutant loads, then it is conceivable that the heating air change energy loss could be reduced to approximately a third of the current level. The consequent reduction in the total carbon dioxide emissions from the service and residential sectors (for all end uses) would be in the region of 20% per year.

These results emphasise that air change related energy losses are as important as conduction and equipment losses (including 'flue' losses) in dissipating delivered space conditioning energy from buildings. In fact, as national standards, regulations or codes of practice improve the thermal integrity of buildings and increase equipment efficiency, it is expected that ventilation and air movement will become the dominant loss mechanism.

Acknowledgements

Some of the results presented here are based on the results of a survey (February 1992) and a workshop (March 1994) conducted by the AIVC. The AIVC would like to gratefully acknowledge the contributions of those who participated in the above. In addition, the following members of the AIVC Steering Group have provided valuable support and co-operation:

Belgium - Peter Wouters, Belgian Building Research Institute

Canada - Mark Riley, Natural Resources Canada and John Shaw, National Research Council

Denmark - Ole Jensen, Danish Building Research Institute

Finland - Jorma Sateri, VTT Building Technology

France - Marie-Claude Lemaire, ADEME

Germany - Fritz Steimle, Universität Essen

The Netherlands - Willem de Gids, TNO

New Zealand - Mark Bassett, BRANZ

Norway - Jørn Brunsell, Norwegian Building Research Institute

Sweden - Johnny Kronvall, J&W Consulting Engineers AB

UK - Earle Perera, BRE

USA - Max Sherman, LBNL, CA

Further comments on the report as a whole were kindly given by:

Donald Colliver, University of Kentucky at Lexington, USA

Steven Emmerich and Andrew Persily, NIST, USA

Also, valuable assistance has been provided by:

Karin Adalberth, J&W Consulting Engineers AB, Sweden

Harry Audus and Paul Freund, IEA Greenhouse Gas Centre, UK

Peter Blom, Norwegian Building Research Institute, Norway

Viktor Dorer, EMPA, Switzerland

Pierre Hérant, ADEME, France

Nance Matson, LBNL, USA

Sarah Moss, Christine Pout, Les Shorrock, and James Willder, BRE, UK

Peter Op 't Veld, Novem, The Netherlands

Jürgen Röben, Universität Essen, Germany

Philip Steadman, Open University, UK

Mike Swinton, National Research Council, Canada

1. Introduction

It is estimated in the Energy Conservation in Buildings and Community Systems Strategy Plan (IEA, 1994a) that about one eighth of all energy is used in service sector[1] buildings and about one quarter of all energy is used in dwellings within the countries of the Organisation for Economic Co-operation and Development. One of the largest uncertainties in energy prediction is how much is lost through ventilation and air infiltration. This includes both the loss of conditioned air (deliberately heated, cooled or moisture content changed) and the energy used by ventilation fans. Furthermore, it is predicted (in IEA, 1994a) that "ventilation and air movement is expected to become the dominant heat and cooling loss mechanism in buildings of the next century."

1.1 Objectives

The objective of this report is to make estimates, as far as currently possible, of air change energy use and the related carbon dioxide emissions due to the service and residential building sectors of each AIVC Participating Country[†]. ('Air change' refers to the combination of ventilation and infiltration related air flows.) This continues the AIVC's programme of estimating the energy impact of air change in buildings. It is intended, within this scope, to provide estimates of what are 'reasonable' values for the air change energy use in each country. The consistency or otherwise of data from various sources is also taken into account.

It should be emphasised that more work is needed to identify characteristics of buildings currently absent from the data collected so far, for example, service sector conditioned floor areas for many countries.

1.2 Energy Use in Buildings

The most significant measure of energy use at the national level is primary energy, while for end-users it is delivered energy. Primary energy represents the total energy available from natural resources, while delivered energy is the amount of energy that is actually available to end users. The difference between primary and delivered energy is accounted for by the energy lost when primary energy is converted to a usable form and in its distribution to end users.

1.2.1 Measurement units for energy

The basic unit of energy in the metric (SI) system is the joule (symbol, J). For our purposes, there are four quantities derived from the joule which have convenient magnitudes. These are the megajoule (1 MJ is equivalent to 10^6 J), the gigajoule (1 GJ is equivalent to 10^9 J), the petajoule (1 PJ is equivalent to 10^{15} J) and the

[1] 'Sector' refers here to the building use, as opposed to the economic activity of the building owner.

[†] Countries participating in this project were: Belgium, Canada, Denmark, Finland, France, Germany, The Netherlands, New Zealand, Norway, Sweden, Switzerland, UK, and USA.

exajoule (1 EJ is equivalent to 10^{18} J). For example, in order to give an indication of the magnitude of these quantities, the total annual energy use for a single dwelling is typically in the region of 50 GJ to 100 GJ. Furthermore, the total residential sector energy use in, for instance, New Zealand (with a population of 3.53 million people) was about 50 PJ in 1994, whilst for the USA (with a population of 261 million people) it was 10 EJ (IEA, 1996).

Units based on the British thermal unit (Btu) are commonly used in the USA, with 1 Btu equivalent to 1050 J. Another often quoted unit, is the kilowatt hour (kWh), with 1 kWh equivalent to 3.60 MJ, which is frequently used in the context of electricity use. The terawatt hour (1 TWh is equivalent to 3.60 PJ) is of appropriate magnitude in the context of national energy use. National energy balances are published by the IEA (see IEA, 1996) in the form of million tonnes of oil equivalent (Mtoe), where 1 Mtoe being equivalent to 41.9 PJ is an accepted conversion.

1.2.2 Lower versus higher heating values for fossil fuels

Certain published national energy balances for fossil fuels (IEA, 1996) are expressed in terms of *lower heating values* (net calorific values). This means that the resultant latent heat of vaporisation of water vapour produced during fuel combustion is excluded from the value of the energy released during that process. In *higher heating values* (gross calorific values), the latent heat of vaporisation of water vapour is included. This is an area of possible discrepancy when comparing energy use, and in a 'worst case' could involve errors of up to 10%.

In addition, note that, for example, the primary energy equivalent of delivered natural gas is greater than just its higher heating value, because extraction, processing and distribution of fossil fuels each require energy expenditure.

1.2.3 Total energy use

Figure 1, derived from data given in IEA (1996), shows the estimated annual contribution each major energy using sector makes to total primary energy use. This Figure is an aggregate that includes all of the AIVC Participating Countries. Furthermore, the residential sector uses almost double the primary energy compared to the service sector, as illustrated by Figure 2. Energy used in the construction of buildings and the manufacture and transportation of building materials is not included in the total energy value for either service or residential buildings.

1.2.4 Space heating and cooling in relation to other end uses

It is assumed that air change related losses are accounted for solely by delivered space conditioning (heating and cooling) energy and not from any other energy use. Therefore, space conditioning use is an important quantity that should be examined. The estimated total of the space heating and cooling energies for the 13 countries considered here is presented in Figure 3, which relies on hot water and space cooling use published by the International Energy Agency Heat Pump Centre (HPC, 1994). The space heating data were either taken from published sources, or estimates were made for each country using the total delivered energy use as the upper limit. The

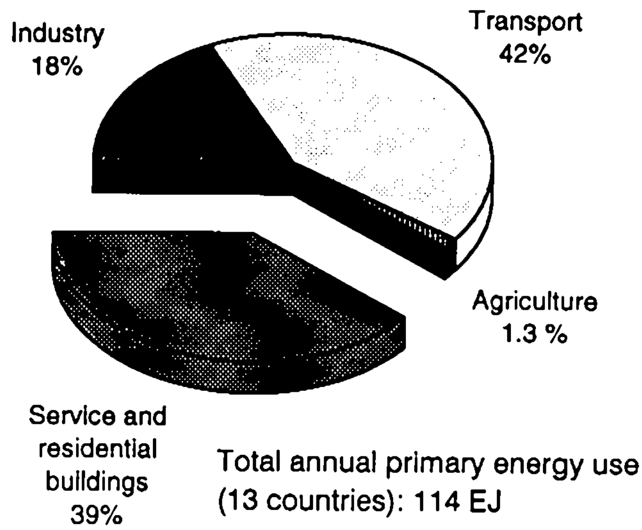

Figure 1 Primary energy shares of the major energy using sectors

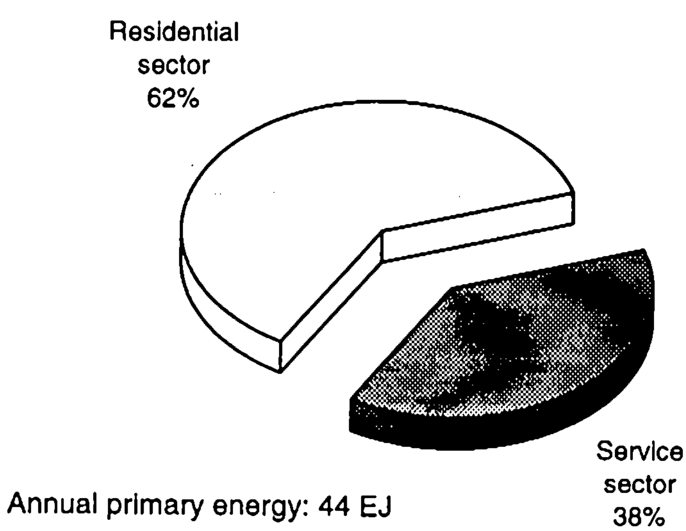

Figure 2 The approximate service and residential sector shares of primary energy use for 13 countries

data for the remaining uses (i.e. cooking, lighting and appliances) were deduced from the difference between the total use and the other uses.

1.2.5 Air change-related energy use

There are certain 'obvious' constraints on the acceptability of the calculated energy values. For instance, it is contradictory if values obtained for delivered air change related energy (or space conditioning) are greater than the total energy used by the

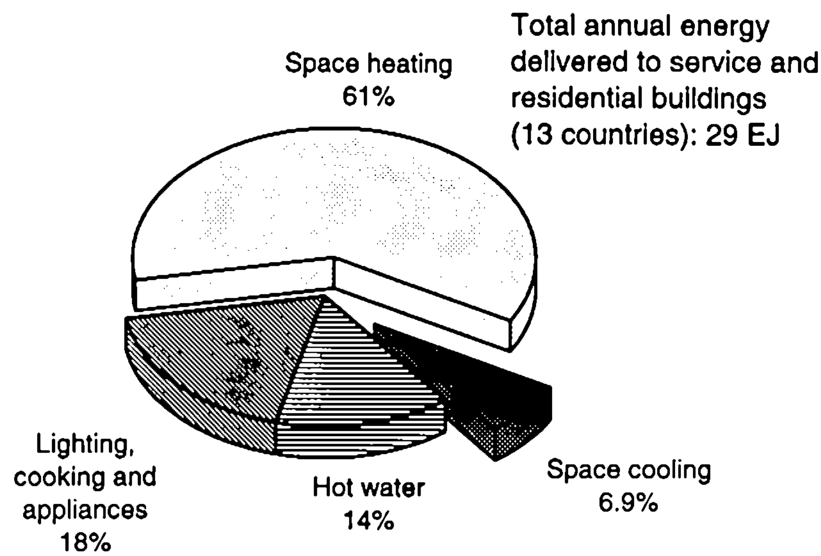

Figure 3 End use shares of delivered energy in the service and residential sectors

building sector. Moreover, other processes, such as lighting and the operation of electrical appliances, contribute to building energy use, and therefore air change related energy will amount to only part of the total delivered energy use.

The ways in which delivered space conditioning energy is dissipated can be seen in Figure 4. It summarises the estimate of the current position for the 13 countries. It is interesting to note that air change heating losses (purely arising from the loss of enthalpy) seem to be as important as other forms of energy loss. This, of course, is only an approximate guide, due to the large number of assumptions that have been made in order to deduce this result.

Heating air change and conduction losses are both associated with a proportion of the heating equipment losses. So, a reduction in one of these will cause a proportional drop in heating equipment losses. The basis of Figure 4 is the sum of the air enthalpy changes for the 13 countries studied, described later in Section 4.

The total space conditioning was found from the sum of the delivered space cooling energy together with the sum of space heating energy use for the countries, as described for Figure 3. The origins of these are explained in Section 3.3. The same Section also contains details of the assumed heating equipment losses.

In fact, other studies have been carried out for the service and residential sectors that provide an indication of the magnitude of energy use due to air change. For example, VanBronkhorst et al (1995) have estimated that air infiltration alone accounts for roughly 18% of the heating load in all office buildings in the USA. Also, Herring et al (1988) state that ventilation accounts for 20% of the energy losses in UK service sector buildings.

