MANAGING THE URBAN ENVIRONMENT: THE SOLAR ENERGY POTENTIAL OF DWELLINGS

Stuart John Gadsden, B.Eng (Hons.)

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De Montfort University, Leicester

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Abstract

Many local authorities have set Local Agenda 21 targets to reduce carbon dioxide emissions and increase the use of renewable energy. Solar energy technologies have significant potential for deployment in urban residential areas but existing city planning systems do not enable local authorities to readily evaluate and manage this resource. A new Solar Energy Planning (SEP) system has been developed to assist energy advisers and planners. The SEP system predicts the baseline energy demand of dwellings and determines their potential to utilise solar energy. It predicts the energy and CO_2 benefits that the wide scale deployment of solar domestic hot water (DHW) and photovoltaic (PV) systems might bring. This thesis describes the models and procedures underpinning the SEP system.

The baseline energy consumption of dwellings establishes a benchmark against which the energy contributed by active solar technologies can be compared. The energy used for space heating, hot water, cooking, lights and appliances is calculated using BREDEM-8. BREDEM-8 is a reputable, validated model which performs calculations rapidly and at a level of detail appropriate to city planners. It is a monthly calculation procedure which is advantageous for considering active solar systems. To fulfil the data needs of BREDEM-8, a new dwelling classification system was developed. This classification system allows the baseline energy consumption of a group of dwellings to be predicted, even when the amount of data available for each dwelling varies considerably. Authoritative sources were used to develop a robust, nationally applicable default data set for the dwellings in each class.

Solar DHW and PV potential are considered using a new three-stage approach. This approach identifies and then targets suitable dwellings for the installation of these systems and finally predicts the solar energy yield. The calculation methods are at the appropriate level of complexity to allow rapid results to be generated from within the SEP system. Proposals are presented to extend the scope of the SEP system to consider the passive solar design of new housing estates.

The potential of the SEP system is assessed for an area of Leicester consisting of approximately 400 dwellings. Recommendations for modifying the default data set and for the further development of the system are made. The SEP system is shown to be a valuable tool for energy advisers and planners concerned with managing the urban environment.

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Abbreviations

ACE	Association for the Conservation of Energy
BIPV	Building-Integrated Photovoltaic
BRE	Building Research Establishment
BREDEM	Building Research Establishment Domestic Energy Model
BREHOMES	Building Research Establishment Housing Model for Energy Studies
BSI	British Standards Institution
CIBSE	Chartered Institution of Building Services Engineers
D	Detached
DEM	Digital Elevation Model
DETR	Department of the Environment, Transport and the Regions
DHW	Domestic Hot Water
DoE	Department of the Environment
DoE&WO	Department of the Environment and the Welsh Office
DREAM	Dynamic Regional Energy Analysis Model
DTI	Department of Trade and Industry
DUKES	Digest of United Kingdom Energy Statistics
EEAC	Energy Efficiency Advice Centre
EEP	Energy and Environmental Prediction (model)
EPSRC	Engineering and Physical Sciences Research Council
EHCS	English House Condition Survey
ESIF	European Solar Industry Federation
ESRU	Energy Systems Research Unit
ET	End Terrace
ETSU	Energy Technology Support Unit
F	Flat
FABLE	Forum for a Better Leicestershire
FES	Family Expenditure Survey
GIS	Geographical Information System
HCS	Housing and Construction Statistics

HECA	Home Energy Conservation Act
HEES	Home Energy Efficiency Scheme
IESD	Institute of Energy and Sustainable Development
LA21	Local Agenda 21
LCC	Leicester City Council
LEEAC	Leicestershire Energy Efficiency Advice Centre
LT	Lighting and Thermal
MT	Mid Terrace
MTUP	Mid Terrace with Unheated Passageway
NEF	National Energy Foundation
NES	National Energy Services Limited
NHER	National Home Energy Rating
NOCT	Nominal Operating Cell Temperature
ONS	Office for National Statistics
OS	Ordnance Survey
PRECis	Potential for Renewable Energy in Cities
PV	Photovoltaic
SAP	Standard Assessment Procedure
SD	Semi-Detached
SEP	Solar Energy Planning (system)
SEL	Solar Energy Laboratory
STC	Standard Test Conditions
UHA	Urban Horizon Angle
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WSA	Welsh School of Architecture

Glossary of Symbols

Chapter 3. Domestic Energy Modelling

N	Number of occupants (-)
TFA	Total floor area of the dwellings (m^2)

Chapter 4. Active Solar Technologies I: Solar Domestic Hot Water

English

A'	Effective aperture area of the collector (m^2)
B	Dimensionless parameter (-)
C_g	Orientation factor for peak irradiance (-)
C_h	Orientation factor for irradiation (-)
C_p	Specific heat capacity (J/kgK)
F	Dimensionless parameter (-)
G	Annual mean daily peak irradiance on a horizontal surface (W/m^2)
G_{TILT}	Annual mean daily peak irradiance on an inclined surface (W/m^2)
H	Annual mean daily irradiation on a horizontal surface (MJ/m^2)
H_{TILT}	Annual mean daily irradiation on an inclined surface (MJ/m^2)
K	Collector performance parameter (-)
L	Daily load (MJ/day)
M	Collector sizing parameter (-)
N	Number of occupants (-)
Q_{annual}	Annual solar energy supplied by a solar DHW system (MJ/year)
$Q_{monthly}$	Monthly solar energy supplied by a solar DHW system (MJ/month)
R	Storage parameter (-)
T	Annual mean air temperature (°C)
T_a	Annual mean daytime air temperature (°C)
T_c	Annual mean cold water supply temperature (°C)
T_d	Desired hot water draw off temperature (°C)
U	Collector heat loss coefficient (W/m^{2}K)
V	Daily mean hot water requirement (litres)
V_s	Volume of the preheat storage vessel (litres)

Greek

η_0	Zero loss collector efficiency (-)
ρ	Density (kg/m^3)
λ	Dimensionless parameter (-)

Chapter 5. Active Solar Technologies II: Photovoltaics

English

A_{array}	Area of PV array (m^2)
A_{module}	Area of PV module (m^2)
$\bar{E}_i$	Hourly average array electrical energy output (Wh)
G_T	Incident irradiation under Standard Test Conditions (W/m^2)
$G_{T,NOCT}$	Solar irradiation at nominal operating cell temperature conditions (W/m^2)
I_{mp}	Current at maximum power point (A)
$\bar{I}_o$	Hourly extraterrestrial irradiation (MJ/m^2)
$\bar{I}_T$	Hourly solar irradiation incident on the PV array (MJ/m^2)
$\bar{k}_T$	Hourly clearness index (-)
R_b	Ratio of beam irradiation on the tilted surface to that on the horizontal surface (-)
$\bar{T}_{a,i}$	Hourly average air temperature (°C)
$T_{a,NOCT}$	Ambient temperature at nominal operating cell temperature conditions (°C)
$T_{c,NOCT}$	Nominal operating cell temperature (°C)
T_{ref}	Reference cell temperature at Standard Test Conditions (°C)
U_L	Heat loss coefficient (W/m^2K)
V_{mp}	Voltage at maximum power point (V)
Z_i	Sun position correction factor (-)

Greek

α	Absorptance of the PV module (-)
β	Inclination of PV array (°)
η_{df}	Decreasing factor (-)
η_e	Efficiency of power conditioning equipment (-)
$\bar{\eta}_i$	Monthly hourly average array efficiency (-)
η_{inv}	Inverter efficiency (-)
$\eta_{mp,ref}$	Maximum power point efficiency of the PV module (-)
η_{wire}	Wire efficiency factor (-)
μ_{mp}	Temperature coefficient of maximum power efficiency (-)
μ_{Voc}	Temperature coefficient of open circuit voltage (-)
ρ	Ground reflectivity (-)
τ	Transmittance of the cover over the cells (-)

Chapter 6. Passive Solar Design

English

H	Height of the obstruction (m)
L	Distance from the obstruction to the affected surface (m)
UHA	Urban horizon angle (°)

Greek

$\gamma_{obstruct}$	Angle between the obstruction and the façade normal (°)

Appendix A. Description of the Space Heating Procedure in BREDEM-8

English

d	Number of days in the month (-)
G_u	Mean useful gains (W)
H	Specific heat loss (W/K)
Q(m)	Monthly space heating requirement (GJ)
T_{ext}	Mean external temperature (°C)
T_{int}	Mean internal temperature (°C)

Greek

φ	Mean rate of heat output from the heating system (W)

Appendix F. Calculating the Solar Irradiation Incident on an Inclined Surface

English

F_1	Circumsolar brightness coefficient (-)
F_2	Horizon brightness coefficient (-)
G_{sc}	Solar constant (W/m^2)
$\overline{H}$	Monthly average daily total irradiation on a horizontal surface (MJ/m^2)
$\overline{H}_d$	Monthly average daily diffuse irradiation on a horizontal surface (MJ/m^2)
$\overline{H}_o$	Monthly average daily extraterrestrial irradiation on a horizontal surface (MJ/m^2)
I	Hourly total irradiation on a horizontal surface (MJ/m^2)
I_b	Hourly beam irradiation on a horizontal surface (MJ/m^2)
I_{bn}	Hourly normal or beam incidence irradiation (MJ/m^2)
$I_{b,\beta}$	Hourly beam irradiation on an inclined surface (MJ/m^2)

I_d	Hourly diffuse irradiation on a horizontal surface (MJ/m^2)
$I_{d,\beta}$	Hourly diffuse irradiation on an inclined surface (MJ/m^2)
$I_{g,\beta}$	Hourly ground-reflected irradiation on an inclined surface (MJ/m^2)
$\bar{I}_o$	Hourly extraterrestrial irradiation (MJ/m^2)
I_{on}	Hourly extraterrestrial normal incidence irradiation (MJ/m^2)
$I_{T,\beta}$	Hourly total irradiation on an inclined surface (MJ/m^2)
$I_{T,\beta,shaded}$	Hourly total irradiation on an inclined surface experiencing overshading (MJ/m^2)
$\bar{k}_T$	Hourly clearness index (-)
$\bar{K}_T$	Monthly average clearness index (-)
m	Air mass (-)
n	Julian day number (1 to 365)
r_d	Ratio of hourly to daily diffuse irradiation on a horizontal surface (-)
r_t	Ratio of hourly to daily total irradiation on a horizontal surface (-)
R_b	Ratio of beam irradiation on an inclined surface to that on a horizontal surface (-)
t	Time (24-hour clock)
UHA	Urban horizon angle (°)

Greek

α_s	Solar altitude angle (°)
β	Slope of the surface (°)
γ	Surface azimuth angle (°)
δ	Solar declination (°)
ε	Atmospheric clearness parameter (-)
θ	Angle of incidence (°)
θ_z	Zenith angle (°)
ρ_g	Diffuse reflectance of the surroundings (-)
ρ_{ow}	Diffuse reflectance of the opposite wall (-)
ϕ	Latitude (°)
ω	Solar hour angle (or angular displacement of the sun from solar noon) (°)
ω_s	Sunset hour angle from noon (°)
Δ	Atmospheric brightness parameter (-)

Author Declarations

During the period of registered study in which this thesis was prepared the author has not been registered for any other academic award or qualification.

The material included in this thesis has not been submitted wholly or in part for any academic award or qualification other than that for which it is now submitted.

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Chapter 1

Introduction

1.1 The need for a solar energy planning system

World energy demand is continually increasing. This demand is primarily being met by burning fossil fuels. At the same time, concern about the environment is at an all time high prompting world leaders to consider the threat of climate change. In 1992, at the United Nations (UN) Earth Summit in Rio de Janeiro, 174 developed countries (including the UK) agreed a voluntary target of returning their emissions of greenhouse gases to 1990 levels by the year 2000 by signing the United Nations Framework Convention on Climate Change (UNFCCC) (UN, 1992b).

Following Rio, however, it became clear that stabilising emissions would have little effect on the climate and that greater reductions were required. After much negotiating, the Kyoto Protocol (UN, 1997) was added to the Convention in December 1997. When ratified, the Protocol will commit developed countries to reduce their emissions of the six principal man-made greenhouse gases (carbon dioxide (CO_2), methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) to 5.2% below 1990 levels averaged over the period 2008-2012. Whilst all participating countries have signed the Protocol, they are not bound by the Protocol until they have ratified it and it becomes a legally binding agreement.

For the Protocol to enter into force it must be ratified by a minimum of fifty-five countries, including at least 55% of developed country emissions. At the sixth session of the UNFCCC Conference of the Parties (COP6) held in The Hague, Netherlands from 13-24 November 2000, discussions aimed at making the Kyoto Protocol a legally binding agreement were suspended as agreement could not be reached between the parties. It is hoped that new negotiations in Bonn in May 2001 will reach a successful conclusion (Brown, 2001).

The Kyoto Protocol permits countries to undertake commitments jointly by forming so-called 'bubbles'. Under this arrangement, the Member States of the European Community agreed to undertake an 8% reduction. This target has been shared out between Member States based on their projections for future greenhouse gas emissions. The UK agreed to take on a reduction target of 12.5% (Department of the Environment, Transport and the Regions [DETR], 1998c). Furthermore, the UK Government has a manifesto target of reducing national CO_2 emissions to 20% below 1990 levels by 2010 (Entec UK Limited, 2000). In 1990, UK CO_2 emissions were 168 MtC (million tonnes carbon equivalent) (DETR, 1998c).

In the UK, the operation of building services for space heating, domestic hot water, lighting, mechanical ventilation, air conditioning, etc. consumes energy which causes CO_2 emissions amounting to 46% of the national total (27% from dwellings and 19% from non-domestic buildings) (DETR, 2000b). Reducing emissions from buildings, by making them more energy efficient, would help the UK meet its CO_2 reduction targets. In addition, the possibility of displacing conventionally produced energy with non-polluting alternatives is receiving much attention. The UK Government recently underlined its commitment to promoting the development of renewable sources of energy as an essential ingredient of its climate change programme (Department of Trade and Industry [DTI], 2000b), emphasising the role that regional and local planning authorities have to play.

At the 1992 UN Earth Summit, the 174 nations also signed an agreement referred to as Agenda 21 (UN, 1992a). This document sets targets and actions for a wide range of environmental and economic objectives including biodiversity, protection of rainforests and aid to developing countries. In addition, the signatories agreed to persuade and instruct local authorities to work with their local communities to develop policies that would support the ideas of sustainable development outlined in the rest of the document. This initiative was called Local Agenda 21 (LA21). In the UK, over 80% of local authorities have adopted strategies towards LA21 (Forum for a Better Leicestershire [FABLE], 1998).

The use of renewable energy sources is an important feature of many LA21 strategies. For example, the LA21 for Leicestershire (FABLE, 1998) has set a target that renewable energy should account for 15% of total energy production in the region by the year 2020. This is alongside its aims of reducing overall energy consumption by 30% and CO_2 emissions by 28% relative to 1990 levels. The city of Leicester has its own LA21 strategy (Leicester City Council [LCC], 1998). This strategy sets even more ambitious targets with 20% of Leicester's energy needs to be met from renewable sources by the year 2020. Furthermore, there is to be a 50% reduction in both energy consumption and CO_2 emissions from 1990 levels by 2025. If these targets are to be met, authorities in Leicestershire will require guidance on how best to exploit the various renewable energy sources available.

Solar energy has long been recognised as a major source of renewable energy for heating and lighting buildings. It can be utilised in many different ways but is usually categorised into two types.

1. Passive solar: including direct solar gain to offset space heating demand and the use of daylight to reduce artificial lighting requirements.
2. Active solar: including solar water heating systems to supply hot water and photovoltaic (PV) systems generating electricity from sunlight.

Strategic studies have quantified the potential yield from solar energy technologies in the UK. For example in Leicestershire, the technically feasible yield of solar energy systems in domestic properties by the year 2010 was estimated to be 305 GWh/year for PV, 229 GWh/year for solar domestic hot water (DHW) and 15.9 GWh/year for passive solar design (Land Use Consultants, 2001). Together, these three solar energy resources could supply 550 GWh/year. This represents approximately one third of the energy consumption in the domestic sector in Leicestershire (Land Use Consultants, 2001). As a result, solar energy technologies have significant potential to help Leicestershire meet its LA21 targets.

At present, however, the huge solar resource available within cities is not exploited. One reason for this is that, on the whole, existing city modelling systems do not encompass tools which are targeted at solar energy planning issues although the need for them has been recognised (Snow, Jones, Lannon & Prasad, 2000; Wood & de Tuberville, 1998). This thesis describes the development of a new planning tool called the Solar Energy Planning (SEP) system which aims to enable local authority planners and energy advisers to consider the urban scale application of solar energy with greatly increased confidence.

1.2 Aims of the research

The research described in this thesis was undertaken as part of the three year Engineering and Physical Sciences Research Council (EPSRC) funded Enlightened Planning Project (Lomas, Bowman & Mardaljevic, 1996), grant code GR/L05372. The primary aim of the Enlightened Planning Project was to develop a set of computer programs which link with a typical Geographical Information System (GIS) and its underlying database to enable the solar energy potential of buildings in an urban context to be described. This is the so-called SEP system.

The SEP system is based on the MapInfo GIS. This was chosen because LCC, one of the collaborating partners, are increasingly using MapInfo to assist in strategic planning e.g. of new roads, urban regeneration etc. Furthermore, the MapInfo macro language MapBasic is very flexible and robust making it suitable for large-scale project development. In the SEP system, MapInfo is used to display a digitised map of the city under investigation. These digital urban maps (depicting man-made and natural features ranging from houses, factories, roads and rivers to marshland and administrative boundaries) are obtained from Ordnance Survey (OS) e.g. Land-Line Plus. GIS technology enables spatially distributed data to be displayed and interpreted more easily than interrogating a database directly. Data can therefore be visualised in a way particularly useful to urban planners; for example results obtained from calculation engines (which work with information in the database) can be viewed as colour coded thematic maps.

The aim of this thesis is to describe the underlying methods developed for modelling domestic energy consumption, solar water heating and photovoltaic (PV) systems and passive solar conditions. This thesis only considers dwellings. The modelling approaches have been realised in GIS-based software developed by the software engineer employed on the EPSRC funded project. At various points throughout the thesis, reference is made to the software. This is necessary to fully describe certain aspects of the modelling approach. The software is only discussed to the extent necessary to describe the important role the research performed for this thesis played in its development. A brief description of the chapter contents will make clear the research to be described in this thesis.

1.3 Outline of the thesis

To place the work described in this thesis in context, existing urban energy models are reviewed in Chapter 2. This review confirms the need for the SEP system. Furthermore, identifying differences between the existing models and comparing their relative strengths and weaknesses allows a concept for the SEP system to be proposed. It is this concept which is described in detail in the remainder of the thesis.

Chapter 3 focuses on domestic energy modelling and particularly the problem of data collection. A new dwelling classification system is proposed and described in detail. This enables the energy consumption of dwellings to be predicted at varying levels of accuracy. These range from predictions based on defaults derived from national statistical data, to detailed data obtained from property surveys. This was necessary due to the importance of establishing an accurate baseline energy consumption before considering the performance of solar energy technologies.

A new three-stage approach for determining the potential solar water heating yield of dwellings is described in Chapter 4. This consists of a filtering process to identify suitable properties for installing a solar domestic hot water (DHW) system based on physical parameters, a targeting procedure to identify the most viable properties according to socio-economic criteria and finally a calculation procedure to quantify the potential solar energy yield.

The approach presented in Chapter 4 has also been adopted for the analysis of PV systems. The PV calculation procedure is described in Chapter 5. The research presented in Chapters 3 to 5 represents the main contribution to knowledge.

Chapters 3, 4 and 5 present the main thrust of the research. However, in addition, an approach to consider the passive solar design of housing estates is proposed in Chapter 6. This approach is not as rigorous as those for solar DHW and PV. Chapter 6 serves to demonstrate one possible method of extending the scope of application of the SEP system.

With the exception of passive solar design, the approaches have been realised in the SEP software. A demonstration of the approach is presented for an area of Leicester in Chapter 7. This case study shows the potential of the SEP system for use as a local authority planning tool. Comparisons are also carried out between the predictions of energy consumption obtained from the different input data levels. This allows refinements to the dwelling classification system to be proposed to increase the accuracy and hence the usefulness of the SEP concept.

The eighth and final chapter presents the main research findings and considers the implications for future research. Overall it is concluded that the research has substantially addressed the need for a solar energy planning system by making valid proposals that, realised in software, have already yielded encouraging and useful results.

The SEP system has the potential to fulfil its aim of allowing planners and energy advisers to consider the urban scale application of solar energy technologies with greatly increased confidence.

Chapter 2

Urban Energy Models

2.1 Introduction

Urban energy models aim to accurately predict the existing energy demand of cities and other urban areas. They also enable the effect of future energy trends to be investigated. Consequently, such models are becoming invaluable tools for urban energy planners in local authorities to assist in the development of policies aimed at reducing energy consumption and greenhouse gas emissions. Renewable energy, in particular solar energy, is often a key component of energy efficiency policies. This chapter reviews current urban energy models to determine the extent to which they address the use of renewable energy in cities. It also, therefore, places the work described in this thesis in context and determines the need for a new solar energy planning system.

2.2 Review of urban energy models

This section reviews existing urban energy models, starting with broad scale models that consider large regions and moving to more detailed models concerned with individual buildings. The review is followed by a discussion which compares differences between the models.

2.2.1 BREHOMES

BREHOMES (Building Research Establishment Housing Model for Energy Studies) (Shorrock & Dunster, 1997) is a physically based model of the energy use of the UK housing stock. It calculates energy use in dwellings using BREDEM-12 (Anderson, Chapman, Cutland, Dickson & Shorrock, 1996), the annual version of the Building

Research Establishment Domestic Energy Model. This is a simplified physical model of energy use in individual dwellings. (BREDEM-12 is described more fully in Section 3.2.) The data required by BREDEM-12 is obtained from a wide range of sources. These include Housing and Construction Statistics (HCS) for Great Britain (e.g. DETR, 2000e), the Family Expenditure Survey (FES) for Great Britain (e.g. Office for National Statistics [ONS], 1999) and the English House Condition Survey (EHCS) (e.g. DETR, 2000a). The HCS and FES are published annually whereas the EHCS is only published every five years. The principal source of data is a regular survey undertaken by a market research company. The sources of data refer to different geographical regions (i.e. England and Great Britain) and thus combining the data sources in BREHOMES requires manipulation of data and common sense adjustments (Shorrock & Dunster, 1997). BREHOMES models the energy use of the housing stock of Great Britain but the results tend to be scaled up to be representative of the UK. (It should be noted that both the HCS and FES are carried out for Northern Ireland and surveys similar to the EHCS are performed in Scotland, Wales and Northern Ireland.)

Once the data, which includes level of insulation and type of space heating systems in use, has been obtained, it is broken down into categories defined by dwelling type, age, tenure, etc. With all the data in place, BREDEM-12 calculations are carried out for each category of dwelling in the UK. Multiplying by the number of dwellings in that category and summing for each category (of which there are currently over 1000) produces an estimate of the entire UK dwelling stock consumption. This is compared with the figure stated in the Digest of United Kingdom Energy Statistics (DUKES) (e.g. DTI, 2000a). DUKES is published annually. Agreement between the BREHOMES prediction and the DUKES figure is usually within a few per cent. To fine-tune the prediction and obtain better agreement, some of the inputs to BREHOMES are adjusted and the calculations repeated. Once the overall total agrees with the aggregate statistics, predictions at more disaggregated levels (e.g. regions) can be used with a reasonable degree of confidence.

The result of the process outlined above is a database of information on housing stock energy use and energy efficiency for the particular year that the statistics relate to.

Important trends in energy use can be identified by performing a BREHOMES calculation for several different years. These historical trends can then form the basis of scenarios to predict future levels of energy use. For example, future energy use could be predicted assuming current trends continue. Alternatively, the effect of introducing energy efficiency measures could be considered. BREHOMES has been widely accepted as a valuable policy advice tool and its users include the DETR e.g. to help derive the carbon savings from a proposed new Home Energy Efficiency Scheme (HEES) as part of the UK's Draft Climate Change Programme (DETR, 2000c).

2.2.2 DREAM-City

The computer model DREAM-City (Titheridge & Boyle, 1995) has been developed by the Energy and Environment Research Unit at the Open University. Its aim is to assist urban energy planners and local authorities in the preparation and monitoring of energy and pollution reduction policies, particularly as part of a LA21 for an urban area. DREAM-City is based on the Dynamic Regional Energy Analysis Model (DREAM) (De Montfort University, 1995). DREAM simulates energy supply and demand on a monthly basis to ensure that important seasonal variations are reflected. The model uses input parameters that are relatively easy to obtain. It is more suited to a national rather than an urban scale, hence the development of DREAM-City. Like DREAM, DREAM-City is divided into four sectors - Domestic, Services, Industrial and Transport - which can be run independently of each other. Monthly energy demand in each sector is calculated using a range of parameters based on regional averages. The model simulates the use of a wide range of energy sources including gas, electricity, district heating, oil, solid fuel and renewable energy. City-wide estimates of CO_2 emissions are produced. According to Titheridge and Boyle (1995), the model has been validated using data obtained for an area of Leicester over the ten-year period 1984-1994. It has been found to be producing reasonably accurate results for annual demand predictions, especially for gas and electricity where data is more readily available. Monthly demand predictions tend to be considerably less accurate.

Once DREAM-City has established the existing energy consumption of a city, local authorities can use the model to assess the impact of different energy-use scenarios. For example, the model was used to demonstrate that Leicester's target of reducing CO_2 emissions to 50% of 1990 levels by 2025 is achievable if 'green' policies encouraging the use of renewable sources of energy are adopted (De Montfort University, 1995). DREAM-City is therefore useful in considering energy utilisation options on a city-wide scale to influence policy decisions.

2.2.3 The Energy and Environmental Prediction (EEP) model

The Energy and Environmental Prediction (EEP) model (e.g. Jones, Vaughan, Sutcliffe & Lannon, 1996; Jones, Lannon, Williams & Prasad, 1999) developed at the Welsh School of Architecture, University of Wales, Cardiff is an environmental auditing and decision making tool for use by planners in their pursuit of sustainable development in cities. The EEP model is based on the MapInfo GIS and incorporates a number of sub-models to account for the energy consumed and emissions produced by domestic and non-domestic buildings, transport systems and industry. In this respect it is similar to the DREAM-City model (Section 2.2.2).

The domestic sub-model in EEP is of particular interest. It uses a statistical clustering method to estimate the Standard Assessment Procedure (SAP) (DETR, 1998b) energy ratings for domestic properties. (The SAP is described in more detail in Section 3.2.) Clustering is carried out on the basis of only four variables related to built form: heated ground floor area, total façade area (i.e. front and rear walls), ratio of window area to wall area and the end area (i.e. side walls) (Welsh School of Architecture [WSA], 1996). The heated ground floor area and the end area of the property are obtained by manually drawing round building outlines on the digital urban map in the GIS. The total façade area and the ratio of window area to wall area are estimated from site surveys by counting bricks (for wall height and length) and assuming standard brick dimensions. After standardising these four variables using the statistical procedure of z-scores (Mendenhall & Sincich, 1995), twenty clusters are produced. Apparently, this was found to be the most suitable number of clusters for use in the EEP domestic sub-model.

The clustering method is based on nearest centroid sorting i.e. a property (a case) is assigned to the cluster where the distance between the centroid and the case is the smallest. For each cluster, the centroid is the mean of the four variables for all cases within that cluster. The twenty clusters are further divided into one hundred clusters using five age groups: pre-1919, 1919-1944, 1945-1964, 1965-1980 and post 1980. It is important that the data collected to establish the clusters incorporates the entire range of properties located within the city of interest (WSA, 1996). The larger the sample, the more accurate the clusters and the greater the likelihood that all one hundred clusters will be represented.

SAP ratings are then calculated for the property located nearest to the centre of each cluster. Additional input data required by the SAP that is not obtained from either the digital map or the site survey is based on global assumptions, for example all properties are single-glazed with the glazing facing east and space heating is carried out by a central heating system with a wall mounted gas boiler. The domestic sub-model calculates the average SAP rating, the annual total domestic energy use and the annual total domestic CO_2 emissions for each postcode within a city. The number of dwellings per cluster in each postcode is known but it is not possible to identify the cluster to which an individual dwelling belongs.

A recent addition to the EEP model is a building-integrated photovoltaic (BIPV) sub-model (Snow et al., 2000). A graphical user interface has been designed to couple the GIS in the EEP model with an existing BIPV simulation tool. The simulation tool aims to model significant aspects of BIPV system performance using readily available climate data and simple product parameters. A ray-tracing approach is used in conjunction with detailed geometry of surrounding objects to perform time-step calculations of shading effects on the BIPV surface. This approach renders a three-dimensional (3D) photo-realistic computer image of the city area being modelled. The overall method of analysing BIPV systems in the EEP model requires considerable user interaction.

2.2.4 LT Urban

The development of LT Urban (Ratti, Robinson, Baker & Steemers, 2000) by the Martin Centre at Cambridge University was one aspect of an EU funded project called PRECis - assessing the Potential for Renewable Energy in Cities. LT Urban predicts annual building energy consumption (heating, lighting, ventilating and cooling energy use) using a modified version of the Lighting and Thermal (LT) energy model (Robinson & Baker, 2001). Currently, LT Urban only considers non-domestic buildings.

Parameters which describe the building fabric (for example, orientation of façades and angles of obstruction of the sky) are derived using image processing techniques based on Digital Elevation Models (DEMs) (Richens, 1997). A DEM is an image in which each pixel has a grey-level proportional to the height of the urban surface (Figure 1). Two hundred and fifty-six levels of grey are usually employed with zero representing street level. The remaining inputs to LT Urban are assigned sensible default values. However if detailed data is known for a building, it can be assigned to a pixel in an additional image.

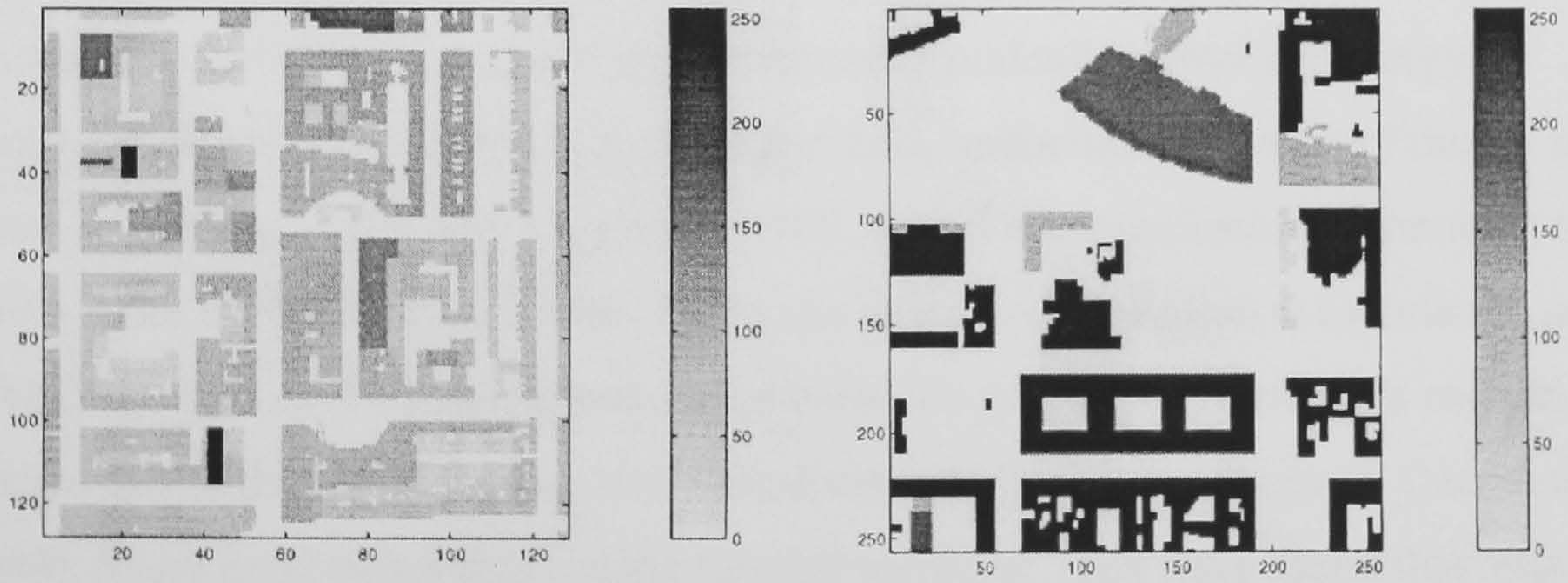


Figure 1. Examples of Digital Elevation Models for part of London (left) and Berlin (right). (From Ratti et al., 2000.)

Once the building energy consumption within the urban neighbourhood of interest has been predicted, LT Urban is used to explore the relationships between urban form and building energy usage. LT Urban is able to consider energy conservation and efficiency measures including optimal glazing ratio and U-values of the building fabric. It has also been developed to consider solar water heating and PV systems to predict the renewable energy potential of the site of interest (D. Robinson, developer of LT Urban, written communication, January 31, 2001).

2.2.5 National Home Energy Rating (NHER) software

National Home Energy Rating (NHER) software developed by National Energy Services Limited (NES) can be used to predict the energy demand of individual dwellings. There are nine different programs in the suite of NHER software, many of which are increasingly being used by local authorities. These programs have been designed to operate at different levels of data input from Level 0 (pronounced 'level zero') to Level 3 as described below.

The Level 0 data set comprises a minimum of ten data items as shown in Table 1. No dimensional information on the dwelling is required as it is the collection of this data that takes time and increases costs. External dwelling dimensions (e.g. ground floor area, wall area, etc.) are estimated from knowledge of the dwelling age, built form, number of storeys and number of rooms using a geometrical model derived by P. F. Chapman (1994). The remaining inputs required to calculate dwelling energy consumption are based on national statistical data, undocumented rules of thumb and in-house expertise (N. Cutland, Director of NES, verbal communication, February 14, 2000). Like BREHOMES (Section 2.2.1), the energy consumption is calculated using BREDEM-12. Level 0 calculations are intended for general stock analysis and can be carried out by the Stock Profiler and Auto-Evaluator NHER programs (J. Chapman, 1994). Many local authorities use the Level 0 software. They have found that most of the required data is readily available for the social housing sector. However, analysis of private sector dwellings using Level 0 software is more difficult as most of the data needs to be collected. This is a major problem in light of the Home Energy Conservation Act 1995 (HECA) (DETR, 2000d) which requires all UK local authorities

Table 1. Characteristics of the different data levels of the NHER software. (Adapted from NES, 1999.)

NHER data level	**Number of data items**	**Description of data items**	**Accuracy and application**	**NHER programs**
Sub-Level 0	Minimum of 2	Age Built Form	HECA results from minimum possible data	Stock Profiler II
Level 0	Minimum of 10	*As Sub-Level 0 plus:* Number of rooms Number of storeys Insulation in the wall, floor and roof Glazing type Space heating system type and fuel Water heating system type and fuel	General stock analysis	Stock Profiler and Auto-Evaluator
Enhanced Level 0	15 - 25	*As Level 0 plus:* Floor area Further details of the heating system	As Level 0 plus reliable advice to householders on energy efficiency improvements	As Level 0 plus HECA Home Energy Advisor
Level 1	50 - 100	*As Enhanced Level 0 plus:* Storey heights Heating system controls Boiler types	Fast site audits with accurate SAP ratings and good advice to householders	Surveyor III
Level 2	200	*As Level 1 plus:* All dimensional information for the dwelling Accurate U-values (calculated from detailed construction of all elements)	Full SAP and NHER ratings with standard occupancy (primarily new dwellings)	Builder
Level 3	250	*As Level 2 plus:* Actual occupancy data (e.g. hours and demand temperatures of space heating)	Accurate SAP, NHER and running costs with actual occupancy (existing dwellings)	Evaluator

with housing responsibilities to provide annual reports to the Secretary of State on the energy efficiency of all housing in their region.

To help local authorities meet their HECA requirements, especially the auditing of private sector stocks, a new sub-Level 0 program (Table 1) has been introduced in the form of NHER Stock Profiler II (NES, 1995). This can produce results with just two data items per dwelling - namely the age and built form e.g. detached, semi-detached, mid terrace, etc. A system of defaults is used to generate representative dwelling types. Where more detailed data exists for part of the stock, this is used in preference to the default values. Stock Profiler II is capable of performing calculations up to full Level 0.

Although results based on Level 0 data are useful for fulfilling policy requirements, they cannot be used to provide detailed energy efficient improvement advice to individual householders. This is a major problem for local authorities as one of the key elements of HECA is persuading private householders to make improvements to the energy efficiency of their homes. To overcome this problem, HECA Home Energy Advisor (NES, 1999) has been developed to perform an Enhanced Level 0 calculation. This adds the floor area and further details of the heating system to the Level 0 data set (Table 1). This additional information is usually readily available for public sector stocks. For private sector stocks, however, it needs to be collected. Simple questionnaires, with between 20 and 30 questions about the dwelling, are distributed to householders to obtain the Enhanced Level 0 data. Default values are used when questionnaires contain inconsistent or incomplete data.

Site surveys can also be used to collect Enhanced Level 0 data. When collecting data by survey, however, it takes very little extra time to collect sufficient data to allow a Level 1 calculation to be performed using NHER Surveyor III (NES, 1995). At Level 1, data is still not collected for items including the window areas and the U-values of the building elements (which are still assessed from the construction, insulation and age of the dwelling) but an accurate SAP rating can now be calculated for the majority of dwellings (Table 1). Improved energy efficiency advice can also be given to householders.

Levels 2 and 3 provide the most accurate results (Table 1). At both levels, all the dimensional information must be assessed for the property and U-values must be calculated from knowledge of the composition of each element. Such data can really only be collected during full property surveys. The only difference between the results obtained from each level is that Level 2 is based on standard occupancy data whereas Level 3 is based on actual occupancy data (i.e. hours and temperatures of space heating, use of hot water and appliances, etc.). Level 2 therefore lends itself well to the analysis of new buildings using NHER Builder (NES, 1995). Level 3 is used to analyse existing dwellings using NHER Evaluator (J. Chapman, 1994).

At all levels, SAP ratings, NHER ratings, energy consumption, running costs and CO_2 emissions are available. Of course, the accuracy of these results improves with increased data collection i.e. Level 3 is far more accurate than sub-Level 0. Results are only available on an annual basis.

2.3 Discussion of the models

This section compares the urban energy models described in the previous section and discusses differences in their approach. The relative strengths and weaknesses are identified. Table 2 summarises the key characteristics of the models and the following discussion centres on the contents of this table. At the end of the discussion, a concept for the SEP system is proposed.

The models have different areas of application and consider different energy use sectors. Both DREAM-City and EEP are concerned with the four energy use sectors of domestic and non-domestic buildings, industry and transport. DREAM-City, however, can only consider whole cities whereas EEP is capable of analysing smaller postcode regions within cities and aggregating results for application to whole cities. LT Urban focuses on non-domestic buildings within cities. BREHOMES and NHER are the only two urban energy models solely interested in domestic buildings. They analyse dwellings at very different physical scales with BREHOMES considering the whole UK dwelling stock (although it can consider smaller regions with a reduction in accuracy)

Table 2. A summary of the key characteristics of the urban energy models.

Urban Energy Model	Area of application	Applied to energy use sector	Data sources	Predictions	Solar component	GIS used	Computing platform	Developer	Users
BREHOMES (Section 2.2.1)	UK	Domestic	National statistics	Annual: Energy use	None	None	PC	Building Research Establishment (BRE)	DETR
DREAM-City (Section 2.2.2)	City	Domestic Services Industry Transport	Regional statistics	Monthly: Energy use Fuel use CO_2	None	None	PC	Energy and Environment Research Unit, Open University	Aimed at local authorities - users unknown
EEP (Section 2.2.3)	Postcode area within a city	Domestic Non-domestic Industry Transport	Map-derived data; rapid site surveys; defaults based on global assumptions.	Annual: Energy use CO_2 SAP	BIPV sub-model	MapInfo	PC	Welsh School of Architecture, University of Wales, Cardiff	Welsh local authorities currently assessing EEP
LT Urban (Section 2.2.4)	Individual buildings within cities	Non-domestic	Image processing techniques based on DEMs[a]. Standard default values.	Annual: Energy use	Considers solar water heating and PV systems	None	PC	The Martin Centre, Cambridge University	Development only just completed
NHER (Section 2.2.5)	Stock analysis down to individual buildings (Table 1)	Domestic	National statistics; rules of thumb and in-house expertise; household questionnaires; rapid/detailed site surveys.	Annual: Energy use CO_2 SAP NHER Costs	None	None	PC	National Energy Services Limited (NES)	Local authorities

[a] Digital Elevation Models

and the different NHER programs producing results from a large stock of dwellings, e.g. a city, down to a single individual dwelling. The results available from NHER software are the most flexible in terms of physical scale but more than one program is required.

From analysis of the models, it is clear that one of the major problems in urban energy modelling is data collection. The models use a range of sources to collect sufficient data to allow meaningful results to be obtained. BREHOMES bases its prediction of UK dwelling energy consumption on national statistics. The accuracy of this prediction is improved by comparison with the actual consumption figure published by the DTI. This allows fine-tuning of the inputs. Although results are presented for the whole of the UK, some of the input statistics correspond to a different geographical area e.g. England or Great Britain. This has required interpretation of the input data using common sense judgements. BREHOMES is also used at more disaggregated levels but the results still correspond to the UK statistics. The model is not able to use more detailed data even if it exists.

At low data levels (i.e. sub-Level 0 through to Level 1), NHER software uses simple questionnaires and rapid site surveys to obtain the required data. The remaining data is obtained from national statistics. Unlike BREHOMES, however, if more detailed data exists, this can be used to improve the accuracy of the results. At Levels 2 and 3 (Table 1), detailed property surveys must be performed to collect all data required to predict the energy consumption of individual dwellings.

DREAM-City uses a slightly different approach to BREHOMES in that its data is obtained from regional rather than national statistics. This makes the data more applicable to the city of interest and should allow more accurate predictions of energy consumption at the urban level. The EEP model, like NHER, uses rapid site surveys to collect some of its required data. Some useful data is also derived from the digital urban map viewed through the MapInfo GIS. The remaining data, however, is based on global assumptions rather than traceable statistical sources. LT Urban uses a completely different approach to acquire its required data. It uses image-processing techniques based on DEMs and assumes standard defaults.

Of all the models, only DREAM-City and LT Urban predict results for a monthly period. This is to ensure that important seasonal variations are reflected. The remaining models only generate annual results. All the models establish the existing energy use for the area of interest before making predictions about the effect of future developments or the installation of energy efficiency measures.

The EEP model is the only model which currently considers the use of solar energy technologies in dwellings. The recent BIPV sub-model added to EEP, however, is process-intensive and appears to require considerable user interaction and expertise. It is not clear whether there are future plans to automate the operation of the BIPV sub-model to make it more usable in a planning tool. LT Urban considers solar water heating and PV systems for non-domestic buildings.

The use of GIS technology is also unique to the EEP model. This uses the MapInfo GIS to store input data and results which can then be viewed on the digital urban map. All models are based on PCs.

BREHOMES and NHER are the most widely used models. The DETR is one of the major users of BREHOMES and they have used the model to help develop several policies. The DETR continues to fund research into its development. NHER software is sold commercially and is used by many local authorities throughout the country. It has become established as one of the leading energy rating programs. Of the remaining models, EEP is undergoing assessment in some Welsh local authorities, the use of DREAM-City is unknown (although not thought to be widespread) and the development of LT Urban has only recently been completed.

2.4 The SEP concept

The need for a solar energy planning system was established in Section 2.3 as existing urban energy models do not consider solar energy technologies in much detail. It is unlikely that urban energy planners in local authorities will have expertise in the area of solar energy and thus the SEP system should provide decision support and an approach to automate the analysis of solar energy as far as possible. Furthermore, the SEP system, like the DREAM-City model, should predict results on a monthly basis. This is likely to be important when considering solar energy technologies to predict the effect of the variation in solar radiation throughout a year.

From the preceding sections, it is clear that it is necessary to predict domestic energy consumption for different physical areas. For example, central government requires national information and local government requires regional information to develop policies that will impact on sustainable development e.g. HECA and LA21. However, the success of such policies depends on an ability to identify individual properties which could benefit from energy efficiency improvements or solar energy technologies. None of the models discussed previously are capable of considering both individual dwellings and whole cities.

Computing power today allows rapid calculations to be carried out on a house-by-house basis for large numbers of dwellings. The SEP system should therefore be able to predict the energy demands of individual dwellings and aggregate these up to the whole city level.

In Section 2.3, the collection of data was identified as one of the key problems in urban energy modelling. The models used a range of sources to collect different amounts of data at different levels of detail. The SEP concept should therefore be flexible enough to allow operation of the system at various levels of input data. National data obtained from traceable statistical sources should form the least accurate prediction of domestic energy consumption. If regional or city-wide statistical data is available for the area of interest, this should be used instead. Data collection techniques such as rapid site surveys and household questionnaires should be considered to identify their usefulness in improving the accuracy of predictions. The SEP system should also be designed to allow use of detailed data obtained from individual property surveys. This detailed data is increasingly available as local authorities strive to implement HECA and LA21 strategies. It can be assumed that detailed data collection will continue in the future as even greater importance is placed on accurately predicting the energy consumption of the domestic housing stock.

To ensure credibility of the SEP system, existing and well-established calculation models should be used to predict the domestic energy consumption and the performance of the different solar energy technologies. Such an approach has proved beneficial to both BREHOMES and NHER which are now widely used. In addition, the successful use of the MapInfo GIS in the EEP model gives confidence for its use in the SEP system (Section 1.2).

2.5 Summary

This chapter has reviewed existing urban energy models. It was established that there is a need for a solar energy planning system as existing models do not consider solar energy technologies (e.g. solar water heating, PV systems and passive solar design) in great detail. Comparison of the relative strengths and weaknesses of the different models allowed the concept of a new GIS-based SEP system to be proposed. Initially, the system will focus on dwellings. The SEP system should:

- accurately predict domestic energy consumption for individual dwellings and whole cities;
- function at various levels of data input ranging from national statistics through to detailed information for an individual property;
- use well-established models to predict domestic energy consumption and solar energy potential to ensure credibility of the approach;
- calculate results on a monthly basis to show the variation in the performance of solar energy technologies throughout a year.

With the concept of the SEP system now clearly defined, Chapter 3 goes on to describe the domestic energy modelling approach of the SEP system which addresses the major problem of data collection using a new dwelling classification system.

Chapter 3

Domestic Energy Modelling

3.1 Introduction

The beneficial effects of energy efficiency measures and solar energy technologies can be better understood in the context of the existing energy consumption of a dwelling (e.g. Jones et al., 1999; Shorrock & Dunster, 1997). Improvements to the dwelling can then be quantified in terms of potential energy savings and reductions in CO_2 emissions relative to this consumption. This allows specific recommendations to be given for each dwelling instead of more general advice. The SEP system therefore requires a domestic energy model to predict the energy consumption of dwellings. This chapter justifies the choice of the domestic energy model used in the SEP system and proposes a new dwelling classification system to overcome the problem of data collection discussed in Section 2.3.

3.2 Selecting a domestic energy model for the SEP system

When selecting the domestic energy model for the SEP system, a number of criteria were considered. These are listed below.

- Most importantly, the model should represent the fundamental physical process with acceptable accuracy without entailing onerous input data requirements.
- The calculation should be undertaken on a monthly basis to account for solar sensitive energy systems.
- Results should be generated quickly as planners could be analysing thousands of dwellings.
- The model should be easily integrated into the planning system.

- The model should make no assumptions about the level of user expertise.

The use of detailed simulation models such as ESP-r (Energy Systems Research Unit [ESRU], 1995) and TRNSYS (Solar Energy Laboratory [SEL], 2000) was quickly ruled out. Although these models can produce accurate predictions of energy consumption, they require large quantities of input data and considerable user expertise which planners cannot be expected to have. Even if planners were trained to use these models, they could not be easily integrated into the SEP system. Therefore, attention was focused on simpler domestic energy models.

The Government's SAP produces energy ratings for dwellings based on the calculated annual energy cost for space and water heating (DETR, 1998b). The SAP energy rating is widely used to show the energy efficiency of dwellings and forms the calculation procedure in the domestic sub-model in the EEP model (Section 2.2.3). Since 1 July 1995, all new dwellings or those undergoing change of use involving building work must have a SAP rating which can be used to show compliance with the Building Regulations (Department of the Environment and the Welsh Office [DoE&WO], 1995b). The SAP rating does not take account of the energy consumed by lights, appliances and cooking. For future expansion of the SEP system, it would be useful to employ a domestic energy model which calculates this energy use. The main disadvantage of the SAP, however, stems from research carried out at the Building Research Establishment (BRE). Silver and Parand (1999) showed that the SAP tends to underestimate the solar contribution to the space heating load because it:

- uses a single location for the UK;
- calculates solar fluxes over October to April whereas the heating season is taken as October to May;
- neglects solar gain on the walls and roof;
- assumes that windows have 30% frame.

These limitations in the SAP prevented its use in the SEP system where the calculation of passive solar gain is an important consideration.

The SAP calculation is based on BREDEM-9 (Anderson, Clark, Baldwin & Milbank, 1985), one of the standardised versions of the Building Research Establishment Domestic Energy Model. This is a simplified version of BREDEM-12 which predicts dwelling energy consumption on an annual basis using a nominal heating season of eight months (i.e. October to May). BREHOMES (Section 2.2.1) and NHER software (Section 2.2.5) use BREDEM-12 as their domestic energy model. Another version called BREDEM-8 (Anderson, Chapman, Cutland, Dickson, Doran et al., 1997) predicts dwelling energy consumption on a monthly basis. Unlike SAP, both BREDEM-8 and BREDEM-12 consider lights, appliances and cooking in addition to space and water heating. The major disadvantage of BREDEM-12 is its use of a fixed eight month heating season. For example, improved insulation and passive solar design could significantly reduce the length of the heating season but this would not be reflected in the BREDEM-12 calculation. As BREDEM-8 is a monthly calculation, it has the advantage that information is available on seasonal variations and thus it is able to consider solar sensitive energy systems (one of the criteria defined earlier).

Dickson, Dunster, Lafferty and Shorrock (1996) compared the performance of BREDEM-8 (and BREDEM-12) against measurements in real dwellings and predictions from three detailed simulation models (ESP-r, SERI-RES and HTB2). They found that BREDEM-8 (and BREDEM-12) predicted annual energy consumptions which were equally as accurate as the detailed simulation models.

BREDEM-8 requires input data for approximately 80 parameters to predict dwelling energy consumption. Although 80 input parameters may seem considerable, the quantity of input data required by BREDEM-8 is, of course, commensurate with both the SAP and BREDEM-12. According to J. Chapman (1991), these models provide the correct balance between data requirements and predictive accuracy. In addition, both of these calculation procedures have been used in other urban energy models (e.g. EEP, BREHOMES and NHER described in Chapter 2) where data collection problems have been overcome.

There should be no problems integrating BREDEM-8 into the SEP system where it should be capable of generating results quickly. The model does not require much user expertise. BREDEM-8 appears to adequately meet all the criteria defined earlier and thus it was chosen as the domestic energy model for the SEP system.

3.3 Description of BREDEM-8

BREDEM-8 is a simple steady-state model that can be used to calculate the monthly energy consumption in dwellings for space heating, water heating, lighting, electrical appliances and cooking. There is also an optional section to consider the effect of a conservatory. This is not considered in the present study. Space heating energy requirement is calculated using an analytical approach balancing heat losses against gains. Empirical functions estimate quantities such as the utilisation of gains. Predictions of energy consumption for water heating, cooking, lights and appliances are based on measurements of actual consumption. Figure 2 shows the energy balance principle used in BREDEM-8. The following sections briefly describe the model. Further details about the model are given in Appendix A.

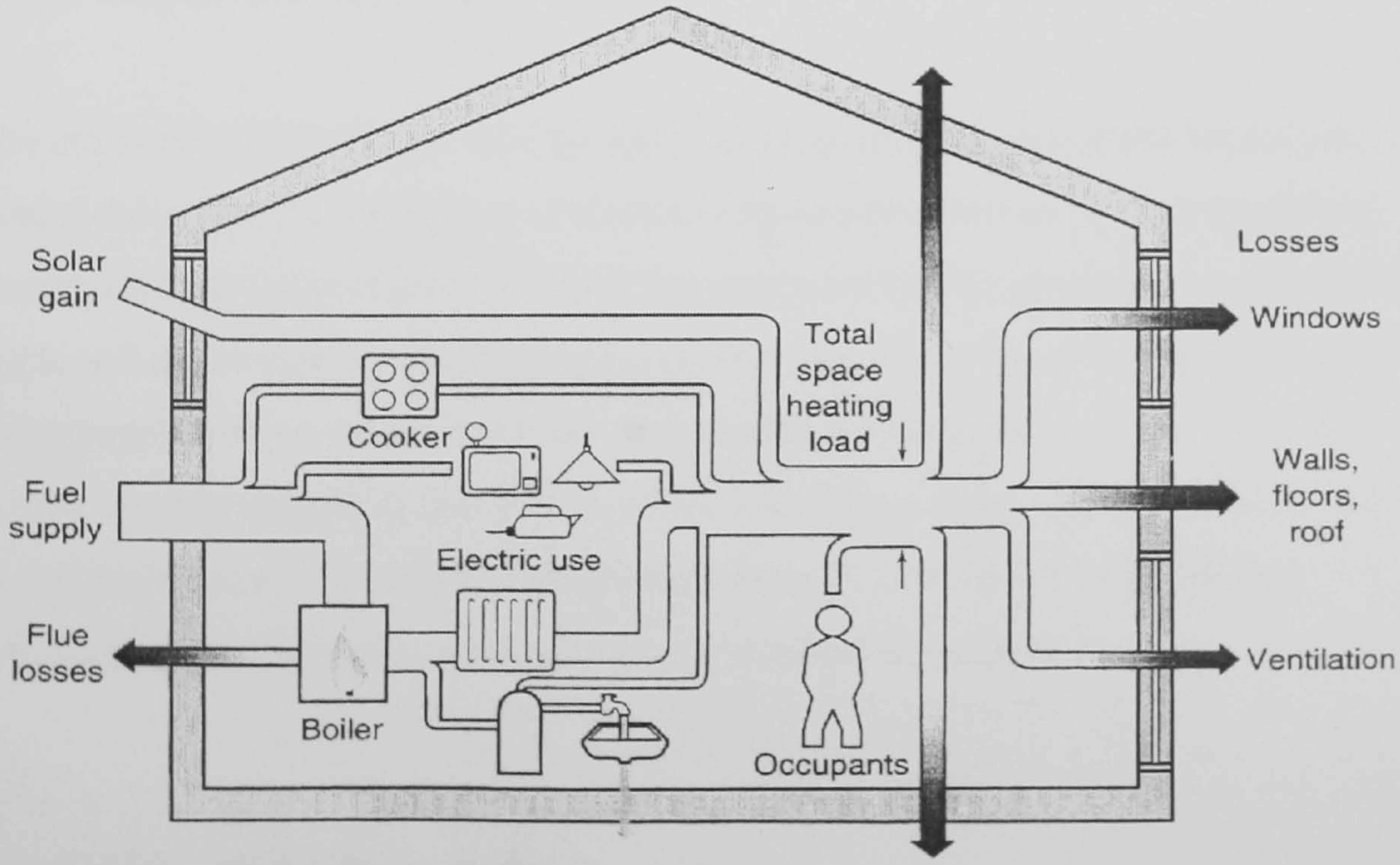


Figure 2. Schematic illustration of the energy balance principle used in BREDEM-8. (From Anderson et al., 1997.)

3.3.1 Water heating

In BREDEM-8, the hot water demand is calculated based on the number of occupants. The different forms of heat loss are then calculated.

- Tank losses are determined from the volume and insulation of the tank.
- Primary pipework losses depend on the level of insulation surrounding the pipes and the presence of a hot water cylinder thermostat.
- Distribution losses between the cylinder and the tap are based on the energy leaving the tap.

Although BREDEM-8 can calculate the contribution from a solar panel, this procedure was ignored in the SEP system as solar DHW is considered more rigorously using the approach described in Chapter 4. The monthly hot water energy requirement can then be calculated assuming demand to be uniform throughout the year. The delivered fuel requirement depends on the efficiency of the water heating appliance. Finally, an estimate is made of the hot water gains.

3.3.2 Lights and appliances

The estimation of electricity used by lights and appliances is important because as households make increasing use of electrical appliances, the electricity expenditure becomes a large proportion of the total fuel expenditure. The electricity consumption for lights and appliances is calculated based on the total floor area of the dwelling. If the actual number of occupants is known, this can be used to produce a more accurate prediction. The electricity use is reduced for low energy lights and increased for heating or ventilating pumps and fans. The monthly energy consumption and gains are estimated assuming electricity demand to be uniform throughout the year.

3.3.3 Cooking

The delivered fuel requirement for cooking varies with the number of occupants and the type of fuel used. The monthly cooking fuel use and cooking gains are estimated assuming demand to be uniform throughout the year.

3.3.4 Space heating

To estimate the space heating requirement, BREDEM-8 divides the dwelling into two zones. Zone 1 represents the living area which is heated to a higher temperature than zone 2, the rest of the dwelling. Zone 1 is always fully heated but zone 2 can be only partly heated or unheated. The use of this two-zone approach means that for ease of use, BREDEM-8 requires implementation on a personal computer (PC). (By contrast, BREDEM-9 (the SAP) is a single zone model that can be calculated by hand on a worksheet.)

It is necessary to calculate the fabric and ventilation losses (i.e. the specific loss) for each zone. Interzone heat transfer is also considered as this affects the temperature difference between the two zones. Solar gains are calculated for every opening in both zones and the metabolic gains are also determined. These gains are added to those previously calculated for water heating, lights, appliances and cooking to give the total gains. The gains are distributed between the two zones as shown in Table 3.

Table 3. Distribution of gains. (Redrawn from Anderson et al., 1997.)

Gain	**Zone 1**	**Zone 2**	**Kitchen**[a]
Cooking	None	None	100%
Water heating	None	50%	50%
Lights and appliances	30%	20%	50%
Metabolic	50%	50%	None
Solar	Zone 1 openings	Zone 2 openings	Kitchen openings

[a]The kitchen gains are allocated to the zone in which it is situated (usually zone 2 but in an open plan arrangement, the kitchen could be in zone 1).

The space heating requirement depends on the temperature difference between outside and inside. The mean monthly external temperatures for twenty-one different regions are given in the BREDEM-8 model description. These regions are shown in Appendix A. BREDEM-8 calculates the mean internal temperature of each zone from the zone demand temperature (i.e. the temperature required by the occupants during the heating period) and the zone background temperature (i.e. the resultant temperature if there was no heating). This is explained in more detail in Appendix A. With the internal and external temperatures and the heat losses and gains now determined for each zone, the monthly space heating requirement can be calculated. It should be noted that a degree day approach (described in Appendix A) similar to that used in SAP and BREDEM-12 is not used in BREDEM-8 as it was found to only make a small difference which did not justify the increased complexity (Anderson et al, 1997).

BREDEM-8 then calculates the delivered fuel requirement based on the efficiencies of the heating systems in the dwelling. A maximum of two heating systems can be specified. A primary system, e.g. gas fired central heating or electric storage heating, and a secondary system which provides additional heat when required, e.g. gas, electric or coal fires.

3.3.5 Total energy consumption

The total energy consumption of the dwelling can then be determined by summing the individual energy requirements i.e. water heating, lights, appliances, cooking and space heating. This is calculated on a monthly basis but these values can obviously be added together to estimate the annual energy demand.

3.3.6 Implementation in the SEP system

As no suitable computer implementation of BREDEM-8 exists, one was implemented in the SEP system as a database application (Rylatt, Gadsden, Lomas, in press). The implementation of BREDEM-8 links to an underlying relational database storing dwelling data and to the MapInfo GIS to permit visualisation of results.

3.4 Dwelling classification system

As mentioned in Section 3.2, BREDEM-8 requires input data for approximately 80 parameters. This poses considerable problems for energy modelling on an urban scale. Leicester, for example, has approximately 110,000 dwellings. It is extremely unlikely that sufficient data will become available for every property to allow a full BREDEM-8 calculation to be performed. To overcome this problem of data collection, a dwelling classification system was developed as part of the approach described in this thesis.

The proposed dwelling classification system aims to provide a reliable platform for estimating the baseline energy consumption of a dwelling i.e. the energy consumption assuming all default input data. Defaults are derived from traceable sources and can be applied to any region in the country. As detailed data becomes available for a specific region or urban area, it can be incorporated into the dwelling classification system to modify the defaults and enhance the baseline prediction of energy consumption. The dwelling classification system divides the input data required by BREDEM-8 into just six categories as shown in Table 4. Each category is described in turn in the following sections to show how default values were derived for every input parameter.

3.4.1 Category 1: Regional location

BREDEM-8 considers the United Kingdom to be divided into twenty-one different regions (Appendix A). By reference to the regional location of a dwelling, the site latitude, horizontal solar flux, wind speed and monthly external temperature at sea level are available from BREDEM-8 reference tables. The height of the dwelling above sea level is available from a digital urban map such as the Ordnance Survey's Land-Line Plus.

3.4.2 Category 2: Built form

Various studies exist showing dwellings classified according to their built form (e.g. P. F. Chapman, 1994; WSA, 1996). The classification system used in the NHER software

Table 4. BREDEM-8 input data: default sources and data collection methods.

BREDEM-8 input parameter	**Source of default**	**Location of default in thesis**	**Possible improvement by:**		**ONLY available from full survey**[a]
			Rapid site survey	**Home Energy Survey Form**	
Category 1: Regional Location (Section 3.4.1)					
1. Degree day region	Known parameter	(Regions shown in Appendix A)	N/A	N/A	N/A
2. Regional wind speed	BREDEM-8 reference table	N/A	N/A	N/A	N/A
3. Horizontal solar flux	BREDEM-8 reference table	N/A	N/A	N/A	N/A
4. Latitude of site	BREDEM-8 reference table	N/A	N/A	N/A	N/A
5. Monthly external temperature at sea level	BREDEM-8 reference table	N/A	N/A	N/A	N/A
6. Height above sea level	GIS (map derived data)	N/A	N/A	N/A	N/A
Category 2: Built Form (Section 3.4.2)					
7. Type of dwelling	GIS (map derived data)	Tables 6, 7, 8 & 9 Appendix B	√	√	
8. Dwelling exposure	Assumed default	Tables 7 & 9	√		
9. Number of storeys	Assumed default or local user knowledge	Tables 6 & 8	√	√	
10. Relation of zone 1 to zone 2	Assumed default	Tables 6 & 8			√
11. Zone 1 ground floor area	GIS (map derived data) and standard dwelling configurations	Tables 7 & 9 Appendix B			√
12. Zone 2 ground floor area	GIS (map derived data) and standard dwelling configurations	Tables 7 & 9 Appendix B			√
13. Zone 1 total floor area	GIS (map derived data) and standard dwelling configurations	Tables 7 & 9 Appendix B			√
14. Zone 2 total floor area	GIS (map derived data) and standard dwelling configurations	Tables 7 & 9 Appendix B			√
15. Zone 1 volume	GIS (map derived data) and standard dwelling configurations	Tables 7 & 9 Appendix B			√
16. Zone 2 volume	GIS (map derived data) and standard dwelling configurations	Tables 7 & 9 Appendix B			√
17. Zone 1 external wall area	GIS (map derived data) and standard dwelling configurations	Tables 7 & 9 Appendix B			√
18. Zone 2 external wall area	GIS (map derived data) and standard dwelling configurations	Tables 7 & 9 Appendix B			√

Table 4 (continued). BREDEM-8 input data: default sources and data collection methods.

BREDEM-8 input parameter	**Source of default**	**Location of default in thesis**	**Possible improvement by:**		**ONLY available from full survey**[a]
			Rapid site survey	**Home Energy Survey Form**	
19. Zone 1 window area	Building Regulations and standard dwelling configurations	Tables 7, 9 & 10 Appendix B			√
20. Zone 2 window area	Building Regulations and standard dwelling configurations	Tables 7, 9 & 10 Appendix B			√
21. Zone 1 door area	Assumed default	Tables 6 & 8			√
22. Zone 2 door area	Assumed default	Tables 6 & 8			√
23. Zone 1 roof area	GIS (map derived data) and standard dwelling configurations	Tables 6 & 8 Appendix B			√
24. Zone 2 roof area	GIS (map derived data) and standard dwelling configurations	Tables 6 & 8 Appendix B			√
25. Zone 1 window orientation	GIS (map derived data) and assumed default	N/A			√
26. Zone 2 window orientation	GIS (map derived data) and assumed default	N/A			√
27. Zone 1 door orientation	GIS (map derived data) and assumed default	N/A			√
28. Zone 2 door orientation	GIS (map derived data) and assumed default	N/A			√
Category 3: Age (Section 3.4.3)					
29. Age of dwelling	Records held by local authorities or local user knowledge	Table 10	√	√	
30. Height of storeys	P. F. Chapman (1994)	Table 10			√
31. Type of wall construction	NES (1995)	Table 10	√	√	
32. Wall U-value	Building Regulations and BREDEM-8 reference table	Table 10		√	
33. Type of window frame	Building Regulations and BREDEM-8 reference table	Table 10	√		
34. Type of window glazing	Building Regulations	Table 10	√	√	
35. Window U-value	Building Regulations and BREDEM-8 reference table	Table 10	√	√	
36. Draught stripping on windows	Building Regulations	Table 10		√	
37. Tightness of windows	Assumed default	Table 10	√		
38. Type of door	Assumed default	Table 10	√		

Table 4 (continued). BREDEM-8 input data: default sources and data collection methods.

