Electric Load in the Domestic Sector and its Modulation by Building Integrated Photovoltaic: Findings of a Detailed Monitoring Study of Energy Consumption in UK Buildings

By
Nico Kreutzer
February 2010

Ph.D.

The Welsh School of Architecture
University of Wales
Cardiff

ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106-1346

Declaration

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed ......Nico Keul...................................... (candidate)

Date ....20/03/2010...........................

STATEMENT 1

This thesis is the result of my own investigations, except where otherwise stated.

Other sources are acknowledged by footnotes giving explicit references.
A bibliography is appended.

Signed ......Nico Keul...................................... (candidate)

Date ....20/03/2010...........................

STATEMENT 2

I hereby give consent for my thesis, if accepted, to be available for photocopying and for inter-library loan, and for the title and summary to be made available to outside organisations.

Signed ......Nico Keul...................................... (candidate)

Date ....20/03/2010...........................

Abstract

The future energy supply is highly likely to be a mix of central and decentralised energy sources, therefore knowledge of on-site generation, such as photovoltaic systems, and energy consumption patterns with a good degree of certainty will be necessary to ensure the current quality of supply that we enjoy at present from non-renewable resources.

This thesis describes the outcome of a detailed electric energy monitoring campaign on 5 different sites in a total number of 81 households predominantly undertaken in the social housing sector in the United Kingdom. The 5 minute data (and 1 minute short term) have been derived during the Department of Trade and Industry Photovoltaic Domestic Field Trial Program, where over a period of two years electric energy consumption by the households and electric energy generation by their photovoltaic systems were monitored by the author as part of this study.

The consumption data obtained underwent a detailed analysis in order to give an understanding of the characteristics of the electric load in terms of base load, peak load, the load fluctuation and the energy consumption. The measured electric load profiles were separated into weekday and weekend profiles, and summer and winter profiles were also derived.

The results are presented as overall load profiles for the entire set of dwellings; as site specific load profiles and, for a smaller number of dwellings, as dwelling specific load profiles. Another outcome of this research is the development of several publicly available measured annual data sets suitable for use in modelling (5 minute interval data).

The findings of this energy consumption analysis and the long term real data sets can be used for computer modelling purposes in general, but particular in the field of on-site generation, where the need for available realistic data sets is immense.

In order to create a link between the energy consumption characteristics and socio-economic factors an occupant survey was undertaken among the people living in the monitored dwellings. The survey included questions regarding the following aspects: the number of tenants living in the household, tenant's age, ownership of electrical appliances and the general times of use of appliances and occupancy in the household.

The results of this survey, carried out in 46 dwellings, can be applied to improve electric load models in general and especially the parts of the models that present the social housing sector. The findings will also help to investigate the options of load shifting, based on the time of use analysis of the 17 appliances.

This study has investigated the options of reducing the electric load in the domestic sector by building integrated PV-systems. Therefore the influence of simulated PV-generation profiles on the recorded electric load profiles was analysed.

The outcome can help to size PV-systems when the direct use of the PV-energy in order to reduce losses in the public grid is desired. The findings of this study are also of use when knowledge is required on the electric demand of small networks when connected to a large PV-generator as opposed to the connection of one dwelling to one small PV-system. The results can be used to size storage systems (e.g. batteries) if a self sustaining schedule of dwellings is needed.

The findings of this study were used in the International Energy Agency Energy Conservation in Buildings and Community Systems Annex 42 to provide the profiles needed for modeling the performance of Fuel Cells and Cogeneration systems in residential properties.

Acknowledgements

The author wishes to thank Dr. Ian Knight from Cardiff University for the supervision of this research, Bruce Cross from Energy Equipment Testing Service for allowing the data to be used in this thesis, and Prof. Dr. Hans Georg Beyer from the University of Applied Science Magdeburg for the scientific support of this study.

Ein besonderer Dank geht natürlich an meine Frau Laura, die mich stets tatkräftig unterstützt hat und maßgeblich zur Vollendung dieser Arbeit beitrug. Grazie per tutto!

Auch Sarah, unserer kleinen Tochter, möchte ich hiermit Danke sagen.

Bedanken möchte ich mich auch vielmals bei meinen Eltern, die mich während meiner gesamten Studien- und Ausbildungszeit in allen Aspekten unterstützten.

En ultimo, pero no menos importante, gracias a mi amigo Greg para su suporte y su tiempo.

Contents

List of Figures

List of Tables

1. Introduction

1.1. Background to this study

The world's power demand is currently satisfied mainly by oil, gas and coal. In 2006 the global electricity energy production was covered by more than 66% of fossil fuels [EIA, 2007].

The dependency on these energy sources to ensure the economical survival of many countries can become a dangerous situation. For instance, the majority of the proven oil reserves are located in the Middle East, predominantly in Saudi Arabia, Iran and Iraq. These regions are known to be politically unstable.

Furthermore fossil fuels are not infinite. A study of the German Federal Ministry of Economics Technology states that the oil reserves[1] will last 43 years, the natural gas reserves 64 years and the coal reserves around 200 years [BUND, 2009]. Those periods are estimations and will possibly change if, for example, the mining technology evolves.

The energy of oil, gas and coal is extracted by burning which emits mainly carbon dioxide into the atmosphere. This emission contributes to about 70% of the potential climate change effect [DTI, 2006]. Effects of global warming, caused by anthropogenic emissions, are: ice caps retreating from many mountain peaks, global mean sea level rose by an average of 1-2mm a year during the 20th century and weather-related economic losses to communities and businesses have increased ten-fold over the last 40 years [DTI, 2006]. This is only a small selection of results of the climate change caused by human behaviour.

The first step to decrease the emission of greenhouse gases was made in 1997 when the Kyoto protocol was signed. 165 countries have ratified the treaty so far, where 35 and the European Economic Community are required to reduce the emissions below the levels specified. The overall global cut in green house gas emissions is aimed to be at least 5% in the commitment period 2008-2012 [UNFCCC, 2006].

---

[1] Reserves which on the available evidence are virtually certain to be technically and commercially producible, i.e. have a greater than 90% chance of being produced

The Government of the United Kingdom went even further by the commitment of reducing emissions. It accepted the recommendations of the Royal Commission on Environmental Pollution, which means that the carbon dioxide emissions will be cut by 80% of 1990 level until 2050.

The production of electricity in the United Kingdom still relies heavily on fossil fuels. The required 373TWh in 2004 were generated mainly by gas (42%) and coal (35%) [DECC, 2004]. It is envisaged that the energy system in 2020 is more diverse than today, with a much greater mix of electric sources and technologies. This implies that there will be micro-generation, for example, photovoltaic systems or combined heat power.

The usage of photovoltaic systems in the urban environment has become a common method of on-site generation. The arrays, integrated into facades or roofs, usually have a power rating between 2kWp and 5kWp. These grid connected systems have the potential to relieve the load on the national electrical grid and to generate excess energy. In 2007 the total capacity of grid connected installations in the UK was 18MWp [IEA, 2007].

Figure 1-1: Building integrated grid connected photovoltaic system in the urban environment

In order to evolve the integration of micro-generation systems, an improved knowledge of the electric demand side in the domestic sector at an individual house level is required. The energy consumption but especially the electric load profiles, which determine the energy used at a certain time of the day, week or month are necessary to give detailed information of how on-site generation systems can be better integrated and sized to provide the best use of resources.

1.2. Aims and objectives of the thesis

The aims of this study are:

- To establish a new set of high resolution electric load profiles and electric consumptions for the domestic sector in the United Kingdom
- To characterise, in detail, the monitored electric load data
- To investigate the effect on the domestic load by photovoltaic systems

The following objectives are identified to meet these aims:

(1) Review existing literature regarding the electric energy consumption in the domestic sector

(2) Obtain, process and analyse electric power demand data obtained by a monitoring campaign of 81 households

(3) Undertake an occupant survey in the monitored dwellings, and a comparison with previous studies

(4) Application of photovoltaic generation profiles to the obtained electric demand load profiles

The four level structure and the content of each chapter of the thesis is shown in figure 1-2. The first level, containing the general introduction and the specific introduction, covers objective (1). The second level, the main part of the work, will deal with objectives (2) and (3). The investigation on the modulation of the domestic load by photovoltaic takes part in level 3, where objective (4) is met.

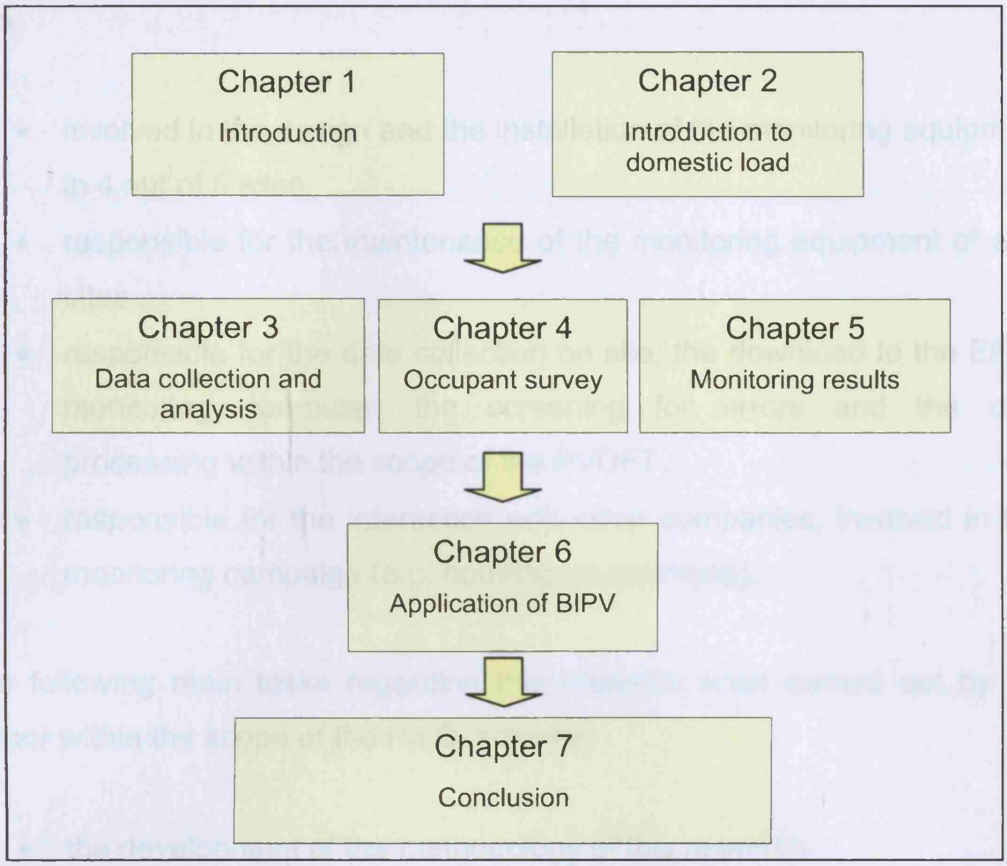


Figure 1-2: Thesis structure and chapter content

1.3. *The role of the author in the electric energy monitoring campaign of the 98 households*

The basis of this work is the monitoring campaign, conducted by Energy Equipment Testing Service [EETS, 2006] between 2002 and 2005, where the performance of photovoltaic systems and the electric energy consumption of 98 households (81 were used for this research) were investigated, as part of the Department of Trade and Industry (DTI[2]) Photovoltaic Domestic Field Trial (PVDFT).

---

[2] The DTI was replaced by the Department for Business, Enterprise and Regulatory Reform and the Department for Innovation, Universities and Skills on 28th June 2007

The author was an employee of EETS and at the same time a part-time Ph.D. student in Cardiff University. As part of this employment the author was:

- involved in the design and the installation of the monitoring equipment in 4 out of 5 sites.
- responsible for the maintenance of the monitoring equipment of all 5 sites.
- responsible for the data collection on site, the download to the EETS monitoring computer, the screening for errors and the data processing within the scope of the PVDFT.
- responsible for the interaction with other companies, involved in this monitoring campaign (e.g. housing associations).

The following main tasks regarding this research were carried out by the author within the scope of the Ph.D. scheme:

- the development of the methodology of this research
- characterisation of the buildings and households
- the detailed data analysis regarding the electric load study
- the very high resolution data (1 minute) monitoring and analysis
- the development, realisation and analysis of the questionnaire in the households
- the investigation of the domestic load modulation by BIPV

The conducting of the questionnaire and the characterisation of the houses were possible due to the connections of the author established as a member of EETS, and as the main contact person with the housing associations during this work.

2. Review of electric load and load modulation by BIPV in the domestic sector

2.1. Introduction

This chapter reviews national and international monitoring campaigns. Here it has been distinguished between metering campaigns and the derivation of data from modelling. Then the influential factors and the composition of the electric load are described.

The second part of the chapter deals with the basics of photovoltaic and solar radiation as well as building integrated, grid connected photovoltaic systems and its impact on the energy consumption and the load profile of domestic buildings. It reviews the studies on load modulation by BIPV carried out in the UK.

The last part of this chapter summarises the review and describes the derivation of the research problem of this thesis.

2.2. Load profile acquisition – previous studies

2.2.1. Monitoring campaigns

There are two levels of monitoring the load profiles of single households. The first is the whole house monitoring, where demand data is recorded at the incoming mains of the dwelling, and second, the end-use metering of single appliances in the household. The latter gives detailed results on the load signature of each appliance and often the total demand, either recorded or an aggregation of all loads.

This section gives an overview of selected national and international campaigns of whole house metering and single appliances, their motivation and findings in brief.

There are several reported monitoring campaigns in the United Kingdom where electric load profiles of individual dwellings were obtained or/and the characteristic load profiles of single appliances has been recorded.

The most intensive investigation was carried out in the nineties when the Load Research Group of the Electricity Association [EA, 1998] metered

1200 households with a thirty minute monitoring interval. Within this project, but on a smaller scale, single electric appliances like cooking, cooling and lighting as well as the whole house metering took place. In addition a survey regarding the household type, social-economic characteristics and the ownership level of appliances in the monitored dwellings was carried out. Figure 2-1 shows the electric load profile of a weekday for the domestic sector for the UK, obtained by the Electricity Association, with the maxima in the morning and in the afternoon (summer profile daily consumption: 8.28 kWh, winter profile: 11.49kWh). As expected, the lowest level of power demand occurs in the early morning hours, the so-called base load. This set of data is very often referred to when studies are carried out involving the UK electricity demand characteristics. The average annual consumption of the Load Research Group of the Electricity Association monitoring campaign, including electric space heating was 4345kWh. Elsewhere the Load Research Group reported a national annual consumption of 3782kWh for unrestricted consumers [Stokes, 2005]. An unrestricted costumer pays the same price per energy unit during the day, there are other tariffs where the energy unit is cheaper during the night.

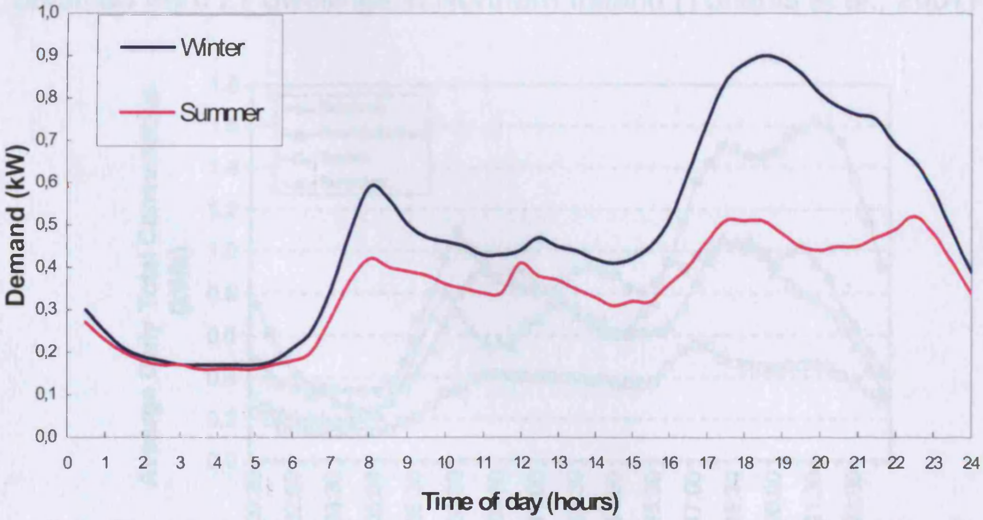


Figure 2-1: Electric load profile of a typical weekday for the UK obtained by the Electricity Association [EA, 1998]

A monitoring campaign involving 27 homes in diverse locations in Northern Ireland was carried out between 2003 and 2005 from the School of Built Environment, University of Ulster [Yohanis et al., 2007]. The monitoring interval was 30 minutes, data were sent via mobile phone connection from the meter to the monitoring computer.

The income level of the tenant of the monitored homes as well as the dwelling type varied in order to present an adequate average of the population in Northern Ireland. This study included investigations on the relation of energy consumption and floor area, figure 2-2 shows a good correlation between these two parameters. Furthermore, overall load profiles for the different types of dwelling as well as load profiles in relation to several parameters were developed. Figure 2-3 shows load profiles of the investigated types of dwellings.

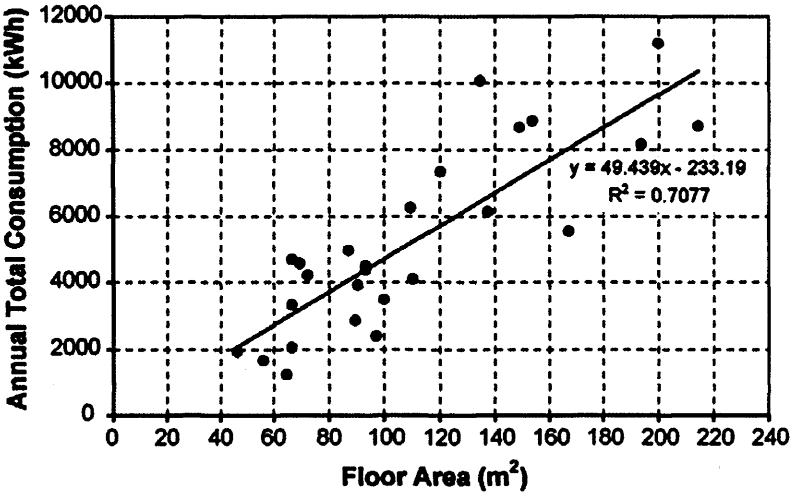


Figure 2-2: Annual total electricity consumption as a function of the floor area obtained from 27 dwellings in Northern Ireland [Yohanis et al., 2007]

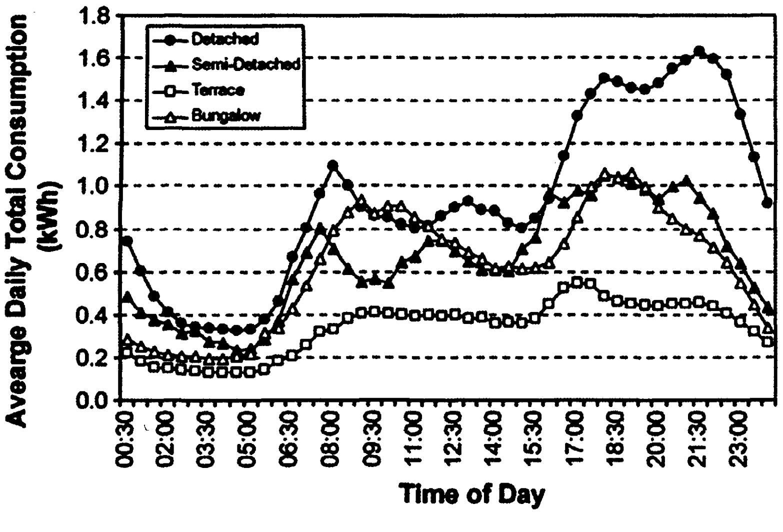


Figure 2-3: Electric load profile for different dwelling types obtained from 27 dwellings in Northern Ireland [Yohanis et al., 2007]

Another monitoring campaign was carried out by the Applied Energy Group of Cranfield University, where electricity demand data from 30 households was collected with a monitoring interval of 1 minute over a period from 1-4 weeks. Some of the main findings were that the peak demands usually ranges between 4kW and 7kW, that the base load is mainly below 0.25kW and that the annual consumption varies between 2628kWh and 8760kWh [Newborough and Augood, 1999]. The emphasis of this project was to find solutions in order to reduce power peaks, for a smoothing of local and national electrical demand profiles. Therefore, in addition to the monitoring work, a test facility was built to obtain the load signature of single applications, such as cookers and washing machines. Several methods of demand modulation, for example, peak load reduction or peak avoidance by thermal storage have been examined. Figure 2-4 shows the peak load reduction method realised by modulating the duty cycle of an electric hob. This figure shows the control applied by a commercial hob (conventional) and the control modified by the researchers to reduce the peaks (cascade).