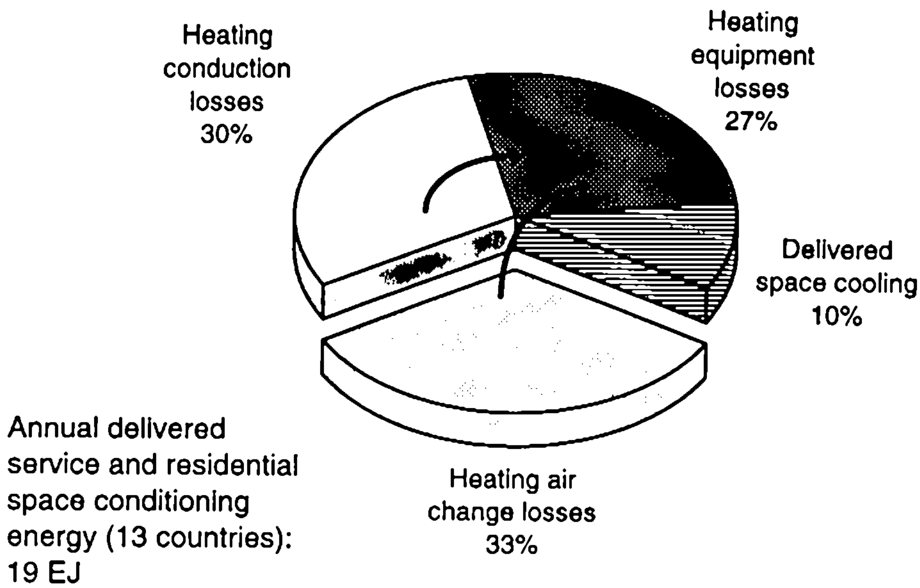

Figure 4 Dissipation of delivered space conditioning energy in the service and residential sectors

1.2.6 The potential for reducing air change related energy losses

At the present time, it is not possible to estimate accurately by how much the energy use associated with air change may be reduced, on account of the large uncertainties and deficiencies in essential data. Ultimately, once the service and residential building characteristics have been determined, the most important quantities that will remain to be established are the average air change rates. (These are needed to calculate the volume of air that must be heated or cooled every year.) These may be deduced perhaps through either large-scale measurement programmes, or through modelling representative building types for each country.

Subject to the above caveats, it has still been possible to derive an approximation of the extent by which delivered air change energy use may be reduced. For example, if a ventilation rate of 10 litres per second per person were to be universally adopted, it is conceivable that air change heat losses may be reduced to one third of the current estimated level. The assumption that fresh outdoor air is only supplied to meet occupant requirements is the basis of Figure 5, which excludes fan energy use. It has also been assumed that ventilation air is supplied continuously throughout the year, for each of the service and residential sectors.

The upper long-dashed line on the graph shown in Figure 5 depicts the current total delivered air change related energy use. This total is equal to the sum of the estimated heating air enthalpy change losses and the associated fraction of the heating equipment losses. The lower continuous line indicates the level to which the current total could theoretically be reduced, for given outdoor air supply rates per occupant. The example reduction is shown by the short-dashed line at the 10 litres per second per person level.

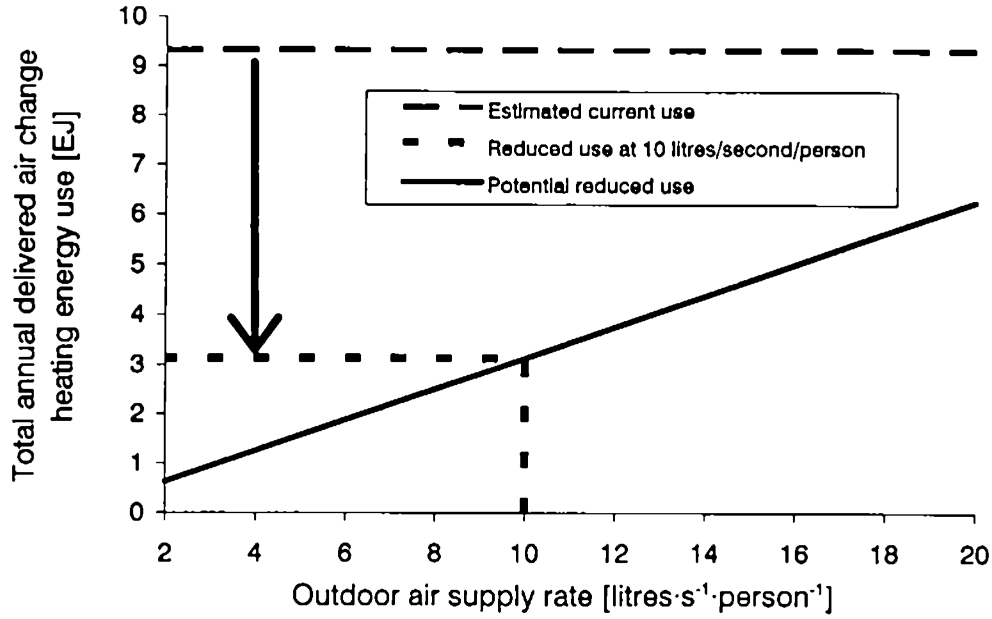

Figure 5 Potential delivered air change energy saving for the service and residential sectors (13 countries)

Sufficient ventilation must always be provided to satisfy the health and comfort needs of occupants. Such requirements are the subject of Standards, Regulations, and Codes of Practice (e.g. ASHRAE Standard 62). Minimum levels normally take into account metabolic needs, and pollutant loads. In addition, considerably greater amounts of air change may be necessary to satisfy cooling needs when mechanical cooling is not used.

Practical measures for the reduction of air change energy use would be linked to:

- avoiding unnecessary air change (i.e. dealing with leaky buildings),
- introducing good control strategies (for example to avoid the use of window and door opening during periods of active cooling or heating),
- minimising the heat load during cooling periods to restrict excessive heat gains,
- optimising fan efficiency,
- optimising other equipment efficiencies (such as heating equipment), and
- the introduction of guidelines indicating expected best levels.

However, barriers still remain concerning the adoption of such measures. For example, there is often a conflict of interest between building owners who would pay for them, and building occupiers who would benefit from reduced energy expenditure.

2. Background

2.1 Definitions of the Service and Residential Sectors

It is possible to categorise the total building-related energy use of a country into residential, service, and industrial sectors. Depending on its function, a building can be considered as belonging to one (or possibly more) of these groups. (It should be noted that energy use due to transportation is distinct from each of these sectors, and is not included in the following discussion.) In practical terms, often a building is assigned to a particular sector according to its principal activity, if more than 50% of its floor space is devoted to that activity. Both the service and the residential sectors will be discussed here. Current patterns of demand for ventilation and infiltration energy are thought to differ quite considerably between these sectors.

2.1.1 Buildings constituting the service sector

The first step in the process is to identify which buildings belong to the service sector. In general, they are buildings used either for commercial (non-industrial) purposes, or for public service (such as government or education). The service sector is sometimes also known as the commercial and public sector, or simply the commercial sector.

In practice, different countries adopt definitions of the sector which may or may not include certain classes of buildings. For instance, there is variation between countries whether warehouses and other storage and distribution facilities are included in the definition of the service sector. It should therefore be remembered that in making comparisons between countries, one may not always be strictly comparing 'like with like'.

By way of example, the USA Commercial Buildings Energy Consumption and Expenditure Survey (DOE/EIA, 1995) breaks the commercial sector (including government-owned buildings) into the following sub-sectors of buildings, according to their use:

a) education (e.g. schools),
b) food sales,
c) food service (e.g. restaurants, pubs, bars),
d) health care,
e) lodging (e.g. hotels, residential and retirement homes),
f) mercantile and service,
g) office,
h) parking garage,
i) public assembly,
j) public order and safety,
k) religious worship,
l) warehouse, and
m) other.

This sector is very diverse in nature, and ideally we would wish to sub-divide it into its component sub-sectors. The occupancies and space-conditioning characteristics vary widely between these sub-sectors, and consequently it is most appropriate to treat them individually. However, for this study this has not been possible, because for many of the countries, essential data for each of the sub-sectors have yet to be located.

2.1.2 Buildings constituting the residential sector

The residential sector consists of both single family dwellings, which may possibly be attached to one or more other residences, and apartments (flats). Examples of single family dwellings are detached houses, which are isolated from other buildings, and semi-detached houses, which share a common wall with one other dwelling. Also, row (terraced) houses are joined to at least two other dwellings, with common walls. Apartments are residences built one above another, each of which may contain more than one floor.

The key difference between different types of dwellings is that there is almost always air leakage between those which share either a common wall or floor. In fact, there is usually heat transfer from one dwelling to another by conduction or air movement, or both. The presence of an adjoining dwelling means that there is no air leakage to or from the outside through the shared walls or floors. Moreover, common walls are by definition shielded from external meteorological conditions. As a consequence, uncontrolled wind-driven air leakage is also reduced on each dwelling due to the shielding provided by the adjoining dwelling(s). Therefore conditioned air (and thus energy) losses through the shared structures are often reduced, because the air transferred between dwellings is likely to be at least partially conditioned. However, this air may also transport pollutants between dwellings.

2.2 Definition of Air Change Energy

2.2.1 Primary and delivered energy as measures of use

Primary energy is defined to be the sum of energy utilised directly by end-users (which is known as *delivered or final energy*) and the energy lost in the production and delivery of energy products. (See for example p.57 Schipper and Meyers, 1992 for a further discussion of these terms.) For instance, consider energy used by electrical resistance heating from fossil-fuel derived electricity. This incurs a much higher 'penalty' in terms of total primary energy use, than would be needed using the same amount of delivered energy in the form of natural gas from which heat can be generated by combustion. This is due to the magnitude of the efficiency of electricity production and transmission losses. As an approximate guide, total final consumption (TFC) is about 70% of the total primary energy supply (TPES), with the other 30% lost in the production and transmission of final energy. Exact values depend on how individual countries generate electricity and heat.

The straightforward ratios of TFC and TPES are shown in Column 2 of Table 1. This Table shows the ratio applicable for overall national energy use and includes not just the service and residential building sectors, but also that used by industry and transport. This ratio differs between the various energy consuming sectors, and is, in general, influenced by the fraction of electrical energy use within a sector. For end-users, the delivered energy use is most important, while for national level energy studies, the emphasis is generally on primary energy use.

Table 1 Primary to delivered energy ratios

	Primary to delivered energy ratio 1994 (derived from IEA 1996)
Belgium	1.38
Canada	1.33
Denmark	1.37
Finland	1.28
France	1.48
Germany	1.39
Netherlands	1.28
New Zealand	1.31
Norway	1.24
Sweden	1.42
Switzerland	1.29
UK	1.40
USA	1.48

2.2.2 Enthalpy transport by air change

When cooling, heat gain to the conditioned space results in increased thermal loads, whereas when heating, heat loss from the conditioned space is detrimental. Waste heat from energy conversion processes, such as the operation of electrical equipment, can contribute to space heat gains. The heat transport mechanism with which we are concerned is heat transfer by mass transport of air (i.e. air change) into and out of buildings. There can be up to two purely building-related components contributing to the overall air change rate:

- ventilation provided intentionally by means of a purpose-designed system, and
- background infiltration through cracks and gaps in the building structure.

Also, there may be a significant contribution to the air change rate from occupant-related airing, either intentionally (for example, by window opening) or unintentionally (for example, by door opening).

The energy content of the air flowing through a building is referred to as the air enthalpy. So, estimates of air change energy can be based on knowledge of the absolute value of the difference in specific enthalpy [$J \cdot kg^{-1}$] between the supply air before and after conditioning, which then describes an enthalpy change. This is then called the *air enthalpy change* [J]. (This is the basis of the 'microscopic' approach.) In order to convert an expression for delivered energy to an enthalpy change (and vice versa), an average efficiency of conversion must be defined. In this context efficiency refers to the efficiency of ventilation-related equipment, including space heating systems, ventilation systems, and air-conditioning equipment.

2.3 Air Change Energy in the Context of Building Energy Use

All energy will degrade to heat, and so delivered energy is ultimately dissipated from any building by:

(i) the disposal of heated water through the sewage system,
(ii) the exhaustion of waste heat directly to the outside, produced by air cooling or dehumidification equipment,
(iii) thermal conduction of heat to the outside through the building shell when heating,
(iv) mass transport of heated (or humidified) air, exhausted to the outside by either ventilation or exfiltration, and
(v) the exhaustion of waste heat directly to the outside, produced by air or water heating equipment (through for example flues or chimneys).

Delivered energy accounts for only part of the energy for each of the above Items, except Item (v) which is accounted for solely by delivered energy. The other component relevant to each Item is accumulated by the internal building environment from incidental sources such as solar gains and occupants. (During cooling, heat gains to the conditioned space are eliminated via the exhaustion of waste heat from cooling equipment.) However, for our purposes, these 'incidental' gains are assumed to be fixed, so a decrease in air change rate will result in a proportional decrease in the required enthalpy change. Delivered electrical energy used for appliances and lighting is also converted to thermal energy, which contribute to the space heat gains. During periods when heating is desired, these will decrease the amount of deliberate air heating that is required. If air cooling is wanted, then these delivered energy gains are likely to increase the amount of cooling that is necessary. Moreover, they can account for a large part of the cooling load, together with other incidental gains (as opposed to gains from heat entering via the building envelope). As an example, VanBronkhorst et al (1995) estimate that for a sample of office buildings air infiltration can account for an average of 18% of the annual heating load, but only 2% of the annual cooling load.

2.4 Fan Energy and Heat Recovery

The electrical power that ventilation system fans use must be examined in connection with the energy impact of ventilation, but it is important to stress that this use is in addition to the previously defined air change energy. For estimates of the energy used directly by fans, it is necessary to know how many are installed, and for how long and at what power they operate.