BREDEM-8 input parameter	**Source of default**	**Location of default in thesis**	**Possible improvement by:**		**ONLY available from full survey**[a]
			Rapid site survey	**Home Energy Survey Form**	
39. Door U-value	Assumed default	Table 10	√		
40. Draught stripping on doors	Building Regulations	Table 10		√	
41. Tightness of doors	Assumed default	Table 10	√		
42. Ground floor U-value	Building Regulations and assumed default	Table 10		√	
43. Roof U-value	Building Regulations and BREDEM-8 reference table	Table 10		√	
44. Type of hot water tank insulation	Building Regulations	Table 10		√	
45. Thickness of hot water tank insulation	Building Regulations	Table 10		√	
46. Insulation of primary pipework	Building Regulations	Table 10		√	
47. Presence of hot water cylinder thermostat	Building Regulations	Table 10		√	
48. Sealing of loft hatch	Building Regulations	Table 10			√
49. Number and type of fans	Building Regulations	Table 10			√
Category 4: Heating and cooking systems (Section 3.4.4)					
50. Type of primary space heating system	EHCS and BREDEM-8 reference table	Tables 11, 12, 13 Appendix C		√	
51. Control of primary space heating system	BREDEM-8 reference table	Table 14		√	
52. Type of secondary space heating system	EHCS and BREDEM-8 reference table	Table 15 Appendix C			√
53. Type of hot water system	EHCS and BREDEM-8 reference table	Table 18 Appendix C		√	
54. Type of cooking system	EHCS and BREDEM-8 reference table	Table 19 Appendix C			√
Category 5: BREDEM-8 standard occupancy defaults (Section 3.4.5)					
55. Number of occupants	BREDEM-8 standard formula	Equation 3.16			√
56. Zone 1 demand temperature	BREDEM-8 standard default	Table 21			√
57. Desired temperature difference between zones 1 and 2	BREDEM-8 standard default	Table 21			√
58. Heating period for zone 1	BREDEM-8 standard default	Table 21			√

Table 4 (continued). BREDEM-8 input data: default sources and data collection methods.

BREDEM-8 input parameter	**Source of default**	**Location of default in thesis**	**Possible improvement by:**		**ONLY available from full survey**[a]
			Rapid site survey	**Home Energy Survey Form**	
59. Heating period for zone 2	BREDEM-8 standard default	Table 21			√
60. Level of usage of hot water	BREDEM-8 standard default	Table 21			√
61. Level of usage of lights and appliances	BREDEM-8 standard default	Table 21			√
62. Level of usage of cooking	BREDEM-8 standard default	Table 21			√
Category 6: Assumed defaults (Section 3.4.6)					
63. Location of kitchen	BREDEM-8 typical case	Table 22			√
64. Location of hot water tank	BREDEM-8 typical case	Table 22			√
65. Site exposure factor	BREDEM-8 average case	Table 22	√		
66. Level of overshading – zone 1	BREDEM-8 average case	Table 22	√		
67. Level of overshading – zone 2	BREDEM-8 average case	Table 22	√		
68. Draught lobby on main door	Assumed default	Table 22	√		
69. Volume of hot water tank	Assumed default	Table 22			√
70. Mechanical ventilation with heat recovery	Assumed default	Table 22			√
71. Number of low energy light bulbs	Assumed default	Table 22		√	
72. Number and type of pumps	Assumed default	Table 22			√
73. Number and type of vents	Assumed default	Table 22			√
74. Number of chimneys	Assumed default	Table 22			√
75. Number and type of flues	Assumed default	Table 22			√
76. Type of ground floor	Assumed default	Table 22			√
77. Fraction of zone 2 that is heated	Assumed default	Table 22			√

[a] Of course, all BREDEM-8 input data is available from a full survey. This column shows the data which can only be accurately collected by full survey and no other means.

(Section 2.2.5) and the Home Energy Survey Form (NEF, no date) distributed by Energy Efficiency Advice Centres was adopted for the approach described in this thesis. This was selected as local authorities already have considerable data stored in this format. The proposed classification system divides dwellings into six main classes of built form:

1. detached;
2. semi-detached;
3. end terrace;
4. mid terrace;
5. mid terrace with unheated connecting passageway;
6. flat.

The built form of a dwelling can usually be inferred from inspection of its outline on a digital urban map or by site survey. Although flats are one of the main classes of built form listed above, they can take many different forms. For example, the 1996 EHCS (DETR, 2000a) divides them into purpose built high rise flats, purpose built low rise flats and converted flats. They represent 1.6%, 13.2% and 4.5% of the English dwelling stock respectively (a combined total of 19.3%). Flats can also be classified as either ground, mid or top floor which complicates the description of their built form still further. Therefore, it was decided to remove flats to a separate list for consideration on an individual basis. It is possible to highlight blocks of flats on a digital urban map because each individual flat has its own address point. If a dwelling has more than one address point, it can be classified as flats.

Although knowledge of the built form is important, it is not enough in itself to generate the geometrical data required by BREDEM-8. To determine all the element areas required by BREDEM-8 it is necessary to know, at the very least, the ground floor area and the exposed perimeter of the dwelling. Detailed site surveys are time-consuming and expensive and therefore attention turns to estimating these values from the digital urban map.

In a typical GIS view composed of one or more superimposed map layers, building outlines, referred to as footprints, appear to form closed polygons. This is not the case. A building outline is formed from one or more intersecting polylines – graphical objects with numerous line segments. A closed polygon can be created by manually drawing round the visual outline of the footprint on an additional superimposed layer. The EEP model (Section 2.2.3) uses this approach. This is an extremely time-consuming exercise to contemplate on a large scale even though it is still much cheaper than the alternative of site survey. To overcome these problems, a customised GIS tool known as the 'Footprint Tool' (Rylatt, Gadsden & Lomas, in press) was developed by the software engineer employed on the EPSRC project. The Footprint Tool automatically extracts the outline of buildings as closed polygons, or footprints, from digital urban maps such as the Ordnance Survey's Land-Line Plus. Once the Footprint Tool has identified the closed polygon, it can readily calculate the ground floor area. For the majority of dwellings, the roof area is approximately equal to the ground floor area (P. F. Chapman, 1994). This assumes that roof insulation is applied horizontally. The dwelling classification system uses this assumption as the default for all domestic properties. The Footprint Tool can also determine the lengths of the dwelling walls and their nature (party, external, etc.) can be described.

Software was also developed to automatically determine the orientation of the dwelling. This calculates the angle subtended from north to the principal façade (i.e. the façade parallel to the road). This allows the orientation of windows and doors to be estimated by assuming that they are located on the front and rear façades of the dwelling. Table 5 lists all the data which can be extracted from the digital urban map.

Table 5. Data extracted from the digital urban map.

Data extracted from the digital urban map
Height of the dwelling above sea level
Built form of the dwelling
Ground floor area of the dwelling
Lengths of the dwelling walls
Nature of the dwelling walls (e.g. party, exposed, etc.)
Orientation of the dwelling

Of course, it is not possible to automatically infer the number of storeys of a dwelling from its built form. Local user knowledge, however, may allow the number of storeys to be specified with a reasonable degree of certainty. Where the user is unsure, it is proposed that two storeys are entered as the default. (From rapid site surveys, it was clear that the majority of dwellings have two storeys.) P. F. Chapman (1994) provides a relationship between the age of a dwelling and the height of its storeys: 2.6m pre-1950, 2.5m 1950-1965 and 2.4m thereafter. From a knowledge of the number and height of storeys (assuming every storey has the same plan), the dwelling total floor area, gross external wall area (i.e. wall area including windows and doors) and volume can be calculated.

A further complication is that BREDEM-8 requires a dwelling to be divided into two zones. The definition of these zones is different for each built form and so defaults were developed for the dwelling classification system described in this thesis. These defaults are based on standard dwelling configurations defined by Allen and Pinney (1990) of the BRE. They consider these standard dwelling configurations to be representative of each type of built form within the UK dwelling stock. Appendix B describes in detail the process used to derive these defaults. Tables 6 and 7 show the default input data for dwellings with one storey (i.e. bungalows). Tables 8 and 9 show the default input data for dwellings with two or more storeys.

Table 6. Default input data independent of built form: dwellings with one storey.

BREDEM-8 input parameter	**Default value**
Number of storeys	1
Relation of zone 1 to zone 2	1 storey dwelling
Zone 1 door area	0
Zone 2 door area	2 standard doors Front façade = 1.64m^2 Rear façade = 1.64m^2
Zone 1 roof area	20% of dwelling ground floor area
Zone 2 roof area	80% of dwelling ground floor area

Table 7. Default input data dependent on built form: dwellings with one storey.

Input Parameter	Detached	Semi-detached
Dwelling exposure factor	Exposed 4 sides	3
Zone 1 ground floor area	20% of dwelling ground floor area	20%
Zone 2 ground floor area	80% of dwelling ground floor area	80%
Zone 1 total floor area	20% of dwelling ground floor area	20%
Zone 2 total floor area	80% of dwelling ground floor area	80%
Zone 1 volume	20% of dwelling volume	20%
Zone 2 volume	80% of dwelling volume	80%
Zone 1 external wall area	25% of dwelling gross external wall area – Zone 1 window area	20%
Zone 2 external wall area	75% of dwelling gross external wall area – Zone 2 window and door area	80%
Zone 1 window area	15% of dwelling window area[a] All on front facade[b]	15% All on front
Zone 2 window area	85% of dwelling window area[a] Front = 35% of dwelling window area[b] Rear = 50% of dwelling window area[b]	85% 35% 50%

[a] Dwelling window area is calculated using the relationships in Table 10.

[b] It was assumed that dwelling window area is equally divided between the front and rear façades.

Table 8. Default input data independent of built form: dwellings with two or more storeys.

BREDEM-8 input parameter	Default value
Number of storeys	2
Relation of zone 1 to zone 2	Stairs do not link zone 1 and zone 2 directly
Zone 1 door area	0
Zone 2 door area	2 standard doors Front façade = 1.64m^2 Rear façade = 1.64m^2
Zone 1 roof area	0
Zone 2 roof area	Equal to dwelling ground floor area

Table 9. Default input data dependent on built form: dwellings with two or more storeys.

Input Parameter	**Detached**	**Semi-detached**	**End terrace**[a]	**Mid terrace**	**Mid terrace with unheated connecting passageway**
Dwelling exposure factor	Exposed 4 sides	3	3	2	2
Zone 1 ground floor area	40% of dwelling ground floor area	35%	35%	35%	35%
Zone 2 ground floor area	60% of dwelling ground floor area	65%	65%	65%	65%
Zone 1 total floor area	40% of dwelling ground floor area	35%	35%	35%	35%
Zone 2 total floor area	60% of dwelling ground floor area + 1st + 2nd + 3rd, etc. floor areas (each floor area = dwelling ground floor area)	65% + other	65% + other	65% + other	65% + other
Zone 1 volume	20% of dwelling volume	15%	15%	15%	15%
Zone 2 volume	80% of dwelling volume	85%	85%	85%	85%
Zone 1 external wall area	20% of dwelling gross external wall area – Zone 1 window area	10%	15%	15%	20%
Zone 2 external wall area	80% of dwelling gross external wall area – Zone 2 window and door area	90%	85%	85%	80%
Zone 1 window area	15% of dwelling window area[b] All on front facade[c]	15% All on front	20% All on front	20% All on front	20% All on front
Zone 2 window area	85% of dwelling window area[b] Front = 35% of dwelling window area[c] Rear = 50% of dwelling window area[c]	85% 35% 50%	80% 30% 50%	80% 30% 50%	80% 30% 50%

[a] These defaults apply to end terraces with or without an unheated connecting passageway.
[b] Dwelling window area is calculated using the relationships in Table 10.
[c] It was assumed that dwelling window area is equally divided between the front and rear façades.

To simplify the specification of the default orientation of doors in the SEP system, it was assumed (for all dwellings) that there is one door on the front façade and one door on the rear façade (Tables 6 and 8). In reality, many dwellings have one of the doors located on a side façade and not the rear façade. However, the door area is small in comparison to other element areas and this assumption is unlikely to have a significant effect on the prediction of dwelling energy consumption.

The standard dwelling configurations of Allen and Pinney (1990) assume all bungalows to be detached (Appendix B). It is common, however, for bungalows to be semi-detached and thus defaults were also proposed for this built form (Table 7).

When considering a mid terrace with unheated connecting passageway (Table 9), the ground floor passageway wall must be included in the calculation of external wall area. The additional exposed floor area due to the passageway is not currently determined by the Footprint Tool. This area is small in comparison to other element areas and it was assumed not to be a significant factor contributing to the heat loss of a dwelling. This assumption could be revised once real data has been obtained for a large number of dwellings. Furthermore, development of the Footprint Tool is continuing to determine whether this area can be automatically extracted in future.

3.4.3 Category 3: Age

The age of a dwelling is also a useful general attribute from which to derive generic data. Nine age groups are defined in both the NHER software and the Home Energy Survey Form that correspond to major changes in construction standards in the UK. Up to 1965, standards of performance were listed in Public Health Acts and By-laws. In 1965, all building legislation was brought together to produce the Building Regulations and these have applied, with revisions, since then. These age groups were adopted for the dwelling classification system proposed in this thesis and are listed below:

1. pre-1900;
2. 1900-1929;

3. 1930-1949;
4. 1950-1965;
5. 1966-1976;
6. 1977-1981;
7. 1982-1990;
8. 1991-1995;
9. post 1995.

The Government are currently reviewing Approved Document L (Conservation of Fuel and Power) of the Building Regulations (DETR, 2000b). This is the Approved Document affecting many of the BREDEM-8 input parameters and thus a further age group can be added to those listed above when the new Regulations come into force in 2001.

It is not possible to extract the age of dwellings from digital urban maps unless local user knowledge enables broad assignments to be made. The age can usually be determined from records held by local authorities or from historical local street directories. Once the age of a dwelling has been specified, a set of characteristics taken from the appropriate building standard is applied to it. These characteristics are shown in Table 10.

As stated earlier, the intention of the dwelling classification system is to provide a sound basis for estimating the baseline energy consumption of dwellings throughout the country. It is probable that some of the defaults proposed in Table 10 could be modified once detailed data becomes available for a specific region or urban area. For example, pre-1982 dwellings are assumed to have no hot water tank insulation and pre-1977 dwellings have roof U-values greater than 1 W/m^2K. It is likely that national campaigns aimed at encouraging householders to install energy efficiency measures such as hot water tank insulation and loft insulation will mean that these defaults are incorrect for many regions. In addition, dwelling window area is assumed to be the maximum allowable area specified by the Building Regulations at the time of construction. This assumption is likely to overestimate dwelling window area (see Appendix B).

Table 10. Default parameters for age.

Input Parameter	**Pre-1900**[a]	**1900-1929**[a]	**1930-1949**[a]	**1950-1965**[a]	**1966-1976**[a]
Height of storeys (m)[f]	2.6	2.6	2.6	2.5	2.4
Type of wall construction[g]	Solid	Solid	Cavity (Unfilled)	Cavity (Unfilled)	Cavity (Unfilled)
Wall U-value (W/m^{2}K)[h]	2.12	2.12	1.6	1.6	1.5
Type of window frame	Wood	Wood	Wood	Wood	Wood
Type of window glazing	Single	Single	Single	Single	Single
Window U-value (W/m^{2}K)[i]	4.3	4.3	4.3	4.3	4.3
Dwelling window area[j]	*12% of perimeter wall area (max.)*	*12% of perimeter wall area (max.)*	*12% of perimeter wall area (max.)*	*12% of perimeter wall area (max.)*	*12% of perimeter wall area (max.)*
Draught stripping on windows	No	No	No	No	No
Tightness of windows[k]	*Loose*	*Loose*	*Loose*	*Loose*	*Loose*
Type of door[l]	*Solid wood*	*Solid wood*	*Solid wood*	*Solid wood*	*Solid wood*
Door U-value (W/m^{2}K)	*3.0*	*3.0*	*3.0*	*3.0*	*3.0*
Draught stripping on doors	No	No	No	No	No
Tightness of doors[k]	*Loose*	*Loose*	*Loose*	*Loose*	*Loose*
Ground floor U-value (W/m^{2}K)[m]	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*
Roof U-value (W/m^{2}K)[h]	2.0	2.0	2.0	1.5	1.0
Type of hot water tank insulation	None	None	None	None	None
Thickness of hot water tank insulation	None	None	None	None	None
Insulation of primary pipework	No	No	No	No	No
Presence of cylinder thermostat	No	No	No	No	No
Sealing of loft hatch	No	No	No	No	No
Number and type of fans	0	0	0	0	0

Table 10 (continued). Default parameters for age. (Notes on next page.)

Input Parameter	**1977-1981**[b]	**1982-1990**[c]	**1991-1995**[d]	**Post 1995**[e]
Height of storeys (m)[f]	2.3	2.3	2.3	2.3
Type of wall construction[g]	Cavity (Unfilled)	Cavity (Part-filled)	Cavity (Part-filled)	Cavity (Part-filled)
Wall U-value (W/m^{2}K)[h]	1.0	0.6	0.45	0.45
Type of window frame	Wood	Wood	Wood	Wood
Type of window glazing	Single	Single	Single	Double
Window U-value (W/m^{2}K)[i]	4.3	4.3	4.3	2.8
Dwelling window area[j]	*12% of perimeter wall area (max.)*	12% of perimeter wall area (max.)	15% of total floor area (max.)	22.5% of total floor area (max.)
Draught stripping on windows	No	No	No	Yes
Tightness of windows[k]	*Loose*	*Tight*	*Tight*	*Well fitting*
Type of door[l]	*Solid wood*	*Solid wood*	*Solid wood*	*Solid wood*
Door U-value (W/m^{2}K)	*3.0*	*3.0*	*3.0*	*3.0*
Draught stripping on doors	No	No	No	Yes
Tightness of doors[k]	*Loose*	*Tight*	*Tight*	*Well fitting*
Ground floor U-value (W/m^{2}K)[m]	1.0	0.6	0.45	0.45
Roof U-value (W/m^{2}K)[h]	0.6	0.35	0.25	0.25
Type of hot water tank insulation	None	Spray Foam	Spray Foam	Spray Foam
Thickness of hot water tank insulation	None	35mm	35mm	35mm
Insulation of primary pipework	No	No	No	Yes
Presence of cylinder thermostat	No	Yes	Yes	Yes
Sealing of loft hatch	No	No	No	Yes
Number and type of fans	0	0	2 extract fans	2 extract fans

Notes to accompany Table 10.

Italics indicate that the data is not obtained from Building Regulations and an assumed default is used (described in the notes below).

[a] Data for pre-1977 obtained from Elder (1975) (unless otherwise stated).
[b] Data for 1977-1981 obtained from Elder (1977) (unless otherwise stated).
[c] Data for 1982-1990 obtained from Elder (1986) and Ferguson (1985) (unless otherwise stated).
[d] Data for 1991-1995 obtained from Stephenson (1993) (unless otherwise stated).
[e] Data for post 1995 obtained from DoE&WO (1995a, 1995b) (unless otherwise stated).
[f] Height of storeys from P. F. Chapman (1994).
[g] Wall construction based on assumptions used in NHER software (NES, 1995).
[h] U-value pre-1966 from BREDEM-8 reference tables.
[i] In Building Regulations, maximum U-value for a single glazed window (pre-1995) is given as 5.7 W/m^{2}K. However, for a single glazed window with a wooden frame, BREDEM-8 uses 4.3 W/m^{2}K. The BREDEM-8 value was selected for use.
[j] No regulations for dwelling window area pre-1982 and thus area assumed to be the same as stipulated in 1982 regulations.
[k] The tightness of windows and doors affects infiltration through the building fabric.
[l] No guidance given in Building Regulations on door construction. Solid wood doors assumed for all age groups as this is likely to be typical. The choice of door is, however, unlikely to have a major impact on energy consumption.
[m] Post 1977 ground floor U-value from Building Regulations. No regulations pre-1977 and so assumed a U-value of 1.5 W/m^{2}K.

3.4.4 Category 4: Heating and cooking systems

The EHCS is produced by the DETR every five years to provide information on the changing condition and composition of the housing stock and the characteristics of the households living in different types of housing. The most recent survey was carried out in 1996 (DETR, 2000a). The 1996 EHCS contains data on the primary and secondary space heating systems, the water heating system and the cooking system commonly in use in dwellings. Although the data relates to national trends it can, in the absence of other data, be usefully applied at a local scale.

The EHCS data is not, however, in a format suitable for use in the dwelling classification system proposed in this thesis. The data was therefore interpreted and simplified where possible. This process is described in detail in Appendix C. The following sections use the results of this interpretation of the EHCS data to show the proposed method of calculating the energy consumed by space heating, water heating and cooking.

3.4.4.1 Space heating

The proportion of primary space heating systems by built form and age are given in Table 11. From Table 11, it can be seen that only three types of primary space heating system are considered: gas boiler, electric storage heater and fixed heating. In the EHCS, gas boiler implies a central heating system with radiators. Fixed heating includes systems which are physically fixed to a wall (connected via a gas point or fused spur) and open fireplaces which are not permanently blocked. It was necessary to propose default specifications for each type of primary system.

It was found that fixed heating can be any one of three systems: mains gas fire, fixed electric heater or solid fuel open fire (Appendix C). Default specifications for these systems are given in Table 12 (see Appendix C for details of how these systems were derived). From the EHCS, it was possible to derive the relative proportion of each type of system making up the fixed heating system (Table 12). This allowed the three types of fixed heating system to be combined into one default system by multiplying the individual efficiencies and responsiveness' by the relative proportions and summing the results (described in Appendix C). By only using one default fixed heating system, the number of BREDEM-8 calculations required to predict space heating energy consumption are reduced. This is an important consideration for the SEP system to ensure calculation times are not excessively long. Furthermore, it can be seen from Table 11 that the proportion of fixed heating is small in comparison to gas and electricity and so it was considered unlikely that this simplification would introduce significant errors into the calculation of primary space heating energy use. The specification for the default fixed heating system is shown in Table 13. Table 13 also gives the specifications for the default gas boiler and default electric storage heater.

Table 11. Primary space heating system by built form and age.

Built form and age	**Gas boiler (%)**	**Electric storage heater (%)**	**Fixed heating (%)**
Detached house: pre-1919	84	9	7
Detached house: post 1919	90	10	0
Semi-detached and terraced houses: pre-1919	69	7	24
Semi-detached and terraced houses: 1919-1944	76	8	16
Semi-detached and terraced houses: 1945-1964	77	9	14
Semi-detached and terraced houses: post 1965	85	9	6
Bungalow: all ages	85	9	6

Table 12. Default specifications of different fixed heating systems.

Type of fixed heating system	**Efficiency (%)**	**Responsiveness**[a]	**Proportion of default fixed heating system (%)**
Mains gas fire	68	1.0	80
Electric heater	100	1.0	12
Solid fuel open fire	43	0.5	8

[a] The responsiveness of a heating system is a measure of how quickly the heat output drops when heating is no longer required. A responsive system (i.e. responsiveness = 1.0) is one where the heat output falls to zero soon after the end of a heating period (see Appendix A for more details).

Table 13. Specifications of default primary space heating systems.

Default primary space heating system	**Efficiency (%)**	**Responsiveness**	**Controllable fraction**
Gas boiler	70	1.0	N/A
Electric storage heater	100	N/A	0.2
Fixed heating	70	0.96	N/A

It was necessary to specify control systems for each of the primary space heating systems listed in Table 13. With no guidance available from the EHCS, standard control systems were selected from reference tables in the BREDEM-8 model description. To simplify the dwelling classification, control systems were chosen which had no effect on either the primary space heating efficiency or the zone 1 demand temperature. The control systems are given in Table 14. The level of independent temperature control in zone 2 is also affected by the control system as shown in Table 14.

Table 14. Specifications of default control systems.

Default primary space heating system	**Type of control**	**Change in space heating efficiency**	**Change in zone 1 demand temperature**	**Level of independent temperature control in zone 2**
Gas boiler	Programmer and room thermostat	0	0	No control
Electric storage heater	Automatic charge control[a]	0	0	Full control
Fixed heating	Appliance or room thermostat	0	0	Full control

[a] Automatic charge control ensures the heater receives the correct charge in relation to ambient temperatures during the charge period. Manual charge control is probably more common in practice but automatic was selected to ensure the electric storage heater control system had similar properties to the control systems of the other primary space heating systems.

The type of secondary space heating system by primary space heating system is given in Table 15. From Table 15, it can be seen that there is only a secondary heating system if the primary system is a gas boiler or electric storage heater. As with the fixed heating system described previously, secondary heating can be provided by one of three systems: mains gas fire, fixed electric heater or solid fuel open fire. As before, these

Table 15. Type of secondary space heating system by primary space heating system.

Built form and age	Fraction of heat from secondary system if main system is gas boiler	Fraction of heat from secondary system if main system is electric storage heater	Default secondary system		Proportion of delivered fuel		
			Efficiency (%)	Responsiveness	Gas (%)	Electric (%)	Solid fuel (%)
All dwellings	0.10	0.11	69	0.93	70	15	15

were combined to generate one default secondary system. This reduces the number of BREDEM-8 calculations required. Although there is only one default secondary system, the fraction of heat that it supplies is dependent on the type of primary space heating system (Table 15). The relative proportions of the delivered fuels, representing the individual systems making up the default secondary heating system, are also shown in Table 15. These proportions allow CO_2 emissions to be estimated.

With the default primary and secondary space heating systems now defined, it is possible to show how this information is used in the BREDEM-8 implementation in the SEP system to calculate space heating energy use. Three separate calculations are carried out using the space heating calculation procedure in BREDEM-8. These are described in Table 16.

Table 16. Characteristics of space heating calculations carried out using BREDEM-8.

	Primary space heating system (Table 13)	**Secondary space heating system (Table 15)**	**Results generated**
Calculation 1	Default gas boiler	Default secondary system	Primary energy use 1 Secondary energy use 1
Calculation 2	Default electric storage heater	Default secondary system	Primary energy use 2 Secondary energy use 2
Calculation 3	Default fixed heating	No secondary system	Primary energy use 3

The advantage of defining just one fixed heating system can be seen from Table 16. If the fixed heating system had been left as three individual systems, a further two calculations would be required thus increasing calculation time. Similarly, the advantage of defining just one secondary space heating system becomes clear. For every additional secondary system, two more calculations would have been required i.e. one extra for both default gas boiler as the primary system and default electric storage heater as the primary system. This would have greatly increased the calculation time.

The default primary energy use can now be calculated using Equation 3.1.

$$\text{Default primary energy use} = \text{Gas boiler primary} + \text{Electric storage primary} + \text{Fixed primary} \quad (3.1)$$

where

$$\text{Gas boiler primary} = \text{Proportion of primary as gas boiler (Table 11)} \times \text{Primary energy use 1 (Table 16)} \quad (3.2)$$

$$\text{Electric storage primary} = \text{Proportion of primary as electric storage (Table 11)} \times \text{Primary energy use 2 (Table 16)} \quad (3.3)$$

$$\text{Fixed primary} = \text{Proportion of primary as fixed heating (Table 11)} \times \text{Primary energy use 3 (Table 16)} \quad (3.4)$$

The default primary energy use can then be broken down into the energy delivered by different fuels.

$$\text{Delivered gas} = \text{Gas boiler primary} + (\text{Proportion of fixed as mains gas fire (Table 12)} \times \text{Fixed primary}) \quad (3.5)$$

$$\text{Delivered electric} = \text{Electric storage primary} + (\text{Proportion of fixed as electric heater (Table 12)} \times \text{Fixed primary}) \quad (3.6)$$

$$\text{Delivered solid fuel} = \text{Proportion of fixed as solid fuel open fire (Table 12)} \times \text{Fixed primary} \quad (3.7)$$

Equations 3.5, 3.6 and 3.7 allow the CO_2 emissions associated with the primary space heating system to be estimated by multiplying the delivered energy use with the relevant CO_2 emission factor. These CO_2 emission factors are given in Table 17 and have been taken from the SAP.

Table 17. CO_2 emission factors for delivered energy. (Redrawn from DETR, 1998b.)

Fuel type	**CO_2 emission factor (kg CO_2 per GJ)**
Gas (mains)	54
Smokeless solid fuel	109
Electricity[a]	142

[a]The CO_2 emission factor for electricity is liable to vary over time as a result of changes in the national generation mix.

Secondary energy use 1 and secondary energy use 2 (Table 16) relate to the same secondary heating system (Table 15). To calculate the default secondary energy use, the relative proportion of the two secondary energy uses must be determined. This is the same as the relative proportions of the 'primary systems with an associated secondary system' i.e. the default gas boiler and default electric storage heater primary systems. This was calculated in Appendix C (Table C-4) during the construction of Table 11. It was found that 90% of all 'primary systems with an associated secondary system' have a gas boiler primary system and the remaining 10% have an electric storage heater primary system. This allows default secondary energy use to be calculated using Equation 3.8.

Default secondary energy use = 90% of secondary energy use 1 + 10% of secondary energy use 2 (3.8)

The default secondary energy use can be broken down into the energy delivered by different fuels.

Delivered gas = Default secondary energy use × Proportion of gas as secondary (Table 15) (3.9)

Delivered electric = Default secondary energy use × Proportion of electric as secondary (Table 15) (3.10)

Delivered solid fuel = Default secondary energy use × Proportion of solid fuel as secondary (Table 15) (3.11)

Equations 3.9, 3.10 and 3.11 allow the CO_2 emissions associated with the secondary space heating system to be estimated using the emission factors in Table 17.

3.4.4.2 Water heating

The type of default water heating system by built form and age is given in Table 18. As before, the EHCS data was simplified to a single water heating system for each dwelling type to reduce the number of BREDEM-8 calculations required. The default hot water energy use is calculated by BREDEM-8 using the efficiencies given in Table 18. This can be broken down into the energy delivered by different fuels.

Delivered gas = Default hot water energy use × Proportion of water heating by gas (Table 18) (3.12)

Delivered electricity = Default hot water energy use
× Proportion of water heating by electricity (Table 18) (3.13)

Once again, CO_2 emissions can then be estimated using the emission factors in Table 17.

Table 18. Type of water heating system by built form and age.

Built form and age	**Efficiency of water heater (%)**	**Proportion of electricity used (%)**	**Proportion of gas used (%)**
Detached house: pre-1919	79	35	65
Detached house: post 1919	80	36	64
Semi-detached and terraced houses: pre-1919	77	29	71
Semi-detached and terraced houses: 1919-1944	78	31	69
Semi-detached and terraced houses: 1945-1964	80	36	64
Semi-detached and terraced houses: post 1965	80	37	63
Bungalows	81	40	60

3.4.4.3 Cooking

At the time of developing the dwelling classification system, data was not available from the 1996 EHCS on the type of cooking system. Data from the 1991 EHCS (Department of the Environment [DoE], 1993) was used instead. The type of cooking system by built form is shown in Table 19.

Table 19. Type of cooking system by built form.

Built form	**Gas cooker (%)**	**Electric cooker (%)**	**Dual fuel cooker (%)**
Detached	31	44	25
Semi-detached	50	38	12
End terrace	54	36	10
Mid terrace	62	30	8
Bungalow	40	41	19

In the BREDEM-8 model description, formulas are presented for calculating cooking fuel use and cooking gains. These are given in Table 20. From the formulas given in Table 20, general formulas were derived to allow a default cooking system to be specified for every built form.

$$\text{Gas cooking fuel used} = A\,[2.98 + 0.6\,N] + B\,[1.49 + 0.3\,N] \qquad (3.13)$$

$$\text{Electric cooking fuel used} = C\,[1.70 + 0.34\,N] + B\,[0.85 + 0.17\,N] \qquad (3.14)$$

$$\text{Cooking gains} = C\,[48.5 + 9.7\,N] + A\,[70.9 + 14.3\,N] + B\,[59.7 + 12.0\,N] \qquad (3.15)$$

where A is the fraction of gas cookers from Table 19, B is the fraction of dual fuel cookers from Table 19 and C is the fraction of electric cookers from Table 19.

From these energy use figures it is, of course, possible to estimate CO_2 emissions.

Table 20. Cooking fuel use and associated gains. (Adapted from Anderson et al., 1997.)

Cooking system	**Cooking fuel used (GJ/year)**	**Cooking gains (W)**
Gas cooker	$2.98 + 0.60\,N^a$	$70.9 + 14.3\,N$
Electric cooker	$1.70 + 0.34\,N$	$48.5 + 9.7\,N$
Gas hob and electric oven	$1.49 + 0.30\,N$ (gas) $0.85 + 0.17\,N$ (electricity)	$59.7 + 12.0\,N$

[a] N is the number of occupants.

3.4.5 Category 5: BREDEM-8 standard occupancy defaults

The occupants of a dwelling determine the heating regime, the demand temperatures and the heating patterns. In addition, the use of hot water, cooking, lights and appliances and the contribution made by metabolic gains depends on the number of occupants. When the number and behaviour of occupants is unknown, the BREDEM-8 model description defaults to a standard occupancy. This standard occupancy was assumed in the dwelling classification system proposed in this thesis. The standard number of occupants, N, is estimated using Equation 3.16.

$$N = 0.0365\ \text{TFA} - 0.00004145\ \text{TFA}^2 \qquad \text{for TFA} \leq 450\text{m}^2$$

$$N = \frac{9}{\left(1 + \frac{54.3}{\text{TFA}}\right)} \qquad \text{for TFA} > 450\text{m}^2 \qquad (3.16)$$

where TFA is the total floor area of the dwelling (m^2).

The remaining defaults based on standard occupancy are given in Table 21.

Table 21. BREDEM-8 standard occupancy defaults.

BREDEM-8 input parameter	**Standard default**
Number of occupants	Calculated using Equation 3.16
Zone 1 demand temperature	21°C
Desired temperature difference between zones 1 and 2	3°C
Heating periods for zone 1	Weekday: 07.00 to 09.00 and 16.00 to 23.00 Weekend: 07.00 to 23.00
Heating periods for zone 2	Weekday: 07.00 to 09.00 and 16.00 to 23.00 Weekend: 07.00 to 23.00
Level of usage of hot water	Average
Level of usage of lights and appliances	Average
Level of usage of cooking	Average

3.4.6 Category 6: Assumed defaults

There are a small number of BREDEM-8 input parameters for which default values cannot be derived from knowledge of the regional location, built form or age or given a standard default. It has been necessary to assume default values for these parameters as shown in Table 22.

Table 22. Assumed default values.

BREDEM-8 input parameter	**Assumed default value**
Location of hot water tank	Zone 2
Location of kitchen	Zone 2
Site exposure factor	Average
Level of overshading of zone 1	Average
Level of overshading of zone 2	Average
Draught lobby on main door	No
Volume of hot water tank	110 litres
Mechanical ventilation with heat recovery	No mechanical ventilation present
Number of low energy light bulbs	0
Number and type of pumps	1
Number and type of vents, chimneys and flues	1 unbalanced flue
Type of ground floor	Sealed suspended timber floor
Fraction of zone 2 that is heated	All (i.e. fully heated)

The hot water tank and kitchen were both assumed to be located in zone 2 and the site exposure factor and level of overshading of zones 1 and 2 were given average values as defined in BREDEM-8. This corresponds to the situation for a typical dwelling. It seemed reasonable to assume no draught lobby, no mechanical ventilation system and no low energy light bulbs as these are unlikely to be present in most dwellings. The volume of the hot water tank was set to 110 litres after examining Level 3 data obtained from LCC for a number of dwellings. (This data is used in detail in Chapter 7.) One central heating pump was assumed as a gas boiler central heating system is the most common primary space heating system (Table 11). Due to the way in which the default space heating systems were defined (Section 3.4.4.1), the number of vents, chimneys and flues were difficult parameters to set defaults for as there were a number of possible variations. It was decided to select a default which would not introduce significant errors to the prediction of dwelling energy consumption. One unbalanced flue was selected as this has the average air infiltration rate of the three components. Similarly, the type of ground floor was assumed to be a sealed suspended timber floor as this represents the average air infiltration rate of the different floor types in BREDEM-8. Finally, it was decided to assume that all of zone 2 is heated as most dwellings have central heating systems and it was assumed that the majority of householders would heat their whole dwelling. Furthermore, in an ideal world, all householders would heat their entire dwelling to ensure high levels of comfort and to reduce health risks. Those householders who cannot afford to heat their entire dwelling are considered to be fuel poor and this is a problem which the UK Government is attempting to overcome (e.g. Gilroy, 2000; Association for the Conservation of Energy [ACE], 2000).

3.4.7 Predicting energy consumption

All the input data required by BREDEM-8 has had a default value assigned to it in the preceding sections (summarised in Table 4). To use these defaults it is necessary to know a minimum amount of information about the dwelling:

- regional location;
- age;
- built form;
- ground floor area (derived from digital urban map);
- exposed perimeter (derived from digital urban map);
- orientation (derived from digital urban map).

With this minimum data, BREDEM-8 can predict the baseline energy consumption of a dwelling. This baseline energy consumption corresponds to the minimum requirements of a sub-level 0 data set i.e. knowledge of the built form and age (Table 1). At this level of calculation, it is possible to provide results which are useful for fulfilling HECA requirements.

Clearly, the accuracy of the predictions from BREDEM-8 will be improved if it is fed with more reliable input data. The following section describes methods of collecting the input data.

3.5 Collecting the data

The input data required by BREDEM-8 can be obtained in three main ways. These methods collect varying amounts of data ranging from only a few parameters to a full data set. The implementation of BREDEM-8 in the SEP system was designed to be flexible to enable operation at these various levels of input data. The data collection methods are described in the following sections. Their relative strengths and weaknesses are discussed in Section 7.4 where these data collection methods were applied to a case study area.

3.5.1 Rapid site survey

Various techniques exist for collecting and recording data from rapid site surveys (e.g. WSA, 1996; Krause, 2000). These include photographing and video recording properties, audio tape recording a verbal description of the property and writing notes. For the method proposed in this thesis, it was decided to opt for a paper-based rapid site survey similar to that described by Krause (2000). This makes use of a standard survey form developed specifically for the project. One of the main advantages of using a standard form is that, with brief instructions, different people should be able to perform the site surveys to the same level of consistency i.e. there should be little variability in the quality of collected data. In future, there could be scope to complete the form on a palm-top computer which would enable data to be downloaded directly into the underlying property database of the SEP system.

Having considered all the input data required by BREDEM-8, it was possible to identify parameters which could be collected from a rapid site survey. These are given in Table 4 but for convenience, they are listed separately in Table 23.

Although sixteen BREDEM-8 input parameters can be collected from the rapid site survey (representing approximately one-fifth of the total data required), there is still not sufficient data to allow a full Level 0 calculation to be performed. However, the site survey does collect the number of storeys and the type of window glazing (allowing window U-value to be estimated). Both of these are important parameters and they are included in the Level 0 data set (Table 1). In addition, the site survey determines the wall construction (i.e. solid or cavity). This is a useful parameter to know as it affects the ability of a dwelling to make use of wall insulation. The remaining items are thought to be of less significance although overall, the rapid site survey should improve upon the accuracy of the baseline prediction of energy consumption.

Table 23. BREDEM-8 input data available from a rapid site survey (see Appendix D for details of how to determine these parameters).

BREDEM-8 input parameter
1. Type of dwelling
2. Age of dwelling
3. Number of storeys
4. Type of wall construction
5. Type of window frame
6. Type of window glazing
7. Window U-value (estimated from frame and glazing type)
8. Tightness of windows
9. Type of door
10. Door U-value (estimated from door type)
11. Tightness of doors
12. Draught lobby on main door
13. Dwelling exposure
14. Site exposure factor
15. Level of overshading – zone 1
16. Level of overshading – zone 2

In the EEP model (Section 2.2.3), an important part of the site survey was to count bricks to obtain estimates of parameters such as storey height and glazed area on the front façade. A similar approach was considered for the rapid site survey proposed in this thesis but it soon became clear that it was not appropriate. For example, the element areas (e.g. window and external wall area) required by BREDEM-8 must be obtained separately for zone 1 and zone 2. The definition of these zones cannot be reliably obtained from a rapid site survey. Furthermore if it is only possible to observe the front façade, assumptions will be required to estimate the other façade areas.

Collecting dimensional data also increases the time required to perform a survey. As its name suggests, a rapid site survey aims to record data which can be collected quickly and easily. It was thought that the extra time required to collect approximate dimensional data could not be justified as it was unlikely to greatly improve the accuracy of the default assumptions. Therefore, it was decided not to include a procedure for collecting dimensions in the rapid site survey proposed in this study. This decision could be reconsidered at a later date if the default method of calculating areas appears to be producing extremely inaccurate results.

In the rapid site survey proposed as part of this project, the data listed in Table 23 is collected from observing the front (i.e. street-facing) façade of a dwelling. For the majority of dwellings, it is necessary to assume that the rear façade has the same characteristics (i.e. same type of windows, doors and level of overshading) as there is unlikely to be access to the rear of the property. This assumption should not introduce significant errors into the data set. Of course, where the rear façade can be accessed the actual data can be recorded. For some dwelling types, especially long rows of terraced houses, it may be possible to see a small number of rear façades. If this is the case, the characteristics can be usefully applied to similar dwellings where the rear is inaccessible. The rapid site survey form is given in Appendix D along with instructions on how to complete the form. During the rapid site survey, a digital photograph can also be taken of any property. (For the research in this thesis (Chapter 7), many dwellings were photographed.)

In addition to collecting some of the input data required by BREDEM-8, the rapid site survey is also used to collect data describing the roof. This includes roof inclination and possible shading problems. This information is required by both the solar water heating and photovoltaic models as discussed in Chapters 4 and 5.

The rapid site survey can also detect other features including room in the roof conversions and garages integral and adjacent to dwellings. The dwelling classification system described previously does not make allowances for these features. Currently, a room in the roof is assumed to be another storey with the same floor plan as the ground floor. This assumption needs to be refined as real data becomes available. It is also important to identify dwellings with a room in the roof as this could have implications for installing active solar systems on the roof. Unheated spaces such as garages provide shelter to dwelling elements, effectively reducing their U-values. In the BREDEM-8 implementation in the SEP system, only one U-value can be entered per dwelling element (i.e. wall, roof, and floor). Future revisions of the system should allow more than one U-value to be entered for each element to allow the effect of garages and other unheated spaces to be calculated.

3.5.2 Home Energy Survey Form

Home Energy Survey Forms (National Energy Foundation [NEF], no date) are distributed to householders by the 52 Energy Efficiency Advice Centres (EEACs) located throughout the UK. These forms contain a number of simple questions designed to obtain more information about a dwelling. The complete form is shown in Appendix E. The Home Energy Survey Form collects information which is required by BREDEM-8. This is shown in Table 4 and listed separately in Table 24.

Table 24. BREDEM-8 input data available from a Home Energy Survey Form.

BREDEM-8 input parameter
1. Type of dwelling
2. Age of dwelling
3. Number of storeys
4. Type of wall construction
5. Wall U-value (form asks for type and thickness of wall insulation)
6. Roof U-value (form asks for thickness of loft insulation)
7. Ground floor U-value (form asks for thickness of floor insulation)
8. Type of window glazing
9. Window U-value
10. Draught stripping on windows
11. Draught stripping on doors
12. Type of primary space heating system
13. Control of primary space heating system
14. Type of hot water system
15. Type of hot water tank insulation
16. Thickness of hot water tank insulation
17. Insulation of primary pipework
18. Presence of hot water cylinder thermostat
19. Number of low energy light bulbs

The Home Energy Survey Form collects a similar number of input parameters to the rapid site survey. In fact, by comparing Tables 23 and 24 it can be seen that the two methods collect some of the same parameters. However, the data obtained from the Home Energy Survey Form permits a Level 0 calculation to be carried out as information is now known about the level of insulation in the wall, floor and roof and about the space and water heating systems.

In the standard Level 0 data set (Table 1), the number of rooms is given as an essential data item. This is used in conjunction with the dwelling age, built form and number of storeys to obtain geometrical areas i.e. total floor area, ground floor area, roof area, wall area and window area (P. F. Chapman, 1994). The dwelling classification system proposed in this thesis calculates these areas using map derived data and standard dwelling configurations (Section 3.4.2). Although the Home Energy Survey Form collects the number of rooms (Appendix E), it is not required by BREDEM-8.

3.5.3 Full property survey

The method which would obtain all the inputs required by BREDEM-8 is a full property survey. Such a survey has been developed as part of the NHER scheme (NES, 1995). The survey collects all dwelling details (including dimensions) and also involves interviewing the householder to obtain actual occupancy data. A full survey permits a BREDEM-8 calculation at Level 3 (Table 1). It also allows a Level 2 calculation to be performed using standard occupancy details in place of the actual occupancy data. Full property surveys take a trained surveyor about thirty minutes to perform (NES, 1999).

3.6 Testing the BREDEM-8 implementation

Tests were required to show that the new implementation of BREDEM-8 embedded in the SEP system was producing results which were identical to those obtained from manual calculations using the equations given in the BREDEM-8 document (Anderson et al., 1997). This would demonstrate that the computer code was a faithful interpretation of the algebraic formulation. The ability of BREDEM-8 to accurately predict the energy consumption of real dwellings was not of primary concern. As described in Section 3.2, validation exercises aimed at proving the absolute accuracy of BREDEM-8 in relation to dynamic simulation models and real dwellings have been performed by others e.g. Dickson et al, 1996. To test the correctness of the BREDEM-8 implementation in the SEP system, two comparisons were carried out. These are described in the following sections.

3.6.1 Comparison with a manual calculation

The BREDEM-8 implementation was compared against the results obtained from a manual calculation. The manual calculation was performed for a detached dwelling of one-storey. The dwelling was assumed to have been constructed to the Building Regulations for the period of 1982 to 1990 (Table 10). Standard occupancy defaults were also assumed (Table 21). The key characteristics of the dwelling are given in Table 25.

Table 25. Key characteristics of the dwelling for which a manual calculation was performed.

Dwelling characteristic	**BREDEM-8 input parameter**
Location	Midland
Year constructed	Between 1982 and 1990
Zone 1 ground floor area	20m^2
Zone 2 ground floor area	79m^2
Type of primary space heating system	Boiler system with radiators
Type of boiler	Gas boiler, fan assisted flue, low thermal capacity (Efficiency = 72%)
Type of secondary space heating system	Modern gas fire, glass enclosed front (Efficiency = 60%)
Type of water heating system	From central heating system
Cooking fuel	Gas
Occupancy	Standard occupancy defaults

The manual calculation took approximately three days to perform and ran to over fifty sides of A4 paper. The majority of the time was spent performing the space heating calculation which includes procedures for calculating the solar gain through all windows, the usefulness of the total gains, the background temperature and the mean internal temperature during each non-heating period. These calculations had to be performed for both zone 1 and zone 2 and they had to be carried out twelve times i.e. one calculation for each month of the year. This shows the impracticability of using BREDEM-8 as a manual method. Furthermore, in such a long and involved manual calculation there is obviously considerable scope for error. Consequently, only one manual calculation was performed.

The energy consumption predictions obtained from the manual calculation are shown in Table 26. The predictions are broken down by both application and month. It can be seen from Table 26 that as expected, space heating consumes the most energy. Space heating energy consumption also varies considerably throughout the year with no demand during summer. The results for water heating, cooking, lights and appliances are relatively constant because BREDEM-8 assumes demand to be uniform throughout the year.

Table 26. Energy consumption predictions obtained from the manual calculation.

Month	**Total energy use (GJ)**	**Primary space heating (GJ)**	**Secondary space heating (GJ)**	**Water heating (GJ)**	**Lights and appliances (GJ)**	**Cooking (GJ)**
January	12.854	8.479	1.796	1.379	0.784	0.417
February	10.918	7.087	1.501	1.246	0.708	0.376
March	9.499	5.710	1.209	1.379	0.784	0.417
April	6.681	3.454	0.731	1.335	0.758	0.403
May	4.390	1.494	0.316	1.379	0.784	0.417
June	2.496	0	0	1.335	0.758	0.403
July	2.579	0	0	1.379	0.784	0.417
August	2.579	0	0	1.379	0.784	0.417
September	2.977	0.397	0.084	1.335	0.758	0.403
October	5.642	2.527	0.535	1.379	0.784	0.417
November	9.442	5.732	1.214	1.335	0.758	0.403
December	11.894	7.686	1.628	1.379	0.784	0.417
Annual	81.950	42.566	9.014	16.239	9.228	4.907

The results from the computer implementation were compared with those from the manual calculation. Initially, agreement was not good. As a result, the results obtained from the computer implementation for every BREDEM-8 equation were checked with those from the manual calculation. It should be noted that at each stage of the manual calculation, results were calculated to eight significant figures to ensure rounding errors were not introduced into the results. This ensured consistency with the computer implementation. Using this rigorous approach, all errors in the computer code were detected and subsequently corrected until the results from the manual and computer calculations were identical.

Clearly, the test described above showed that the BREDEM-8 implementation was producing the correct results for only one specific case. Further sensitivity tests were carried out to observe if changes in some of the most important input parameters produced the expected effect. Changes were made to the U-values of the building fabric, the efficiency of the primary space heating system (and hence the hot water system), the zone demand temperatures and the heating regimes. In all cases, the modifications produced the anticipated result. For example, using a more efficient gas condensing boiler reduced the total energy consumption by reducing space and water heating requirements. Increasing the zone demand temperatures by 2°C increased the overall energy consumption and specifically the space heating requirement. The tests showed that, for at least one dwelling, the new implementation of BREDEM-8 in the SEP system was faithfully reproducing the results obtained from the algebraic description given in Anderson et al. (1997).

3.6.2 Inter-model comparison with NHER Evaluator

NHER Evaluator (Section 2.2.5) is widely used by local authorities to produce energy ratings for dwellings in their region. It is based on BREDEM-12. As described in Section 3.2, BREDEM-12 predicts dwelling total energy consumption on an annual basis whereas BREDEM-8 predicts monthly results. It was still considered useful, however, to compare the results from the two models as they should produce broadly similar estimates of annual total energy consumption (Dickson et al., 1996).

The annual total energy consumption figures predicted by NHER Evaluator (Version 3.10) for ten different dwellings were obtained from Mr. R. Holmes of the Leicestershire Energy Efficiency Advice Centre (LEEAC) (written communication, November 9, 2000). These are shown in Table 27. It can be seen from Table 27 that results were provided for a range of built forms. The results were accompanied by the data input into NHER Evaluator which was collected by LEEAC employees during full

Table 27. Comparison of predictions between the BREDEM-8 implementation in the SEP system and NHER Evaluator (Version 3.10).

Address	**Built form**[a]	**Age**	**Number of storeys**	**Annual energy consumption (GJ)**		**Difference BREDEM-8 - NHER Evaluator**	
				NHER Evaluator	**BREDEM-8**	**GJ**	**%**
70 Cranmer Street	MT	Pre-1900	2	60.5	57.9	- 2.6	- 4.3
50 Latimer Street	MT	Pre-1900	2	49.3	51.8	+ 2.5	+ 5.1
29 Westleigh Drive	MT	Pre-1900	3	263.5	252.2	- 11.3	- 4.3
14 Cranmer Street	MTUP	Pre-1900	2	92.2	100.2	+ 8	+ 8.7
40 Tyndale Street	MTUP	Pre-1900	2	109.7	117.7	+ 8	+ 7.3
49 Ridley Street	ET	Pre-1900	2	115.1	129.3	+ 14.2	+ 12.3
224 Fosse Road South	SD	Pre-1900	2	175.9	180.9	+ 5	+ 2.8
12 Westcotes Drive	SD	Pre-1900	3	313.3	354.2	+ 40.9	+ 13.1
19 Westleigh Avenue	D	Pre-1900	2	238.5	240.7	+ 2.2	+ 0.9
17 Westcotes Drive	D	Pre-1900	3	507.2	527.8	+ 20.6	+ 4.1
Average values considering all ten dwellings				192.5	201.3	+ 8.8	+ 4.5

[a] Abbreviations for built form: MT = mid terrace; MTUP = mid terrace with unheated connecting passageway; ET = end terrace; SD = semi-detached; D = detached.

property surveys. This data included the element U-values, type of primary and secondary space heating systems, type of water heating system and actual occupancy information (i.e. heating regimes and demand temperatures).

The data obtained from LEEAC was manually entered into BREDEM-8. The predictions of total energy consumption obtained from BREDEM-8 are compared with those from NHER Evaluator in Table 27. It can be seen from Table 27 that for all ten dwellings, the results from the two models were within 15%. The average agreement for the ten dwellings was + 4.5%. BREDEM-8 produced higher predictions of energy consumption than NHER Evaluator for eight of the ten cases. These observations compare favourably with those of Dickson et al. (1996) who showed that predictions from BREDEM-8 and BREDEM-12 tend to be within 10% and BREDEM-8 tends to produce higher estimates of energy consumption.

One reason for the differences between the predictions could be that for all ten dwellings, the BREDEM-8 calculation used standard values given in the model documentation to determine the fraction of space heating provided by the secondary space heating system. These values were the same for both zones. In NHER Evaluator, the fraction of space heating provided by the secondary system was entered separately for each zone based on information obtained from the full property survey. This parameter affects the calculation of background temperature. As described in Section 3.3.4 and Appendix A, the background temperature influences the mean internal temperature and hence the space heating requirement. This was not investigated further as the BREDEM-8 documentation suggests using the standard values and the BREDEM-8 implementation in the SEP system was intended to faithfully replicate the procedure described in the document.

Based on these results, it was concluded that the BREDEM-8 implementation in the SEP system is producing broadly similar results to the BREDEM-12 implementation in NHER Evaluator (Version 3.10). Although these comparisons do not test the correctness of every individual equation, they build further confidence in the overall predictions obtained from BREDEM-8.

3.7 Summary

This chapter initially explained the need to predict the existing energy consumption of dwellings before the effect of solar energy technologies can be considered. After evaluating different models, BREDEM-8 was implemented as the domestic energy model in the SEP system. BREDEM-8 is used to predict the baseline energy consumption of a dwelling using defaults derived as part of a new dwelling classification system. These defaults were inferred from traceable sources and make use of data obtained from the digital urban map in the GIS. Once the baseline energy consumption has been established, it is possible to improve the accuracy of the prediction by collecting data using rapid site surveys, household questionnaires and full property surveys. This illustrates that the BREDEM-8 implementation can be performed at various levels of input data and the uncertainties associated with the defaults proposed in the dwelling classification system can be minimised. Detailed comparison with a manual calculation showed that the new BREDEM-8 implementation was a faithful interpretation of the algebraic formulation given by Anderson et al. (1997).

Now that the existing energy consumption (and hence the associated CO_2 emissions) of a dwelling can be predicted, methods can be considered for reducing the reliance on fossil fuels to meet this demand. Chapter 4 describes a new approach for predicting the potential yield of domestic solar water heating systems.

Chapter 4

Active Solar Technologies I: Solar Domestic Hot Water

4.1 Introduction

Solar domestic hot water (DHW) systems can significantly reduce the conventional fuel required to provide hot water for a dwelling. In addition, they reduce CO_2 emissions. Consequently, solar DHW systems have the potential to help local authorities meet LA21 targets. This chapter briefly describes the current position of the solar water heating industry and discusses general design principles of solar DHW systems. A new approach is proposed for the SEP system to predict their potential yield.

4.2 The solar DHW market

Early in the twentieth century, the use of solar water heaters was reasonably common in places such as Florida and California (Duffie & Beckman, 1991). At the start of World War One, many of the basic principles were widely understood and a high level of technical expertise had been achieved. Such systems disappeared, however, when cheap alternative fuel sources such as oil and natural gas became available.

Following the 1973 oil crisis, a number of countries started to promote solar water heating systems as a means of reducing dependence on oil and other imported fuels. Many types of solar system were installed during the late 1970s, not all of them reliable due to 'the wild claims and poor engineering of many cowboy manufacturers' (Allen, 1997, p.11). Consequently, the credibility of the industry suffered. Coupled with the fall in fuel prices in the early 1980s, this resulted in a reduction in the rate of installation of solar heating systems. During recent years, however, concern about the environment has regenerated interest in solar energy and the rate of installation has increased once more (European Solar Industry Federation [ESIF], 1998).

In Europe, for example, the solar thermal industry has reached maturity after twenty years of technical development. High quality products are available, solar systems are reliable and their productivity can be guaranteed. Since 1989, the market has grown at an average annual rate of 18% and all the signs point to further market growth (European Commission, 1996). This market growth is encouraging but it does not hide the fact that by 1997, only 1.4 million households in Europe had installed a solar DHW system. This represents only 1% of the potential market (Allen, 1997). In the UK, there are only approximately 40,000 solar DHW systems installed (Elliott, 2001). The low uptake of solar DHW is primarily explained by economics.

Since domestic hot water requirements do not vary greatly between summer and winter, a system designed to provide most of the summer demand can provide between 30 and 60% of the annual demand. This is equivalent to a saving of around 1500 kilowatt-hours per year for a 'typical' household (Horne, 1995). The value of this saving depends on the type of energy displaced. For example, if electricity is displaced the annual fuel saving is approximately £120 (assuming the cost of a kilowatt-hour of electricity to be 8 pence). If gas is displaced, however, the annual fuel saving is only approximately £30 (assuming the cost of a kilowatt-hour of mains gas to be 2 pence). To have a complete solar DHW system supplied and installed by professional contractors will usually cost between £1500 and £3500, depending on the system (Horne, 1995). Therefore, the simple pay back time is anything from about ten years to over thirty years. This discourages many potential householders from installing a solar DHW system. An alternative approach is to build and install DIY collectors which can be achieved for only about £500. These home-made systems will very probably be less efficient but may have shorter pay back times. The expensive, higher efficiency systems will, however, save more energy and thus have more effect in reducing CO_2 emissions.

In order for solar thermal systems to realise their full potential and become a major sustainable heating technology, strong renewable energy policies need to be implemented at national and EU levels. If policies are developed which actively push solar systems through incentives aimed at increasing market penetration, there is no reason why the current growth in the European solar market cannot be increased from 18% to 25% by the year 2005 (ESIF, 1998).

4.3 Solar DHW systems in use in the United Kingdom

There are two main types of solar DHW system commonly installed in the UK. These are shown in Figures 3 and 4. The design principles of each system are briefly described below.

The main component of a solar DHW system is the solar collector. The two most common types of solar collector used are flat plate collectors and evacuated tube collectors. In a flat plate collector (Figures 5 and 6), the absorber plate absorbs solar radiation incident on the surface and converts it to heat which it transfers to the heat transfer fluid flowing in the fluid passages. The absorber plate may have a special selective coating to improve its performance. The transparent cover above the absorber plate greatly reduces long wave radiation and convection losses from the collector. A second covering layer can further improve the temperatures available. The insulation behind the absorber plate reduces conduction heat loss from the rear and sides of the collector.

Evacuated tube collectors (Figures 7 and 8) consist of a series of evacuated glass tubes, each of which contains an absorbing plate and a tube through which a heat transfer fluid flows. The vacuum reduces heat loss by suppressing convection and conduction in the gas. As a result, evacuated tube collectors are, per unit absorber area, more efficient than flat plate collectors. For example, a 'typical' solar DHW system in the UK requires 4m^2 of flat plate collectors but only 3m^2 of evacuated tubes (European Commission, 1996). The lower efficiencies of flat plate collectors are, however, compensated for by lower cost. This lower cost is one reason why flat plate collectors are more widely used in solar DHW systems. In addition, they produce maximum temperatures of up to about 70°C above ambient making them ideal for use in solar DHW systems. Evacuated tube collectors can generate temperatures in excess of 100°C above ambient making them particularly suited to higher temperature applications.

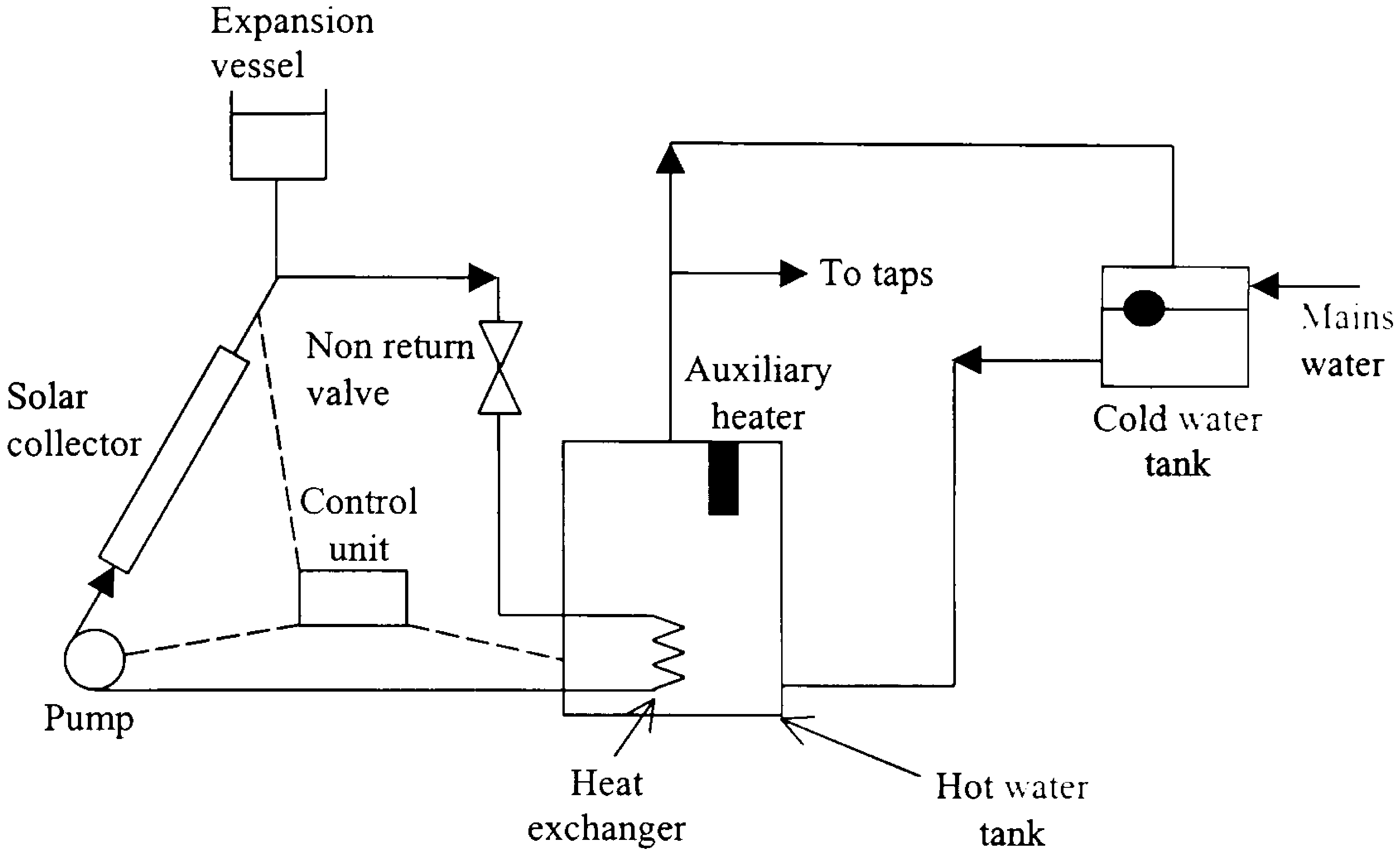


Figure 3. Typical single tank solar DHW system. (Redrawn from DTI, 1996.)

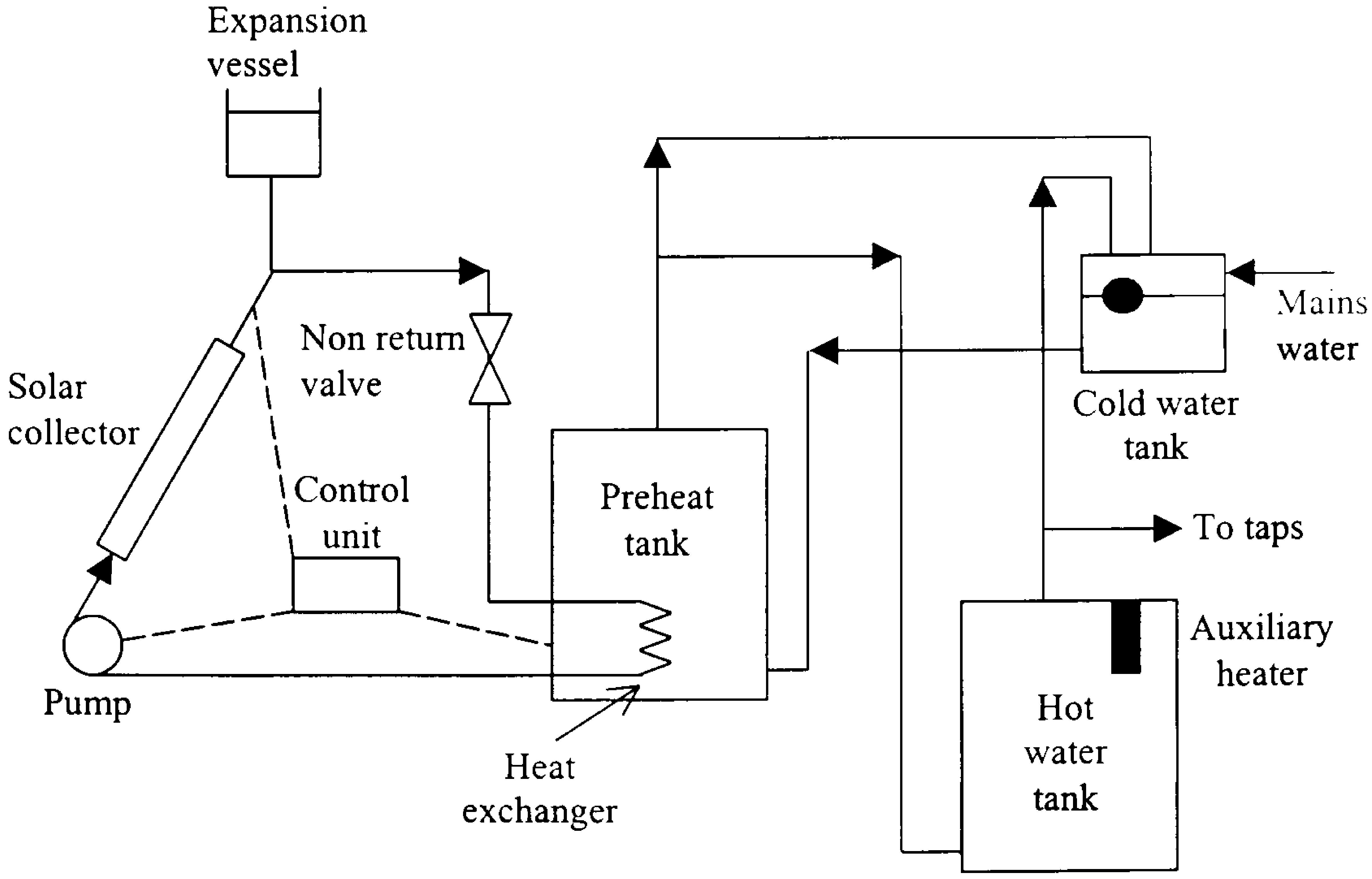


Figure 4. Typical twin tank solar DHW system. (Redrawn from DTI, 1996.)