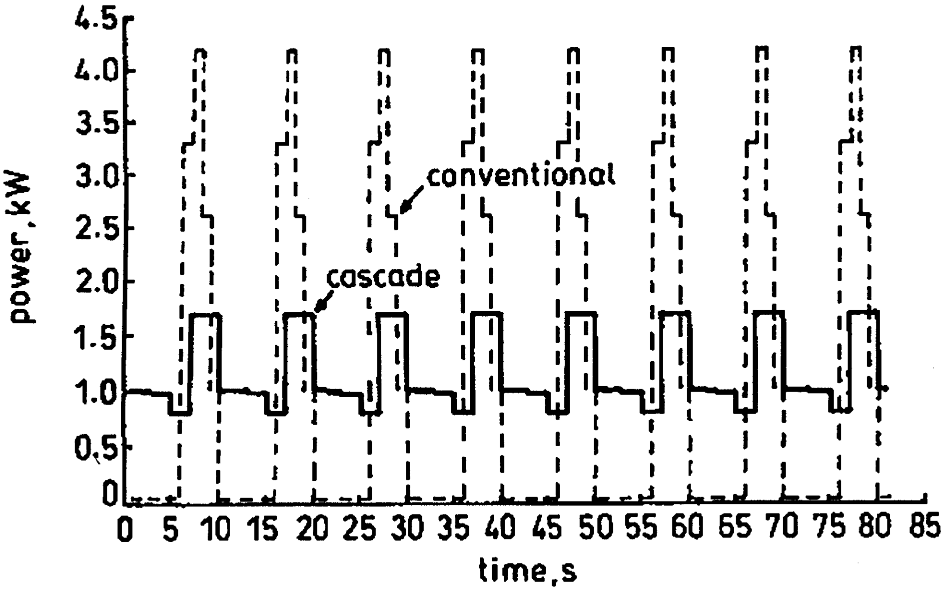


Figure 2-4: Modulation of the duty cycle of a hob to reduce peak power demands [Newborough and Augood, 1999]

There have been two more reported metering campaigns in the UK, where the focus was on one single application or on specific load types in the household.

The School of Mechanical Engineering of Cranfield University conducted a project in which the energy consumption of electric cookers in 36 homes was monitored (average daily consumption 1.3kWh). This work also describes three different methods of influencing the user to reduce the energy consumption for cooking appliances, firstly, by sending out an

information pack, secondly, by installing an energy consumption indicator and, thirdly, by applying both methods [Mansouri and Newborough, 1999].
In another investigation, carried out by the Environmental Change Institute of Oxford University, the standby demand of all electronic appliances (in total 282 items) was measured in 32 households and the results were used to estimate the standby power demand for each dwelling [Vowles, 2000]. It was shown that the mean annual standby consumption within the sample was 276.7kWh, ranging from 27.7kWh to 620.0kWh. This is between <1% and 16.3% of the total annual household consumption compared to the Load Research Group of the Electricity Association average annual consumption figures, with an average of 7.3%.

At the international level, there were several electrical energy monitoring campaigns. In the following section, beginning with the European, only the most influential are described.

In the French CIEL campaign, a wide range of different appliances used in the domestic sector were monitored [Sidler, 1996]. A total number of 720 appliances in 100 households were measured every 10 minutes. Figure 2-5 shows the electric load profile of the 3 typical wash-cycles of a washing machine. The first peak is the heating phase and the second main peak is the spinning-dry phase with energy consumed by the motor.

A questionnaire, regarding brand, type, age, location of the application was distributed to each household, in order to understand and classify the metered consumption.

It was intended by the project members to establish an extensive data base of all common appliances in the household in order to support the future challenges of domestic energy demand by, for example, demand site management.

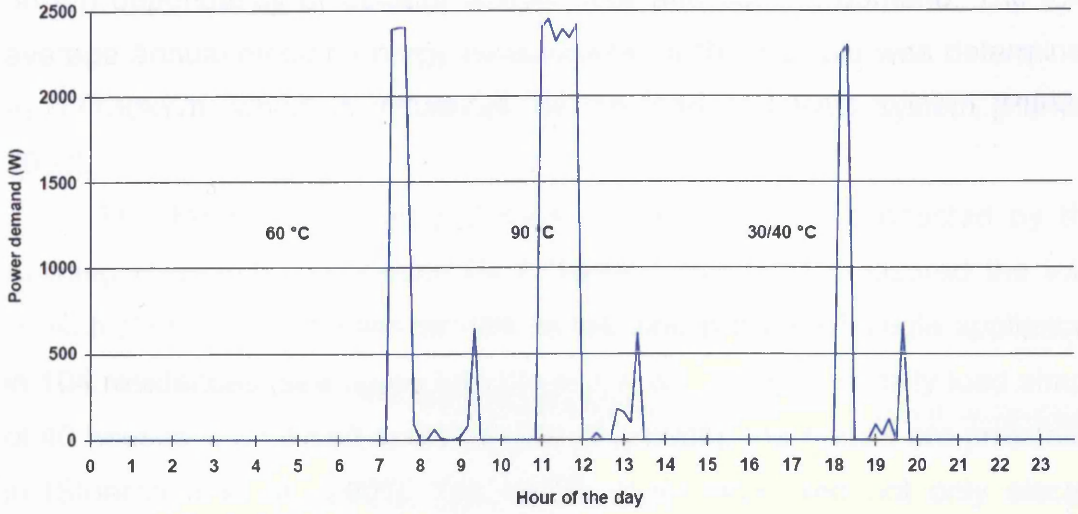


Figure 2-5: Power-load profiles for a clothes-washer at three different wash cycle temperatures [Sidler, 1996]

Further end-use monitoring campaigns have been realised in Portugal (CCE), Sweden (NUTEK) and a second project in France (ECODROME). The results are presented in [Lebot et al., 1997].

In the USA the End-Use Load and Consumer Assessment Program (ELCAP) conducted by the Pacific Northwest Laboratory investigated the electricity consumption patterns of 454 residences and 140 commercial buildings. The monitoring interval in this study was 60 minutes. The findings of this work are partly presented in [Pratt et al, 1993] including whole house metering data and the consumptions in 13 end-use classes. To identify the drivers of electric energy consumption, the loads were split by household characteristics, namely, climate zone, number of occupants, household income, utility type, floor area and year of construction. The analysis of the whole house metering data showed an average annual load of 975W (8541kWh/year) excluding Heating, Ventilation and Air Conditioning (HVAC), which compared to European results is a much higher value.

Another American investigation was carried out by the Florida Solar Energy Centre in Central Florida. This study was realised in order to identify possibilities to reduce peak loads, and obtain appliance characteristics and load profiles. Here 15 minute whole house demand data in 204 residences as well as major end-uses such as space heating, cooling, domestic water heating and either pool, dryer or range were collected. This monitoring campaign was carried out in a hot climate, therefore emphasis was also put on the dependency of outdoor temperature and cooling demand. The total average annual electric energy consumption of this sample was determined as 17130kWh, which is influenced by the load of HVAC system [Parker, 2002].

The Household Energy End-use Project (HEEP) conducted by the Building Research Association New Zealand (BRANZ) measured the total consumption of 293 houses as well as the load profiles of single appliances in 104 residences (see figure 2-6) [Isaacs et al., 2005]. The daily load shape of 40 houses is analysed and classified (6 groups), the results are presented in [Stoecklein et al., 2001]. The HEEP study measured not only electric energy consumption, but also the entire range of fuel type consumption used in the domestic sector in New Zealand.

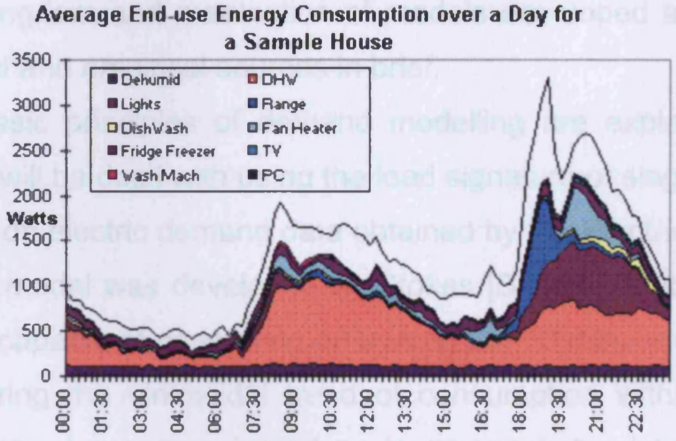


Figure 2-6: Aggregation of electric load obtained during the HEEP study in New Zealand [Isaacs et al., 2005]

A comprehensive literature review of load profiles research has been conducted by the Canadian Residential Energy End-use Data and Analysis Centre (CREEDAC). This study includes data in numeric and graphic format of electric, gas and water profiles, which are summarized in a data base [Aydinalp et al., 2001]. The electric profiles are usually daily standard profiles, averaged over a certain number of households which removes the fluctuations in the load.

2.2.2. *Synthetic profiles*

Electrical energy monitoring, as described above, is a very expensive research field. It demands costly equipment and staff to maintain the monitoring systems and, following the measurement, the analysis and presentation of the data. In many cases, it is not possible to monitor a sufficient sample size of different types of occupancy or types of dwellings in order to get statistically representative results. But there is a need to predict the domestic load even when no data for a certain group of occupants is available.

This situation therefore requires the development of reliable models which allow the user to generate different levels of consumption and especially load profiles. This section treats “bottom up” models developed in the United Kingdom and a selection of models developed abroad including their statistical and empirical sources in brief.

The basic principles of demand modelling are explained in section 2.3.2 when it will be dealt with using the load signature of single appliances.

Based on electric demand data obtained by the Electricity Association, a three layer model was developed by Stokes [Stokes, 2005]. Layer one of this model is capable of generating an average of 30 minute electric demand data considering the sinusoidal trend of consumption within a year for a group of homes. Layer two, based on layer one but producing data for a single dwelling, considers the characteristics of a specific home by applying factors which represent, for example, the occupancy type or the social-economic background of the occupants. Layer 3 uses knowledge of load signatures of single appliances, their usage pattern and random generation to break down the 30 minute consumption data into 1 minute data.

Yao and Steemers [Yao and Steemers, 2004] developed a model for five different occupancy types common in the UK. This statistical model uses previous surveys and information on usage patterns of occupants to generate the data (simulation intervals can be set from 1 minute to 30 minutes). The modelled data have been compared to an Electricity Association load profile and there is a good agreement.

Another statistical model for the domestic sector in the UK was developed by Lampaditou and Leach [Lampaditou and Leach, 2005]. It is based on activities of occupants in the household and linked to the usage of electrical appliances. The activities were grouped into ten categories: hygiene, cooking, house cleaning, dishwashing, laundry, ironing, TV and video watching, use of computer / internet and listening to music. This study also used the results from the Electricity Association as a comparison.

For the development of the models described above, various statistical resources regarding the UK have been used. One important source was the Mansouri study [Mansouri et al., 1996]. This investigation analysed results from a survey of 1000 adults mainly undertaken in South-East England.

Further sources are the Domestic Equipment and Carbon Dioxide Emissions [Decade, 1995], Department of Trade and Industry [DTI, 2002] and the various statistics from National Statistics Online [National Statistics, 2009], here especially the UK 2000 Time of Use Survey with information on activities in the household [National Statistics, 2002].

Capasso developed a model for the Italian residential sector by using national statistics, an occupancy survey and field measurements [Capasso et al., 1994].

A model, based on a survey of over 100 occupants, for the Australian residential sector has been developed by Michalik [Michalik et al., 1997].

A 1 minute random profile generator embedded into Excel has been developed by Manning [Manning et al., 2005] for the Canadian sector. Here the settings, like power demand and stand by power of the appliances and the periods of occupancy are changeable, which makes this generator applicable also for other countries.

The outputs of these models can be utilised to predict the demand of areas, cities or even on a country scale. A simulation on city scale was undertaken by Shimoda [Shimoda et al., 2003] where the load profiles of several occupancy groups were aggregated in order to derive the total demand of Osaka.

2.3. Characterisation of the electric load in the domestic sector

2.3.1. Factors effecting the electric load

Determining and categorising the factors that influence the electric load in a household is a complex task, since all of them are linked to each other. The socio-economic factors will have, for example, an effect on ownership level of appliances and on the occupancy pattern.

Number of occupants

The number of occupants living in the household influence the number of appliances, the size of appliances and the frequency of usage. A flat occupied by a single person possesses less electrical appliances than a flat with several occupants (e.g. children will have their own TV, DVD player or PC). The size or number of refrigeration appliances will increase with the number of occupants as well as the frequency of usage, for example, of the washing machine. The Mansouri study [Mansouri et al., 1996] determined a difference in wash cycles per week between a single person household and a family of four by the factor 2.84.

Socio-economic factor

This factor describes the financial characteristics and the social level of the occupants. The survey of Mansouri shows that the electric energy consumption increased as the level of income increased (see figure 2-7).

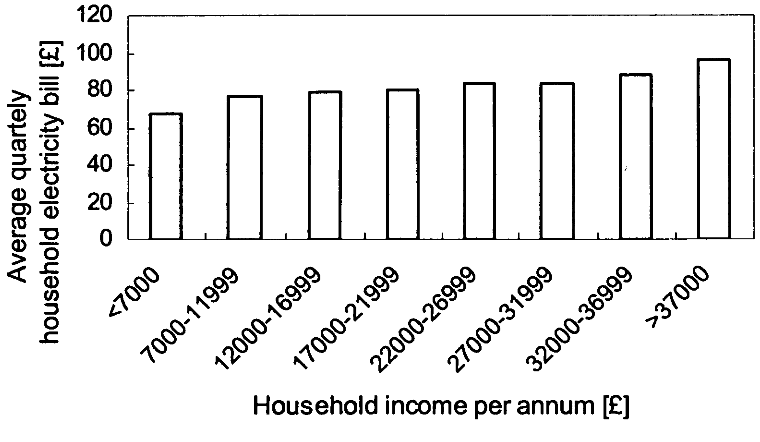


Figure 2-7: The relation of house income and domestic energy consumption in the UK [Mansouri et al., 1996]

Floor area

The power demand will increase with the size of the dwelling due to the fact that the number of occupants will rise and more appliances are possessed.

Ownership level of appliances

Depending on the quantity and range of appliances, but especially on the fuel type for cooking, heating and Domestic Hot Water (DHW) preparation, the energy consumption will differ strongly between differently equipped households.

The usage of air conditioning equipment is unusual in northern and central Europe; in southern parts it is common and it has a big impact on the electric demand and hence on the load profile.

Occupancy pattern

The occupancy pattern in the course of a year is controlled by the climate, which determines where activities of the occupants, and therefore the usage of electricity in the household, take place.

During periods of low temperature as in the winter months, the time will be spent mainly indoor. The same correlation can be realised looking at the number of daylight hours during the year. In the course of a week, there is a difference in the occupancy pattern between weekday and weekend; since more free time is available on the weekend, more activities can take place at home. Here the season of the year is also considered as mentioned above.

The variation of occupancy during the day depends on many factors; age, life style, employment to name a few. Still, there is a recognisable pattern in the daily load profile of the Electricity Association (EA) with low consumption at night, a morning peak and a second peak occurring in the evening.

Figure 2-8 shows an average of the total energy consumption of the domestic sector in the UK in the period from 2001 to 2005 [DECC, 2005] in the course of a year, with the Y-axis values reversed for energy consumption, and the averaged monthly temperatures as well as the hours of daylight [Weather, 2006] [Timeanddate, 2006]. This comparison shows the correlation between the electric load and the temperature as well as the hours of daylight.

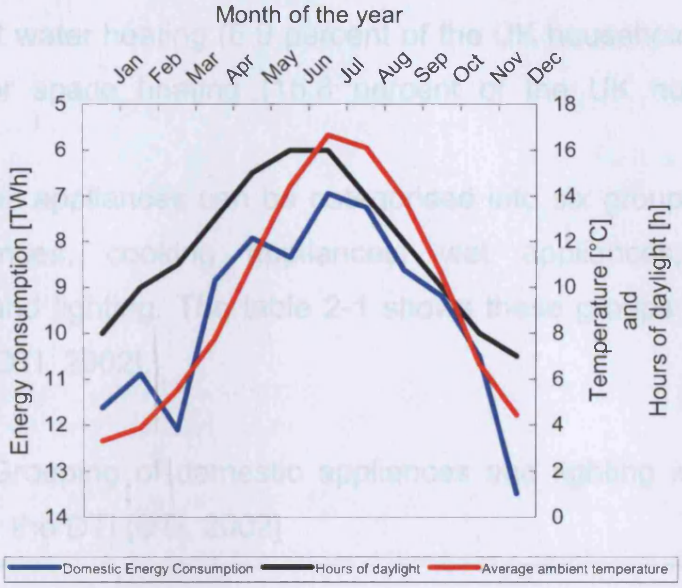


Figure 2-8: Monthly variation on energy consumption, hours of daylight and average ambient temperature over the course of a one year [Weather, 2006] [Timeanddate, 2006] [DECC, 2005]

Geographical location

There are differences in consumption caused by the location of the dwelling which includes the differences in the climate and electrical equipment in the house. For example the need for air conditioning in hot climates (e.g. Italy and Spain) can double the daily energy consumption. In the UK, a country with moderate summer temperatures, the daily energy consumption for the summer without air conditioning amounts to around 8kWh (see section 2.2.1). A 2.3kW air conditioning system for a dwelling [Global Cooling, 2009] running for around 4 hours a day will create a daily consumption of 9,2kWh. This basic estimation shows the potential influence of the air conditioning on the daily energy consumption of a dwelling in hot climate.

Climate

Climatic factors such as temperature not only determine the occupancy pattern of individuals but they also have a direct effect on non-occupant driven electrical appliances. The results from the CIEL study [Sidler, 1996] show an increase in consumption of energy by chest freezers between winter and summer of 54%.

2.3.2. *Composition of electric load*

The electric load is an aggregation of the load signatures of each appliance used in the household. The load can also contain electric demand for domestic hot water heating (6.9 percent of the UK households use electricity for DHW) or space heating (15.8 percent of the UK households) [ECI, 2000a].

Electric appliances can be categorised into six groups: brown goods, cold appliances, cooking appliances, wet appliances, miscellaneous appliances and lighting. The table 2-1 shows these groups and their typical appliances [DTI, 2002].

Table 2-1: Grouping of domestic appliances and lighting into 6 categories defined by the DTI [DTI, 2002]

Appliance group	**Appliances**
Brown goods	Electronic consumer goods – TVs, VCRs, music centers & satellite & cable TV equipment
Cold appliances	Refrigerators, freezers and combined fridge-freezers
Cooking appliances	Electric ovens, electric hobs, kettles, microwaves & small cooking appliances
Wet appliances	Washing machines, tumble dryers & Dishwashers
Miscellaneous appliances	Vacuum cleaner, irons, electric showers, central heating pumps, PCs & other office equipment
Lighting	Portable and fixed lights

Figure 2-9 shows the composition of the total electricity demand in an average UK household. Lighting and cold appliances are the groups with the highest demand and together they account for 45 percent of the total demand in the household [DTI, 2002].

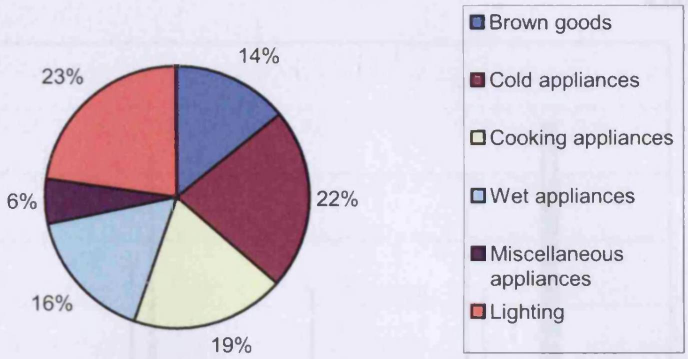


Figure 2-9: Breakdown of electricity energy consumption by domestic appliances and lighting for the UK [DTI, 2002]

Another option for categorizing domestic load is the separation into non-occupant driven and occupant driven appliances [Michalik et al., 1997]. The non-occupant driven are appliances which belong to the cold appliances group. These devices are thermostat controlled and the influence of their consumption by the occupant is relatively low. The energy consumption of these appliances depends on the room temperature thermostat setting, content, appliance design and the frequency of door opening.

The models developed to generate synthetic load profiles, mentioned in section 2.2.2, differentiate also between non-occupant and occupant driven loads. The usage of washing machines, as an example of an occupant driven load, is two washing cycles per person per week [Mansouri et al., 1996]. This usage will be assigned during a period of occupancy, also considering the most probable hour of use, by random generation. Non-occupant driven loads like a refrigerator will be assigned continuously, obviously considering the on and off times of the compressor. Figure 2-10 shows a simulation of the electric load for a Canadian household in the course of a day.