Fan power demand depends on the volume flow rate of air moved by the fan and system pressure losses, as well as characteristics of individual fan types. They are sized according to ventilation system characteristics, mainly total component pressure loss. (Performance data are usually presented as curves or multi-rating tables.) A reduction in flow rate for a particular fan does not necessarily lead to a proportional drop in power use. Therefore the optimum choice of fan (in terms of power use versus air flow rate) for a particular ventilation system under one specified set of operating conditions may not be the optimum choice if those operating conditions change (e.g. with a change of building use).

Exhaust air heat recovery essentially relies on the presence of a mechanical extract system (as part of either a balanced system or as an extract-only system), which uses one or more fans. The delivered energy savings achieved by the heat recovery must justify the delivered energy expenditure necessary for fans, and the presence of heat recovery devices themselves may increase fan power demand. The recovered energy may be used to heat incoming air or domestic hot water. Irving (1994) gives an introduction to the application of air-to-air heat recovery in ventilation systems.

2.5 The Influence of Occupancy

Occupancy refers both to the number of people present and to the times during which they are present. The main hours of occupancy of service sector buildings, in general, fall during the daytime. Therefore, the largest proportion of the space conditioning energy requirement for the sector is used during the daytime, for either heating or cooling (and perhaps dehumidification). Equally, solar gains can be an important consideration, especially during the summer months (with a consequent effect on cooling needs).

For the residential sector the highest periods of occupancy are likely to occur at night and at weekends, with residences being unoccupied more frequently with decreasing household size (less occupants per dwelling - a general trend in most industrialised countries.) Generally, the rate of conditioning energy use will be lower per dwelling during unoccupied periods.

3. Methods Used to Calculate Air Change Energy

3.1 Introduction

Two approaches for the estimation of air change-related energy use are used here: the microscopic ('bottom-up') approach in which air change energy is estimated from physical principles when outside air is heated or cooled to certain temperature (and humidity) set-points; and the macroscopic ('top-down') approach, in which estimates are made from the delivered energy use used for space conditioning (heating and cooling). Each method has its drawbacks, involving making assumptions about key data. Ideally, heating and cooling should be separated and the energy impact of each evaluated.

Throughout this report the air change rate (or volume flow rate) refers to the volume of fresh outdoor air introduced into buildings either intentionally (ventilation) or incidentally (air infiltration). No attempt has been made to account for recirculation of existing indoor air or for the inclusion of exhaust air heat recovery devices, for which increased fan energy use would be needed.

Also, all building volumes referred to are net volumes, that is excluding the space occupied by construction elements such as walls and floors. A possible source of discrepancy is when only building floor areas based on gross area are available. For heating energy calculations the relevant area is the net heated building area, and similarly for cooling energy it is the net cooled area. These are often substantially less than the gross building area.

3.2 Total Delivered Energy for the Service and Residential Sectors

The total service sector delivered energy data were found from energy balances published by the International Energy Agency (IEA, 1996), except for Finland (from Sateri, 1997), the UK (from Moss, 1994) and the USA (from DOE/EIA, 1995), as were the majority of the total delivered energy data for the residential sector. The International Energy Agency data give detailed "energy accounts" for each OECD country, equating primary energy sources with delivered energy and production and transmission losses. They list the usage statistics for all energy-using sectors in terms of delivered energy used by source. The data year selected for this study was 1994, being the most recent one for which data was available. Another exception to this was for the residential sector in the UK, information about which was received from Shorrock (1995).

3.3 Estimates of Space Heating and Cooling Energy Use

Delivered space conditioning energy is defined as the delivered energy which must be supplied for heating and cooling in order to achieve thermal comfort. Column 2 of Table 2 indicates the space conditioning percentage of total delivered energy for the residential sector, while Column 4 gives the percentage for the service sector.

The climates of the AIVC Participating Countries are diverse: The USA by itself has varied and contrasting climatic regions, ranging from areas with high dehumidification (latent cooling) loads, for example Texas and Florida, to regions with large winter sensible heating loads, for instance Washington State. On the other hand, only certain European regions, such as the Mediterranean coast of France, require much dehumidification for thermal comfort, and then only requiring a few percent of the energy needed in Texas or Florida. Heating is the dominant form of space conditioning energy expenditure for northern Europe.

Rough estimates for the total service sector space conditioning energy use have been made for Belgium, Canada, Denmark, The Netherlands, New Zealand, Norway, Sweden and Switzerland. Data from the International Energy Agency Heat Pump Centre (HPC, 1995) proved to be useful in this task: these gave totals for all heat used in buildings. Approximations for space conditioning energy that were consistent with known total sector use (IEA, 1996) were then made.

Estimates for service sector space conditioning data for France (ADEME, 1995), the UK (Pout, 1997) and Germany (Schipper et al, 1986) were found by applying an estimate of the fraction of total sector energy use accounted for by space conditioning to the most recently available total sector use data. The space conditioning energy for the USA was found by summing data from a number of sources, whilst Sateri (1997) supplied data for space heating in the service sector in Finland.

The space conditioning energy data for the residential sector were found by taking estimated fractions of the total delivered energy to the residential sector, as shown by the percentages in Column 2 of Table 2.

Table 2 Space conditioning share of total delivered energy

	Residential sector space conditioning percentage of total delivered energy	Reference	Residential sector average equipment efficiency, η	Service sector space conditioning percentage of total delivered energy	Reference
Belgium	66%	Estimate	0.60	54%	Estimate
Canada	68%	Riley and Lawton (1989)	0.75	72%	Estimate
Denmark	65%	Schipper et al (1992)	0.75	57%	Estimate
Finland	58%	Heikkinen (1994)	0.69	63%	Sateri (1997)
France	72%	Lemaire (1995)	0.75	33%	1994, ADEME (1995) (includes hot water)
Germany	66%	Estimate	0.78	64%	1982, Schipper et al (1986) (includes 4% cooling)
Netherlands	66%	Estimate	0.70	54%	Estimate
New Zealand	66%	Estimate	0.75	46%	Estimate
Norway	67%	Schipper et al (1992)	0.90	57%	Estimate
Sweden	64%	Schipper et al (1992)	0.90	58%	Estimate from HPC (1994), IEA (1996)
Switzerland	66%	Estimate	0.75	54%	Estimate from HPC (1994), IEA (1996)
UK	62%	Shorrock (1994)	0.65	61%	1994, Pout (1997) (includes 4% cooling)
USA	64%	Schipper et al (1992) (includes 6% cooling)	0.80	60%	VanBronkhorst et al (1995) heating; DOE/EIA (1995) + HPC (1994) cooling

3.4 Air Change Energy

Specific tools exist that can help to find the air change energy use. Heating degree-days are widely used and published. Other techniques are currently only practical for certain countries, mainly those in which they have been developed. These include infiltration degree-days, tables of which have been published for locations across the USA (Sherman, 1986), and ventilation degree-days, which can be used for Germany (DIN 4710). These methods are generally used to determine enthalpy changes and are explained in Appendix A.

3.4.1 Data required for estimates

There are several key data that are needed before a basic estimate of the air change energy use can be made. Principally, these are the number of buildings, the average conditioned volume (or equivalently the average floor area and room height) that is heated or cooled, and the duration and level of occupancy. More detailed information can be derived if the above factors are available for each sub-sector. Appendix B lists the available characteristics of the service sector buildings for each AIVC Participating Country. Adjustments have been made to the actual floor areas used in the service sector calculations for all countries except Finland, France, Norway, Sweden and the USA. On-going work in the UK (Bruhns et al, 1994) has revealed important information about a large part of the service sector in that country.

Relevant data for the residential sector are shown in Table 3. Also, it is essential to know average air change rates and the required outdoor to indoor specific air enthalpy changes. The product of the conditioned internal volume with the air change rate will give the volume flow rate of air to be conditioned.

3.4.2 Service sector

For the service sector in Belgium, Denmark, France, The Netherlands, the UK and the USA, the enthalpy change calculations were based on the work of Colliver (1995), although these values will tend to slightly overestimate the required space heating. Separate calculations were performed for heating and cooling in the USA, which was split into regions and then the population-weighted average of the specific enthalpy changes taken. The heating and cooling (including dehumidification) enthalpy changes were also converted to delivered energy use separately. For the other countries (Canada, Finland, Germany, New Zealand, Norway, Sweden and Switzerland) the basis was heating degree days (described in Appendix A, Section A.1.1). No allowance was made for non-continuous occupancy. Due to the absence of more appropriate data, residential sector conversion efficiencies were applied in order to express the calculated air enthalpy changes in terms of delivered energy (shown in Column 3 of Table 2).

Table 3 Background data for the residential sector in the 13 countries

Country	Population [10^6] (1994)	Heating degree-days, D_d^h [K·d]	Number of dwellings, N [10^6]	Mean dwelling volume, $\overline{V}$ [m^3]
Belgium	10.1	2300	3.90	351
Canada	29.3	4300	9.60	340
Denmark	5.21	2900	2.00	259
Finland	5.09	(5000)	2.30	234
France	57.9	(2450)	22.0	231
Germany	81.4	3600	34.0	225
Netherlands	15.4	2800	6.00	250
New Zealand	3.53	1700	1.19	223
Norway	4.34	(3800)	1.75	266
Sweden	8.78	3600	4.04	263
Switzerland	6.99	3000	3.16	234
UK	58.4	(2500)	24.1	210
USA	261	(2700)	96.6	337

The average air change rate in service sector buildings was assumed to equal 0.75 ach (air changes per hour). The justification for choosing this value is that there is some evidence that air infiltration alone in some countries is in the region of 0.5 ach. Ventilation rates are often considerably higher than this, although they include a large proportion of recirculated air that does not require the same level of conditioning. However, recirculation of air requires additional fan energy use. In addition, airing by building occupants may increase the overall air change rate.

For instance, a study involving measurements taken in 40 non-residential buildings in the USA (CEC, 1995) produced an average air infiltration rate of 0.56 ach. As a further example, it has been predicted that for a sample of 12 UK (naturally ventilated) office buildings the overall average air change rate would be 0.61 ach (Potter et al, 1995). Using a higher air change rate than would be provided by air infiltration alone allows for the extra ventilation air. Determination of the actual air change rates in non-residential buildings is an area that requires more investigation.

3.4.3 Residential sector

The assumed values of the conversion efficiency used in the residential sector study are shown in Column 3 of Table 2. Note that the value indicated for the UK, 0.65, is based on higher heating values for fossil fuels (see Section 1.2.2). In terms of lower heating values, this is believed to be in the region of 0.7. Table 4 presents a summary of the methods used to estimate the residential sector air change energy. A check '✓' in Column 2 of this Table indicates that the heating degree-day method was used for the air change energy calculation, as described in Appendix A, Section A.1.1. For those countries for which this method was employed, the appropriate data can be found in Tables 3 and 4. In particular, Column 3 of Table 4 contains assumed values for the air change rate. If no reference is indicated, then these should be taken to be estimates.

Table 4 Methods used for estimating the residential sector air change energy

	Heating degree-days and average air change rate	Assumed air change rate Q_{ach} [h^{-1}]	Published source for average air change rates determined by measurement survey	Modelling representative sample of dwelling types	Other source
Belgium	✓	0.75			Wouters, 1994
Canada	✓	0.4			Swinton, 1995
Denmark	✓	0.5	(Bergsøe, 1993 and 1994)		
Finland			(Ruotsalainen et al, 1992)		Heikkinen, 1994
France		0.5			Lemaire, 1995
Germany	✓	0.5			Steimle, 1994
Netherlands	✓	0.5			de Gids, 1994
New Zealand	✓	0.5			
Norway					Brunsell, 1994
Sweden	✓	(0.4)	Norlén et al, 1993		Kronvall, 1994
Switzerland	✓	0.7			Dorer, 1994
UK					Shorrock et al, 1992
USA				Sherman et al, 1996	

3.5 The Influence of Occupancy

Occupancy refers both to the number of people present and to the times during which they are present. The main hours of occupancy of service sector buildings, in general, fall during the daytime. Therefore, the largest proportion of the space conditioning energy requirement for the sector is used during the daytime, for either heating or cooling (and perhaps dehumidification). Also then, solar gains can be an important consideration, especially during the summer months (with a consequent effect on cooling needs). Table 5 presents information from the ILO (1995), which lists employment levels for certain sub-categories of the service sector.

Estimates based on the number of occupants (for example by specifying a design ventilation rate in litres per second per person) are complicated for some sub-sectors by the presence of people in addition to employed workers. This is illustrated, for instance, by the education sub-sector, in which it is necessary to know the number of students present, as well as the number of workers.

The employment statistics listed in Table 5, when combined with service sector floor areas for countries which are known, can be used to estimate the total service sector floor areas for the other countries. In fact, this procedure was used to produce initial (but subsequently revised) estimates for Belgium, The Netherlands and New Zealand, for which no floor area data had previously been found. The total heated service sector floor areas for these three countries have been approximated (using also the total energy use for the sector in each country) in relation to the situation in nine other countries.