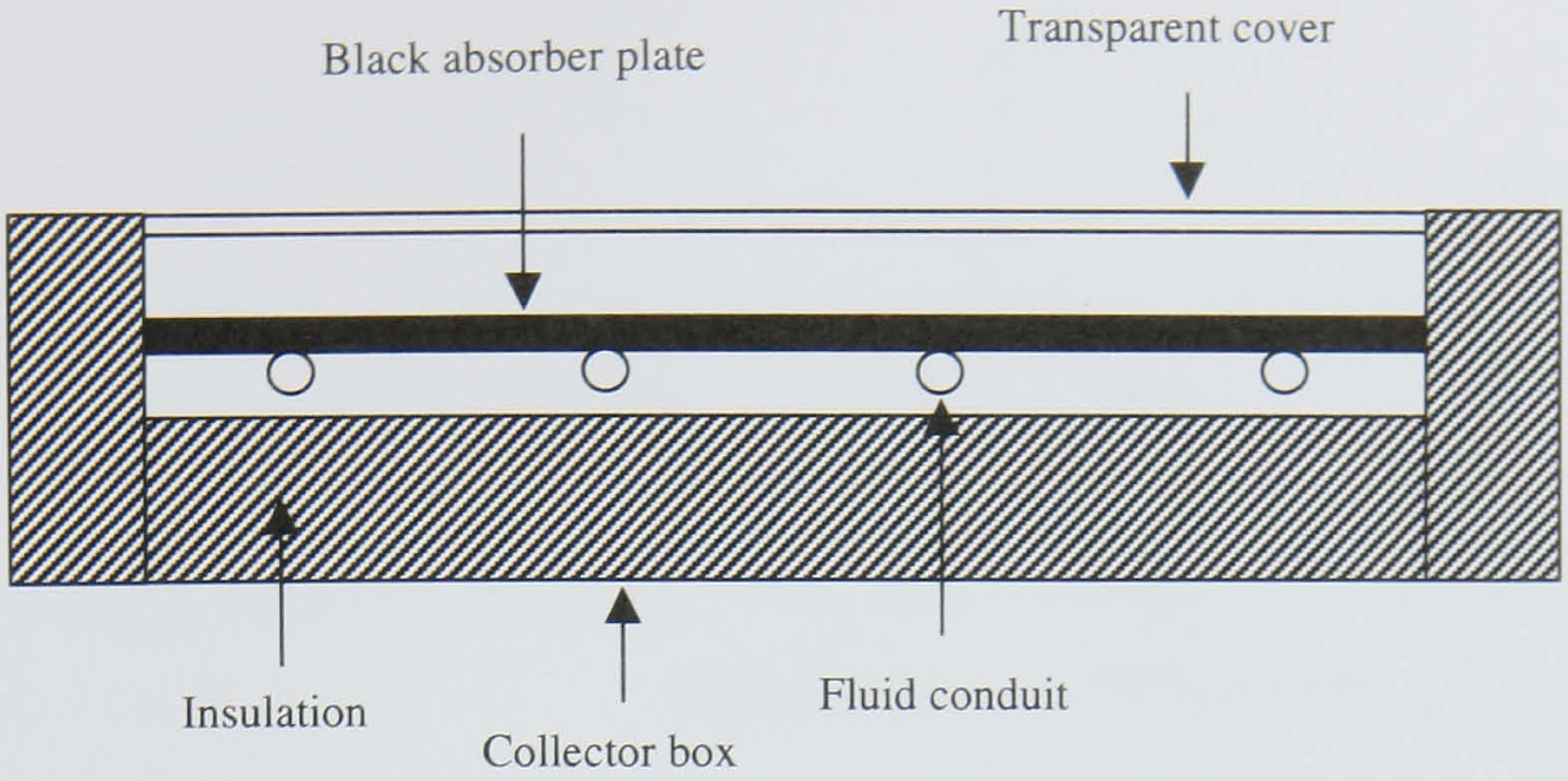


Figure 5. Cross-section of a basic flat plate collector. (Redrawn from Duffie and Beckman, 1991.)

Figure 6. A flat plate solar collector being installed on a house in Melton Mowbray, Leicestershire.

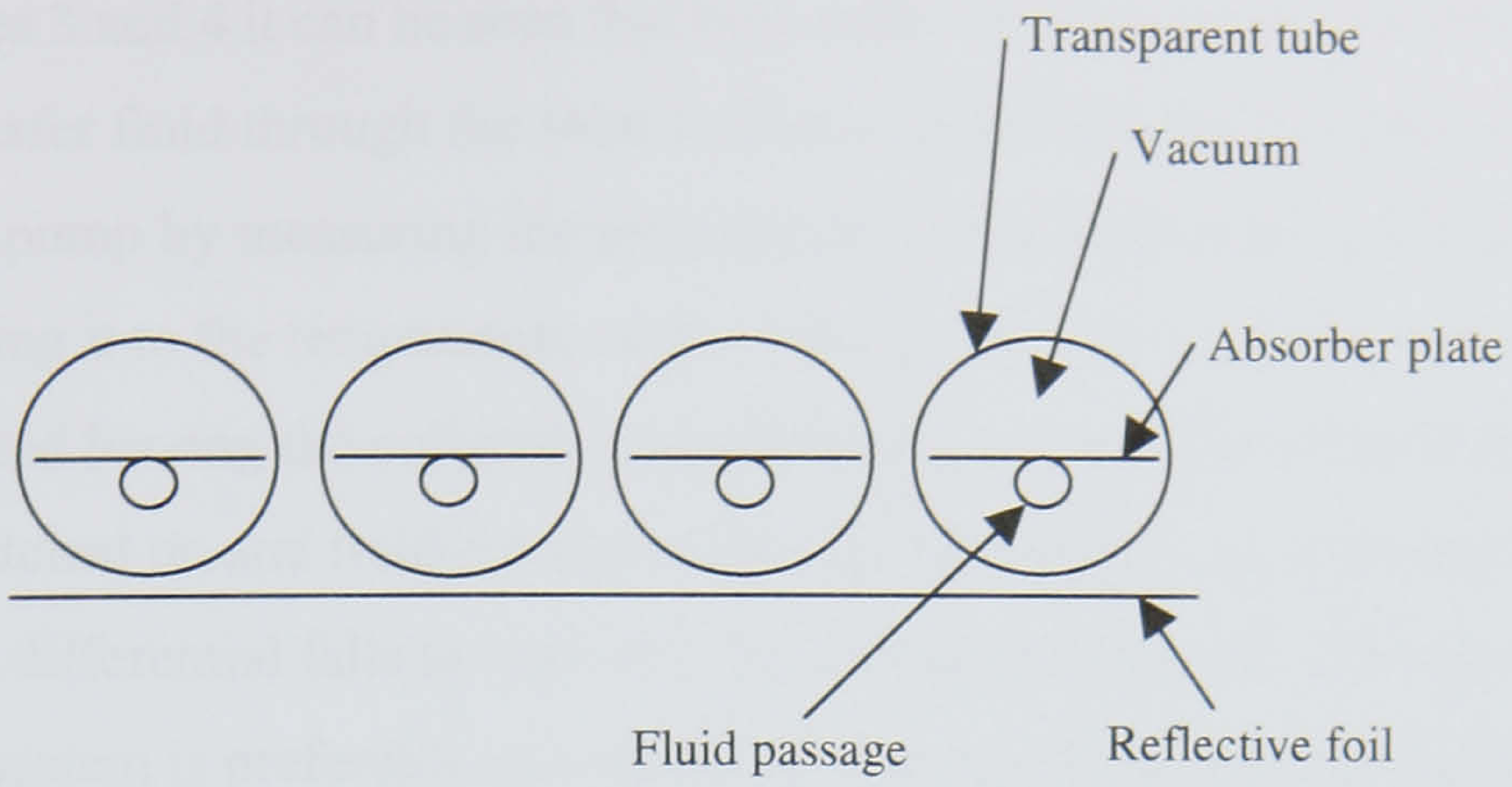


Figure 7. Cross section through an evacuated tube collector. (Redrawn from ESIF, 1998.)

Figure 8. An evacuated tube collector installed on an exhibition centre in Leicester.

From Figures 3 and 4 it can be seen that both solar DHW systems use a pump to drive the heat transfer fluid through the solar collector. A differential thermostat usually controls the pump by measuring the temperature of the fluid leaving the solar collector and comparing it to the temperature of the water in the bottom of the storage tank. When the fluid leaving the collector is significantly warmer than that in the tank, the pump is switched on and fluid circulates through the system. As soon as this temperature differential falls to near zero, the pump switches off. This type of forced circulation system is preferable to a thermosyphon system as there is no restriction on collector positioning. In a thermosyphon system, the storage tank must be located above the collector to ensure the fluid circulates by means of natural convection. This is not possible in most dwellings as roofs are often the best places for collectors making it difficult to locate the storage tank at an even higher level.

In addition, both systems are indirect i.e. the water which is to be delivered for use does not flow directly through the collector. Instead a heat transfer fluid filled with non-toxic antifreeze (usually propylene glycol) and corrosion inhibitor is used. The use of antifreeze is essential in Northern European climates where freezing is a major problem. Heat is transferred to the water in the storage tank by means of a heat exchanger (Figures 3 and 4).

In the UK, where weather conditions are not ideal, solar collectors are only able to preheat the water for much of the year. A conventional DHW system will have to provide the top-up heat. This can be achieved using either one or two storage tanks (Figures 3 and 4). All solar collectors are much better suited to raising fluid temperatures from 20°C to 40°C rather than from 40°C to 60°C (Horne, 1995). By using two tanks, the preheat tank and the conventional hot water tank are kept separate (Figure 4). This ensures that the solar coil preheats cold water entering the preheat tank and thus its efficiency will be relatively high. Disadvantages of a twin-tank system include the long distance from the preheat tank to the taps and the space required for a second hot water cylinder in an existing dwelling. In a typical single tank arrangement (Figure 3), the solar heat exchanger is situated in the bottom of the cylinder below the conventional heater. This ensures the solar coil has the coldest part of the tank to work on. In general, a single tank system is likely to be more efficient on those days when the solar collectors can provide all the hot water needs. At other times, a twin-tank system is likely to perform better.

4.4 Determining the potential yield of solar DHW systems

It is now important to consider how local authority planners and energy advisers could increase the uptake of the solar DHW systems described in the preceding section. Planners essentially require guidance on how to identify suitable properties for installing a solar DHW system. They also need to estimate the potential yield of the installed systems. To meet these requirements, a new three-stage approach (Figure 9) was developed as part of the method described in this thesis. The three different stages enable the approach to operate at various levels of detail thus increasing the flexibility of the SEP system. The stages are described in detail in the following sections.

4.4.1 Stage 1: Filtering

The filtering process focuses on a small subset of parameters in order to determine the viability of dwellings for the installation of solar DHW systems (Figure 9). These characteristics are regarded as key indicators that can be used to filter out the most unpromising candidates. The detailed filtering criteria are described below.

1. Identify restrictions which may prevent the installation of a solar DHW system e.g. listed building, conservation area or Article 4 Direction (DTI, 1996). Local authorities keep records of buildings affected by these restrictions (e.g. LCC, 1997, 1999).

2. Roof orientation must lie between ± 45° of south. In the Northern Hemisphere, the orientation for optimum system performance is close to south but provided the orientation is anywhere between south-east and south-west then the system will function close to its optimum (e.g. King, 1995; Horne, 1995). This is important to maximise the potential solar energy yield.

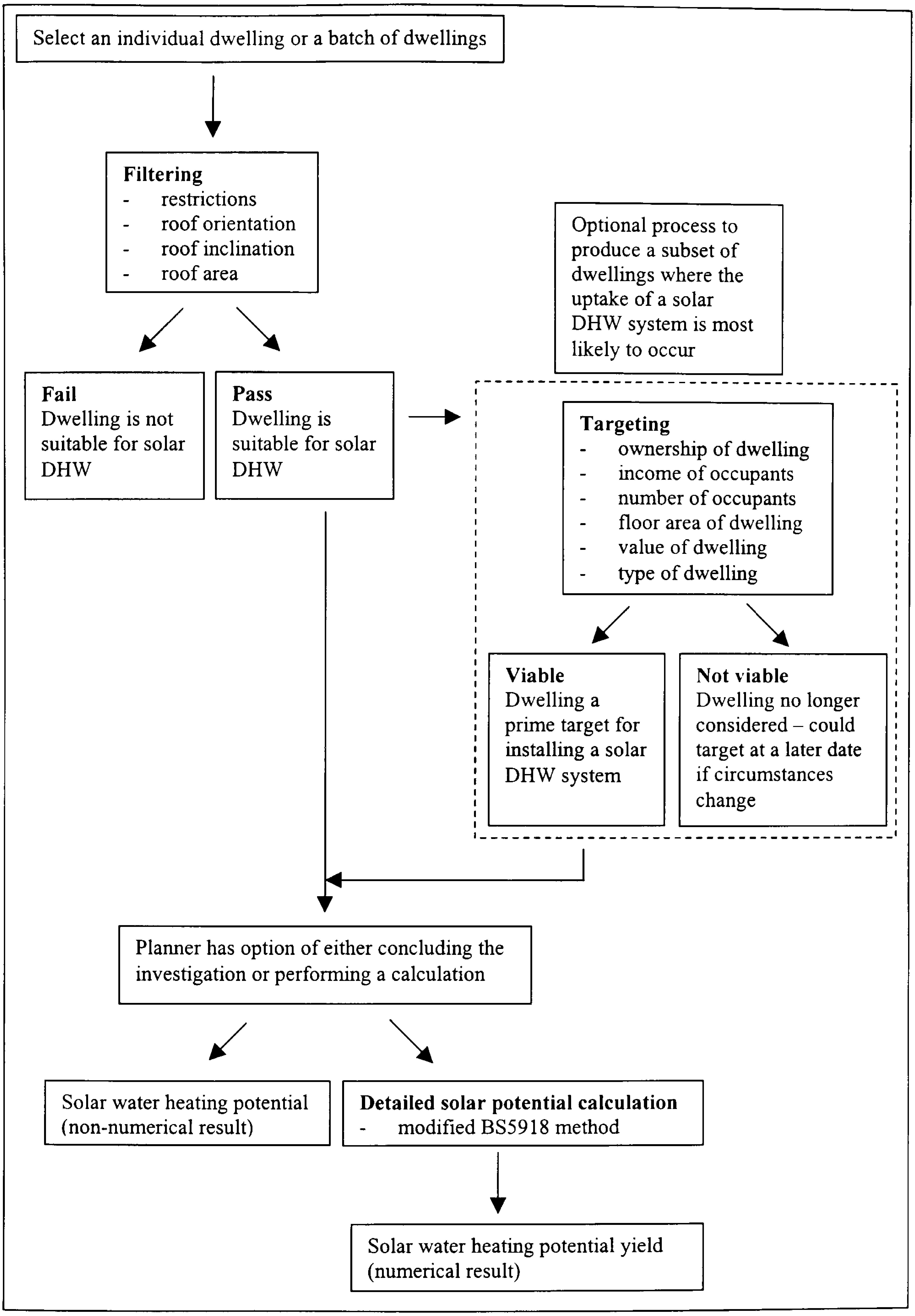


Figure 9. Approach to determine the solar DHW potential of a dwelling. (Redrawn from Gadsden, Rylatt, Lomas and Robinson, 2000.)

3. Roof inclination must lie between 0° and 60°. In dwellings where the roof inclination is less than 5°, however, the solar collector should be inclined between 5° and 60° to ensure that the annual solar energy supplied is at least 90% of that obtained at the optimum collector position (British Standards Institution [BSI], 1989). Furthermore, collectors are particularly prone to air locks if placed horizontally (Cross & Lockhart-Ball, 1995).

4. Roof area must be greater than $3m^2$. A typical solar DHW system in the UK employs a collector area of $3m^2$ of evacuated tube collectors, $4m^2$ of flat plate collectors or $5m^2$ of DIY panels (European Commission, 1996).

Dwellings affected by restrictions under (1) are removed to a temporary list for further inquiries by the planner on a case-by-case basis. It would be inappropriate to apply further procedures until the uncertainty is resolved. If the restrictions prove no obstacle then these dwellings can be submitted to the remaining steps of the filtering process. These steps can be applied in any order to each identifiable roof plane (e.g. a simple pitched roof with two equal planes and one ridge). If no plane can be found within the boundary limits of a particular step, the candidate dwelling is removed from the batch being considered.

Software especially developed for the SEP system by the project software engineer semi-automatically calculates the orientation and area of each roof plane (Rylatt et al., in press). As the ridge height of the dwelling is unknown, it is not possible to calculate each roof plane's inclination but a rough assessment can be obtained based on local knowledge. In the absence of any other data, an approximate rule of thumb based on the age of the dwelling can be used. This was suggested by Mr. N. Morris of LCC's Housing Department (verbal communication, February 2, 1999). For pre-1930 dwellings it was assumed that roof inclination is 30° and for post 1930 dwellings it was assumed that roof inclination is 22.5°. Although it is very difficult to give a precise inclination angle, it is reasonable to assume that most roof planes will be inclined between 5° and 60°. A more accurate inclination angle can be determined during a rapid site survey (Section 3.5.1).

Possible shading problems on the roof plane can also be identified as part of the rapid site survey. Obstructions include surrounding trees and tall buildings and roof components such as chimneys and television aerials located to the south of the dwelling. Partial shading does not seriously affect the performance of a solar DHW system but prolonged periods of shading should be avoided.

For some purposes, simply identifying suitable properties for installing a solar DHW system may be sufficient to satisfy the planner and thus the analysis would terminate at this point. Alternatively, a planner may wish to quantify the potential solar DHW yield of these dwellings by using the calculation procedure (Figure 9). If, however, the planner wishes to focus on those dwellings where the uptake of a solar DHW system is most likely to occur, dwellings that pass the filtering stage should undergo a targeting procedure (Figure 9).

4.4.2 Stage 2: Targeting

The targeting process compares each dwelling against a set of parameters which are based on socio-economic factors and related information that is inferred from physical aspects of the dwelling. The physical built form factors are secondary indicators that allow inferences to be made where the primary information is absent. The method uses a set of rules based on these parameters to assess the advantages of targeting a particular dwelling. The parameters are listed below in order of importance.

1. Ownership of dwelling

Whether the dwelling is owner occupied, local authority rented, housing association rented or private rented. Studies have shown that owner-occupiers are the most likely to install energy efficiency measures (LCC, 2000). Therefore, it is reasonable to assume that installation of a solar DHW system is more likely if the property is owner occupied rather than rented. This is partly because an owner-occupier will directly benefit from the resultant reduced fuel bills obtained after paying for the system's installation. In rented accommodation, however, the landlord would pay for the system installation but the tenants would benefit from the reduced bills. Hence there is little incentive (at least in the usual 'seller's market' operative in the UK) for a landlord to install a solar DHW system. Incentive schemes aimed at landlords might change this situation, but in their absence it seems reasonable to give owner occupied dwellings a higher priority than rented dwellings.

Local authorities obviously have records of their own rented properties. Housing associations will be able to provide a list of their properties. It is difficult to identify owner occupied and private rented dwellings. This information may only be available from the Home Energy Survey Form (Appendix E).

2. Income of occupants

Due to the relatively high installation cost of a solar DHW system, the income of occupants is another important factor suggesting that higher income groups should be targeted before lower income groups. A study by Leicester City Council (2000) showed that the higher the income, the greater the willingness to pay more for an energy efficient appliance. This rule, however, also needs to be weighed against the availability of house improvement grant support that may become available.

3. Number of occupants

The number of occupants is also highly relevant as this is an indicator of the overall hot water demand. A solar DHW system would be most cost-effective where the number of occupants and hence the demand is greatest.

4. Dwelling floor area

The floor area of a dwelling can give an approximate indication of the standard number of occupants using a relationship given in BREDEM-8 (Equation 3.16). Hence the likely hot water consumption can be determined. As discussed in Section 3.4.2, the floor area of a dwelling can be extracted automatically from the digital urban map.

5. Dwelling value

If no data is available regarding occupant income, it can be assumed that people of a higher income occupy dwellings of a higher value. Therefore, it is more appropriate to target dwellings of a higher value as the householder is more likely to install a solar DHW system. Local authorities know the council tax band of every property. This relates to the dwelling value.

6. Type of dwelling

This parameter is another secondary indicator of occupant income which can be used to infer the ability to pay for the installation. It can be assumed that people with higher incomes will own larger dwellings.

As the targeting process is only intended to provide an indication of the likelihood that householders will install a solar DHW system, it lends itself well to the use of fuzzy logic techniques. The rules proposed in this thesis were implemented as fuzzy rule sets in the SEP system by the project software engineer (Rylatt et al., in press). The fuzzy logic system analyses the available data and performs expert reasoning to produce an index of the suitability of solar DHW for each dwelling. The system indicates the degree of confidence that can be placed on its conclusions and permits inspection of its reasoning process in each case. The planner therefore has access to built-in expertise to aid the decision making in an area where they may lack specific knowledge. Using this suitability index, the targeting process proposed in this thesis produces a subset of dwellings for which solar DHW is considered most viable and these dwellings should be targeted first. Dwellings not included in this subset are considered less viable and thus there is less chance of a solar DHW system being installed. Such dwellings could, however, be targeted at a later date if circumstances change.

4.4.3 Stage 3: Calculating

Following the first two stages, calculations can be performed to quantify the potential solar DHW yield of the targeted dwellings (Figure 9). It was necessary to choose an appropriate calculation model as discussed in the following section.

4.5 Selecting a solar DHW calculation model

There are a number of different methods for modelling solar DHW systems. These methods vary considerably in their degree of complexity. When selecting a solar DHW calculation model for the SEP system, a number of criteria were considered. These are listed below.

- Most importantly, the model should predict the performance of a solar DHW system with acceptable accuracy whilst minimising input and computational overheads.
- The model should require minimal user expertise as planners with little knowledge in the field of solar DHW will eventually use the system.
- The model should be easily integrated into the SEP system.
- The model should predict the monthly performance of a solar DHW system.

The use of detailed simulation models such as ESP-r and TRNSYS to predict the overall energy consumption of a dwelling was ruled out in Section 3.2. This was primarily because these models require large quantities of input data and considerable user expertise which planners cannot be expected to have. Detailed simulation models were therefore considered unsuitable for use as the solar DHW calculation model. Instead, a number of models which are simpler to use and have reduced input data requirements were considered. These are briefly described below and their key features listed in Table 28.

As mentioned in Section 3.3.1, BREDEM-8 can calculate the energy supplied by a solar DHW system. However, the calculation procedure makes a number of assumptions. The most critical of these is that a fixed 'collection efficiency' (i.e. the proportion of incident horizontal solar radiation delivered to the hot water tank) of 50% is assumed. This effectively gives the collector a fixed orientation and inclination. In addition, the calculation is only applicable to flat plate solar collectors. It was therefore decided to only use BREDEM-8 to predict the existing hot water energy requirement of a dwelling.

Table 28. Summary of solar DHW calculation methods.

Model name	Developer	Implementation	Approximate number of inputs	Results period	Advantages	Disadvantages
T*SOL	Innovative Engineering Software (Germany)	PC under Windows	Minimum of 40	Hourly	These programs allow detailed design of solar DHW systems.	Difficulties in implementing these programs into the SEP system. Majority of inputs likely to be unknown placing a heavy reliance on defaults.
SolarPro 2.0	M. J. Pelosi, Maui Solar Energy Software Corporation (USA)	PC under Windows	Similar to T*SOL	Monthly		
Solar Master 2.01	Thermomax (UK)	PC under Windows	25	Monthly		
f-chart method	University of Wisconsin (USA)	PC under Windows or a hand calculation	20	Monthly	Reduced number of inputs. Widely validated.	Monthly calculation is inaccurate and not widely used. Collector data is not readily available.
BS 5918	University of Wales (UK)	Hand calculation	10	Annual	Approved and respected approach in the UK. Minimum input data requirements. Collector data readily available from manufacturers.	Only generates annual results but has potential to produce monthly results.

T*SOL (Valentin, 1997) is a planning and simulation program for thermal solar heating systems developed by Innovative Engineering Software of Berlin, Germany. A demonstration version of the program was evaluated. T*SOL operates through Windows on a PC. It can consider the performance of five different solar water heating systems including the two systems described in Section 4.3. A minimum of forty input parameters are required to describe the solar DHW system. These inputs cover categories such as the solar collector, storage tank, auxiliary heater and heat exchanger. The majority of input parameters will probably be unknown although the software does provide sensible defaults. However, the value of using T*SOL would be diminished if there was excessive reliance on the use of defaults. Results are presented on an hourly basis. This level of detail is not required in the SEP system. The overriding impression was that T*SOL is primarily intended for use by specialist engineering consultants to design the optimum solar DHW system for their clients. It appears to be a useful design tool allowing the influence of individual components on solar DHW system performance to be investigated in detail but it is not suitable for use in a general planning system.

SolarPro 2.0 (Maui Solar Energy Software Corporation, 1999), developed by Michael J. Pelosi, also runs through Windows. Unfortunately, no demonstration version of the software was available. SolarPro 2.0 appears to have similar data requirements to T*SOL and thus was not pursued further.

Solar Master 2.01 (Thermomax, 1997) is a PC-based analysis program produced by Thermomax, manufacturers of evacuated tube collectors. A copy of the program was obtained directly from Thermomax. Solar Master 2.01 can consider the performance of five different solar DHW systems. Like T*SOL, these include the two common systems installed in the UK. Approximately twenty-five input parameters are required covering the solar collector, storage tank, hot water consumption and piping. Although this is a smaller data set than that required by T*SOL, reliance would have to be made on standard defaults for a large number of inputs. Results are available on a monthly basis. No information was available regarding the mathematical basis of the program and it was difficult to assess the accuracy of the algorithms used to calculate the available solar radiation and the performance of a solar DHW system.

One of the major disadvantages of using T*SOL, Solar Pro 2.0 or Solar Master 2.01 was obtaining permission from the developers to either use their software directly or, more usefully, implement their source code in the SEP system. This could have proved a difficult, time-consuming and costly exercise. As none of the programs seemed to fully meet the desired criteria, it was decided not to pursue this issue further. Instead, attention turned to two hand calculation methods which could be more easily integrated into the SEP system.

A well-known calculation technique developed at the University of Wisconsin is the f-chart method (Beckman, Klein & Duffie, 1977). It was originally developed as a hand calculation worksheet although it has recently been made into a computer program running under Windows (Klein & Beckman, 1998). The method does not require much input data (approximately twenty input parameters). This data relates to hot water consumption, solar irradiation incident on the collector, the performance of the solar collector and the performance of a heat exchanger in the storage tank. The f-chart method uses monthly meteorological data and produces both monthly and annual estimates of system performance. Rigorous validation with detailed simulation models has shown good agreement for annual solar fractions but poor agreement for monthly fractions (Duffie & Beckman, 1991). As a result, the f-chart method is only used for estimating annual performance. One other disadvantage of the f-chart method is that much of the data required to describe the solar collector is not readily available from manufacturers.

The other hand calculation method considered is presented in BS 5918, the British Standard code of practice relating to solar heating systems for DHW (BSI, 1989). This method is based on research carried out at the Solar Energy Unit, University of Wales, Cardiff (Kenna, 1984). The BS method requires less input data than the f-chart method (approximately ten parameters). These describe the location, the hot water consumption, the solar collector and the storage tank. It is an annual calculation but there is potential to produce monthly estimates of system performance. The BS method is an approved and respected approach in the UK and manufacturers of solar collectors quote the parameters required by the method. Most of the input data is therefore readily available. For these reasons, it was decided to select the BS method for use as the solar DHW calculation model. The implementation of the BS method in the SEP system is described in the following section.

4.6 Implementation of BS 5918 in the SEP system

The input data required by the original BS 5918 method is given in Table 29. Table 29 also lists the sections which propose how this input data can be obtained.

Table 29. Input data required by the original BS 5918 calculation method.

Parameter	**Symbol**	**Units**	**Discussed in thesis**
Annual mean daily irradiation on a horizontal surface	H	MJ/m^2	Section 4.6.1
Annual mean daily peak irradiance on a horizontal surface	G	W/m^2	
Orientation factor for irradiation	C_h	-	
Orientation factor for peak irradiance	C_g	-	
Daily mean hot water requirement	V	Litres	Section 4.6.2
Volume of the preheat storage vessel	V_s	Litres	
Collector heat loss coefficient	U	W/m^{2}K	
Zero loss collector efficiency	η_0	-	
Effective aperture area of the collector	A'	m^2	
Annual mean air temperature	T	°C	Section 4.6.3
Annual mean daytime air temperature	T_a	°C	
Annual mean cold water supply temperature	T_c	°C	
Desired hot water draw off temperature	T_d	°C	

4.6.1 Climate data

In the original BS 5918 method, the annual mean daily irradiation on a horizontal surface, H (MJ/m^2), is determined (for the location of interest) from Figure 10. The annual mean daily peak irradiance on a horizontal surface, G (W/m^2), is estimated using

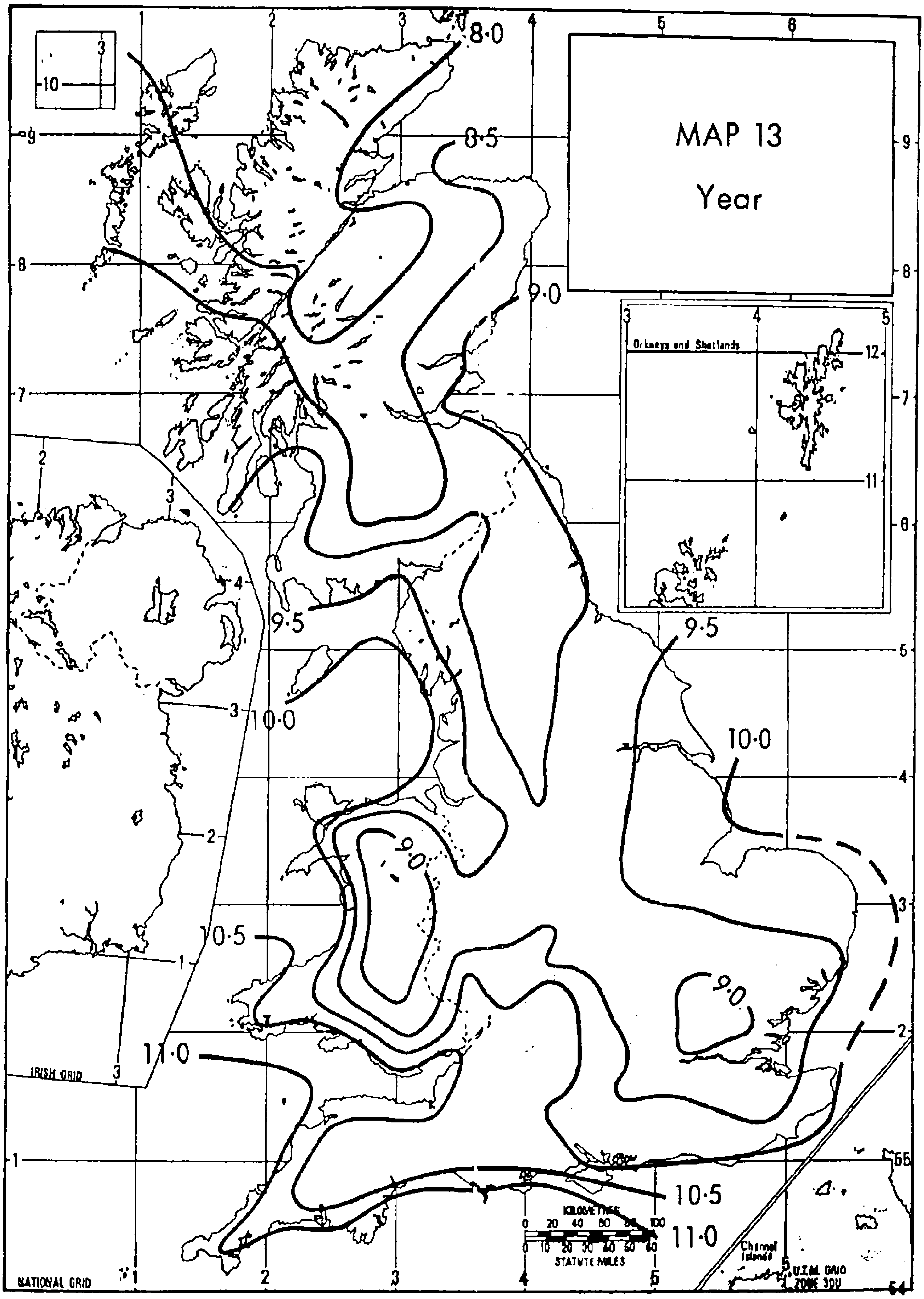


Figure 10. Variation over the UK of the annual mean daily global irradiation on a horizontal surface. (From BSI, 1989.)

$$G = 40\,H \tag{4.1}$$

To determine the annual mean daily irradiation incident on the solar collector (i.e. the irradiation incident on an inclined surface), H is multiplied by an orientation factor for irradiation, C_h. The value of C_h depends on the inclination and orientation of the solar collector and is determined from Figure 11. Similarly, the annual mean daily peak irradiance incident on the solar collector is determined by multiplying G by an orientation factor for peak irradiance, C_g, obtained from Figure 12.

These graphical methods do not lend themselves to computerisation within the SEP system. In addition, they require user interaction which could result in inaccuracies. It was therefore proposed to automatically calculate the annual mean daily irradiation and the annual mean daily peak irradiance incident on the solar collector using the Perez diffuse irradiance model for tilted surfaces (Perez, Seals, Ineichen, Stewart & Menicucci, 1987). The Perez model is an anisotropic sky model which is based on a detailed analysis of all three components of diffuse irradiation from the sky - isotropic, circumsolar diffuse and horizon brightening. The Perez tilted surface model is widely used and is generally considered to produce accurate predictions of diffuse irradiation (e.g. Feuermann & Zemel, 1992; Reindl, Beckman & Duffie, 1990). The beam irradiation and the diffuse irradiation reflected from the ground and adjacent buildings are then added to give the total solar irradiation incident on the solar collector. The implementation of the Perez model is briefly described below and the full approach is given in Appendix F.

The Perez model calculates the diffuse irradiation on an inclined surface from knowledge of the total irradiation on a horizontal surface. BREDEM-8 reference tables provide the monthly mean daily irradiation on a horizontal surface for twenty-one different regions (Appendix A). These tables also provide the representative latitude for each region. As the Perez model is an hourly calculation, some simple solar geometry processing is required to calculate the hourly direct, diffuse and total irradiation on a horizontal surface. This process is carried out for each daylight hour on the mean day of every month. The solar geometry algorithms are described fully in Appendix F.

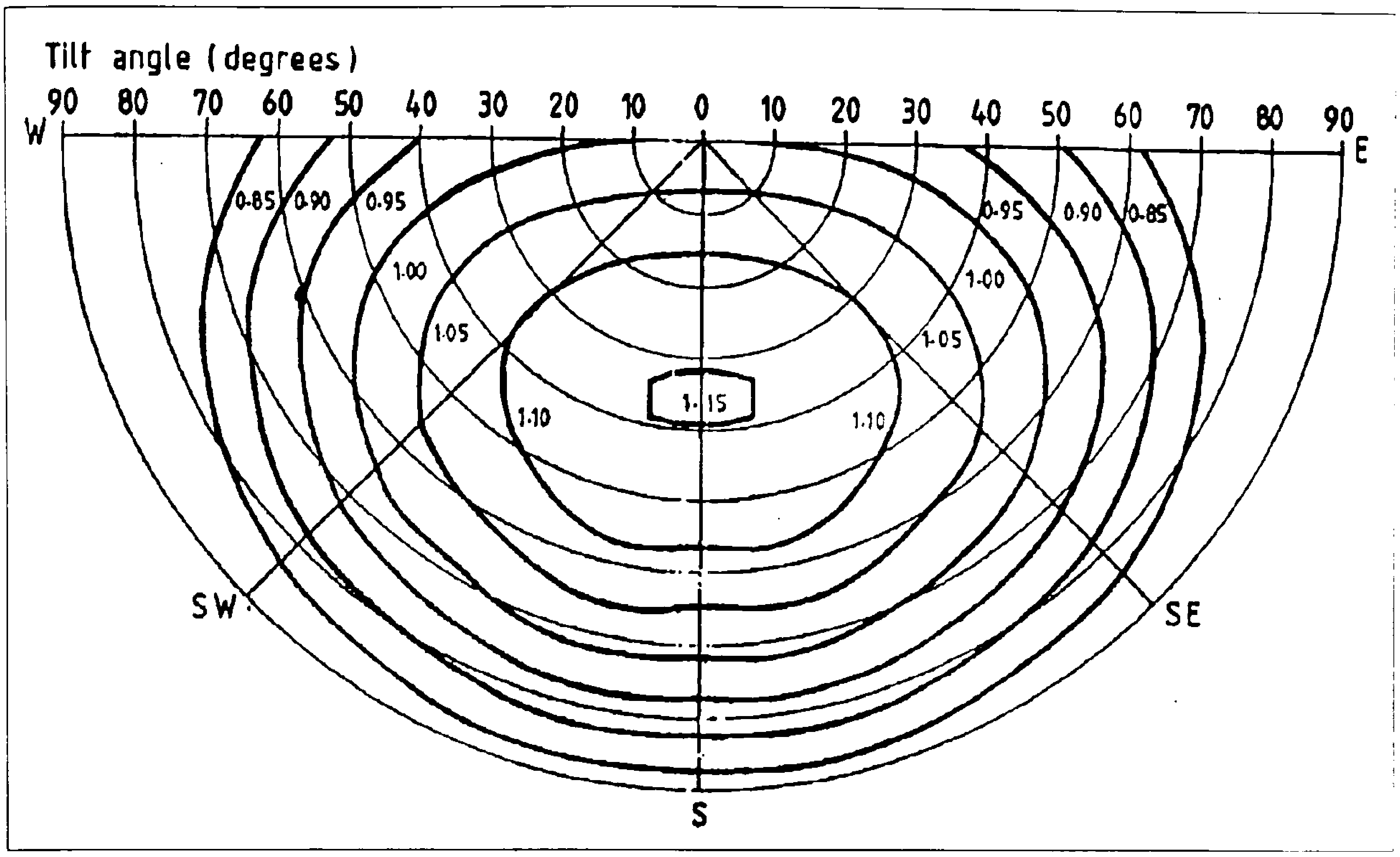


Figure 11. Orientation factor C_h for irradiation. (From BSI, 1989).

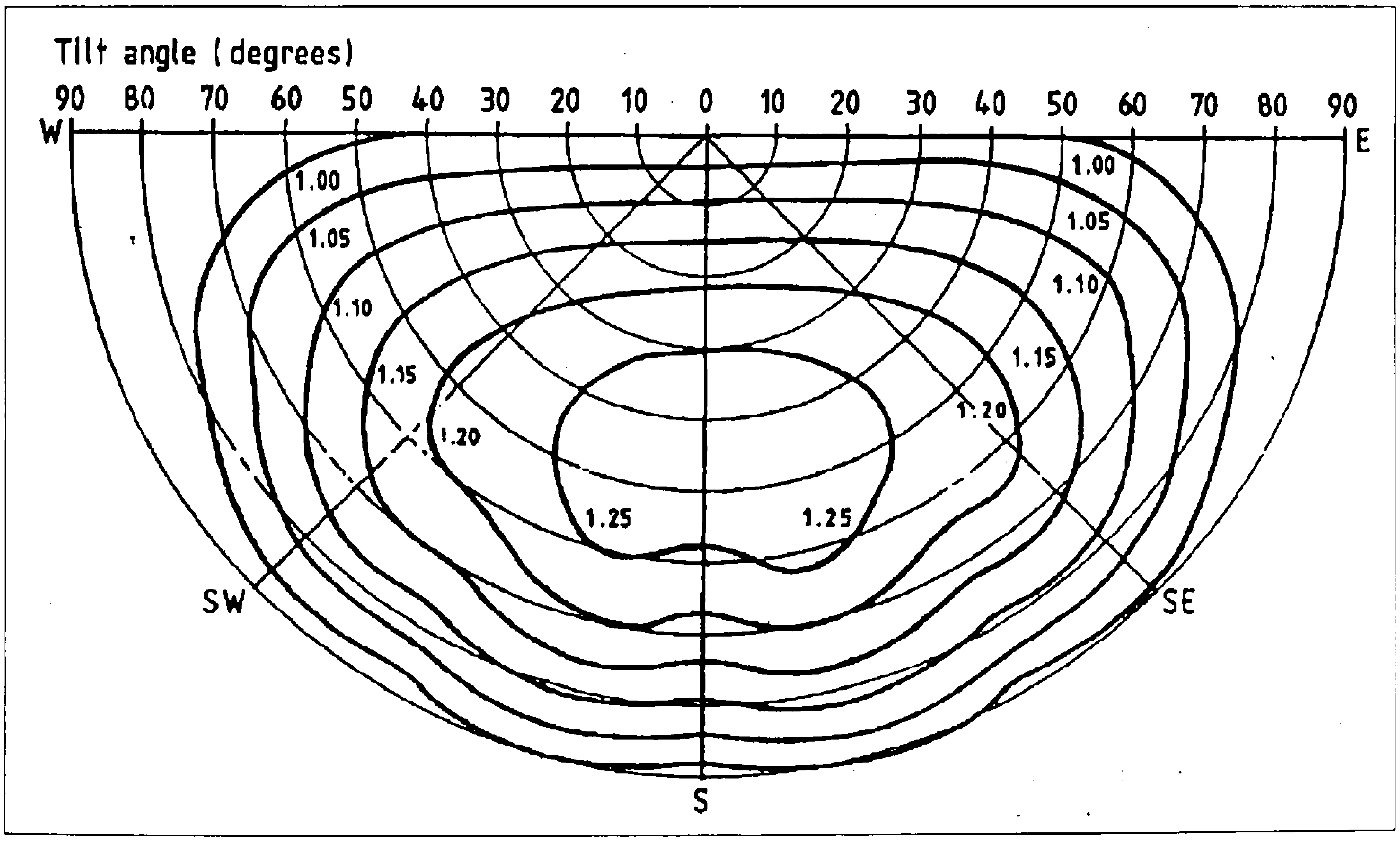


Figure 12. Orientation factor C_g for peak irradiance. (From BSI, 1989).

Once the hourly irradiation on a horizontal surface has been calculated, the Perez diffuse irradiance model for tilted surfaces can be used to calculate the hourly diffuse irradiation incident on the solar collector. The inclination and orientation of the collector are obtained during the filtering process described in Section 4.4.1. Adding the hourly direct and reflected irradiation gives the hourly total irradiation incident on the solar collector. Summing the hourly total irradiation values calculated for each hour of the mean day of every month gives the monthly mean daily irradiation on the solar collector. The irradiance calculated at 12 noon is the monthly mean daily peak irradiance on the solar collector.

As the original BS 5918 method uses several coefficients statistically derived from annual simulation results (Section 4.6.4), it was necessary to calculate the annual mean daily irradiation on an inclined surface, H_{TILT} (MJ/m^2), and the annual mean daily peak irradiance on an inclined surface, G_{TILT} (W/m^2), by summing the monthly values and dividing by twelve. This ensures that the revised method of calculating the solar irradiation data is compatible with the standard algorithms used in the original BS 5918 method. The use of the monthly irradiation values to estimate the monthly solar energy supplied by a solar DHW system is described in Section 4.6.4.

4.6.2 Solar collector and storage tank data

Section 4.6.1 described an approach to automate the calculation of solar radiation data required by the BS 5918 method. This reduces the level of user interaction required. It was decided to apply this idea of automation to the data needed to describe the solar collector and the hot water storage tank.

The daily mean hot water requirement of a dwelling, V (litres), is obtained from BREDEM-8 using

$$V = 38 + (25 \times N) \qquad (4.2)$$

where N is the number of occupants. As described in Section 3.4.5, BREDEM-8 uses either the actual number of occupants or determines the standard occupancy from knowledge of the total floor area of a dwelling (Equation 3.16).

The preheat storage tank volume, V_s (litres), needs to be given a default value. Many sources exist which give 'rules of thumb' to estimate the preheat storage tank volume from the daily mean hot water requirement (e.g. Cross & Lockhart-Ball, 1995; King, 1995; Marko & Braun, 1994). These 'rules of thumb' vary from one to two times the daily mean hot water requirement. Tests were carried out with the original BS 5918 method to observe the effect that varying the preheat storage tank volume had on the annual solar energy supplied. Example results are given in Table 30. It can be seen that a preheat storage tank volume of 1.7 or 1.8 times the daily mean hot water requirement supplies the maximum solar energy. It was decided to use the smaller preheat storage tank volume as the default input to reduce the space required for the tank in a dwelling. This gives

$$V_s = 1.7 \times V \qquad (4.3)$$

Table 30. Effect of varying preheat storage tank volume on the annual solar energy supplied by a solar DHW system[a].

Vs	**Annual solar energy supplied (kWh) for V equal to:**				
(litres)	**63 litres**	**88 litres**	**113 litres**	**138 litres**	**163 litres**
1 x V	953	1281	1559	1793	1989
1.1 x V	970	1304	1588	1826	2026
1.2 x V	986	1325	1613	1855	2057
1.3 x V	998	1342	1634	1878	2084
1.4 x V	1008	1355	1650	1898	2105
1.5 x V	1016	1366	1663	1912	2121
1.6 x V	1021	1373	1672	1922	2132
1.7 x V	1024	1377	1676	1927	2138
1.8 x V	1024	1377	1677	1928	2139
1.9 x V	1022	1374	1673	1924	2134
2 x V	1018	1368	1666	1915	2124

[a] All other parameters describing the solar DHW system were kept constant i.e. a Midlands location with 4.28m^2 of Thermomax evacuated tubes facing due south on a 50° slope.

In Section 4.3, it was stated that both twin tank and single tank systems are installed in the UK. In a single tank system, it is commonly assumed that the preheat volume represents the bottom two-thirds of the hot water cylinder (e.g. BSI, 1989; Thermomax, 1997). This assumption was proposed for this method to ensure that the calculation could be applied to both single (Figure 3) and twin tank (Figure 4) systems.

Table 31 shows how the collector characteristic U/η_0 (W/m^{2}K) relates to the typical collector technology associated with each class. To automate the BS 5918 calculation, it was necessary to specify a default collector area for each class which would meet a certain daily mean hot water requirement during peak summer months. For economic reasons, solar DHW systems are typically designed to provide all the hot water needs of a dwelling during the peak month of solar radiation (usually June in the UK). This means that only a proportion of the hot water requirement is met during the other months. Increasing the collector area above this size significantly increases the installation cost but it does not result in a corresponding increase in energy savings.

Table 31. Solar collector classification. (Adapted from BSI, 1989.)

Collector class	**Range of collector characteristics** $\frac{U}{\eta_0}$ **(W/m^{2}K)**	**Typical collector technology for the class**	**Area of collector required per 40 litres of hot water demand (m^2)**
B	Less than 3	Evacuated tube	0.75
C	3 to 6	Advanced flat plate[a]	1.00
D	6 to 9	Single glazed with selective coating	1.25
E	9 to 13	Single glazed with matt black coating	1.50
F	Greater than 13	Unglazed	1.75

[a] An advanced flat plate collector typically has two transparent covers to reduce heat loss. In addition, these tend to be special covers which have a higher solar transmittance than normal glass. For example, the AES Double Sun Panel (Table 32) has one outer layer of Tedlar film and one inner layer of Teflon giving a solar transmittance of 0.95. The solar transmittance of glass varies from approximately 0.83 to 0.9 (Boyle, 1996).

'Rules of thumb' suggested by Duffie and Beckman (1991), Horne (1995) and the DTI (1996) relate hot water consumption per person per day (assumed to be 40 litres) to required collector area. The collector area required per 40 litres of hot water demand is shown for each collector class in Table 31. Hence, the theoretical collector area required to meet a certain hot water demand can be calculated using

$$\text{Theoretical collector area} = \text{Area per 40 litres hot water demand (Table 31)} \times \frac{V}{40} \qquad (4.4)$$

This theoretical collector area is assumed to correspond to the maximum value of U/η_0 specified for each collector class in Table 31 (e.g. 6 for advanced flat plate collectors).

In reality, however, solar collectors are manufactured in standard module sizes. Table 32 shows the module sizes, the collector heat loss coefficient, U (W/m^2K), and the zero loss collector efficiency, η_0, for some real collectors. This data was obtained directly from the manufacturers. The number of modules required of a particular type of solar collector can then be calculated by dividing the theoretical collector area for the particular class (Equation 4.4) by the actual module area. This is rounded up to the nearest whole number. A worked example is given below to clearly illustrate the automatic approach of obtaining the input data described in this section.

Table 32. Collector characteristics of some real solar collectors.

Manufacturer	**Module name**	**Collector type**	**U (W/m^2K)**	η_0	$\frac{U}{\eta_0}$	**Effective aperture area (m^2)**
Thermomax	THS 400	Evacuated tube	1.07^a	0.801^a	1.34	2.14
NEG	Suntube DP6-2800	Evacuated tube	1.434^b	0.752^b	1.91	2.32
AES	Double Sun Panel	Advanced flat plate	4.0^c	0.82^c	4.88	1.2

[a] Data from Institut fur Solarenergieforschung, 1996.
[b] Data from Universitat Stuttgart, 1992.
[c] Data from University College Cardiff, 1983.

Consider a dwelling with four occupants. From Equation 4.2, the daily mean hot water requirement is 138 litres. The required preheat storage tank volume is therefore 235 litres (from Equation 4.3). The householder intends to install an advanced flat plate collector (Table 31). The theoretical collector area required is calculated using Equation 4.4.

$$\text{Theoretical collector area} = 1.00 \times \frac{138}{40} = 3.45\text{m}^2$$

Therefore, 3.45m^2 of an advanced flat plate collector with a value of U/η_0 equal to six (Table 31) is required. However, the householder intends to install AES Double Sun Panel collectors (Table 32). The number of AES modules required can therefore be determined:

$$\text{Number of AES modules required} = \frac{3.45}{1.2} = 3$$

The householder should therefore install three AES Double Sun Panel collectors (area of 3.6m^2). This represents the area required to meet the hot water requirement during the peak summer months.

4.6.3 Temperature data

In the original BS 5918 method, the annual mean air temperature, T (°C), is obtained from Figure 13. However, BREDEM-8 reference tables provide the monthly mean air temperatures for the twenty-one different regions. The annual mean air temperature for each region can obviously be automatically determined from these values. The annual mean daytime air temperature, T_a (°C), and the annual mean cold water supply temperature, T_c (°C), are unknown for each region. These can be determined from formulae presented in BS 5918:

$T_a = T + 1$ and (4.5)

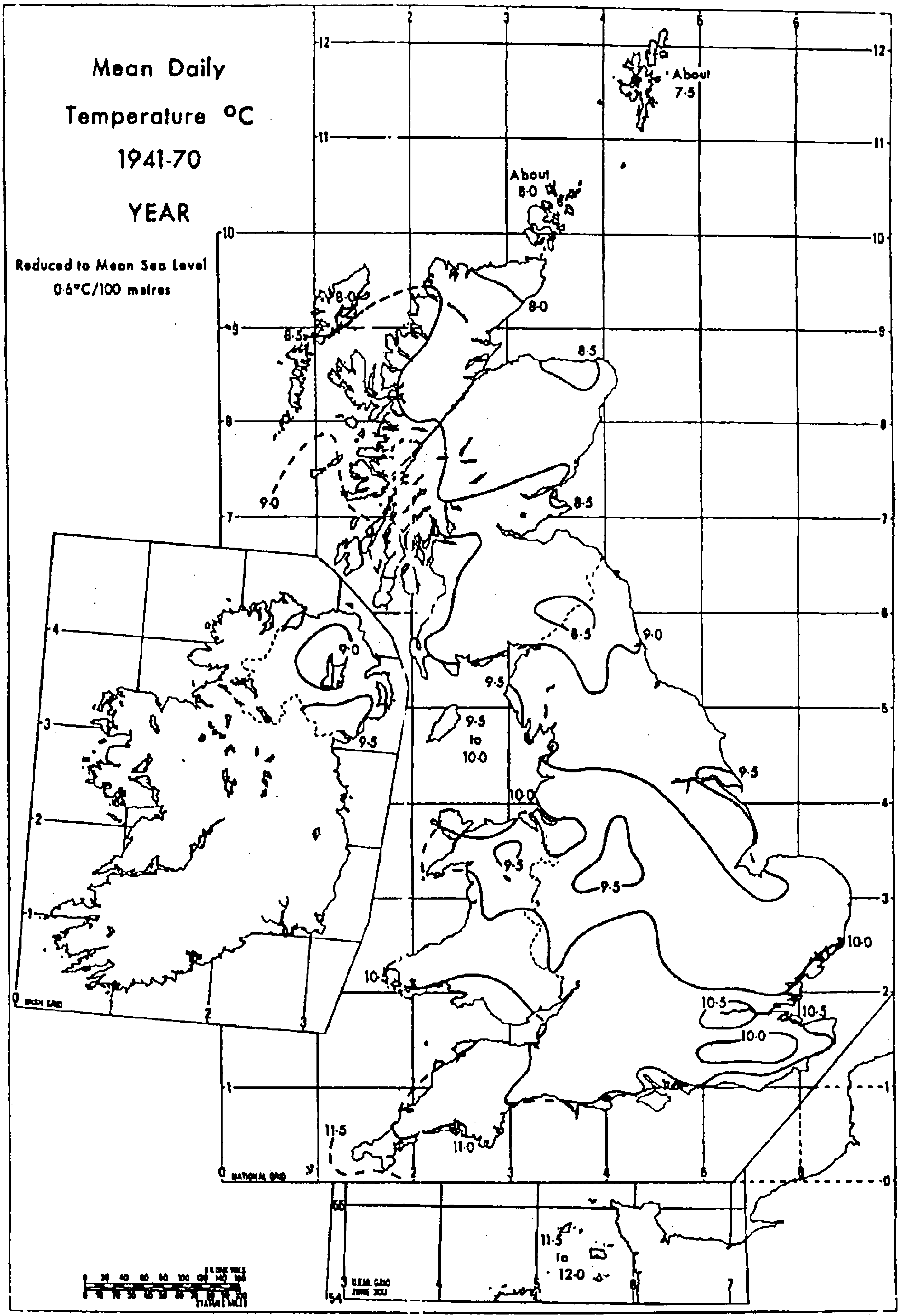


Figure 13. Variation over the UK of the annual mean daily temperature. (From BSI, 1989.)

$$T_c = T + 2 \quad (4.6)$$

The desired hot water draw-off temperature, T_d (°C), is set at a constant 60°C. This is the minimum temperature for storing hot water to prevent the risk of infection from legionnaires' disease (BSI, 1989).

4.6.4 Calculating the solar energy supplied by a solar DHW system

When all the input data has been obtained, the total annual solar energy supplied by a solar DHW system can be calculated using a revised version of BS 5918. Initially, parameters relating to system performance are calculated. The collector sizing parameter, M, represents the ratio of solar energy available to hot water energy demand and is calculated using

$$M = \frac{A'}{L}\left[H_{TILT} + 0.0432\frac{U}{\eta_o}\left(T_a - T_c\right)\right] \quad (4.7)$$

where H_{TILT} replaces HC_h used in the original BS 5918 method. The daily load, L (MJ/day) is given by

$$L = 0.00418 \times V \times \left(T_d - T_c\right) \quad (4.8)$$

The value of 0.00418 in Equation 4.8 approximates

$$L = \rho \times C_p \times V \times \left(T_d - T_c\right) \quad (4.9)$$

where ρ is the density of water at ambient temperature (998 kg/m^3) and C_p is the specific heat capacity of water at ambient temperature (4190 J/kgK). Multiplying ρ and C_p gives approximately 4.18×10^6 J/m^{3}K. Dividing Equation 4.9 by one thousand to convert V from litres to cubic metres and dividing again by 1×10^6 to convert ρC_p from joules to megajoules gives the 0.00418 used in Equation 4.8.

The collector performance parameter, K, represents the ratio of collector loss to collector gain and is calculated using

$$K = \frac{U}{\eta_o} \times \frac{(T_d - T_c)}{\left[G_{TILT} + \frac{U}{\eta_o}(T_a - T_c) \right]} \tag{4.10}$$

where G_{TILT} replaces GC_g used in the original BS 5918 method.

The storage parameter, R, represents the number of days storage available and is calculated using

$$R = \frac{V_s}{V} \tag{4.11}$$

Knowing the above allows a further set of dimensionless parameters (F, B and λ) to be calculated. These coefficients were statistically derived from annual simulation results (Kenna, 1984).

$$F = 0.554 + 0.342\,R - 0.097\,R^2 \tag{4.12}$$

$$B = 0.383\,K - 0.066\,K^2 \tag{4.13}$$

$$\lambda = 1.121 + 0.212\,K\text{, for } K \leq 1 \text{ and } \lambda = 0.71(1 + K)\text{, for } K > 1 \tag{4.14}$$

Hence, the annual solar energy supplied by the solar DHW system, Q_{annual} (MJ/yr), can be calculated using

$$Q_{annual} = 365\,L\,(F - B)[1 - \exp(-\lambda\,M)] \tag{4.15}$$

It is useful to determine the solar energy yield on a monthly basis. A monthly calculation is advantageous as it highlights the wide variation in solar energy supplied throughout the year and the periods in the year when auxiliary water heating is required. It is proposed to estimate the monthly solar energy yield using the following approach.

In Section 4.6.1, the monthly mean daily irradiation incident on the solar collector was calculated. This can be multiplied by the number of days in the month to give the monthly total irradiation incident on the solar collector. Summing the monthly values gives the annual total irradiation incident on the solar collector. The fraction of annual irradiation received in a month can therefore be given by

$$\text{Monthly fraction of annual irradiation} = \frac{\text{Monthly total irrad.}}{\text{Annual total irrad.}} \tag{4.16}$$

Multiplying the annual solar energy supplied by the solar DHW system by the monthly fraction of annual irradiation allows the monthly solar energy supplied, $Q_{monthly}$ (MJ/month), to be estimated i.e.

$$Q_{monthly} = Q_{annual} \times \text{Monthly fraction of annual irradiation} \tag{4.17}$$

It is also useful to obtain the solar fraction i.e. the fraction of hot water demand met by solar energy. The solar fraction is a measure of how effective the solar DHW system is at replacing conventional fuel. The annual solar fraction is calculated using

$$\text{Annual solar fraction} = \frac{Q_{annual}}{\text{Annual energy required to heat water}} \tag{4.18}$$

where the annual energy required to heat water is calculated by BREDEM-8. It is also possible to calculate the monthly solar fractions.

To calculate savings in the delivered fuel requirement and reductions in CO_2 emissions, it is necessary to know the efficiency of the conventional DHW system and the type of delivered fuel which the solar energy is replacing:

$$\text{Delivered fuel savings} = \frac{Q_{\text{annual}}}{\text{Efficiency of conventional DHW system}} \quad \text{and} \qquad (4.19)$$

$$CO_2 \text{ emissions reduction} = \text{Delivered fuel savings} \times CO_2 \text{ emission factor for fuel} \qquad (4.20)$$

The CO_2 emission factors for different fuels are given in Table 17.

4.7 Inter-model comparisons

It was useful to compare the revised BS 5918 method proposed in this thesis with the original version. This allows the effect of the revisions to be observed. In addition, both of these calculation methods were compared against Solar Master 2.01 (Section 4.5) to observe how they performed against a more detailed simulation model. These inter-model comparisons are described in the following sections.

4.7.1 Comparisons between the original and revised versions of BS 5918

Using the approach described in Section 4.6.2, a base case solar DHW system was specified for a dwelling with four occupants. This gave a daily mean hot water requirement of 138 litres (Equation 4.2) and a preheat storage tank volume of 235 litres (Equation 4.3). Thermomax THS 400 evacuated tube solar collectors (Table 32) were chosen for the system and it was found that two modules were required i.e. a total area of $4.28m^2$. Collector inclination and orientation were then varied to compare the models over a range of cases.

The values of annual mean daily irradiation and annual mean daily peak irradiance incident on the solar collector that were input into the original and revised versions of the BS 5918 method are compared in Table 33. It can be seen that there are some differences between the two sets of input data. The effect that these differences in input data have on the results obtained from the two calculation models can be seen by comparing the predictions of annual solar energy supplied (Table 34). It should be noted that the annual mean air temperature was found to be 9.5°C for both versions (obtained from Figure 13 for the original method and from BREDEM-8 reference tables for the revised version).

Table 33. Variation in inputs between original and revised versions of BS 5918.

Case	**Orientation**	**Inclination**	**Annual mean daily irradiation (MJ/m^2)**		**Annual mean daily peak irradiance (W/m^2)**	
			Original (HC_h)	**Revised (H_{TILT})**	**Original (GC_g)**	**Revised (G_{TILT})**
A	South	0°	9.5	9.5	380	342.5
B	South	25°	10.7	11.8	463.6	458.8
C	South	50°	10.6	12.4	482.6	503.5
D	South	60°	9.7	11.5	448.4	481.5
E	South	90°	7.9	9.6	372.4	410.7
F	South-east	50°	10.2	11.1	463.6	432.9
G	East	50°	8.6	8.2	380	262.7
H	West	50°	8.6	8.2	372.4	262.7
J	South-west	50°	10.2	11.1	459.8	432.9

Table 34. Annual solar energy supplied: a comparison between the original and revised versions of BS 5918.

Case[a]	**Annual solar energy supplied (kWh)**		**Difference Revised - Original (kWh)**	**Percentage difference (%)**
	Original	**Revised**		
A	1808	1795	- 13	- 0.7
B	1914	1970	+ 56	+ 2.9
C	1912	2009	+ 97	+ 5.1
D	1871	1963	+ 92	+ 5.0
E	1667	1827	+ 160	+ 9.6
F	1877	1930	+ 53	+ 2.8
G	1740	1650	- 90	- 5.2
H	1737	1650	- 87	- 5.0
J	1877	1930	+ 53	+ 2.8
Avge.	1823	1858	+ 35	+ 1.9

[a] For orientation and inclination refer to Table 33.

It can be seen from Table 34 that for all cases, the results obtained from the new implementation are within 10% of those from the original method. The average difference between the nine cases is only 1.9%. Furthermore, considering only those cases which would pass the filtering stage described in Section 4.4.1 (i.e. inclination between 0° and 60° and orientation between SE and SW), the results are within 5%. It was therefore concluded that the new implementation of the BS calculation is producing results which are acceptably close to the original version. This gives confidence in the use of the revised version of the BS 5918 method proposed in this thesis.

4.7.2 Comparison with Solar Master 2.01

The base case solar DHW system described in Section 4.7.1 was input into Solar Master 2.01 to allow comparison with the two versions of the BS 5918 method. As shown in Table 28, Solar Master 2.01 requires more input data than the BS 5918 method. Where input data was unknown, defaults supplied by the program were used, e.g. hot water draw-off was assumed to occur at four times throughout the day. Solar Master 2.01 simulations were performed for all the cases of orientation and inclination. The predictions of annual solar energy supplied from all the calculation methods are compared in Table 35. These results are also compared in Figure 14.

Table 35. Annual solar energy supplied: a comparison between Solar Master 2.01 and the two versions of BS 5918.

Case[a]	**Annual solar energy supplied (kWh)**			**Revised - Solar Master (kWh)**	**Percentage difference (%)**
	Original	**Revised**	**Solar Master 2.01**		
A	1808	1795	1671	+ 124	+ 7.4
B	1914	1970	1842	+ 128	+ 6.9
C	1912	2009	1902	+ 107	+ 5.6
D	1871	1963	1758	+ 205	+ 11.7
E	1667	1827	1463	+ 364	+ 24.9
F	1877	1930	1800	+ 130	+ 7.2
G	1740	1650	1605	+ 45	+ 2.8
H	1737	1650	1051	+ 599	+ 57.0
J	1877	1930	1624	+ 306	+ 18.8

[a]For orientation and inclination refer to Table 33.