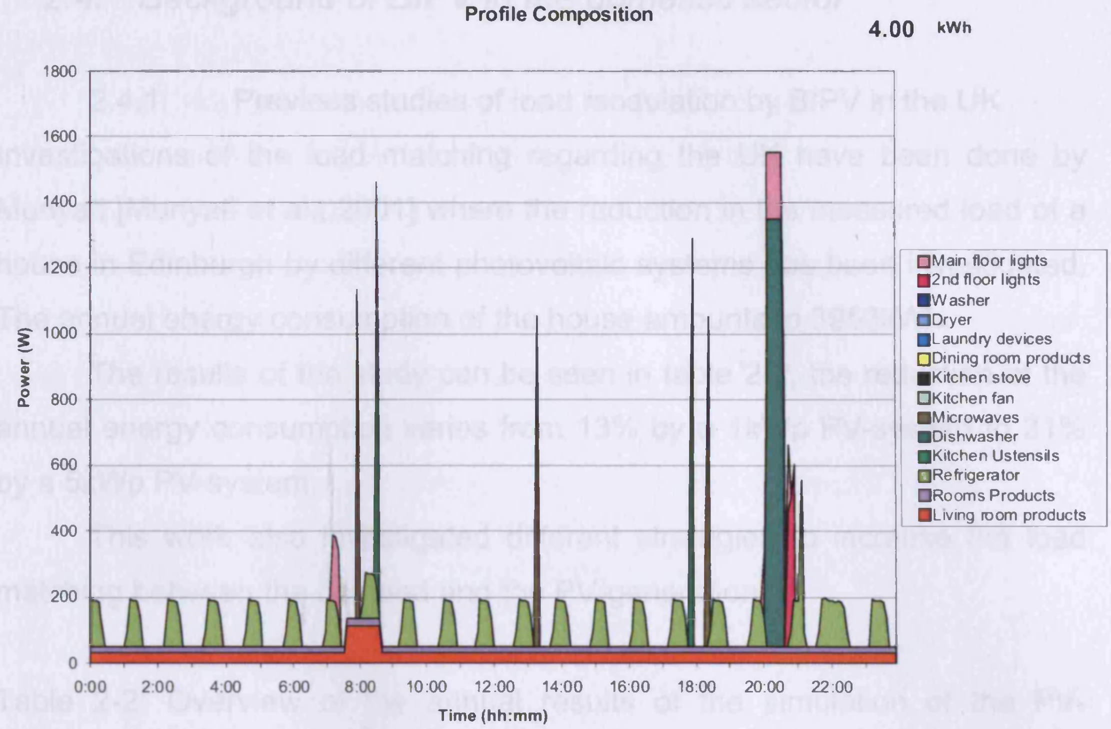


Figure 2-10: One day of simulation of domestic load, aggregated by single electric loads of domestic appliances [Manning et al., 2005]

2.4. Background of BIPV in the domestic sector

2.4.1. Previous studies of load modulation by BIPV in the UK

Investigations of the load matching regarding the UK have been done by Munyati [Munyati et al., 2001] where the reduction in the measured load of a house in Edinburgh by different photovoltaic systems has been investigated. The annual energy consumption of the house amounts to 3953kWh.

The results of the study can be seen in table 2-2, the reduction of the annual energy consumption varies from 13% by a 1kWp PV-system to 31% by a 5kWp PV-system.

This work also investigated different strategies to increase the load matching between the demand and the PV-generation.

Table 2-2: Overview of the annual results of the simulation of the PV-generation and the reduction of load (annual energy consumption of the household: 3953kWh) [Munyati et al., 2001]

PV-system size [kWp]	1	2	3	4	5
AC yield (the AC-output of the PV-system) [kWh]	712	1413	2125	2793	3492
Reduction of load [kWh]	514	830	988	1107	1225
Reduction of load [%]	13	21	25	28	31

During the "40% House Project", which studies behaviour and technology changes in order to achieve a 60% reduction in CO2 emission in the UK by 2050, a brief investigation of the impact of photovoltaic on the demand profile and the load factor during a summer and a winter day was carried out [Peacock and Newbough, 2004].

The study came to the conclusion that 76% of the PV-output can be used on a sunny winter day and 73% on a sunny summer day. However, there is no information available on the size of the PV-system, it is only known that the area is 17.5m².

The reduction on the electric load was presented graphically, but not in terms of kWh (see Figure 2-11).

The study also made crude assumptions on the impact of a large photovoltaic generator connected to a small grid of dwellings. It was also estimated what the reduction on the UK level may be.

This work presents the results regarding the reduction of PV-systems on the electric load of domestic dwellings in a very rudimentary manner, however the nature of this study is to give a general overview of this subject.

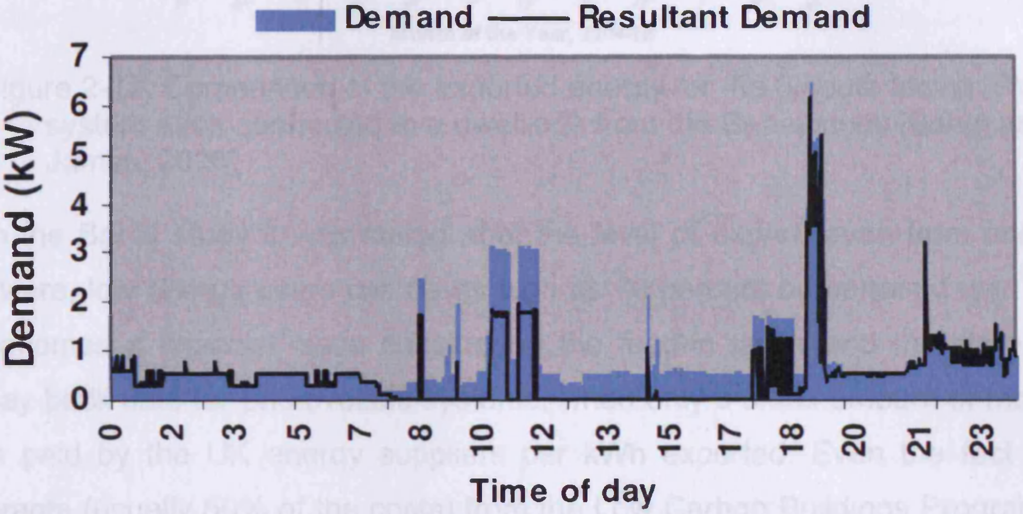


Figure 2-11: Results from the one day simulation of the reduction of the domestic load by photovoltaic on a sunny day in August [Peacock and Newbough, 2004]

In the study of Bahaj [Bahaj and James, 2006] the monitoring results from 9 low-energy social housing units from one site equipped with photovoltaic systems are presented. It was concluded, that the average annual consumption of the 9 low-energy dwellings of around 4400kWh can be reduced by 17% when a 1,5kWp PV-array is connected to each house. Figure 2-12 shows the exported energy of the Dwellings connected to a south facing PV-array.

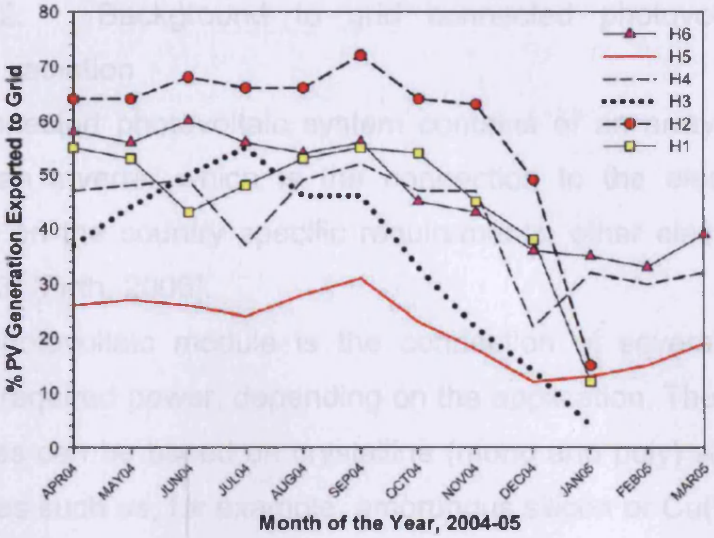


Figure 2-12: Comparison of the exported energy for the 6 south facing PV-system each connected to a dwellings from the Bahaj study [Bahaj and James, 2006]

In the Bahaj study it was stated, that the level of export, even from energy aware, low energy users can be as high as 70 percent on certain days. This becomes a financial issue considering the feed-in tariffs and therefore the pay back time for photovoltaic systems, when only a small amount of money is paid by the UK energy suppliers per kWh exported. Even the fact that grants (usually 50% of the costs) from the Low Carbon Buildings Program of the DTI [EST, 2006] are available when the photovoltaic system is purchased, does not change the long pay back times [Muneer et al., 2003].

A very different financial scenario is present in countries with high export tariffs. For instance in Germany, the energy supplier is obliged to buy the photovoltaic energy and pay around 0.5€ per kWh [BMU, 2009]. This fact leads to a very different way of integrating the photovoltaic system into the main distribution board. Here the entire energy is exported to the grid and the demand in the house will be covered by imported energy; bought for around 0.20€/kWh. This situation is very different to the UK, where the solar energy should be used directly in order to reduce the pay back time of the system.

Feed-in tariffs, as the German one, appear very important to develop the renewable energy technologies. Feed-in tariffs usually decrease from one year of installation to the next year of installation, this ensures that the industry is obligated to develop better products each year. Feed-in tariffs are necessary to build the market, however as with every market it has to become self sufficient in the near future.

2.4.2. Background to grid connected photovoltaic and solar radiation

A grid connected photovoltaic system contains of an array of photovoltaic modules, an inverter which is the connection to the electrical grid and, depending on the country specific requirements, other electrical equipment (figure 2-13) [Firth, 2006].

A photovoltaic module is the connection of several solar cells, to obtain the required power, depending on the application. The cell material for the modules can be based on crystalline (mono and poly) silicon or thin film technologies such as, for example, amorphous silicon or Cu(In,Ga)Se_2 (CIS). Each of these materials shows advantages under different conditions. Mono-crystalline silicon and poly-crystalline silicon modules have a higher efficiency than thin-film materials; but the production is more cost intensive [Quaschning, 1998]. Their performance is more sensitive to temperature; the energy output will decrease with higher module temperatures. The less temperature sensitive thin film materials, like amorphous silicon, are therefore suitable for hot climates with very high module temperatures [Kreutzer et al., 2002]. Another advantage of thin-film material is the possibility to produce semi-transparent modules which can be integrated easier into photovoltaic facades or roofs, when the daylight is intended to be used.

Modules based on crystalline silicon use either a glass-glass or a glass-Tedlar laminate structure to embed the fragile cells and give them protection against the weather or mechanical stress. Thin film material, with much lower production costs, are applied directly onto the glass followed by several other processes.

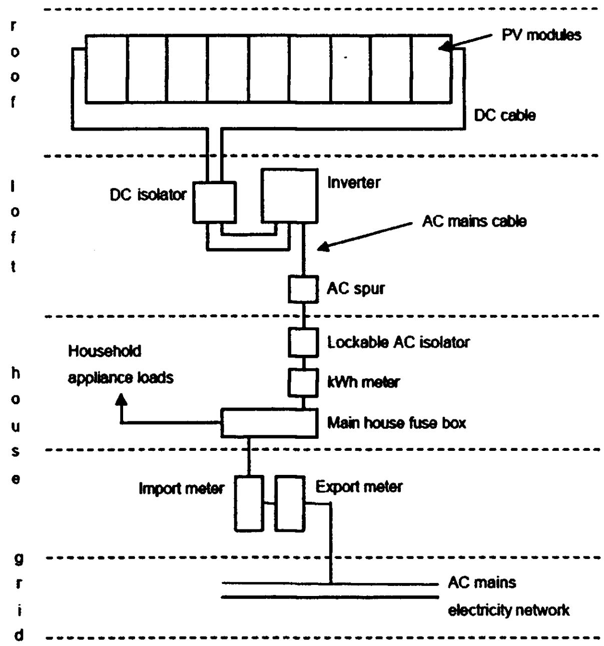


Figure 2-13: Installation scheme of a grid connected PV system according to the requirements of the PVDFT of the DTI [Firth, 2006]

The modules used in grid connected system are connected in such a manner that the voltage and current of the array matches the ranges of the inverter. The inverter connects the photovoltaic array to the grid but it also serves as an electrical isolation between the DC and the AC side and keeps the power of the system at the highest point with the MPP tracker (maximum power point tracker). The MPP tracker is necessary to calculate in certain time steps (usually in the range of seconds) the optimum of the power output of the photovoltaic array, this output changes with the varying irradiance and the temperature of the array.

Larger photovoltaic arrays can be connected via a three phase inverter to the electric grid, although there is the tendency to use multiple single phase inverters. This approach leads to better reliability and the reduction of DC and AC voltages. It also increases the overall performance of the array since the MPP tracker controls a smaller area of the array.

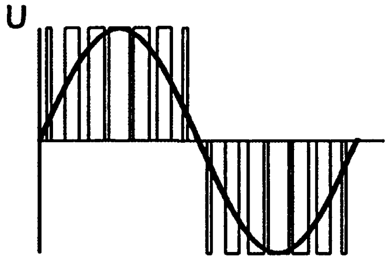


Figure 2-14: The derivation of a sinusoidal voltage by a pulse width modulation used in inverters [Markvart and Castaner, 2003]

The basic principle of a simple one phase inverter is the reverse of the polarity of the supplied DC voltage on a cycling basis. Switches in these circuits serve MOSFET[3], IGBTs[4] or bipolar transistors depending on the voltage or power. To reduce harmonic distortion many modern inverters use the Pulse Width Modulation (PWM) technique to synthesize a sinusoidal output. The principle is the same as for all inverters, i.e. the voltage will be reversed to provide an AC output, but occurring at a much higher frequency and with a varying width of the pulse. The mean output over the switching period results in a sinusoidal shaped voltage as shown in figure 2-14.

Besides the isolation between the DC voltage and the AC voltage side of the photovoltaic system, using, for example, power frequency transformers, the inverter has to serve another safety purpose. In case of the loss of supply from the utility the inverter must disconnect from the grid and shut down. The continued energising of the grid after the loss of supply, referred to as islanding, would present a safety hazard for personnel and to the utility [Markvart and Castaner, 2003].

Other electrical equipment used in a grid connected system depends on the requirements of the country. In the UK, the connection of photovoltaic systems up to 5kW is covered by the regulations of the G83/1 (larger systems are included in G59/1) [EA, 2003]. Here two AC-isolators, one near the inverter and one close to the distribution board (when inverter and distribution board are located in two different rooms) are required. There is a third isolator to disconnect the array from the inverter when, for example, maintenance on the DC side of the system is carried out [Itpower, 2006].

The annual energy production by photovoltaic system depends on the location and therefore the amount of solar radiation available. Table 2-3 shows the mean daily solar radiation for several cities in Europe and the north of Africa. Bouarfa located in the Sahara shows a radiation two to three times higher than the cities in central Europe. Within the British Islands, there is a variation of around 25% from the north to the south [ESRA, 1998].

---

[3] Metal Oxide Semiconductor Field Effect Transistor

[4] Insulated Gate Bipolar Transistor

Table 2-3: The values of average daily solar irradiation of selected cities, including location [ESRA, 1998]

City	**Location**	**Annual average daily irradiance [kWh/m²*day]**
Bergen	60°24' North	2.07
Stockholm	59°21' North	2.52
Berlin	52°28' North	2.68
London	51°31' North	2.55
Paris	48°51' North	3.05
Madrid	40°27' North	4.52
Lisboa	38°43' North	4.60
Bouarfa	32°34' North	6.01

The variation of the average monthly radiation for London is shown in figure 2-15 [ESRA, 1998]. The irradiation (time integral of the irradiance over a defined period) levels vary between summer and winter months by a factor of ten. The monthly average of the irradiation during the course of a day for a summer month, winter month and the mean is presented in figure 2-16. The differences are significant, in December at 17:00 the irradiance is zero, whereas in June 0.253kWh/m² is still available.

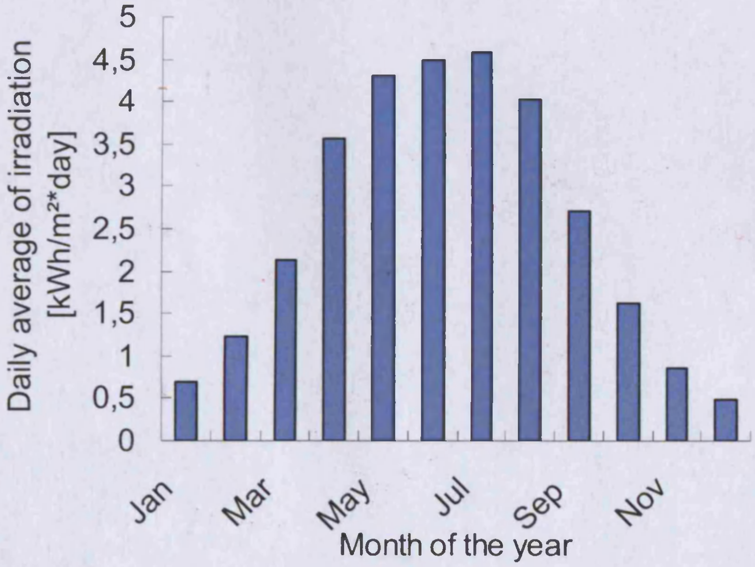


Figure 2-15: Daily mean values of irradiation for the location London for one year [ESRA, 1998]

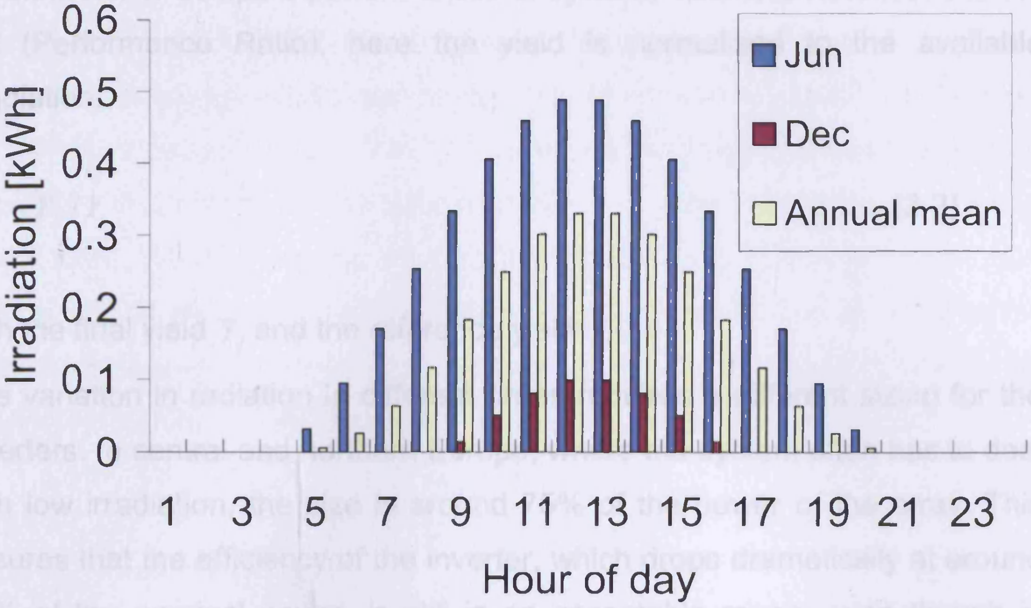


Figure 2-16: Hourly mean values of irradiation for a day in June, December and for the average day for the location London [ESRA, 1998]

The daily production of a photovoltaic system E_d can be estimated using the following formula:

$$E_d = P_0 * PSH \quad (2\text{-}1)$$

where P_0 is the nominal array power at 1000W/m². The PSH is the peak solar hours. The magnitude of peak solar hours is equal to the length of an equivalent day with a constant irradiance equal to 1000W/m², resulting in the same value of the daily irradiation.

A more accurate model to estimate the generation including module temperature and the varying efficiencies of the array and the inverter is presented in chapter 6, when the modulation of electric load by BIPV is investigated.

Modelled values [Šúri et al., 2007] have shown that the typical annual final yield (final yield is defined as the AC energy output from the inverter normalised by the system rating) of Sweden is 810kWh/kWp, for Germany is 868kWh/kWp and for Spain is 1190kWh/kWp. The value for the UK is 707kWh/kWp. These values are country averages and vary with the location.

A parameter to compare performances of systems at different locations is the PR (Performance Ratio), here the yield is normalised to the available irradiation:

$$PR = Y_f / Y_r \qquad (2\text{-}2)$$

with the final yield Y_f and the reference yield Y_r.