Table 5 Employment in the economic service sector

Country	Ref. Year	Trade, restaurants and hotels [10^3]	Transport, storage, communication [10^3]	Financing, insurance, real estate, business services [10^3]	Community, social and personal services [10^3]	Total [10^3]
Belgium	1992	630	260	340	1400	2600
Canada	1993	2900	770	1500	3900	9100
Denmark	1993	400	180	260	930	1800
Finland	1994	290	160	180	700	1300
France	1994	3700	1400	2300	7700	15000
Germany	1994	5400	2200	3200	11000	22000
Netherlands	1994	1200	420	700	2400	4700
New Zealand	1993	320	91	150	430	990
Norway	1994	350	170	160	780	1500
Sweden	1994	570	270	380	1600	2800
Switzerland	1994	750	240	480	1100	2500
UK	1996	5000	1300	3800	6700	17000
USA	1994	26000	7100	14000	43000	90000

Source: ILO (1995) except UK (ONS, 1997)

4. Estimates of Energy Use

4.1 Overview

Figure 6 shows the components of energy use in the service sector for all AIVC Participating Countries, whilst Figure 7 presents the data for the residential sector. Each axis, including the supplementary energy axis on the right hand side of both Figures 6 and 7 are logarithmic, and the lengths of the lines joining the data points for each country are proportional to the ratio between the energy quantities. There is a vast difference in size for both sectors between the smallest and the largest country in terms of building volume. For the service sector, the largest country, the USA, uses 190 times the total energy in 105 times the building volume as the smallest country, New Zealand. For the residential sector, the largest country, again the USA, uses 210 times the energy in 120 times the volume as the smallest country, again New Zealand.

In Figures 6 and 7, the estimates of the space conditioning energy are linked with the totals of delivered energy, as are the delivered air change energy values with the air enthalpy changes. It can be seen in Figure 7 that total estimated delivered energy to the residential sector in each country is in proportion to the total internal volume of dwellings. This is less apparent for the service sector (Figure 6). Note that the air enthalpy changes for the USA residential sector in Figures 7, 9, 10 and 11 include heating only, whereas the delivered air change energy includes both heating and cooling.

There are differences in the ratios between components of the total delivered energy, which is evident from the differing lengths of the lines joining the components. The air change energy data also seem to be in proportion to the total net volume for the residential sector, although the trend is less pronounced than for the total delivered energy.

In countries requiring little space heating (for instance New Zealand), it is difficult to evaluate the component of energy lost through ventilation. The main reason is that most residential buildings are heated intermittently and in only one or two rooms. Inter-zone air flows can carry a significant fraction of this heat to cooler parts of the building thus adding to heating requirements and to the fraction carried away by air.

4.2 Normalised Data

The service sector energy use data per unit volume are shown for each country in Figure 8. The air enthalpy changes illustrated in this Figure are effectively purely climate dependent, because the same air change rate (0.75 ach) was assumed for all countries, as discussed in Section 3.4.2. For Belgium, Canada, The Netherlands, New Zealand, and Switzerland it was necessary to estimate both the service sector space conditioning energy use and the total sector volume. Consequently, there is a great deal of uncertainty associated with the space conditioning energy values per unit volume illustrated in this Figure.

It is apparent from Figure 9, which shows residential energy use per unit volume, that with the exception of New Zealand, there are few similarities between the residential sector and the service sector of any country. The normalised air enthalpy changes are observed to be very similar for most countries, except for Norway, Germany and the USA, which are close together at a larger value.

Included in Figure 10, which expresses residential energy use per person, are values for total residential delivered energy per person. These are perhaps known with the greatest certainty of any values presented in this report. The total use per person ranges in magnitude from New Zealand to Canada and Finland, both at roughly three times as high.

In Figure 11, the energy data are normalised to express average values per dwelling. This is simply achieved by dividing all quantities by the number of dwellings in a country. Therefore, the air enthalpy change per dwelling, $E_{enthalpy}^{dwelling}$, equals

$$E_{enthalpy}^{dwelling} = \frac{E_{enthalpy}}{N},$$

whilst the delivered air change energy per dwelling, $E_{delivered}^{dwelling}$, is given by

$$E_{delivered}^{dwelling} = \frac{E_{delivered}}{N}.$$

(The derivations of the total air enthalpy change, $E_{enthalpy}$, and the delivered air change energy , $E_{delivered}$, are described in Appendix A.) The most prominent feature of Figure 11, which shows the energy use per dwelling, is the wide variation in energy used by an 'average' dwelling in each country. This can be partially explained by the varied climatic circumstances of each country. The total energy use per dwelling ranges in magnitude from New Zealand to Canada, at roughly three times as high. In general, the air enthalpy changes do not seem to have a particularly good correlation with total use. A reason for this may be the wide range of air change rates assumed for the different countries.

4.3 Fan Energy Use

No attempt has been made here to make a proper evaluation of fan energy use. Jagemar (1996) discusses energy efficiency of HVAC (heating, ventilation and air-conditioning) systems in some detail.

Specific fan power demand (i.e. kilowatts of electrical power per cubic metre per second of air moved) typically lies in the range of 1 $kW \cdot s \cdot m^{-3}$ (good performance) to 3 $kW \cdot s \cdot m^{-3}$ (poor performance). Assuming a specific fan power of 2 $kW \cdot s \cdot m^{-3}$ would imply that at a continuous air change rate of 0.75 ach, fan energy use would be up to 10% - 20% in addition to delivered air change energy use for the service sector of the 13 countries studied, regardless of climate. If the consequences of air recirculation on fan energy use are considered, then it would not be unreasonable to expect that this value may be two to three times higher.

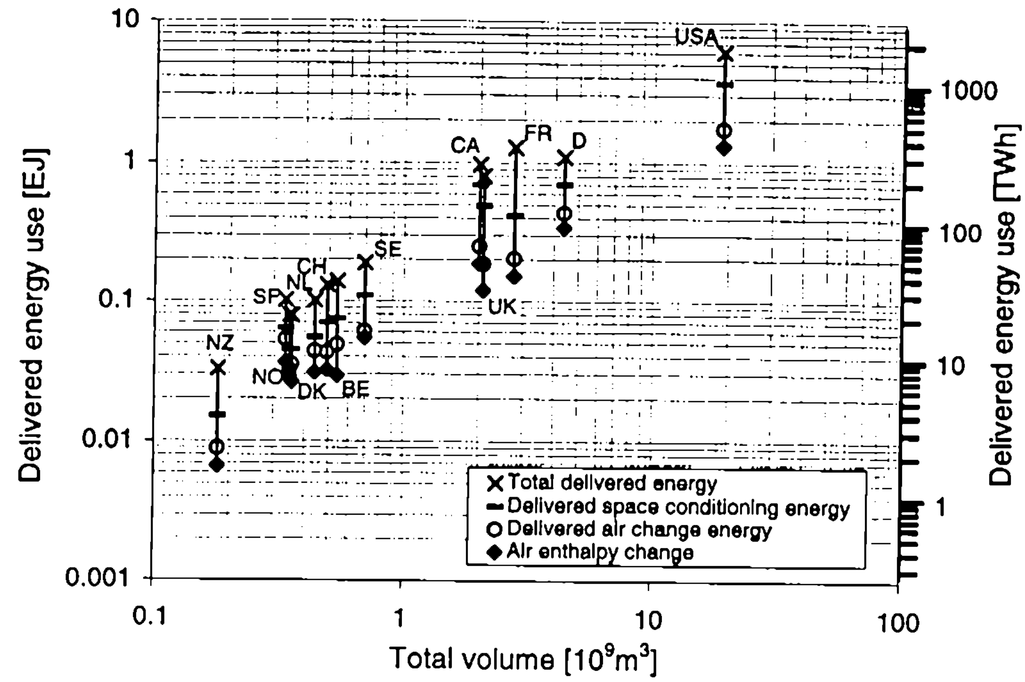

Figure 6 Service sector - annual delivered energy use in relation to total sector building volume

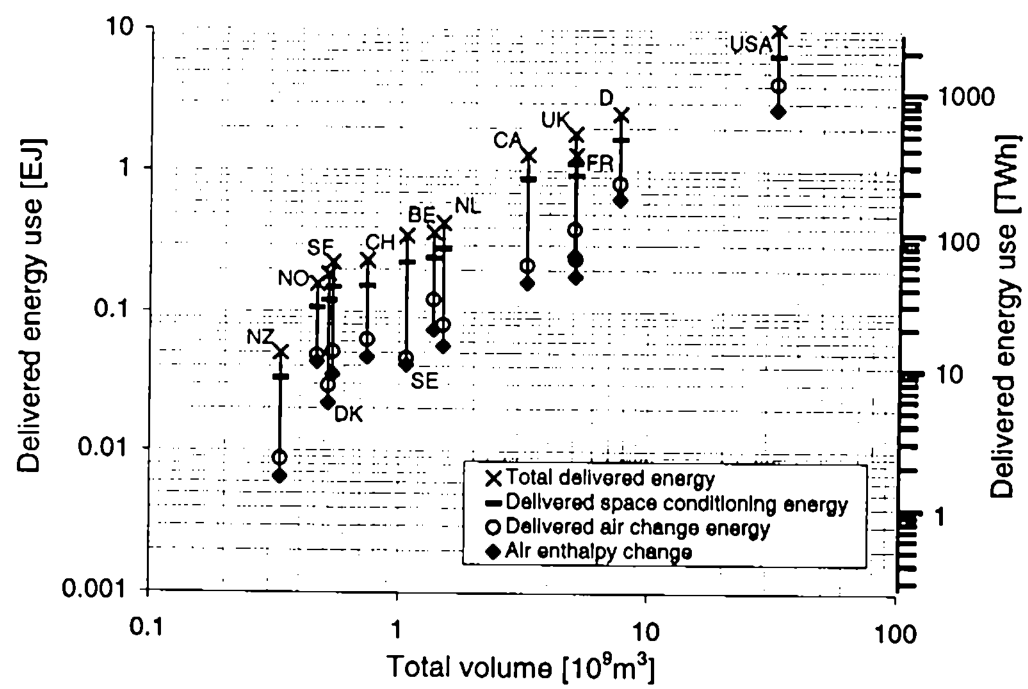

Figure 7 Residential sector - annual delivered energy use in relation to total sector building volume

BE - Belgium, CA - Canada, DK - Denmark, SF - Finland, FR - France, D - Germany, NL - Netherlands NZ - New Zealand, NO - Norway, SE - Sweden, CH - Switzerland, UK - United Kingdom, USA - United States of America