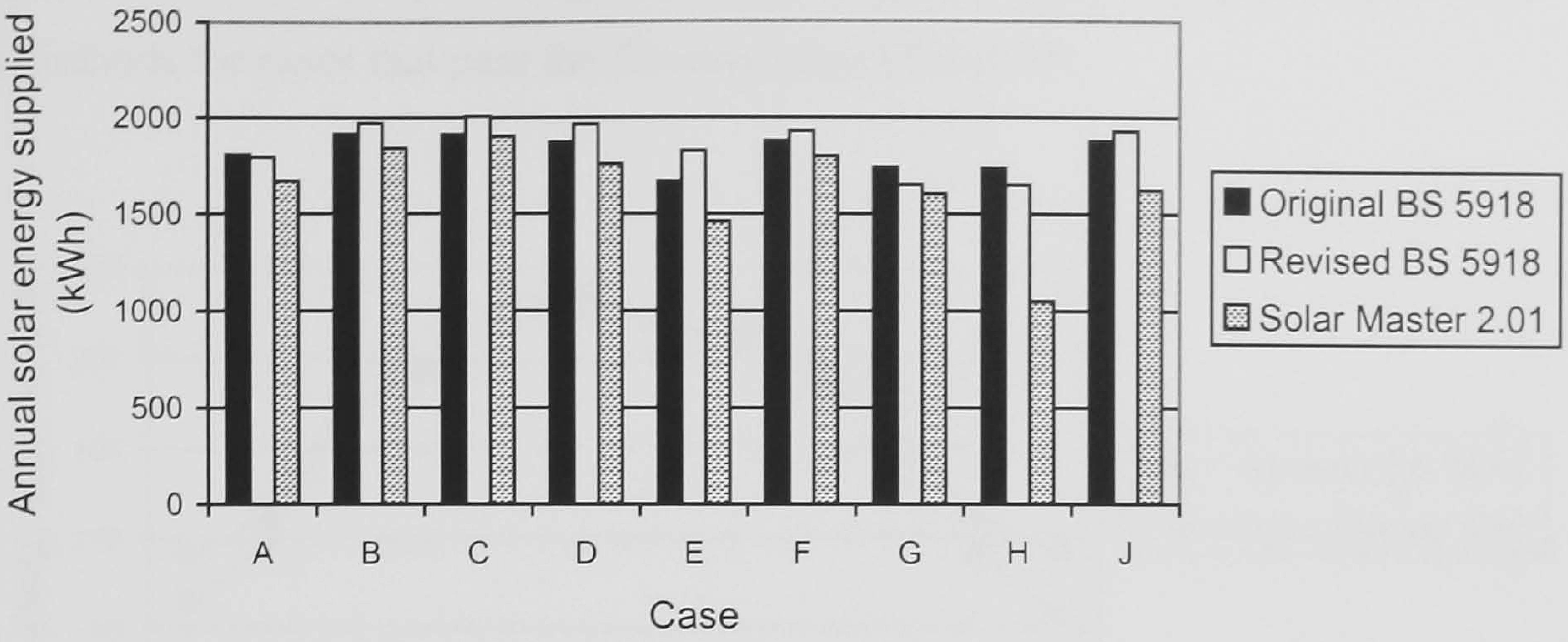


Figure 14. Comparison of the two versions of BS 5918 with Solar Master 2.01.

It can be seen from Figure 14 that Solar Master 2.01 consistently produces lower estimates of annual solar energy supplied than the two versions of BS 5918. Differences between Solar Master 2.01 and the revised version of BS 5918 range from only 2.8% for case G to 57% for case H (Table 35). However, these two cases are outside the range of typical systems described in the filtering process. Considering only those cases that would pass the filtering stage (i.e. cases A, B, C, D, F and J), it can be seen that the differences are under 10% except for cases D and J. These two cases, however, represent an inclination angle of 60° and an orientation of south-west respectively i.e. they are at the extremes of orientation and inclination that pass the filtering stage. It is likely that these cases will be less common in practice.

The differences between Solar Master 2.01 and the two versions of the BS 5918 method are probably a result of the different input requirements of the calculation models. For example, the need to specify hot water draw-off times in Solar Master 2.01 could have a significant influence on the prediction of annual solar energy supplied. The effect of these inputs was not considered further as it was not the intention to introduce further inputs to the BS 5918 method.

The monthly results from the revised BS 5918 were also compared with those from Solar Master 2.01 to observe if they follow similar trends. Results are shown for case C (Figure 15) and case J (Figure 16). These two cases are shown as they represent the minimum and maximum percentage differences between the annual predictions of the two methods for cases that pass the filtering stage (Table 35).

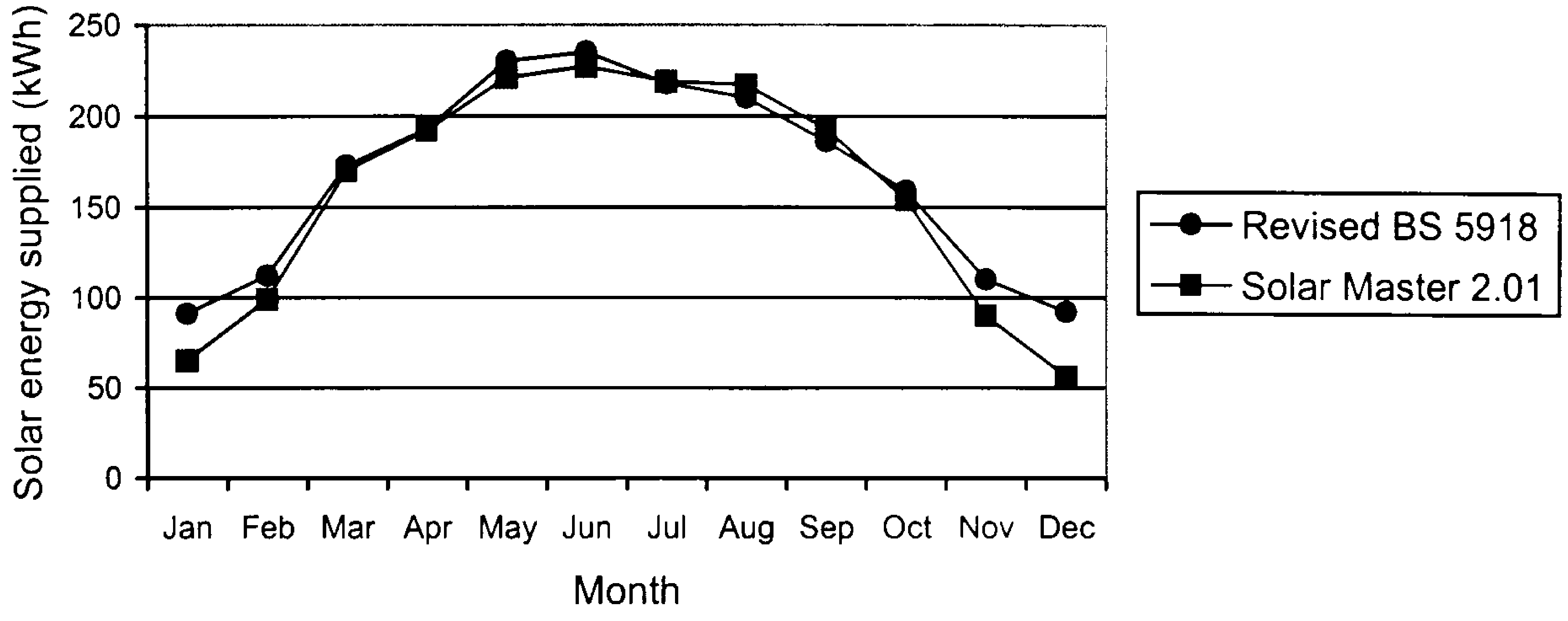


Figure 15. Comparison of predictions of monthly solar energy supplied for case C.

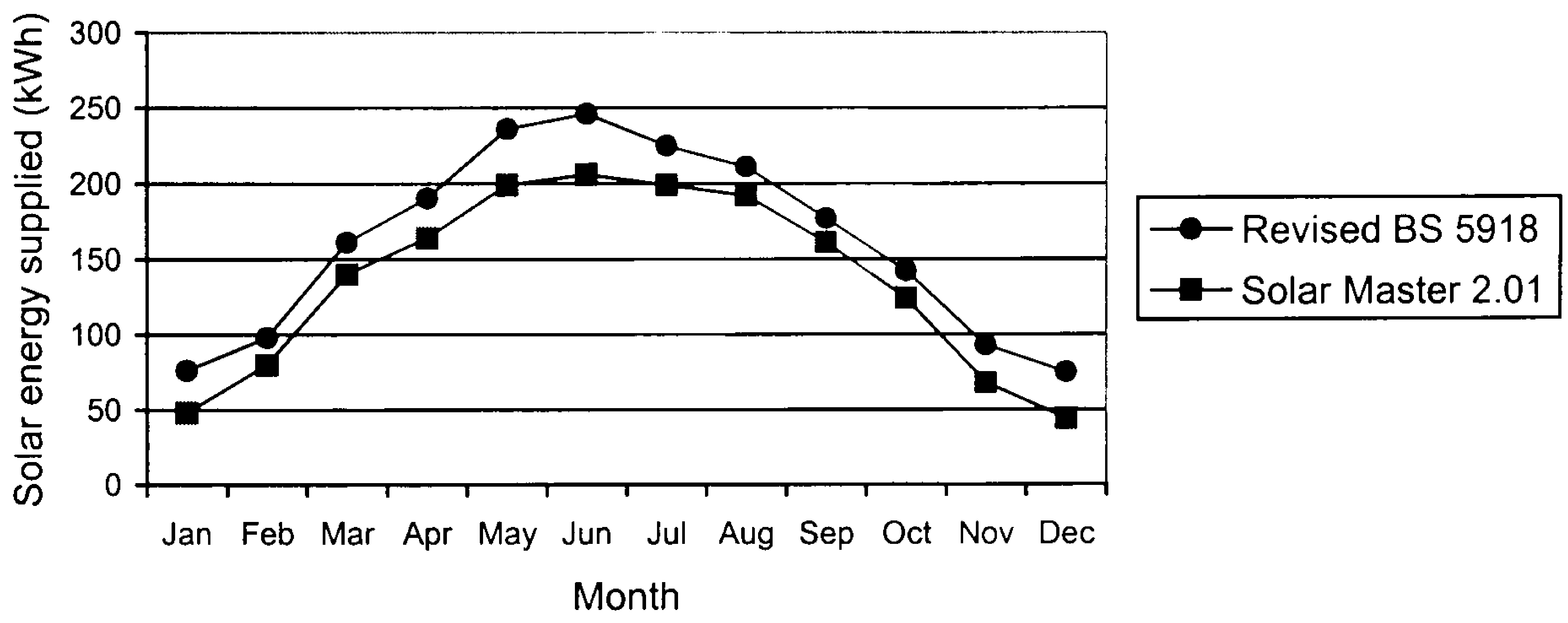


Figure 16. Comparison of predictions of monthly solar energy supplied for case J.

It can be seen from Figures 15 and 16 that the monthly predictions obtained from the revised version of BS 5918 closely follow the same pattern as those obtained from Solar Master 2.01. For case C (Figure 15), the two calculation models produce monthly predictions which are within 5% between the months of March and October. The results are not as close for case J (Figure 16) but this is because the annual predictions from the two calculation methods differ by nearly 20% (compared to only 6% for case C). Based on these results it was concluded that the monthly predictions from the revised version of BS 5918 are exhibiting similar trends to a more detailed calculation model.

4.7.3 Predictive accuracy and the performance of a solar DHW system

It is useful to compare the effect that the different predictions from the three calculation methods have on the absolute cost savings and reductions in CO_2 emissions achieved by a solar DHW system. This will show whether differences in the predictive accuracy of the methods result in any significant difference in the performance of a solar DHW system. Comparisons were carried out for case B, a typical installation.

The two main fuels used to supply hot water are mains gas and electricity. The unit price of each fuel was obtained from the SAP and these are shown in Table 36. The CO_2 emission factors are given in Table 17 but they are repeated in Table 36 for convenience.

Table 36. Unit prices and CO_2 emission factors for different fuels.

Fuel	**Unit price (pence/kWh)**	**CO_2 emission factor (kg CO_2 per kWh)**
Gas (mains)	1.5	0.19
Electricity (on-peak)	8	0.51
Electricity (off-peak)	2.8	0.51

The efficiency of an independent electric immersion heater is 100% and so the actual delivered electricity saved by the solar DHW system is the same as the solar energy supplied (Equation 4.19). For a gas boiler, the actual delivered mains gas saved is higher than the solar energy supplied due to the reduced DHW system efficiency (Equation 4.19). A gas boiler efficiency of 70% was assumed (this corresponds to the default gas boiler specified in Table 13). The cost savings and CO_2 reductions are shown for an electric immersion heater in Table 37 and for a mains gas boiler in Table 38.

Table 37. Annual cost savings and reductions in CO_2 emissions for an electric DHW system.

Calculation method	Annual solar energy supplied (kWh)	Delivered electricity saved (kWh)	Cost Savings		Reductions in CO_2 emissions (kg)
			On-peak (£)	Off-peak (£)	
Original BS 5918	1914	1914	153.12	53.59	976
Revised BS 5918	1970	1970	157.60	55.16	1005
Solar Master 2.01	1842	1842	147.36	51.58	939

Table 38. Annual cost savings and reductions in CO_2 emissions for a mains gas DHW system.

Calculation method	Annual solar energy supplied (kWh)	Delivered mains gas saved (kWh)	Cost Savings (£)	Reductions in CO_2 emissions (kg)
Original BS 5918	1914	2734	41.01	519
Revised BS 5918	1970	2814	42.21	535
Solar Master 2.01	1842	2631	39.47	500

From Tables 37 and 38 it can be seen that the different predictions of annual solar energy supplied do not have a significant influence on the absolute cost savings or reductions in CO_2 emissions. The revised BS 5918 method and Solar Master 2.01 differed by 128 kWh in their predictions of annual solar energy supplied. This represents differences in cost savings of £10.24 for on-peak electricity, £3.58 for off-peak electricity and £2.74 for mains gas. Over a ten year period, for example, the differences in savings predicted by the two models would range between approximately £30 for mains gas and £100 for on-peak electricity. These differences are small in comparison to the cost of a solar DHW system which ranges from about £1500 to £3000. Accordingly, differences in predictive accuracy between the models are unlikely to have a significant effect on the prediction of payback times.

Similarly, the reductions in CO_2 emissions predicted by the revised BS 5918 method and Solar Master 2.01 differ by only 66kg for electricity and 35kg for mains gas. These differences are small and are unlikely to affect the decision to install solar DHW systems.

4.8 Summary

After initially describing the design principles of solar DHW systems commonly installed in the UK, a new three-stage approach for predicting the potential yield of solar DHW systems was proposed in this chapter. Filtering identifies suitable dwellings for the installation of a solar DHW system based on physical characteristics of the dwelling. Targeting then uses socio-economic factors to focus on those dwellings where the householder is more likely to install a solar DHW system. Finally, the potential solar energy yield and the associated reduction in CO_2 emissions are quantified using a revised version of the calculation method presented in BS 5918. This revised version automatically calculates the required input data to reduce the level of user interaction required. In addition, the original method has been modified to produce monthly estimates of solar energy supplied. Inter-model comparisons with the original BS 5918 method and Solar Master 2.01 have shown that the revised method proposed in this thesis is producing results which are acceptably accurate for use in the SEP system.

Of all the active solar technologies, solar DHW systems are the most commonly installed in the UK domestic sector. However, the use of photovoltaic systems to generate electricity from the sun is a technology which has been gathering momentum in recent years. Chapter 5 considers the potential of domestic PV systems in the UK.

Chapter 5

Active Solar Technologies II: Photovoltaics

5.1 Introduction

Photovoltaic (PV) systems have significant potential to contribute to the reduction of CO_2 emissions by displacing electricity generated from fossil fuels. However, they are not currently economically feasible in the UK and so are not widely used. This chapter discusses the global PV market to compare the UK situation with other developed countries. It also briefly describes the general principles of PV cells and system design. Finally, a procedure is proposed for predicting the potential yield of PV systems.

5.2 The use of PV technology in buildings

In the UK, the number of buildings using PV-generated energy is very small when compared to many other developed countries. Progress is, however, being made. In particular, the use of building-integrated photovoltaic (BIPV) systems is receiving much attention for use in institutional and commercial buildings. BIPV systems are integrated within the building fabric rather than being mounted over existing building elements. This has the advantage that the cost of the BIPV system can be offset against the cost of the building element it replaces. In extreme cases, there is no additional cost in using BIPV e.g. when replacing expensive glass curtain walling or polished stone. Examples of BIPV systems in the UK include the Jubilee Campus at Nottingham University (Studio E Architects Ltd., 2000) and Doxford Solar Office in Sunderland (Pearson, 1998) which boasts Europe's largest integrated PV wall.

In the domestic sector, one of the most notable examples of the use of BIPV systems is Dr. Susan Roaf's Solar House in Oxford (Chartered Institution of Building Services

Engineers [CIBSE], 2000). The Solar House (Figure 17) was constructed as a demonstration project to show the potential for grid-connected BIPV systems in the UK. This potential is being demonstrated on a larger scale at Ladbroke Grove, London where planning permission has recently been granted for a new housing scheme which includes the installation of $1500m^2$ of PV modules ("Developing sustainable," 2000). The scheme, proposed by London housing association and regeneration agency the Peabody Trust, represents the UK's largest BIPV project. In addition to BIPV systems in new-build dwellings, PV systems can also be retrofitted to existing dwellings. An example is shown in Figure 18 where solar roof tiles have replaced the original roof tiles.

Despite these examples, the use of PV systems is still not currently economically feasible in the UK. This situation could change, however, if the UK Government were to follow the lead of other countries. For example, Germany launched a five year publicly financed market introduction programme in 1999 to install 100,000 residential grid-connected rooftop PV systems (Studio E Architects Ltd., 2000). Originally, assistance to householders took the form of a ten-year, interest-free loan to cover the cost of installing a PV system in their dwelling. This loan was to be repaid in nine annual instalments with the final year instalment of 10% being waived. In addition, early in 2000 the German Government offered 99 Pfennig (approximately 30 pence) for every kilowatt-hour of PV-generated capacity (Maycock, 2000). The combination of the two subsidies made PV fully economic in comparison with conventional electricity generation (Table 39). Interest from the German public exceeded expectations and the Government revised the original loan conditions (now 4.5% interest rate with no 10% subsidy) to ensure the whole project remained financially viable. However, the cost of electricity generated from PV under this revised programme is still comparable with that generated from conventional means (Table 39). It can also be seen from Table 39 that PV electricity would be considerably more expensive than conventional electricity without any form of Government subsidy.

Figure 17. The Solar House in Oxford: grid-connected with PV system integrated into the roof. (From CIBSE, 2000.)

Figure 18. Solar roof tiles installed on a dwelling in the UK. (From Toggweiler, 1999.)

Table 39. Economics of German residential grid-connected rooftop PV programme. (Adapted from Maycock, 2000.)

Option	**Conventional electricity price ($/kWh)**	**PV electricity price ($/kWh)**
No Government subsidy	0.22	0.60
Original plan: 10% subsidy 0% interest 99 Pfennig for PV-generated electricity	0.50	0.34
Revised plan: no subsidy 4.5% interest 99 Pfennig for PV-generated electricity	0.50	0.525

Japan also has a residential grid-connected rooftop PV programme which aims to install approximately 70,000 PV systems (Maycock, 2000). It started in 1994 with a Government subsidy for 50% of the cost of the installed system. This reduced to about 35% in 1999. Despite this reduction in the subsidy, the Government received over 17,000 applications for systems in 1999 (Table 40). As this was more than double the number of applicants of the previous year (Table 40), the Japanese Government decided that PV is now a 'real business' and it is intending to stop the subsidy in 2002 (two years earlier than originally planned).

Table 40. Progress of Japan's rooftop PV programme. (Adapted from Maycock, 2000.)

Fiscal year	**Number of systems**	**Cumulative number of systems**	**System price ($/Wp)**	**Installed capacity (MW)**
1993	0	0	12.00	0.03
1994	539	539	11.00	1.9
1995	1065	1604	10.50	3.9
1996	1986	3590	10.00	7.5
1997	5654	9288	9.50	19.5
1998	8229	17,473	9.00	31.6
1999	17,000	34,473	8.50	54-68

The programs described for Germany and Japan are not unique. Government supported residential rooftop PV programmes also exist in the USA, Switzerland, Italy, the Netherlands, Spain and Australia (Maycock, 2000). If the UK Government funded a similar incentive scheme, it is likely that the rate of installation of domestic PV systems in the UK would greatly increase. In February 1999, the UK Government launched a field trial for around 100 dwellings across the country to test a variety of actual PV installations under real conditions (DTI, 1999). Recently, the Government announced its intentions to launch a more substantial demonstration programme (Ends Daily, 2001) but the details have still to be finalised. It is therefore important to include an approach for considering PV systems in the SEP system to allow local authorities to plan for their future uptake. Before describing the approach (Section 5.5), the important concepts in PV system design are explained.

5.3 The photovoltaic cell

PV cells essentially consist of a junction between a ‘p’ (positive)-type semiconductor and an ‘n’ (negative)-type semiconductor i.e. a p-n junction (Figure 19). These semiconductors are usually made from silicon, one of the most common elements on earth. P-type semiconductors are doped with small amounts of an impurity (usually boron) which causes the material to have a deficit of free electrons (or a surplus of holes). N-type semiconductors are doped with a different impurity (usually phosphorus) and possess a surplus of free electrons.

Light can be considered to consist of discrete energy units called photons. When light of a suitable wavelength falls on the p-n junction, a photon is absorbed by an atom of silicon. Provided the photon has sufficient energy, an electron from the outer shell of the atom is freed. This process results in the formation of a hole-electron pair: a hole where there is no electron and an electron moving freely throughout the material. Some of the electrons and holes will recombine almost immediately but this recombination process is reduced by the p-n junction. This barrier inhibits the free migration of electrons, leading to a build up of electrons in the n-region and a deficiency of electrons in the p-region. The flow of electrons to the n-region is an electric current. If there is an external circuit for the current to flow through, the moving electrons will eventually flow out of the semiconductor via one of the metallic contacts on the top of the cell (Figure 19). The holes, meanwhile, move in the opposite direction through the material until they reach another metallic contact on the bottom of the cell (Figure 19). Here they recombine with the electrons entering from the other half of the external circuit.

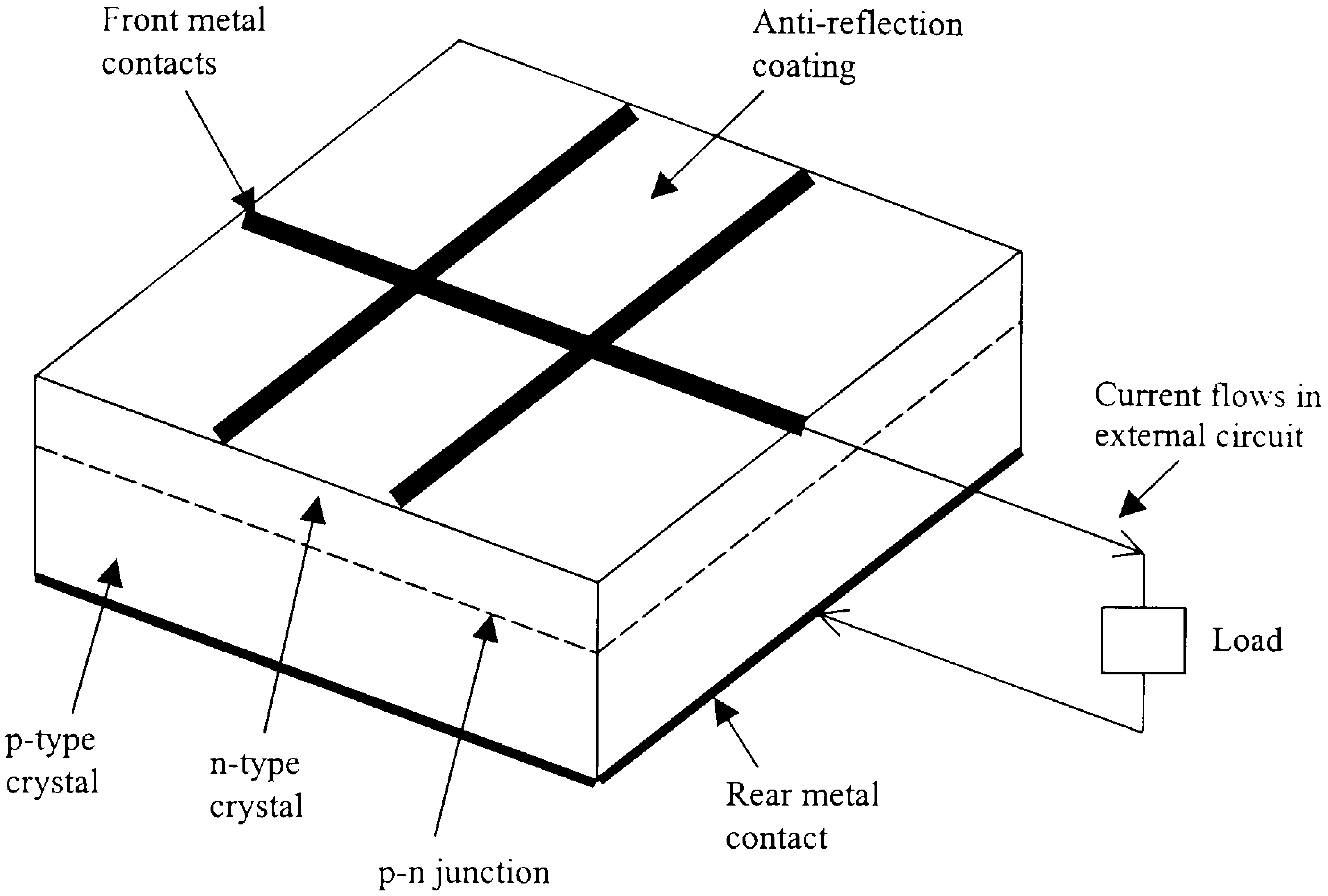


Figure 19. A silicon solar cell. (Redrawn from Treble, 1991.)

The electrical output from a single PV cell is small. Cells are therefore connected together and encapsulated (usually behind glass) to form a module. Any number of modules can be connected together to give the desired electrical output. There are several different types of PV module available. Expenditure on research and technology has been concentrated on increasing the efficiency and reducing the manufacturing costs of these modules. The efficiency of a PV module is simply its electrical energy output divided by the incident solar irradiation. The higher the efficiency, the greater the electrical output for the same solar irradiation. It is also important to reduce manufacturing costs to make PV generated electricity more economic in comparison with conventional forms of electricity generation. The three most common cell types currently used in PV modules are monocrystalline silicon, polycrystalline silicon and thin film amorphous silicon.

Monocrystalline silicon cells are made using a slice from a single crystal of silicon that has virtually no defects or impurities. PV modules made from monocrystalline cells are the most efficient (Table 41) but they also tend to be the most expensive to manufacture (Table 42).

Table 41. PV module efficiencies for production modules on the market. (Adapted from Maycock, 1999.)

PV cell technology	**PV module efficiency (%)**		
	1998	**2000**	**2010 (forecast)**
Monocrystalline silicon	14-16	18	22
Polycrystalline silicon	13-15	16	20
Amorphous silicon	6-8[a]	10[b]	14[b]
Copper indium diselenide	7-8	12	14
Cadmium telluride	7-8	12	14

[a] The lower value is for single junction cells; the higher value for multi-junction cells.
[b] These values correspond to multi-junction cells.

Table 42. PV module manufacturing costs for production modules on the market. (Adapted from Maycock, 1999.)

PV cell technology	**PV module manufacturing cost ($/W)**		
	1997	**2000**	**2010 (forecast)**
Monocrystalline silicon	3.90 - 5.00	2.00 - 3.50	1.20 - 2.50
Polycrystalline silicon	3.90 - 4.25	1.50 - 2.50	1.20 - 2.00
Amorphous silicon	2.50 - 4.00	1.20 - 2.00	0.75 - 1.25
Copper indium diselenide	-	1.20 - 2.00	0.72 - 1.25
Cadmium telluride	-	1.20 - 2.00	0.75 - 1.25

Polycrystalline silicon cells essentially consist of small grains of monocrystalline silicon. Modules made from polycrystalline cells are usually easier and cheaper to manufacture than monocrystalline modules (Table 42) but they are less efficient (Table 41) as the electrons and holes can recombine at the boundaries between the grains.

In thin film amorphous silicon cells, the silicon atoms are much less ordered than in the crystalline form. The cells are made by depositing a thin layer of amorphous silicon (only a few microns thick) on a suitable substrate (backing material) such as stainless steel. PV modules made from thin film amorphous silicon are cheaper to produce than crystalline modules (Table 42) but they have substantially lower efficiencies (Table 41). Traditional thin film amorphous silicon cells, however, have only a single PV junction. Recent developments in thin film technology have shown that layering two (or more) PV junctions on top of one another to create a so-called multi-junction cell can significantly improve overall efficiencies (Table 41) (Boyle, 1996).

A number of other promising modules are being developed with the aim of reducing cost and increasing efficiencies. For example, thin film cells using cadmium telluride and copper indium diselenide are now in production. These tend to be cheaper to produce than the expensive crystalline silicon technologies (Table 42) but typically offer higher efficiencies than amorphous silicon (Table 41).

It can be seen from Tables 41 and 42 that the efficiencies of all types of PV modules are forecast to increase while manufacturing costs are predicted to decrease. If these trends occur, the cost to the consumer of purchasing PV modules will decrease. However for these forecasts to become reality, the subsidised grid connected rooftop PV programmes described in Section 5.2 need to stimulate the installation of quality, reliable systems in sufficient quantities to encourage the investment in large-volume manufacturing plants (Maycock, 1999).

5.4 Typical PV systems in the UK domestic sector

The necessary electrical demand of a typical UK household – i.e. its demand for energy in forms (such as lighting, radio and television) that necessitate the use of electricity – is currently around 1000 kWh a year (Boyle, 1996). To supply this necessary electrical demand, at least 10m^2 of PV panels with a 1 kW capacity would be required. However, this would not guarantee an adequate electricity supply. In the UK, the electrical output from a PV system is at its maximum in summer when demand is at its lowest and at its minimum in winter when demand is at its peak. Furthermore, electricity is only generated during the day but consumption is likely to be required at night. This might suggest the need for an extremely large battery to store PV-generated electricity until it is required but the size and cost of such a battery would currently be prohibitive in most cases. Alternatively, at considerable extra cost, the PV array could be made much larger than is necessary for summer use to provide satisfactory power levels in winter. Or a second, backup energy system (such as a diesel generator) could be installed to provide power when the output of the PV array is inadequate. These autonomous (i.e. non grid-connected) PV power systems are only economically viable in the most remote locations which are a considerable distance from the electricity grid. In urban locations, auxiliary electricity requirements are supplied by the grid.

The configuration of a typical grid-connected PV system is shown in Figure 20. An inverter converts the direct current (DC) generated by the PV modules to the alternating current (AC) required by normal appliances. In addition to importing additional power from the grid when required, any excess power generated by the dwelling can be exported to the grid. This has the potential to reduce overall electricity bills for the householder. UK electricity companies, however, typically only pay as little as 2 pence/kWh for power sold to them but charge up to 7 pence/kWh for power bought from them (Elliott, 2001). This obviously reduces the attractiveness of grid-connected PV systems. Contrast this with Germany where the Government is paying 99 Pfennig (approximately 30 pence) for each kilowatt-hour of PV-generated electricity (Section 5.2). Pressure is being put on UK electricity companies to accept the idea of 'net metering'. This would ensure that consumers who export power to the grid are only charged, at reasonable rates, for the net amount of power transferred to them from the grid. One UK electricity company (Eastern, now part of TXU Europe) is offering this option (Elliott, 2001).

Now that the general principles of PV cells have been explained and it has been described how grid-connected PV systems are suitable for installation in dwellings, an approach for determining the potential yield of domestic PV systems is proposed.

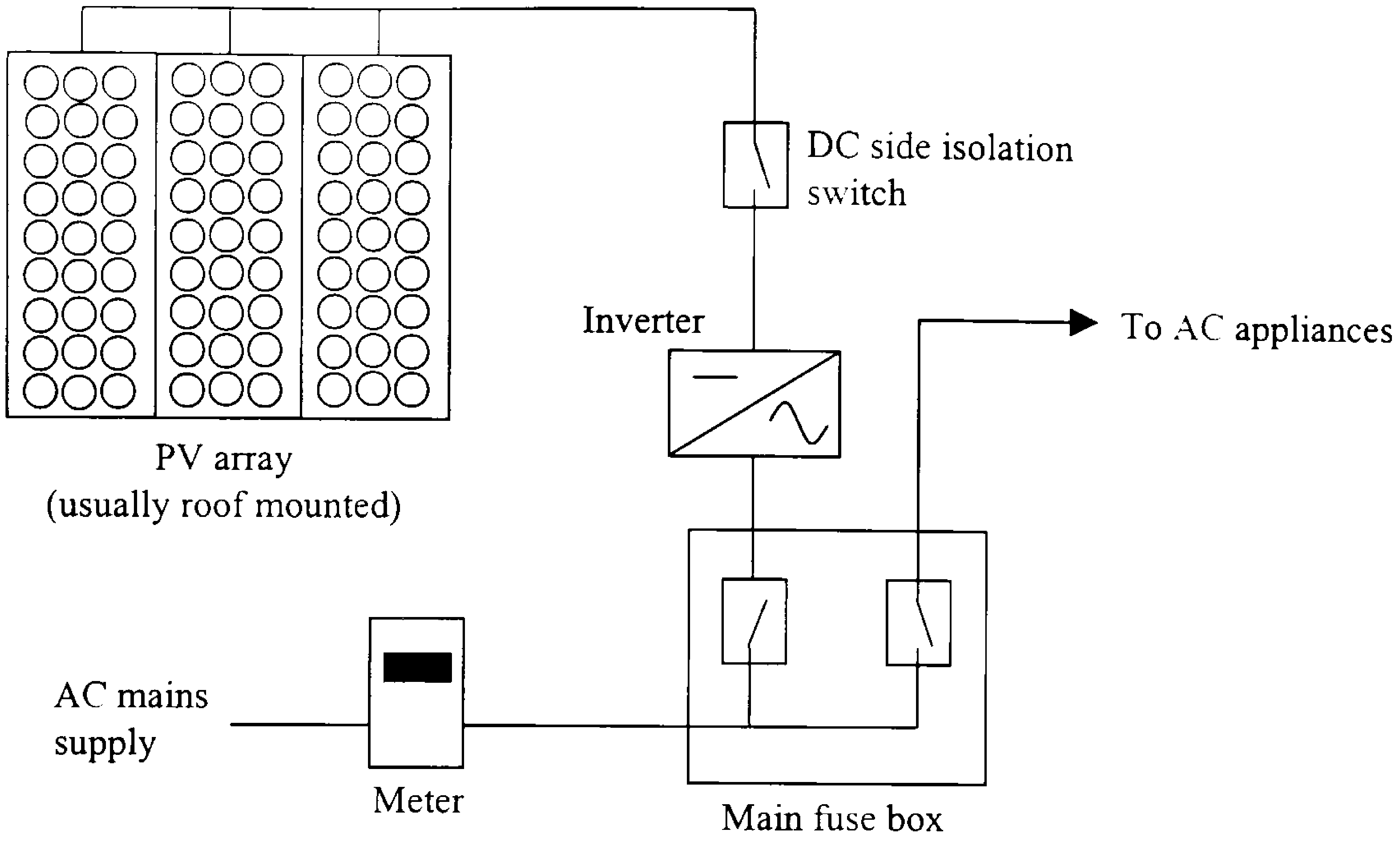


Figure 20. A typical grid-connected PV system in the UK. (Redrawn from British Photovoltaic Association, 2000.)

5.5 Determining the potential yield of domestic PV systems

The proposed three-stage approach for determining the potential yield of solar DHW systems (Section 4.4) provides a useful framework for analysing domestic PV systems as described in the following sections.

5.5.1 Stage 1: Filtering

As with solar DHW systems, it can be assumed that most domestic PV systems will be installed on the roof. This allows the first three filtering criteria described in Section 4.4.1 to be used directly.

1. Identify restrictions which may prevent the installation of a domestic PV system.
2. Roof orientation must lie between ± 45° of south.
3. Roof inclination must lie between 0° and 60°.

The final filtering criterion proposed for solar DHW systems was that roof area must be greater than $3m^2$. It was discussed in Section 5.4 that a PV array area of approximately

$10m^2$ is required to meet the 'necessary' electrical demand of a dwelling during peak summer months. Consequently, the criterion proposed for domestic PV systems was that roof area must be greater than $10m^2$. This could be changed in future as PV modules become more efficient and hence the required area decreases.

Another important aspect to consider is shading on the roof plane. Unlike solar DHW systems, the performance of a PV system is extremely sensitive to even slight overshading. This is because the cells in PV modules are wired together in series strings (Figure 21). If cell A in Figure 21 is shaded, it effectively acts as a resistive load in the series string in which it is connected. The operating current of the string is greatly reduced resulting in decreased energy output from the PV module. An example of the effect of shading on the performance of a roof mounted monocrystalline array is given in Figure 22.

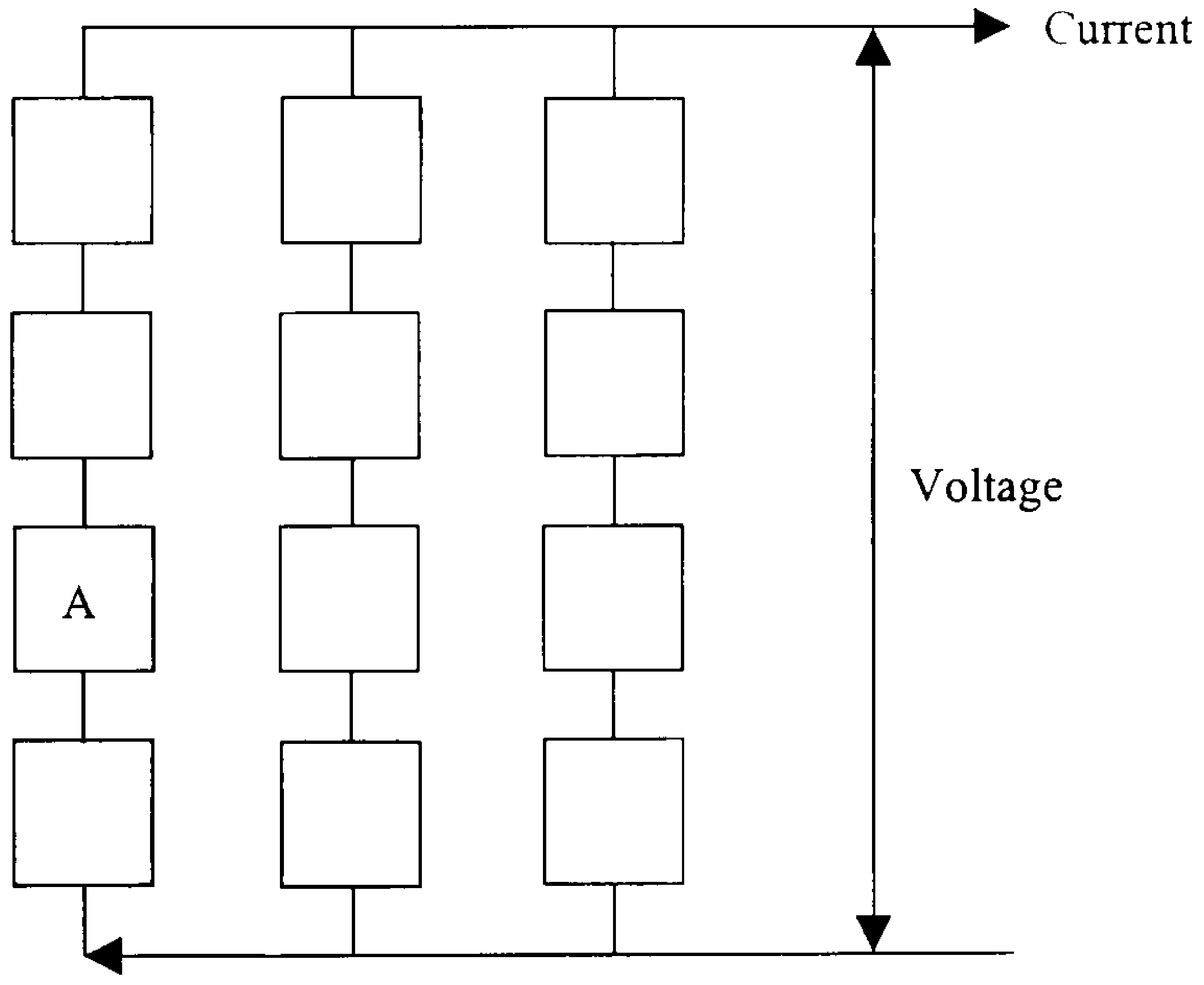


Figure 21. Typical wiring arrangement of a PV module. (Adapted from Max Fordham & Partners, 1999.)

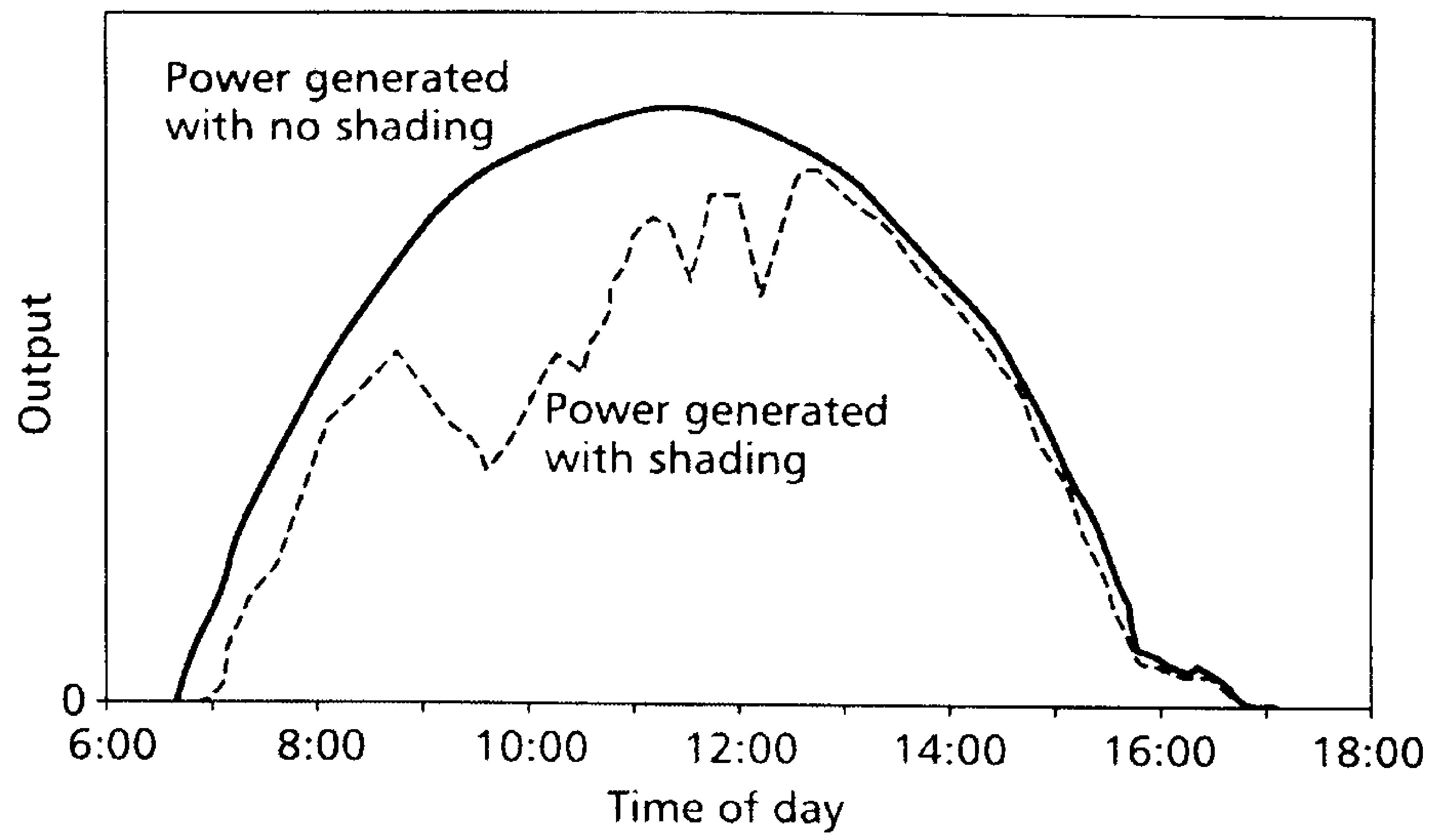


Figure 22. An example of the effect of shading on power output from a PV array. (From CIBSE, 2000.)

As for solar DHW systems, it was proposed that the rapid site survey described in Section 3.5.1 would be used to identify possible shading problems on the roof plane. If a dwelling meets all the filtering criteria it can be passed to the remaining stages with the proviso that a rapid site survey is performed.

5.5.2 Stage 2: Targeting

The targeting approach described in Section 4.4.2 compares dwellings against a set of socio-economic parameters to provide an indication of the likelihood that householders will install a solar DHW system. As PV systems are currently not economically feasible in the UK, the targeting process was omitted from the proposed approach to determine the potential yield of domestic PV systems. It could be included in future if (and when) PV systems fall to a more affordable level. For example, the targeting process could be used to target wealthy owner occupiers if the Government introduces a subsidised rooftop PV programme.

5.5.3 Stage 3: Calculating

It was necessary to choose an appropriate calculation model to quantify the potential yield of domestic PV systems. This selection process is described in the following section.

5.6 Selecting a PV calculation model

There are a number of different methods for modelling PV systems. The main criteria when selecting the PV calculation model were the same as those described for the solar DHW calculation model (Section 4.5). Briefly these were that the model should predict the monthly performance of a domestic PV system with acceptable accuracy whilst minimising input and computational overheads. In addition, the model should require minimal user expertise and be easily integrated into the SEP system.

A report published by the Energy Technology Support Unit (ETSU) (Studio E Architects Ltd., 1997) contains an extensive review and assessment of PV design tools. The report identifies twenty-four suppliers of computer- and paper-based PV design tools in Europe and North America. Of these, the nine most widely used tools were evaluated (Table 43). The ETSU report categorised the PV design tools into three groups to represent the three main stages in the design of a building: preliminary design, outline technical design and detailed technical design (Table 43).

At the preliminary design stage, a quick and easy to use PV tool is required. This should give an informed estimate of the likely potential of PV according to basic building parameters. At outline technical design, the PV tool should provide a reliable forecast of PV output using locally obtained weather data and knowledge of site shading. The tool should also include a comprehensive PV component library describing modules, inverters, etc. Finally at the detailed technical design stage, the tool should aid the design of the optimum PV configuration, wiring and system connections. The requirements of the PV calculation model for the SEP system are commensurate with the preliminary design group.

Table 43. PV design tools evaluated in the ETSU report. (Adapted from Studio E Architects Ltd., 1997.)

Tool	**Country of origin**	**Format**	**Preliminary design**	**Outline technical design**	**Detailed technical design**
WATSUN PV	Canada	DOS	√	√	
PV Syst	Switzerland	Windows	√	√	
PV Cad	USA	DOS	√	√	
PV Calc	Austria	DOS	√		
PVS	Germany	Windows	√		
PV Form	USA	DOS	√		
ECOFYS	Holland	Nomogram	√		
Realgoods	USA	Worksheet	√		
Alternative energy	USA	Worksheet	√		

It can be seen from Table 43 that none of the PV models evaluated in the ETSU report are capable of performing detailed technical design. Only three of the models (WATSUN PV, PV Syst and PV Cad) are able to analyse PV systems at the outline technical design stage. Of these three computer-based models, PV Syst was considered to be reasonably comprehensive covering most aspects of PV design. However, it requires considerable PV and computing expertise. WATSUN PV and PV Cad were also considered to require a steep learning curve before they could be used successfully. None of these models appeared to meet the requirement of the SEP system that the PV calculation model should require minimal user expertise.

Three of the tools which are only able to consider PV at the preliminary design stage are also computer-based. These are PV Calc, PVS and PV Form. The ETSU report concluded that PVS was the best model at this design stage. Although these three models consider PV systems at a level of detail better suited to the SEP system, they are all proprietary software programs. This poses problems of obtaining permission to either use the software directly or, more usefully, implement the source code within the SEP system. As with the solar DHW calculation model (Section 4.5), it was decided not to use an existing software programme in this project.

The remaining design tools considered in the ETSU report (ECOFYS, Realgoods and Alternative Energy) are paper-based evaluation models which have the potential to be made into customised computer applications. ECOFYS uses a nomogram to determine PV electrical output. Graphical methods are not well suited to computerisation and so the use of this method was not pursued further. The Alternative Energy worksheet (SolarElectric.com, 2000) bases its method on knowledge of the electrical load of a building. This is unlikely to be accurately known for the vast majority of dwellings in a city. Consequently, this worksheet was not suitable for use as the domestic PV calculation model. It was not possible to obtain a copy of the Realgoods worksheet and so this model could not be evaluated.

A PV calculation method described in Duffie and Beckman (1991) also has potential to be made into a customised computer application for use in the SEP system. The method is based on research carried out by Evans (1981), Siegal, Klein and Beckman (1981) and Clark, Klein and Beckman (1984). Studies have shown that this model produces annual results which are comparable with that of more detailed simulation models (Clark et al., 1984). In addition, the model does not require much input data and most of it is relatively easy to obtain. The method is able to predict the monthly output from a PV system. As this model seemed to meet all the necessary criteria, it was chosen as the PV calculation model for the approach proposed in this thesis. Its implementation in the SEP system is described in the following section.

5.7 Implementation of the PV model in the SEP system

The input data required by the PV model is given in Table 44. Most of the data is either readily available or can be calculated from knowledge of other, easily obtained parameters. This section describes how the input data is obtained.

Table 44. Input data required by the PV model.

Parameter	**Symbol**	**Units**
Maximum power point efficiency of the PV module	$\eta_{mp,ref}$	-
Temperature coefficient of maximum power efficiency	μ_{mp}	-
Reference cell temperature at Standard Test Conditions	T_{ref}	°C
Transmittance of the cover over the cells	τ	-
Absorptance of the PV module	α	-
Heat loss coefficient	U_L	W/m^2K
Hourly solar irradiation incident on the PV array	$\bar{I}_T$	MJ/m^2
Sun position correction factor	Z_i	-
Hourly average air temperature	$\bar{T}_{a,i}$	°C
Efficiency of power conditioning equipment	η_e	-
Area of PV array	A_{array}	m^2

To obtain the maximum power point efficiency of the PV module, $\eta_{mp,ref}$, it is necessary to first select a suitable PV module. Several different modules are listed in Table 45. To enable comparison between different modules, their performance characteristics are measured under Standard Test Conditions (STC):

- incident irradiation, G_T, of 1000 W/m^2;
- reference cell temperature, T_{ref}, of 25°C;
- spectral power distribution of Air Mass (AM) 1.5.

At these STC, the PV module is connected to different resistive loads varying between zero (to give the short circuit current) and infinity (to give the open circuit voltage). This allows the so-called 'I-V curve' (or current-voltage curve) of the PV module to be created. An example I-V curve for a typical silicon PV module is shown in Figure 23. The cell delivers maximum power when the external resistance is adjusted so that its value corresponds to the maximum power point (Figure 23). The current at maximum power point, I_{mp} (A), and the voltage at maximum power point, V_{mp} (V), can then be determined (Table 45). Knowledge of these two parameters allows the maximum power point efficiency of the PV module to be calculated using

$$\eta_{mp,ref} = \frac{I_{mp} V_{mp}}{A_{module} G_T} \tag{5.1}$$

Table 45. Characteristics of different PV modules.

Manufacturer	**Model number**	**Type of solar cell**	**P_{mp} (W)**	**I_{mp} (A)**	**V_{mp} (V)**	**Width (mm)**	**Length (mm)**	**μ_{Voc} (V/°C)**	**$T_{c,NOCT}$ (°C)**	**Default no. of modules**
BP Solar	BP585F	Monocrystalline	85.0	4.72	18.0	530	1188	-0.086	47	16
BP Solar	BP580F	Monocrystalline	80.0	4.44	18.0	530	1188	-0.086	47	16
BP Solar	BP280F	Monocrystalline	80.0	4.70	17.0	530	1188	-0.0792	47	16
AstroPower	AP-1106	Monocrystalline	110	6.6	16.7	660	1476	-0.08	45	11
AstroPower	AP-1206	Monocrystalline	120	7.1	16.9	660	1476	-0.08	45	11
AstroPower	AP-50	Monocrystalline	50	3.0	16.7	660	858	-0.10	45	18
Siemens	SM55	Monocrystalline	55	3.15	17.4	329	1293	-0.077	45	24
Siemens	SP75	Monocrystalline	75	4.4	17.0	527	1200	-0.077	45	16
Solarex	SX-65	Polycrystalline	65	3.77	17.2	502	1105	-0.08	47	19
Solarex	SX-40	Polycrystalline	40	2.37	16.8	502	762	-0.08	47	27
Solarex	MSX-50	Polycrystalline	50	2.92	17.1	502	934	-0.08	47	22
Solarex	MSX-120	Polycrystalline	120	3.5	34.2	991	1108	-0.16	47	10
ASE	300-DGF/17	Polycrystalline	300	17.4	17.2	1282.7	1892.3	-0.076	45	5
ASE	300-DGF/50	Polycrystalline	265	5.3	50.0	1282.7	1892.3	-0.228	45	5
ASE	50-ATF/17	Polycrystalline	50	2.9	17.2	452.1	965	-0.076	45	23
Siemens	ST20	Thin film	20	1.29	15.6	747	328	-0.1	47	41
Siemens	ST40	Thin film	38	2.29	16.6	329	1293	-0.1	47	24

where A_{module} (m^2) is the PV module area (found by multiplying the length and width of the module in Table 45).

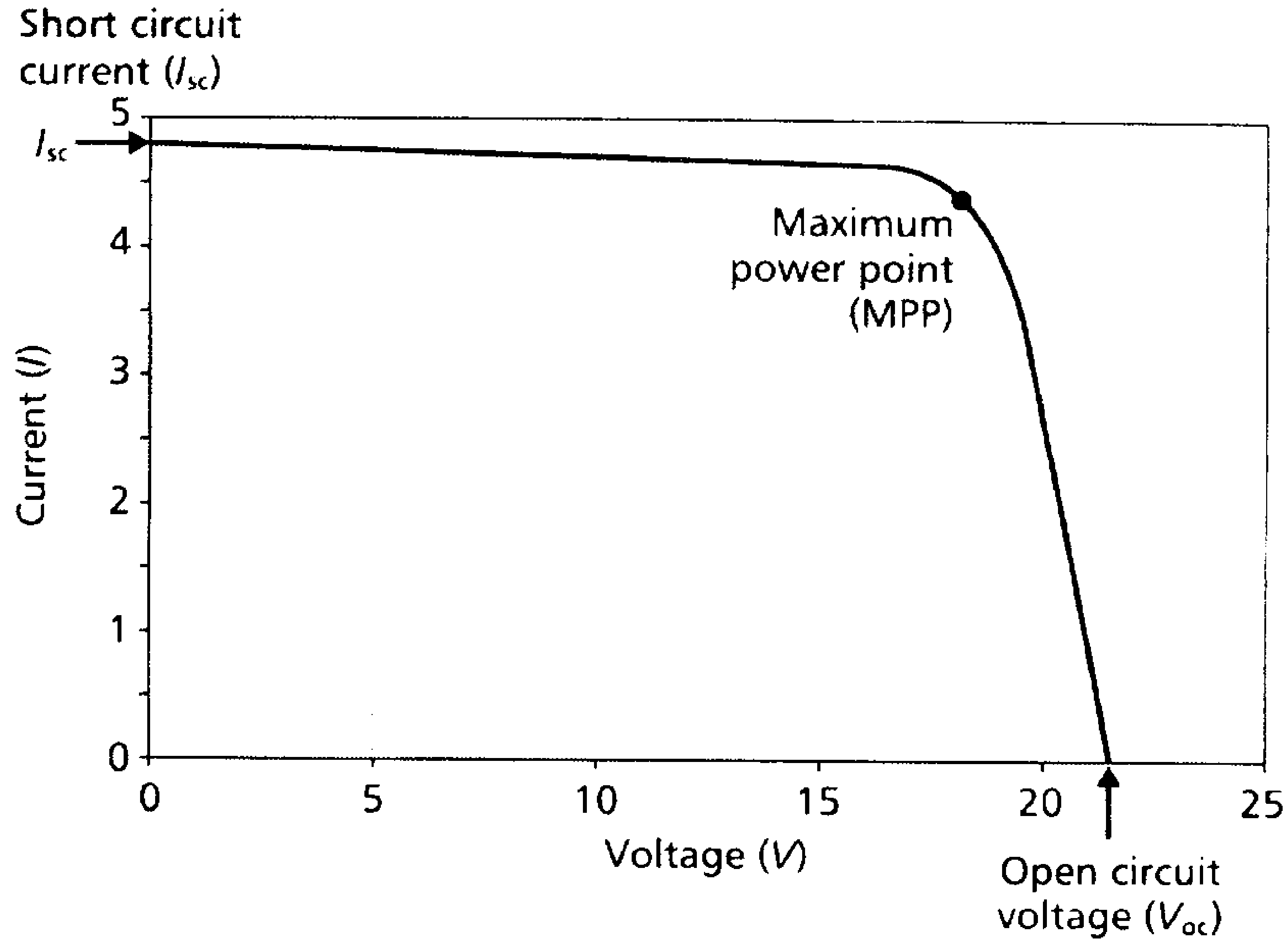


Figure 23. A typical current-voltage (I-V) curve for a PV module. (From CIBSE, 2000.)

From the module characteristics given in Table 45, it is also possible to calculate the temperature coefficient of maximum power efficiency, μ_{mp}. This is a measure of the temperature dependence of the maximum power point efficiency and is given by

$$\mu_{mp} = \eta_{mp,ref} \frac{\mu_{Voc}}{V_{mp}} \tag{5.2}$$

where μ_{Voc} is the temperature coefficient of the open circuit voltage.

PV modules operate most efficiently at low temperatures. However, the solar energy that is absorbed by a module is converted partly into thermal energy and partly into electrical energy. Heat transfer from the module should therefore be maximised to ensure the cells are operating at the lowest possible temperature. The heat transfer rate is represented by the ratio $\tau\alpha/U_L$ (m^2K/W) where τ is the cover transmittance, α is the module absorptance and U_L (W/m^2K) is the heat loss coefficient. To calculate $\tau\alpha/U_L$ it is necessary to know the nominal operating cell temperature, $T_{c,NOCT}$ (°C). This is given for the different modules in Table 45. The NOCT is defined as the cell or module temperature that is reached when the cells are mounted in their normal way at a solar irradiation level $G_{T,NOCT}$ of 800 W/m^2, a wind speed of 1 m/s, an ambient temperature $T_{a,NOCT}$ of 20°C and no load operation. This gives

$$\frac{\tau\alpha}{U_L} = \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOCT}} \tag{5.3}$$

The hourly solar irradiation incident on the PV array, $\bar{I}_T$ (MJ/m^2) is calculated using the approach adopted for the solar DHW calculation method (Section 4.6.1). This approach applies simple solar geometry processing to the monthly mean daily irradiation on a horizontal surface, given for twenty-one different regions in BREDEM-8 reference tables, to obtain hourly irradiation values. The Perez diffuse irradiance model for tilted surfaces is then used to calculate the diffuse irradiation incident on the PV array. Beam irradiation and the diffuse irradiation reflected from the ground are then added to give the hourly total solar irradiation incident on the PV array. The full approach is described in detail in Appendix F. The orientation and inclination of the PV array are determined at the filtering stage (Section 5.5.1).

The non-dimensional parameter Z_i (Table 44) accounts for variations in sun position, for a given hour, over the month. It is calculated using an empirical approach after Duffie and Beckman (1991):

$$Z_i = \left(\frac{\bar{I}_o}{\bar{I}_T}\right)^2 (a_1 b_1 + a_2 b_2 + a_3 b_3) \tag{5.4}$$

where

$$a_1 = R_b^2 + \rho(1 - \cos\beta)R_b + \frac{\rho^2(1 - \cos\beta)^2}{4} \tag{5.5}$$

$$a_2 = R_b(1 + \cos\beta - 2R_b) + \frac{\rho(1 + \cos\beta - 2R_b)(1 - \cos\beta)}{2} \qquad (5.6)$$

$$a_3 = \left[\frac{1 - \cos\beta}{2} - R_b\right]^2 \qquad (5.7)$$

$$b_1 = -0.1551 + 0.9226\,\bar{k}_T \qquad (5.8)$$

$$b_2 = 0.1456 + 0.0544 \ln \bar{k}_T \qquad (5.9)$$

$$b_3 = \bar{k}_T(0.2769 - 0.3184\,\bar{k}_T) \qquad (5.10)$$

and $\bar{I}_o$ is the hourly extraterrestrial irradiation (MJ/m^2), R_b is the ratio of beam irradiation on the tilted surface to that on the horizontal surface, ρ is the ground reflectivity (assumed to equal 0.2), β is the slope of the PV array (degrees) and $\bar{k}_T$ is the hourly clearness index. The values of $\bar{I}_o$, R_b and $\bar{k}_T$ are obtained during the procedure used to calculate the hourly solar irradiation incident on the PV array as described in Appendix F.

The hourly average air temperatures for the twenty-one regions listed in BREDEM-8 reference tables are unknown. However, the observations of Evans (1981) and Clark et al. (1984) showed that the sensitivity of array efficiency to ambient temperature is such that the monthly mean air temperature can be assumed for each hour without introducing significant error. The hourly air temperatures are approximated using the monthly mean daytime air temperatures calculated by Equation 4.5.

The efficiency of power conditioning equipment (or the balance of system efficiency), η_e, is the efficiency of the PV system excluding the PV modules (Sick & Erge, 1996). It is made up of three different factors.

1. The wire efficiency factor, η_{wire}, accounts for losses due to wiring and switchgear. PV systems should be designed to ensure the wire loss is less than 3% (i.e. $\eta_{wire} > 0.97$).
2. The inverter efficiency, η_{inv}, accounts for losses from converting the DC output of the PV array to AC. Inverter efficiencies are available from manufacturers. When unknown, it is usual to assume a value of 0.85.
3. The decreasing factor, η_{df}, accounts for losses from the remainder of the system including controls, meters and array imbalance. It is usually given a value of 0.9.

It was therefore possible to calculate a default value for the efficiency of power conditioning equipment using

$$\eta_e = \eta_{wire} \times \eta_{inv} \times \eta_{df} = 0.97 \times 0.85 \times 0.9 = 0.74 \tag{5.11}$$

Finally it was necessary to specify an array area, A_{array} (m^2). To allow the PV calculation to proceed automatically without user intervention, it was decided to specify a default number of modules for each of the modules shown in Table 45. Defaults were selected to make the PV array area approximately $10m^2$ i.e. the PV array area typically required to meet the 'necessary' electrical demand of a dwelling. For example, the BP585F module has an area of approximately $0.63m^2$. Hence, it has a default of sixteen modules giving an array area of $10.08m^2$. The default calculation automatically uses the most efficient PV module (BP585F) from Table 45. The user has the ability to change both the default module type and the default array area. In future, the calculation procedure could be modified so that the PV array was sized to meet the base electrical load of the dwelling during summer months. This would ensure that most of the PV generated electricity was being used locally and not exported to the grid.

5.7.1 Calculating the electrical power output of a PV system

With all the input data now obtained, the PV calculation is able to proceed. It is carried out for every daylight hour on the mean day of every month. The monthly hourly average array efficiency, $\overline{\eta}_i$, is calculated using

$$\overline{\eta}_i = \eta_{mp,ref}\eta_e\left[1+\frac{\mu_{mp}}{\eta_{mp,ref}}\left(\overline{T}_{a,i}-T_{ref}\right)+\frac{\mu_{mp}\,\overline{I}_T}{\eta_{mp.ref}}\frac{1\times10^6}{3600}\frac{\tau\alpha}{U_L}\left(1-\eta_{mp,ref}\right)Z_i\right] \tag{5.12}$$

The hourly average array electrical energy output, $\overline{E}_i$ (Wh), can then be calculated by multiplying this efficiency by the solar irradiation incident on the PV array and the array area i.e.

$$\overline{E}_i = \left(\overline{\eta}_i\ A_{array}\ \overline{I}_T\right)\times\frac{1\times10^6}{3600} \tag{5.13}$$

where $1\times10^6/3600$ converts from MJ to Wh.

Summing the hourly average array electrical energy output for each hour of the day gives the daily average array electrical energy output. This figure can be multiplied by the number of days in the month to get the monthly array electrical energy output and all months added together to obtain the annual PV electrical yield.

It is assumed that all of the electrical energy output from the PV system is used either directly in the dwelling or fed into the grid. However, the actual split between the two is not calculated. This requires knowledge of the electrical load of the dwelling for each hour of the day. If this data could be determined, a calculation procedure could be added to the PV model in future to show the relative proportions of electricity used in the dwelling and exported to the grid.

The reduction in CO_2 emissions can be found by multiplying the electrical energy output of the PV array by the CO_2 emission factor for electricity (0.51 kg CO_2 per kWh from Table 36).

5.8 Empirical comparison with the Oxford Solar House

As stated in Section 5.6, the PV calculation model proposed for the SEP system was compared against detailed simulation models and was shown to be producing acceptably accurate results (Clark et al., 1984). This gives confidence in the use of the model. However, it was important to check that the implementation of this model in the SEP system was producing accurate results. This was achieved by comparing the model with both the predicted and actual performance of the PV system installed in the Oxford Solar House (Figure 17).

Initially, the input data required by the PV calculation model had to be determined. According to the regions defined in BREDEM-8 (Appendix A), the Oxford Solar House is located in Thames Valley. As a result, all climate data entered into the PV calculation model corresponded to this location. The PV array faces due south (i.e. surface azimuth angle = 0°) and is located on the roof which has an inclination of 50°. The array consists of forty-eight BP585F monocrystalline modules (characteristics shown in Table 45). The inverter efficiency of the PV system is 79% which gives an efficiency for power conditioning equipment of 0.69 (after Equation 5.11).

The annual electrical energy output predicted by the PV calculation model implemented in the SEP system is given in Table 46 along with the actual output of the system for 1996 (Roaf &Walker, 1997). Also shown in Table 46 is the electrical energy output predicted by BP Solar (installers of the PV system in the Oxford Solar House) during the design stage of the PV system (Roaf &Walker, 1997).