The variation in radiation in different areas requires a different sizing for the inverters. In central and northern Europe, where the system often has to deal with low irradiation, the size is around 75% of the power of the array. This ensures that the efficiency of the inverter, which drops dramatically at around 20% of the nominal power, is still in an acceptable range, even though in periods of very high radiation losses are unavoidable. In regions with constant high irradiation, such as southern Europe or Africa, the inverter can have the same size as the array, since less hours of part load are to be expected.

In the United Kingdom the daily profile of irradiance and the demand profile of a typical household does not necessarily match (see figure 2-17). This figure is using the same data as figure 2-16 and the Electricity Association [EA, 1998] average load profile. It can be seen that the morning and the evening peak are not covered by the irradiation profile.

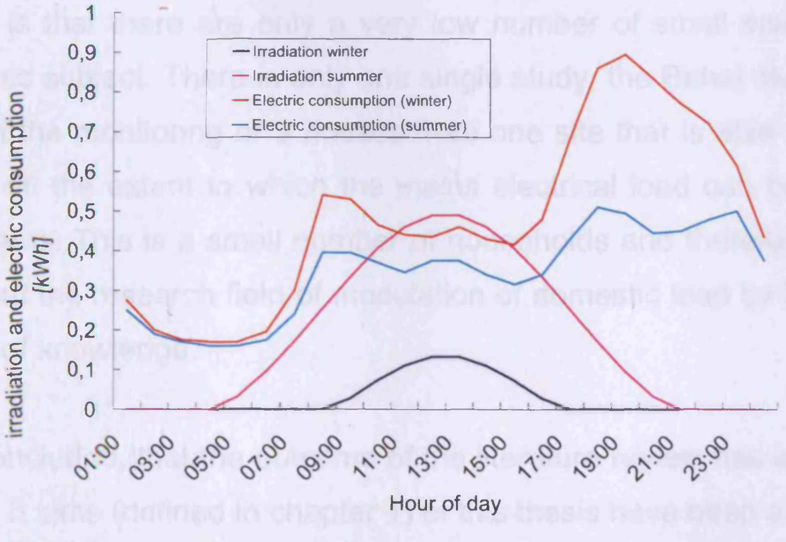


Figure 2-17: Comparison of the irradiation profile of London (winter and summer profile) and the impact of a 1kWp photovoltaic system on the typical electric load profile of the UK [EA, 1998]

Countries with hot climates, where the demand in domestic buildings is strongly influenced by the usage of air conditioning, present another option for a better coverage of the load profile by photovoltaic systems. The demand of this end-use is related to the ambient temperature and therefore irradiance. But also here the typical occupancy pattern is to be considered which shifts the peak of the air conditioning demand to the late afternoon [Parker, 2002] while the peak of the photovoltaic system is at noon. A better load matching will occur in, for example, non domestic buildings with air conditioning, such as offices, which show a very different occupation.

2.5. Summary

The first part of this chapter reviewed the derivation of electric load profiles (monitoring campaigns and synthetic profiles), and the background to electric load in dwellings, including affecting factors and the dwelling composition. The review has shown that apart from the EA data sets, which are not publicly available, no other monitoring campaign in the UK with a sufficient sample size, monitoring interval and monitoring period, could be found that would be useful for general modelling purposes.

This chapter has also presented a review on grid connected BIPV and its influence on the electric load in domestic buildings of the UK. The finding of this review is that there are only a very low number of small scale studies regarding this subject. There is only one single study, the Bahaj study, which is based on the monitoring of 9 houses from one site that is able to provide knowledge on the extent to which the mains electrical load can be reduced by PV-systems. This is a small number of households and therefore there is a need to put the research field of modulation of domestic load by BIPV on a wider base of knowledge.

It can be concluded, that the outcome of the literature review has shown that none of the 3 aims (defined in chapter 1) of this thesis have been achieved in the past in such a way that further research can be based on the detailed results.

Therefore the research problem that this study is attempting to solve is whether it is possible to derive from the available monitoring data of the PVDFT a representative, analysed set of load profiles for the domestic sector in the UK and, based on these results, to what extent is it possible to reduce these domestic load profiles by the use of BIPV.

If this thesis proves capable of providing a representative new set of domestic electric load profile data, and to estimate the reduction possible by BIPV on the load, this will be an original contribution to the body of knowledge, and the results and profile outputs will be an excellent reference point for further research in the field of domestic load profile research and on-site generation.

3. Data collection, analysis and correction

3.1. Introduction

This chapter describes the location and the physical characteristics of the monitored dwellings. It presents the specifications of the data records, the data processing, the data analysis and the data quantity.
It will be described how the erroneous part of the photovoltaic data was discovered and how the errors have been eliminated from the data.
The last part of this chapter presents an error analysis of the data used in this research.

3.2. Data acquisition

3.2.1. Locations and characteristics of sites

During the UK Photovoltaic Domestic Field Trial program of the Department of Trade and Industry, 22 sites were monitored. The project began in 2001 and the aim was to gather information on buildability, operating performance, reliability and maintainability of building integrated Photovoltaic systems [DTI, 2005a].

The present study employs data from sites in Llanelli, Newcastle, Dartington, Nottingham and Derry, recorded by Energy Equipment Testing Service Ltd. [EETS, 2006]. The sites have not been selected by EETS, there was an application process for the monitoring campaign of each site.

The monitoring took place in Wales, England and Northern Ireland, as shown in figure 3-1. In total 98 photovoltaic systems and the energy balance in the corresponding dwellings were monitored. Due to non occupancy or abnormally low consumption, the number of usable data sets were reduced to 81.

Figure 3-1: Location of the 5 monitoring sites that have been used for this work

The 6 town-houses investigated in Llanelli are located in a three storey building, completed in 2003. The average house size is 104m², varying between 95m² and 120m². Here the photovoltaic array is an over-tile system with a total power of 8.16kWp, being split into 1.36kWp for each house. Figure 3-2 shows the front view with the photovoltaic façade which feeds an office, also located in the building. The monitoring of this site began in January 2003 and ended in December 2004. This project comprised of a further 12 flats, used by the National Children's Home. The floor area is very small and the occupancy is not continuous, hence these dwellings were excluded from the energy consumption analysis.

In the three storey maisonette building in Newcastle, shown in figure 3-3, 25 flats and their grid connected photovoltaic systems were monitored. The floor area varies between 65m² and 80m² with an average of 70m². The monitoring began in August 2004 and ended in July 2006. There are 3 roof integrated arrays orientated south, west and east with a total nominal power of 38kWp. The sub arrays for each flat range from 0.7kWp to 2.55kWp. A detailed picture of the mounting system is shown in figure 3-7.

Figure 3-2: Building with building integrated photovoltaic at Llanelli

Figure 3-3: Building with building integrated photovoltaic at Newcastle

The Dartington project involved 8 dwellings built in the 1970s. The floor area of the detached houses varies from 80m² to 108m², with an average of 101m². Each of the two bungalows and the 6 two storey houses is retrofitted with a 1kWp over tile mounting system. This site was monitored from May 2002 until April 2004. The figure 3-4 shows one of the bungalows before the installation of the photovoltaic system.

The Nottingham project (figure 3-5) included 21 semi-detached, one storey dwellings, built mainly for elderly people in 2002. The monitoring started June 2002 and finished in May 2004. The floor area is smaller than the other projects with an average of 55m², ranging from 52m² to 71m². The size of the roof integrated photovoltaic systems varies from 1.5kWp to 1.7kWp.

Figure 3-4: Building at Dartington

Figure 3-5: Building with building integrated photovoltaic at Nottingham

During the project in Derry (figure 3-6), 25 newly built semi-detached, two storey houses and bungalows were monitored from June 2003 until May 2005. The average floor area was 86m², ranging from 69m² to 125m². The size of the roof integrated photovoltaic systems is between 1.7kWp and

2.5kWp. Due to abnormally low energy consumption or non-occupation only 21 dwellings are used in the analysis.

Figure 3-6: Building with building integrated photovoltaic at Derry

Figure 3-7: The installation of a building integrated photovoltaic system at Nottingham

The information on the size of the photovoltaic systems and the floor areas of the dwellings was derived from internal design reports from Energy Equipment Testing Service Ltd., which undertook the photovoltaic installation and the monitoring. The site in Dartington is an exception. Here the installation was carried out by Cholwell Energy System Ltd. This company was contacted and the physical characteristics of the houses could be derived from the floor plans.

The inverters employed for the five sites are all from the same manufacture [SMA, 2006]. These inverters from the “sunny boy” series vary from 700W up to 3000W, depending on the array size. They also include an internal monitoring system, which is capable of measuring all the parameters required to evaluate the performance of the array and the inverter.

The energy consumption data sets used in this work were mainly obtained from the social housing sector. In total, 73 flats and houses are rented from a housing association. The data of the Dartington project is from owner-occupied houses and the family income could be considered as medium [Upmystreet, 2006]. This fact means the data of low-income and medium income dwellings is treated separately in order to have pure social housing results. For certain analysis’s both data sets were used, low income and medium income, however this is clearly described in the corresponding part of the thesis.

The term `social housing` refers to housing mainly provided by local authorities and registered social landlords. The prices for dwellings rented within the social housing are below the prices for privately rented houses. There are usually waiting lists where people apply for this type of housing. The access criteria, set by the government, is not necessarily low income but it will usually contribute to the decision [Ditch et al, 2001]. Members of the social housing sector are, for example, elderly or lone parent families (45% of lone parent in the UK live in social housing) [FSA, 2008].

3.2.2. Specification of the monitoring System

Before the Photovoltaic Domestic Field Trial began specifications regarding the quantity and quality of the measurements were developed, in order to obtain a data set which could characterize the usage and output of photovoltaic systems under the present climatic conditions in the UK.

The monitoring during the Photovoltaic Domestic Field Trial covered the performance of the photovoltaic systems as well as the energy balance in the dwellings. In order to analyse the photovoltaic systems performance in detail the ambient-temperature, module-temperature, the irradiation in plane, horizontal irradiation, energy output of the array and the energy output of the inverter were monitored.

The energy balance in each flat was measured with two additional meters connected at the incoming mains. One measured the imported electrical energy to the dwelling and the other one the exported electrical energy. When more energy was generated by the photovoltaic system than was used in the household, then the surplus energy was exported [BRE, 1998].

The data storage interval of 5 minute was specified by the BRE [BRE, 1998]. A detailed documentation on the monitoring strategy is presented in appendix A, including a description for the monitoring system for each site.

During the analysis of during the thesis, a problem with the data sets from the SMA inverters was discovered. The recording period was set to 5 minutes, assuming that the data acquisition would be realised by integration of the corresponding period; but in fact, the measurements taken were instantaneous. Short term data sets, tested after installation did not identify this issue. Furthermore, the company employed to ensure the data quality before sending it to the Building Research Establishment (BRE) also did not notice this mistake (the role of the BRE in the Photovoltaic Domestic Field Trial was to collect, store and analyse the data from the different sites). It was only when the detailed analysis took place in order to obtain the electric load profiles on a 5 minute interval that the problem was found, as negative values occurred.

The energy consumption is calculated using the following equation:

$$E_{cons} = E_{IO} + E_{imp} - E_{\exp} \qquad (3\text{-}1)$$

where E_{cons} is the energy consumption, E_{IO} is the inverter energy output, E_{imp} is the energy imported to the dwelling and $E_{\exp}$ is the energy exported from the dwelling into the grid.

Due to the low sample size of the inverter energy-output E_{IO} and the resulting errors in the data, negative values in the energy consumption E_{cons} occurred.

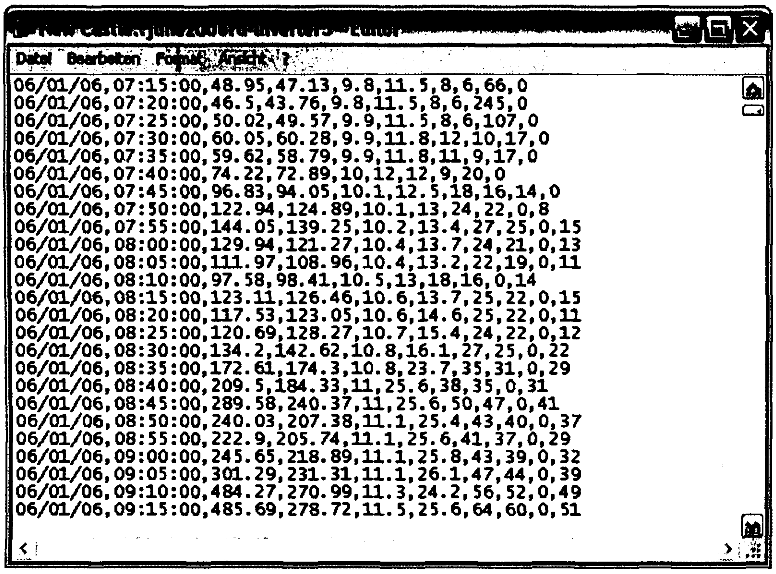
This problem concerned the monitoring data at the sites Derry, Newcastle and Llanelli (sampling rate of the inverter output was 5 minutes). Nottingham, also using the same internal monitoring system of the SMA inverters, was set to a 1 minute sampling rate, which is lower than the requirements of the Domestic Field Trial, but the results are still in a range that could be accepted

The datasets obtained from Derry, Newcastle and Llanelli were not usable for a 5 minute analysis in their raw state. To correct the data a model from the PVSAT2 project [PVSAT2, 2006] was applied. This correction procedure and an evaluation of the results are explained fully in section 3.3.

3.2.3. *Processing of the monitoring data*

The daily data sets obtained on site and sent to the main computer in Cardiff were processed into monthly files according to the specifications of the Domestic Field Trial. Figure 3-8 shows a typical file with date, time and the 8 parameters, ordered as shown in table A-1 in the appendix A.

The LabVIEW program developed for the Domestic Field Trial joins together the meteorological data, the photovoltaic data and the import/export data.



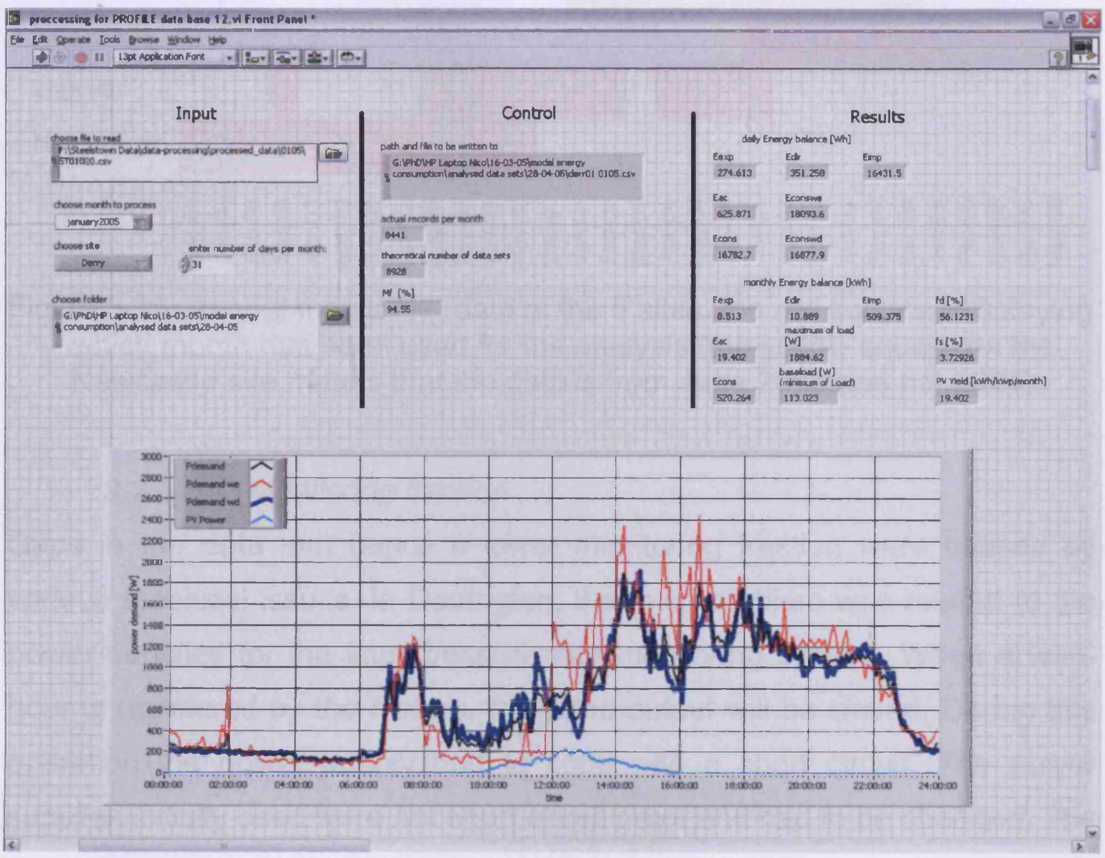
```
06/01/06,07:15:00,48.95,47.13,9.8,11.5,8,6,66,0
06/01/06,07:20:00,46.5,43.76,9.8,11.5,8,6,245,0
06/01/06,07:25:00,50.02,49.57,9.9,11.5,8,6,107,0
06/01/06,07:30:00,60.05,60.28,9.9,11.8,12,10,17,0
06/01/06,07:35:00,59.62,58.79,9.9,11.8,11,9,17,0
06/01/06,07:40:00,74.22,72.89,10,12,12,9,20,0
06/01/06,07:45:00,96.83,94.05,10.1,12.5,18,16,14,0
06/01/06,07:50:00,122.94,124.89,10.1,13,24,22,0,8
06/01/06,07:55:00,144.05,139.25,10.2,13.4,27,25,0,15
06/01/06,08:00:00,129.94,121.27,10.4,13.7,24,21,0,13
06/01/06,08:05:00,111.97,108.96,10.4,13.2,22,19,0,11
06/01/06,08:10:00,97.58,98.41,10.5,13,18,16,0,14
06/01/06,08:15:00,123.11,126.46,10.6,13.7,25,22,0,15
06/01/06,08:20:00,117.53,123.05,10.6,14.6,25,22,0,11
06/01/06,08:25:00,120.69,128.27,10.7,15.4,24,22,0,12
06/01/06,08:30:00,134.2,142.62,10.8,16.1,27,25,0,22
06/01/06,08:35:00,172.61,174.3,10.8,23.7,35,31,0,29
06/01/06,08:40:00,209.5,184.33,11,25.6,38,35,0,31
06/01/06,08:45:00,289.58,240.37,11,25.6,50,47,0,41
06/01/06,08:50:00,240.03,207.38,11.1,25.4,43,40,0,37
06/01/06,08:55:00,222.9,205.74,11.1,25.6,41,37,0,29
06/01/06,09:00:00,245.65,218.89,11.1,25.8,43,39,0,32
06/01/06,09:05:00,301.29,231.31,11.1,26.1,47,44,0,39
06/01/06,09:10:00,484.27,270.99,11.3,24.2,56,52,0,49
06/01/06,09:15:00,485.69,278.72,11.5,25.6,64,60,0,51
```

Figure 3-8: Screenshot of the specified Photovoltaic Domestic Field Trial Data format with the date, the time stamp and the values the 8 parameters (ambient-temperature, module-temperature, the irradiation in plane, horizontal irradiation, energy output of the array and the energy output of the inverter)

For the electric load analysis a more complex program had to be developed. In order to derive monthly load profiles, the energy consumption data (calculated by using formula 3-1) with the same time tag were averaged and stored temporarily. After finishing all runs, the mean 288 values of energy consumption are then written to an output file. During this process the monitoring fraction (the monitoring fraction is defined as the amount of data collected as a percentage of the maximum possible in that period), the monthly energy consumption, the minimum electric load and the maximum electric load are calculated as well.

The results are displayed on the surface of the program and written likewise to the output file. This enables the user to immediately evaluate the findings, and errors in the data sets can be detected easily.

Load profiles were derived from weekend days, weekdays and from the complete set of data. After the program run, a graph on the user-surface of the program shows the shape of the 24-hour electric load profiles, which is another control mechanism to avoid faulty results (see figure 3-9).



processing for PROFILE data base 12.vi Front Panel *

Input

choose file to read: F:\Steelstown Data\data-processing\processed_data\0105\ST01000.csv

choose month to process: january2005

choose site: Derry

enter number of days per month: 31

choose folder: G:\PhD\HP Laptop Nico\16-03-05\model energy consumption\analysed data sets\28-04-05

Control

path and file to be written to: G:\PhD\HP Laptop Nico\16-03-05\model energy consumption\analysed data sets\28-04-05\derr01 0105.csv

actual records per month: 8441

theoretical number of data sets: 8928

Mf [%]: 94.55

Results

daily Energy balance [Wh]

Eexp: 274.613
Edir: 351.258
Eimp: 16431.5
Eac: 625.871
Econswe: 18093.6
Econs: 16782.7
Econswd: 16877.9

monthly Energy balance [kWh]

Eexp: 8.513
Edir: 10.889
Eimp: 509.375
fd [%]: 56.1231
Eac: 19.402
maximum of load [W]: 1884.62
fs [%]: 3.72926
Econs: 520.264
baseload [W] (minimum of Load): 113.023
PV Yield [kWh/kWp/month]: 19.402

Figure 3-9: Screenshot of the LabVIEW load profile program with load profile display

3.2.4. *Monitoring periods*

The consumption records for this work were obtained between December 2002 and June 2005. In order to increase the probability that the monitoring data was from the same occupants, where possible the data used was from consecutive months. Due to low monitoring fractions in certain months, data from another year had to be used to complete annual records.