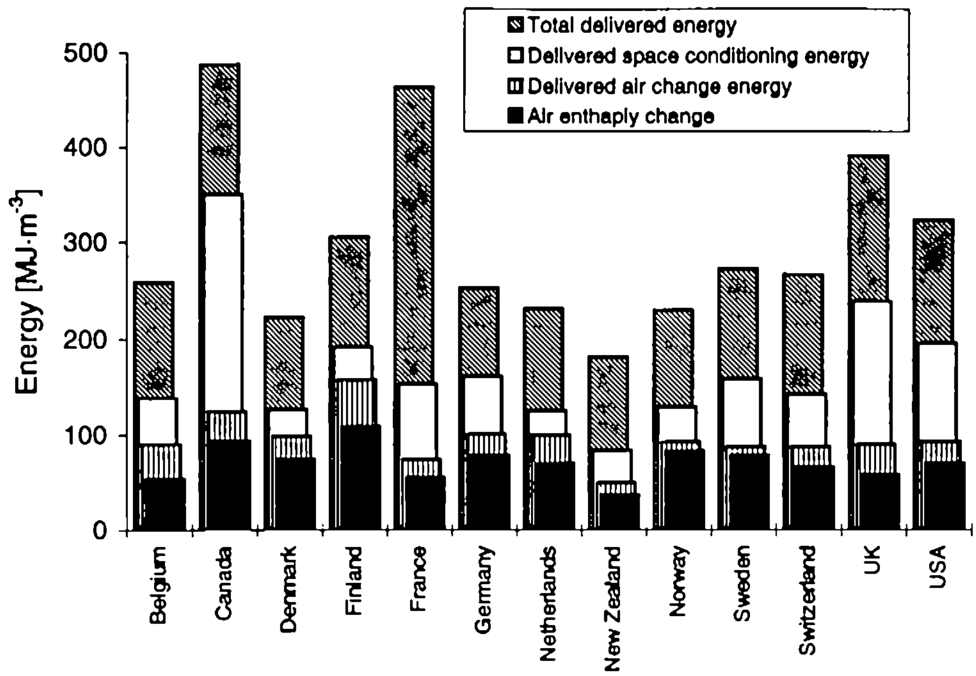

Figure 8 Service sector - annual delivered energy use per unit volume

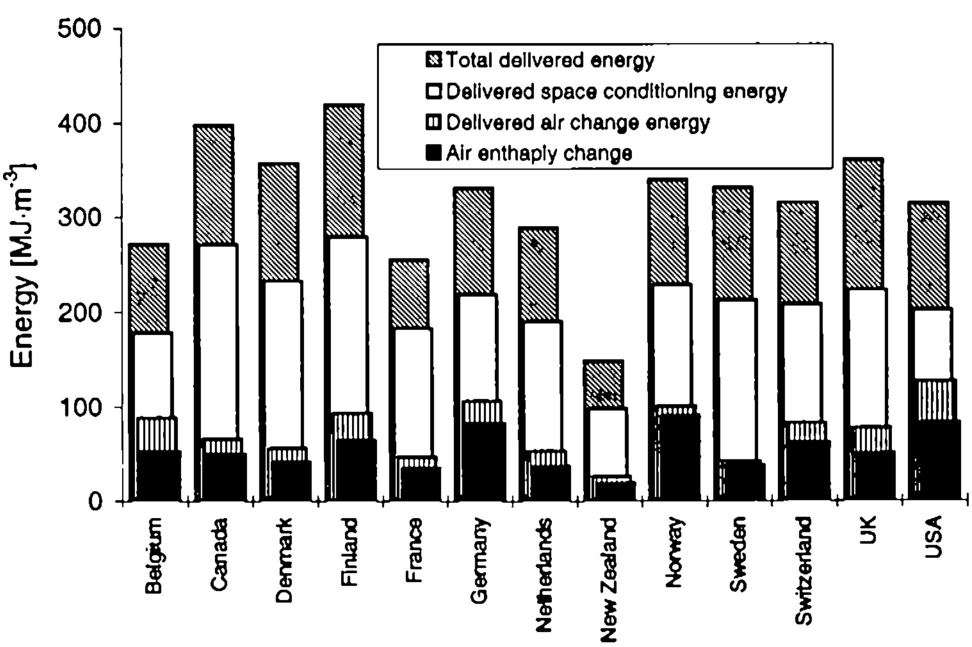

Figure 9 Residential sector - annual delivered energy use per unit volume

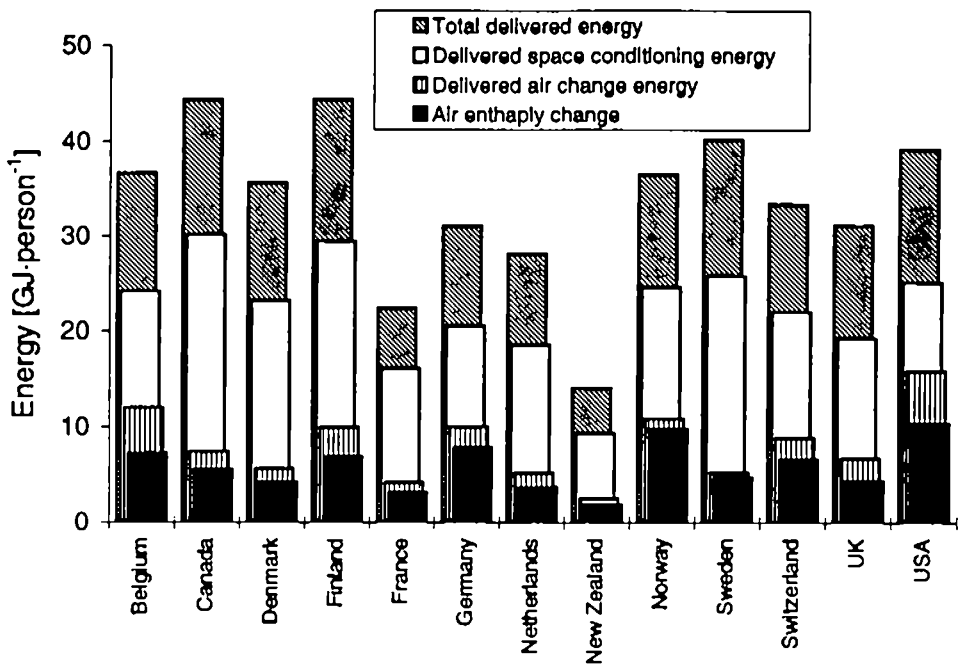

Figure 10 Residential sector - annual delivered energy use normalised per person

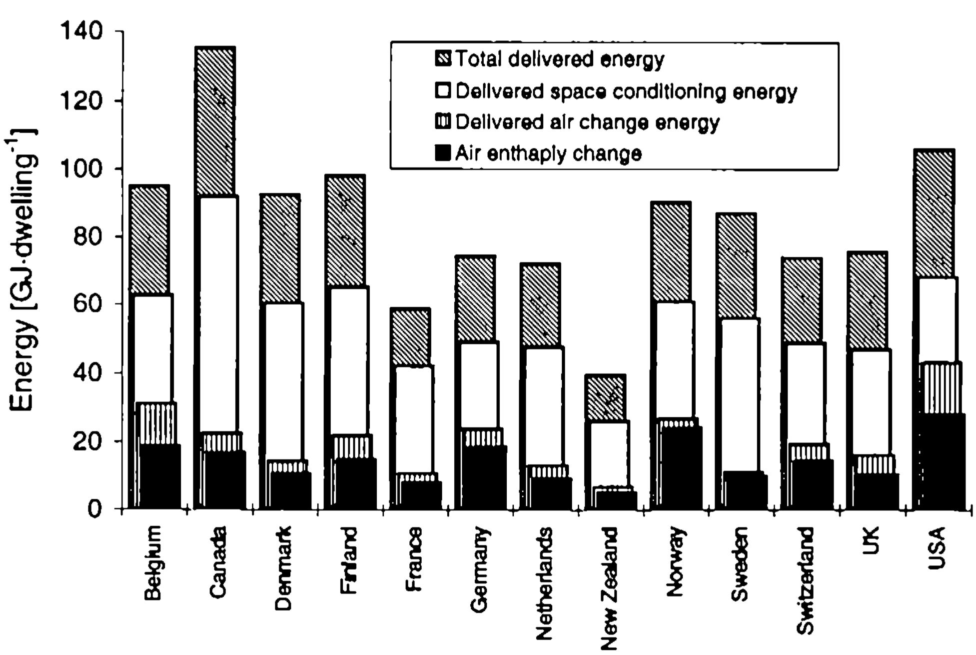

Figure 11 Residential sector - annual delivered energy use normalised per dwelling

4.4 Humidification in very cold climates

Humidification of air in very cold climates, which is often necessary, has not been accounted for in the preceding analysis. For example, to condition air saturated with moisture at -20 °C to air at 20 °C and 40% relative humidity would require an enthalpy change of about 14 $kJ \cdot kg^{-1}$ of air for the change in moisture content alone. For comparison, the enthalpy change needed to raise the temperature of the air (sensible heating) would be of the order of 40 $kJ \cdot kg^{-1}$, demonstrating that the energy needed for humidification is not negligible. This is an area requiring further investigation.

5. Estimates of Carbon Dioxide Emissions due to Air Change Energy Use

The carbon dioxide (CO_2) emissions resulting from energy use were estimated from the total annual CO_2 emissions from energy-related sources for each country (IEA, 1994b). This involved taking the sum of the CO_2 produced directly from fossil fuel TFC (total final consumption - see Section 2.2.1) and that emitted indirectly, due to electricity use by each sector. These were obtained by weighting the amount of fossil fuel derived energy used in electricity production against the fossil fuel energy used directly, taking into account transformation and production losses. The CO_2 emission factors thus determined due to energy-related use of both electricity and fossil fuels are shown in Table 6. Columns 3 and 4 of this Table are equivalent except that Column 3 is expressed in the units 'kg CO_2 per GJ electricity use', whilst Column 4 is expressed in the units 'kg CO_2 per kWh electricity use'. Pout (1994) has produced more detailed emission factors for the UK applicable to the service and residential sector and these are the basis of the UK factors presented in Table 6. The factors shown in the Table for all other countries are averages for all sectors (i.e. buildings, industry, agriculture, etc). An important assumption made is that the mass of CO_2 emitted is proportional to the magnitude of the fossil fuel derived primary energy use.

Electricity generation is dominated by nuclear power in France and Belgium, by hydro-electric power in New Zealand, Norway and Canada, and by a combination of both in Finland, Sweden and Switzerland. Therefore in those countries the carbon dioxide emission factors for electricity production (shown in Table 6) are lower than in the remaining countries, which rely heavily on fossil fuel generated electricity.

The total emissions of CO_2 for the service and residential sectors are given in Table 7. These have been derived for each country by multiplying the relevant factors given in Table 6 by the direct fossil fuel use and electricity use, and then summing the two calculated quantities for each sector. The estimated CO_2 emissions from the service sector can be found in Figure 12, including the particular energy end use in which we are interested, space conditioning, and the air change energy use with which it is associated. Note that the horizontal and vertical scales are logarithmic. In a similar fashion, Figure 13 shows the estimated CO_2 emissions due to each component of residential energy use. Again, both horizontal and vertical scales are

Table 6 Estimated carbon dioxide emission factors in 1992

	kg CO_2/ GJ fossil fuel TFC	kg CO_2/ GJ electricity TFC	kg CO_2/ kWh electricity TFC
Belgium	76	83	0.30
Canada	76	53	0.19
Denmark	81	130	0.46
Finland	83	42	0.15
France	71	25	0.090
Germany	77	150	0.55
Netherlands	66	140	0.49
New Zealand	81	63	0.23
Norway	100	0.48	0.0017
Sweden	74	11	0.040
Switzerland	68	4.5	0.016
UK	61	190	0.59
USA	76	150	0.55

logarithmic. The fractions of CO_2 emissions attributed to space conditioning and air change energy use, were assumed to equal the fraction of energy used by the total sector. However, in reality, actual fossil fuel use is likely to vary according to end use. It has been supposed here that, for instance, the fraction of space conditioning energy use constituted by electrical energy, is the same fraction as for all end uses. The same is taken to be true for other energy sources. The calculations based on these assumptions are not necessarily accurate, but were considered to be acceptable because of the lack of relevant national information. The biggest contrast between the two sectors is perhaps seen in the case of France, which has a high proportion of

Table 7 Estimated carbon dioxide emissions of the service and residential sectors in 1992

	Service sector 1992 emissions/ Mtonne CO_2	Residential sector 1992 emissions/ Mtonne CO_2
Belgium	11	30
Canada	62	74
Denmark	8.9	17
Finland	1.7	12
France	76	44
Germany	120	230
Netherlands	12	33
New Zealand	2.3	2.8
Norway	1.2	1.5
Sweden	4.5	6.0
Switzerland	7.0	13
UK	85	160
USA	760	960

oil use in its service sector in comparison with other energy sources. This effectively cancels the low CO_2 emissions arising from its service sector electricity use.

Figure 14 depicts the service sector CO_2 emission intensity, expressing CO_2 emissions per unit building volume. Similarly, Figure 15 shows the residential sector CO_2 emission intensities, again expressing CO_2 emissions per unit building volume.

The majority of Norway's non-industrial building-related energy use is obtained through electricity derived from hydro-electric power generation. This is reflected in the low intensity of CO_2 emissions in both the service sector, in which oil constitutes about one fifth of delivered energy, and the residential sector, in which oil constitutes about one tenth of delivered energy, with most of the remainder in each accounted for by electricity. The situation is similar in Sweden, except that oil accounts for approximately one third of delivered energy use in each sector, with the remainder derived from electricity. (This is mainly produced from both nuclear and hydro-electric power in equal proportions.) Other countries do not use such high proportions of delivered electrical energy for space conditioning.

6. Uncertainties in the Estimates

The quantities presented cannot be claimed to be very accurate. In fact, some of the more approximate estimates may only be accurate to within ±50% of their true values. However, subject to the often large uncertainties associated with some of the input data, some broad trends can still be seen. There is expected to be a certain amount of annual variation in the air change energy values. For instance, if there is a change in the size of the (service or residential) building sector through a net difference between new construction and demolitions, then correspondingly this change will be reflected in the total sector energy use, as well as in its individual components, such as air change energy use.

Infiltration-related loads will be subject to variation because of year to year differences in the climate (such as different average temperatures or wind speeds). Annual ventilation-related loads will mainly be affected by year to year fluctuations in average outdoor temperature (and often humidity when applicable). For these reasons, air change energy values compared with total energy use quoted for a single reference year (in this case 1994) should not be taken as specifically applying to that year. It is very unlikely that an exact year by year analysis of infiltration and ventilation related total energy use could be performed.