Table 46. Comparing actual performance with predictions of electrical energy output for the PV system installed in the Oxford Solar House.

	Annual electrical energy output	**Difference: Prediction - Actual**		**Difference: SEP - BP**	
		kWh	**%**	**kWh**	**%**
Actual performance	2937	N/A	N/A	N/A	N/A
Prediction: BP Solar	3200	+ 263	+ 9.0	N/A	N/A
Prediction: SEP system	3355	+ 418	+ 14.2	+ 155	+ 4.8

It can be seen from Table 46 that both BP Solar and the SEP system overestimated the annual electrical energy output from the actual PV system (by 9% and 14.2% respectively). There could be a number of reasons for this overestimation including differences between the solar irradiation data used in the calculation models and that experienced by the actual PV array. In addition, it has also been found that the cable from the inverter to the distribution board in the actual PV system is undersized and probably introduces an unnecessary voltage drop (CIBSE, 2000). This could have an adverse effect on the performance of the PV system.

The predictions from BP Solar and the PV model implemented in the SEP system differ by under 5% (Table 46). The prediction from BP Solar was considered to represent a good estimate of performance and so it was concluded that the PV model implemented in the SEP system was producing results which could be used with confidence. In addition, this difference between the predictions only results in a small difference in absolute cost savings (approximately £12.40 assuming electricity at 8 pence/kWh). This is insignificant when compared to the actual cost of the PV system of £28,300 (CIBSE, 2000). Although it is estimated that the system cost would have fallen to £16,000 by 1999, it can be seen that PV systems are still extremely expensive and thus small differences in performance prediction are not important in determining payback times.

The monthly predictions of electrical energy output from the PV model implemented in the SEP system are shown in Figure 24. No data was available to compare these predictions with the actual performance of the PV system. It can be seen from Figure 24 that the PV model predicts more than double the electrical energy output for the peak summer months when compared to the winter months. This corresponds with the real PV system where most of the output occurs during summer (CIBSE, 2000).

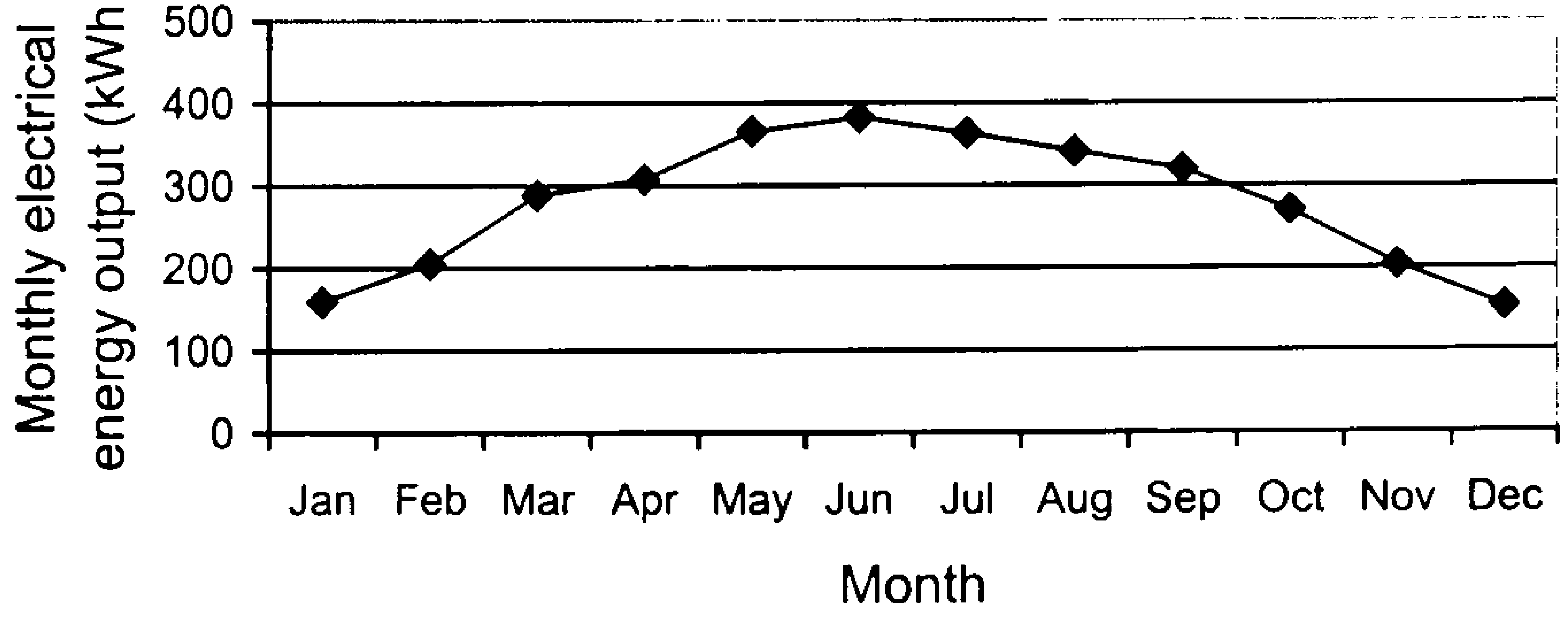


Figure 24. Predictions of monthly electrical energy output from the PV model implemented in the SEP system.

It was concluded that the PV model implemented in the SEP system is producing acceptably accurate predictions of electrical energy output. However, it would be useful to compare the model against real monthly data if it became available.

5.9 Summary

This chapter initially described the current position of the PV market in the UK. Government incentive schemes in Germany and Japan were discussed and it was shown that they are increasing the number of residential grid-connected PV systems installed in these countries. It was postulated that a similar scheme in the UK could rapidly increase the installation rate of PV systems. As a result, it was considered important to include an approach for estimating the potential yield of domestic PV systems in the SEP system. The proposed approach makes use of the three stages developed for evaluating solar DHW systems in Chapter 4: filtering, targeting and calculating. The calculation procedure is based on a method presented in Duffie and Beckman (1991) after the work of Evans (1981), Siegal et al. (1981) and Clark et al. (1984). All the input data is obtained automatically to reduce the level of user interaction required. Empirical comparisons with data from the Oxford Solar House have shown that the method proposed in this thesis is producing results which are acceptably accurate for use in the SEP system.

Some of the methods described in Chapters 3 to 5 have the potential to be developed into an approach to allow the passive solar design of dwellings to be considered. Some initial proposals are discussed in Chapter 6 which could form the basis of an extension to the SEP system.

Chapter 6

Passive Solar Design

6.1 Introduction

The passive solar design of buildings aims to intentionally use solar radiation as a source of energy for heating. It is primarily of importance for new housing estates, where careful consideration of site layout can greatly increase potential for direct solar gain. Existing dwellings obviously have a fixed location and are unlikely to benefit from passive solar design measures.

In the UK, approximately 200,000 new dwellings are built each year (Boardman, 1997). This represents only about 1% of the total UK dwelling stock. Although it is important to reduce the energy demand of new dwellings by good passive solar design, the installation of active solar technologies in existing dwellings has greater potential for energy savings and reductions in CO_2 emissions (Section 1.1). In this thesis, passive solar design was not considered in such depth as solar DHW and PV systems. This chapter presents initial proposals for considering the main aspects of passive solar design. These build upon some of the approaches described in the preceding chapters. The work is intended to be the basis of an extension to the SEP system.

6.2 Considering passive solar design in the SEP system

The passive solar design of housing estates can produce energy savings of up to 10% when compared to a conventional estate layout (DoE, 1997b). Although these savings are significant when applied over a whole site of houses, they are small when compared to other energy efficiency measures. For example, the ratio between the energy benefit of good insulation to solar layout is of the order of 10 to 1 (NBA Tectonics, 1995).

Passive solar design should therefore always be considered as part of a low energy design approach.

The use of BREDEM-8 to predict the energy consumption of dwellings was described in Chapter 3. It also has the capability to consider the passive solar design of dwellings as demonstrated by NBA Tectonics (1993a, 1995). One of the reasons for choosing BREDEM-8 as the domestic energy model for the SEP system was that it produces results on a monthly basis and so can consider solar sensitive energy systems (Section 3.2). BREDEM-8 would therefore appear to be well suited as the basis for considering the layout of new housing estates. Such a tool could be useful to planners for the following reasons.

On land owned by local authorities, planners have control over the design and layout of proposed new housing estates. They can set energy consumption targets which developers are required to meet to ensure the proposed estate does not consume excessive energy. For example LCC, in partnership with the Institute of Energy and Sustainable Development (IESD), De Montfort University, are currently formulating an energy strategy for their new Ashton Green development (Ajiboye, Fleming & Devine-Wright, 2001). There are plans to include up to 4000 dwellings on the site and draft proposals expect these dwellings to meet the zero CO_2 standard suggested by the DETR (1998a). Energy use within zero CO_2 dwellings is approximately 50% lower than dwellings built to current building regulations. In addition, zero CO_2 dwellings rely on the concept that all delivered energy is supplied from renewable sources. Hence, it would be useful for planners to have a single tool which enabled them to consider both passive solar design and active solar technologies.

There are essentially two important concepts in passive solar design: design of the individual dwellings on the estate and the layout of the estate. Unless there are passive solar design features in the individual dwellings, there is little or no scope for the site layout to take advantage of either better orientation or the avoidance of overshading (NBA Tectonics, 1995). For example, there is no advantage from a southern orientation if there is no particular façade in the dwelling which benefits from facing south.

Accordingly, the following section discusses important passive solar measures which should be considered when designing a dwelling. It also proposes approaches which planners could use to identify design improvements that reduce energy consumption.

6.3 Passive solar design of individual dwellings

6.3.1 Compact form

One of the major concerns when designing for reduced space heating demand is to produce a compact building form (e.g. DoE, 1997b; NBA Tectonics, 1993b). In general, the smaller the exposed envelope area enclosing a heated volume the lower the heat loss (Figure 25). It can be seen from Figure 25 that factors affecting the size of a dwelling's external envelope include the number of storeys and its detachment from other dwellings. Insulation levels can be increased to offset the energy penalty of a non-compact form but this is likely to result in higher construction costs. In addition, dwellings with irregular forms such as L- or U-shapes (Figure 25) may overshadow themselves if given the wrong orientation. It should be noted that minimising the external surface area can reduce the scope for daylighting and natural ventilation. However, this is only likely to affect non-domestic buildings and there should be no such problems in dwellings.

It is difficult to sensibly quantify the 'compactness' of a dwelling. Even though rows of terraces will nearly always be more compact than a detached dwelling, some estates specifically require detached dwellings. Furthermore, dwellings of the same type will have different heated volumes (e.g. a 4-bedroom detached dwelling is likely to be much larger than a 2-bedroom detached dwelling). Compact form is an issue which planners must be aware of but it is unlikely that an approach could be developed to help them consider this issue.

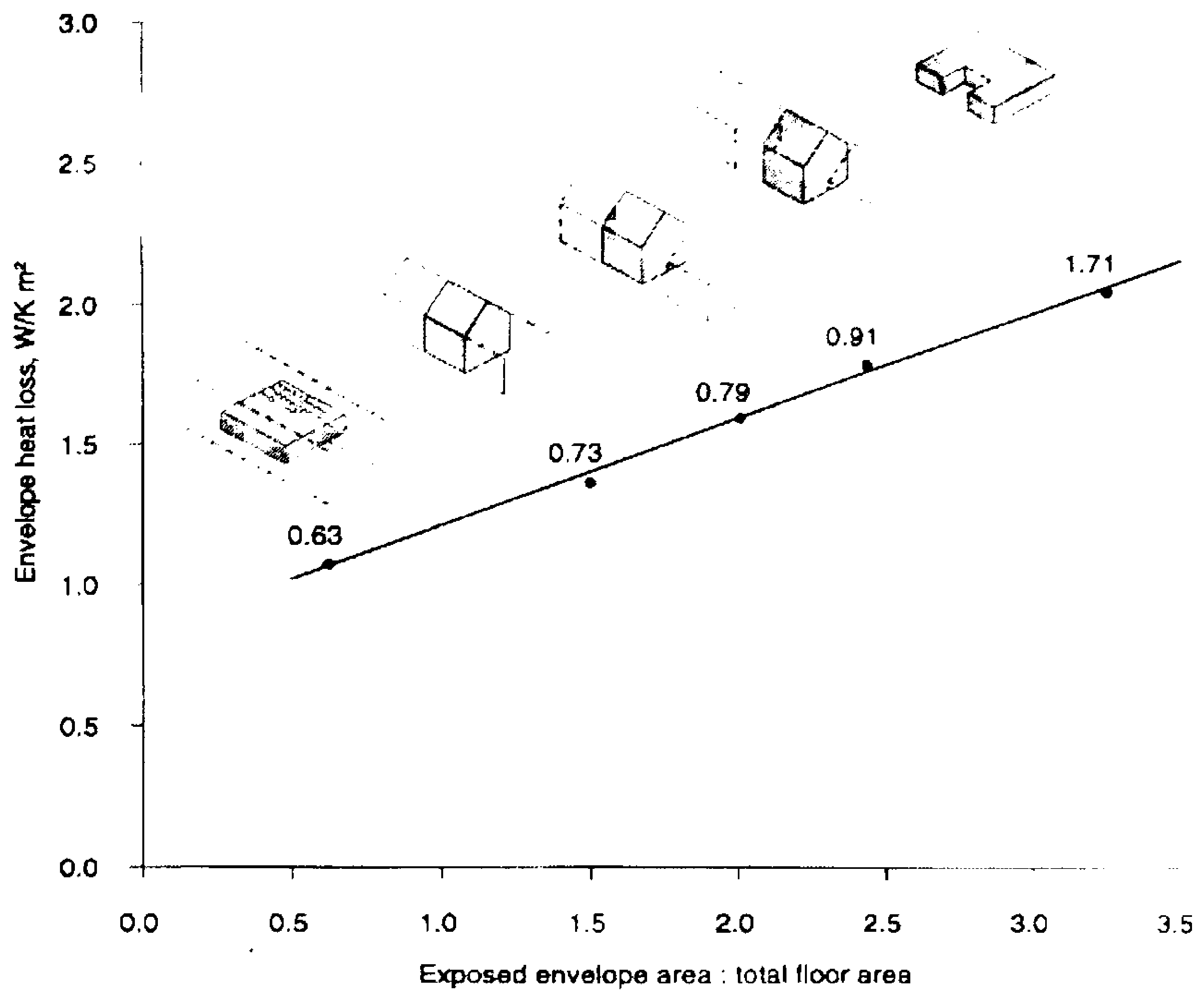


Figure 25. Heat loss through building envelope as a function of dwelling type (based on fixed floor area and volume and using 1990 Building Regulations). (From Yannas, 1994a.)

6.3.2 Internal layout

The internal layout of dwellings also influences their ability to make use of direct solar gain. The highest heat demand is commonly associated with living rooms and so they benefit from a southerly orientation. Bedrooms can also usefully benefit from solar gain, especially if they are used as children's play areas. Studies have shown that wide frontage dwellings allowing both living and dining rooms to have a southerly aspect have no significant advantage over the traditional through living/dining room (NBA Tectonics, 1993b). Rooms and spaces which have a low heat demand such as kitchens, bathrooms, little used guest rooms, halls and stairs can be given a northerly aspect.

The effect of different internal layouts on energy consumption can be quantified by BREDEM-8 as this divides a dwelling into two zones. Zone 1 is designated as the living room and zone 2 is the rest of the dwelling. In addition, BREDEM-8 can also be used to consider the relationship between the two zones using four different options:

1. the dwelling is one storey;
2. stairs enter zone 1 directly from zone 2;
3. stairs do not link zone 1 and zone 2 directly;
4. zone 1 is all of one storey.

These different options affect energy consumption. For example in a multiple storey dwelling, open plans with living rooms opening directly to the staircase should be avoided. This is because in most dwellings, the demand temperature in zone 1 is higher and better controlled than that in zone 2. If there is a large transfer of heat from zone 1 to zone 2, the temperature in zone 2 will increase resulting in an increase in the total energy loss from the dwelling and hence an increase in the energy consumption. BREDEM-8 can quantify this increase.

6.3.3 Glazing

Conventionally designed dwellings tend to have their glazing area equally divided between the front and rear façades (Yannas, 1994a). Passive solar dwellings, however, show glazing area biased towards the south e.g. the two real housing estates considered by NBA Tectonics (1995) had more than 70% of their glazed area facing south. Such glazing distributions are usually achieved by reducing the window area on the north, east and west façades rather than dramatically increasing the window area on the south façade. Glazing on the north of a dwelling loses more heat than is replaced by solar gain and should be reduced to the minimum size that will still afford adequate daylight, typically 10% of the room floor area (Yannas, 1994a). (This assumes net glazing area i.e. not allowing for frames.) In some dwellings (usually open plan arrangements), the window may have to satisfy Building Regulations requirements for means of escape in case of fire. In these situations, the window should have a minimum unobstructed opening size of 850mm high by 500mm wide (Stephenson, 1993). These conventions can be used to size windows on the north façade of a dwelling.

One of the most important aspects of passive solar design is adjusting the area of south facing glazing to achieve the optimum balance between useful gains and losses. The optimum glazing area depends on four main factors:

1. geographical location of the dwelling;
2. level of envelope insulation;
3. type of glazing e.g. single, double, low-emissivity (low-e) coated;
4. thickness of window frames.

All of the above factors can be considered by BREDEM-8. It is therefore possible to develop a parametric calculation procedure which could be used to optimise glazing area. It is proposed that this procedure would predict the annual space heating requirement of the dwelling for different glazing areas with all other parameters held constant. A graph could then be produced showing space heating energy requirement versus glazing area (Figure 26). The current energy consumption of the dwelling would be noted on the graph to observe if any energy savings were possible.

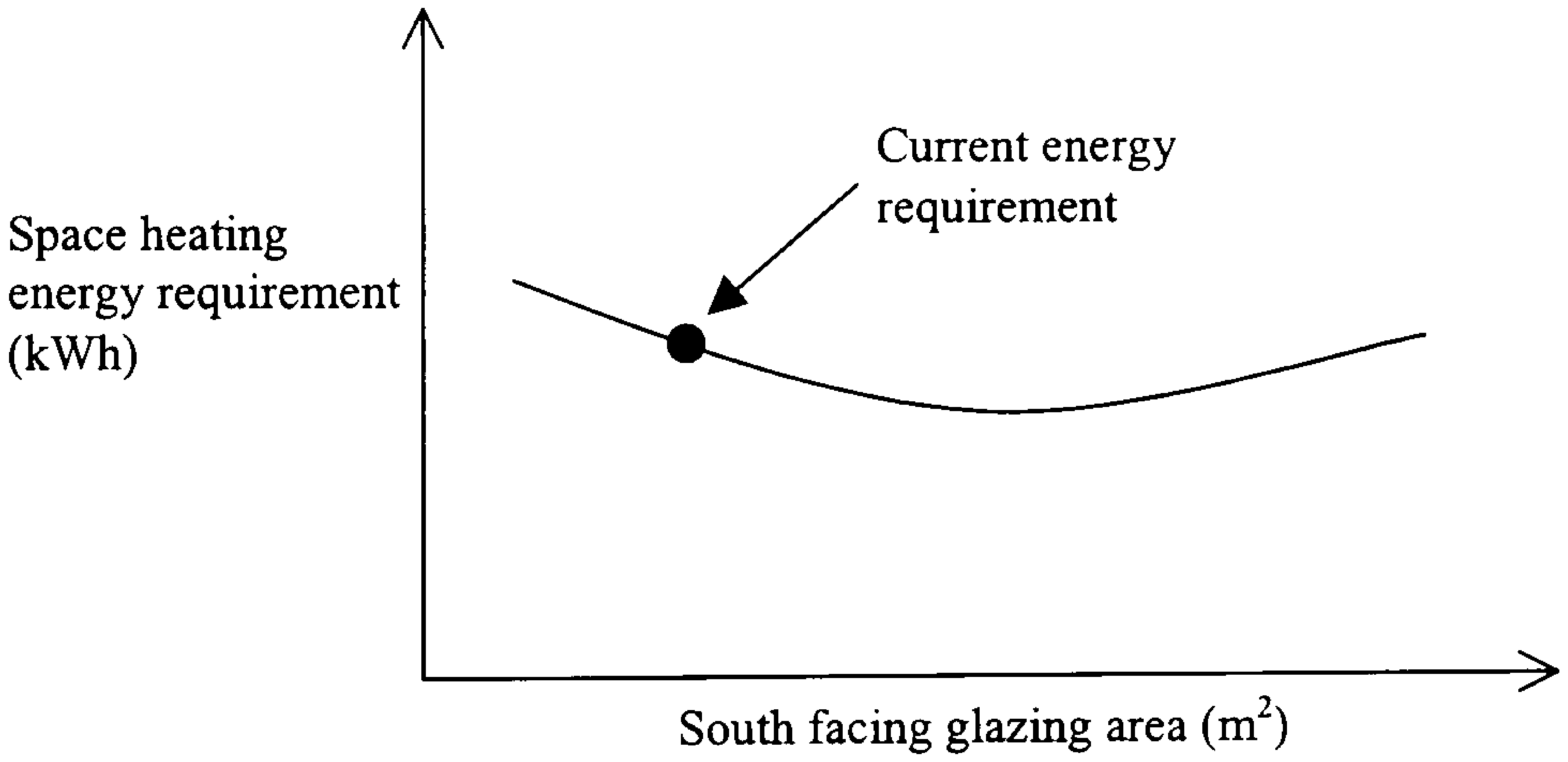


Figure 26. Possible output from the proposed parametric calculation procedure.

Similar calculations could be carried out using different types of glazing or different thicknesses of frame to allow the effect of these parameters on glazing area to be considered. Alternatively, glazing area could be kept constant while these parameters were varied over a range of cases to identify possible energy savings by using higher insulating glass or narrower frames. There will also need to be some consideration of the cost of the different measures to aid the planning process e.g. low-e double glazing will produce greater energy savings than normal double glazing but it is more expensive.

Not all solar gains make a useful contribution to reducing the space heating demand. Some gains will occur when the dwelling is sufficiently warm and will lead to overheating (usually during peak summer months). The usefulness of the gains is estimated by comparing them to the losses. In general, the greater the gains compared to the losses then the lower the usefulness of the gains. BREDEM-8 calculates an overheating index based on the ratio of gains to losses. This shows if there is a risk of overheating in the dwelling. It would be possible to develop a parametric calculation procedure comparing south facing glazing area against the overheating index instead of space heating energy requirement.

6.3.4 Thermal buffering

Unheated spaces that share building elements with heated rooms can act as thermal buffers. Examples include conservatories, garages and draught lobbies. This is because the temperature in the unheated space tends to be higher than the outdoor temperature. However, unheated spaces are not a substitute for thermal insulation and building elements in contact with these spaces should be insulated to the same standards as external elements.

BREDEM-8 can consider the sheltering effect of garages using reduction factors for U-values. These reduce the actual U-value of the building elements in contact with the garage. The potential for garages to reduce heat loss can be quantified. However, care should be taken to ensure garages are not located where they could provide overshading.

There is an optional procedure within BREDEM-8 to consider conservatories. As stated in Section 3.3, this has not been implemented in the SEP system but it could be added in future. This calculation procedure assumes conservatories are used in the manner intended i.e. as buffer zones. Conservatories, however, are commonly treated as an additional living space and are heated for year round use. This considerably increases the energy consumption of a dwelling. It could therefore be argued that planners should discourage their use.

Draught lobbies have the potential to reduce air leakage from a dwelling by providing an air lock between the dwelling and outside. They are only of benefit if they allow the outer door to be closed before the inner one is opened. Studies have shown that even if used correctly, draught lobbies do not provide significant savings in energy consumption (NBA Tectonics, 1993b). Nevertheless, BREDEM-8 provides an air infiltration factor to allow the effect of a draught lobby on energy consumption to be quantified.

6.4 Passive solar design of estate layouts

In Section 6.3, it was proposed that BREDEM-8 could be used to improve the design of individual dwellings to make use of passive solar measures and hence reduce energy demand. However, the benefits of designing dwellings according to passive solar design principles can only be realised if the estate layout is designed to maximise direct solar gain. The main considerations when designing estate layouts are described in the following sections. Approaches are also proposed which could be implemented in the SEP system to allow planners to maximise the passive solar design potential of proposed new housing estates.

6.4.1 Orientation

Dwellings designed according to passive solar design principles are more sensitive to orientation than conventional dwellings. This is due to the bias of glazing towards the façade with the living room (zone 1) (Section 6.3.2). This façade should face within ±30° for all dwellings on an estate (e.g. DoE 1997b; Littlefair, 1991; Terence O'Rourke plc, 1999). It would be useful to identify all dwellings meeting this criterion and represent this as a percentage of the total number of dwellings on the estate. Of course the higher the percentage, the more potential the site has to maximise direct solar gain. In addition, dwellings with poor orientations will be identified and planners could make suggestions as to how the layout could be improved.

An example where this criterion has been met is the Willow Park development in Chorley, Lancashire (Yannas, 1994b). It can be seen from the site layout in Figure 27 that all dwellings have a south-facing façade. This has been facilitated by having different dwelling types where access can be from the back, front or side. The use of these different dwelling types has also avoided the visual monotony normally associated with an estate where a high proportion of dwellings face in the same general direction.

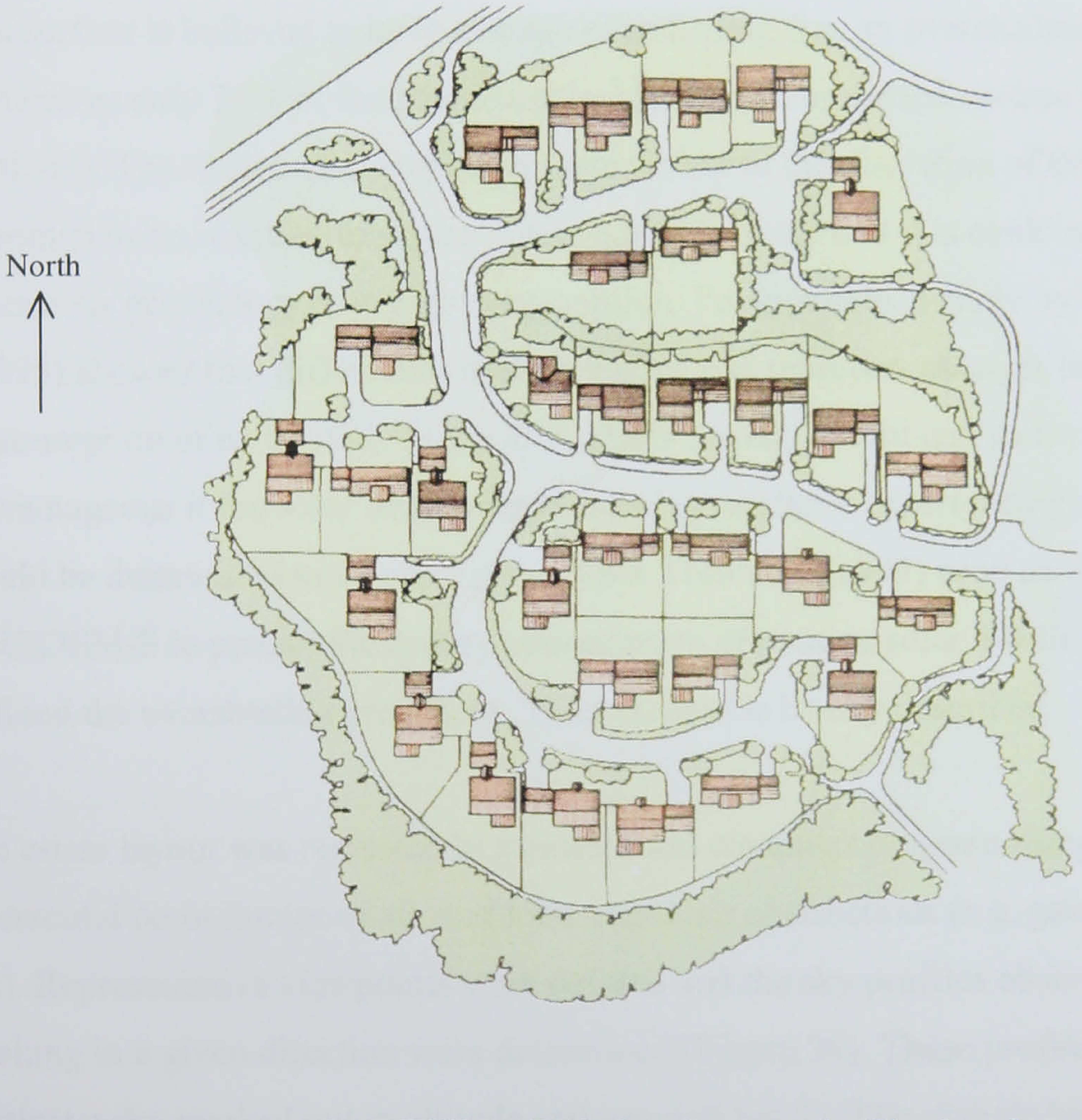


Figure 27. Site layout of the Willow Park development in Chorley, Lancashire. (From Terence O'Rourke plc, 1999.)

6.4.2 Overshading

It is important that excessive overshading does not reduce the beneficial effects of having a southerly orientation. BREDEM-8 considers the effect of overshading on energy consumption using so-called overshading factors. There are five different factors to choose from:

- 1.0 for open outlook;
- 0.9 for below average overshading;
- 0.7 for average overshading;
- 0.5 for above average overshading;
- 0.3 for much above average overshading.

If a surface is believed to have average overshading (i.e. an overshading factor of 0.7), it receives only 70% of the irradiation incident on an unshaded surface (i.e. open outlook). The choice of overshading factor is left to the discretion of the user and it is assumed to be constant throughout the year. It is likely that this could result in erroneous predictions of energy consumption. For example, a study by NBA Tectonics (1995) showed that differences in overshading can represent changes in energy consumption of up to 10%. These differences are significant and so it would be advantageous if the solar irradiation incident on surfaces experiencing overshading could be determined more accurately. NBA Tectonics (1995) used an early version of BREDEM-8 to predict the energy consumption of passive solar dwellings but they refined the overshading procedure. Their method is briefly described.

An estate layout was recreated in a customised computer program using the vertical and horizontal co-ordinates of all roof lines and other obstructions (e.g. garages) (Figure 28). Representative viewpoints were defined and the sky profiles observed from looking in a given direction were determined (Figure 28). These profiles were matched against a sky marked out in altitude and azimuth bands. The altitude bands occurred every 5° and the azimuth bands every 15°. These bands divided the sky into cells. Each cell was given a pre-calculated value of total solar irradiation corresponding to a fixed heating season. Calculations then determined how much irradiation fell below the sky profile (obscured) and how much was above it (unobscured) (Figure 28). The proportion between the two is a measure of the solar access of that representative viewpoint. This procedure was carried out for the remaining viewpoints and an average solar access factor was calculated for the estate. This was fed directly into BREDEM-8 to replace the original overshading factor and the energy consumption was subsequently calculated.

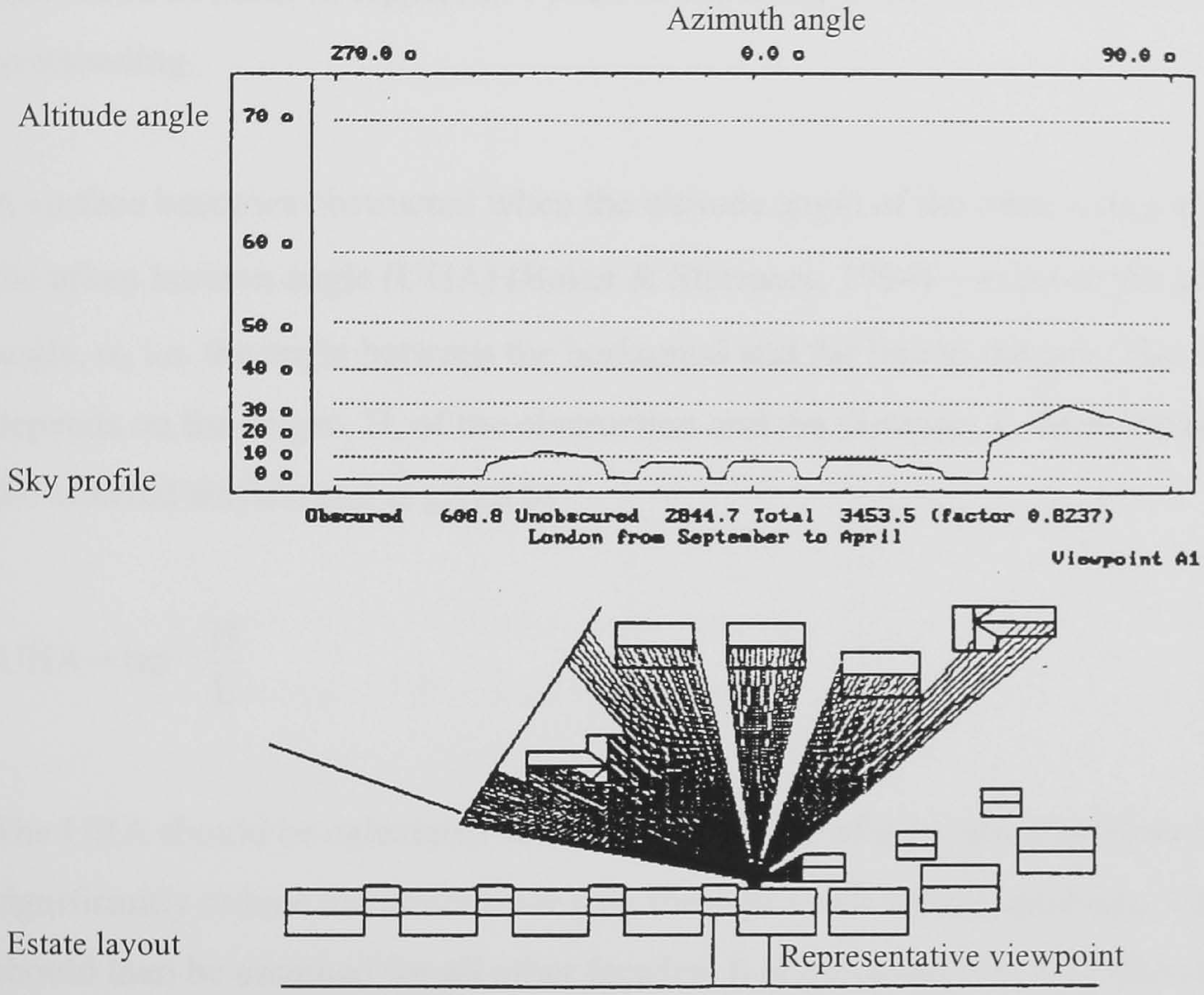


Figure 28. Sky profile approach for evaluating solar access factors used by NBA Tectonics. (Adapted from NBA Tectonics, 1995.)

The computerised method described above was specifically developed for the study by NBA Tectonics (1995) and is not available for general use. Although it estimates solar access factors in a rigorous fashion, the method does not calculate factors for individual dwellings. This could potentially hide serious overshading problems on an estate. Furthermore, it only considers a fixed heating season and not individual months. However, the study demonstrated the need to more accurately consider overshading in

BREDEM-8 when considering passive solar design. It is proposed that a different approach to that used by NBA Tectonics could be implemented within the current framework of the SEP system.

As described in previous chapters, a calculation procedure was implemented in the SEP system to calculate the total solar irradiation incident on inclined surfaces. This was required to predict the potential yield of solar DHW and PV systems. It was assumed that these systems would only be installed on unshaded surfaces. However the approach (described in detail in Appendix F) can be modified to consider the effects of overshading.

A surface becomes obstructed when the altitude angle of the obstructing object – i.e. the urban horizon angle (UHA) (Baker & Steemers, 1994) – exceeds the solar altitude angle, α_s i.e. the angle between the horizontal and the line to the sun. The UHA depends on the height, H, of the obstruction and the distance, L, from the obstruction to the affected surface and is given by

$$\mathrm{UHA} = \tan^{-1}\frac{\mathrm{H}}{\mathrm{L}} \qquad (6.1)$$

The UHA should be calculated for the south façade of a dwelling as overshading can significantly reduce the direct solar gain through south facing openings. This value should then be assumed for all other façades. It is proposed that the UHA should be calculated for a point one metre above ground level on the affected surface to represent the bottom of a window.

In a uniform layout where dwellings have similar heights and are separated by the same distance, the UHA of a dwelling corresponds to the maximum obstruction angle in the perpendicular direction. This uniformity is likely to exist for many housing estates because site planning practice suggests that privacy distances are the overriding criterion for determining the distance between dwellings. Typically, privacy distances are set at twenty-one metres (DoE, 1997b). It is important that an appropriate feeling of privacy for living rooms is achieved without obscuring the main solar collecting windows as this may prevent householders from using net curtains and venetian blinds. Their use defeats the object of passive solar design by reducing about 20% of the incoming solar gain (DoE, 1997b).

Where layouts are less uniform, however, all possible obstructions within ±60° of the affected surface should be considered. This should ensure that all significant buildings are included in the prediction of overshading. The UHA should then be calculated for all obstructions. Buildings in directions away from the façade normal have less impact on obstructing solar irradiation in proportion to the cosine of $\gamma_{obstruct}$, the angle between the obstruction and the façade normal (i.e. $-60° \leq \gamma_{obstruct} \leq 60°$). This gives

$$\mathrm{UHA} = \tan^{-1} \frac{\mathrm{H} \cos \gamma_{obstruct}}{\mathrm{L}} \tag{6.2}$$

The maximum UHA of all the obstructions is taken to be the UHA for the dwelling.

For every daylight hour of the mean day of every month, the UHA is compared against the solar altitude angle. When there is no shading, the solar irradiation incident on the surface is calculated using the same approach as that for solar DHW and PV systems (Appendix F). When shading occurs, the calculation of total solar irradiation no longer includes the direct irradiation component. The diffuse and reflected irradiation components are modified by the UHA using formulae given in Appendix F. Summing the solar irradiation values calculated for shaded and unshaded hours allows the daily total solar irradiation incident on the surface to be accurately calculated. Multiplying by the number of days in the month gives the monthly total solar irradiation. These monthly values can be used directly in BREDEM-8 to calculate the solar gain through openings and hence provide a prediction of energy consumption. Comparison with the energy consumption of an unshaded dwelling will show where potential overshading problems exist. In addition, it would also be possible to show the number of hours during the mean day of every month that the surface is shaded.

The proposed implementation of the above calculation procedure in BREDEM-8 may also improve the estimate of solar irradiation on unshaded surfaces. It would be useful to compare this approach with the original BREDEM-8 method to observe any differences in the prediction of energy consumption. This could show whether there would be any benefit in using the proposed procedure to predict the energy consumption of existing dwellings as described in Chapter 3.

6.4.3 Amenity

There are also 'non-energy' issues associated with passive solar design which need to be considered. One of the most important is to ensure that adequate sunlight reaches gardens and play areas. It has been suggested in a BRE report (Littlefair, 1991) that for a garden to appear adequately sunlit throughout the year, no more than two-fifths and preferably no more than a quarter of its area should be prevented by buildings from receiving any sun on the 21 March. This could be estimated using the approach described in Section 6.4.2. The UHA could be calculated for different points in the garden and compared against the solar altitude angle for all daylight hours on 21 March to determine if the garden receives any direct sun.

It could also be useful to calculate the relative proportion of dwellings on the site where the main 'sunny' garden is the 'back garden'. Householders may prefer sunnier back gardens as these tend to face away from the road and offer more privacy than 'front gardens'. However, across a whole estate, it is likely that some front gardens will receive more sun than back gardens. In these situations, careful design is required to maximise solar access and ensure sufficient privacy. For example, these dwellings could be situated towards the north of their plots to maximise the sunny garden space and increase the distance of the dwelling from the road.

6.5 Implementation in the SEP system

The approaches proposed in the two previous sections for considering the passive solar design of new housing estates have not been implemented in the SEP system. However, there should be no major problems in adding these proposals to the system in future.

To consider a proposed new housing estate within the existing framework of the SEP system, the layout will need to be incorporated into the GIS. This should not present serious difficulties although it is an issue which must be carefully considered. The use of GIS technology has some advantages. For example, it allows the proposed estate to be positioned with respect to existing buildings and developments. This could identify any potential overshading problems. In addition, digital urban maps provide detailed height information of the terrain. This is also useful when considering overshading as the topography of a site can have a major influence on layout and solar access. Incorporating the proposed estate layout into the GIS also allows the potential yield from solar DHW and PV systems to be calculated using the approaches described in Chapters 4 and 5 respectively. If necessary, the dwelling classification system described in Chapter 3 could be used to predict the energy consumption of the dwellings on the estate but it is likely that sufficient data will be available from developers drawings and specifications to allow a complete BREDEM-8 data set to be defined.

The calculation of the UHA (Section 6.4.2) requires knowledge of the obstruction height and the distance from the affected surface. It is thought that customised GIS tools could be developed to identify possible obstructions and calculate their distance from the affected surface. The height of dwellings and other possible obstructions could be taken from developers specifications and associated with the respective building footprints. The use of a 3D modelling approach to calculate the UHA is probably not necessary although this possibility could be considered in more depth. The implementation of the proposed parametric calculation procedures (Section 6.3.3) would be a relatively trivial task.

6.6 Summary

This chapter has described how passive solar design measures could be considered in future within the existing framework of the SEP system. An approach was proposed which initially considers the passive solar design of individual dwellings. BREDEM-8 can be used to show how different design measures affect the energy consumption of dwellings. It was proposed that a parametric calculation procedure could be developed to determine the optimum south facing glazing area, a key parameter in passive solar design. Once the individual dwellings incorporate passive solar measures, an approach was proposed to consider the layout of the estate to ensure it maximises the potential for direct solar gain. The primary factors are orientation and the avoidance of overshading. BREDEM-8 does not consider overshading in a rigorous fashion. It was proposed that the solar irradiation incident on windows experiencing overshading could be calculated more accurately by using the UHA to modify the calculation procedure adopted for solar DHW and PV systems (Appendix F). This should allow a more accurate prediction of energy consumption. At all points in the approach, dwellings failing to make full use of passive solar design can be identified allowing planners to suggest possible improvements.

The next chapter describes the application of the overall approach proposed in this thesis, as implemented in the SEP system, to a case study area of Leicester. All aspects of the approach (except, of course, passive solar design which has yet to be implemented in the software) are considered in an attempt to show how the SEP system could potentially be used in practice.

Chapter 7

Solar Energy Potential of Urban Dwellings: a Case Study

7.1 Introduction

This chapter describes the application of the SEP system to a case study area. There were three primary aims of the case study as listed below.

1. There was a need to demonstrate the SEP system to show the different types of results available and how these are presented. It was considered useful to select a case study area of interest to LCC, one of the collaborating partners on the EPSRC project.
2. It was necessary to demonstrate the SEP system for a range of data levels from the original default data set proposed in Chapter 3, to full data sets obtained from individual property surveys. This would show differences in the predictions of total energy consumption and solar energy potential obtained from each data set. In addition, it would highlight practical issues associated with using the SEP system at different data levels e.g. the time taken to collect data.
3. It was important to test the proposal described in Chapter 3 that the original defaults could be modified to account for regional specific data in order to enhance the prediction of baseline energy consumption.

7.2 Selection of case study area

In 1994, LCC developed an energy strategy to improve the energy efficiency of dwellings across Leicester (LCC, 1994). The council were particularly interested in an inner city area of predominantly pre-war housing, the so-called 'City Challenge' area.

The area contains several thousand dwellings and LCC considered it to be a prime target for urban regeneration. The Leicestershire Energy Efficiency Advice Centre (LEEAC) performed full property surveys to obtain Level 3 data for 185 dwellings within this area. This data was used to provide detailed energy efficiency advice to householders.

The availability of Level 3 data made the City Challenge area attractive for the case study as this data is the most difficult to obtain. However, the City Challenge area is vast and it was decided that such an extensive case study was not necessary, or indeed feasible, for the purposes of demonstration. Furthermore, the Level 3 data is widely distributed across the area. It was therefore considered beneficial to concentrate on a small part of the City Challenge area where a significant quantity of data was available. As a result, the area shown in Figure 29 was selected as the case study area.

There are a total of 394 dwellings in the case study area. The breakdown of dwellings by built form is shown in Table 47. It can be seen from Table 47 that the majority of dwellings in the case study area are terraces. This is the most common type of dwelling in Leicester. However, there are a small number of detached and semi-detached dwellings so allowing the SEP system to be applied to a wide range of built forms. Level 3 data collected by employees of the LEEAC was available for fifty-one dwellings in the case study area. These are distributed across the case study area as shown in Figure 29. The breakdown of dwellings with Level 3 data by built form is shown in Table 48. It can be seen from Table 48 that Level 3 data was available for all the types of dwelling in the case study area. In addition, comparing Tables 47 and 48 shows that the percentage breakdowns for the different built forms with Level 3 data closely match those for the whole case study area. This is likely to mean that conclusions drawn from analysis of the dwellings with Level 3 data will be representative of all the dwellings in the case study area. For example, modified defaults proposed for the sample of fifty-one dwellings could be inferred for the whole case study area.

Figure 29. Case study area: the yellow pins indicate dwellings with Level 3 data. (N.B. where footprints are not coloured, the Footprint Tool was unable to automatically extract the dwelling footprint. These can be manually extracted by the system user.)

Table 47. Breakdown of dwellings in case study area by built form.

Built form	**Number of dwellings**	**Percentage of total**
Mid terrace with unheated connecting passageway	224	56.9
Mid terrace	100	25.4
End terrace	24	6.1
Semi-detached	14	3.6
Detached	9	2.3
All dwellings	394	100

Table 48. Breakdown of dwellings with Level 3 data by built form.

Built form	**Number of dwellings**	**Percentage of total**
Mid terrace with unheated connecting passageway	28	54.9
Mid terrace	16	31.4
End terrace	5	9.8
Semi-detached	1	2.0
Detached	1	2.0
All dwellings	51	100

The main disadvantage with the case study area is that all dwellings were constructed prior to 1900. No Level 3 data was available for newer dwellings in Leicester. This obviously restricts the demonstration of the SEP system to only one of the nine possible age groups (Section 3.4.3).

7.3 Application of the SEP system to the case study area

The following sections describe the application of the SEP system to the selected case study area using the minimum amount of input data (Section 3.4.7). They show how the SEP system can be used to quickly generate useful results without the need for data collection. This aspect of the system should be of considerable importance to many local authorities as their resources are often limited.

7.3.1 Baseline energy consumption

Initially, the footprint of every dwelling in the case study area was extracted from the digital urban map using the Footprint Tool (Section 3.4.2). The built form of each dwelling was also inferred. (The different coloured footprints in Figure 29 represent different built forms.) This allowed the ground floor area, exposed perimeter and orientation of each dwelling to be automatically determined. From records held by the LEEAC, it was known that all dwellings in the case study area were constructed before 1900. Data from the Footprint Tool and age were supplemented by local knowledge which allowed the number of storeys to be entered for each dwelling. It was known that all dwellings on Westcotes Drive (Figure 29) have three storeys and so this was entered to override the default of two storeys (Section 3.4.2). Once this information had been entered, BREDEM-8 calculations were automatically performed for every dwelling in the case study area. The results generated by BREDEM-8 can be interrogated in a number of ways.

A thematic map showing the prediction of baseline total energy consumption for every dwelling was created (Figure 30). It can be seen from Figure 30 that the results are broadly as expected i.e. the greater the exposed envelope area, the higher the total energy consumption. The baseline energy consumption values predicted for every dwelling were added together to give the total baseline energy consumption of the case study area which was found to be 58,686 GJ/year. The total energy consumption is broken down into the energy consumed by different applications in Table 49. As expected, space heating consumes the most energy. It is important to know the energy consumed by different applications as this allows the potential of solar energy technologies to be quantified e.g. the energy supplied by solar DHW systems can be compared with the hot water energy consumption.

Figure 30. Thematic map showing predictions of total energy consumption.

Table 49. Energy consumed by different applications for the case study area.

Application	Energy consumption (GJ/year)	Percentage of total
Primary space heating	43,004	73.3
Secondary space heating	4,783	8.1
Water heating	5,784	9.9
Lights and appliances	3,587	6.1
Cooking	1,528	2.6
Total	58,686	100

The energy delivered by different fuels was also determined allowing the CO_2 emissions for the case study area to be calculated. The total CO_2 emissions for the area were found to be 4,626 tonnes/year. A thematic map showing CO_2 emissions for every dwelling can be generated but this is similar to Figure 30 and is not presented here. The reduction in CO_2 emissions available from solar DHW and PV systems can be quantified relative to this baseline.

7.3.2 Identifying sites for active solar technologies

Once the baseline energy consumption was established, the three-stage approach proposed in Section 4.4 was used to identify dwellings with the potential to install a solar DHW system. The first stage is filtering. Consultation with LCC records (LCC, 1997, 1999) showed that the case study area was not a conservation area and none of the dwellings were listed or covered by Article 4 Directives i.e. there were no restrictions preventing the installation of solar DHW (or PV) systems. The dwelling footprints were then displayed over an aerial photograph allowing the roof planes to be manually drawn using software developed for the SEP system (Figure 31). The area, orientation and inclination were determined and stored in the underlying property database. In long rows of terraces where dwellings have similar roof planes, the roof plane characteristics can be determined for one dwelling and then inherited by the remaining dwellings. Applying the filtering criteria showed that 240 dwellings in the case study area (61% of the total number of dwellings) had a roof plane suitable for installing a solar collector. These dwellings are shown in Figure 32.

As stated in Section 4.4.2, the targeting stage is an optional process intended to provide an indication of the likelihood that householders will install a solar DHW system. There was no scope within this project to collect the necessary socio-economic data (especially ownership of property, income and number of occupants) required to perform the targeting process for the case study area. However, tests performed during development of the SEP system showed that useful results can be obtained from this process and it is likely to be of benefit to the end-user. For example, if grant funding was available to householders to reduce the cost of installing a solar DHW system then

Roof plane # 2of 4
Area = 26.9226 SqM
Surface azimuth angle: -36.6493 deg.

Enter inclination: Standard (Modern)
Front facade? ☐
Next action: Analyse roof plane #3

Figure 31. Analysis of roof planes in the SEP system.

Figure 32. Thematic map showing filtering results: red footprints indicate a pass and white footprints a fail.

perhaps all dwellings passing the filtering stage would be targeted. However, if no grant funding was available then planners would probably only target those householders who were considered most likely to install a solar DHW system. Mr. N. Morris, Team Leader of LCC's Home Energy Strategy, believes the SEP system could be used to encourage investment from national and European government to allow such a grant funding initiative to be implemented in Leicester (verbal communication, February 1, 2001).

Finally, in order to quantify the potential energy yield from installing solar DHW systems, the calculation procedure was applied to all dwellings that passed the filtering stage. A thematic map displaying the results is shown in Figure 33. The potential energy savings from installing solar DHW systems were estimated to be 1307 GJ/year. This represents delivered energy savings of 1700 GJ/year (accounting for the efficiency of the conventional water heating system) or 29.4% of the DHW energy consumption of the case study area (Table 49). Consequently, the total energy consumption of the case study area will be 2.9% below the baseline value. Reductions in CO_2 emissions for the case study area were estimated to be 202 tonnes/year or 4.4%.

The SEP system was also used to identify dwellings in the case study area with potential for PV. Due to the requirement that suitable roof planes must have a minimum area of $10m^2$ (Section 5.5.1), only 87 dwellings passed the filtering stage. As described in Section 5.5.2, the targeting process is not applied when considering PV systems as they are currently too expensive for widespread installation in the domestic sector. The PV calculation model was applied to these 87 dwellings and they were predicted to supply 377 GJ/year of electrical energy. If this PV generated electricity was considered to replace the electricity for lights and appliances (i.e. the necessary electrical demand as defined in Section 5.4), it would give savings for the case study area of 10.5%. The equivalent reductions in CO_2 emissions were estimated to be 53 tonnes/year or 1.2% of the emissions from the case study area. The potential for installing solar DHW and PV systems in the case study area is summarised in Table 50.

Figure 33. Thematic map showing predictions of solar energy supplied.

Table 50. Potential for installing solar DHW and PV systems in the case study area.

Installation measure	**No. of dwellings passing filtering**	**Delivered fuel savings**		**Reduction in CO_2 emissions**	
		GJ/year	**Percentage of baseline total energy consumption**	**Tonnes/year**	**Percentage of baseline total emissions**
Solar DHW	240	1700	2.9	202	4.4
PV	87	377	0.6	53	1.2

7.3.3 Results for an individual dwelling

In addition to considering large areas of a city, the SEP system can also present results for individual dwellings. For example consider 5 Shaftesbury Road (Figure 34), a typical mid terrace property in the case study area. This dwelling was estimated to have a baseline total energy consumption of 132 GJ/year. The energy consumed by different applications is shown in Table 51. The subsequent CO_2 emissions for the dwelling were 8.6 tonnes/year.

Figure 34. Terraced houses on Shaftesbury Road, Leicester.

Table 51. Energy consumed by different applications for 5 Shaftesbury Road, Leicester.

Application	**Energy consumption (GJ/year)**	**Percentage of total**
Primary space heating	92.9	70.4
Secondary space heating	10.3	7.8
Water heating	15.6	11.8
Lights and appliances	9.0	6.8
Cooking	4.2	3.2
Total	132.0	100

From Figure 29, it can be seen that Shaftesbury Road runs from east to west. Dwelling number 5 is located on the north of the road and thus its front façade faces nearly due south. The front roof plane (Figure 34) has an area of approximately 13m^2 making it an ideal location for a solar collector or a PV panel. Results from the SEP system showed that a solar DHW system would meet about 52% of the hot water energy demand. The monthly distribution of energy supplied by the solar DHW system is compared against the hot water energy demand in Figure 35. It can be seen that most of the summer demand for hot water is met by the solar DHW system. The energy supplied by the solar DHW system would give delivered fuel savings of about 8.2 GJ/year (Table 52). This represents just over 6% of the baseline total energy consumption of the dwelling and would reduce CO_2 emissions by approximately 5.9%

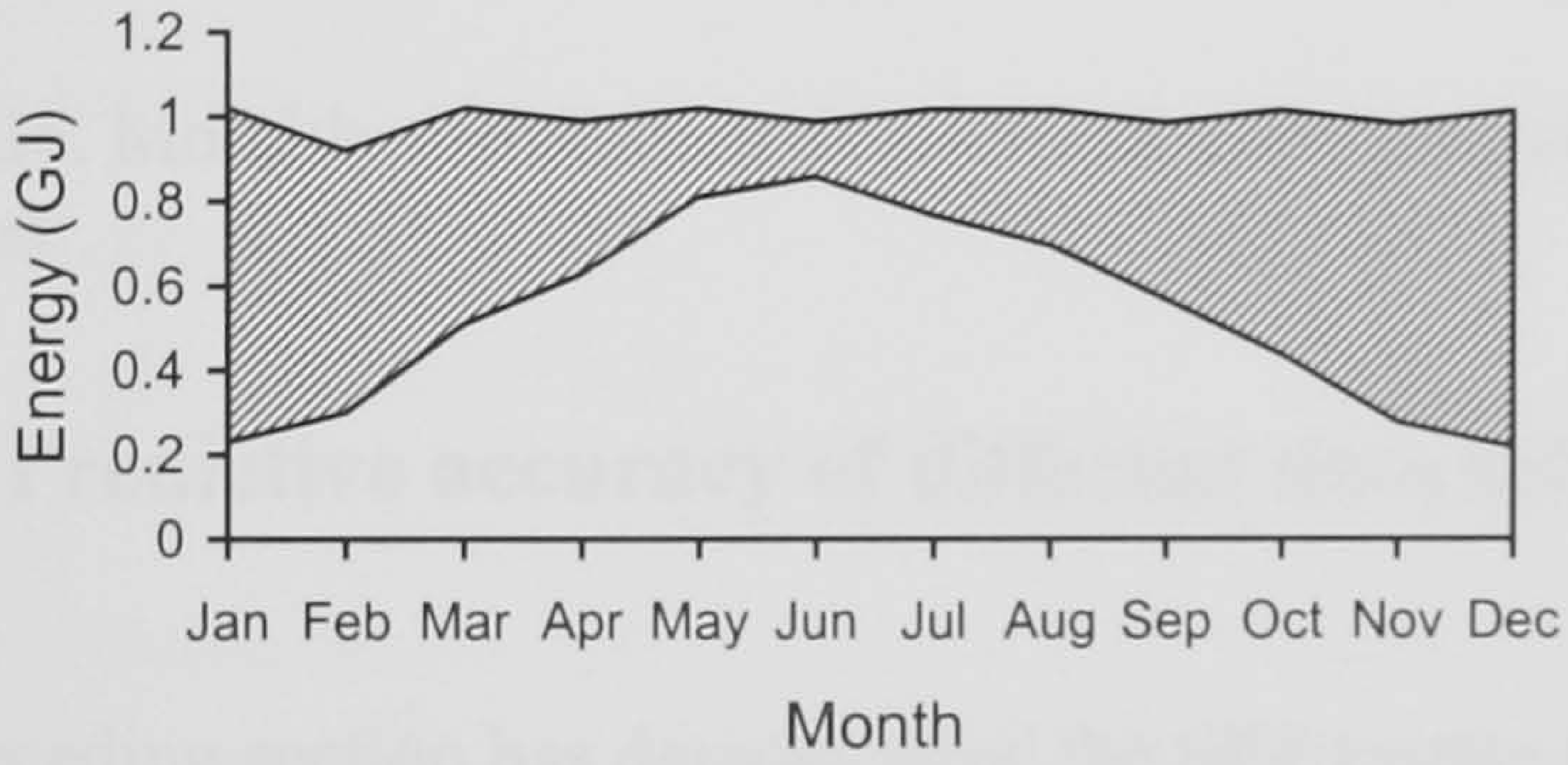


Figure 35. Monthly distribution of solar energy supplied for 5 Shaftesbury Road, Leicester.

Table 52. Potential for installing a solar DHW or PV system on 5 Shaftesbury Road, Leicester.

Installation measure	**Delivered fuel savings**		**Reduction in CO_2 emissions**	
	GJ/year	**Percentage of baseline total energy consumption**	**Tonnes/year**	**Percentage of baseline total emissions**
Solar DHW	8.2	6.2	0.5	5.9
PV	4.3	3.3	0.6	7.2

If a PV system was installed on the south facing roof plane, it would supply nearly 50% of the electricity required by lights and appliances. The monthly distribution of electrical energy supplied by the PV system is compared against the electricity required by lights and appliances in Figure 36. It can be seen that more than half of the summer demand for electricity is met by the PV system. The PV system would give electrical energy savings of approximately 4.3 GJ/year (Table 52). This represents just over 3% of the baseline total energy consumption of the dwelling and would reduce CO_2 emissions by approximately 7.2%.

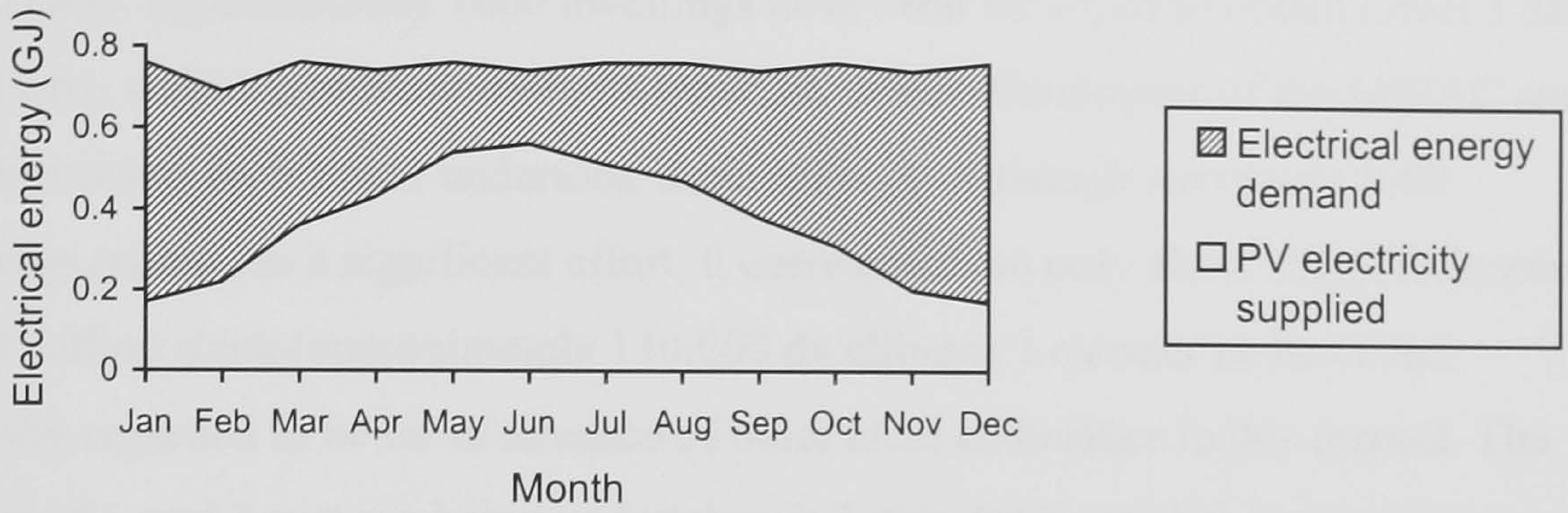


Figure 36. Monthly distribution of electrical energy supplied for 5 Shaftesbury Road, Leicester.

7.4 Predictive accuracy of different data sets

The preceding section has demonstrated the SEP system using the minimum amount of input data. As described in Section 3.5, however, the SEP system was designed to operate at different levels of input data. This allows the data to be collected using various techniques. The following sections compare the predictions of energy consumption at the different data levels for the fifty-one dwellings in the case study area for which Level 3 data was available. The experiences of LCC in administering some of the data collection techniques are also described to identify the relative strengths and weaknesses of the techniques.

7.4.1 Full property survey – actual occupancy

The most accurate prediction of energy consumption is achieved if full property surveys are carried out for all dwellings in an area. These surveys collect all the input data required by BREDEM-8 including actual occupancy information. Accordingly, they provide a Level 3 data set (Table 1, Section 2.2.5). Although the different data levels apply specifically to the input data required by NHER software (Section 2.2.5), they can be usefully applied to the implementation of BREDEM-8 in the SEP system where the broad meaning is the same i.e. Level 3 implies a complete data set using actual occupancy.

In Leicester, approximately 1000 dwellings have been surveyed to obtain Level 3 data (N. Morris, verbal communication, October 24, 2000). Employees of the LEEAC and LCC's housing department undertook these surveys. Although surveying 1000 dwellings represents a significant effort, it corresponds to only about 1% of Leicester's total dwelling stock (approximately 110,000 dwellings). Leicester is, however, generally regarded to be far in advance of other local authorities in this respect. The number of Level 3 surveys being undertaken in Leicester is steadily increasing to improve knowledge of the energy efficiency of the dwelling stock and to allow more accurate reporting of HECA requirements. At the current rate, it will take many years for the whole stock to be surveyed.

The main disadvantages with detailed property surveys are that they are time-consuming and expensive. Each survey takes a trained surveyor at least thirty minutes to perform and so not many can be carried out by one person in a single day. In addition, once the data has been recorded on the survey form it has to be manually entered into a property database thus adding to the time required. The use of default data to predict energy consumption is therefore necessary for broad city areas.

The Level 3 data provided by LEEAC was still in its original form of hand completed data sheets filled out during property visits. This data was manually entered into BREDEM-8. The predictions of energy consumption for the fifty-one dwellings are given in Table 53. These results represent the best available estimate of actual energy consumption and so provide a good reference from which to compare the predictions from other data sets.

Table 53. Predictions of dwelling total energy consumption using different data sets.