Consecutive periods were analysed from the sites in Derry and Nottingham. In Dartington, Newcastle and Llanelli, months from other years were used to complete the annual data sets. Figure 3-10 shows the years of monitoring for each site. The yellow square in the Newcastle schedule indicates that the June data was recorded in 2006. The Newcastle data of 2006 could not be used since the monitoring fraction was to low.

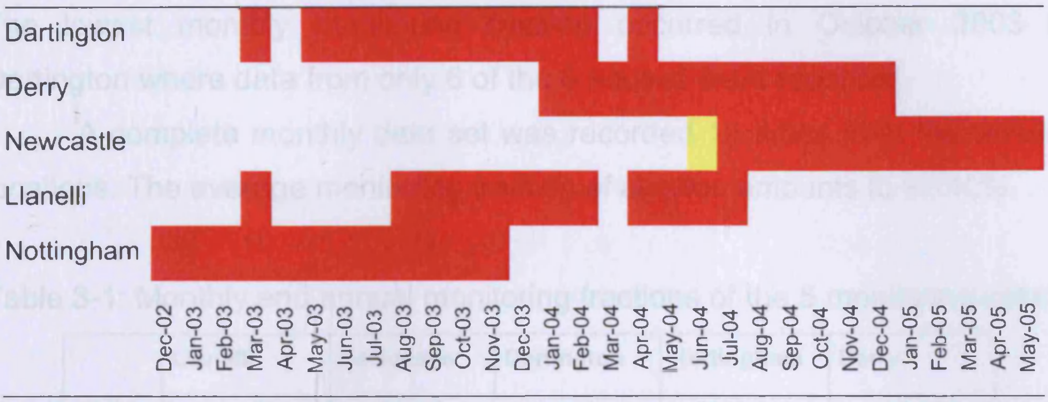


Figure 3-10: Annual monitoring data of the 5 sites, the red squares displaying which month has been used for the analysis (the yellow square on the Newcastle site means that the data is from June 2006 and not 2004)

3.2.5. Monitoring fraction

Gaps in the data and hence a lower monitoring fraction were caused by various technical issues. In Dartington, the main problem was related to the power supplies for the import/export data monitoring system. When a watt-hour is registered by the meters, the pulse output will be closed. During this operation the power supply had to cope with a short circuit. The power supplies initially used were not short circuit proof and had to be changed. The monitoring equipment was located in the dwellings and the occupants had to be contacted and a site visit arranged. This delayed the rectification of the problem and long periods without import and export data occurred.

In terms of the monitoring fraction, the most common problem at all sites was the monitoring computer. Although higher quality industrial PC's were used, they frequently stopped working. Since these computers were located on site, it was difficult to organise the reboot. In some cases a remote reboot over the telephone modem connection was possible. In other cases, site visits had to be arranged or local organisations, involved in the project, were asked to realise the reboot of the monitoring PC.

Table 3-1 shows the monitoring fractions for each site in the corresponding months. Nottingham, with a value of more than 95%, was the most reliable site in terms of the monitoring system. Due to the issue with the power supplies, Dartington was the location with the lowest overall monitoring fraction. Here certain houses did not send import and export data over periods of several months.

The lowest monthly monitoring fraction occurred in October 2003 in Dartington where data from only 6 of the 8 houses were recorded.

A complete monthly data set was recorded 14 times from the various locations. The average monitoring fraction of all sites amounts to 92.42%.

Table 3-1: Monthly and annual monitoring fractions of the 5 monitoring sites

	Llanelli	**Newcastle**	**Dartington**	**Nottingham**	**Derry**
Jan	87.07	99.96	86.76	100.00	80.81
Feb	96.58	100.00	99.84	99.99	99.96
Mar	93.90	72.39	98.63	100.00	99.93
Apr	100.00	76.45	99.88	73.08	93.33
May	97.73	100.00	85.97	89.52	87.10
Jun	75.37	74.81	87.35	100.00	92.88
Jul	100.00	80.52	71.80	99.98	97.94
Aug	100.00	99.87	80.32	100.00	91.25
Sep	100.00	99.94	74.90	93.69	99.42
Oct	100.00	100.00	71.65	99.96	99.97
Nov	83.03	97.09	74.57	94.64	100.00
Dec	100.00	100.00	85.81	99.98	99.98
Mean	*94.47*	*91.75*	*84.79*	*95.90*	*95.22*

3.3. *Correction of the erroneous photovoltaic data*

3.3.1. Problem definition

Due to the low sampling rate of the photovoltaic monitoring system (internal inverter measurements), an error has been introduced into the overall monitoring data during the hours of daylight.

The five minute instantaneous data points did not consider changes in the performance of the inverter within this period. It is possible, that, for example, four minutes of high energy generation of the photovoltaic system is stored as low performance or vice versa. This could occur if the irradiance, and hence the inverter output, changes dramatically between the records. In winter months, with low radiation levels and thus little changes in radiation, this problem is not as significant as in summer months.

Figure 3-11 shows photovoltaic generation data versus irradiance from a Dartington dwelling, recorded in August 2003. Here the data is recorded continuously with electric meters. It can be observed that the relationship between these two parameters is nearly linear (a non-linearity at certain levels of irradiation is to be expected due to the characteristic of photovoltaic modules).

Figure 3-12 shows the August inverter data from Newcastle, where data have been recorded instantaneously every 5 minutes. The fact that the Newcastle photovoltaic system is 84Wp bigger than the Dartington installation can be ignored for this comparison. The data points of the Newcastle records show a linear tendency but the data is strongly spread.

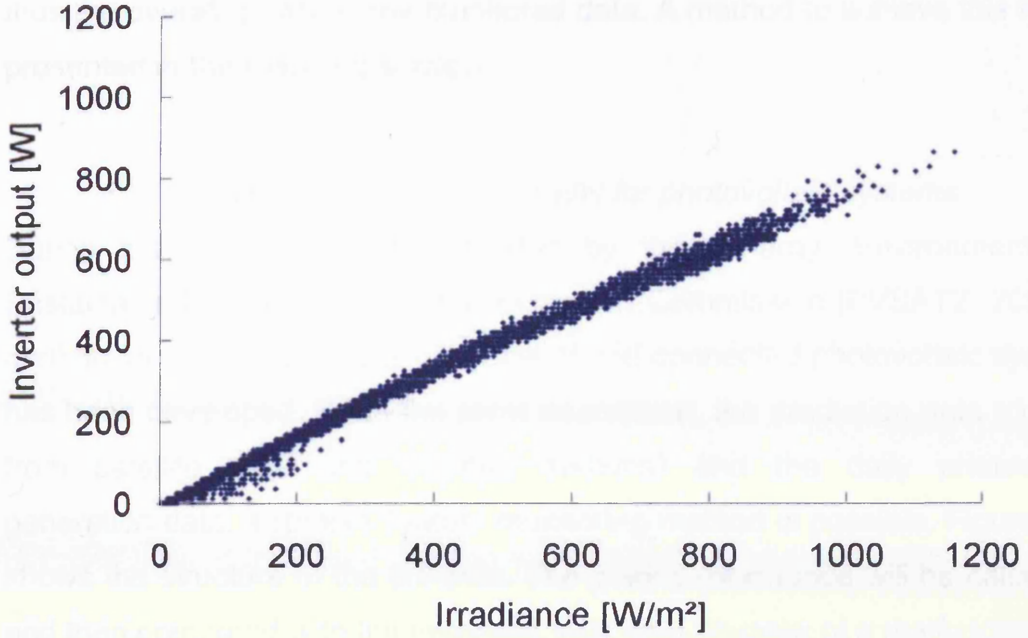


Figure 3-11: Continuously integrated inverter output data vs. irradiance of Dartington, data show linear trend as expected from correct data

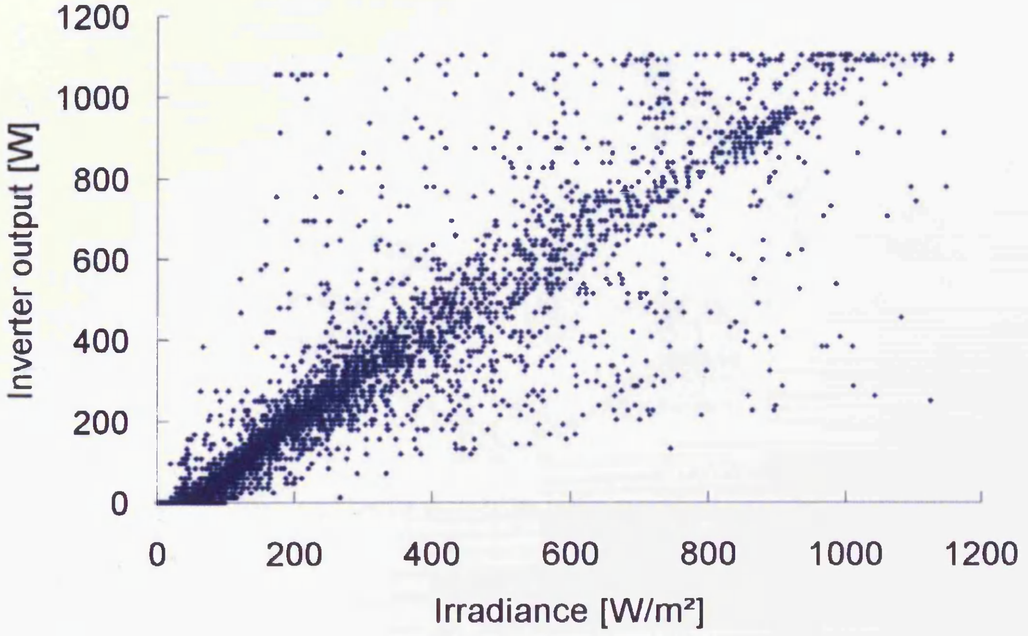


Figure 3-12: Instantaneous (5 min) inverter output data vs. irradiance of Newcastle, data points are spread and therefore partly incorrect

It was not possible to directly use this data for a five minute energy consumption analysis, since the error will have a large effect on the quality of the results during hours of daylight. It was therefore necessary to find a method to improve the quality of the data from the photovoltaic readings and thus the overall quality of the monitored data. A method to achieve this will be presented in the following section.

3.3.2. *MPP performance model for photovoltaic systems*

During the PVSAT2 project, funded by the "Energy, Environment and Sustainable Development" of the European Commission [PVSAT2, 2006], a method for checking the performance of grid connected photovoltaic systems has been developed. From the plant description, the irradiation data (derived from satellite data and weather stations) and the daily photovoltaic generation data, a remote system monitoring method is possible. Figure 3-13 shows the structure of the scheme. The plant performance will be calculated and then compared with the recorded, real data. In case of a malfunction, the operator will be notified and the problem can be rectified.

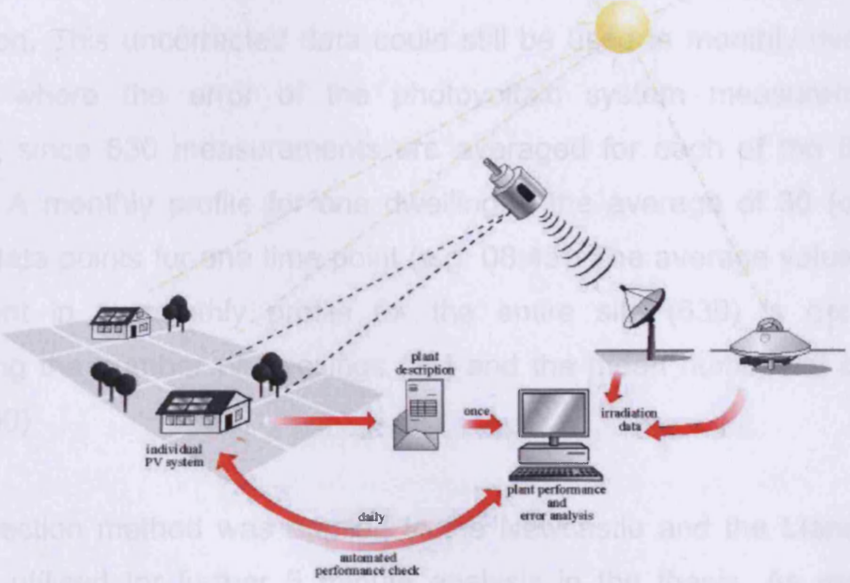


Figure 3-13: PVSAT2 project scheme with satellite, monitoring equipment and PV-system [PVSAT2, 2006]

The model for the photovoltaic generation derives the AC-yields from the module-temperature, the irradiance and from the efficiency characteristic of the array and the inverter. This model has been tested in many cases and showed very reliable results [Beyer, 2004] [Prignitz, 2005]. Thus it is proposed that in this work the same methodology can be applied to the inaccurate measurements, in order to improve the photovoltaic generation data and hence, the overall quality of the results for the present energy consumption analysis. In the following part the model and its application to the monitored data of the present study is described.

The necessary meteorological data, such as irradiation and module-temperature, have been recorded during the Domestic Field Trial. The characteristics of the arrays can be derived from averaged hourly values (also recorded during the Domestic Filed Trial); this reduces the error in the data. The models for the SMA inverters were already developed during the PVSAT2 project. The parameters for the inverters are shown in appendix B.

For the data recorded in Derry, this correction was not applicable. The reference cell, measuring the irradiance, and parts of the photovoltaic installation were destroyed by vandalism. This resulted in a long period of missing irradiation data which is needed for the modelling of the photovoltaic generation. This uncorrected data could still be used in monthly overall site profiles, where the error of the photovoltaic system measurements is reduced, since 630 measurements are averaged for each of the 5 minute records. A monthly profile for one dwelling is the average of 30 (days per month) data points for one time point (e.g. 08:45). The average value for one data point in a monthly profile for the entire site (630) is derived by multiplying the number of dwellings (21) and the mean number of days per month (30).

The correction method was applied to the Newcastle and the Llanelli data, which is utilised for further 5 minute analysis in the thesis. As mentioned earlier (section 3.2.2), for the monitoring system in Dartington, a very different and better monitoring technique was used. This data, used in the 5 minute single dwelling analysis, did not need to be corrected.

The Nottingham data have been recorded with a higher sampling rate (one minute), thus no correction procedure is needed. Figure 3-14 shows the irradiance versus inverter output diagram. The relationship between these two parameters is similar to the Dartington diagram (see figure 3-11), where continuously integrated data is available.

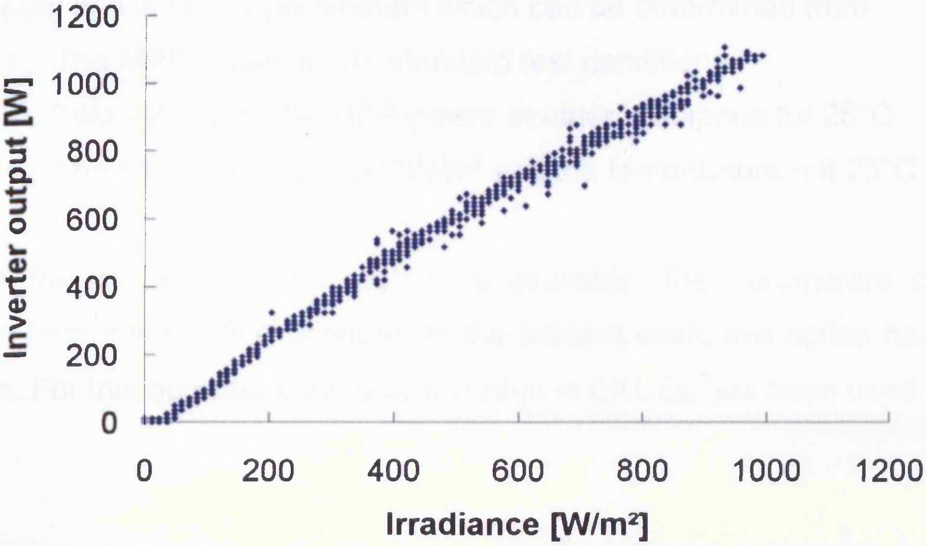


Figure 3-14: Instantaneous (1 min) inverter output data vs. irradiance of Nottingham, data show linear trend as expected from correct data

The model for the characteristics of the photovoltaic array describes the dependency of the efficiency from the irradiance and the module-temperature at the maximum power point (MPP). The relation between irradiance and efficiency at a module temperature of 25°C can be described with the following equation [Beyer, 2004]:

$$\eta_{MPP}(G,T) = a_1 + a_2 * G + a_3 * \ln G \tag{3-2}$$

where a_1-a_3 are array specific parameters and G the Irradiance.

Efficiency values for module-temperatures, others than 25°C, can be modelled with:

$$\eta_{MPP}(G,T) = \eta_{MPP}(G,25°C) * (1 + \alpha(T - 25°C)) \tag{3-3}$$

with α the temperature coefficient of the modules. Equation 3-2 and 3-3 combined is then:

$$\eta_{MPP}(G,T) = (a_1 + a_2 * G + a_3 * \ln G) * (1 + \alpha(T - 25°C)) \tag{3-4}$$

The model has in total 4 parameters which can be determined from:

- The MPP-power at the standard test conditions
- Two values for the MPP-power at other irradiance for 25°C
- The MPP-power at 1000W/m² and the temperature not 25°C

If data for the photovoltaic system is available, the parameters can be derived from a linear fit procedure. In the present work, this option has been chosen. For this operation, the solver Add-in in EXCEL has been used.

The solver tool searches for the lowest value for the deviation of the calculated efficiency and the modelled efficiency by adjusting the 4 parameters:

$$\delta = \left(\eta_{\mathrm{model}}(G,T) - \eta_{calculated}(G,T)\right)^2 \qquad (3\text{-}5)$$

where δ is the deviation, $\eta_{\mathrm{model}}(G,T)$ the modelled efficiency and $\eta_{calculated}(G,T)$ the calculated efficiency from hourly averaged recorded data.

If α is known from the data sheet of the module manufactures, it can be left as a constant and only three parameters have to be calculated.

Figure 3-15 shows the efficiency curve of the roof integrated photovoltaic installation in Newcastle, derived from one year of data.

The model parameters for equation 3-3 are: a_1=-0.11526, a_2=-0.00005, a_3=0.04222 and α=-0.0050 (α is obtained from the data sheet of a BP585 Module which is used in Newcastle [OKSOLAR, 2006]). The blue dots in figure 3-15 are measured data and the red dots represent the modelled values. Since all systems in Newcastle are installed in a similar manner, for example wired with the same size of cable, comparable cable lengths and using an identical mounting system, this characteristic can be used to model the complete set of photovoltaic systems. The results could be applied to any roof-integrated mono-crystalline array, assuming the electrical installation has been carried out in the same way as at the Newcastle site.

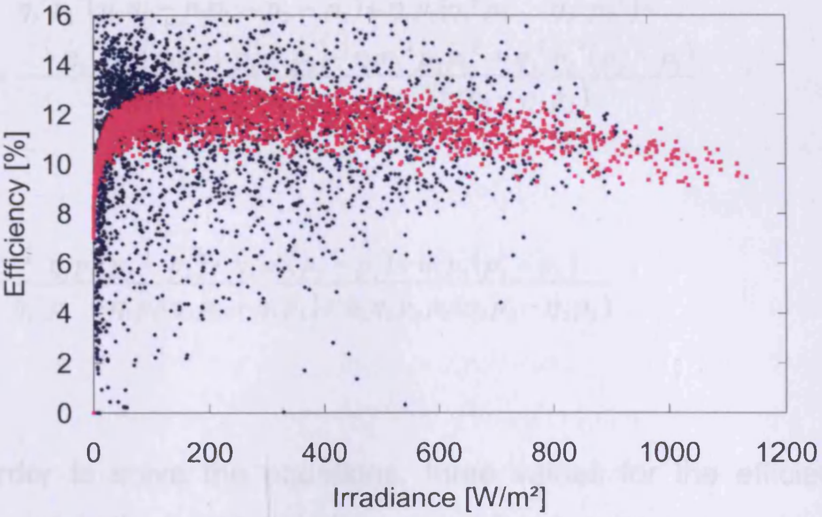


Figure 3-15: Comparison of incorrect measured efficiency curve with blue dots (one year of hourly averaged data) and modelled efficiency curve (red dots) of Newcastle

The calculations described so far only consider the DC character of the photovoltaic system. For the AC generation by the inverter, another efficiency model has to be utilised [Eicker, 2001]:

$$\eta_{inv} = \frac{p_{dc}}{(p_{dc} + p_{self} + p_{dc} * v_{loss} + p_{dc}^{2} * r_{loss})} \tag{3-6}$$

with:

$$p_{dc} = \frac{P_{input}}{P_{nominal}} \tag{3-7}$$

where P_{input} is the instantaneous DC-power of the inverter and $P_{nominal}$ is the nominal power of the inverter.