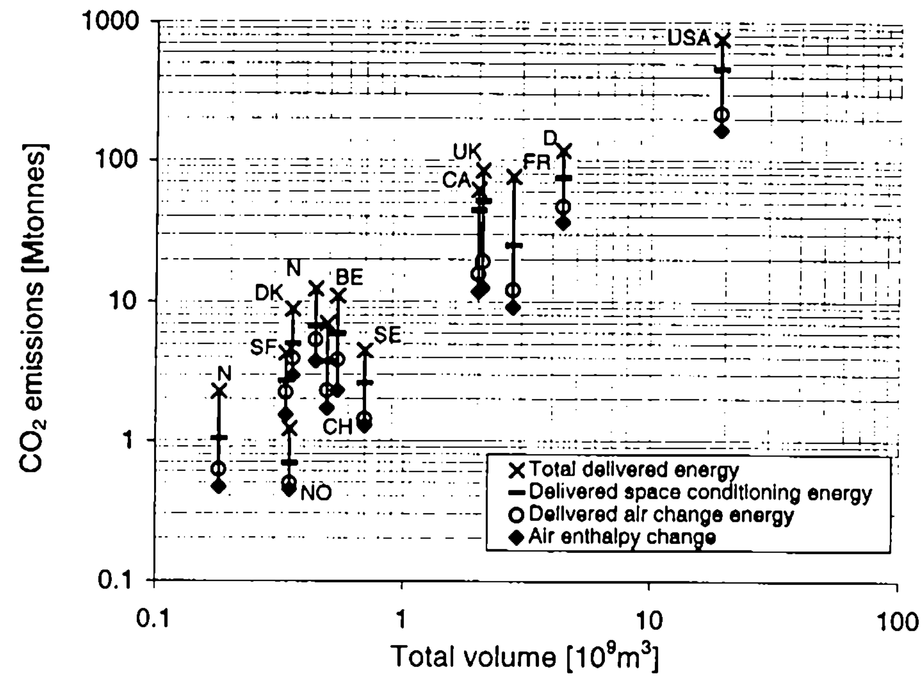

Figure 12 Service sector - annual carbon dioxide emissions in relation to total sector building volume

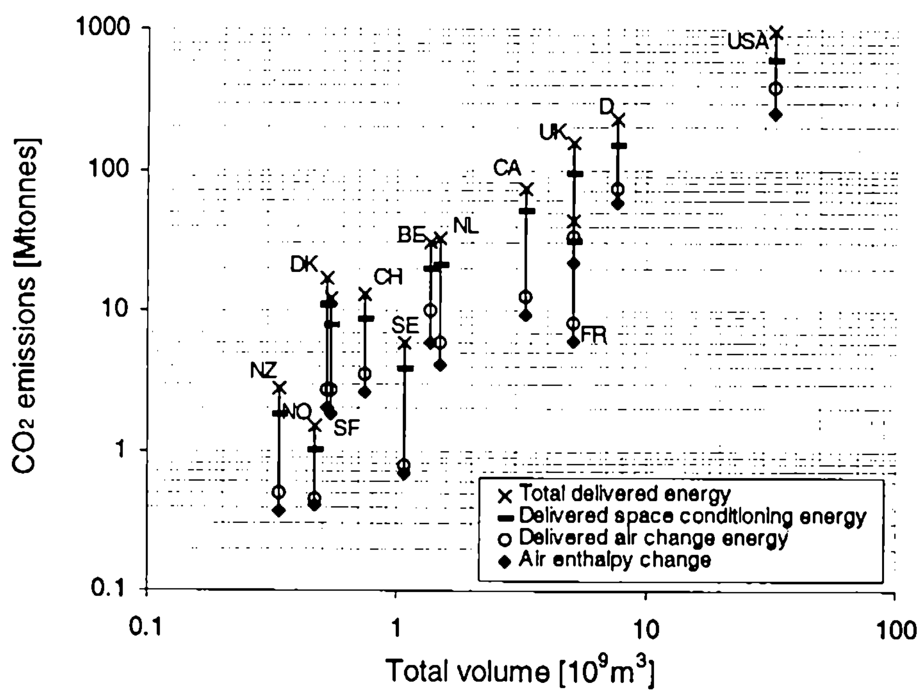

Figure 13 Residential sector - annual carbon dioxide emissions in relation to total sector building volume

BE - Belgium, CA - Canada, DK - Denmark, SF - Finland, FR - France, D - Germany, NL - Netherlands NZ - New Zealand, NO - Norway, SE - Sweden, CH - Switzerland, UK - United Kingdom, USA - United States of America

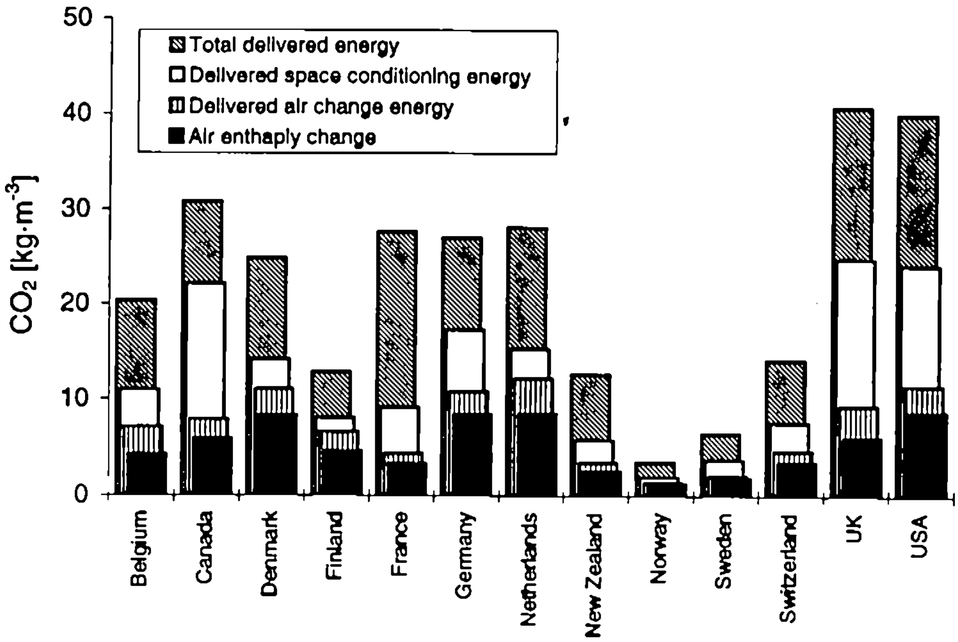

Figure 14 Service sector - annual carbon dioxide emissions per unit building volume

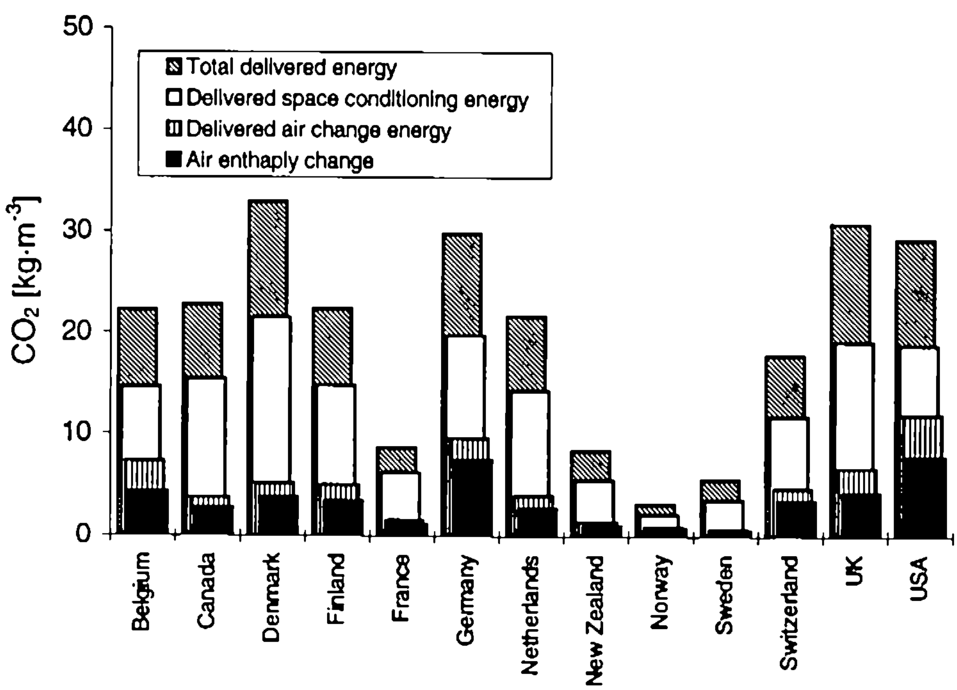

Figure 15 Residential sector - annual carbon dioxide emissions per unit building volume

7. Conclusions

In this report, estimates have been made, to quantify the energy impact of air change on total energy use in service sector and residential buildings for 13 major industrialised countries. This involved undertaking a basic analysis of currently available data sources, together with the estimation of essential 'missing' data. The potential for reduced energy use by improved ventilation control has also been briefly reviewed. In addition, the effect that air change energy use has on carbon dioxide emissions due to the use of fossil fuels has been discussed.

An examination of the relative importance of service and residential building energy use as compared to other energy sectors demonstrates that total building energy demand is of comparable significance to the transport sector and more than twice that of industrial demand. Therefore it is important to understand why the building sector uses such a significant quantity of energy, and, in particular, the impact of ventilation and air infiltration (i.e. air change) on this demand.

On the basis of the estimates presented here, it appears that there is less variation in the total residential sector energy use intensity for all end uses compared to the service sector. (Energy intensity is measured here in terms of megajoules per cubic metre of building volume.) The service sector air enthalpy changes are generally based on higher assumed air change rates than the residential sector. Therefore, as would be predicted, most of the corresponding energy use intensities are higher.

As may be expected, the lowest annual carbon dioxide emission intensities (measured in kilograms of carbon dioxide per cubic metre of building volume) are observed to be achieved by countries that rely mainly on non-fossil fuel derived electrical energy for space conditioning. This is the current situation in, for example, Norway and Sweden.

Considering the non-industrial building stock of the 13 countries collectively, the total loss of heating energy due to air change is estimated to amount to 48% of delivered space conditioning energy (including heating equipment losses). Stated in terms of delivered space heating energy alone (i.e. excluding space cooling), this rises to 53%. If the outdoor air supply rate per occupant were to be universally reduced to a minimum level, taking into account metabolic needs and pollutant loads, then it is conceivable that the heating air change energy loss could be reduced to approximately a third of the current level. Further reductions may be possible by the efficient use of heat recovery or heat pump technology. The consequent reduction in the total carbon dioxide emissions from the service and residential sectors (for all end uses) would be in the region of 20%, with the carbon dioxide emissions being reduced by about 600 million tonnes per year.

These results emphasise that air change related energy losses are as important as conduction and equipment losses (including 'flue' losses) in dissipating delivered space conditioning energy from buildings. In fact, as national standards, regulations or codes of practice improve the thermal integrity of buildings and increase equipment efficiency, it is expected that ventilation and air movement will become the dominant loss mechanism.

A more rigorous understanding of building-related energy balances could be achieved through further research. There is still much uncertainty in air change energy use and the potential for its reduction. Essential information is still to be found for some countries to enable satisfactory estimates to be made. However, given improved input data where necessary, it is possible to apply the same methodology to produce better estimates. Least information was found concerning the service sector. For many countries, data such as total heated or cooled floor area, air infiltration rates, ventilation rates, and equipment efficiencies need to be collected.

References

ADEME (1994), *Les Chiffres Clés du Bâtiment 1994*, Agence de l'Environnement et de la Maîtrise de l'Energie, France.

ADEME (1995), *Les Chiffres Clés du Bâtiment 1995*, Agence de l'Environnement et de la Maîtrise de l'Energie, France.

ASHRAE (1995), *1995 HVAC Applications Handbook*, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA, USA.

Bergsøe N C (1993), "Potential Energy Savings from Modified Ventilation of Dwellings", *Proceedings of the 14th AIVC Conference*, "Energy Impact of Ventilation and Air Infiltration", held Copenhagen, Denmark, 21-23 September 1993, pp. 11-21. # 7008

Bergsøe N C (1994), "Investigation of Ventilation Conditions in Naturally Ventilated Single Family Houses", *Proceedings of 15th AIVC Conference*, "The Role of Ventilation", held Buxton, UK, 27-30 September 1994, Volume 1, pp. 93-99. # 7959

Bruhns H, Steadman P, Rickaby P (1994), *The National Non-Domestic Building Stock: Some Preliminary Analyses of the Valuation Support Application (VSA) Database*, Centre for Configurational Studies, The Open University, September 1994.

Brunsell J (1994), Communication to AIVC Workshop, "The Energy Impact of Ventilation", Horgen, Switzerland, March 1994 (unpublished).

CEC (1995), *Air Change Rates in Non-Residential Buildings in California*, California Energy Commission, July 1995.

CEREN (1996), *Suivi du parc et des consommations d'énergie Evolutions de 1993 à 1994 Secteur Tertiaire*, France.

Colliver D (1995), *Energy Requirements for Conditioning of Ventilating Air*, AIVC Technical Note 47, Air Infiltration and Ventilation Centre, Coventry, UK. # 9104

DIN 4710, *Meteorologische Daten zur Berechnung des Energieverbrauchs*, Beuth-Verlag GmgH, Berlin 11.1992.

DOE/EIA (1995), *Commercial Buildings Energy Consumption and Expenditures 1992*, Energy Information Administration, US Department of Energy.

Dorer V (1994), Communication to AIVC Workshop, "The Energy Impact of Ventilation", Horgen, Switzerland, March 1994 (unpublished).

de Gids W (1994), Communication to AIVC Workshop, "The Energy Impact of Ventilation", Horgen, Switzerland, March 1994 (unpublished).

Heikkinen J (1994), Communication to AIVC Workshop, "The Energy Impact of Ventilation", Horgen, Switzerland, March 1994 (unpublished).