Case	Address[a]	Built form	Level 3 (actual occup.) GJ[b]	Level 2 (standard occupancy)		Baseline (using defaults)			Rapid site survey			Level 0 (Home Energy Survey Form)			Modified default		
				GJ[b]	% 3[c]	GJ[b]	% 3[c]	% 2[d]	GJ[b]	% 3[c]	% 2[d]	GJ[b]	% 3[c]	% 2[d]	GJ[b]	% 3[c]	% 2[d]
1.	56 Ridley Street	MTUP	**56.8**	**47.5**	-16.4	**151.0**	+166	+218	**136.3**	+140	+187	**113.5**	+99.8	+139	**128.2**	+126	+170
2.	43 Ridley Street	MTUP	**60.0**	**101.3**	+68.8	**142.7**	+138	+40.9	**128.9**	+115	+27.2	**109.6**	+82.7	+8.2	**119.8**	+99.7	+18.3
3.	21 Cranmer Street	MTUP	**60.5**	**101.5**	+67.8	**175.1**	+189	+72.5	**160.8**	+166	+58.4	**135.0**	+123	+33.0	**147.1**	+143	+44.9
4.	29 Ridley Street	MTUP	**66.3**	**110.4**	+66.5	**168.9**	+155	+53.0	**152.6**	+130	+38.2	**136.1**	+105	+23.3	**145.4**	+119	+31.7
5.	77 Latimer Street	MTUP	**67.1**	**104.5**	+55.7	**153.6**	+129	+47.0	**150.2**	+124	+43.7	**128.9**	+92.1	+23.3	**128.9**	+92.1	+23.3
6.	85 Tyndale Street	MTUP	**68.6**	**122.5**	+78.6	**144.9**	+111	+18.3	**143.7**	+109	+17.3	**124.8**	+81.9	+1.9	**121.0**	+76.4	-1.2
7.	54 Tyndale Street	MTUP	**68.6**	**116.7**	+70.1	**156.1**	+128	+33.8	**152.3**	+122	+30.5	**136.7**	+99.3	+17.1	**129.9**	+89.4	+11.3
8.	49 Tyndale Street	MTUP	**77.7**	**86.5**	+11.3	**162.5**	+109	+87.9	**145.6**	+87.4	+68.3	**123.0**	+58.3	+42.2	**137.4**	+76.8	+58.8
9.	53 Cranmer Street	MTUP	**79.0**	**95.0**	+20.3	**145.2**	+83.8	+52.8	**130.9**	+65.7	+37.8	**108.0**	+36.7	+13.7	**120.8**	+52.9	+27.2
10.	94 Tyndale Street	MTUP	**79.3**	**115.0**	+45.0	**116.5**	+46.9	+1.3	**110.0**	+38.7	-4.3	**91.9**	+15.9	-20.1	**92.9**	+17.2	-19.2
11.	41 Ridley Street	MTUP	**79.6**	**125.8**	+58.0	**102.0**	+28.1	-18.9	**100.0**	+25.6	-20.5	**85.5**	+7.4	-32.0	**81.0**	+1.8	-35.6
12.	78 Tyndale Street	MTUP	**80.3**	**104.2**	+29.8	**115.0**	+43.2	+10.4	**106.3**	+32.4	+2.0	**86.2**	+7.3	-17.3	**91.7**	+14.2	-12.0
13.	49 Cranmer Street	MTUP	**86.8**	**91.1**	+5.0	**150.7**	+73.6	+65.4	**149.5**	+72.2	+64.1	**127.4**	+46.8	+39.8	**125.8**	+44.9	+38.1
14.	79 Tyndale Street	MTUP	**97.7**	**94.8**	-3.0	**116.8**	+19.5	+23.2	**107.1**	+9.6	+13.0	**84.8**	-13.2	-10.5	**93.1**	-4.7	-1.8
15.	87 Cranmer Street	MTUP	**98.5**	**114.2**	+15.9	**149.0**	+51.3	+30.5	**145.6**	+47.8	+27.5	**127.4**	+29.3	+11.6	**125.1**	+27	+9.5
16.	14 Cranmer Street	MTUP	**100.2**	**104.3**	+4.1	**151.5**	+51.2	+45.3	**150.3**	+50	+44.1	**130.0**	+29.7	+24.6	**126.9**	+26.6	+21.7
17.	47 Cranmer Street	MTUP	**101.6**	**105.2**	-3.5	**123.3**	+21.4	+17.2	**121.1**	+19.2	+15.1	**104.2**	+2.6	-1.0	**98.6**	-3.0	-6.3
18.	88 Tyndale Street	MTUP	**103.0**	**112.7**	+9.4	**148.4**	+44.1	+31.7	**135.1**	+31.2	+19.9	**111.1**	+7.9	-1.4	**122.9**	+19.3	+9.1
19.	76 Tyndale Street	MTUP	**108.0**	**119.3**	+10.5	**143.6**	+33.0	+20.4	**140.5**	+30.1	+17.8	**125.7**	+16.4	+5.4	**119.5**	+10.6	+0.2
20.	80 Tyndale Street	MTUP	**112.2**	**116.5**	+3.8	**149.0**	+32.8	+27.9	**146.4**	+30.5	+25.7	**127.1**	+13.3	+9.1	**122.4**	+9.1	+5.1
21.	28 Tyndale Street	MTUP	**113.5**	**125.6**	+10.7	**150.7**	+32.8	+20.0	**144.0**	+26.9	+14.6	**127.1**	+12.0	+1.2	**121.2**	+6.8	-3.5
22.	79 Cranmer Street	MTUP	**114.9**	**103.5**	-9.9	**148.9**	+29.6	+43.9	**135.9**	+18.3	+31.3	**116.4**	+1.3	+12.5	**125.0**	+8.8	+20.8
23.	74 Ridley Street	MTUP	**119.2**	**109.3**	-8.3	**110.3**	-7.5	+0.9	**101.3**	-15.0	-7.3	**82.3**	-31.0	-24.7	**88.2**	-26.0	-19.3
24.	40 Tyndale Street	MTUP	**120.3**	**115.0**	-4.4	**143.6**	+19.4	+24.9	**140.8**	+17.0	+22.4	**126.9**	+5.5	+10.3	**116.1**	-3.5	+1.0
25.	21 Ridley Street	MTUP	**123.5**	**113.6**	-8.0	**142.4**	+15.3	+25.4	**129.6**	+4.9	+14.1	**109.1**	-11.7	-4.0	**120.0**	-2.8	+5.6
26.	61 Tyndale Street	MTUP	**126.7**	**112.2**	-11.4	**156.6**	+23.6	+39.6	**140.9**	+11.2	+25.6	**119.6**	-5.6	+6.6	**131.1**	+3.5	+16.8
27.	76 Ridley Street	MTUP	**127.8**	**114.4**	-10.5	**145.8**	+14.1	+27.4	**144.5**	+13.1	+26.3	**122.1**	-4.5	+6.7	**120.9**	-5.4	+5.7
28.	96 Tyndale Street	MTUP	**132.2**	**122.1**	-7.6	**152.4**	+15.3	+24.8	**140.8**	+6.5	+15.3	**123.1**	-6.9	+0.8	**127.3**	-3.7	+4.3
29.	17 Cranmer Street	MTUP	**134.8**	**121.0**	-10.2	**153.4**	+13.8	+26.8	**152.1**	+12.8	+25.7	130.7	-3.0	+8.0	**127.7**	-5.3	+5.5

Table 53 (continued). Predictions of dwelling total energy consumption using different data sets.

Case	Address[a]	Built form	Level 3 (actual occup.) GJ[b]	Level 2 (standard occupancy)		Baseline (using defaults)			Rapid site survey			Level 0 (Home Energy Survey Form)			Modified default		
				GJ[b]	% 3[c]	GJ[b]	% 3[c]	% 2[d]	GJ[b]	% 3[c]	% 2[d]	GJ[b]	% 3[c]	% 2[d]	GJ[b]	% 3[c]	% 2[d]
30.	52 Latimer Street	MT	45.7	74.9	+63.9	97.2	+113	+29.8	96.2	+111	+28.4	80.5	+76.1	+7.5	78.2	+71.1	+4.4
31.	58 Ridley Street	MT	51.0	68.7	+34.7	97.4	+91.0	+41.8	89.3	+75.1	+30.0	72.7	+42.5	+5.8	78.5	+53.9	+14.3
32.	50 Latimer Street	MT	51.8	63.5	+22.6	103.8	+100	+63.5	102.7	+98.3	+61.7	79.7	+53.9	+25.5	82.8	+59.8	+30.4
33.	28 Cranmer Street	MT	57.8	84.1	+45.5	118.2	+104	+40.5	116.9	+102	+39.0	100.0	+73.0	+18.9	93.9	+62.5	+11.7
34.	70 Cranmer Street	MT	57.9	84.5	+45.9	114.1	+97.1	+35.0	106.0	+83.1	+25.4	94.0	+62.3	+11.2	92.0	+58.9	+8.9
35.	90 Cranmer Street	MT	61.7	98.4	+59.5	110.4	+78.9	+12.2	109.2	+77.0	+11.0	108.3	+75.5	+10.1	87.8	+42.3	-10.8
36.	66 Cranmer Street	MT	66.1	82.8	+25.3	117.0	+77.0	+41.3	115.8	+75.2	+39.9	97.5	+47.5	+17.8	94.5	+43.0	+14.1
37.	68 Ridley Street	MT	69.4	64.4	-7.2	100.6	+45.0	+56.2	100.0	+44.1	+55.3	81.1	+16.9	+25.9	81.0	+16.7	+25.8
38.	46 Cranmer Street	MT	81.5	72.9	-10.6	118.7	+45.6	+62.8	115.1	+41.2	+57.9	93.6	+14.8	+28.4	95.5	+17.2	+31
39.	10 Cranmer Street	MT	85.5	88.0	+2.9	114.6	+34.0	+30.2	105.2	+23.0	+19.5	85.6	+0.1	-2.7	92.1	+7.7	+4.7
40.	56 Cranmer Street	MT	89.6	81.9	-8.6	118.5	+32.3	+44.7	117.3	+30.9	+43.2	94.6	+5.6	+15.5	95.2	+6.3	+16.2
41.	34 Cranmer Street	MT	93.3	108.2	+16.0	126.0	+35.0	+16.5	124.7	+33.7	+15.2	128.7	+37.9	+18.9	101.0	+8.3	-6.7
42.	94 Ridley Street	MT	96.1	89.4	-7.0	113.0	+17.6	+26.4	111.8	+16.3	+25.1	96.3	+0.2	+7.7	90.7	-5.6	+1.5
43.	80 Cranmer Street	MT	106.5	112.6	+5.7	117.3	+10.1	+4.2	116.1	+9.0	+3.1	115.8	+8.7	+2.8	94.9	-10.9	-15.7
44.	26 Ridley Street	MT	111.0	101.9	-8.2	116.2	+4.7	+14.0	115.0	+3.6	+12.9	93.8	-15.5	-7.9	92.4	-16.8	-9.3
45.	64 Tyndale Street	MT	115.1	117.9	+2.4	137.8	+19.7	+16.9	127.2	+10.5	+7.9	101.5	-11.8	-13.9	108.3	-5.9	-8.1
46.	63 Ridley Street	ET	115.1	119.6	+3.9	138.3	+20.2	+15.6	134.9	+17.2	+12.8	117.5	+2.1	-1.8	115.4	+0.3	-3.5
47.	49 Ridley Street	ET	129.3	132.9	+2.8	163.5	+26.5	+23.0	146.5	+13.3	+10.2	143.1	+10.7	+7.7	138.1	+6.8	+3.9
48.	93 Latimer Street	ET	148.8	156.1	+4.9	172.8	+16.1	+10.7	168.6	+13.3	+8.0	145.6	-2.2	-6.7	145.2	-2.4	-7.0
49.	100 Cranmer St.	ET	168.0	172.6	+2.7	163.9	-2.4	-5.0	162.3	-3.4	-6.0	139.8	-16.8	-19.0	135.1	-19.6	-21.7
50.	12 Westcotes Dr.	SD	354.0	368.6	+4.1	352.0	-0.6	-4.5	330.2	-6.7	-10.4	329.9	-6.8	-10.5	283.6	-19.9	-23.1
51.	17 Westcotes Dr.	D	521.4	546.7	+4.9	783.0	+50.2	+43.2	710.6	+36.3	+30.0	639.7	+22.7	+17.0	652.2	+25.1	+19.3
Total energy consumption			5441	6016	+10.6	7764	+42.7	+29.1	7365	+35.4	+22.4	6414	+17.9	+6.6	6384	+17.3	+6.1

[a] All dwellings were constructed pre-1900 and have 2 storeys (except cases 50 and 51 which have 3 storeys).

[b] These columns show the prediction of annual total energy consumption obtained from BREDEM-8.

[c] These columns show the percentage difference between the predictions of energy consumption at Level 3 and at that particular level.

[d] These columns show the percentage difference between the predictions of energy consumption at Level 2 and at that particular level.

7.4.2 Full property survey – standard occupancy

The detailed data obtained from a full property survey can be used with standard occupancy information in place of actual occupancy. This represents a Level 2 data set and allows the effect of occupant behaviour on energy consumption to be observed. The standard occupancy inputs given in Table 21 (Section 3.4.5) were entered into BREDEM-8 to replace the actual data. The predictions of energy consumption obtained from Level 2 data are given in Table 53.

It can be seen from Table 53 that there is wide variation between Level 2 and Level 3 predictions. For the majority of cases, Level 2 over predicts energy consumption in comparison to Level 3. For fifteen cases, however, Level 2 produces estimates lower than Level 3. The main reason for these differences is that none of the dwellings employed the standard heating pattern assumed in BREDEM-8. In practice, some had extended hours of heating but the majority had less hours of heating. It should be noted, however, that the data collection forms completed by the LEEAC employees only allowed one heating pattern to be specified for the whole week. Standard occupancy assumes different heating patterns for weekdays and weekends. Consequently, the heating regimes specified at Level 3 could never exactly match those assumed at Level 2. It was decided not to change the standard heating pattern as it is a standard default given in the BREDEM-8 documentation. Furthermore, it seemed likely that the assumption at Level 3, that the heating regime was constant throughout the week, could be erroneous. Nonetheless, the results obtained from Level 3 were still considered to represent the best estimate of the actual energy consumption of the dwellings.

Summing the energy consumption values for the fifty-one dwellings to give the total energy consumption for the sample showed that the use of standard occupancy information overestimated the Level 3 prediction by 10.6% (Table 53). It was therefore concluded that, as expected, occupant behaviour has a significant influence on energy consumption. As reduced data sets assume standard occupancy, their predictions of energy consumption are likely to be significantly different from those obtained at Level 3. However, comparison with Level 2 results should permit conclusions to be drawn regarding the appropriateness of the system of generating defaults. This is described in the following sections.

7.4.3 All defaults – baseline calculation

The quickest method of estimating energy consumption is to use data derived from the digital urban map in conjunction with the defaults proposed in Chapter 3. This process was carried out for the whole case study area in Section 7.3. The results for the fifty-one dwellings being considered here are given in Table 53.

It can be seen from Table 53 that the default level overestimates the Level 3 prediction of total energy consumption of the fifty-one dwellings by 42.7%. For some individual dwellings, the default prediction is more than double that obtained from Level 3 data e.g. cases 1 to 8. There are only three dwellings (cases 23, 49 and 50) where the default prediction is less than the Level 3 estimate.

The results obtained from the default data are much closer to the Level 2 results where the total energy consumption differs by just under 30% (Table 53). In addition, the default predictions for each individual dwelling show better agreement with only case 1 overestimating the Level 2 result by more than 100%. Again, however, the default predictions were only lower for three dwellings (cases 11, 49 and 50).

The generally poor agreement between the default results and the Level 2 and 3 results is to be expected as the fifty-one dwellings were all constructed prior to 1900. As a result, there is considerable scope for energy efficiency improvements to reduce the heating requirements of the dwellings. This can make the dwellings much more energy efficient than is suggested by the pre-1900 Building Regulation defaults. For example, the default system assumes that there is no loft insulation and no hot water tank insulation in these dwellings (Table 10, Section 3.4.3). From the Level 3 data sets obtained from LEEAC, this assumption was shown to be incorrect for the majority of dwellings. Modifications to the original defaults are proposed in Section 7.4.6. Despite the poor agreement, the default data set provides a reliable platform from which to enhance the predictions of energy consumption by collecting data. This is described in the following sections.

7.4.4 Rapid site survey

It was proposed in Section 3.5.1 that the accuracy of the baseline predictions of energy consumption could be improved by collecting some of the input data required by BREDEM-8 from rapid site surveys. To test this proposal, rapid site surveys were performed for the fifty-one dwellings. Data was recorded using the form in Appendix D.

The rapid site survey was useful for confirming the number of storeys. For all fifty-one dwellings, the assumptions made at the default level were correct. However, some of the other dwellings in the case study area had a room in the roof (Figure 37). Currently, these are considered to be equivalent to an extra storey in the default data set (Section 3.5.1). It was apparent from the site surveys that this assumption would introduce errors into the prediction of energy consumption as rooms in the roof tend not to have the same floor plan as the ground floor. This assumption needs to be considered in more detail in future but perhaps all that is required is a reduction factor e.g. multiply ground floor area by 0.75 to estimate the floor area of the room in the roof.

Another useful parameter determined from the rapid site surveys was the type of glazing. Many of the properties had double glazing instead of the original single glazing. This alters the U-value, air infiltration rate and solar transmittance. During the surveys it was not possible to observe the rear façades of the dwellings and thus they were assumed to have the same properties as the front façade e.g. same glazing type. The dwelling and site exposure factors were considered to be sheltered for the majority of dwellings in the case study area as the dwelling density is high (i.e. closely packed rows of terraces). Most of the other parameters collected from the survey were similar to the default parameters e.g. all dwellings had solid walls.

Figure 37. Room in the roof: implications for energy consumption and installation of active solar technologies.

The data collected from the rapid site survey was entered into BREDEM-8 to override the relevant default values. The predictions of energy consumption obtained from the rapid site survey data are given in Table 53.

Using the rapid site survey data, the prediction of total energy consumption for the fifty-one dwellings reduced by just over 5% in comparison with the default data. This resulted in closer agreement with Level 3 and Level 2 results although the predictions are still higher (35.4% and 22.4% higher respectively) (Table 53). The effect of the rapid site survey on improving the prediction of energy consumption in comparison to the baseline value varied from dwelling to dwelling. For example, there was little difference in the predictions from these two data sets for cases 6, 13 and 16 (in all cases an absolute difference of 1.2 GJ/year). In these cases, the dwellings had single glazing. For cases 1, 3 and 9, the absolute difference between the two levels is approximately 15 GJ/year. These dwellings all had double glazing installed. Based on these results, it was concluded that the type of glazing has a significant effect on dwelling energy consumption.

It took just under two hours to perform rapid site surveys for the fifty-one dwellings. This represents approximately two minutes per dwelling. Although this is extremely quick in comparison to a full property survey, it would take about 500 days or at least two man-years to perform rapid site surveys for the whole dwelling stock in Leicester. Careful consideration therefore needs to be given to the advantages and disadvantages of performing rapid site surveys before embarking on a city wide surveying exercise. For example, it could be argued that the small improvement in the prediction of energy consumption is insignificant when compared to the amount of time and hence expenditure required to perform the surveys.

There are, however, other reasons for carrying out rapid site surveys. In particular, they are a useful method of identifying potential shading problems on the roof of a dwelling. One of the neighbouring streets to the case study area had a row of tall trees in front of the south-facing roofs (Figure 38). These trees are likely to shade the roof plane, especially during summer months (confirmed by a local resident). This obviously reduces the potential for solar DHW and PV systems. It was stated previously that identifying dwellings with a room in the roof was important for predicting the energy consumption. In addition, a room in the roof may also prevent the installation of a solar collector (Figure 37). Minor obstructions were also identified which could potentially cause shading problems (Figure 39). These obstructions are especially critical for PV systems. As the rear façades of dwellings could not be viewed, it was difficult to identify shading problems where the south facing roof was at the rear.

When carrying out the rapid site surveys, photographs were taken of every dwelling e.g. Figure 34. These photographs can be stored in the SEP system allowing the user to view the property at any time. Mr. R. Holmes, Energy Officer at the LEEAC, considered these photographs to be a useful visual aid when advising and encouraging householders to install energy efficiency measures or solar energy technologies (verbal communication, November 9, 2000). For example, Energy Officers at the LEEAC could

Figure 38. Potential shading problems from trees observed from a rapid site survey.

Figure 39. Minor obstructions causing shading problems on a roof.

use the SEP system to calculate the existing energy consumption of a dwelling based on an interview with the householders. They could then calculate the energy savings available from different measures. A photograph of the dwelling would emphasise that the energy savings were specific to that particular householder and that the LEEAC was interested in the householder as an individual (and not just as a statistic in a city wide energy efficiency campaign). From the above, it is clear that a rapid site survey is important for reasons other than improving the accuracy of the prediction of energy consumption.

It could be beneficial to reduce the quantity of data collected in a rapid site survey to the following: the type of glazing, presence or absence of a room in the roof, possible shading problems and a photograph of the dwelling. This would presumably reduce the time of the survey but the most important parameters would still be collected.

7.4.5 Home Energy Survey Form

Another way of improving the accuracy of the default prediction of energy consumption is to use the Home Energy Survey Form (Appendix E). Data collected from this household questionnaire is commensurate with a Level 0 data set (Table 1, Section 2.2.5). A Level 0 data set aims to specify accurate information for some of the most important parameters affecting the energy consumption of a dwelling: insulation levels, glazing type, space heating system type and water heating system type.

In Leicester, approximately 50,000 householders have completed a Home Energy Survey Form (A. McKinnon, Energy Officer at the LEEAC, verbal communication, November 23, 2000). This represents nearly half of the total dwelling stock. The data collection was primarily co-ordinated by the LEEAC but some was also collected by LCC's housing department. Based on the information contained within the forms, advice is provided to householders on possible energy efficiency improvement measures e.g. increased loft insulation or installing a condensing boiler. As with Level 3 data, it is generally regarded that Leicester has significantly more information at Level 0 than most other UK local authorities.

One of the problems encountered by LCC when using Home Energy Survey Forms is that some householders do not answer all the questions. This obviously reduces the value of the questionnaire as a complete Level 0 data set cannot then be obtained. In some cases, the forms are not returned. Furthermore, the data collected from the forms cannot be assumed to be completely reliable as inaccuracies are common in questionnaire returns (NES, 1999). Depending on the inaccuracies, this could lead to significant errors in the prediction of energy consumption. There is also a major problem in processing the data obtained from the questionnaires. LCC have not been able to enter all Level 0 data into one central database due to the considerable time involved (R. Holmes, verbal communication, October 25, 2000). Despite these problems, Home Energy Survey Forms have the potential to capture important data.

For the fifty-one dwellings being considered here, no completed Home Energy Survey Forms were available. There was obviously no need for LEEAC to send the householders one of these forms as Level 3 surveys had already been carried out. To allow the accuracy of the results obtained from a Level 0 calculation to be determined, the data obtained from a Home Energy Survey Form was derived from the Level 3 data sets. It should be noted that this is likely to lead to more accurate Level 0 data sets than if householders had completed the forms. This data was entered into BREDEM-8 to override the relevant default values. The predictions of energy consumption obtained from Level 0 are given in Table 53.

The total energy consumption of the fifty-one dwellings at Level 0 is 17.9% greater than that predicted by the Level 3 data set (Table 53). Although still significant, this is a major improvement over the accuracy of the predictions from the default level and the rapid site survey. Furthermore, the predictions for individual dwellings are much improved. For example, Level 0 predictions are now twice the Level 3 results for just two dwellings (cases 3 and 4).

More important, however, is the difference between the Level 0 results and those predicted at Level 2. It can be seen from Table 53 that the predictions of total energy consumption obtained from Level 0 and Level 2 data sets differ by only 6.6%. This was considered to represent good agreement. The predictions also show close agreement for individual dwellings with nearly half showing differences of less than 10%.

The residual differences arise because the Home Energy Survey Form provides data for only about ten to twenty BREDEM-8 input parameters and so default values are required for the remaining sixty parameters. The defaults may not match reality in four key areas.

1. Although the Home Energy Survey Form asks for information on the type of primary space heating system (e.g. gas boiler and radiators), it does not require the actual boiler type (e.g. low thermal capacity or condensing) to be specified. This is important as the efficiencies of boilers vary considerably and so they have a considerable effect on the total energy consumption. As a result, it was decided to use the default primary space heating system efficiencies given in Table 13.
2. In some cases, the water heating system efficiency is accurately known e.g. independent electric immersion heater. Where water heating was provided by the central heating system, however, it was necessary to assume default system efficiencies.
3. The Home Energy Survey Form does not ask for information on secondary space heating systems or cooking systems and so defaults were used for these parameters.
4. Finally, the Level 0 data set uses default dimensions derived from the digital urban map and standard dwelling configurations (Section 3.4.2) whereas Level 2 uses real dimensions obtained from a full property survey.

It should be noted that the differences between the predictions of energy consumption from Level 0 and Level 2 are at the same order of magnitude as the differences observed from the inter-model comparisons between BREDEM-8 and NHER Evaluator (Section 3.6.2). Using identical data, the two calculation models showed an average difference of 4.5% for ten dwellings. Based on these results, it was concluded that the use of Level 0 data introduces errors into the prediction of baseline energy consumption which are no more significant than the choice of calculation model.

Overall, given the similarity of the Level 0 and the Level 2 results, it was concluded that the majority of the defaults derived in Chapter 3, including those for heating and cooking systems and dwelling dimensions, were producing acceptably accurate results. However, there was scope to modify some of the other default values (especially element U-values) by analysing the Level 3 data sets. This is described in the following section.

7.4.6 Modified default level – case study specific

When analysing the Level 3 data obtained from the LEEAC, it became apparent that some parameters had values that were consistently different from the proposed default values. Accordingly, modified default values specific to the fifty-one dwellings were proposed for a small number of parameters as shown in Table 54.

Table 54. Original and modified defaults for selected parameters.

BREDEM-8 input parameter	**Original default**	**Modified default**
Wall U-value (W/m^2K)	2.12	1.97
Ground floor U-value (W/m^2K)	1.5	0.85
Roof U-value (W/m^2K)	2.0	0.62
Type of hot water tank insulation	None	Fitted jacket
Thickness of hot water tank insulation (mm)	None	37
Type of ground floor	Sealed suspended timber	Solid
Site exposure factor	Average	Sheltered
Dwelling exposure factor	D: 4 sides SD: 3 sides ET: 3 sides MT: 2 sides MTUP: 2 sides	All dwellings now fully sheltered

The modified element U-values are the average U-values calculated from the fifty-one Level 3 data sets. There is not a significant change in the wall U-value as the solid walls of pre-1900 dwellings are difficult to improve thermally. The improvement is primarily because the Level 3 data sets obtained from the LEEAC use a solid wall U-value of 2.04 W/m^2K whereas BREDEM-8 assumes a default value of 2.12 W/m^2K. Some dwellings have also installed extensions where the wall is highly insulated. This was included in determining the average wall U-value for the fifty-one dwellings. However, it could prove beneficial to consider dwellings with extensions separately i.e. two default wall U-values could be proposed, one for dwellings with no extension and one for dwellings with an extension.

The original default for the ground floor U-value was based on an assumption as there were no regulations governing this parameter prior to 1900 (Table 10, Section 3.4.3). The modified default value was found to be significantly lower for the fifty-one dwellings. There was also a significant change in the roof U-value due to the installation of loft insulation. With one exception, all dwellings also had an insulated hot water tank. The type and thickness of hot water tank insulation were selected to correspond to the average tank heat loss calculated by BREDEM-8 for the Level 3 data sets.

The remaining three parameters (Table 54) were changed to the most common situation recorded on the Level 3 survey forms. Sheltered site and dwelling exposure factors reflect the fact that the case study area is an inner city area where dwelling density is high. These three parameters could probably be modified for specific regions without Level 3 data being available.

The modified defaults given in Table 54 were entered into BREDEM-8 in conjunction with the original defaults for the remaining input parameters. The predictions of energy consumption for the fifty-one dwellings were re-calculated using this modified default set. The results are given in Table 53.

The total energy consumption of the fifty-one dwellings predicted by the modified defaults is 17.3% greater than that predicted at Level 3 (Table 53). This is a major improvement over the results obtained from the original default data set. The predictions are also marginally better than the Level 0 data set (and it was stated in Section 7.4.5 that the Level 0 result presented in Table 53 is likely to be more accurate than that obtained in practice).

The difference between the modified defaults and Level 2 is only 6.1% (Table 53). Again, this represents a significant improvement over the original defaults and is equivalent to the predictions obtained from Level 0. The results for individual dwellings using the modified defaults also display close agreement with the Level 2 data sets with nearly half showing differences of less than 10%. These results reinforce the conclusion stated in Section 7.4.5 that the remaining defaults originally proposed in Chapter 3 are acceptably accurate.

To improve the results still further to allow closer agreement with Level 3 predictions, it would be necessary to change the standard heating regime specified in the BREDEM-8 model description. It was stated in Section 7.4.2 that the actual heating regimes recorded for the fifty-one dwellings could be erroneous and thus the available Level 3 data was not considered to be sufficiently reliable to allow refinement of the standard occupancy defaults to be carried out with confidence. This could be performed in future if more reliable data was available.

Clearly, it was only possible to modify the defaults for pre-1900 dwellings. However, it is likely that the original default values for the parameters in Table 54 could also be enhanced for other age groups (especially pre-1980 dwellings) by comparison with Level 3 data sets. One other method of modifying the defaults for a specific region could be to use data collected from a regional house condition survey. For example, Shrewsbury and Atcham Borough Council (2000) have performed a detailed housing condition survey of the private sector housing stock within their region. This could improve the defaults derived from national statistics contained within the EHCS.

7.4.7 Analysis of different built forms

The total energy consumption for all fifty-one dwellings predicted by the six data sets are shown in Figure 40. It is interesting to note that as the quality of the input data gradually improves, the predictions of energy consumption fall.

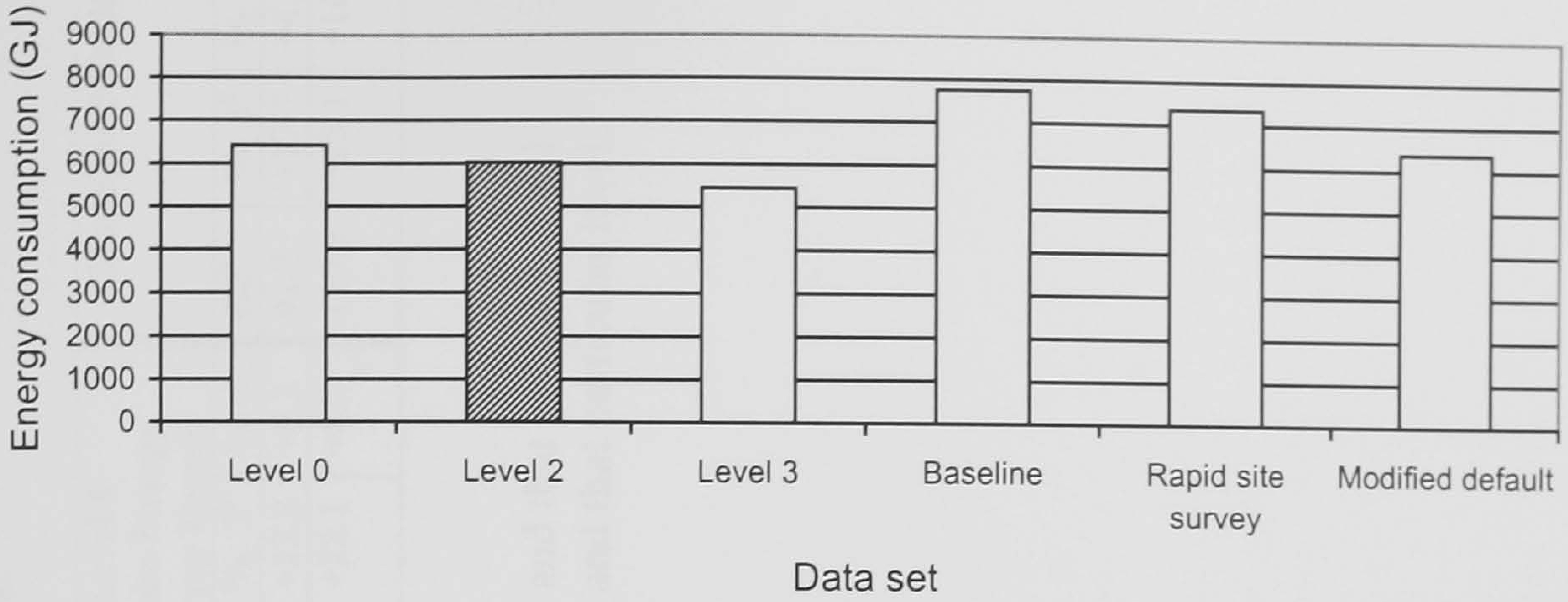


Figure 40. Comparison of energy consumption predictions for the different data sets.

It was also useful to consider the accuracy of the different data sets when predicting the energy consumption of dwellings with different built forms. This would show if the prediction of total energy consumption was biased by one particular type of dwelling. No meaningful analysis could be carried out for end terrace, semi-detached or detached dwellings as insufficient data was available for these built forms (Table 53). However, useful results were obtained for the built forms of mid terrace (MT) and mid terrace with unheated passageway (MTUP). The average energy consumption predicted by the different data sets for these built forms are shown in Table 55. The results are presented in Figures 41 and 42 for MT and MTUP respectively.

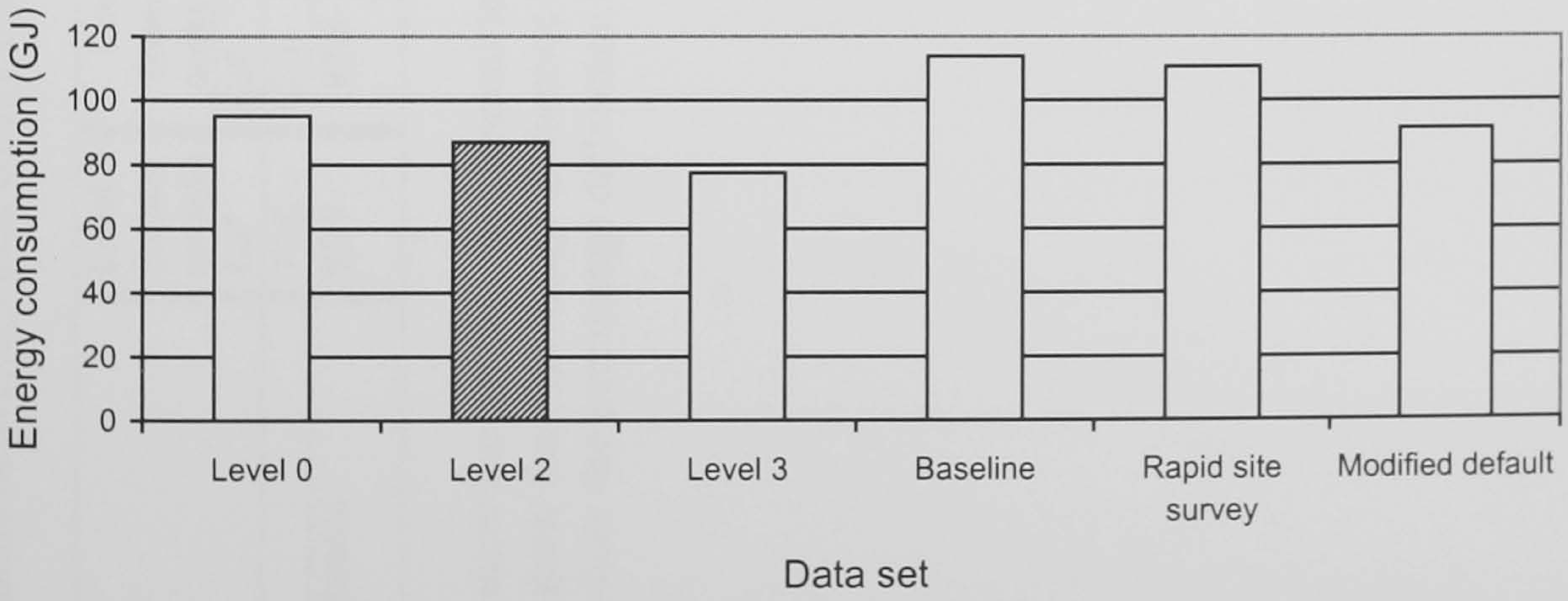


Figure 41. Comparison of average energy consumption predictions from the different data sets for the mid terrace built form.

Table 55. Predictions of average total energy consumption using different data sets for different built forms.

Built form	**Level 3 (actual occup.)**	**Level 2 (standard occupancy)**		**Baseline (using defaults)**			**Rapid site survey**			**Level 0 (Home Energy Survey Form)**			**Modified default**		
	GJ[a]	**GJ[a]**	% 3[b]	**GJ[a]**	% 3[b]	% 2[c]	**GJ[a]**	% 3[b]	% 2[c]	**GJ[a]**	% 3[b]	% 2[c]	**GJ[a]**	% 3[b]	% 2[c]
Mid terrace	77.5	87.1	+12.4	**113.8**	+46.8	+30.7	**110.5**	+42.6	+26.9	**95.2**	+22.8	+9.3	**91.2**	+17.7	+4.7
Mid terrace with unheated passageway	**95.3**	**107.8**	+13.1	**143.8**	+50.9	+33.4	**136.0**	+42.7	+26.2	**116.4**	+22.1	+8.0	**119.2**	+25.1	+10.6

[a] These columns show the prediction of annual total energy consumption obtained from BREDEM-8.

[b] These columns show the percentage difference between the predictions of energy consumption at Level 3 and that particular level.

[c] These columns show the percentage difference between the predictions of energy consumption at Level 2 and that particular level.

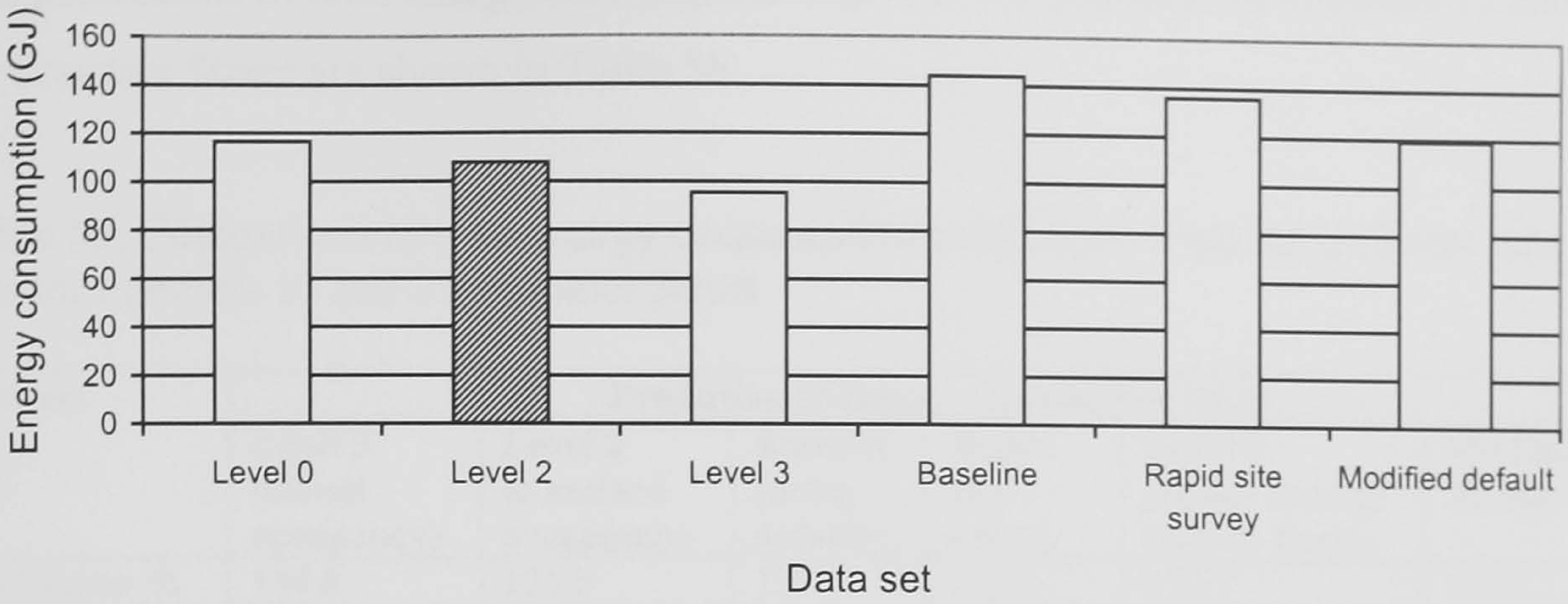


Figure 42. Comparison of average energy consumption predictions from the different data sets for the mid terrace with unheated passageway built form.

The modified default results for the MT differ by less than 5% when compared to Level 2 data (Table 55). They are also more accurate than Level 0 predictions (Table 55). Comparing Tables 53 and 55 shows that the MT built form is achieving better results than those obtained for all fifty-one dwellings.

Agreement is not so good for the built form of MTUP where the predictions from the modified default data set differ by 10.6% from Level 2 (Table 55). In addition, the results are not as accurate as Level 0 predictions (Table 55). Comparing Tables 53 and 55 shows that the MTUP built form gives rise to worse results than those obtained for all fifty-one dwellings. It could therefore be beneficial to derive modified defaults for each specific built form rather than simply calculating average defaults for all built forms. These results could also be indicating that the dimensional default data is more accurate for MT rather than MTUP built forms. The dimensional defaults could be considered in more detail by comparison with real dimensions in the Level 3 data sets.

Although the modified defaults appear to be producing reasonably accurate predictions of energy consumption for a large number of dwellings in an area, they are much less reliable predictions of the energy consumption of an individual dwelling. This is because the actual energy consumption in dwellings of the same built form varies considerably. For example, consider two similar MTUP dwellings on Cranmer Street.

The predictions of total energy consumption from the six data sets for numbers 17 and 21 Cranmer Street are shown in Table 56.

Table 56. Comparison of total energy consumption predictions from the different data sets for numbers 17 and 21 Cranmer Street.

Address	**Prediction of energy consumption (GJ)**					
	Level 3 (actual occupancy)	**Level 2 (standard occupancy)**	**Baseline (using defaults)**	**Rapid site survey**	**Level 0 (Home Energy Survey Form)**	**Modified default**
17 Cranmer St.	134.8	121.0	153.4	152.1	130.7	127.7
21 Cranmer St.	60.5	101.5	175.1	160.8	135.0	147.1

Comparing the Level 3 predictions of these two dwellings shows that 17 Cranmer Street consumes more than twice the energy of 21 Cranmer Street (Table 56). There are a number of reasons for this difference including different insulation levels, different heating systems and different heating regimes. The modified default prediction for 17 Cranmer Street is only 7.1 GJ/year less than the Level 3 prediction (Table 56). For 21 Cranmer Street, however, the modified default prediction is 86.6 GJ/year more than the actual consumption (Table 56). Similar results can be observed if considering the other data levels i.e. no data level predicts similar results to Level 3 for 21 Cranmer Street (Table 56) but most are reasonable for 17 Cranmer Street (Table 56). Therefore it was concluded that where detailed information is required about the energy consumption of an individual dwelling, there is no substitute for a detailed property survey. It should be noted that the proposed dwelling classification system was never intended to accurately estimate the energy consumption of individual dwellings. However if predictions are required for larger areas making data collection default, it is likely that defaults will produce acceptably accurate results.

7.5 Accuracy of predictions of solar DHW potential

Of the fifty-one dwellings considered in the previous section, twenty-six were suitable for installing a solar DHW system. This section compares how the different data sets affect the prediction of solar water heating potential for these twenty-six dwellings.

The modified default, Level 0 and Level 2 data sets all predict the same value of solar energy supplied by a solar DHW system because they use the same standard occupancy numbers to determine the daily mean hot water requirement of a dwelling. As described in Section 4.6.2, the daily mean hot water requirement is used to calculate the area of solar collector required and hence determines the solar energy supplied. The Level 3 data set predicts different values of solar energy supplied as it uses actual occupancy numbers to determine the daily mean hot water requirement. It is more useful, however, to compare the reduction in the fuel consumed for DHW. These savings in delivered energy depend on the efficiency of the conventional water heating system. The savings predicted by the different data levels are shown for the individual dwellings in Table 57. Summing the predictions for the individual dwellings gives the total savings in delivered energy and these are compared in Figure 43.

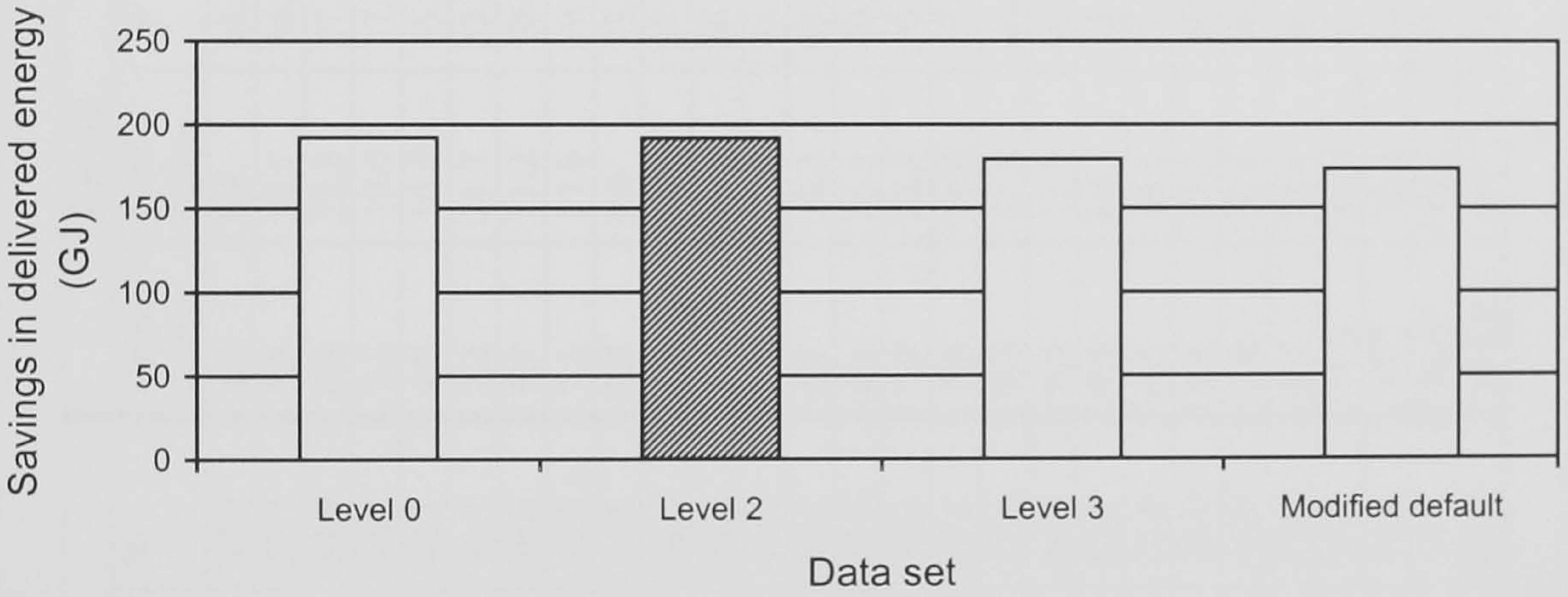


Figure 43. Comparison of predictions of savings in delivered energy from the different data sets.

It can be seen from Figure 43 that the absolute delivered energy savings do not vary much with the level of default data. The difference between the modified default level and Level 2 is only 18.3 GJ/year which is approximately 10.5% (Table 57). The differences between the predictions at the modified default level and Levels 0 and 2 are primarily due to differences in hot water system efficiency. The default hot water system has an efficiency of 77% or more (Table 18) whereas data obtained at Levels 0 and 2 showed that the majority of hot water systems actually had efficiencies of 70% or less. This shows that there is scope to modify the default data set still further to consider

Table 57. Predictions of solar DHW potential using different data sets.

Case	Address	Built form	Level 0			Level 2			Level 3			Modified default		
			Saving[a] GJ/yr	Fuel[b] GJ/yr	%[c]	Saving[a] GJ/yr	Fuel[b] GJ/yr	%[c]	Saving[a] GJ/yr	Fuel[b] GJ/yr	%[c]	Saving[a] GJ/yr	Fuel[b] GJ/yr	%[c]
1.	56 Ridley Street	MTUP	**4.5**	9.4	47.9	**4.5**	8.8	51.2	**3.3**	6.6	51.0	**5.9**	14.2	41.5
2.	43 Ridley Street	MTUP	**8.3**	14.3	57.7	**5.5**	10.1	54.0	**5.6**	9.8	56.8	**5.9**	14.4	41.1
3.	77 Latimer Street	MTUP	**6.7**	20.2	32.9	**6.5**	23.8	27.2	**4.6**	20.5	22.6	**6.1**	14.7	41.1
4.	85 Tyndale Street	MTUP	**6.6**	14.5	45.7	**7.1**	19.0	37.4	**5.1**	13.5	38.1	**6.0**	14.6	41.1
5.	54 Tyndale Street	MTUP	**4.8**	11.3	42.1	**4.8**	10.5	45.5	**4.2**	9.5	44.0	**6.2**	15.1	41.0
6.	94 Tyndale Street	MTUP	**6.7**	16.4	41.1	**7.3**	21.7	33.4	**7.4**	23.7	31.2	**6.1**	15.0	41.0
7.	78 Tyndale Street	MTUP	**8.5**	15.1	56.6	**5.7**	11.2	50.6	**5.0**	9.8	51.6	**6.1**	14.8	41.1
8.	87 Cranmer Street	MTUP	**6.6**	14.4	45.5	**7.1**	17.8	39.7	**5.1**	12.0	42.8	**6.0**	14.6	40.9
9.	14 Cranmer Street	MTUP	**6.5**	9.9	65.8	**6.5**	9.0	73.0	**6.6**	8.2	80.3	**6.0**	14.7	40.5
10.	47 Cranmer Street	MTUP	**6.8**	20.8	32.6	**6.6**	24.3	27.0	**6.4**	23.2	27.6	**6.2**	15.1	40.7
11.	79 Cranmer Street	MTUP	**6.6**	20.0	32.8	**6.4**	24.3	26.2	**11.1**	34.7	31.9	**6.0**	14.6	40.9
12.	74 Ridley Street	MTUP	**6.8**	14.6	46.6	**5.8**	12.6	45.8	**5.8**	12.6	46.1	**6.2**	14.6	42.6
13.	61 Tyndale Street	MTUP	**6.7**	10.2	66.1	**6.7**	10.5	63.7	**6.9**	10.5	65.2	**6.1**	14.9	41.0
14.	52 Latimer Street	MT	**6.3**	13.4	47.0	**6.1**	15.1	40.5	**4.6**	10.8	42.8	**5.7**	13.9	41.2
15.	70 Cranmer Street	MT	**6.5**	19.9	32.4	**7.0**	22.8	30.6	**7.1**	22.3	31.8	**5.9**	14.5	40.5
16.	90 Cranmer Street	MT	**6.5**	13.3	49.2	**7.0**	19.0	37.0	**5.1**	15.5	33.1	**5.9**	14.7	40.5
17.	66 Cranmer Street	MT	**6.5**	20.0	32.4	**6.3**	23.6	26.8	**9.9**	31.5	31.5	**5.9**	14.6	40.5
18.	46 Cranmer Street	MT	**6.6**	14.7	44.8	**6.4**	13.8	46.4	**6.7**	18.6	35.9	**6.0**	14.8	40.4
19.	10 Cranmer Street	MT	**6.5**	9.8	66.2	**6.5**	8.6	75.9	**4.8**	5.9	81.5	**5.9**	14.6	40.5
20.	34 Cranmer Street	MT	**6.7**	27.9	24.0	6.5	30.6	21.3	**13.0**	47.9	27.1	**6.1**	15.2	40.2
21.	94 Ridley Street	MT	**6.6**	20.0	32.9	**6.4**	23.8	26.9	**6.4**	23.2	27.6	6.0	14.6	41.2
22.	63 Ridley Street	ET	**6.5**	14.1	46.0	**7.0**	20.0	34.8	**5.1**	16.9	30.5	**5.9**	14.3	41.1
23.	93 Latimer Street	ET	**8.7**	15.7	55.4	**8.7**	14.4	60.3	**13.0**	19.3	67.3	**6.2**	15.2	40.9
24.	100 Cranmer Street	ET	**9.0**	15.8	57.1	**11.5**	26.4	43.7	**8.7**	30.1	29.0	**8.2**	15.7	52.6
25.	12 Westcotes Drive	SD	**12.7**	24.7	51.6	**13.7**	30.8	44.5	**6.4**	16.4	39.2	**11.6**	22.2	52.0
26.	17 Westcotes Drive	D	**17.1**	35.8	47.7	**18.4**	42.8	43.0	**11.0**	31.6	34.7	**15.6**	25.8	60.3
Total			**192.2**	436.3	44.1	**191.8**	495.1	38.7	**179.1**	484.8	36.9	**173.5**	401.3	43.2

[a] Delivered energy savings from installing a solar DHW system.

[b] Delivered energy requirement to meet the hot water demand of the dwelling (before the installation of a solar DHW system).

[c] Delivered energy savings from installing a solar DHW system as a percentage of the delivered energy requirement e.g. for case 1, 4.5/9.4 x 100 47.9.

water heating system efficiency. Comparison between the predictions at the modified default level and Level 3 showed extremely good agreement with the results differing by only 5.6 GJ/year or 3.2% (Table 57). It was concluded that for a large area, the modified default level is producing acceptably accurate predictions of absolute delivered energy savings from installing solar DHW systems.

It was also important to compare the predictions of delivered energy required for hot water from the different data levels. This allows the percentage of the hot water requirement met by solar energy to be calculated. The results are shown for the individual dwellings in Table 57. Summing for the twenty-six dwellings allows the total delivered energy requirement to be compared in Figure 44.

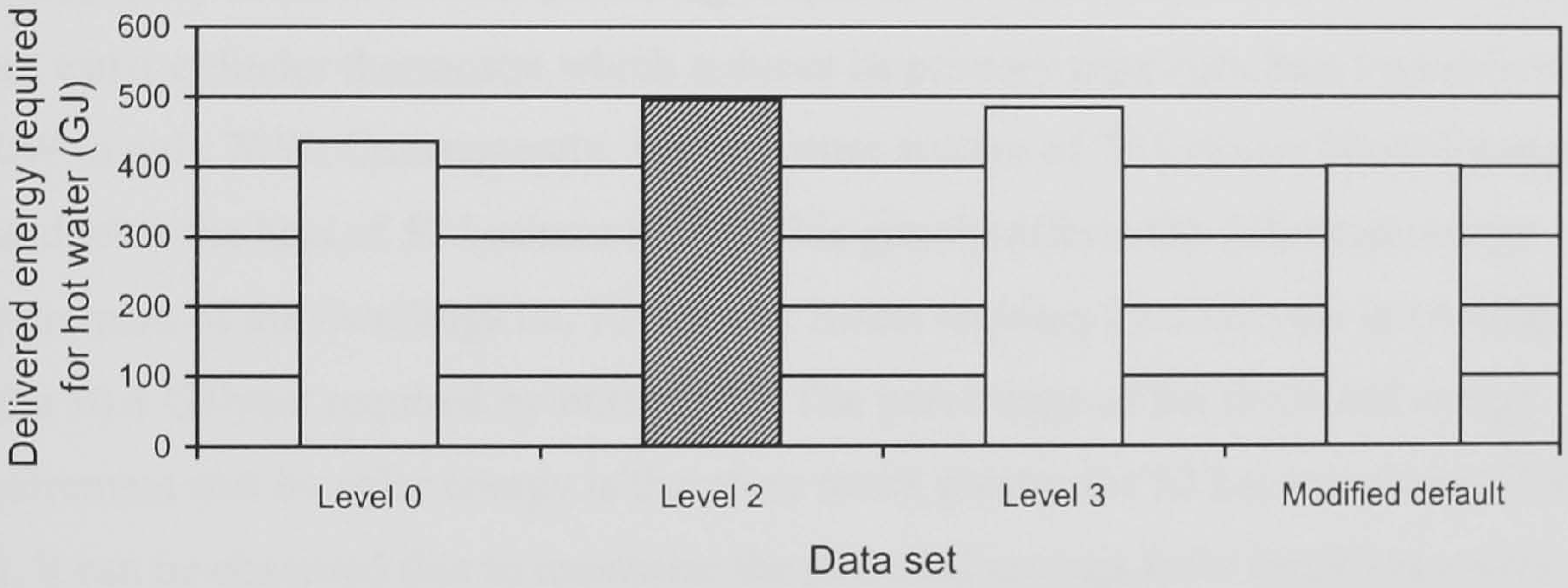


Figure 44. Comparison of predictions of delivered energy required for hot water from the different data sets.

It can be seen from Figure 44 that the predictions of delivered energy requirement vary considerably between the different data sets. The modifed default data set underestimates the requirement predicted at all other levels. There is a difference of 93.8 GJ/year or 23.4% between the modified default set and the Level 2 prediction. These differences are again primarily due to variations in the hot water system efficiency. In addition, the delivered energy requirement depends on the heat loss from the tank and the primary pipework. These losses are uniform for all dwellings at the default level (Table 54) but vary considerably in practice. It is useful to observe how the heat losses from the hot water system affect the delivered energy requirement by comparing the Level 3 predictions from two similar dwellings.

Consider 52 Latimer Street (Case 14 in Table 57) and 77 Latimer Street (Case 3 in Table 57). Both dwellings have only one occupant and so they have the same daily mean hot water requirement. As a result, they both require the same collector area to meet their requirements. From Level 3 surveys, it was found that both dwellings have the same type of gas boiler providing their hot water. Therefore, the predicted delivered energy savings are the same in each case i.e. 4.6 GJ/year from Table 57. However, 52 Latimer Street has 25mm of spray foam insulating the hot water tank whereas 77 Latimer Street only has a 25mm loose jacket. For cylinder volumes of 110 litres, the tank losses are 55W and 176W respectively (calculated using BREDEM-8). This is because spray foam has better insulating properties. Furthermore, 52 Latimer Street has a hot water cylinder thermostat which reduces its primary pipework heat losses from 140W to only 70W. Consequently, the hot water system of 77 Latimer Street loses more than double the heat of 52 Latimer Street. This greatly affects the delivered energy requirement of the dwellings i.e. 77 Latimer Street requires 20.5 GJ/year in comparison to the 10.8 GJ/year required by number 52. The percentage of the delivered energy requirement met by solar energy is therefore much greater for 52 Latimer Street (Table 57). It can be observed that to maximise the potential savings from installing a solar DHW system, the hot water tank should be well insulated and its temperature should be controlled.

These differences also show that although the modified default level produces acceptably accurate predictions of delivered energy savings for a large number of dwellings, defaults cannot be relied upon to accurately predict the savings for individual dwellings. For example, the modified default level predicts delivered energy savings of 41.2% for 52 Latimer Street. This is close to the Level 3 prediction of 42.8% (Table 57). However, the results for 77 Latimer Street are considerably different i.e. 41.1% at the default level but only 22.6% at Level 3 (Table 57). As stated in Section 7.4.7, it was not the intention to accurately estimate the results for individual dwellings.

7.6 Summary

This chapter described the application of the SEP system to a case study area of Leicester containing approximately 400 dwellings. The SEP system was used at its minimum data level to predict the solar energy potential of the case study area. It was demonstrated that useful results could be generated quickly. Level 3 data was obtained for a small subset of fifty-one dwellings to allow comparison of the predictions of baseline energy consumption from different data sets. This resulted in modifications being made to the original default data set proposed in Chapter 3. The modified default data set produced results which compared favourably with detailed dwelling data using standard occupancy (i.e. Level 2). Actual occupancy patterns were found to have a significant effect on dwelling energy consumption and so the default data set did not show such good agreement with Level 3 data. Accordingly, it was concluded that the default predictions were acceptably accurate when considering large regions but, as expected, the results for individual dwellings were less reliable. The prediction of solar DHW potential at the modified default level was shown to compare favourably with that predicted at Level 2 for large regions. Again, however, results were less accurate for individual dwellings.

The next and final chapter presents the main conclusions from the research performed for this thesis. It also proposes further work which could be carried out to both improve the performance of the SEP system and extend its scope of application.

Chapter 8

Conclusions and Suggestions for Further Work

8.1 Conclusions

The primary aim for the research described in this thesis was to develop new procedures for predicting the solar energy potential of urban dwellings. These procedures were then implemented, by another researcher, in a GIS-based Solar Energy Planning (SEP) system. This system is aimed at energy advisers and planners within local authorities, who currently lack any supportive tools of this kind. The work was timely because increased exploration of renewable energy sources in cities is now a key part of national and local government strategies to meet CO_2 emissions reduction targets. As dwellings are responsible for a high proportion of these emissions, it was appropriate to focus on this sector.

8.1.1 Domestic energy modelling

A strategy for estimating the baseline energy consumption of dwellings was required (Chapter 3) so an implementation of BREDEM-8 (the monthly version of the Building Research Establishment Domestic Energy Model) was developed. The data requirements of BREDEM-8 pose considerable problems for domestic energy modelling on an urban scale. To overcome these problems, a dwelling classification system was proposed.

From this work, the following conclusions can be drawn.

- It is important to establish the baseline energy consumption of a dwelling (i.e. the total energy consumed by space and water heating, lights, appliances and cooking) before considering solar energy measures.
- BREDEM-8 is at the appropriate level of detail for predicting the baseline energy consumption of dwellings on an urban scale. It is a monthly calculation procedure which is advantageous when considering solar sensitive active and passive energy systems. However, BREDEM-8 is not suitable for use as a manual calculation method and requires implementation in software.
- The correctness of the BREDEM-8 implementation in the SEP system was tested against a manual calculation carried out using the equations given in the model documentation (Anderson et al., 1997). For one particular dwelling (a one-storey detached house constructed between 1982 and 1990), the BREDEM-8 implementation was shown to be a faithful interpretation of the algebraic formulation.
- Further confidence in the correctness of the BREDEM-8 implementation was achieved by performing sensitivity tests. Changes to the key parameters of element U-values, space and water heating system efficiencies, zone demand temperatures and heating regimes all produced the expected effect.
- Inter-model comparisons were made between the implementation of BREDEM-8 in the SEP system and the implementation of BREDEM-12 (the annual version of the BREDEM model) in NHER Evaluator (version 3.10). Identical data sets for ten different dwellings (covering a range of built forms, insulation levels, heating systems and heating regimes) were entered into the calculation models. The prediction of average total energy consumption for the ten dwellings was only 4.5% higher from BREDEM-8 than from BREDEM-12. NHER Evaluator is widely used by local authorities and so these results give added confidence in the BREDEM-8 implementation.
- It is possible to derive a dwelling classification system such that the baseline energy consumption of a group of dwellings can be predicted, even when the amount of data available for each dwelling varies considerably.
- Software based on geographical information system (GIS) technology can be used to automatically extract the geometrical data needed by BREDEM-8.

- Authoritative sources, including the Building Regulations and the English House Condition Survey (EHCS), can be used to derive the remaining data necessary to produce BREDEM-8 predictions. These sources yield a nationally applicable default data set for the dwellings in each class.
- The robust, traceable and documented procedure for deriving the national defaults provides a reliable platform from which to produce defaults that are specific to a particular region or urban area.

Conclusions concerning the need for specific regional defaults and the reliability of BREDEM-8 for predicting the baseline energy consumption of large urban areas are given in Section 8.1.5.

8.1.2 Active solar technologies I: solar domestic hot water

A method for determining the solar domestic hot water (DHW) potential of dwellings was required (Chapter 4). A three-stage approach was devised to guide planners to appropriate dwellings where solar collectors could be installed. The calculation stage to predict the energy supplied by a solar system was based on a method presented in BS 5918 (the British Standard code of practice relating to solar heating systems for DHW).

This work led to the following conclusions.

- It is possible to use geometrical data describing the dwelling (roof plane orientation, inclination and area) to identify suitable locations for solar collectors. These data can be derived from digital urban maps and aerial photographs. This reduces the need for expensive site surveys.
- Socio-economic data could be used to estimate the likelihood that a householder will install a solar DHW system.
- The BS 5918 calculation method is, in principle, at the correct level of detail for estimating the potential yield from solar DHW systems in an urban area. It is applicable to the two most common types of solar DHW system installed in the UK i.e. pumped, indirect systems with one or two storage tanks.

- However, the BS 5918 method uses a graphical approach to determine the irradiation incident on a solar collector. This was not suitable for computerisation within the SEP system. Consequently, an analytical calculation procedure using the widely validated Perez tilted surface model (Perez et al., 1987) was devised. The method first predicts diffuse irradiation and then adds the components of beam and reflected irradiation. This modification automated the calculation of solar irradiation and so could be implemented in the SEP system.
- The revised method only requires data for approximately ten input parameters, most of which are readily available. In addition, it provides a monthly breakdown of the solar energy supplied by a solar DHW system: the original BS 5918 method produces only an annual prediction.
- Rules of thumb, based on knowledge of the daily mean hot water requirement (which can be found from the number of occupants or total dwelling floor area), can be used to estimate the required solar collector area. This automates the calculation of energy yield from a solar DHW system and eliminates the need for user interaction. This is important for a system which pre-supposes a lack of user expertise in the field of solar water heating.
- Predictions of the annual solar energy supplied by 4.28m^2 of Thermomax THS 400 evacuated tube solar collectors were produced by the revised BS 5918 method. These were compared with the predictions of the original method. Nine different systems were considered: collector inclination was varied between 0° and 90°; collector orientation was varied between east and west; and all were given a Midlands location (as defined in the BREDEM-8 model documentation). The predictions from the revised method were within 10% of the predictions from the original method for all nine systems. The average difference between the two calculation methods for the nine systems was 1.9%. This demonstrates that the revised version is a reasonable representation of the original BS 5918 method.
- The revised BS 5918 method was compared against Solar Master 2.01, a monthly calculation model developed by Thermomax. Predictions were made for 4.28m^2 of Thermomax THS 400 evacuated tube solar collectors with orientations between south-east and south-west and inclinations between 5° and 60°. The annual predictions of the solar energy supplied from the two models were within 10% for

all cases except those near the limit of the normal range of installation (e.g. a south-west orientation with a 50° inclination). Where annual results were within 10%, monthly predictions of solar energy supplied were within 5% between the months of March and October.

- Small differences in the absolute prediction of delivered fuel savings obtained from different calculation methods do not have a significant effect on cost savings. They are unlikely to affect the predicted payback period of a solar DHW system. Much more important is the fuel which the solar energy replaces.

8.1.3 Active solar technologies II: photovoltaics

It was necessary to develop a method for determining the photovoltaic (PV) potential of dwellings (Chapter 5). A three-stage approach similar to that proposed for solar DHW systems was adopted. The calculation procedure was based on a method presented in Duffie and Beckman (1991) after the work of Evans (1981), Siegal et al. (1981) and Clark et al. (1984). This work revealed the following.

- PV systems are not currently economically feasible in the UK domestic sector but if the UK government introduced subsidised residential PV rooftop programmes similar to those in other countries (e.g. Germany and Japan) then PV generated electricity could become economically competitive with conventional electricity. In this light, it was important to include PV in the SEP system to predict its future potential.
- As for solar DHW, it is possible to use the physical shape of dwellings to identify suitable sites for installing PV panels.
- Targeting, based on socio-economic parameters, could become important in the future but such a strategy is unlikely to yield useful results at present due to the high cost of PV systems.
- The calculation method proposed in Duffie and Beckman (1991) is at the correct level of complexity for predicting PV potential in an urban area. Approximately ten input parameters are required, most of which are readily available from manufacturers of PV panels.