The parameter p_{self} represents the self consumption of the inverter, the parameter v_{loss} describes the losses which occur in the electronic circuits and r_{loss} stands for the ohmic losses. These three parameters can be calculated with the following equations:

$$p_{self} = \frac{p_1 p_2 p_3 \left(\eta_1^{2} p_1 (\eta_2 - \eta_3) + \eta_1 \left(\eta_3^{2} p_3 - \eta_2^{2} p_2\right) + \eta_2 \eta_3 (\eta_2 p_2 - \eta_3 p_3)\right)}{\eta_1^{2} p_1^{2} - \eta_1 p_1 (\eta_2 p_2 + \eta_3 p_3) + \eta_2 \eta_3 p_3 p_2 (\eta_2 p_2 - \eta_3 p_3)} \tag{3-8}$$

$$v_{loss} = \frac{\eta_1^{\,2} p_1^{\,2}\left(p_2\eta_2 - p_3\eta_3 - p_2 - p_3\right) + \eta_1 p_1\left(\eta_3^{\,2} p_3^{\,2} - \eta_2^{\,2} p_2^{\,2}\right) + \ldots \atop \ldots + \eta_2^{\,2} p_2^{\,2}\left(p_3\eta_3 + p_1 - p_3\right) - \eta_2\eta_3^{\,2} p_2 p_3^{\,2} + \eta_3^{\,2} p_3^{\,2}\left(p_2 - p_1\right)}{\left(\eta_1 p_1 - \eta_2 p_2\right)\left(\eta_2 p_2 - \eta_3 p_3\right)\left(\eta_3 p_3 - \eta_2 p_2\right)} \quad (3\text{-}9)$$

$$r_{loss} = \frac{\eta_1 p_1\left(p_2 - p_3\right) + \eta_2 p_2\left(p_3 - p_1\right) + \eta_3 p_3\left(p_1 - p_2\right)}{\eta_1^{\,2} p_1^{\,2} - \eta_1 p_1\left(\eta_2 p_2 + \eta_3 p_3\right) + \eta_2\eta_3 p_3 p_2\left(\eta_3 p_3 - \eta_2 p_2\right)} \quad (3\text{-}10)$$

In order to solve the equations, three values for the efficiency and three values for the corresponding normalised power p_{dc} are needed. This information can be obtained from the data sheets of the inverters and should be at p_{dc}=(0.1; 0.5; 1). In appendix B is a complete set of inverter efficiencies over the nominal power for several inverter types shown. Figure 3-16 shows the comparison of one year of five minute data from a 1100W SMA inverter of Newcastle and the modelled data.

The parameters for equation 3-10 are p_{self} = 0.00010, v_{loss} =-0.98974, r_{loss} =0.00091 and $P_{nominal}$ =1100.

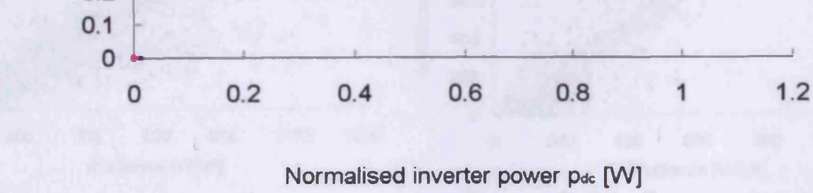


Figure 3-16: Comparison of one year of modelled and measured efficiency data of a Sunny Boy 1100 SMA inverter [Eicker, 2001]

3.3.3. *Results of the correction procedure*

The results from the modelling showed an improvement in the quality of the data. The faulty measurements could be corrected to an extent, where a further usage of the data in a five minute analysis is possible. Figures 3-17 to 3-20 show the results from the correction procedure. The red dots in the diagrams present the five minute interval modelled data and blue dots the five minute interval instantaneous recorded data. The combination of the MPP performance model and the inverter model are able to reduce the spreading of the data and derive a curve similar to the Dartington data (see figure 3-11). The data used for this comparison is from a 1100W inverter and from a photovoltaic system with an array size of 1360Wp.

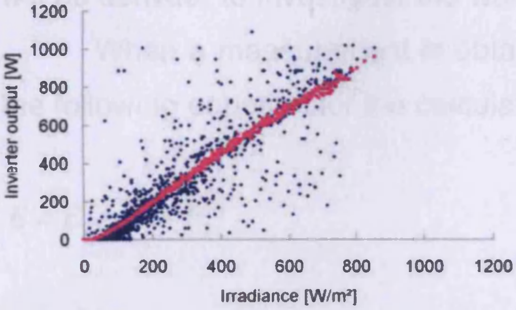


Figure 3-17: Comparison of modelled inverter output (red dots) and recorded incorrect inverter output (blue dots) for February

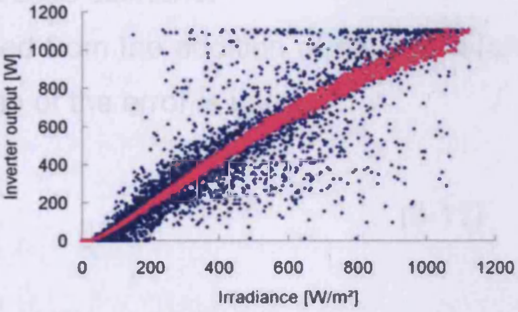


Figure 3-18: Comparison of modelled inverter output (red dots) and recorded incorrect inverter output (blue dots) for May

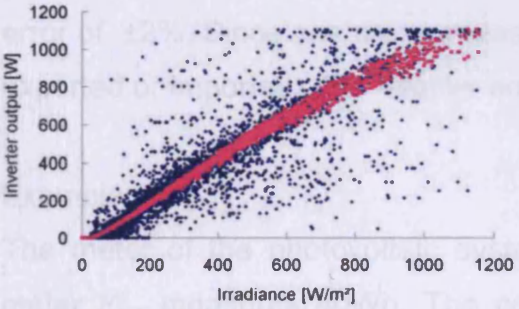


Figure 3-19: Comparison of modelled inverter output (red dots) and recorded incorrect inverter output (blue dots) for August

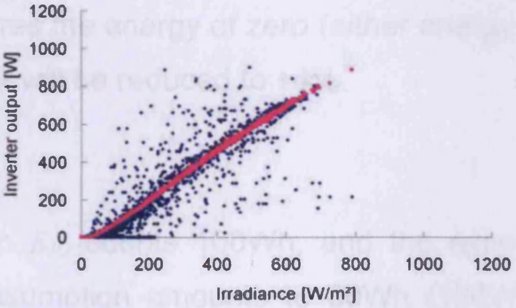


Figure 3-20: Comparison of modelled inverter output (red dots) and recorded incorrect inverter output (blue dots) for November

It can be seen, that in low ranges, up to 500W/m² of irradiance, the modelled data is of a narrow shape as it is in figure 3-11. In irradiance ranges over 500W/m², the data is more spread than in Dartington.

3.4. Error analysis of the energy consumption data

If the result of a measurement is calculated from various independent parameters, the rules of error propagation have to be applied to assess the overall accuracy of the data.

In the following section, the maximal error of the measurement equipment utilised during the monitoring is obtained (linear error propagation). The maximal error of a measurement assumes that, when combined, the errors have the same sign and maximum magnitude. In reality, and assumed that the measurements are not correlated, the error of one measuring instrument will sometimes cancel out the error of the other measuring instrument (Gaussian error propagation). Here the maximum error will be derived, to investigate the worst case scenario.

When a measurement is obtained from the addition of several results, the following equation for the calculation of the error is used:

$$E = E_1 + E_2 + E_3 \qquad (3\text{-}11)$$

with *E*, the total absolute error and E_1-E_3, the absolute errors of the individual measuring instruments.

As mentioned in section 3.1.2, the data of the Dartington project is obtained with three electrical meters. The energy consumption of the dwelling is then calculated with equation 3-11. Each of the meters has an relative error of ±2%. Since one meter measures the energy of zero (either energy is exported or imported), the relative error will be reduced to ±4%.

Example:

The meter of the photovoltaic system E_{IO} counts 100Wh, and the export-meter E_{exp} measures 40Wh. The consumption amounts to 60Wh (100Wh-40Wh) with an error of 2.4Wh (4% of 60Wh).

In Nottingham, the data from two electrical meters and the records from the SMA sunny boy control is used to derive the electric energy consumption of the dwellings. The relative error of the sunny boy control data logger amounts to ±3%, which is outside the specification of the Domestic Field Trial by 1% (see table A-2). The total relative error of the energy consumption data in

Nottingham is ±7%. This means, that a measured power demand of 1000W, actually is 1000W±70W, assuming the worst case scenario.

The error analysis for the sites with modelled photovoltaic data is more complex.

In order to derive the errors, a photovoltaic system with electrical meters has been used to derive the model parameters for equation B-3 from hourly averages of power generation data. Then the photovoltaic model and the inverter model is applied and the results are compared with the measured data.

The Dartington AC photovoltaic data is measured with an electrical meter. Unfortunately, the inverters at this site are oversized. For the 1020kWp arrays a 1100W inverter has been installed. The energy consumption of the dwellings are measured properly, but the photovoltaic data could not be used for testing the model.

Therefore, the data from a 4kWp system of St. Mary's Church in London [DTI, 2004] has been used to test the photovoltaic and the inverter model. To put the results into context, the errors were normalised to a 1100W inverter, which is the most common inverter used in Newcastle and Llanelli (1*850W; 24*1100W; 3*1700W and 3*2500W).

Figure 3-21 shows the modelled efficiency characteristics and the recorded characteristic of the installation at St. Mary's Church derived from measured values. Figure 3-22 compares measured and modelled 5 minute data. The blue line in the graph presents a perfect model for orientation. It can be seen, that there is a good agreement between the modelled and the measured data. The actual absolute errors are discussed in the following.

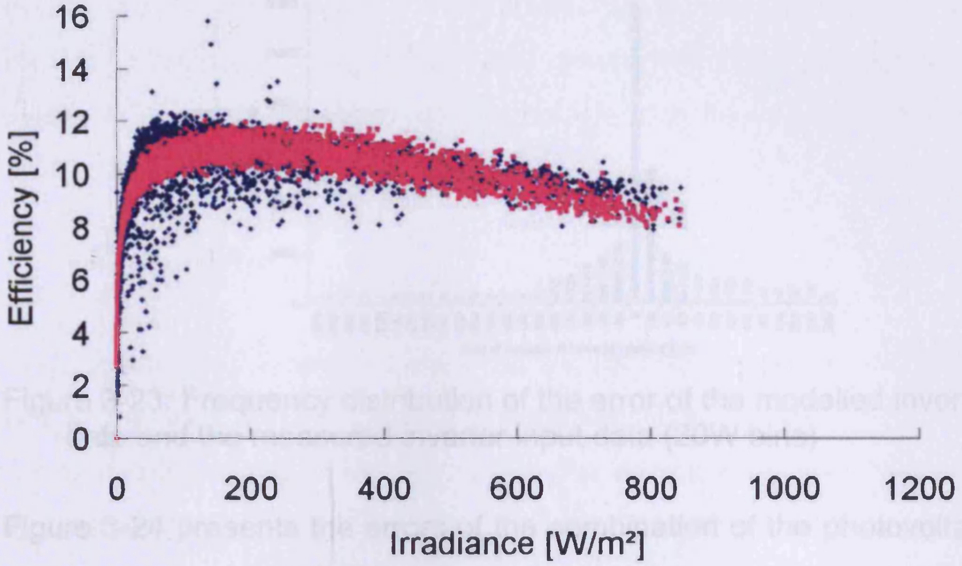


Figure 3-21: Comparison of measured efficiency curve (blue dots, one year of hourly averaged data) and modelled efficiency curve (red dots, one year of 5 minute data)

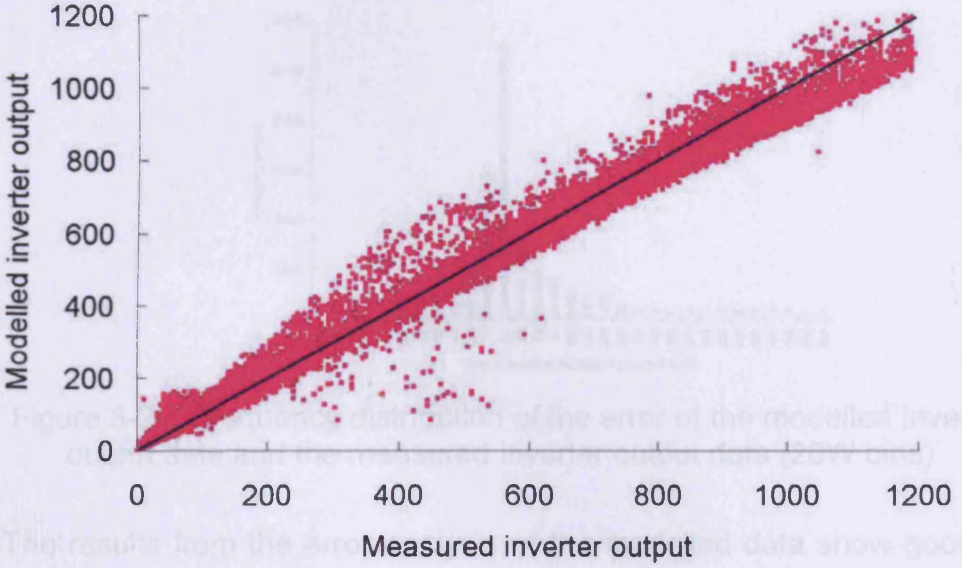


Figure 3-22: Comparison of measured and modelled 5 minute inverter output of one year of data (blue line presents an ideal model)

The comparison of one year of modelled data and one year of recorded data with the monitoring system (using electrical meters) is shown in Figure 3-23. The analysis revealed that 87% of the errors are below ±40W and 95% are in the range of ±60W. The frequency distribution also shows that the majority of the errors is ±100W.

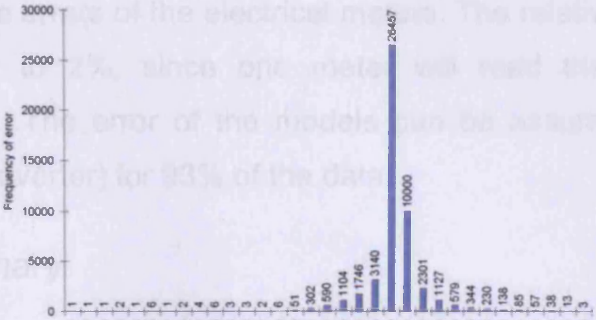


Figure 3-23: Frequency distribution of the error of the modelled inverter input data and the measured inverter input data (20W bins)

Figure 3-24 presents the errors of the combination of the photovoltaic model and the inverter model. Due to the additional error, introduced by the second model, the number of errors in the range of ±60W has been reduced to 93%. It can be concluded, that the model overestimates the inverter output.

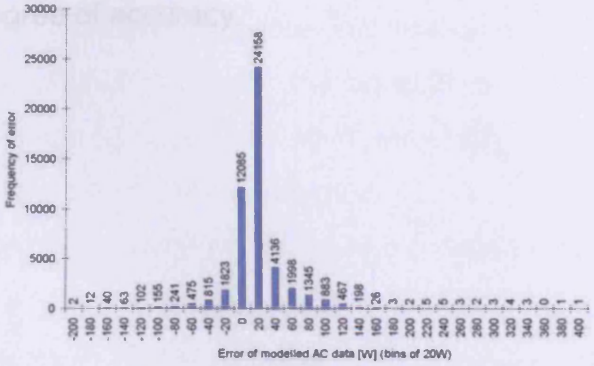


Figure 3-24: Frequency distribution of the error of the modelled inverter output data and the measured inverter output data (20W bins)

The results from the error analysis of the modelled data show good results. Only 7% of the data have an error greater than 60W. These errors occurred when the irradiance changes dramatically. In this case, the inverter disconnects from the grid and the MPP tracker has to find a new optimum. This can take several minutes, in this period the inverter does not convert the energy, supplied by the photovoltaic array. The models are not able to reproduce this characteristic and faulty data is produced.

When simulated photovoltaic data is used (during the periods with daylight) in the energy consumption analysis, the error of the entire monitoring system could be obtained by adding the error of the two models (DC output and AC output) and to the errors of the electrical meters. The relative error of the two meters amounts to 2%, since one meter will read the value zero, as explained above. The error of the models can be assumed to be ca. 5% (60W of 1100W inverter) for 93% of the data.

3.5. Summary

This chapter has presented the physical and socio-economic characteristics of the dwellings and the location of each site within the UK.

It has described the model applied to the erroneous photovoltaic data. This successful correction of the PV-data was essential to the outcome of this research since this data was required for the calculation of the consumption data of the dwellings.

The last part of this chapter described the outcome of the error analysis of the simulated and the monitored data. It can be concluded that the data shows a good degree of accuracy.

4. Occupant surveys in UK social housing

4.1. Introduction

This chapter deals with the results from the occupant survey conducted in 46 of the 73 monitored households belonging to the social housing. The characterisation of the occupants, their electric energy usage pattern and the possession of electrical appliances is described in detail. Additionally an evaluation of the results with an estimation of the energy consumption based on the survey data was realised.

4.2. Methodology

The aim of this survey was to link the obtained electric energy consumption data to the number of occupants and the electric appliances present in the monitored dwellings. Therefore a questionnaire (see appendix C), consisting of 25 questions, was designed to obtain information on the:

- Number of tenants living in the household
- Tenants age (grouped into adult and child)
- Ownership of selected appliances
- Frequency and duration of use of the appliances
- Times of use of the appliances
- Occupancy in the household
- Type of fuel used for space heating, cooking and domestic hot water

One occupant of each dwelling was surveyed (by the author in 2005) face to face and the interview took around 10 minutes. When possible, the corresponding housing association was involved to inform the tenants about the interview. In order to survey the working and the non-working occupants, each site was visited at least twice at different times of the day. To ensure the cooperation of the participants of the survey, it was made clear, that the results are treated confidentially and would only be used for scientific purposes. The conduction of the survey was possible because of the involvement of EETS in the Photovoltaic Domestic Field Trial. Due to this fact, the housing associations agreed on the investigation and the resulting disturbance of the privacy of the occupants. Within the sample there is a very small number of cases where the results of the occupants survey can not be linked entirely to the obtained monitoring data. This occurred, for example, when the occupants moved into the flat during the monitoring or moved out before the monitoring was finished.

Some of the statistics referred to in this chapter are obtained only in England, however, the monitoring took place also in Wales and Northern Ireland.

4.3. The sample

4.3.1. Classification in terms of socio-economical aspects

It was known that the surveyed occupants belong to the social housing sector and therefore to a certain social class. However, it was not known to which social class the tenants from Dartington belong. In order to answer this question and to classify the sites from the social housing sector more accurately, the data source ACORN has been used [Acorn, 2006] [Upmystreet, 2006].

The desired information was obtained from the postcode of the corresponding area. ACORN is a consumer targeting tool which combines geography with demographics and lifestyle information. There are 56 types of lifestyles, beginning with "wealthy mature professional, large houses" (type 1) and ending with "multi ethnic crowded flats" (type 56). It is intended that this information gives simply a general and additional overview, as the ACORN system has not been designed for scientific purposes.

The occupant survey was undertaken in the sector of social housing. According to the ACORN classification, "family income" and "education" in the Newcastle dwellings (lifestyle type 51) is to be considered as "very low". The Llanelli (lifestyle type 43) and the Nottingham (lifestyle type 45) households are considered in the "family income" category as "low". The people living in this area are classified as "low" in the "education" category. The postcode area of the Derry site, located in Northern Ireland, is not included in the ACORN system.

The households in Dartington (lifestyle type 7) do not belong to the social housing sector. These people can be considered as "medium" in the "family income” category as well as in the “education” category. The fact that the Dartington dwellings are owner-occupied, and the indications from the ACORN system, justifies the separation of this data from the otherwise “pure” social housing sector energy consumption data. The Dartington data has been used for site-specific profiles, annual energy consumption analysis and for household-specific investigations, it has not been integrated into the overall social housing profiles. The following sections therefore exclude the Dartington survey results. There is a detailed description of the dwellings and the ownership level of appliances in section 5.5.1, where the site-specific findings from the energy monitoring are presented. The sample size of Dartington, where 6 houses were surveyed, is too low for a separate investigation.

4.3.2. Composition of the households and families

The following section deals with the establishment of the composition of the surveyed households. The results were compared with the ′Social Trends′ report from National Statistics [National Statistics, 2007].