Herring H, Hardcastle R, and Phillipson R (1988), *Energy Use and Energy Efficiency in UK Commercial and Public Buildings up to the Year 2000*, UK Department of Energy, HMSO. #3254

HPC (1994), *International Heat Pump Status and Policy Review. Part 1 - Analysis*, 2A HPC-AR3, IEA Heat Pump Centre, Sittard, The Netherlands. # 9510

IEA (1994a), *Energy Conservation in Buildings and Community Systems (BCS) Strategy plan 1994 - 97*, International Energy Agency, August 1994. # 9269

IEA (1994b), *Climate Change Policy Initiatives 1994 Update*, Organisation for Economic Co-operation and Development/International Energy Agency, Paris, France.

IEA (1996), *Energy Balances of OECD Countries 1993 -1994*, Organisation for Economic Co-operation and Development/International Energy Agency, Paris, France.

ILO (1995), *Yearbook of Labour Statistics 1995*, International Labour Office, Geneva, Switzerland.

Irving S (1994), *Air-to-Air Heat Recovery in Ventilation*, AIVC Technical Note 45, Air Infiltration and Ventilation Centre, Coventry, UK.

Jagemar L (1996), *Design of Energy Efficient Buildings - Applied on HVAC Systems in Commercial Buildings*, PhD Thesis, Chalmers University of Technology, Göteborg, Sweden. # 9641

Kronvall J (1994), Communication to AIVC Workshop, "The Energy Impact of Ventilation", Horgen, Switzerland, March 1994 (unpublished).

Lemaire M-C (1995), Personal Communication.

Moss S A (1994), *Energy Consumption in Public and Commercial Buildings*, BRE Information Paper IP 16/94, October 1994, Building Research Establishment, Watford, UK.

Norlén U, and Andersson K (Editors) (1993), *The Indoor Climate In The Swedish Housing Stock*, The Swedish Council for Building Research (Byggforskningsrådet), Stockholm, Sweden. # 7836

Novem (1994), *Energiegids*, Novem, Sittard, The Netherlands.

ONS (1997), *Annual Abstract of Statistics - 1997 Edition*, Office for National Statistics, London: The Stationery Office, No. 133, Editor: Daniel Wisniewski, UK.

Potter I N, Jones T J and Booth W B (1995), *Air Leakage of Office Buildings*, BSRIA Technical Note 8/95, Building Services Research Information Association, Bracknell, UK. # 8939

Pout C H (1994) "Relating CO2 Emissions to End-Uses of Energy in the UK", *Proceedings of the First International Conference on Buildings and the Environment*, 16-20 May, 1994, Session: Energy, Paper 1, Building Research Establishment, UK. # 8763

Pout C H (1997), Personal Communication.

Recknagel, Sprenger and Hönmann (1992), *Taschenbuch für Heizing und Klimatechnik*, 66. Auflage, Herausgeber: Schramek, E.R., R. Oldenbourg-Verlag-München-Wien.

Riley M and Lawton M (1989), "Air Infiltration in Canadian Homes - a Decade of Change", *Proceedings of the 10th AIVC Conference*, "Progress and Trends in Air Infiltration and Ventilation Research", held Dipoli, Finland, 25-28 September 1989, pp. 253-267. # 3588

Ruotsalainen R et al (1992), "Indoor Climate and the Performance of Ventilation in Finnish Residences", *Indoor Air*, Vol. 2, pp. 137-145. # 6365

Sateri J (1997), Personal Communication.

Schipper L, and Meyers S (1992), *Energy Efficiency and Human Activity*, Cambridge University Press.

Schipper L, Meyers S, and Ketoff, A N (1986), "Energy use in the service sector: an international perspective" *Energy Policy*, Vol. 14, No. 3, June 1986, pp. 201-218.

Sherman M H and Grimsrud D T (1980), *Measurement of Infiltration Using Fan Pressurization and Weather Data*, LBL-10852, Lawrence Berkeley Laboratory, Berkeley, CA, USA. #608

Sherman M H (1986) "Infiltration Degree-Days: A Statistic for Infiltration-Related Climate." *ASHRAE Transactions*, January 1986. # 1748

Sherman M H, and Matson N (1996), "Residential Ventilation Energy Characteristics", *Proceedings of the 17th AIVC Conference*, "Optimum Ventilation and Air Flow Control in Buildings", held Gothenburg, Sweden, 17-20 September 1996, pp. 197-207. # 9848

Shorrock L D, Henderson G, and Bown J H F (1992), *Domestic Energy Fact File*, Building Research Establishment, Watford, UK. # 5881

Shorrock L D (1994), Personal Communication.

Steimle F (1994), Communication to AIVC Workshop, "The Energy Impact of Ventilation", Horgen, Switzerland, March 1994 (unpublished).

Swinton M (1995), Personal Communication.

VanBronkhorst D A, Persily A K, and Emmerich S J (1995), "Energy Impacts of Air Leakage in US Office Buildings", *Proceedings of the 16th AIVC Conference*, Volume 2, pp. 379-391, Palm Springs, CA, USA. # 9074

Wouters P (1994), Communication to AIVC Workshop, "The Energy Impact of Ventilation", Horgen, Switzerland, March 1994 (unpublished).

Appendix A - Definitions of Degree-Days

A.1 Heating Degree-Days

Heating degree-days are based on the period (length of time) during which the outside temperature is less than a certain 'base temperature'. Typically they are found by, first of all, determining the summation of the differences between the base temperature and each hourly average outside temperature (taken over all hours during the heating season), for the hours during which the outside temperature is less than the base temperature. This sum is then known as the number of heating degree-hours. The number of degree-hours is divided by 24 to determine the number of degree-days for a particular location.

At the base temperature the rate of heat loss by conduction equals the rate of 'free' heat gain inside a building for a given average internal temperature. The base temperature varies from country to country, depending on the average internal temperature of buildings and the 'free' gains (such as solar heating). It also depends on the thermal transmittance. In practice, there is no uniform agreement as to what the base temperature should be, with the result that different countries select different values. Examples are presented in Table A1. Almost always a 'correction' formula is supplied to recalculate to alternative base temperatures, for example allowing for different internal temperatures.

Table A1 Heating degree-days base temperatures for different countries

	Heating base temperature, T^{h}_{base} [°C]
Belgium	15
Canada	18
Denmark	17
Finland	17
France	16 - 18
Germany	20
Netherlands	18
New Zealand	18
Norway	17
Sweden	17
Switzerland	20
UK	15.5
USA	18.3

Sherman (1986) explains the above ideas in the following way: Strictly speaking, conventional heating degree-hours are based on the heat loss due to conduction only, ignoring infiltration and ventilation losses. However, their use does allow infiltration losses to be estimated, by quantifying the average temperature rise needed for space heating throughout the heating season. The instantaneous conduction loss, $F_{conduction}$ [$J \cdot s^{-1}$], can be found from

$$F_{conduction} = UA(T_{in}^h - T_{out}),$$

where U [J·s^{-1}·m^{-2}·K^{-1}] is the average thermal transmittance of the building envelope, A [m^2] is the area of the envelope, T_{out} [K] is the outdoor temperature and T_{in}^h [K] is the indoor temperature when heating. The instantaneous heating load F^h [J·s^{-1}] is then given by

$$F^h = F_{conduction} - F_{free},$$

where F_{free} [J·s^{-1}] is the rate of heat gain to the internal space from incidental heat sources.

A heating base temperature, T_{base}^h [K], can be defined such that

$$T_{base}^h = T_{in}^h - \frac{F_{free}}{UA}.$$

If the external temperature, T_{out}, equals the base temperature, T_{base}^h, then the conduction losses equal the incidental heat gains and no additional heat input, F^h, is needed. In terms of this base temperature, the heating load is then expressed by

$$F^h = UA(T_{base}^h - T_{out}) \text{ for } T_{base}^h > T_{out}.$$

In order to find the annual heating energy consumption due to conduction losses, E^h [J], it is necessary to sum the instantaneous heating load over the heating season, thus producing

$$E^h = 3600 \sum_{hours} F^h = 3600UA \sum_{hours} (T_{base}^h - T_{out}) \text{ for } T_{base}^h > T_{out},$$

where the summation is over hours in the heating season during one year.

By defining heating degree-days, D_d^h [K·d], as

$$D_d^h = \frac{1}{24} \sum_{hours} (T_{base}^h - T_{out}) \text{ for } T_{base}^h > T_{out},$$

the annual heating energy consumption can be reformulated as

$$E^h = 86400UAD_d^h.$$

The related concept of cooling degree-days is not as widely accepted as that of heating degree-days. This is mainly on account of the humidity changes which are often necessary when cooling. These changes include a latent heat component that does not change the air temperature, only the state of the moisture it contains.

A.1.1 Estimation of air change energy from heating degree-days

For some countries, with low levels of dehumidification (or humidification) and cooling, the heating degree-day method alone can be used to estimate air change related energy consumption. In those cases, the values of the estimated annual air enthalpy change, $E^h_{enthalpy}$ [J], are derived from,

$$E^h_{enthalpy} = 24Q_{ach}V_{total}D^h_d\rho C_p .$$

In the above equation, D^h_d [K·d] represents heating degree-days. Evaluations of $E^h_{enthalpy}$ are based on providing ventilation at an air change rate, Q_{ach} [h^{-1}]. A conversion constant equal to 24 h·d^{-1} is also needed to convert from degree-days to degree-hours. (Air density, ρ, is approximately equal to 1.2 kg·m^{-3}, and the specific heat capacity of air, C_p, is equal to 1000 J·kg^{-1}·K^{-1}.) The total net volume of all buildings in a country or region is V_{total} [m^3], which can be found from the relationship $V_{total} = \overline{V}N$, with N the total number of buildings, and $\overline{V}$ [m^3] the average net volume of each building. The assumption was made whenever necessary that average room heights were 4 m, allowing the size of the service sector, which for many countries is expressed in terms of floor area, to be converted into a volume.

The delivered air change energy, $E^h_{delivered}$ [J], can then be found from $E^h_{enthalpy}$ by means of the relationship,

$$E^h_{delivered} = \frac{E^h_{enthalpy}}{\eta},$$

where η is the average efficiency of conversion from delivered energy to 'useful' energy (which in this case is the part of the delivered energy that actually changes the enthalpy of the incoming air). In this context efficiency (see for example Column 3 of Table 2) refers to the efficiency of ventilation-related equipment, including space heating systems, ventilation systems, air-conditioning equipment, etc.

Because of non-continuous occupancy, it is possible that the heating degree-day (degree-hour) method may tend to overestimate the energy consumed for heating. However, some heating may still occur during unoccupied periods, particularly in very cold climates.

A.2 Infiltration Degree-Days

The degree-day concept has been extended by Sherman (1986) to incorporate both effects of air infiltration and latent heat changes. Average specific infiltration rates, s_0 [m·s^{-1}] are used to account for infiltration. Average specific infiltration rates have been tabulated for various locations across the USA, with an average value of 0.75 m·s^{-1}. For cooling calculations, a base enthalpy is employed to overcome the lack of consideration of latent heat changes in conventional cooling degree-days.

A.2.1 Heating infiltration degree-days

In addition to heat loss due to conduction, one can consider heat loss due to infiltration, $F_{infiltration}$ [J·s^{-1}], with

$$F_{infiltration} = \rho C_p A_4^{eff} s(T_{in}^h - T_{out}),$$

where A_4^{eff} [m^2] is the effective leakage area at 4 Pa pressure difference and s [m·s^{-1}] is the specific infiltration rate, which may be calculated using the 'LBL' infiltration model (Sherman and Grimsrud, 1980). Adding this term to the previously stated expression for the instantaneous heating load, one obtains,

$$F^h = F_{conduction} + F_{infiltration} - F_{free} \text{ and } F^h > 0,$$

or explicitly,

$$F^h = UA(T_{in}^h - T_{out}) + \rho C_p A_4^{eff} s(T_{in}^h - T_{out}) - F_{free}.$$

I_U [J·s^{-1}·m^{-2}·K^{-1}] is defined by,

$$I_U = \rho C_p s_0,$$

and is analogous to the conduction-related thermal transmittance U. The base temperature then becomes slightly modified by the inclusion of the term $I_U A_4^{eff}$, which allows for heat loss through infiltration. This then becomes,

$$T_{base}^h = T_{in}^h - \frac{F_{free}}{UA + I_U A_4^{eff}}.$$

The infiltration-related component of the energy consumption depends on heating infiltration degree-days, D_{dI}^h [K·d], which is in turn defined by,

$$D_{dI}^h = \frac{1}{24} \sum_{hours} \frac{s}{s_0} (T_{base}^h - T_{out}) \text{ for } T_{base}^h > T_{out}.$$

Substituting this into the expression for the instantaneous heating load and summing over the heating season gives the annual energy consumption, E^h [J],

$$E^h = 86400(UAD_d^h + I_U A_4^{eff} D_{dI}^h).$$

A.2.2 Cooling infiltration degree-days

Incidental heat gains to a conditioned space add to the cooling load. Therefore the instantaneous cooling load, F^c [J·s^{-1}], is given by,

$$F^c = UA(T_{out} - T_{in}^c) + \rho A_4^{eff} s(h_{out} - h_{in}^c) + F_{free} \text{ and } F^c > 0.$$

where T_{in}^{c} [K] is the indoor temperature when cooling. Also in the above equation, h_{out} [J·kg^{-1}] is the outdoor specific air enthalpy, and h_{in}^{c} [J·kg^{-1}] is the indoor specific air enthalpy when cooling.