- The incident irradiation calculation procedure used in the solar DHW calculation method was also used to estimate the solar irradiation incident on a PV panel. From this, it was concluded that the calculation procedure could be used in many applications.
- Empirical comparisons were carried out between the PV calculation model in the SEP system and the PV system installed on the Oxford Solar House (Roaf & Walker, 1997). The PV calculation model overestimated the annual electrical output by 14.2%. However, simulations performed by BP Solar, the designers of the PV system, overestimated actual performance by 9%.
- The PV calculation model overestimated the BP Solar predictions by only 4.8%. It was concluded that the PV model implemented in the SEP system was acceptable for predicting the yield of unshaded PV systems in urban areas.
- It was demonstrated that small differences in the prediction of electrical output from a PV system are unlikely to affect the predicted payback period.
- The PV calculation process was automated in the SEP system. As for the solar DHW calculation, this was an important consideration for a planning system which makes no assumptions about user expertise.
- The PV calculation model predicts electrical energy output on a monthly basis. This enables variations in electrical energy yield throughout the year to be observed.

8.1.4 Passive solar design

Based on the work described in the previous chapters, it was possible to propose an extension to the SEP system to allow the passive solar design potential of new housing estates to be considered (Chapter 6). The approach was not implemented in the SEP system and represents an area for further work but some initial conclusions can be drawn.

- On land owned by local authorities, planners have control over the design and layout of proposed new housing estates. They can set energy consumption targets which developers are required to meet. These targets increasingly specify the use of renewable energy technologies. It would be useful for planners to have a single tool which enabled them to consider both passive solar design and active solar technologies.

- The implementation of BREDEM-8 in the SEP system could be used to consider different passive solar design options for individual dwellings. A parametric calculation procedure could be developed to consider the effect of changing individual parameters on dwelling energy consumption. This would be particularly useful for determining the optimum area of south-facing glazing.
- In BREDEM-8, the effect of shading by nearby obstructions on the solar irradiation incident on a surface is considered by crude overshading factors. These could be replaced by the solar irradiation procedure used in the solar DHW and PV calculation models. This uses the concept of the urban horizon angle (i.e. the altitude angle of the obstructing object) to calculate the solar irradiation incident on a surface experiencing shading. Consequently, a more accurate estimate of the effect of overshading on dwelling energy consumption would be calculated.
- The existing framework of the SEP system could be extended to consider passive solar design.

8.1.5 Solar energy potential of urban dwellings: a case study

In Chapter 7, the SEP system was demonstrated for part of the City Challenge area of Leicester, an inner city area of urban regeneration. This case study area contained 394 dwellings of different built forms. For fifty-one of the dwellings, full data sets were obtained from the Leicestershire Energy Efficiency Advice Centre (LEEAC). The case study produced the following conclusions.

- The SEP system can be used to identify suitable locations for installing active solar technologies within an urban area. Savings in delivered fuel requirements and the subsequent reductions in CO_2 emissions can be predicted and the results usefully displayed through the GIS. The SEP system has the potential to fulfil its goal of allowing planners and energy advisers to consider the urban scale application of solar energy technologies with greatly increased confidence.

- Predictions in energy consumption from different levels of input data vary considerably. For the fifty-one dwellings for which full data sets were available, Level 2 (standard occupancy conditions) predicted a total energy consumption which was 10.6% higher than that predicted at Level 3 (actual occupancy conditions). It is evident that occupancy related factors, such as heating regimes and dwelling demand temperatures, have a significant effect on actual energy consumption.
- It is more useful to compare the predictions of total energy consumption obtained from reduced data sets with Level 2 results than with Level 3 results as reduced data sets assume standard occupancy. The derived national defaults were used to calculate the baseline energy consumption of the fifty-one dwellings. The total energy consumption of the sample was 29.1% higher than that predicted using Level 2 data.
- The difference between the predictions from the national default data set and the Level 2 data set were to be expected as all dwellings were constructed prior to 1900. Consequently, there is considerable scope for energy efficiency improvements to reduce the heating requirements of the dwellings. This can make the dwellings much more energy efficient than is suggested by the pre-1900 Building Regulation defaults. There is a need for the national defaults to be modified using real data in order to improve the prediction of baseline energy consumption.
- Rapid walk-by site surveys were performed for the fifty-one dwellings to collect data for sixteen input parameters required by BREDEM-8. The prediction of baseline energy consumption for the fifty-one dwellings using the rapid site survey data set was 22.4% higher than using Level 2 data. This does not represent a significant improvement over the prediction from using national defaults. However there was a substantial difference in baseline energy consumption predictions for individual dwellings. Where double glazing had been installed, predictions using rapid site survey data were approximately 15 GJ/year less than the defaults. For dwellings with single glazing (the default parameter), the rapid site survey predictions differed by only 1 GJ/year from the defaults.
- Rapid site surveys for the whole dwelling stock of Leicester would take at least two man-years to perform. This represents a significant undertaking for minimal

improvement in the prediction of energy consumption of an urban area. However, rapid site surveys are important for identifying possible roof shading which will curtail the installation of a solar collector or PV panel. They also identify rooms in the roof. These affect energy consumption and may also prevent the installation of a solar collector.

- It is recommended that the amount of data collected from rapid site surveys should be reduced to only the type of glazing, room in the roof and possible roof shading problems. This would presumably reduce the time of the survey but the most important parameters would still be collected.
- The use of household questionnaires, especially the Home Energy Survey Form, to collect key data at Level 0 was also considered. No actual data was available and so Level 0 data sets were derived from the full Level 3 data sets. The prediction of total energy consumption for the fifty-one dwellings using Level 0 data was only 6.6% higher than using Level 2 data. The good agreement between Level 0 and Level 2 predictions demonstrates that reduced data sets can reasonably predict the energy consumption of dwellings in an urban area.
- The difference between Level 0 and Level 2 predictions is of the same order of magnitude as the difference in predictions between NHER Evaluator and BREDEM-8 obtained from the inter-model comparisons. Thus, the use of Level 0 data introduces errors which are no larger than those resulting from the choice of calculation model.
- Some of the national defaults were modified to account for additional local knowledge obtained from the Level 3 data for the case study area. This allowed a 'Leicester City Challenge: pre-1900' default data set to be derived. The most significant changes were for element U-values and the level of hot water tank insulation. The prediction of total energy consumption for the sample of fifty-one dwellings using the 'Leicester City Challenge: pre-1900' default data set was only 6.1% higher than using Level 2 data. The results clearly demonstrate that the dwelling classification system proposed in this thesis provides a reliable platform from which to produce defaults that are specific to a particular region. The use of these could significantly improve the prediction of the baseline energy consumption of dwellings in an urban area.

- To obtain reliable predictions of the amount of fuel used for domestic water heating it is important to know: the efficiency of the hot water system; the thickness of the insulation surrounding the hot water tank and primary pipework; and whether the temperature of the water in the storage tank is controlled.
- Twenty-six of the dwellings for which full Level 3 data was collected had the potential to install a solar DHW system. The prediction of total delivered energy for DHW for these twenty-six dwellings using the 'Leicester City Challenge: pre-1900' data set was 23.4% higher than using Level 2 data. Although there is a significant variation in delivered energy predicted at the two levels, the predicted delivered energy savings from installing solar DHW systems were similar: 43.2% using the 'Leicester City Challenge: pre-1900' data set and 38.7% using the Level 2 data set. It is evident that the accuracy of the prediction of hot water consumption has little effect on the prediction of delivered energy savings for an urban area.

8.2 Suggestions for further work

During the investigations, a number of interesting possibilities for further research were noted. These can be broadly divided into two categories as described in the following sections.

8.2.1 Domestic energy modelling

Analysis work to modify the original national default data set with region specific data sets should be continued. In this thesis, a default data set called 'Leicester City Challenge: pre-1900' was established for the case study area. This has different, more locally relevant values for insulation of the building fabric, hot water tank insulation and site exposure factors. There are four main ways in which the work could develop.

1. It would be useful to study other key parameters such as type of space and water heating systems, type of cooking system and zone 1 and zone 2 element areas to observe if the inclusion of local defaults for these could enhance the prediction of energy consumption still further.

2. It may be useful to produce modified default values for each individual built form rather than for all dwellings of the same age.
3. Modified defaults were only proposed for pre-1900 dwellings. Region specific data is required for the other age groups to compare the predictions from the different data levels and to propose modifications to the national default data set. It could be the case that the baseline predictions for newer dwellings closely match the Level 2 predictions. This is because there is less scope for energy efficiency improvements in newer dwellings than there is in pre-1900 dwellings as later Building Regulations are much stricter and the apparent need for energy efficiency improvements is less. One problem is that Level 3 data for newer dwellings may not be readily available from either the LEEAC or LCC's housing department because they have concentrated their efforts on improving the energy efficiency of the oldest dwellings.
4. As it could prove difficult to obtain Level 3 data for a large number of dwellings, it may be possible to derive useful region specific defaults from Level 0 data sets. The LEEAC and LCC have considerable data available at this level.

The process of modifying the national default data set is especially important in the light of recent concerns expressed by the DETR that commercial energy ratings such as NHER need to be rationalised and unified (N. Cutland, Director of National Energy Services Limited, verbal communication, February 1, 2001). The concept of Level 0 predictions is now widely accepted in domestic energy modelling circles but the reliability of these reduced data sets is unknown. The implementation of BREDEM-8 in the SEP system can be used to determine the accuracy of the prediction of energy consumption based on small data sets. Sensitivity analyses could be performed to identify the most important input parameters. The minimum default data set proposed in this thesis could be used as the platform to derive a single reduced data set which is robust and well-documented and provides reliable predictions of the energy consumption of dwellings on an urban scale.

The data collection techniques of rapid site surveys and household questionnaires could also be refined using the results of sensitivity analyses. For example, the number of parameters collected from a rapid site survey could be reduced to only those that have a significant influence on energy consumption. In addition, the questions on the Home Energy Survey Form could be changed to ensure they were collecting data on the most important parameters. Any changes to the design of the questionnaire would need to be carefully considered to ensure it remained simple to complete.

The original assumption that rooms in the roof have the same floor area as the ground floor of a dwelling needs to be re-considered. It was suggested in Section 7.4.4 that perhaps all that is required is a reduction factor which is applied to the dwelling ground floor area. In addition, it will also be necessary to consider the effect that a room in the roof has on the roof U-value. It is likely that extra roof insulation will be installed in dwellings with a room in the roof.

8.2.2 Extending the scope of the SEP system

The Solar Energy Planning system has been developed with BREDEM-8, the GIS and the underlying property database as the core components. Numerous applications could be added to make use of the existing functions and to broaden its scope. In this extended planning system, the solar DHW, PV and passive solar design models would be three separate tools. Some suggestions for other tools are described below.

It could be possible to apply the concept of filtering, targeting and calculating proposed for solar DHW and PV systems to more general energy efficiency measures. For example, planners may wish to consider the potential energy savings from installing cavity wall insulation. This measure cannot of course be applied to dwellings with solid walls. Accordingly, filtering would remove all pre-1930 dwellings as these are likely to have solid walls. Targeting could then be used to identify householders most likely to install the measure. Finally, BREDEM-8 would be used to quantify the energy savings and subsequent reductions in CO_2 emissions from installing cavity wall insulation.

A parametric calculation procedure, similar to that proposed for passive solar design in Chapter 6, could also be developed to consider energy efficiency measures. For example, the thickness of loft insulation could be varied to see the effect that it had on energy consumption. This would allow the optimum thickness to be specified. It would also be useful to include economic information on the different measures to allow their payback times to be calculated.

As part of their HECA requirements, local authorities need to report on the average SAP rating of the dwelling stock in their region. The potential for deployment of the SEP system within local authorities would be enhanced if a SAP calculator was included. This was confirmed by A. Brown, Assistant Director of Housing at Oadby and Wigston Borough Council (verbal communication, February 1, 2001).

Oreszczyn and Pretlove (1999) have developed an algorithm, Condensation Targeter, to model the relative humidity of internal surfaces to predict the risk of mould growth in dwellings. The algorithm uses BREDEM-8 to predict internal temperatures. It could be possible to link this algorithm to the implementation of BREDEM-8 in the SEP system. This would be a useful addition to the SEP system because condensation and mould growth are major problems in the UK domestic sector resulting in poor health for the occupants and substantial damage to the fabric of the building.

The PV calculation model described in Chapter 5 could be extended to allow matching of supply and demand using a procedure described in Duffie and Beckman (1991). This would show the times of the day when PV generated electricity is used in the dwelling and when it is exported to the grid. The investigation of these issues is important for a follow-on EPSRC Project entitled 'Solar City' (Lomas & Infield, 2000) which is considering the effect that embedded renewable energy generators could have on the safety and power quality of the electricity distribution system. In the Solar City project, half-hourly electrical loads will be modelled.

The SEP system could also be extended to consider other building sectors. Solar energy, in particular daylighting and PV, has considerable potential to reduce the energy consumption of commercial and office buildings. One of the problems in extending the model to other sectors is accurately predicting the existing energy consumption of non-domestic buildings. Again, these are issues which are likely to be explored in detail in the follow-on Solar City project.

The work described in this thesis has made considerable steps to providing planners and energy advisers with new procedures for predicting the solar energy potential of urban dwellings. It has led to clear recommendations for future work that would extend the energy and greenhouse gas emissions analysis in order to address the broader context of planning for sustainable development.

Appendix A

Description of the Space Heating Procedure in BREDEM-8

A.1 Introduction

This appendix describes how BREDEM-8 determines the space heating requirement of a dwelling. There is also a description of the approach used in both BREDEM-9 and BREDEM-12.

A.2 Space heating equation

The indoor temperature of an unheated dwelling is, invariably, higher than the external temperature. This difference is due to solar and internal gains. Internal gains come from water heating, cooking, the use of lights and appliances and the occupants of the dwelling. The space heating energy required by a dwelling is that needed to raise the temperature from the level of an unheated dwelling to the desired demand temperature specified by the occupants. In BREDEM-8, the mean rate of heat output from the heating system, φ (W), over a specified period of one or more days is given by the space heating equation (Equation A.1).

$$\varphi = H\left(\frac{T_{int} - G_u}{H - T_{ext}}\right) \tag{A.1}$$

where H is the specific heat loss for the dwelling (W/K), T_{int} is the mean internal temperature (°C), G_u is the mean useful gains (W) and T_{ext} is the mean external temperature (°C).

BREDEM-8 calculates the space heating requirement for each month, Q(m) (GJ), using mean monthly internal temperatures, external temperatures and gains as shown in Equation A.2. (This equation is applied to each zone.)

$$Q(m) = 8.64 \times 10^{-5} H \left(\frac{T_{int} - G_u}{H - T_{ext}} \right) d \tag{A.2}$$

where d is the number of days in month m.

If $\left(\frac{T_{int} - G_u}{H - T_{ext}} \right) < 0$, the monthly space heating requirement is set to zero.

The mean monthly external temperatures depend on the location of the dwelling. BREDEM-8 divides the UK into twenty-one different regions. These are shown in Figure A-1. For each region, BREDEM-8 reference tables provide data for the representative latitude, the mean monthly external temperature at sea level, the mean wind speed and the mean monthly daily solar irradiation on the horizontal.

The useful gains include all solar and internal gains which make a useful contribution to reducing the space heating required. The specific heat loss is made up of fabric and ventilation losses. The concept of mean internal temperature is more complex and is described in the following section.

A.2.1 Mean internal temperature

The mean internal temperature in each zone of a dwelling is calculated using relationships based on an idealised temperature time graph. An example is shown in Figure A-2. Figure A-2 shows the temperature variation for a dwelling heated twice a day, for two hours in the morning and seven hours in the evening. During heating periods, the temperature equals the demand temperature i.e. the temperature required by the occupants. The standard zone 1 demand temperature used in BREDEM-8 is 21°C. The zone 2 demand temperature is assumed to be 3°C lower than that of zone 1. Outside

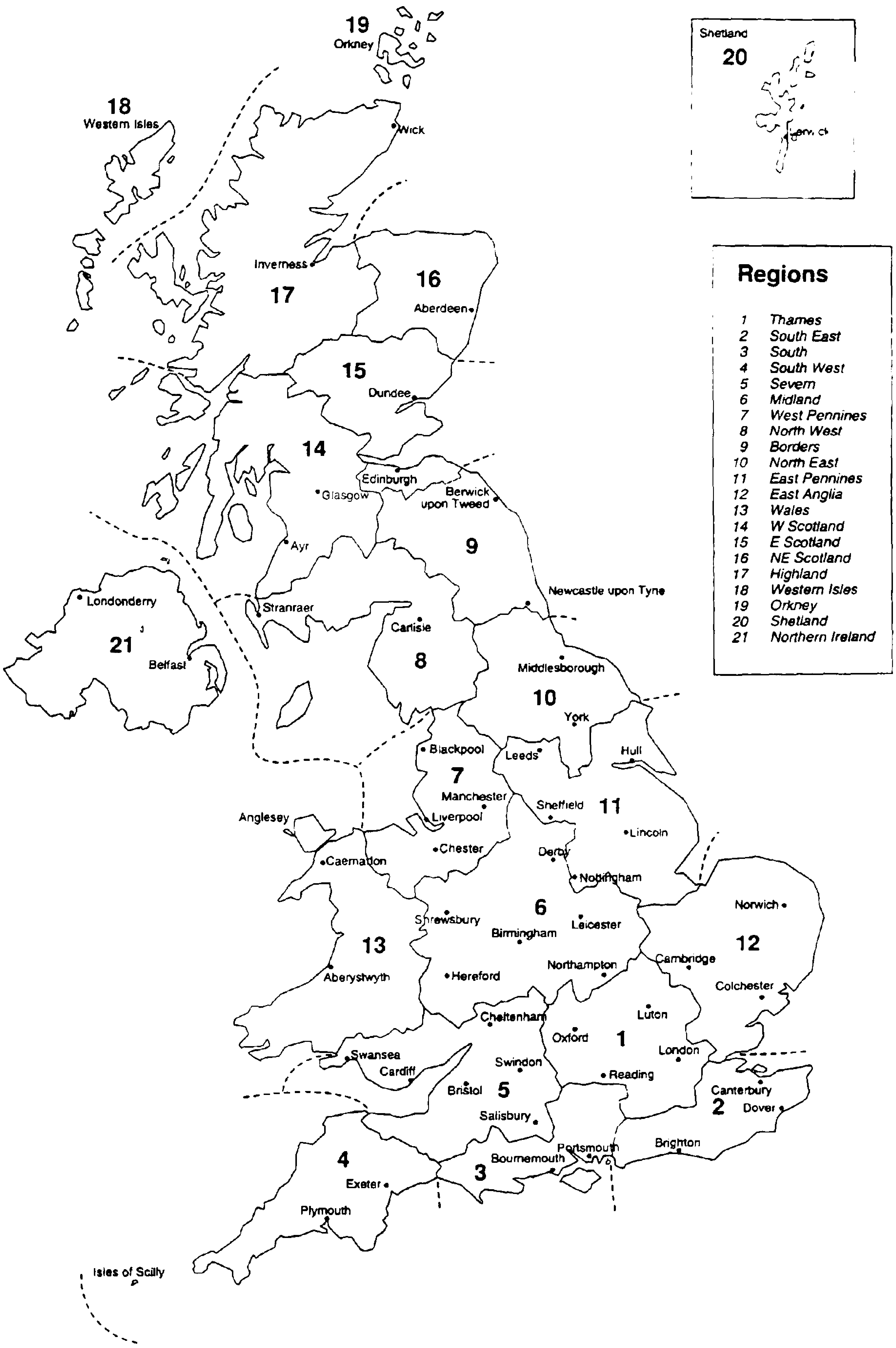


Figure A-1. Location of regions used in BREDEM-8. (Redrawn from Anderson et al., 1997.)

heating periods the internal temperature falls, eventually reaching the background temperature i.e. the temperature that would result if there were no heating. The background temperature depends on how much heat is output by the heating system outside the heating periods. This is characterised by the responsiveness of the heating system.

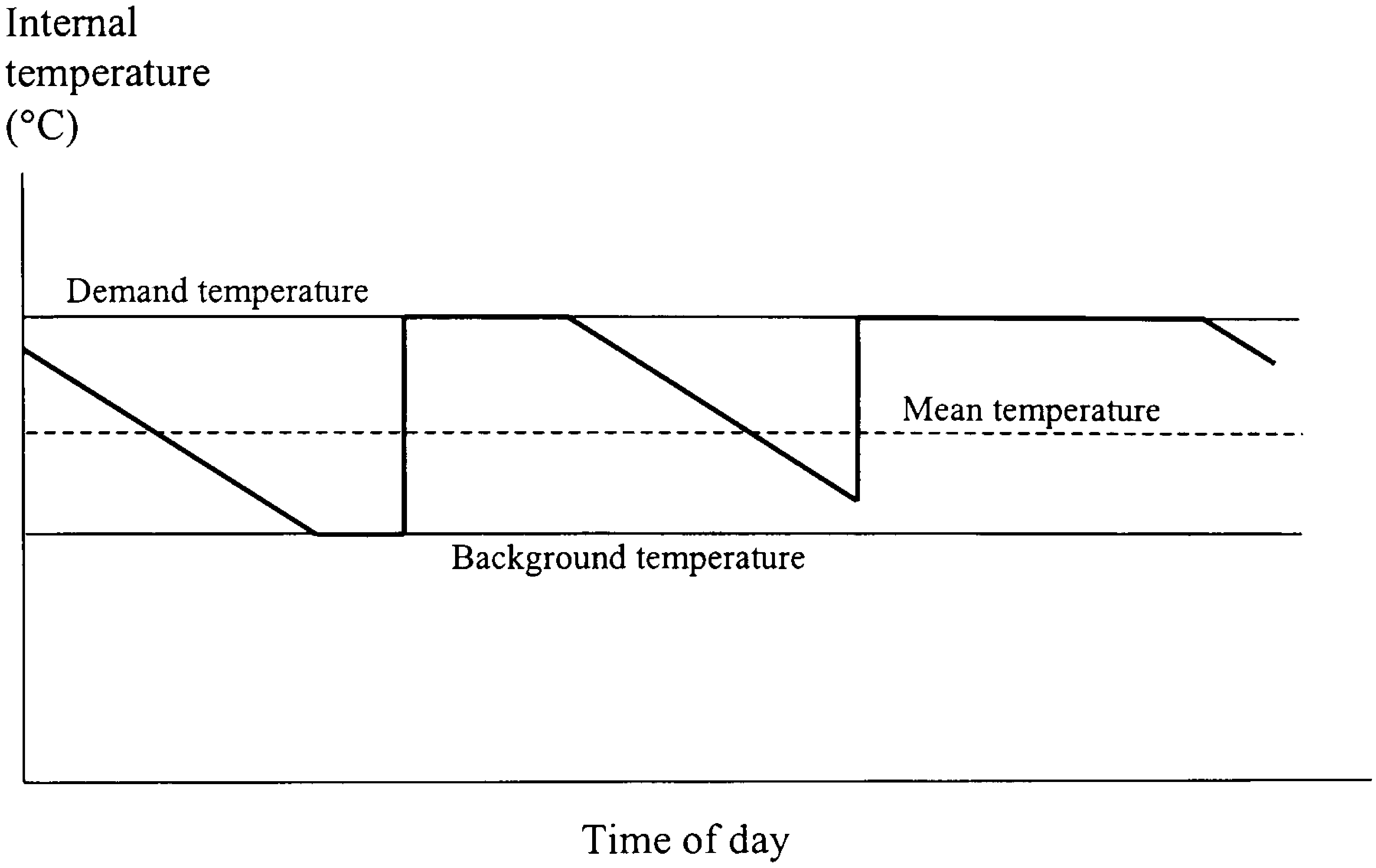


Figure A-2. Idealised temperature time graph. (Redrawn from Anderson et al., 1997.)

The responsiveness of a heating system is a measure of how quickly the heat output drops when heating is no longer required. A responsive system is one where the heat output falls to zero soon after the end of a heating period e.g. gas boiler. However, there are many systems for which this is not the case. These include coal fired appliances and electric storage heaters. Unresponsive heating systems result in a significantly higher internal temperature during periods when no heating is required. This is shown in Figure A.3.

Once the background temperature has been calculated for each zone, the mean internal temperature of each zone can be determined from knowledge of the demand temperatures and the heating periods. The space heating requirement of each zone can then be calculated using Equation A.2.

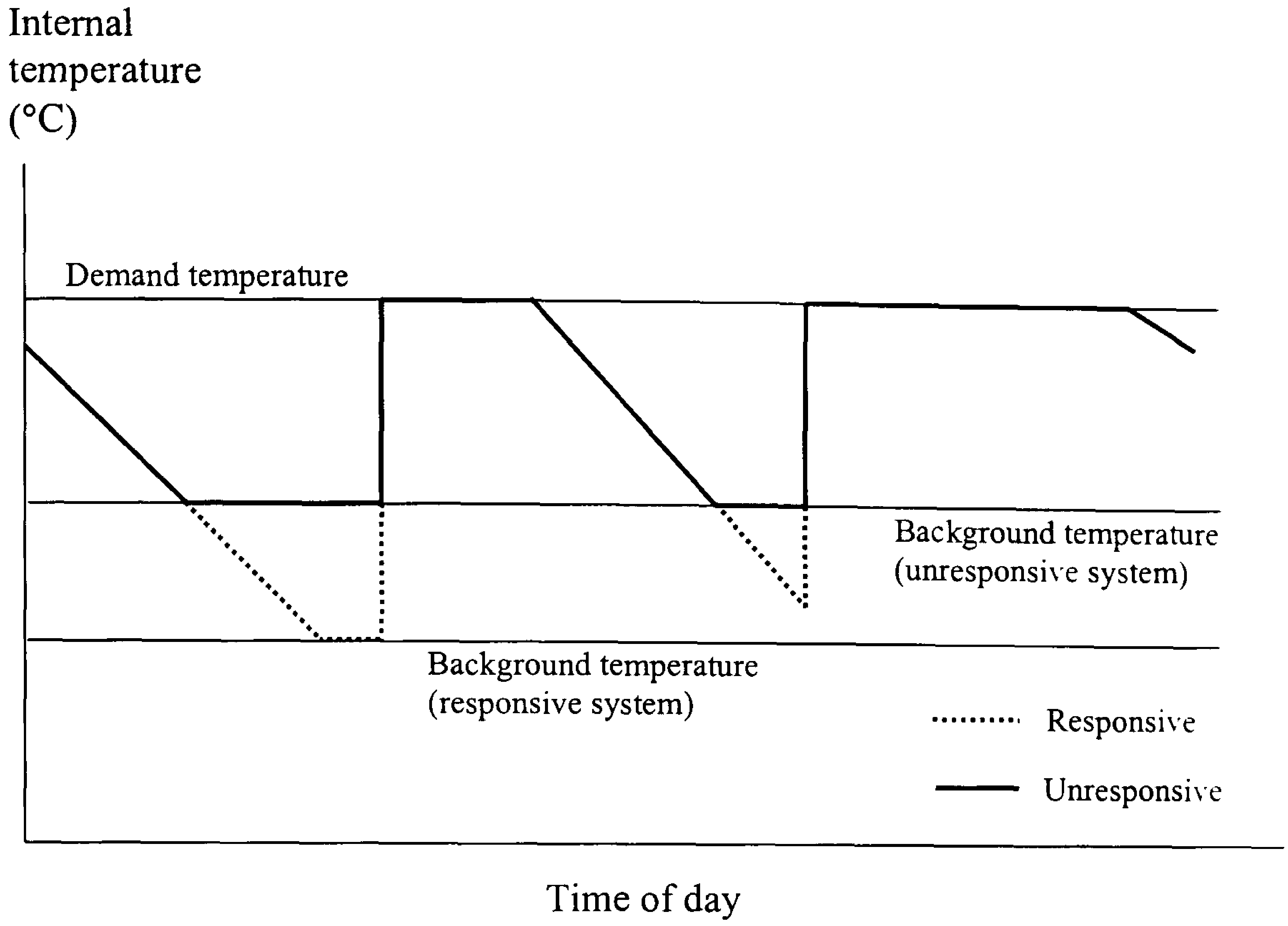


Figure A-3. The effect of heating system responsiveness on internal temperature. (Redrawn from Anderson et al., 1997.)

A.3 Degree-day approach

The calculation procedure used in BREDEM-8 for determining space heating requirement differs from that used in BREDEM-9 and BREDEM-12. In BREDEM-9 and BREDEM-12, the mean internal temperature of a dwelling is calculated for a nominal heating season of October to May. This calculation takes account of the extent to which the dwelling is insulated and how well the heating system can be controlled. The temperature is also increased to take account of the level of heat gains.

Once the mean internal temperature has been established, the space heating requirement for the heating season is calculated using a degree-day approach. The method of degree-days is based on the previously stated fact that the indoor temperature of an unheated building is higher than the outdoor. For a traditional British construction, the difference is taken to be 3°C (McMullan, 1993). To maintain an internal design temperature of 18°C, for example, the dwelling only needs heating when the outdoor temperature falls below 15°C (18 – 3). This base temperature is used as a reference for counting the degrees of outside temperature drop and the number of days for which a drop occurs e.g. one day at 2°C below base temperature gives two degree-days while two days at 1°C below base temperature also gives two degree-days. Degree-days are obviously dependent on the location of the dwelling.

In BREDEM-9 and BREDEM-12, the base temperature is calculated by reducing the mean internal temperature to take account of the heat provided by gains. The number of degree-days relating to this base temperature can be determined from tables containing the number of degree-days relative to known base temperatures. The space heating requirement is then calculated by multiplying the number of degree-days by the specific heat loss of the dwelling.

According to Anderson et al. (1997), a degree-day approach was not used in BREDEM-8 as it was found to make only a small difference which did not justify the increased complexity over the method described in Section A.2.

A.4 Comparison of BREDEM models

Various aspects of the three BREDEM models (BREDEM-8, -9 and -12) have been described in some detail in both Chapter 3 and this Appendix. Table A-1 summarises the main characteristics of each model.

Table A-1. Characteristics of the BREDEM models.

Model	**Energy use considered**	**Predictions**	**No. of zones**	**Nominal heating season**	**Space heating calculation**	**Normal implementation**	**Applied use**
BREDEM-8	Space heating Water heating Cooking Lights and appliances	Monthly	2	None	Space heating equation (Equation A.2)	PC	SEP system
BREDEM-9	Space heating Water heating	Annual	1	8 months i.e. October to May	Degree-day approach	Worksheet	SAP (Section 3.2)
BREDEM-12	Space heating Water heating Cooking Lights and appliances	Annual	2	8 months i.e. October to May	Degree-day approach	PC (although can be carried out on a worksheet)	BREHOMES (Section 2.2.1); NHER software (Section 2.2.5).

Appendix B

Interpretation of Standard Dwelling Configurations to Determine Default Zone Areas

B.1 Introduction

The ground floor area and exposed perimeter of a dwelling can be extracted from the digital urban map with acceptable accuracy using the 'Footprint Tool' (Section 3.4.2). Knowledge of these two parameters allows default zone areas for every dwelling to be estimated using assumptions derived from standard dwelling configurations (Allen & Pinney, 1990). These assumptions are described for each built form in the following sections. It should be noted that the Footprint Tool was developed by the software engineer employed on the EPSRC project and is described in Rylatt et al. (in press).

B.2 Detached house

This section presents the assumptions for a detached house with two storeys. These assumptions also apply to a detached house with more than two storeys. For a detached house with only one storey (i.e. a detached bungalow), see Section B.4.

The floor plans for the two storey detached house are given in Figure B-1. These plans are not to scale and are only intended to show the main characteristics of the dwelling. Zone 1 is designated as the living room and zone 2 is the remainder of the dwelling.

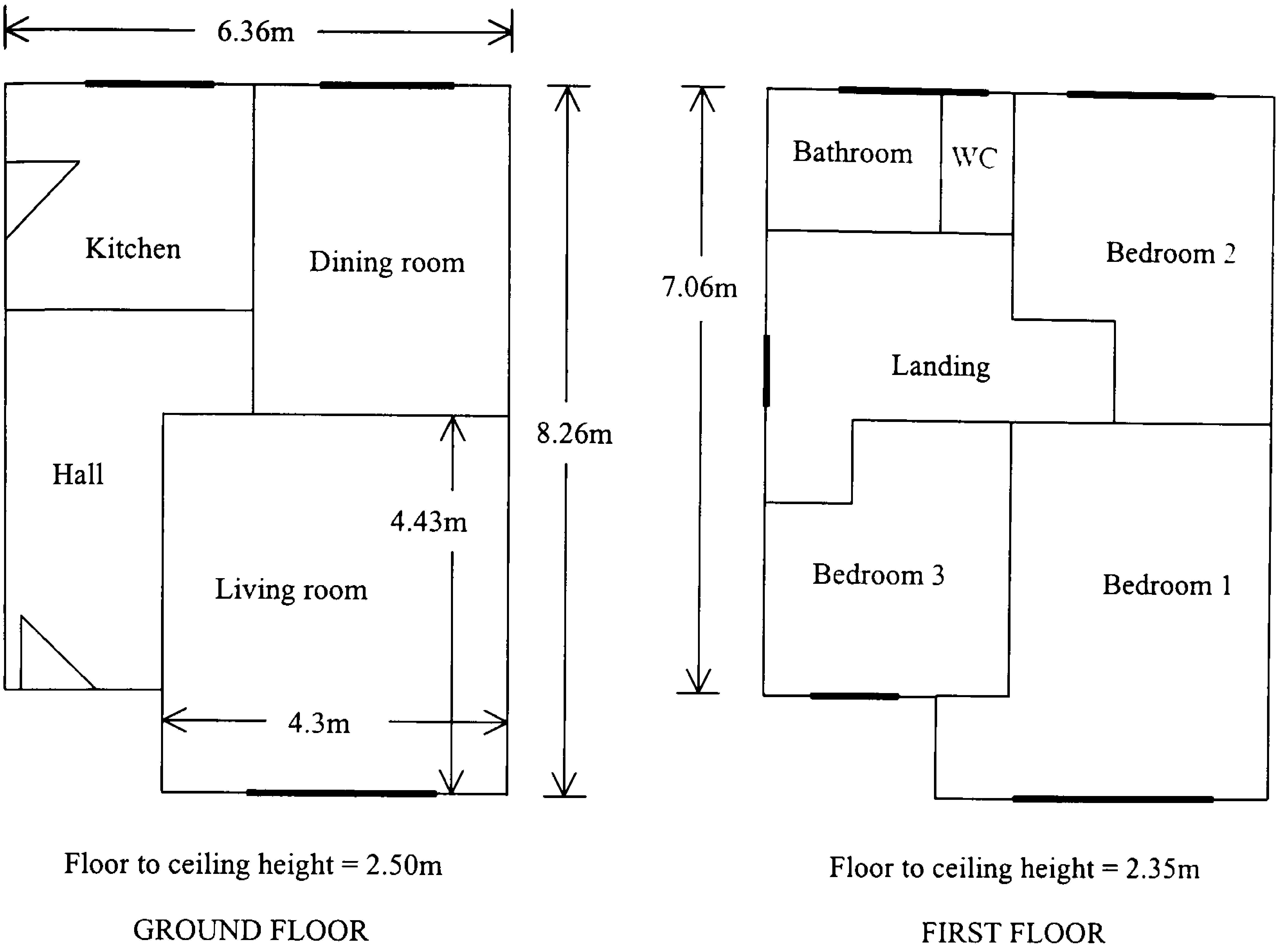


Figure B-1. Detached house plans. (Redrawn from Allen and Pinney, 1990.)

B.2.1 Floor area

To predict the energy consumption of a dwelling, BREDEM-8 requires information on both the ground floor area and the total floor area of each zone. The relevant floor areas for the detached house are listed below.

- Dwelling ground floor area = 50.06m^2
- Dwelling first floor area = Dwelling ground floor area = 50.06m^2
- Zone 1 ground floor area = 19.05m^2
- Zone 2 ground floor area = 31.01m^2
- Zone 2 first floor area = Dwelling ground floor area = 50.06m^2

Zone 1 and zone 2 floor areas were then expressed as a percentage of dwelling ground floor area to give the default areas for use in the dwelling classification system. These percentages were rounded to the nearest 5% to reflect the fact that the defaults are based on assumptions rather than precise knowledge.

- Zone 1 ground floor area $= \frac{19.05}{50.06} \times 100 = 40\%$ of dwelling ground floor area
- Zone 1 total floor area = Zone 1 ground floor area
- Zone 2 ground floor area = 60% of dwelling ground floor area
- Zone 2 total floor area = 60% of dwelling ground floor area + dwelling ground (= first) floor area

For detached houses with more than two storeys, it is assumed that each subsequent storey also has the same floor plan as the ground floor.

B.2.2 Volume

The relevant volumes for the detached house are listed below.

- Ground floor volume = 125.15m^3
- First floor volume = 117.64m^3
- Dwelling volume = 242.80m^3
- Zone 1 volume = 47.62m^3
- Zone 2 volume = 195.18m^3

Zone 1 and zone 2 volumes were then expressed as a percentage of dwelling volume to give the default volumes for use in the dwelling classification system. Once again, these percentages were rounded to the nearest 5%.

- Zone 1 volume $= \frac{47.62}{242.80} \times 100 = 20\%$ of dwelling volume
- Zone 2 volume = 80% of dwelling volume

In the proposed dwelling classification system, the dwelling volume is calculated using an assumed storey height (dependent on age) after P. F. Chapman (1994) (Table 10).

B.2.3 Roof area

The zone 1 roof area is zero as zone 1 is located on the ground floor. Assuming horizontal loft insulation, the zone 2 roof area is equal to the dwelling first (= ground) floor area. This corresponds with the findings of P. F. Chapman (1994).

B.2.4 Gross external wall area

The relevant gross external wall areas (i.e. the wall areas including windows and doors) for the detached house are listed below.

- Ground floor gross external wall area = 73.1m^2
- First floor gross external wall area = 68.71m^2
- Dwelling gross external wall area = 141.81m^2
- Zone 1 gross external wall area = 24.83m^2
- Zone 2 gross external wall area = 116.99m^2

Zone 1 and zone 2 gross external wall areas were then expressed as a percentage of dwelling gross external wall area to give the default gross external wall areas for use in the dwelling classification system. Once again, these percentages were rounded to the nearest 5%.

- Zone 1 gross external wall area = 20% of dwelling gross external wall area
- Zone 2 gross external wall area = 80% of dwelling gross external wall area

To find the net external wall area of each zone, it is necessary to subtract the window and door area of each zone.

B.2.5 Window area

For the proposed dwelling classification system, the default dwelling window area was assumed to be the maximum allowable area specified by the Building Regulations at the time of construction (Table 10). This assumption is discussed in Section B.9. However, the default window areas of zone 1 and zone 2 were both derived from the standard dwelling configurations.

The relevant window areas for the detached house are listed below.

- Dwelling window area = 15.11m^2
- Zone 1 window area = 2.27m^2
- Zone 2 window area = 12.84m^2

Zone 1 and zone 2 window areas were then expressed as a percentage of dwelling window area to give the default window areas for use in the dwelling classification system. Once again, these percentages were rounded to the nearest 5%.

- Zone 1 window area = 15% of dwelling window area
- Zone 2 window area = 85% of dwelling window area

B.2.6 Door area

To simplify the specification of the default orientation of doors in the dwelling classification system, it was assumed that there is one door on the front façade and one door on the rear façade. This is different to the 'standard' detached house which has a door on one of the side façades and not the rear façade. However, the door area is small in comparison to other building elements and this assumption is unlikely to have a significant effect on the prediction of dwelling energy consumption. Both doors were given a standard area of 1.64m^2 and assumed to be located in zone 2.

B.3 Semi-detached house

The assumptions for a semi-detached house with two or more storeys were calculated in exactly the same manner as that described for the detached house in Section B.2. These defaults are shown in Tables 8 and 9 and are not repeated in this Appendix. For a semi-detached house with only one storey (i.e. a semi-detached bungalow), see Section B.5.

The floor plans for the two storey semi-detached house are given in Figure B-2. These plans are not to scale and are only intended to show the main characteristics of the dwelling. Zone 1 is designated as the living room and zone 2 is the remainder of the dwelling. Rapid site surveys confirmed that semi-detached dwellings tend to have their front doors (and hence their hall) adjacent to the external wall and their living rooms adjacent to the attached wall (Figure B-2).

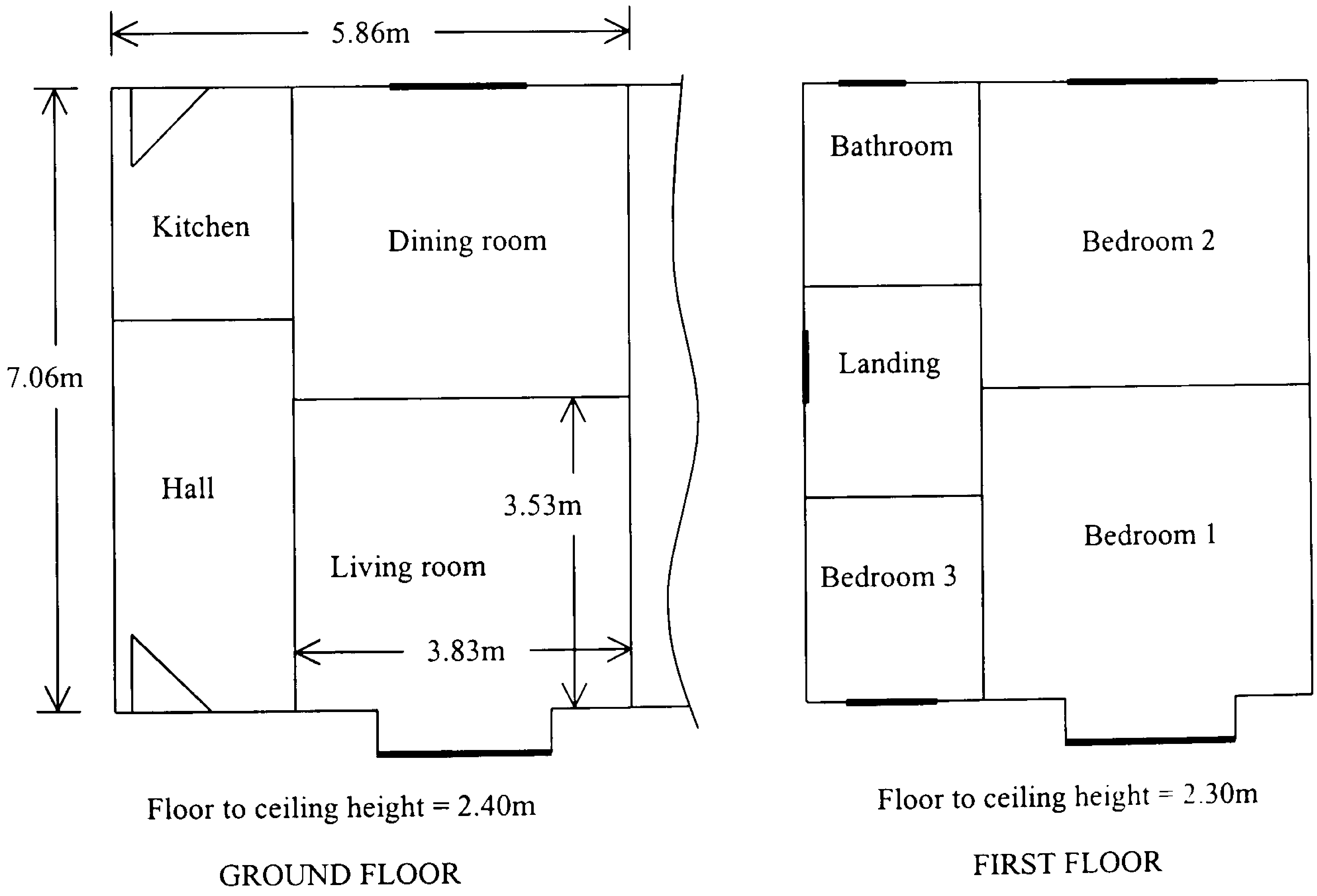


Figure B-2. Semi-detached house plans. (Redrawn from Allen and Pinney, 1990.)

B.4 Detached bungalow

The assumptions for a detached house with one storey (i.e. a detached bungalow) were calculated in exactly the same manner as that described for the detached house in Section B.2. These defaults are shown in Tables 6 and 7 and are not repeated in this Appendix.

The floor plans for the detached bungalow are given in Figure B-3. These plans are not to scale and are only intended to show the main characteristics of the dwelling. Zone 1 is designated as the living room and zone 2 is the remainder of the dwelling.

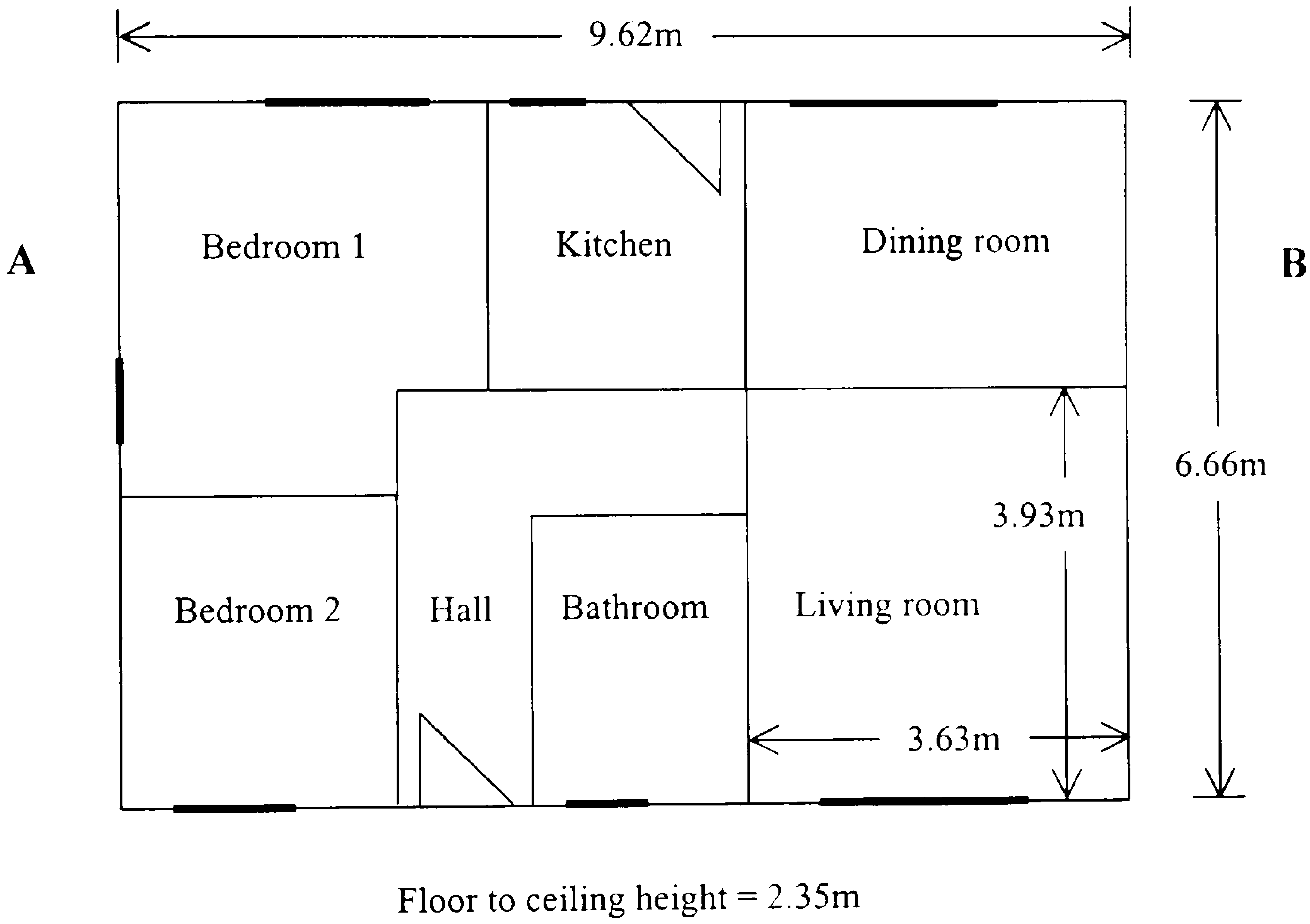


Figure B-3. Detached bungalow plans. (Redrawn from Allen and Pinney, 1990.)

B.5 Semi-detached bungalow

The standard dwelling configurations of Allen and Pinney (1990) do not include a semi-detached bungalow. Although probably not as common as detached bungalows, it was decided that semi-detached bungalows should still be considered. Defaults for a semi-detached bungalow were assumed using the detached bungalow plans of Figure B-3. All the assumptions for a semi-detached bungalow are therefore the same as those for a detached bungalow (Tables 6 and 7) with the exception of gross external wall area. This is discussed in the following section.

B.5.1 Gross external wall area

The semi-detached bungalow can have two possible configurations:

- wall A external with wall B adjoining another dwelling;
- wall B external with wall A adjoining another dwelling (assuming the window in wall A to be relocated to wall B) (Figure B-3).

This obviously affects the relative gross external wall area of each zone. Each configuration was considered separately and the following results were obtained.

For wall A external:

- zone 1 gross external wall area = 14.03% of dwelling gross external wall area
- zone 2 gross external wall area = 85.97% of dwelling gross external wall area

For wall B external:

- zone 1 gross external wall area = 29.22% of dwelling gross external wall area
- zone 2 gross external wall area = 70.78% of dwelling gross external wall area

The results for the two configurations were averaged and then rounded to the nearest 5% to produce default gross external wall areas for zone 1 and zone 2 as given below:

- zone 1 gross external wall area = 20% of dwelling gross external wall area
- zone 2 gross external wall area = 80% of dwelling gross external wall area

B.6 End terrace

The standard dwelling configurations of Allen and Pinney (1990) contain two different terraced houses: a post 1919 terraced house and a period terraced house. These were considered separately for the end terrace as described below.

B.6.1 Post 1919 terrace

The floor plans for the post 1919 terrace are given in Figure B-4. These plans are not to scale and are only intended to show the main characteristics of the dwelling. Zone 1 is designated as the living room and zone 2 is the remainder of the dwelling.

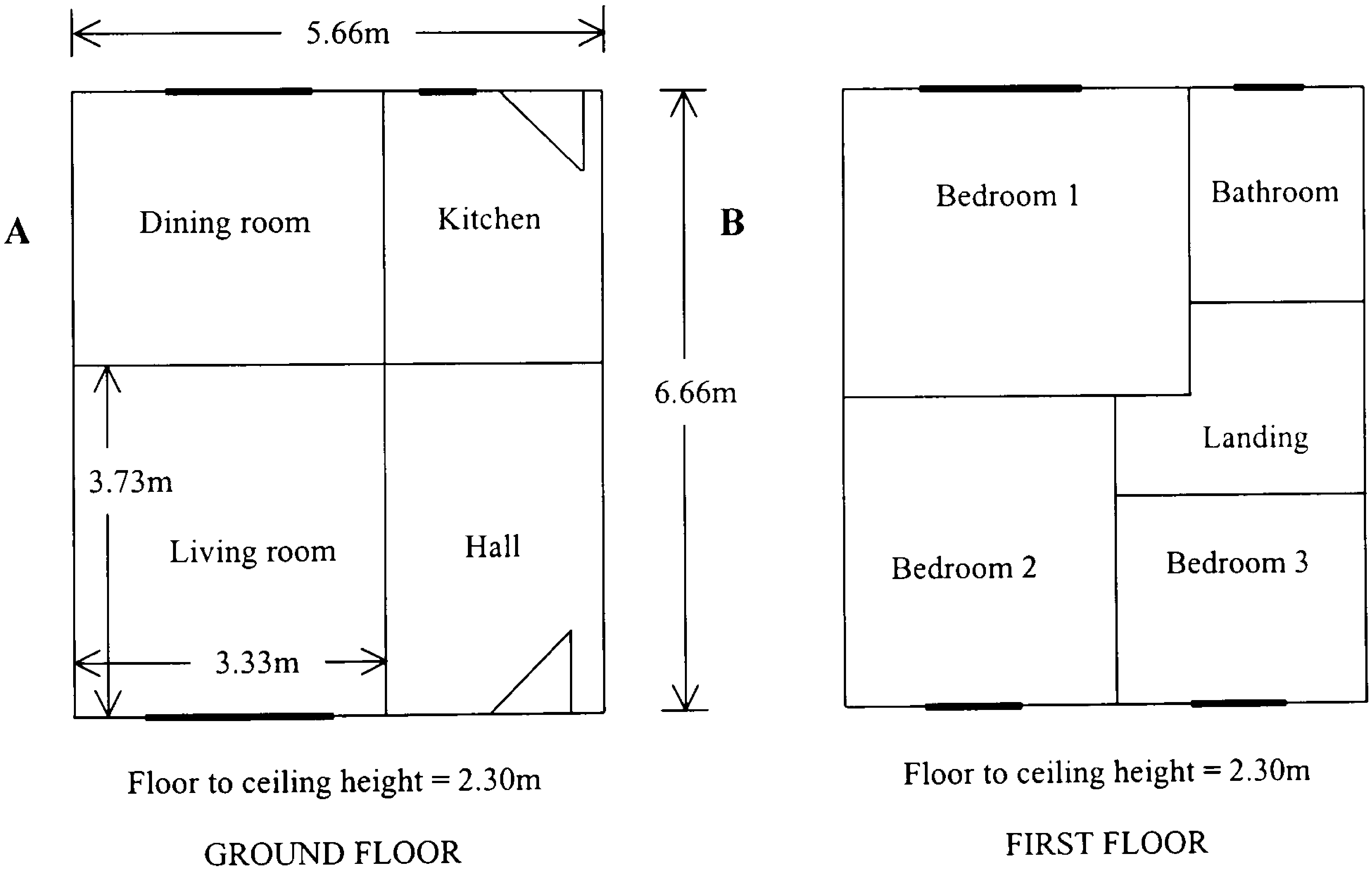


Figure B-4. Post 1919 terrace plans. (Redrawn from Allen and Pinney, 1990.)

The zone 1 and zone 2 post 1919 end terrace assumptions were calculated in the same manner as described for the detached house (Section B.2). They were found to be:

- zone 1 ground floor area = 35% of dwelling ground floor area

- zone 2 ground floor area = 65% of dwelling ground floor area
- zone 1 total floor area = 35% of dwelling ground floor area
- zone 2 total floor area = 65% of dwelling ground floor area + dwelling ground floor area for each subsequent storey
- zone 1 volume = 15% of dwelling volume
- zone 2 volume = 85% of dwelling volume
- zone 1 roof area = 0
- zone 2 roof area = dwelling ground floor area
- zone 1 window area = 15% of dwelling window area
- zone 2 window area = 85% of dwelling window area
- zone 1 door area = 0
- zone 2 door area = 3.28m^2

From rapid site surveys, it was observed that there is a mix of end terrace dwellings and either wall A or wall B (Figure B-4) could be the external wall. As for the semi-detached bungalow (Section B.5), an average was taken of the two configurations.

For wall A external and wall B adjoining another dwelling (Figure B-4):

- zone 1 gross external wall area = 19.63% of dwelling gross external wall area
- zone 2 gross external wall area = 80.37% of dwelling gross external wall area

For wall B external and wall A adjoining another dwelling (Figure B-4):

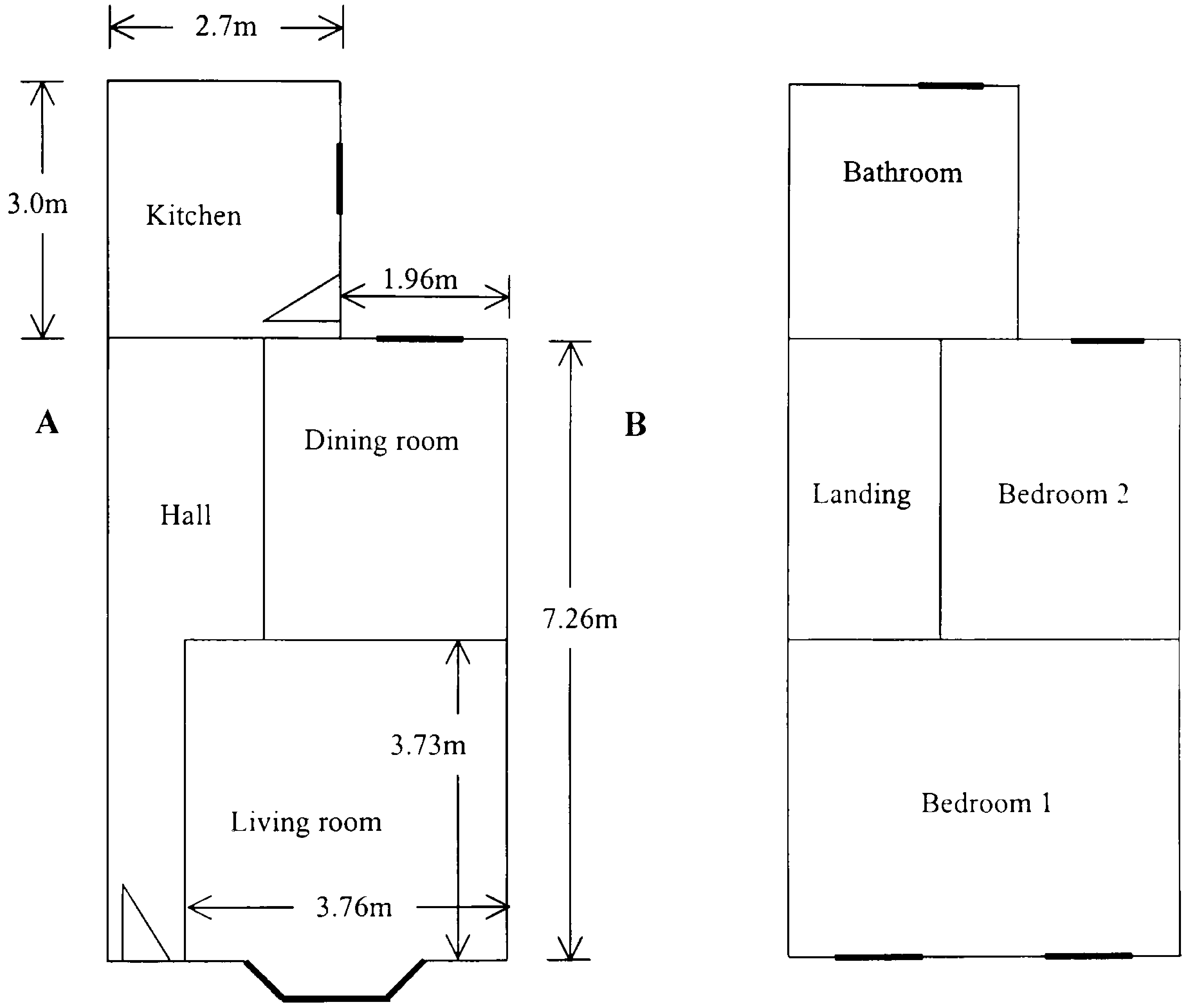
- zone 1 gross external wall area = 9.26% of dwelling gross external wall area
- zone 2 gross external wall area = 90.74% of dwelling gross external wall area

The results for the two configurations were averaged and then rounded to the nearest 5% to produce default gross external wall areas for zone 1 and zone 2 as given below:

- zone 1 gross external wall area = 15% of dwelling gross external wall area
- zone 2 gross external wall area = 85% of dwelling gross external wall area

B.6.2 Period terrace

The floor plans for the period terrace are given in Figure B-5. These plans are not to scale and are only intended to show the main characteristics of the dwelling. Zone 1 is designated as the living room and zone 2 is the remainder of the dwelling.



Floor to ceiling height = 2.60m (main terrace)
= 2.30m (rear extension)

GROUND FLOOR

Floor to ceiling height = 2.50m (main terrace)
= 2.30m (rear extension)

FIRST FLOOR

Figure B-5. Period terrace plans. (Redrawn from Allen and Pinney, 1990.)

The zone 1 and zone 2 period end terrace assumptions were calculated in the same manner as described for the detached house (Section B.2). They were found to be:

- zone 1 ground floor area = 35% of dwelling ground floor area

- zone 2 ground floor area = 65% of dwelling ground floor area
- zone 1 total floor area = 35% of dwelling ground floor area
- zone 2 total floor area = 65% of dwelling ground floor area + dwelling ground floor area for each subsequent storey
- zone 1 volume = 15% of dwelling volume
- zone 2 volume = 85% of dwelling volume
- zone 1 roof area = 0
- zone 2 roof area = dwelling ground floor area
- zone 1 window area = 25% of dwelling window area
- zone 2 window area = 75% of dwelling window area
- zone 1 door area = 0
- zone 2 door area = 3.28m^2

As for the post 1919 terrace (Section B.6.1), the gross external wall area depends on which wall is the external wall. As before, an average was taken of the two possible configurations.

For wall A external and wall B adjoining another dwelling (Figure B-5):

- zone 1 gross external wall area = 20.07% of dwelling gross external wall area
- zone 2 gross external wall area = 79.93% of dwelling gross external wall area

For wall B external and wall A adjoining another dwelling (Figure B-5):

- zone 1 gross external wall area = 8.82% of dwelling gross external wall area
- zone 2 gross external wall area = 91.18% of dwelling gross external wall area

The results for the two configurations were averaged and then rounded to the nearest 5% to produce default gross external wall areas for zone 1 and zone 2 as given below:

- zone 1 gross external wall area = 15% of dwelling gross external wall area
- zone 2 gross external wall area = 85% of dwelling gross external wall area

It could be possible in the future to modify this assumption by using the Footprint Tool to test whether wall A or wall B is the external wall.

B.6.3 Default end terrace

It was found that the post 1919 end terrace and the period end terrace produced the same default assumptions for all parameters except window areas. To simplify the dwelling classification system, it was decided that only one default end terrace would be specified. This required default window areas to be calculated assuming the average of the two different types of terrace which gave:

- zone 1 window area = 20% of dwelling window area
- zone 2 window area = 80% of dwelling window area

All other defaults are as given in Sections B.6.1 and B.6.2 (and shown in Tables 8 and 9).

The above procedure was repeated assuming the end terrace to have an unheated connecting passageway. It was found to have exactly the same default assumptions as the default end terrace (although, of course, it has a larger external wall area due to the passageway).

B.7 Mid terrace

The procedure explained for the end terrace (Section B.6) was repeated for a mid terrace. Once again, the assumptions of the post 1919 terrace (Figure B-4) and the period terrace (Figure B-5) were found to be the same for all parameters except window areas (which are, of course, the same as those previously calculated for the end terrace). One default mid terrace was assumed by averaging the assumptions for the window areas. The default zone 1 and zone 2 assumptions for a mid terrace are shown in Tables 8 and 9 and are not repeated in this Appendix.

B.8 Mid terrace with unheated connecting passageway

The procedure explained for the end terrace (Section B.6) was repeated once more for a mid terrace with unheated connecting passageway. In both the post 1919 terrace (Figure B-4) and the period terrace (Figure B-5), two configurations were possible:

- wall A as the passageway (ground floor only) and wall B adjoining another dwelling
- wall B as the passageway (ground floor only) and wall A adjoining another dwelling

For each terrace type, gross external wall area was taken to be the average of these two configurations. As before, all parameters except window areas were found to be the same for both terrace types. One default mid terrace with unheated connecting passageway was assumed by averaging the assumptions for the window areas. The default zone 1 and zone 2 assumptions for a mid terrace with unheated connecting passageway are shown in Tables 8 and 9 and are not repeated in this Appendix.

B.9 Dwelling window area

As stated in Section B.2.5, the default dwelling window area for the proposed dwelling classification system was assumed to be the maximum area allowed by the Building Regulations at the time of construction. From Table 10, it can be seen that there are three different regulations which depend on age and glazing type.

1. For pre-1991 dwellings, maximum dwelling window area is 12% of perimeter wall area i.e. total perimeter wall area including exposed and non-exposed walls. The glazing type is single.
2. For dwellings constructed between 1991 and 1995, maximum dwelling window area is 15% of total floor area. The glazing type is single.
3. For post 1995 dwellings, maximum dwelling window area is 22.5% of total floor area. The glazing type is double.

The dwelling window areas of the standard dwelling configurations were compared with these regulations. This is shown in Table B-1.

From Table B-1, it can be seen that all of the dwellings (except bungalows) are below the 12% perimeter wall area maximum of pre-1991 dwellings. The detached house is closest to the allowed limit with a dwelling window area of 10.7% of the perimeter wall area. The period terrace has a much smaller dwelling window area of only 6.9% of perimeter wall area. All built forms are close to the 1991-1995 allowable limit of 15% of total floor area (bungalows and detached houses above with the remainder below). None of the built forms approach the post 1995 allowable maximum of 22.5% of total floor area. It should be remembered, however, that the standard dwelling configurations were proposed in 1990 i.e. before the last two regulations came into force.

By assuming the maximum allowable dwelling window area in the proposed dwelling classification system, it is likely that dwelling window area will be overestimated. This will undoubtedly have some effect on dwelling energy consumption. If this assumption appears to be introducing significant errors into the BREDEM-8 calculation, it can be revised at a later date when data for real dwellings is available.

Table B-1. Comparing the dwelling window area of the standard dwelling configurations to the Building Regulations.

Built form	**Dwelling window area (m^2)**	**Perimeter wall area (m^2)**	**Total floor area (m^2)**	**Dwelling window area as a percentage of perimeter wall area (%)**	**Dwelling window area as a percentage of total floor area (%)**
Detached	15.11	141.81	100.12	10.7	15.1
Semi-detached	12.02	121.45	84.74	9.9	14.2
Bungalow (detached and semi-detached)	10.46	76.52	64.07	13.7	16.3
Post 1919 terrace (all types)	10.58	113.34	75.39	9.3	14.0
Period terrace (all types)	10.41	149.95	83.86	6.9	12.4

Appendix C

Interpretation of EHCS Data for Inclusion in the Dwelling Classification System

C.1 Introduction

This appendix describes in detail the process used to interpret and simplify the EHCS data - for primary and secondary space heating, water heating and cooking systems - for inclusion in the dwelling classification system (Section 3.4.4).