Table 4-1 shows the obtained number of persons per household and the national average. With a value of 33%, the present study has the highest proportion of one person households. The UK average shows a higher percentage of two person households with 35% [National Statistics, 2007]. The average household size in the UK amounts to 2.4 persons. This value is very close to the 2.6 persons per household obtained during the survey. According to this comparison, the sample shows similar characteristics to the national average, regarding the number of persons living in each dwelling.

Table 4-1: Comparison of the composition of households in the UK [National Statistics, 2007] and the present investigation

Number of persons in the household	**1**	**2**	**3**	**4**	**5**	**6 or more**
Proportion [%] [National Statistics, 2007]	29	35	16	14	5	2
Proportion [%] (present study)	33	26	15	15	7	4

Figure 4-1 gives a more detailed view on the composition of the families in the households. There are a high proportion of lone parents in this sample with a value of 28%, the UK average of this figure amounts to 10% [National Statistics, 2007]. Also the proportion of couples, 15% in the present study, differs from the average of 29%. Comparing these more detailed results, the difference in the composition of the households in the social housing sector from the national average can be realised.

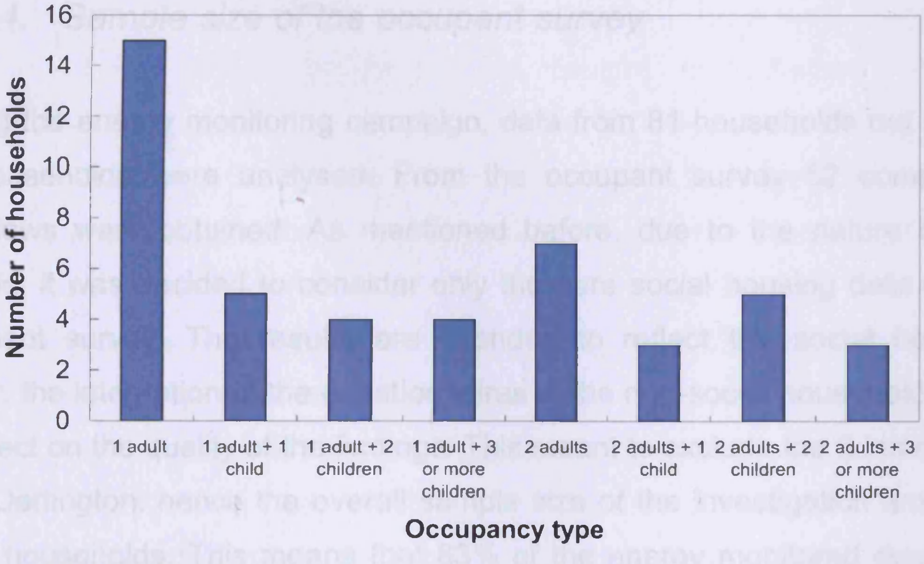


Figure 4-1: Composition of the occupants within the interviewed households obtained during the survey

The housing stock of the United Kingdom consists of 24.7 million households [National Statistics, 2004]. Around 20% of these dwellings can be considered as part of social housing and, using the UK average of 2.4 occupants per dwelling, it can be estimated that this sector of UK society is represented by 12 million people [National Statistics, 2001a] [National Statistics, 2007].

These figures stress the large influence on overall UK domestic electrical energy consumption of this section of society. The behaviour patterns of people living in the social housing sector usually differ slightly from the average pattern; one indicator of this discrepancy is the rate of employment. Statistics show that among people from the social housing sector 33% work, whereas the average of employment in the non-social housing sector (renting from private and owner-occupied) is 60% (see table 4-2).

Table 4-2: Tenure by economic status [National Statistics, 2001a]

	working	**unemployed**	**retired**	**other inactive**[5]
rented from social sector [%]	33	5	35	28
all tenures – UK average [%]	60	2	28	10

4.4. Sample size of the occupant survey

During the energy monitoring campaign, data from 81 households out of the 97 households were analysed. From the occupant survey 52 completed interviews were obtained. As mentioned before, due to the nature of the sample, it was decided to consider only the pure social housing data of the occupant survey. The results are intended to reflect the social housing sector, the integration of the questionnaires of the non-social households had an effect on the quality of the findings. This meant to exclude the 6 interviews from Dartington, hence the overall sample size of the investigation amounts to 46 households. This means that 63% of the energy monitored dwellings were surveyed.

The breakdown of the coverage of the occupant survey for each site is the following: Llanelli 67%, Newcastle 60%, Nottingham 57% and Derry 71%.

---

[5] Includes students, those looking after home or family and long term sick or disabled, who are not working or looking for work.

4.5. Results

4.5.1. Ownership level of appliances

The ownership level of electrical appliances describes the number of these appliances in the households. The results are shown in table 4-3 as a decimal value (0.61 means that 61% of the household own this appliances), and values over one indicate an ownership of more than one of those appliances in the flat. In total 17 appliances were considered in the interview, those assumed to be the most common in a typical British household. The UK averages are here considered to be the results from the Lower Carbon Futures study [ECI, 2000b]. This study presents policy solutions to the problem of domestic carbon emissions.

However, it does not cover the entire set of appliances, hence the missing data is filled with the Mansouri study [Mansouri et al., 1996]. The ECI study was chosen over the Mansouri study since the later one was derived from a sample with a relatively high household income. The value for the computers was obtained from the General Household Survey [National Statistics, 2002].

There were no UK data available for the ownership level of toasters and HIFI (HIFI: defined as not portable device), nevertheless they are included in the analysis. The results from the ECI study and the Mansouri study did not include DVD players, hence the results from the present study (DVD/Video players) could only be compared with the number of video players.

The term refrigeration in table 4-3 the column 1 describes the sum of the appliances fridge freezer, fridge and freezer.

Column 3 presents the resulting value of the Lower Carbon Futures study and the Mansouri study which is then compared to the present study.

Column 2 in Table 4-3 presents the results from the survey in the social housing. The highest level of ownership was in the TV section, on average, each dwelling possesses more than 2 TV's. This is more than twice as much as can be seen from the UK average. There is also a far higher possession of DVD/Video players. The next evident discrepancy, and probably the most influential on the household consumption, is dishwasher possession, only 12% of the households own this appliance, whereas the UK average shows an average of 22%.

Another, smaller difference can also be seen in the comparison of the computers per household (~30% less in the social housing).
The number of vacuum cleaners is below 1 since a wooden floor is present in some surveyed dwellings.

Table 4-3: The comparison of the results of the present study and different UK studies regarding the ownership levels of appliances [ECI, 2000b] [Mansouri et al., 1996]

appliance type	2005 (present study)	Resulting	1997 [ECI, 2000b]	1994 [Mansouri et al., 1996]
Fridge freezer	0.65	0.62	0.62	
Fridge	0.38	0.43	0.43	
Freezer	0.33	0.41	0.41	
Refrigeration	1.37	1.46	1.46	1.77
TV	2.06	0.98	0.98	1.60 (Colour)
DVD/video player	1.65	0.82 (only Video)	0.82 (only Video)	0.76 (only Video)
Computer	0.37	0.54		-
HI-FI	0.79			-
Electric kettle	0.92	0.90		0.90
Toaster	0.69			-
Microwave	0.84	0.77	0.77	0.74
Washing machine	0.96	0.92	0.92	0.93
Dishwasher	0.12	0.22	0.22	0.43
Tumble dryer	0.56	0.50	0.50	0.53
Vacuum cleaner	0.98	1.00		1.00
Iron	0.79	1.00		1.00

4.5.2. Appliances usage frequency and duration

This part of the survey investigation deals with the question, how often and how long the electric appliances were used in the surveyed households. Here only the occupant driven devices were considered, thermostat driven (refrigeration) are generally less affected by the behaviour of the people (door opening, content and room temperature) in the household. There were two kinds of appliances investigated, the ones that are initialised and carry out a cycle automatically (washing machine, toaster) and the ones that are only in an "on" status when the occupant is using it (iron, TV). Thus, the survey results are separated into hours per day for the first group and usage per day for the second group.

During the interviews the occupants were asked to state the difference of usage of certain appliances between weekend and weekday, this excluded washing machine, tumble dryer, vacuum cleaner and iron.

Several occupants expressed the usage in a range, for example "3 to 4 times a day", this answer was considered as 3.5 times a day. The response "on all day", occurring for example in the TV section was rated as 16 hours. Most households posses more than one TV, hence a usage time of more than 24 hours was possible, there was no separate analyse for the second or the third TV carried out.

The duration of usage and the usage frequency of the appliances was analysed for the households where the appliances were present (table 4-4, column 2 and 3) and for all households (column 4 and 5).

The most unexpected result from the survey, see table 4-4, is the duration of TV usage. This value of nearly 10 hours per day on average is far more than the obtained 5.17 hours from the Mansouri study. Certainly, the life style of the occupants is an important factor in this behaviour pattern.

The usage duration for computers was influenced by an occupant who stated they used it 16 hours a day, without this household the result would be ~30% less. The usage of the washing machine amounts to around once a day, this is slightly higher than the findings from Mansouri. This study estimates the wash cycles per person per week of 1.3 to 2.6. Using the average of this range and applying the average number of 2.4 persons per household [National Statistics, 2007], a daily usage of 0.67 can be assumed.

During the survey it has been realised that the usage of the tumble dryer is strongly related to the weather conditions. It is reasonable to use only half of the obtained usage frequency, considering a 50% probability of drying the clothes outside, when the annual energy consumption of this appliance is estimated.

Table 4-4: Usage frequency and usage duration of the appliances obtained during the occupant survey

appliance type	**Households where appliances is present**		**All households**	
	Weekday	**Weekend**	**Weekday**	**Weekend**
TV (h/day)	9.73	9.77	9.51	9.55
DVD player/video (movies per day)	0.85	1.50	0.79	1.39
Computer (h/day)	3.32	2.79	1.08	0.91
hi-fi (h/day)	3.77	4.35	2.54	2.93
electric kettle (usage/day)	8.87	9.74	8.10	8.89
Toaster (usage/day)	0.77	0.80	0.54	0.56
Microwave (usage/day)	1.29	1.30	1.12	1.13
washing machine (usage/day)	1.12	1.12	1.07	1.07
Dishwasher (usage/day)	1.00	1.00	0.09	0.09
tumble dryer (usage/day)	1.20	1.25	0.65	0.65
vacuum cleaner (usage/day)	0.60	0.60	0.55	0.55
Iron (usage/day)	0.64	0.64	0.52	0.52

The employment of information obtained from an occupant survey for a prediction of energy consumption remains a rough estimation. The probability that the interview occupants overestimate or underestimate the usage is relatively high.

Another factor is, how truthfully has the person answered? – a household that use the vacuum cleaner only once a month will probably still answer with a higher frequency as not to appear as someone that does not take care of the flat. Sidler [Sidler, 1997] has stated:

"The conclusion is clear: it is extremely risky to rely on consumer estimates of appliance usage to determine the energy consumption of a given appliances. Nothing can replace in situ monitoring to produce accurate results."

This statement refers to the washing machine usage frequency in the Sidler study, however it could be applied to the range of all electric appliances.

In order to validate the results from the present survey, a basic calculation to obtain the daily consumption has been carried out, see table 4-5. For this estimation, the usage frequency of the tumble dryer was adopted to 0.33 (weather dependence, see above). The activity “watching a movie” in the DVD/Video section was assumed to be 90 minutes (1.5 hours).

For this calculation several data sources, marked in the table, and some estimations were applied. The result is a daily energy consumption of 4.8kWh (see table 4-5), which is a possible figure when compared with the 8.6kWh/day obtained from the monitoring campaign (see section 5.4.1 where the overall annual energy consumption of the monitored dwellings is presented). It considers that there is a part of the consumption which is used for cooking, showering, stand-by load, lighting and appliances that were not covered by the survey.

Table 4-5: The calculation of the daily consumption for selected appliances derived from the occupant survey

appliance type	Power consumption [W]	Duration [h]	Energy consumption per usage [Wh]	Usage per day (all househ.)	Daily energy consumption [Wh]
TV	100 (a)	9.52 (b)	952.35	1.00	952,3
DVD/video player	13 (a)	1.50 (c)	19.50	0.96	18,7
Computer	120 (a, including Monitor)	1.03 (b)	124.08	1.00	124,1
hi-fi	26 (a)	2.65 (b)	68.96	1.00	69,0
electric kettle	2500 I	0.03 I	83.33	8.32	693,3
Toaster	800 I	0.03 I	26.67	0.54	14,4
Microwave	800 I	0.08 I	66.67	1.12	74,7
Washing machine			1500.00 (d)	1.07	1605,0
Dishwasher			1800.00 (d)	0.09	162,0
tumble dryer			2400.00 (d)	0.33	792,0
vacuum cleaner	1500 (c)	0.17 (c)	255.00	0.55	140,3
Iron	1200 I	0.17 I	204.00	0.52	106,1
				Sum	*4751.8*

(a) adapted from Aulenback [Aulenback et al, 2001]

(b) obtained from the present study ((5*weekday value+2*weekend value)/7)

(c) estimated

(d) adapted from Sidler [Sidler, 1997]

4.5.3. Energy usage patterns and adaptation to photovoltaic installation

As mentioned in section 4.2, the behaviour pattern of the people living in the social housing differs from the average. This also leads to different patterns in the use of energy, appliances may be utilised during the day, whereas a working occupant generally uses energy in the hours after work (considering weekdays).

Table 4-6 shows the results from the survey regarding the high demanding appliances washing machine, tumble dryer and dishwasher. The majority of the responses were "no pattern". This is a remarkable fact since the houses are all equipped with photovoltaic systems and a shift of the demand would increase the economical benefit to the occupants. Certainly the housing associations have informed the occupants about the principles of photovoltaics, however according to this survey no adaptation of behaviour took place.

Table 4-6: Usage pattern of three high demanding appliances obtained during the occupant survey

Appliances	No pattern	Morning	Noon	Evening	other
Washing machine	29	5	3	4	3
Tumble dryer	16	2	2	2	3
Dishwasher	0	1	0	3	0

People buying and using renewable energy systems tend to be more conscious about energy consumption in their households. They use energy more carefully than the average. This means that in the UK, where the feed in tariffs, i.e. the payments to householders for exported electricity, for photovoltaic are low, the usage of electric appliances should ideally fall in the hours around noon to maximise the photovoltaic system output.

In the present study, the photovoltaic systems for the social sector were funded entirely by the housing associations with financial support from the DTI. The findings from an occupant survey in the monitored households, the full findings of which will be presented in chapter 5, show that there is no adaptation of the energy usage pattern. For instance, the utilisation of the washing machine was not shifted into the periods when solar energy was available. This is surprising since shifting the load into the hours around noon could have reduced the electricity bill of the tenants. Apparently the education carried out by the housing association regarding the correct usage of the available PV-energy was not sufficient.

The installation of the photovoltaic systems in Dartington has been a private initiative, and the home owners paid a certain part of the costs themselves. Still, the survey in 6 households showed no shifting of the electric load. Also here has to be established, that the information concerning the usage of PV-energy was not transferred properly.

The fact that there is no load shifting justifies the application of the obtained energy consumption data sets, since the energy usage patterns of the monitored dwellings show no usage adaption towards the times of solar energy availability.

4.6. Summary

This chapter presented the findings from the analysis of the occupant survey. It can be concluded that the composition of the surveyed households differ from statistics representing a UK average. The ownership level of appliances shows a higher value of entertainment equipment but a lower value of dishwashers.

The evaluation of the results by using the data obtained from the survey to estimate the daily energy consumption and then comparing this value with the measured daily energy consumption (presented in chapter 5) shows a good agreement.

The findings from this chapter will help to put the results from the energy monitoring campaign into context. The findings are also of use when a general characterisation of the social sector in terms of energy consumption patterns is necessary. An application in load models to refine the accuracy is possible.

5. UK wide domestic electrical energy monitoring trials

5.1. Introduction

This chapter presents the findings from an electrical energy consumption monitoring campaign carried out over a period of two years in 73 dwellings in the United Kingdom.

The first part of this chapter describes the methods which are used to characterise the electric load. The second part deals with the effect of the recording interval of the monitoring system and the problems of underestimating the peaks in the load by averaging over a certain period of time. For this, high resolution data, obtained during the present monitoring campaign was used.

In the main part of this chapter, the results from the electrical energy monitoring in the dwellings are presented, where a separation into overall results, site specific and dwelling specific results was made. The overall results are used to supply a general overview of the characteristics of electric load in the domestic sector.

It is intended that the site specific analysis gives a more detailed knowledge on the electric load in, for example, a network of flats in a building or a network of several detached houses, which is a possible configuration for a future grid structure with on-site generation.

In the last part of the electric load investigation the load demands of a selection of single dwellings are presented. Here the marked peaks and valleys in the demand are still recognisable, which is not the case in loads which are averaged over several dwellings.

5.2. Methods of the characterisation of electric load data

There are different methods in order to characterise the electric load, depending on the field in which the results are intended to be used. The following section describes the methods employed in the present study, where the emphasis is put on the integration of decentralised energy sources into the electric grid.

A common method is the derivation of load profiles which show the electric demand usually over a time period of 24 hours. Here, the daily, weekly, monthly or annual electric power data can be presented. The longer the period over which the load data is averaged, the fewer the number of peaks that will occur in the profile. The method can be used to compare demand profiles and generation profiles, which makes it possible to obtain the level of coverage by, for example, a photovoltaic generator.

The derivation of load distributions represented in histograms gives an overview of how frequently various levels of power demand occur in the data sets. Each dwelling shows a specific shape of the distribution. In the South African electricity industry this method has been used to estimate the voltage drop in the network when the electrification was extended. For each dwelling a different distribution according to the consumer load class was applied and the voltage drop between different nodes in the electric grid has been estimated [Herman, 2002]. The present study uses load distributions in order to illustrate the power demand that can be expected in a domestic dwelling, it also employs this method to show the changes in the electric load.

Another method of characterising electric load data is the presentation of energy consumption values over different time scales. Here the variation during the year and the differences between weekend days and weekdays are important findings that can be obtained from the data.

The variation in the electric demand can be derived from the load factor, which is the ratio of the mean load and the peak load occurring in the observed period. A higher load factor would represent a higher variation on the load.

5.3. The effect of the monitoring interval

Before the findings of the 5 minute data monitoring are presented in the following sections, the results of an investigation on the effect of the monitoring interval on the accuracy of the obtained data are shown. This information is significant, when the 5 minute data is used and a basic knowledge on the not captured peaks of the averaged electric load is required. For this investigation 1 minute electric consumption data of the six houses at the Llanelli site, obtained after the Domestic Field Trial study was analysed. This very high resolution monitoring took place between Friday the 29th of April 2005 and Thursday the 5th of May 2005. These dwellings employ gas for the cooker, the hob and for domestic hot water preparation. There are no dishwashers present but washing machines and tumble dryers. More detailed information on the ownership of appliances can be found in section 5.5.4.

Table 5-1 shows the results from the short term electric energy monitoring. The daily energy consumption recorded during this period varies between 17kWh and 3.52kWh. House 5 shows a daily consumption of 8.70kWh that could be expected from an average household. In house 1 on the other hand, a very high energy consumption has been monitored. The comparison of the peak loads at 1 minute and 5 minute interval shows an average discrepancy of around 1800W. The load factors decrease on the 1 minute data, the loads have more peaks than on the 5 minute interval. House 2 particularly shows this effect, where the load factors were reduced by a scale of 2.5.

The undetected power peaks are calculated by subtracting the 5 minute averaged power from the 1 minute peak load of the same period. This parameter represents which electric spikes occur on top of the load when data is recorded with a 5 minute interval.

Table 5-1: Results from the short term high resolution monitoring in Llanelli: comparison of the results of the different dwellings

Load characteristics	**house 1**	**House 2**	**House 3**	**House 4**	**House 5**	**House 6**
Energy consumption in the corresponding period [kWh]	17.00	3.52	8.63	14.00	8.70	14.81
Mean power demand [W]	708.72	150.78	361.94	584.47	365.14	617.16
Peak load (5 min) [kW]	8.18	0.37	3.07	5.72	4.80	3.82
Peak load (1 min) [kW]	10.02	0.92	4.91	6.46	6.13	5.12
Load factor (5 min)	0.087	0.412	0.118	0.102	0.076	0.161
Load factor (1 min)	0.071	0.164	0.074	0.090	0.060	0.121
Average of the undetected power peaks [W]	213.32	41.88	146.44	134.26	164.91	160.01

Figure 5-1 shows these power peaks over the period of 7 days in the data of house 1. There are a significant number of peaks of more than 2000W. The biggest occurred on day one with more than 4500W. It can be assumed that in this period of high demand several high consuming appliances like the washing machine and the tumble dryer were in use at the same time (see figure 5-2). Possibly an electric kettle, with a relative short but high demand causing large spikes up to 3000W in the load, could have been used. The average of the undetected peaks within the monitored period amounts to 213W.