At base conditions it is assumed that both the sensible component of the cooling load $F_{sensible}^{c} = 0$ and also the latent component of the cooling load $F_{latent}^{c} = 0$.

The conduction gain involves the conventional definition of cooling degree-days, being only a sensible heat change. Assuming that the base enthalpy for infiltration, h_{base}^{c} [J·kg^{-1}], has a base temperature, T_{base}^{c} [K], for its sensible component that is the same as the base temperature for conduction, then this base temperature is given by

$$T_{base}^{c} = T_{in}^{c} - \frac{F_{sensible}^{c}}{UA + I_U A_4^{eff}},$$

and defining cooling degree-days, D_d^c [K·d], in the conventional way,

$$D_d^c = \frac{1}{24}\sum_{hours}(T_{out} - T_{base}^{c}) \text{ for } T_{base}^{c} < T_{out}.$$

The infiltration component depends on the number of cooling infiltration degree-days, which has both sensible and latent contributions. Let $h_{base,latent}^{c}$ [J·kg^{-1}], $h_{in,latent}^{c}$ [J·kg^{-1}], and $h_{out,latent}^{c}$ [J·kg^{-1}] denote respectively the latent components of the cooling base enthalpy, of the inside enthalpy, and of the outside enthalpy. The latent component of the base enthalpy is then

$$h_{base,latent}^{c} = h_{in,latent}^{c} - \frac{C_p F_{latent}^{c}}{I_U A_4^{eff}}.$$

This then allows the total enthalpy difference between the outside and the base to be expressed,

$$h_{out} - h_{base}^{c} = (h_{out,latent} - h_{base,latent}^{c}) + C_p(T_{out} - T_{base}^{c}).$$

Finally making the definition of cooling infiltration degree-days, D_{dI}^{c} [K·d], explicit,

$$D_{dI}^{c} = \frac{1}{24C_p}\sum_{hours}\frac{s}{s_0}(h_{out} - h_{base}^{c}) \text{ for } h_{base}^{c} < h_{out}.$$

The total annual cooling energy, E^c [J], is then the instantaneous cooling load summed over the cooling season, which is, in terms of conventional and infiltration degree-days,

$$E^c = 86400(UAD_d^c + I_U A_4^{eff} D_{dI}^{c}).$$

A.3 Ventilation Degree-Days

Ventilation degree-days are defined in the German Standard (Deutsche Industrie Norm) DIN 4710. These allow for periods of operation of ventilation systems to be included in heating (and cooling) energy calculations for named locations.

So, ventilation degree-hours can account for occupancy insofar as non-continuous periods of operation of ventilation equipment can be considered. The following explanation of ventilation degree-days has been translated from Recknagel et al (1992) §1 112-5 pp 14-16:

The idea of degree-days can also be made use of for the determination of the heat required for air-conditioning. By *ventilation degree-days* is understood the product of the number of ventilation-days and the difference between the supply air temperature, T_{supply} [K], and the mean outside temperature. The number of ventilation degree-days is however greater than the number of heating degree-days, since the base temperature of 15 °C (288 K) assigned for heating, at which heating begins and ends, does not apply for ventilation. For temperatures above 15 °C the outside air is also warmed-up, to the supply air temperature, which is usually taken to be the same as room temperature at 20 or 22 °C, unless the air should be cooled.

So, in general, ventilation systems are in operation only for well-defined times of the day e.g. ventilation of theatres in the evening hours, and it is not correct to take the mean daily temperature as a basis for the calculation of ventilation degree-days, but rather the mean temperature during the operating time.

From Table A2, the annual ventilation degree-hours for Berlin for arbitrary times of day can be inferred. The values can be determined from the definition stated in DIN 4710 for three operating days. Depending on the formation of the mean value in DIN 4710, negligible errors (<5%) result, particularly for low supply air temperatures.

One obtains, therefore, the idea of ventilation degree-hours, D^h_{hV} [h·K], as the product of the number of ventilation hours, t [h], and the difference between the supply air temperature, T_{supply}, and the respective mean outside air temperature, T_{out} [K], over the various times of day,

$$D^h_{hV} = t(T_{supply} - T_{out}).$$

D^h_{hV} is multiplied with the specific heat capacity of air, C_p=1000 J·kg^{-1}·K^{-1}, so the necessary annual heating requirement, Q [J·h·kg^{-1}], for the heating of 1 kg·h^{-1} of air is obtained, as

$$Q = D^h_{hV} C_p.$$

Example:

The number of annual ventilation degree-hours for a ventilation system in daily operation from 8.00 until 18.00 hours, with a supply air temperature of 22 °C is, from Table A2,

$$D_{hV}^{h} = 84149 - 43516 = 40633 \text{ h·K}.$$

Annual heating requirement in terms of kg·h^{-1},

$$Q = 40.633 \text{ MJ·h·kg}^{-1}.$$

Table A2 Annual ventilation degree-hours D_{hV}^{h} [h·K] for Berlin, in relation to the operating time and the supply air temperature.

Operating time	Supply temperature [°C]					
from 0.00 to	18	19	20	21	22	23
1.00	3810	4174	4539	4904	5269	5634
2.00	7736	8465	9195	9925	10655	11385
3.00	11772	12865	13960	15055	16150	17245
4.00	15897	17356	18816	20276	21736	23196
5.00	20067	21891	23716	25541	27366	29191
6.00	24185	26374	28564	30754	32944	35134
7.00	28111	30663	33216	35771	38326	40881
8.00	31850	34763	37679	40597	43516	46436
9.00	35324	38581	41854	45134	48417	51700
10.00	38552	42110	45725	49362	53005	56651
11.00	41556	45402	49318	53301	57301	61306
12.00	44373	48495	52700	56993	61342	65705
13.00	47037	51432	55922	60504	65182	69900
14.00	49606	54268	59042	63913	68892	73961
15.00	52154	57081	62135	67293	72561	77972
16.00	54741	59935	65270	70716	76275	82025
17.00	57430	62897	68517	74252	80118	86215
18.00	60260	66007	71915	77944	84149	90602
19.00	63234	69270	75473	81832	88391	95202
20.00	66353	72685	79220	85936	92852	100023
21.00	69624	76294	83186	90260	97538	105071
22.00	73025	80049	87299	94735	102376	110272
23.00	76571	83953	91564	99363	107367	115628
24.00	80257	88000	95974	104135	112505	121130

Source: DIN 4710 (11.92)

A.4 Degree-Days for the Service Sector in France

CEREN (1996) presents heating degree-day values for France, which apply to the individual sub-sectors of the service sector. These values differ from conventional degree-days by taking into account average occupancy and indoor temperatures for each sub-sector. (So, given the correct ventilation degree-days for the French climate, a good approximation to these service sector degree-days could be found.) They have been calculated for specific years, as well as average values, for each sub-sector and for the entire service sector. These can be seen in Table A3.

Table A3 Degree-days for the service sector in France

	Degree days [K·days]									
	Average	1986	1987	1988	1989	1990	1991	1992	1993	1994
Cafés, hotels, restaurants	1924	2004	2036	1651	1645	1630	2003	1848	1864	1638
Residential facilities	2415	2481	2631	2158	2163	2079	2487	2283	2329	2156
Health, social programmes	3734	3802	3842	3478	3389	3381	3769	3618	3634	3409
Education, research	1919	1804	1803	1431	1411	1636	2009	1830	1843	1616
Sport, leisure, culture	1903	1973	2043	1627	1627	1606	1974	1855	1863	1669
Office, administration	1907	1978	2041	1639	1635	1617	1984	1834	1868	1618
Commerce	1913	1996	2034	1643	1638	1620	1992	1838	1879	1624
Transport	1952	2021	2084	1678	1978	1650	2026	1870	1892	1662
Total service sector	2183	2232	2280	1886	1881	1881	2256	2099	2126	1893

Source: CEREN (1996)

Appendix B - Summary Tables of Service Sector Characteristics

Table B1(a) Service sector characteristics in Belgium and Canada

	Belgium		Canada	
	Size per building [m^2]	Number of buildings [10^3]	Total area (1981) [10^6 m^2]	Number of buildings (1991) [10^3]
Total	Unknown	Unknown	380	410
Sources:			Herring et al (1985), HPC (1994)	

Table B1(b) Service sector: sub-sector characteristics in Denmark and Finland

	Denmark	Finland	
	Total area [10^6 m^2]	Number of buildings [10^3]	Total area [10^6 m^2]
Education	34	8.5	15.1
Public Assembly		5.6	6.83
Office	48	9.7	15.7
Commerce		33	18.1
Transport		36	8.56
Warehouse		18	7.54
Healthcare			8.79
Other	17		
Source:	AIVC Survey	AIVC Survey, Saterl (1997)	

Table B1(c) Service sector: sub-sector characteristics in France and Germany

	France	Germany	
	Total heated area (1989) [10^6 m^2]	Total area (1982) [10^6 m^2]	Number of buildings (1991) [10^3]
Cafés, hotels, restaurants	47		
Residential facilities	45.5		
Health, social programmes	84		
Education, research	147		
Sport, leisure, culture	33.3		
Office, administration	143.5		
Commerce	170		
Transport	20.3		
Total	691	910	3600
Source:	ADEME (1994)	Herring et al (1985), HPC (1994)	

Table B1(d) Service sector: sub-sector characteristics in The Netherlands and New Zealand

	Netherlands		New Zealand	
	Size per building [m²]	Number of buildings [10³]	Size per building [m²]	Number of buildings [10³]
Office	640	55		
Total			Unknown	Unknown
Source:				

Table B1(e) Service sector: sub-sector characteristics in Norway and Sweden

	Norway		Sweden
	Size per building [m²]	Number of buildings [10³]	Total volume [10^6 m³]
Education		24	120
Health care		6.6	130
Office		45	110
Warehouse		10	39
Other		180	98
	Total area (1991) [10^6 m²]		
Total	87		
Source:	AIVC Survey, HPC (1994)		AIVC Survey

Table B1(f) Service sector: sub-sector characteristics in Switzerland and the UK

	Switzerland		UK	
	Total volume [10^6 m³]	Number of buildings (1991) [10³]	Size per building [m²]	Number of buildings [10³]
Office	110		400	250
Distribution			700	170
Shops			230	520
Catering			160	43
Pubs/Clubs			400	81
Residential			1600	25
Retail services			230	66
Local Gov't			1400	3
Education			2500	36
Health			1050	30
Other	280		250	450
Total		140		
Source:	AIVC Survey, HPC (1994)		1994, BRE estimates, non-domestic stock model	

Table B1(g) Service sector: sub-sector characteristics in the USA

	USA				
	Total workers [10^3]	Size per building [m^2]	Number of buildings [10^3]	Occupancy [hrs / week]	Total delivered energy [PJ]
Education	6900	2620	301	49	670
Food sales	840	540	130	108	140
Food service	2200	530	260	91	470
Health care	3400	2590	63	69	420
Lodging	2000	1750	154	158	490
Mercantile and service	16000	900	1272	62	940
Office	27000	1520	749	53	1300
Parking garage	220	6490	24	83	55
Public assembly	2800	1520	278	50	330
Public order and safety	800	1270	60	123	96
Religious worship	2300	950	366	22	110
Warehouse	4500	1400	761	50	620
Other	1200	1520	69	75	280
Source:	1992, DOE/EIA (1995), ASHRAE (1995)				

Table B2 Service sub-sectors total delivered energy in France and The Netherlands

	Total delivered energy [PJ]	
	France (1990)	Netherlands (1992)
Education	110	24
Health	110	26
Governmental	-	22
Elderly Homes	-	12
Sport and recreation	-	6
Social/ Cultural	-	5
Offices	240	46
Shops	270	28
Hotels/ Restaurants	97	22
Other	150	-
Source:	ADEME (1993)	Novem (1994)

Table B3 Service sub-sectors space heating and electricity use in Finland

	Finland	
	Space heating [PJ]	Electricity [PJ]
Education	11	4.0
Public Assembly	5.0	5.0
Office	14	8.3
Commerce	10	14
Transport	18	3.6
Healthcare	5.0	3.2
Source: Sateri (1997)		

The **Air Infiltration and Ventilation Centre** was inaugurated through the International Energy Agency and is funded by the following thirteen countries:

Belgium, Canada, Denmark, Finland, France, Germany, Greece, Netherlands, New Zealand, Norway, Sweden, United Kingdom, United States of America.

The Air Infiltration and Ventilation Centre provides technical support in air infiltration and ventilation research and application. The aim is to provide an understanding of the complex behaviour of the air flow in buildings and to advance the effective application of associated energy saving measures in both the design of new buildings and the improvement of the existing building stock.

Air Infiltration and Ventilation Centre
Unit 3A, Sovereign Court
University of Warwick Science Park
Sir William Lyons Rd
Coventry, CV4 7EZ
United Kingdom

Telephone: +44 (0)1203 692050
Fax: +44 (0)1203 416306
Email: airvent@aivc.org
Web: http://www.aivc.org/

Operating Agent on behalf of the International Energy Agency:
Oscar Faber Group Ltd., Upper Marlborough Road, St Albans, UK.