C.2 Primary space heating system

The proportion of primary space heating systems by built form and age as presented in the 1996 EHCS is given in Table C-1.

Table C-1. Primary space heating system by built form and age: 1996 EHCS.

Built form and age	**Central heating (%)**	**Programmable heating (%)**	**Fixed heating (%)**	**No fixed heating (%)**
Detached house: pre-1919	82.5	10.0	7.2	0.3
Detached house: post 1919	98.7	0.9	0.4	0.0
Semi-detached and terraced houses: pre-1919	69.4	6.4	23.8	0.4
Semi-detached and terraced houses: 1919-1944	79.9	3.7	15.8	0.6
Semi-detached and terraced houses: 1945-1964	79.2	6.1	14.4	0.3
Semi-detached and terraced houses: post 1965	87.5	6.5	5.7	0.3
Bungalow: all ages	81.5	12.4	5.9	0.2

Table C-1 was revised using the following assumptions.

- 'No fixed heating' was ignored as it is always less than 1%.
- 'Central heating' and 'programmable heating' were added together to give 'combined central heating'. They are essentially the same system (and the EHCS itself considers them together in Table C-3).

The application of these assumptions can be seen from a worked example for 'detached house: pre-1919'.

From Table C-1: Combined central heating = 92.5%
Fixed heating = 7.2%
No fixed heating = 0.3%

Ignoring 'no fixed heating' and re-proportioning gives:

Combined central heating = (92.5 / 99.7) x 100 = 93%
Fixed heating = (7.2 / 99.7) x 100 = 7%

where 99.7 = combined central heating + fixed heating (from Table C-1).

Applying this procedure to the remaining data in Table C-1 allowed Table C-2 to be created.

Table C-2. Primary space heating system by built form and age: revised 1996 EHCS.

Built form and age	**Combined Central Heating (%)**	**Fixed Heating (%)**
Detached house: pre-1919	93	7
Detached house: post 1919	100	0
Semi-detached and terraced houses: pre-1919	76	24
Semi-detached and terraced houses: 1919-1944	84	16
Semi-detached and terraced houses: 1945-1964	86	14
Semi-detached and terraced houses: post 1965	94	6
Bungalow: all ages	94	6

The proportions of the different types of central and programmable heating systems as presented in the 1996 EHCS are given in Table C-3.

Table C-3. Types of central and programmable space heating systems: 1996 EHCS.

Types of central and programmable heating systems	**Proportion (%)**
Gas – single purpose boiler	63.9
Gas – back boiler	14.0
Electric storage heaters	8.6
Fuel oil	3.1
Gas – ducted air	3.0
Solid fuel	2.6
Communal system	1.4
Electric floor / ceiling	0.8
Other	2.6

Table C-3 was revised by only considering systems with a proportion greater than 5%. This assumption meant that only three types of system remained:

1. Gas – single purpose boiler (63.9%)
2. Gas – back boiler (14.0%)
3. Electric storage heaters (8.6%)

The new relative proportion of each system was calculated:

1. Gas – single purpose boiler = (63.9 / 86.5) x 100 = 74%
2. Gas – back boiler = 16%
3. Electric storage heaters = 10%

where 86.5 = gas single + gas back + electric storage (Table C-3).

The two types of gas boiler were combined into a single 'gas boiler'. Table C-4 was then created.

Table C-4. Types of primary space heating system making up the combined central heating system: revised 1996 EHCS.

Types of primary space heating system making up the combined central heating system	Proportion (%)
Gas boiler	90
Electric storage heater	10

Tables C-2 and C-4 were combined to create Table C-5. A worked example for 'detached house: pre-1919' shows how Table C-5 was created.

From Table C-2, 93% of all 'detached house: pre-1919' have combined central heating. Of these, 90% are gas boilers and 10% are electric storage heaters (Table C-4). This gives:

- Proportion with gas boiler = 90% of 93% = 84%
- Proportion with electric storage heater = 10% of 93% = 9%

Table C-5 contains the data used in the dwelling classification system proposed in this thesis. (This table is shown as Table 11 in the main body of the thesis.)

Table C-5. Primary space heating system by built form and age for proposed dwelling classification system.

Built form and age	Gas boiler (%)	Electric storage heater (%)	Fixed heating (%)
Detached house: pre-1919	84	9	7
Detached house: post 1919	90	10	0
Semi-detached and terraced houses: pre-1919	69	7	24
Semi-detached and terraced houses: 1919-1944	76	8	16
Semi-detached and terraced houses: 1945-1964	77	9	14
Semi-detached and terraced houses: post 1965	85	9	6
Bungalow: all ages	85	9	6

With the relative proportions of the primary space heating system now defined, default specifications for these systems were required. No guidance was given in the EHCS and so these were derived from systems given in BREDEM-8 reference tables as discussed in the following sections.

C.2.1 Default gas boiler

In the BREDEM-8 reference table describing heating system characteristics, ten different gas boiler central heating systems are listed. These are shown in Table C-6.

Table C-6. Gas boiler central heating systems listed in BREDEM-8. (Redrawn from Anderson et al., 1997.)

Heating system type[a]	**Efficiency (%)**	**Responsiveness**
1. Low thermal capacity	72	1.0
2. High or unknown thermal capacity	68	1.0
3. Condensing	85	1.0
4. Combi	71	1.0
5. Condensing combi	85	1.0
6. Wall mounted	65	1.0
7. Floor mounted, post 1979	65	1.0
8. Floor mounted, pre 1979	55	1.0
9. Combi	65	1.0
10. Room heater and back boiler	65	1.0

[a] Systems 1 to 5 are gas boiler with fan-assisted flue. Systems 6 to 10 are gas boiler with balanced or open flue. All are radiator systems.

The mean values of efficiency and responsiveness were calculated for the ten boilers to give a default gas boiler specification of:

Efficiency = 70%
Responsiveness = 1.0

C.2.2 Default electric storage heater

There are four different electric storage heating systems listed in the BREDEM-8 reference table. These are shown in Table C-7.

Table C-7. Electric storage heating systems listed in BREDEM-8. (Redrawn from Anderson et al., 1997.)

Heating system type	**Efficiency (%)**	**Controllable fraction**
Old (large volume) storage heaters	100	0.0
Modern (slimline) storage heaters	100	0.2
Convector storage heaters	100	0.2
Fan-assisted storage heaters	100	0.4

The mean values of efficiency and controllable fraction were calculated for the four systems to give a default electric storage heater specification of:

Efficiency = 100%

Controllable fraction = 0.2

C.2.3 Default fixed heating system

To obtain the default fixed heating system, reference was made to the EHCS data for type of secondary space heating system by primary space heating system (Table C-8). Only the data under the 'fixed heating' column of Table C-8 is of interest here. (The remainder of Table C-8 is used in Section C.3.)

Table C-8. Type of secondary space heating system by primary space heating system: 1996 EHCS.

Type of secondary space heating system	**Primary space heating system**		
	Central heating (%)	**Programmable heating (%)**	**Fixed heating (%)**
No secondary heating	19.7	12.9	0
Mains gas fire/convector	52.6	21.1	72.6
Fixed electric heater	8.9	37.0	11.0
Solid fuel open fire	10.3	15.6	7.4
Portable electric heater	3.1	6.9	3.1
Other fixed gas heater	2.9	3.0	3.2
Solid fuel stove	2.2	2.1	2.3
Portable LPG or paraffin	0.4	1.3	0.3

From Table C-8 it can be seen that if the primary space heating system is fixed heating, there is always a secondary heating system i.e. no secondary heating equals 0%. It was assumed that this secondary system is also the primary fixed heating system as no guidance was given in the EHCS to describe the different types of primary fixed heating systems. For the purposes of this proposed dwelling classification system, if the primary system is fixed heating then no separate secondary system needs to be specified.

Once again, only those systems with a proportion greater than 5% were considered. From the 'fixed heating' column of Table C-8, this left three types of fixed heating system:

1. Mains gas fire/convector (72.6%)
2. Fixed electric heater (11.0%)
3. Solid fuel open fire (7.4%)

The new relative proportion of each system was calculated:

1. Mains gas fire = (72.6 / 91) x 100 = 80%
2. Fixed electric heater = 12%
3. Solid fuel open fire = 8%

where 91 = mains gas fire + fixed electric heater + solid fuel open fire ('fixed heating' column of Table C-8).

This allowed Table C-9 to be created.

Table C-9. Proportions of different types of primary fixed heating systems: revised 1996 EHCS.

Primary fixed heating system	**Proportion (%)**
Mains gas fire/convector	80
Fixed electric heater	12
Solid fuel open fire	8

As before, default specifications were derived for the primary fixed heating systems using information given in the BREDEM-8 reference table.

There are six different mains gas fires/convectors listed in the BREDEM-8 model description. These are shown in Table C-10.

Table C-10. Mains gas fires/convectors listed in BREDEM-8. (Redrawn from Anderson et al., 1997.)

Heating system type	**Efficiency (%)**	**Responsiveness**
Old style gas fire (open front)	50	1.0
Modern gas fire (glass enclosed front)	60	1.0
Modern gas fire with balanced flue	70	1.0
Modern gas fire with back boiler (no rads.)	65	1.0
Condensing gas fire (fan-assisted flue)	85	1.0
Gas fire or room heater (fan-assisted flue)	79	1.0

The mean values of efficiency and responsiveness were calculated for the six fires to give a default mains gas fire/convector specification of:

Efficiency = 68%

Responsiveness = 1.0

Only one type of fixed electric heater is listed in the BREDEM-8 reference table: panel convector or radiant heaters. This was selected as the default fixed electric heater specification:

Efficiency = 100%

Responsiveness = 1.0

There are three different solid fuel open fires listed in the BREDEM-8 reference table. These are shown in Table C-11.

Table C-11. Solid fuel open fires listed in BREDEM-8. (Redrawn from Anderson et al., 1997.)

Heating system type	**Efficiency (%)**	**Responsiveness**
Open fire in grate	32	0.5
Open fire in grate with throat restrictor	42	0.5
Open fire with back boiler (no radiators)	55	0.5

The mean values of efficiency and responsiveness were calculated for the three fires to give a default solid fuel open fire specification of:

Efficiency = 43%
Responsiveness = 0.5

To simplify the dwelling classification system and to reduce the number of BREDEM-8 calculations required, the default mains gas fire/convector, default fixed electric heater and default solid fuel open fire were combined to give a single default primary fixed heating system. This was achieved by multiplying the efficiency and responsiveness of each individual system with its relative proportion in Table C-9 as shown below:

Efficiency = (0.8 x 68) + (0.12 x 100) + (0.08 x 43) = 70%
Responsiveness = (0.8 x 1.0) + (0.12 x 1.0) + (0.08 x 0.5) = 0.96

where the first term represents mains gas fire/convector, the second represents fixed electric heater and the third represents solid fuel open fire.

Therefore, the default primary fixed heating system specification is:

Efficiency = 70%
Responsiveness = 0.96

C.3 Secondary space heating system

The type of secondary space heating system by primary space heating system as presented in the 1996 EHCS is given in Table C-8. The interpretation of the 'fixed heating' column was described in Section C.2.3. To describe the approach used to revise the 'central heating' and 'programmable heating' columns of Table C-8, a worked example is shown for 'detached house, pre-1919'.

From Table C-1 (using original EHCS data):

central heating as primary space heating system = 82.5%
programmable heating as primary space heating system = 10%

Considering central and programmable heating as one 'combined central heating' (Section C.2), their relative proportions become:

central heating = (82.5 / 92.5) x 100 = 89% of 'combined central heating'
programmable heating = (10 / 92.5) x 100 = 11% of 'combined central heating'

where 92.5 = central + programmable (Table C-1).

It is now possible to determine the relative proportions of the secondary heating systems based on this 'combined central heating'. For example, from Table C-8, 19.7 % of all central heating systems and 12.9 % of all programmable heating systems have no secondary heating. For 'combined central heating', this represents:

(19.7% of 89%) + (12.9% of 11%) = 19%

This means that 19% of all 'combined central heating' systems have no secondary heating system.

This approach was carried out for every secondary heating system listed in Table C-8. The figures for 'combined central heating' were calculated to be:

1. No secondary heating = 19%
2. Mains gas fire / convector = 49%
3. Fixed electric heater = 12%
4. Solid fuel open fire = 11%
5. Portable electric heater = 4%
6. Other fixed gas heater = 3%
7. Solid fuel stove = 2%
8. Portable LPG or paraffin = 1%

These figures were further revised by only considering those secondary systems with a proportion greater than 5% (i.e. systems (1) to (4) on the list above). The revised proportions were calculated to be:

1. No secondary heating = (19 / 91) x 100 = 21%
2. Mains gas fire / convector = 54%
3. Fixed electric heater = 13%
4. Solid fuel open fire = 12 %

where 91 = no secondary + mains gas + fixed electric + solid fuel (original list).

The above figures represent the type of secondary space heating system for a 'combined central heating' primary system for a pre-1919 detached house. A similar approach was carried out for all dwelling types and the results are given in Table C-12.

Table C-12.Type of secondary space heating system if primary space heating system is 'combined central heating'.

Built form and age	**No secondary heating (%)**	**Mains gas fire / convector (%)**	**Fixed electric heater (%)**	**Solid fuel open fire (%)**
Detached house: pre-1919	21	54	13	12
Detached house: post 1919	22	57	10	11
Semi-detached and terraced houses: pre-1919	21	55	12	12
Semi-detached and terraced houses: 1919-1944	21	56	11	12
Semi-detached and terraced houses: 1945-1964	21	55	12	12
Semi-detached and terraced houses: post 1965	21	55	11	12
Bungalows	21	53	14	12

It was considered advantageous, however, to generate just one type of secondary system for each of the default primary systems making up the 'combined central heating' system i.e. gas boiler and electric storage heater (Table C-4). This would greatly reduce the number of BREDEM-8 calculations required i.e. there would only be one secondary system calculation per primary system rather than four secondary system calculations per primary system. Reference was again made to tables in the BREDEM-8 documentation.

To describe the approach used to generate one type of secondary system for each primary system making up the 'combined central heating' system, a worked example is shown for 'detached house, pre-1919'. Table C-13 shows the fraction of heat supplied by the secondary heating systems for the default gas boiler and electric storage heater primary systems.

Table C-13. Fraction of heat supplied by secondary heating systems.

Default primary system	**Secondary system**	**Relative proportion (%) (Table C-12)**	**Fraction (BREDEM-8 Table)**
Gas boiler	Gas fires	54	0.15
	Solid fuel fires	12	0.10
	Electric heaters	13	0.05
	No secondary system	21	0.00
Electric storage heater	Gas fires	54	0.15
	Solid fuel fires	12	0.10
	Electric heaters	13	0.10
	No secondary system	21	0.00

For the gas boiler primary system, one combined fraction can be calculated by multiplying the relative proportions with the individual fractions as shown below:

Combined fraction = gas fires + solid fuel fires + electric heaters + no secondary
= (0.54 x 0.15) + (0.12 x 0.1) + (0.13 x 0.05) + (0.21 x 0)
= 0.10

Performing a similar procedure for the electric storage heater primary system gives:

Combined fraction = 0.11

It was then necessary to combine the secondary systems in Table C-13 into one system. Their relative proportions were calculated:

Gas fires = (54 / 79) x 100 = 68%
Solid fuel fires = 15%
Electric heaters = 17%

where 79 = gas fires + solid fuel fires + electric heaters (Table C-13).

The specification of these secondary systems is the same as for the individual fixed heating systems defined in Section C.2.3. These are shown again below:

Gas fires: Efficiency = 68% Responsiveness = 1.0
Solid fuel fires: Efficiency = 43% Responsiveness = 0.5
Electric heaters: Efficiency = 100% Responsiveness = 1.0

The efficiency and responsiveness of each individual system was multiplied by its relative proportion as shown below:

Efficiency = (0.68 x 68) + (0.15 x 43) + (0.17 x 100) = 70%
Responsiveness = (0.68 x 1.0) + (0.15 x 0.5) + (0.17 x 1.0) = 0.92

Therefore, the secondary heating system specification for 'detached house: pre-1919' is:

Efficiency = 70%
Responsiveness = 0.92

This procedure was carried out for all built forms and the results are shown in Table C-14.

From Table C-14, it can be seen that the specifications for the different built forms are extremely similar. It was therefore decided to define just one secondary system for all built forms and ages based on the mean of the data in Table C-14. This assumption simplifies the specification of a secondary system in the proposed dwelling classification system without introducing a significant error. It also simplifies implementation within the SEP system. This secondary system specification is shown in Table C-15 (shown as Table 15 in the main body).

Table C-14. Type of secondary space heating system by primary space heating system: revised 1996 EHCS.

Built form and age	**Fraction of heat from secondary system if main system is gas boiler**	**Fraction of heat from secondary system if main system is electric storage heater**	**Secondary system**		**Proportion of delivered fuel**		
			Efficiency (%)	**Responsiveness**	**Gas (%)**	**Electric (%)**	**Solid fuel (%)**
Detached house: pre-1919	0.10	0.11	70	0.92	68	17	15
Detached house: post 1919	0.10	0.11	69	0.93	73	13	14
Semi-detached and terraced houses: pre-1919	0.10	0.11	70	0.93	70	16	15
Semi-detached and terraced houses: 1919-1944	0.10	0.11	69	0.93	71	14	15
Semi-detached and terraced houses: 1945-1964	0.10	0.11	69	0.93	70	15	15
Semi-detached and terraced houses: post 1965	0.10	0.11	69	0.93	70	15	15
Bungalows	0.10	0.11	70	0.92	67	18	15

Table C-15. Type of secondary space heating system by primary space heating system for the proposed dwelling classification system.

Built form and age	**Fraction of heat from secondary system if main system is gas boiler**	**Fraction of heat from secondary system if main system is electric storage heater**	**Default secondary system**		**Proportion of delivered fuel**		
			Efficiency (%)	**Responsiveness**	**Gas (%)**	**Electric (%)**	**Solid fuel (%)**
All dwellings	0.10	0.11	69	0.93	70	15	15

C.4 Hot water system

The type of hot water system by built form and age as presented in the 1996 EHCS is given in Table C-16.

Table C-16. Type of hot water system by built form and age: 1996 EHCS.

Built form and age	**Central heating and immersion (%)**	**Central heating only (%)**	**Immersion only (%)**	**Other (%)**
Detached house: pre-1919	58.7	14.6	5.5	21.1
Detached house: post 1919	68.8	16.8	1.7	12.7
Semi-detached and terraced houses: pre-1919	31.7	29.4	13.6	25.2
Semi-detached and terraced houses: 1919-1944	38.9	32.0	11.3	17.8
Semi-detached and terraced houses: 1945-1964	46.6	23.2	13.0	17.2
Semi-detached and terraced houses: post 1965	46.1	25.4	13.4	15.0
Bungalows	48.6	21.2	15.7	14.4

It was considered advantageous to derive a single hot water system for each dwelling type to reduce the number of BREDEM-8 calculations required. To achieve this, a default specification was initially derived for each of the hot water systems shown in Table C-16. Once again, no guidance was given in the EHCS and so reference was made to tables in the BREDEM-8 model description.

In Section C.2, central heating was assumed to be carried out by a gas boiler. This assumption was also applied here. BREDEM-8 specifies ten different gas boiler systems. These are shown with their water heating efficiencies in Table C-17.

Table C-17. Water heating efficiencies for gas boiler central heating systems listed in BREDEM-8. (Redrawn from Anderson et al., 1997.)

Heating system type[a]	**Efficiency (%)**
1. Low thermal capacity	72
2. High or unknown thermal capacity	68
3. Condensing	85
4. Combi	69[b]
5. Condensing combi	83[b]
6. Wall mounted	65
7. Floor mounted, post 1979	65
8. Floor mounted, pre-1979	55
9. Combi	55[b]
10. Room heater and back boiler	65

[a]Systems 1 to 5 are gas boiler with fan-assisted flue. Systems 6 to 10 are gas boiler with balanced or open flue. All are radiator systems.
[b]Water heating efficiency differs from space heating efficiency shown in Table C-6.

The mean efficiency for the ten boilers was calculated to give a default 'central heating only' hot water system efficiency of 68%.

In the BREDEM-8 reference table the efficiency of an 'immersion' heater is given as 100%.

The 'other' column of Table C-16 was assumed to comprise both single-point and multi-point gas water heaters (in the absence of any guidance from the EHCS). Their efficiencies as listed in BREDEM-8 are shown in Table C-18.

Table C-18. Water heating efficiencies for 'other' systems listed in BREDEM-8. (Redrawn from Anderson et al., 1997.)

Water heating system type	**Efficiency (%)**
Single-point gas water heater	70
Multi-point gas water heater	65

The mean efficiency was calculated to give a default 'other' hot water system efficiency of 67.5%.

For 'central heating and immersion', it was assumed that central heating is used to heat the water for 50% of the time and immersion is used for the other 50% of the time (again, there was no guidance from the EHCS on this matter).

With these assumptions defined, a general formula (Equation C.1) was created to determine the efficiency of a single default hot water system from the efficiencies and relative proportions of the individual systems. This can be applied to each dwelling type.

$$\text{Efficiency} = A\,[(0.5 \times 100) + (0.5 \times 68)] + B\,[68] + C\,[100] + D\,[67.5] \qquad (C.1)$$

where A is the fraction of 'central heating and immersion' from Table C-16, B is the fraction of 'central heating only' from Table C-16, C is the fraction of 'immersion only' from Table C-16 and D is the fraction of 'other' from Table C-16.

It was also necessary to derive formulas to determine the relative proportions of gas and electricity used to heat the water to allow calculation of CO_2 emissions and costs.

$$\text{Electricity used} = (A \times 0.5) + C \qquad (C.2)$$

$$\text{Gas used} = (A \times 0.5) + B + D \qquad (C.3)$$

Equations C.1, C.2 and C.3 were applied to Table C-16 and the results are given in Table C-19 (shown as Table 18 in the main body of the thesis).

Table C-19. Efficiency of water heating system and proportion of fuels used by built form and age for the proposed dwelling classification system.

Built form and age	**Efficiency of water heater (%)**	**Proportion of electricity used (%)**	**Proportion of gas used (%)**
Detached house: pre-1919	79	35	65
Detached house: post 1919	80	36	64
Semi-detached and terraced houses: pre-1919	77	29	71
Semi-detached and terraced houses: 1919-1944	78	31	69
Semi-detached and terraced houses: 1945-1964	80	36	64
Semi-detached and terraced houses: post 1965	80	37	63
Bungalows	81	40	60

C.5 Cooking system

At the time of performing this analysis, data was not available from the 1996 EHCS on the type of cooking system. Therefore, data was used from the 1991 EHCS. The type of cooking system by dwelling type as presented in the 1991 EHCS is given in Table C-20.

Table C-20. Type of cooking system by built form: 1991 EHCS.

Dwelling type	**Gas cooker (%)**	**Bottled gas cooker (%)**	**Electric cooker (%)**	**Solid fuel cooker (%)**	**Oil cooker (%)**	**Dual fuel cooker (%)**	**None (%)**
Detached	29.6	1.9	41.8	1.0	1.0	24.1	0.4
Semi-detached	48.7	1.1	37.1	0.7	0.1	11.8	0.6
End terrace	53.1	0.9	35.0	0.4	0.4	9.4	0.8
Mid terrace	60.4	1.3	29.6	0.1	0.1	7.9	0.6

To show how Table C-20 was revised, a worked example is presented for detached houses. Only those systems with a proportion greater than 5% were considered. This assumption meant that only three types of system remained:

1. Gas cooker (29.6%)
2. Electric cooker (41.8%)

3. Dual fuel cooker (24.1%)

The new relative proportion of each system was calculated:

1. Gas cooker = (29.6 / 95.5) x 100 = 31%
2. Electric cooker = 44%
3. Dual fuel cooker = 25%

where 95.5 = gas + electric + dual fuel (Table C-20).

This procedure was performed for each dwelling type. In addition, as no original data was available in the 1991 EHCS for bungalows they were assumed to have the mean proportions of the detached and semi-detached dwellings. These assumptions allowed Table C-21 to be created. (Table C-21 is shown as Table 19 in the main body of the thesis.)

Table C-21. Type of cooking system by built form for the proposed dwelling classification system.

Built form	**Gas cooker (%)**	**Electric cooker (%)**	**Dual fuel cooker (%)**
Detached	31	44	25
Semi-detached	50	38	12
End terrace	54	36	10
Mid terrace	62	30	8
Bungalow	40	41	19

Appendix D

Rapid Site Survey

D.1 Introduction

This appendix presents the rapid site survey procedure developed as part of the proposed dwelling classification system to overcome problems of data collection in domestic energy modelling. The rapid site survey form is shown in Table D.1 and the following section describes the instructions for completing the form.

D.2 Instructions for completing the rapid site survey form

Initial information is required to describe the site survey i.e. name of street being surveyed, name of surveyor and date of survey.

1. House Number

This is simply the number of the house being surveyed.

2. Built form

The built form of the dwelling selected from the following list.

- Detached (D)
- Semi-detached (SD)
- End terrace (ET)
- Mid terrace (MT)
- Mid terrace with unheated connecting passageway (MTUP)
- Flat (F)

Table D.1. Rapid site survey form.

Site survey assessment for: (street name) **Page 1 of 2**

Performed by: (name of surveyor) **Date:** (of survey)

House no.	**Built form**	**Age of dwelling**	**No. of storeys**	**Wall construction**	**Window**			**Door**			
					Frame	**Glazing**	**Tightness**	**Frame**	**Glazing**	**Tightness**	**Draught lobby**

Table D.1 (continued). Rapid site survey form.

Site survey assessment for: (street name) **Page 2 of 2**

Performed by: (name of surveyor) **Date:** (of survey)

House No.	**Dwelling exposure**	**Site exposure**	**Level of shading on vertical façade**	**Roof**				**Garage**	**Photo number**	**Additional information**
				Room in roof	**Level of shading**	**Shape**	**Inclination**			

3. Age of dwelling

Some dwellings explicitly state the year of construction on their front façade. Otherwise leave blank as this will be obtained using other means e.g. records held by the local authority.

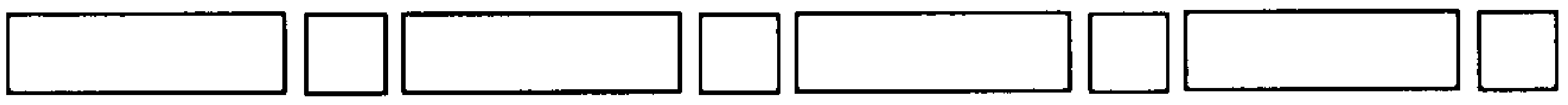
4. Number of storeys

The number of storeys including rooms in the roof.

5. Wall construction

The construction of the main wall as illustrated below.

Cavity wall: all bricks lengthways (DoE, 1997a).



Solid wall: bricks are placed both head-on and lengthways (DoE, 1997a).

6. Window

6.1 Frame

The window frame type selected from the following list.

- Wood
- Metal
- UPVC

6.2 Glazing

The window glazing type selected from the following list.

- Single
- Double
- Triple
- Secondary

6.3 Tightness

The window tightness is based on definitions given in the BREDEM-8 model description. However, there is no guidance on how to apply these definitions. Assumptions proposed for the rapid site survey are listed below.

1. All well fitting and draught sealed: good quality double glazing e.g. frames well maintained.
2. All loose and draught sealed: poor quality double glazing e.g. frames in need of repair.
3. All tight but not sealed: good quality single glazing e.g. frames well maintained.
4. All loose: poor quality single glazing e.g. frames in need of repair.
5. All very loose: extremely poor quality single glazing e.g. frames/windows in need of replacement.

7. Door

7.1 Frame

As definitions for window frame.

7.2 Glazing

As definitions for window glazing with the addition of unglazed.

7.3 Tightness

As definitions for window tightness. In addition, an unglazed door is assumed to be 'tight but not sealed' (3).

7.4 Draught lobby

Note whether there is a draught lobby present.

8. Dwelling exposure

The dwelling exposure is based on definitions given in the BREDEM-8 model description as listed below.

- Exposed all four sides.
- Exposed three sides.
- Exposed two sides.
- Exposed one side.
- Fully sheltered.

According to BREDEM-8, for an obstacle to provide shelter for a dwelling wall it must be:

- at least as high as the dwelling;
- within a distance equal to five times the height of the obstacle;
- wide enough to subtend an angle of at least 75° within the central 90° when viewed from the middle of the wall (Figure D-1).

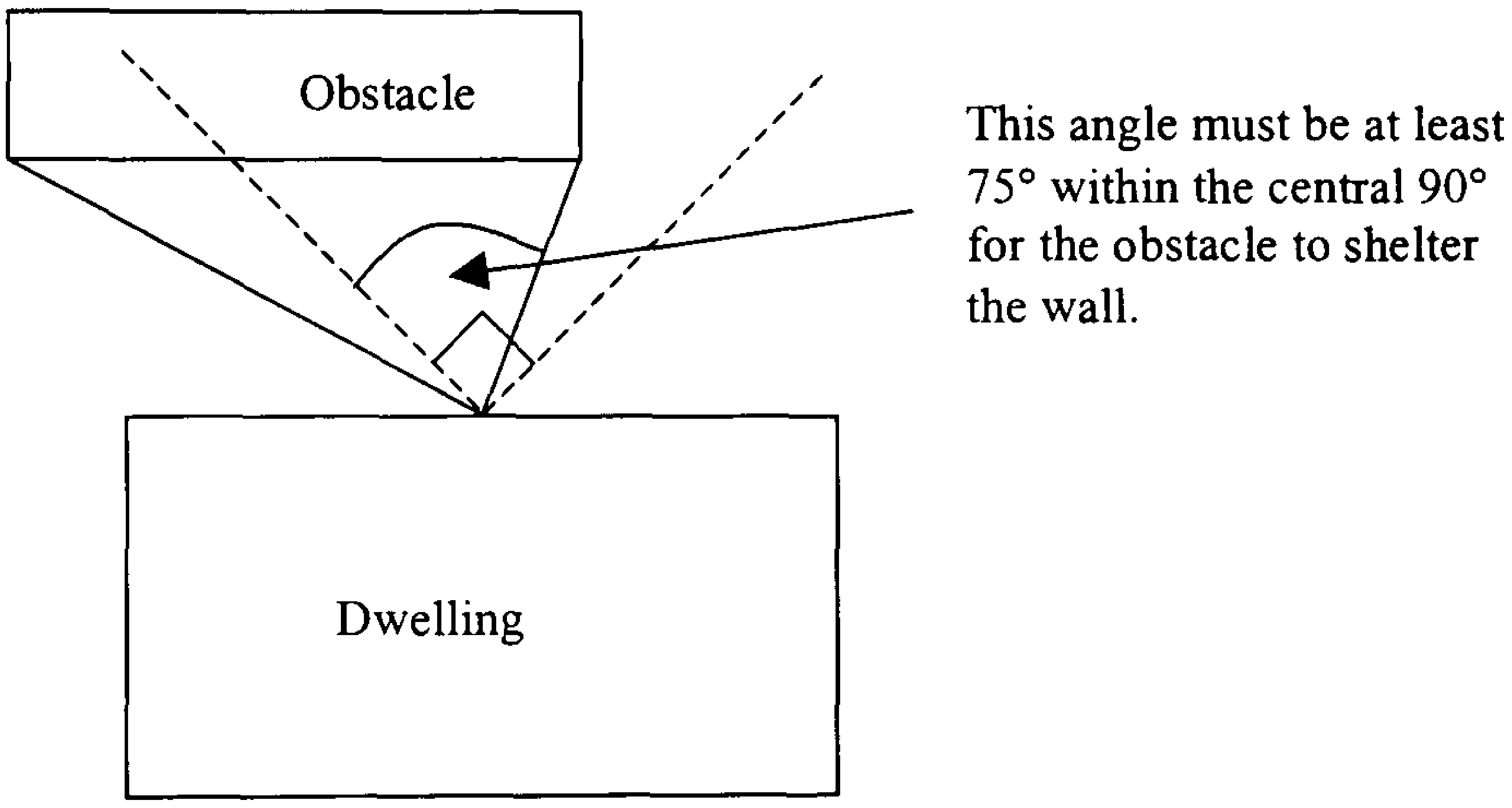


Figure D-1. Shelter angle. (Redrawn from DETR, 1998b.)

9. Site exposure

The site exposure is based on definitions given in the BREDEM-8 model description as listed below.

- Exposed: coastal and hill top sites. Any dwelling on the 10th floor or above in a high rise block.
- Above average: open sites not in the exposed category. Dwellings on 6th to 9th floor of tower blocks.

- Average: most rural and sub-urban sites. Dwellings on the 4th and 5th floors, or on the 3rd floor in an urban location. City centre sites close to high rise developments.
- Below average: partially sheltered urban and rural sites where there is some geographical reduction in local wind speed. Three storey dwellings on sheltered sites.
- Sheltered: sites where the local geography provides shelter from prevailing winds (e.g. valley or local hollow). City centre sites which are not close to high rise developments.

10. Level of shading on vertical façade

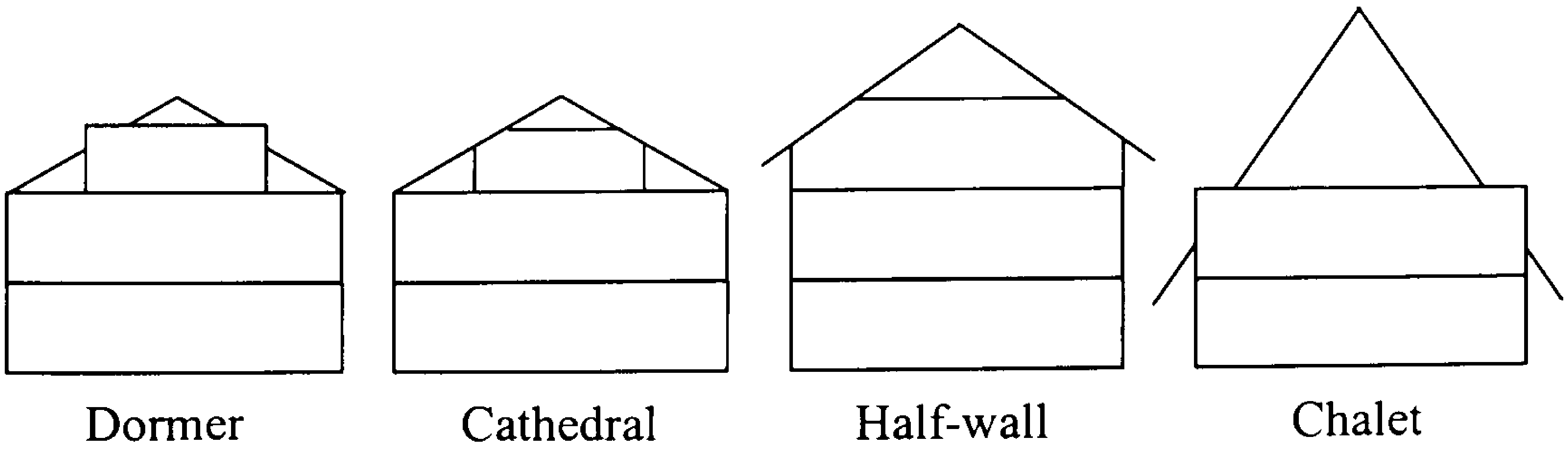
The level of shading on the vertical façade is based on definitions given in the BREDEM-8 model description as listed below. These definitions rely on subjective assessment by the surveyor.

1. Open outlook (i.e. no shading problems).
2. Below average overshading.
3. Average overshading: corresponds to about 30% of the available sunshine being obstructed.
4. Above average overshading.
5. Much above average overshading.

11. Roof

11.1 Room in the roof

The room in the roof can be any one of four possibilities as shown below.



11.2 Level of shading

Where there is likely to be no shading on the roof plane facing closest to south, enter none. If there are potential shading problems, note the approximate height of obstructions (e.g. other buildings and trees taller than the dwelling) and their distance from the affected surface. Note any roof obstructions, e.g. TV aerial, chimney stack, etc., to the south of the potential solar collector or PV panel siting.

11.3 Shape

Draw approximate shape of roof. Allows comparison with the roof shape drawn from the aerial photograph. Note all ridge lines.

11.4 Inclination

Estimate the inclination using Figure D.2.

12. Garage

Note whether there is a garage integral or adjacent to the dwelling. Indicate what dwelling elements are next to the garage.

13. Photo number

Note the number of any digital photographs taken of the dwelling. Possible photographs could include the principal façade and potential roof shading problems.

14. Additional information

Additional information should include anything which the surveyor thinks could be of interest. Examples include the following.

- Is there a damp-proof course (especially older houses)?
- Is there a solar DHW system installed?
- Is there an extension?

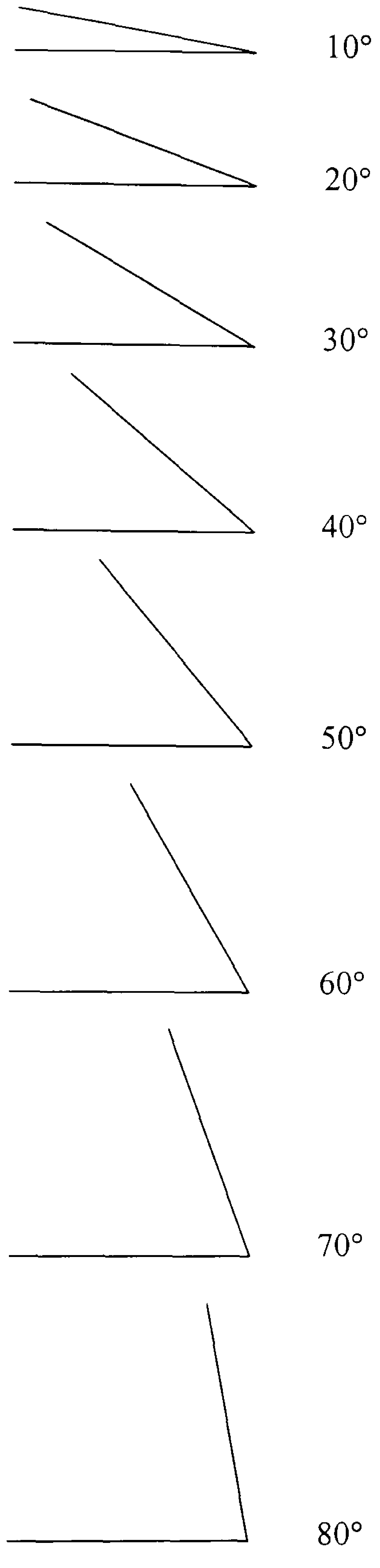
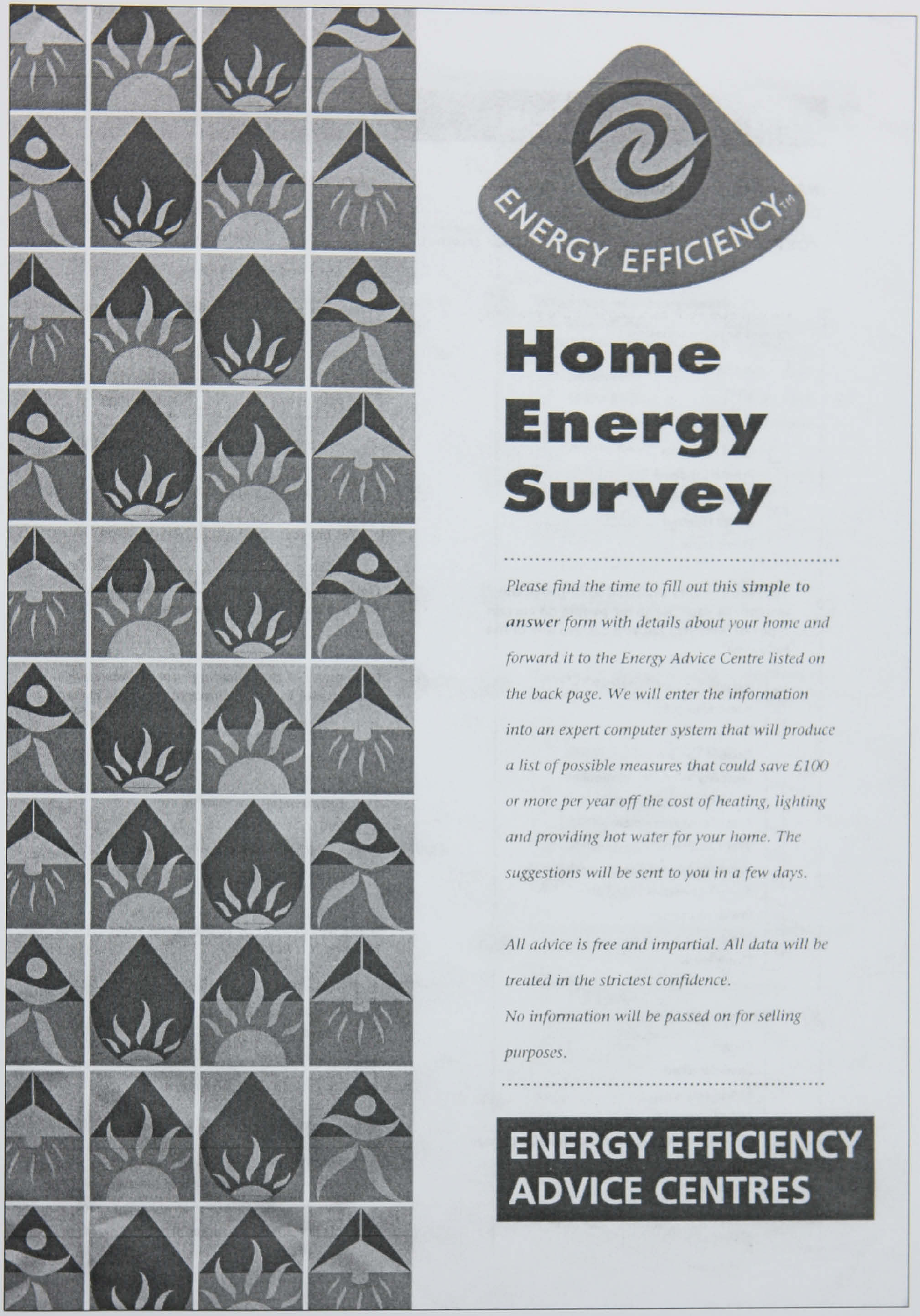


Figure D.2. Guide for estimating roof inclination.

Appendix E

Home Energy Survey Form



ENERGY EFFICIENCY™

Home Energy Survey

Please find the time to fill out this ***simple to answer*** *form with details about your home and forward it to the Energy Advice Centre listed on the back page. We will enter the information into an expert computer system that will produce a list of possible measures that could save £100 or more per year off the cost of heating, lighting and providing hot water for your home. The suggestions will be sent to you in a few days.*

All advice is free and impartial. All data will be treated in the strictest confidence.
No information will be passed on for selling purposes.

ENERGY EFFICIENCY ADVICE CENTRES

Questionnaire

Don't worry if you can't answer all the questions.

NAME: (Mr/Mrs/Ms/Miss).. ADDRESS: ....

....

POSTCODE: .... TELEPHONE: (Home): .... (Work):

1 **Do you own your own home or are you living in rented accommodation ?**

☐ Buying on a mortgage
☐ Own

renting from:
☐ Local Authority
☐ Private Landlord
☐ Housing Association
☐ Other (specify) ....
☐ Don't know

2 **There are grants available to improve the warmth of your home for people on certain types of benefits. Do you receive any of the following?**

☐ Income Support
☐ Housing Benefit
☐ Family Credit
☐ Council Tax Benefit
☐ Disability Working Allowance
☐ Disability Living Allowance
☐ Attendance Allowance
☐ War Disablement Pension
☐ Industrial Injuries Disablement Benefit
☐ Age 60 or over
☐ Prefer not to say
☐ None
☐ Don't know

3 **What type of house do you live in?**

☐ Detached
☐ Semi-detached
☐ End of terrace
☐ Mid-terrace
☐ Mid-terrace with unheated connecting passage
☐ Flat
☐ Maisonette
☐ Other/Don't know

4 **When was your home built?**

☐ Since 1990
☐ 1982 - 1990
☐ 1977 - 1981
☐ 1966 - 1976
☐ 1950 -1965
☐ 1930 - 1949
☐ 1900 - 1929
☐ Before 1900
☐ Don't know

5 **Do you have any rooms in the loft (Such as loft conversions or dormer rooms) ?**

☐ Yes (number.........) ☐ No ☐ Don't know

6 **How many storeys does your home have? (Do not count unheated cellars)**

....

7 **How many of the following rooms does your home have? Please indicate numbers in boxes.**

☐ Living & dining rooms
☐ Bedrooms
☐ Kitchen(s)
☐ Bathroom(s)
☐ WC(s)
☐ Hall & stairs
☐ Other rooms

8 **If you live in a flat or maisonette, what type of building is it in ?**

☐ Tower Block (six or more storeys)
☐ Custom Block (five or less storeys)
☐ Above Shop, Office etc
☐ Divided house
☐ Other type

Where in the property do you live?

☐ Ground floor (or basement)
☐ Above ground with unheated space below
☐ Part of my house is over an unheated space
☐ My home is over another property/heated space

Is there a roof directly above your flat?

☐ Yes the flat has a pitched roof
☐ Yes the flat has a flat roof
☐ Part of the flat has a roof directly above it
☐ No the flat is below another property/heated space

9 **What type of walls do you have ?**

☐ Cavity
☐ Solid
☐ Mixed Cavity & Solid
☐ Timber frame
☐ Don't know

10 **Are your walls insulated ?**

☐ Yes ☐ No ☐ Don't know

If yes please state thickness and type.

....

☐ Yes but don't know thickness

11 **Do you have a loft ?**

☐ Yes ☐ No ☐ Don't know

If so, do you have loft insulation?

☐ Yes ☐ No ☐ Don't know

If yes please state thickness. ....

12 **Do you have floor insulation ?**

☐ Yes ☐ No ☐ Don't know

If yes please state thickness. ....

13 **Do you have any secondary or double glazing ?**

☐ Yes ☐ No ☐ Don't know

If so what proportion of total glazing ?

....

14 **If you have double glazing, what type do you have ?**

☐ Sealed unit double glazing (replacement type)
☐ Fixed secondary glazing
☐ Temporary Secondary glazing
☐ Triple glazing
☐ Double glazed with "Low E" coating
☐ Don't know

15 **Are your external doors and windows draught proofed ?**
If so, please estimate what proportion.

☐ None
☐ Less than 25%
☐ 25% (a few)
☐ 50% (around half)
☐ 75% (most)
☐ 100% (all)
☐ Don't know

16 **What type of heating system do you have ? If you use more than one, please choose the one you use most.**

System

☐ Boiler & radiators
☐ Warm Air system
☐ Room heaters
☐ Storage heaters
☐ Other system
☐ Don't know

Main fuel for heating.

☐ Natural Gas ☐ LPG (bulk) ☐ Bottled Gas
☐ Oil (28 sec) ☐ Oil (35 sec)
☐ Smokeless (processed) ☐ House coal
☐ Anthracite ☐ Peat
☐ Wood
☐ On peak electricity
☐ Economy 7 off peak
☐ Other off peak electricity
☐ Economy 7 and on peak ☐ Don't know

Do you have any of the following?

☐ Foil behind some radiators
☐ Foil behind all radiators
☐ None/Don't know
☐ Some radiator shelves
☐ All radiator shelves
☐ None/Don't know

17 **How old is your heating system ?**

☐ less than 5 years old
☐ 5 to 10 years old
☐ over 10 years old
☐ Don't know

18 **What type of heating controls do you have ? (tick which applies)**

☐ No controls
☐ Timer/Programmer only
☐ Room Thermostat
☐ Room Thermostat and Timer/Programmer

Continued Overleaf

☐ Thermostatic Radiator Valves and Programmer
☐ Room Thermostat/Timer/Programmer/TRVs
☐ Thermostatic Radiator Valves & boiler manager
☐ Automatic charge control on storage heaters
☐ Other (please specify)

☐ Don't know
'TRVs' are Thermostat Radiator Valves

19 How is your hot water provided?

☐ Central Heating system
☐ Dual immersion (on and off peak)
☐ Single immersion (off-peak Economy 7)
☐ Single immersion (on-peak)
☐ Instant Electric
☐ Gas combi boiler/instantaneous
☐ Gas, oil or coal range (AGA, Rayburn)
☐ Don't know

20 Do you have water tank insulation? If so what type and thickness ?

☐ No insulation
☐ 1 inch (25mm or less spray foam)
☐ 2 inches(50mm or more spray foam)
☐ 1 inch thick jacket (25mm)
☐ 2 inches thick jacket (50mm)
☐ 3 inches thick jacket (75mm)
☐ More than 3 inches thick (80mm) jacket
☐ Not applicable /No hot water tank
☐ Don't know

21 Do you have any pipe insulation on the pipes between your boiler and your hot water tank.

☐ Yes ☐ Not applicable/No tank
☐ No ☐ Don't know

22 What hot water control do you have? (tick one)

☐ No control except on/off switch
☐ Programmer/Timer only
☐ Tank thermostat only
☐ Thermostat and timer
☐ Not applicable
☐ Don't know

Do you have any low energy lights (Compact Fluorescent Lamps [CFLs])

☐ No ☐ One ☐ Some
☐ Mostly ☐ Don't know

24 If we were to make suggestions about energy efficiency measures for your home, would you prefer us to include low cost measures only (£50 or less) ☐
or not to limit measures in terms of cost ☐

25 Who might you use to carry out any improvements?

☐ DIY (easy jobs only)
☐ DIY (easy and harder jobs)
☐ Contractors or Builders
☐ Don't know

26 Which of the following would you like advice or information on ? Please tick.

☐ Domestic Appliances
☐ Cooker / Cooking
☐ Solar Water Heating
☐ Energy Labelling
☐ CO_2 Emissions
☐ Condensation Control
☐ Handy Hints

27 Have you already decided to install any particular energy efficiency measures ? If so which ones ?

28 Would you still like any advice on these?

29 Where did you find out about us ?

Thank you for completing this questionnaire, please return it using the business reply paid envelope.

We can then make an evaluation of your energy usage and any possible savings we may identify for you.

The information you provide will be entered on our computer; the system is registered under the Data Protection Act and all the information will be treated in the strictest confidence

If this Questionnaire doesn't apply to yourself please pass it on to someone who could benefit from our advice.

This leaflet has been initiated by Cardiff City Council.

The network of Local Energy Advice Centres is administered on behalf of the Energy Saving Trust by The National Energy Foundation, a registered charity no 298951

Telephone: 01908 501908

Our standards of performance are monitored by BMRB International, who may wish to contact you in a few months to check whether you found our service useful.

Appendix F

Calculating the Solar Irradiation Incident on an Inclined Surface

F.1 Introduction

This appendix describes the approach used in the SEP system to calculate the solar irradiation incident on an inclined surface. The Perez diffuse irradiance model for tilted surfaces (Perez, Seals, Ineichen, Stewart & Menicucci, 1987) is used to calculate the diffuse irradiation. The beam irradiation and the diffuse irradiation reflected from the ground and adjacent buildings are then added to give the total solar irradiation. An accurate prediction of the total solar irradiation incident on an inclined surface is required for estimating the potential yield of both solar DHW and PV systems (Chapters 4 and 5 respectively). This approach could also replace the original solar gains calculation in BREDEM-8 to allow a more detailed analysis of passive solar design (Chapter 6).

F.2 Solar geometry processing

To calculate the diffuse irradiation on an inclined surface, the Perez tilted surface model requires the total irradiation on a horizontal surface. BREDEM-8 reference tables provide the monthly mean daily irradiation on a horizontal surface for twenty-one different regions. These tables also provide the representative latitude for each region. As the Perez model is an hourly calculation, some simple solar geometry processing is required to calculate the hourly direct, diffuse and total irradiation on a horizontal surface. This process is carried out for each daylight hour on the mean day of every month and is described below.

The solar declination angle, δ (degrees), is the angular position of the sun at solar noon with respect to the plane of the equator such that $-23.45° \leq \delta \leq 23.45°$, where north is positive. It is calculated using

$$\delta = 23.45 \sin\left(360 \times \frac{n+284}{365}\right) \tag{F.1}$$

where n is the Julian day number (1 to 365). Values of n corresponding to the mean day of every month are given in Table F-1.

Table F-1. Recommended Julian day numbers corresponding to the mean day of every month. (From Page & Sharples, 1998.)

Month	**Julian day number, n**
January	17
February	46
March	75
April	105
May	135
June	162
July	198
August	228
September	259
October	289
November	319
December	345

The sunset hour angle from noon, ω_s (degrees), is calculated using

$$\omega_s = \cos^{-1}\left(-\tan\phi \times \tan\delta\right) \tag{F.2}$$

where ϕ is the site latitude (degrees). This is the angular location north or south of the equator such that $-90° \leq \phi \leq 90°$, where north is positive. The latitude is found from BREDEM-8 for the region of interest.

This allows the daylength (hours) to be calculated using

$$\text{Daylength} = \frac{2\,\omega_s}{15} \tag{F.3}$$

which shows that the sun traverses the sky at a rate of 15° per hour and the day is assumed symmetrical about noon.

The sunrise and sunset times (24-hour clock) are calculated using

$$\text{Sunrise} = 12 - \frac{\text{Daylength}}{2} \text{ and} \tag{F.4}$$

$$\text{Sunset} = 12 + \frac{\text{Daylength}}{2} \tag{F.5}$$

The solar hour angle or the angular displacement of the sun from solar noon, ω (degrees), at a given time, t (24-hour clock), is calculated using

$$\omega = 15\,(t - 12) \tag{F.6}$$

Calculation of the solar hour angle depends on the daylength and hence the sunrise and sunset times. The hour angle is calculated for the mid-point of every hour. If sunrise is between 1 and 30 minutes past the hour, the mid-point is taken as the half-hour. If sunrise is between 31 minutes past the hour and the hour, the mid-point is taken as the hour. As the day is assumed symmetrical about solar noon, the mid-points in the afternoon follow a similar pattern. These mid-points were selected to prevent a calculation being performed before the sun has risen or after it has set.

Once the above parameters have been calculated, the monthly average daily extraterrestrial irradiation on a horizontal surface, $\overline{H}_o$ (MJ/m^2), can be calculated using

$$\overline{H}_o = \frac{1}{1\times10^6}\left(\frac{24\times3600\times G_{sc}}{\pi}\right)\left(1 + 0.033\cos\frac{360\times n}{365}\right)\left(\cos\phi\cos\delta\sin\omega_S + \frac{\pi\,\omega_S}{180}\sin\phi\sin\delta\right) \tag{F.7}$$

where G_{sc} is the solar constant (1367 W/m^2).

The monthly average clearness index, $\overline{K}_T$, is calculated using

$$\overline{K}_T = \frac{\overline{H}}{\overline{H}_o} \tag{F.8}$$

where $\overline{H}$ is the monthly average daily total irradiation on a horizontal surface (MJ/m^2). This value is obtained from BREDEM-8 reference tables for the region of interest.

The monthly average daily diffuse irradiation on a horizontal surface, $\overline{H}_d$ (MJ/m^2), is then calculated using

$$\overline{H}_d = \overline{H}\left\{0.775 + 0.00606\left(\omega_S - 90\right) - \left[0.505 + 0.00455\left(\omega_S - 90\right)\right]\cos\left(115\,\overline{K}_T - 103\right)\right\} \tag{F.9}$$

Equations F.10 to F.18 are then performed for every daylight hour in the mean day of every month. Equation F.10 calculates r_d, the ratio of hourly diffuse to daily diffuse irradiation on a horizontal surface:

$$r_d = \frac{\pi}{24} \times \frac{\cos\omega - \cos\omega_S}{\sin\omega_S - \frac{\pi\,\omega_S}{180}\cos\omega_S} \tag{F.10}$$

This allows the hourly diffuse irradiation on a horizontal surface, I_d (MJ/m^2), to be calculated using

$$I_d = r_d \times \overline{H}_d \tag{F.11}$$

The ratio of hourly total to daily total irradiation on a horizontal surface, r_t, is calculated using

$$r_t = \frac{\pi}{24}\left(a + b\cos\omega \right)\frac{\cos\omega - \cos\omega_S}{\sin\omega_S - \frac{\pi\,\omega_S}{180}\cos\omega_S} = \left(a + b\cos\omega \right) r_d \tag{F.12}$$

where

$$a = 0.409 + 0.5016\sin\left(\omega_S - 60\right) \text{ and} \tag{F.13}$$

$$b = 0.6609 - 0.4767\sin\left(\omega_S - 60\right) \tag{F.14}$$

The hourly total irradiation on a horizontal surface, I (MJ/m^2), is then calculated using

$$I = r_t \times \overline{H} \tag{F.15}$$

The hourly beam irradiation on a horizontal surface, I_b (MJ/m^2), is then the difference between total and diffuse irradiation.

Before calculating the hourly total irradiation on an inclined surface, $I_{T,\beta}$ (MJ/m^2), it is necessary to determine some other parameters. Equation F.16 is used to determine the angle of incidence, θ (degrees), i.e. the angle between the beam irradiation on a surface and the normal to that surface:

$$\begin{aligned}\cos\theta &= \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega \\ &\quad + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \tag{F.16}$$

where β is the slope of the surface (degrees) such that $0 \le \beta \le 180°$ and γ is the surface azimuth angle (degrees) such that $-180° \le \gamma \le 180°$ with zero due south, east negative and west positive.

The solar altitude angle, α_s (degrees), is the angle between the horizontal and the line to the sun and is given by

$$\sin \alpha_s = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta \tag{F.17}$$

This allows the normal or beam incidence irradiation, I_{bn} (MJ m^{-2}), to be given by

$$I_{bn} = \frac{I_b}{\sin \alpha_s} \tag{F.18}$$

F.3 Determining total irradiation incident on an inclined surface

The total solar irradiation incident on an inclined surface is the sum of beam irradiation, three components of diffuse irradiation from the sky and reflected irradiation from the various surfaces 'seen' by the inclined surface. The beam irradiation on an inclined surface, $I_{b,\beta}$ (MJ/m^2), is calculated using

$$I_{b,\beta} = I_{bn} \times \cos \theta \tag{F.19}$$

Using analytical methods, it is not practical to calculate the reflected energy term in detail to account for every reflecting surface and the inter-reflections between the surfaces. Standard practice is to assume that there is one large horizontal diffusely reflecting ground surface. This allows the ground-reflected irradiation on an inclined surface, $I_{g,\beta}$ (MJ/m^2), to be calculated using

$$I_{g,\beta} = I \times \rho_g \times \left(\frac{1 - \cos \beta}{2} \right) \tag{F.20}$$

where ρ_g is the diffuse reflectance of the surroundings, normally assumed to be equal to 0.2 if unknown.

The Perez tilted surface model is an anisotropic sky model which is based on a detailed analysis of all three components of diffuse irradiation from the sky - isotropic, circumsolar diffuse and horizon brightening. It calculates the diffuse irradiation on an inclined surface, $I_{d,\beta}$ (MJ/m^2), using

$$I_{d,\beta} = \left[I_d \times (1 - F_1) \times \left(\frac{1 + \cos\beta}{2} \right) \right] + \left[I_d \times F_1 \times \frac{a}{b} \right] + \left[I_d \times F_2 \times \sin\beta \right] \tag{F.21}$$

where F_1 and F_2 are circumsolar and horizon brightness coefficients and a and b are terms that account for the angles of incidence of the cone of circumsolar irradiation on the inclined and horizontal surfaces. The three terms in Equation F.21 represent the isotropic diffuse irradiation, the circumsolar diffuse irradiation and the diffuse irradiation from the horizon respectively. The terms a and b are calculated using

$$a = \max\left[0, \cos\theta\right] \tag{F.22}$$

$$b = \max\left[\cos 85, \sin\alpha_s\right] \tag{F.23}$$

The brightness coefficients F_1 and F_2 are functions of three parameters that describe the sky conditions: zenith angle, θ_z (degrees); clearness, ε; and brightness, Δ. These are given by

$$\theta_z = \cos^{-1}(\sin\alpha_s)\,, \tag{F.24}$$

$$\varepsilon = \frac{\dfrac{I_d + I_{bn}}{I_d} + 5.535\times10^{-6}\theta_z^{\,3}}{1 + 5.535\times10^{-6}\theta_z^{\,3}} \quad \text{and} \tag{F.25}$$

$$\Delta = m\frac{I_d}{I_{on}} \tag{F.26}$$

where m, the air mass, is given by

$$m = \frac{1}{\cos\theta_z} \tag{F.27}$$

and I_{on} (MJ/m^2), the hourly extraterrestrial normal incidence irradiation, is given by

$$I_{on} = \left[G_{sc} \times \left(3.6 \times 10^{-3}\right)\right] \times \left(1 + 0.033 \cos \frac{360 \times n}{365}\right) \qquad (F.28)$$

F_1 and F_2 are then calculated using

$$F_1 = \max\left[0, \left(F_{11} + F_{12}\,\Delta + \frac{\pi\,\theta_Z}{180} F_{13}\right)\right] \text{ and} \qquad (F.29)$$

$$F_2 = \left(F_{21} + F_{22}\,\Delta + \frac{\pi\,\theta_Z}{180} F_{23}\right) \qquad (F.30)$$

The brightness coefficients F_1 and F_2 are functions of statistically derived coefficients for ranges of values of ε. These are shown in Table F-2.

Table F-2. Brightness coefficients for Perez tilted surface model. (Adapted from Perez, Ineichen, Seals, Michalsky and Stewart, 1990.)

Range of ε	**F_{11}**	**F_{12}**	**F_{13}**	**F_{21}**	**F_{22}**	**F_{23}**
0 – 1.065	-0.008	0.588	-0.062	-0.060	0.072	-0.022
1.065 – 1.230	0.130	0.683	-0.151	-0.019	0.066	-0.029
1.230 – 1.500	0.330	0.487	-0.221	0.055	-0.064	-0.026
1.500 – 1.950	0.568	0.187	-0.295	0.109	-0.152	-0.014
1.950 – 2.800	0.873	-0.392	-0.362	0.226	-0.462	0.001
2.800 – 4.500	1.132	-1.237	-0.412	0.288	-0.823	0.056
4.500 – 6.200	1.060	-1.600	-0.359	0.264	-1.127	0.131
6.200 +	0.678	-0.327	-0.250	0.156	-1.377	0.251

The hourly total irradiation on an inclined surface, $I_{T,\beta}$ (MJ/m^2), can now be determined by summing the individual irradiation components i.e.

$$I_{T,\beta} = I_{b,\beta} + I_{d,\beta} + I_{g,\beta} \qquad (F.31)$$

This calculation is carried out for every daylight hour on the mean day of every month. The daily total irradiation on an inclined surface is obtained by summing all the hourly values. This is multiplied by the number of days in the month to obtain the monthly total irradiation on an inclined surface. Summing the monthly values gives the annual total irradiation incident on an inclined surface.

F.3.1 Considering the effect of overshading

Equation F.31 assumes that the inclined surface is unshaded. This was assumed to be the case for roof planes suitable for installing solar DHW and PV systems (Chapters 4 and 5 respectively). However, when considering the passive solar design of proposed new estate layouts it is necessary to take overshading of windows into account (Section 6.4.2). This is because overshading can have a significant effect on energy consumption.

To consider overshading on a surface, it is necessary to calculate the altitude angle of the obstructing object i.e. the urban horizon angle (UHA). The calculation of the UHA is described in Section 6.4.2 and is not repeated here. For every daylight hour of the mean day of every month, the UHA of the affected surface is compared against the solar altitude angle, α_s (calculated using Equation F.17). When the UHA is less than α_s there is no shading on the surface and the incident solar irradiation for that hour is calculated using Equation F.31. When the UHA exceeds α_s, the surface is obstructed i.e. it becomes shaded and no longer receives direct solar irradiation. After Robinson (1999), the hourly incident solar irradiation on an inclined surface experiencing overshading, $I_{T,\beta,\text{shaded}}$ (MJ/m^2), is given by

$$I_{T,\beta,\text{shaded}} = \left[I_{d,\beta} \times \frac{90-\text{UHA}}{90}\right] + \left[I_d \times \rho_g \times \left(\frac{1-\cos\beta}{2}\right)\right] + \left[I_{d,\beta} \times \frac{90-\text{UHA}}{90} \times \rho_{ow} \times \frac{\text{UHA}}{90}\right] \tag{F.32}$$

where ρ_{ow} is the reflectance of the opposite wall, assumed to be 0.4 if unknown (McMullan, 1993).

Summing the shaded and unshaded hours gives the daily total irradiation on an inclined surface experiencing overshading.

F.4 Parameters required by the PV calculation model

The PV calculation model implemented in the SEP system (Section 5.7) requires some additional parameters. These are calculated for every daylight hour on the mean day of every month.

The hourly extraterrestrial irradiation, $\bar{I}_o$ (MJ/m^2), is given by

$$\bar{I}_o = G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right)\times\left(\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta\right)\times 3.6\times10^{-3} \qquad \text{(F.33)}$$

The hourly clearness index, $\bar{k}_T$, is given by

$$\bar{k}_T = \frac{I}{\bar{I}_o} \qquad \text{(F.34)}$$

The ratio of beam irradiation on the inclined surface to that on the horizontal surface, R_b, is given by

$$R_b = \frac{\cos\theta}{\cos\theta_z} \qquad \text{(F.35)}$$

Appendix G

List of Related Publications

GADSDEN, S., RYLATT, M., LOMAS, K., & ROBINSON, D. (2000). Energy efficiency and solar energy in urban planning: a GIS-based decision support prototype for the domestic sector. In K. Steemers & S. Yannas (Eds.), *Proceedings of PLEA 2000* (pp. 672-677). London, UK: James & James (Science Publishers) Ltd.

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