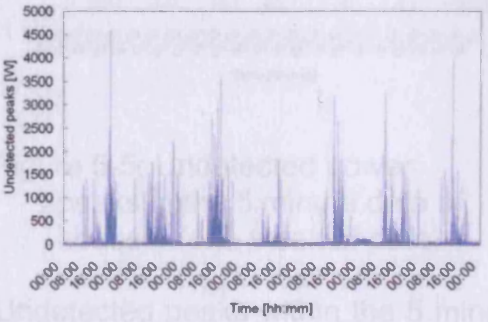


Figure 5-1: Undetected power peaks in the 5 minute data of house 1 (one week of data)

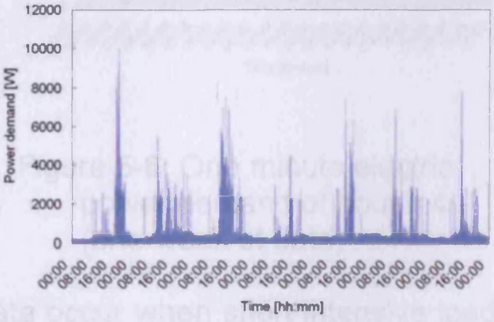
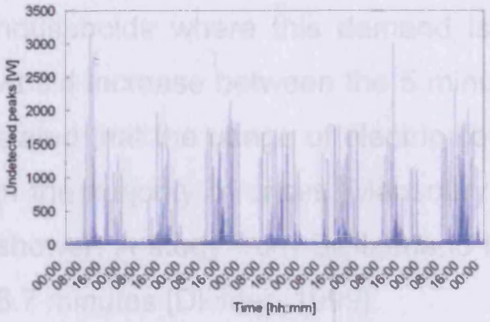


Figure 5-2: One minute electric power demand of house 1 (one week of data)

Figure 5-3 shows the undetected power peaks for house 5, which exceed the 3000W range in two instants. The majority of the peaks are ranging between 1000W and 2000W, the average of the monitored period is 165W.



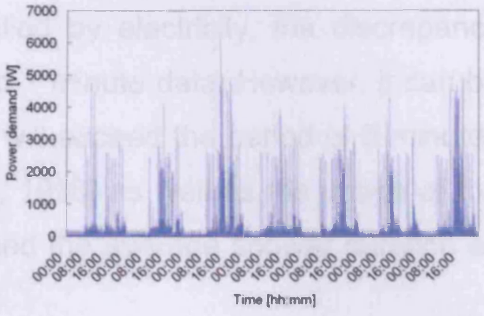
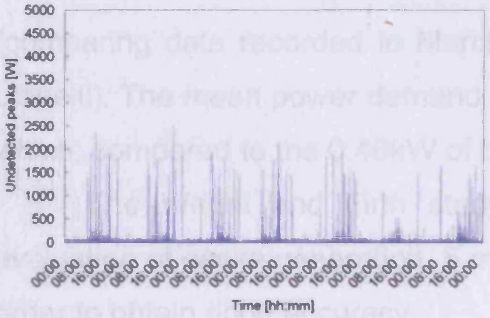


Figure 5-3: Undetected power peaks in the 5 minute data of house 5 (one week of data)

Figure 5-4: One minute electric power demand of house 5 (one week of data)

When the load factor of the 5 minute data and the 1 minute data of house 4 is compared, it can be realised that there is only a decrease of 0.012, which is the lowest in the sample. This can be explained by the fact that the base load at night is very high at ~400W. The load reaches up to 6500W (see figure 5-6) but most undetected peaks are in the range of 2000W, see figure 5-5.

The undetected power peaks, see figure 5-5, are on average 134W with maximums of up to 2500W.



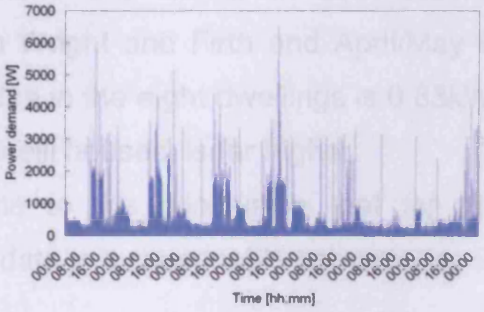


Figure 5-5: Undetected power peaks in the 5 minute data of house 4 (one week of data)

Figure 5-6: One minute electric power demand of house 4 (one week of data)

Undetected peaks within the 5 minute data occur when short intensive loads are switched in the dwelling. These loads can be created by electric kettles, toasters or the spinning phase of the washing machine. Undetected peaks also happen when appliances, which actually have a constant high load signature over a longer period, for example, the heating phase of a washing machine, start or stop working within the 5 minute recording interval.

This short term monitoring took place in dwellings where the energy consumption for cookers/hobs and showers/bath is realised by gas. In households where this demand is supplied by electricity, the discrepancy would increase between the 5 minute and 1 minute data. However, it can be stated that the usage of electric cookers will exceed the period of 5 minutes in the majority of cases [Mansoury et al., 1996] as well as the usage of the shower. A study from Switzerland identified the average shower duration as 8.7 minutes [Dichter, 1999].

According to this low sample size study it can be derived that the usage of 5 minute domestic electric demand data ignores a large number of power peaks and changes in the characteristics in the load, such as the load factor. However, the findings of this study can give some indications to which extent the results from the 5 minute monitoring are reliable.

A very similar electric energy study by Wright [Wright and Firth, 2006], carried out in eight households with a monitoring interval of 1 minute between December 2004 and September 2005 investigated the effect on the time averaging on statistics and onsite generation calculations. The obtained overall load factor and the peak demand are similar in both studies (comparing data recorded in March from Wright and Firth and April/May in Llanelli). The mean power demand recorded in the eight dwellings is 0.83kW, which, compared to the 0.46kW of the Llanelli houses, is far higher.

The Wright and Firth study came to the conclusion that for the evaluation of onsite generation, 5 minute data is a reasonable compromise in order to obtain good accuracy.

With better technology for the data transfer from the monitoring site to the monitoring computer (usually based in an office far away from the monitoring site) the monitoring interval can be increased. When the present study took place, it was common to use a telephone line and a modem, hence the data amount had to be kept small by setting the monitoring interval to only 5 minutes (as specified by the PVDFT [BRE, 1998]). Future monitoring studies can use a faster (broad band) internet connection, therefore the data transfer is not an issue anymore and this makes it possible to increase the monitoring interval.

In order to see the real peaks in the electric load data, the monitoring interval has to be set to, for example, 1 second. Only a very high recording interval ensures that all peaks are captured. However this requires a very expensive and sophisticated monitoring system. It is also necessary to define the purpose of the data, as explained above, the usage of 5 minute data for the present study is reasonable.

5.4. Overall results

5.4.1. Load profiles

This section presents results which are exclusively obtained from the dwellings within the social housing sector. This separation has been carried out in order to present pure results regarding this sector. The findings from Dartington, the only site with owner occupied houses is presented in detail in the next section where site specific analysis is carried out. Also dwellings of the social housing sector where long periods of periods of no occupancy have been realised, were excluded from this investigation.

The analysis for this section is based on the monthly averaged 24 hour profiles (5 minute data), which can only give a general idea on how energy is consumed. On these averaged load profiles the characteristic spikes of a daily profile (switching a kettle or a toaster) are missing. However, if for computer modelling purposes a load profile, presenting the average of a large number dwellings is required, the present results are a good data base.

To understand the range of electricity demand, the averaged daily winter (January) and summer (July) profiles for weekday and weekend days, normalised for floor area, are presented in figures 5-7 to 5-10.

The profiles are normalised to the floor area, since this dwelling characteristic is a constant, where the occupancy may change.

The range encompassed by the deviation bars is plus and minus one standard deviation from the mean value at that point. This means that 68.3% of the data points are represented within this band.

The base load of the demand in the four figures occurs overnight, and is mainly from appliances in stand-by mode and appliances driven by a thermostat e.g. refrigerator. This base load ranges between 0W/m^2-6W/m^2. The figures show that there is not a significant difference in terms of base load between summer/winter and weekend/weekday. The main difference between the weekend and weekday profile is the period between 09:00 and 16:00, where the weekend profile shows a higher demand due to higher occupancy.

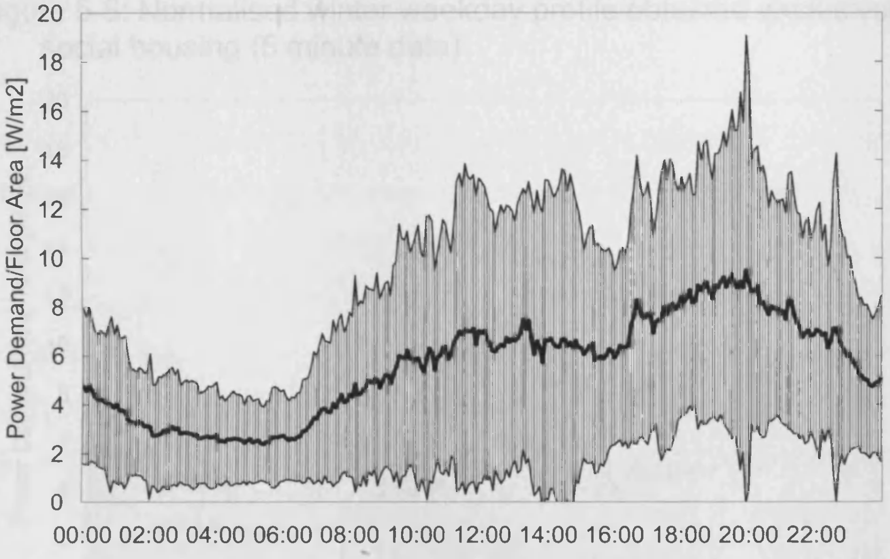


Figure 5-7: Normalised winter weekend profile obtained exclusively in the social housing (5 minute data)

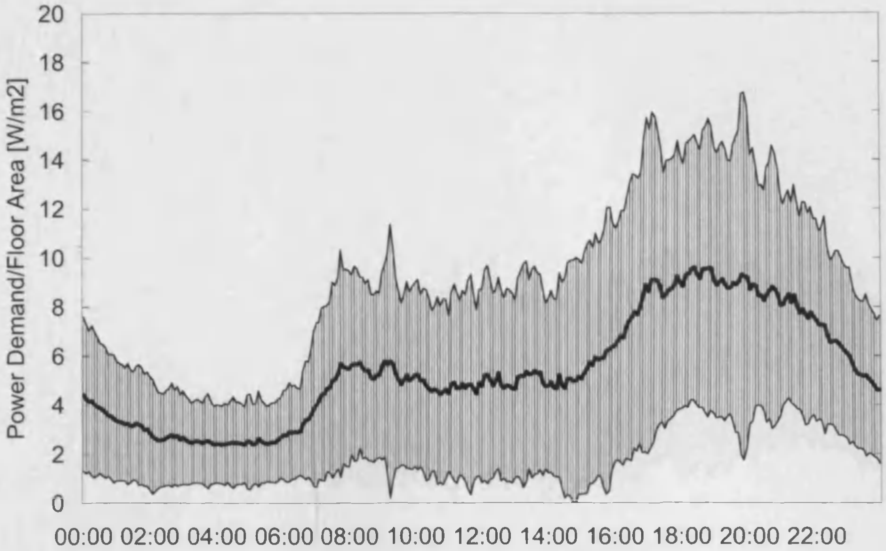


Figure 5-8: Normalised winter weekday profile obtained exclusively in the social housing (5 minute data)

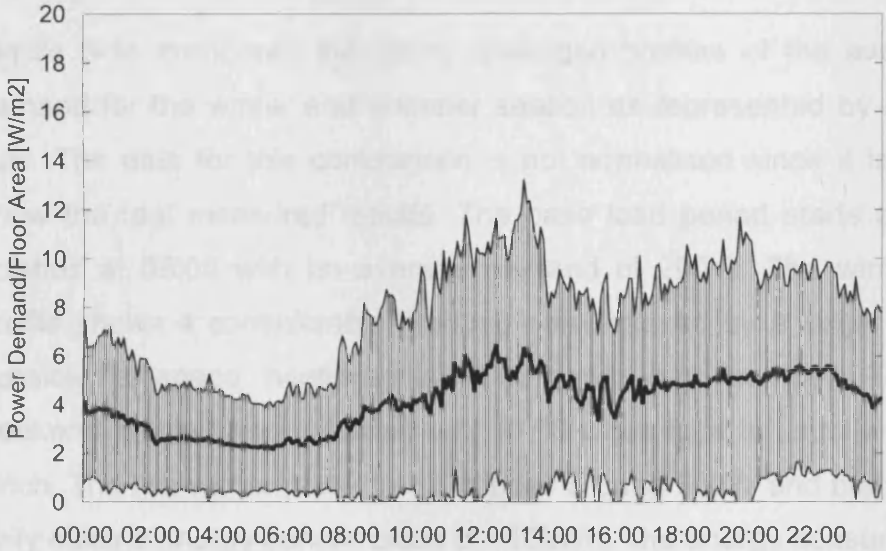


Figure 5-9: Normalised summer weekend profile of obtained exclusively in the social housing (5 minute data)

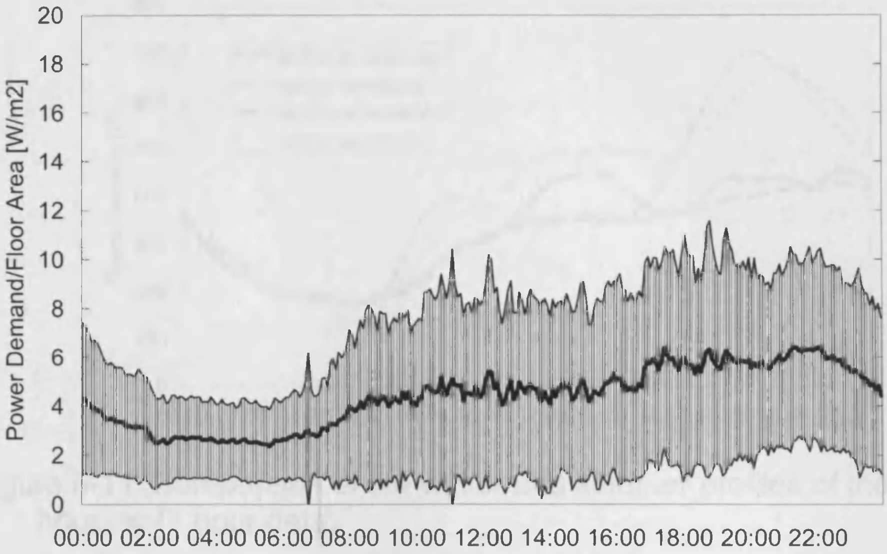


Figure 5-10: Normalised summer weekday profile obtained exclusively in the social housing (5 minute data)

Figure 5-11 compares the hourly averaged profiles of the average power demand for the winter and summer season as represented by January and July. The data for this comparison is not normalised since it is suppose to show the real measured results. The base load period starts at 03:00 and finishes at 06:00 with an average demand of 200W. The winter weekday profile shows a considerable morning peak caused by a larger lighting and possibly a space heating-related demand (e.g. pumps). The summer weekend profile has a peak around 13:00 when food is usually prepared for lunch. The two winter power profiles peak around 700W and both represent a daily electric energy consumption of ~10kWh. The energy consumption of the summer profiles amounts to ~8kWh per day with an evening peak around 450W.

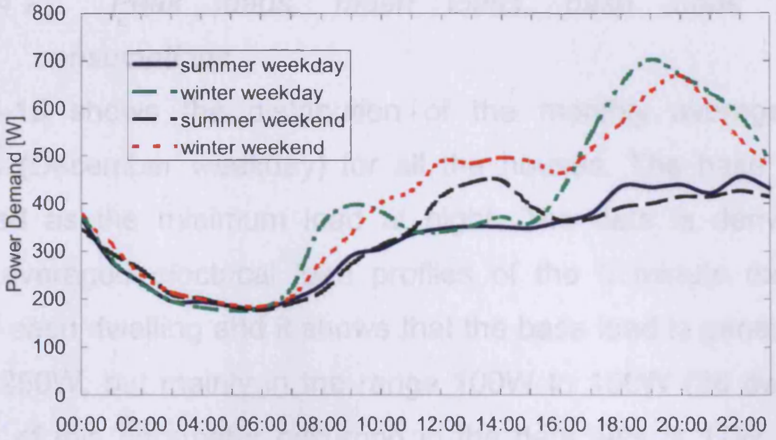


Figure 5-11: Comparison of the winter and summer profiles of the social housing (1 hour data)

Figure 5-12 presents a comparison of the profiles obtained by this study for the social sector and the profiles recorded by the Electricity Association [EA, 1998], here considered to represent the UK average. The figure shows that the period from midnight until 6:00 is very similar; including the base load. Evident is the missing morning peak in the summer weekday profile of the social housing data. Unfortunately nothing is known about the ownership level of appliances, the proportion of electrical space heating or electric cooking within the Electricity Association records, so the main conclusion that can be drawn from the comparison of these two data sets is that they exhibit very similar daily profiles shapes, despite their differing behaviour patterns.

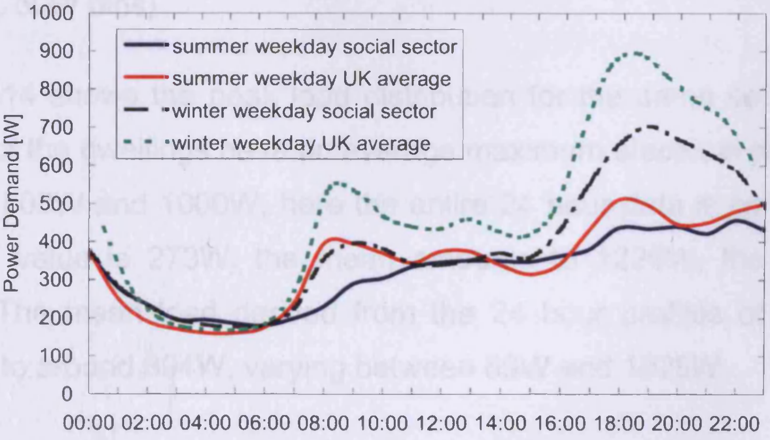


Figure 5-12: Comparison of the UK average profiles and the profiles of the present study (1 hour data)

5.4.2. Peak loads, mean loads, base loads and energy consumptions

Figure 5-13 shows the distribution of the monthly average base load demands (December weekday) for all the houses. The base load is here considered as the minimum load at night. The data is derived from the monthly averaged electrical load profiles of the 5 minute data (00:00 to 07:00) of each dwelling and it shows that the base load is generally between 0W and 250W, but mainly in the range 100W to 150W (26 dwellings). The minimum of this parameter occurring in the data sets is 17W, the mean is 131W and the maximum amounts to 659W.

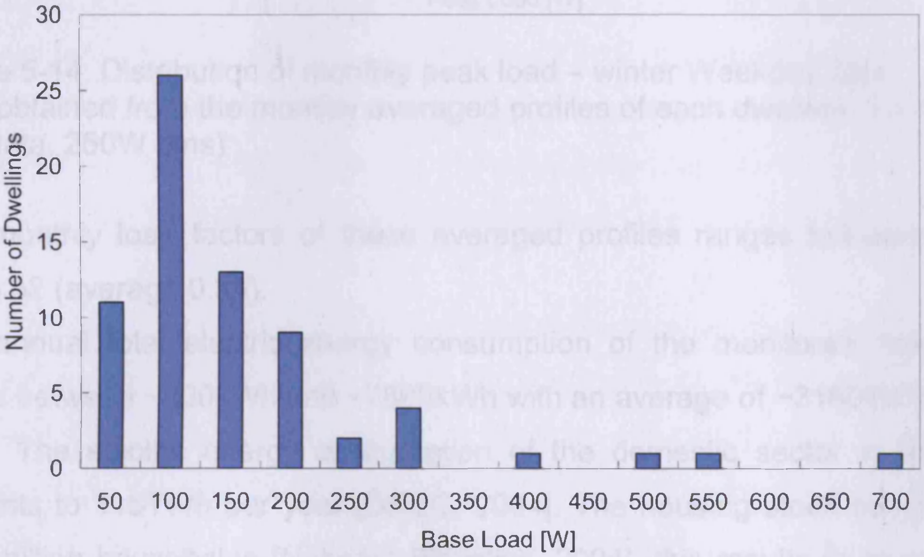


Figure 5-13: Distribution of monthly base load – winter weekday data (obtained from the monthly averaged profiles of each dwelling, 5 minute data, 50W bins)

Figure 5-14 shows the peak load distribution for the same set of data. The majority of the dwellings have an average maximum electrical power demand between 500W and 1000W, here the entire 24 hour data is considered. The minimum value is 273W, the mean amounts to 1226W, the maximum is 3978W. The mean load derived from the 24 hour profiles of the data set amounts to around 394W, varying between 89W and 1025W.

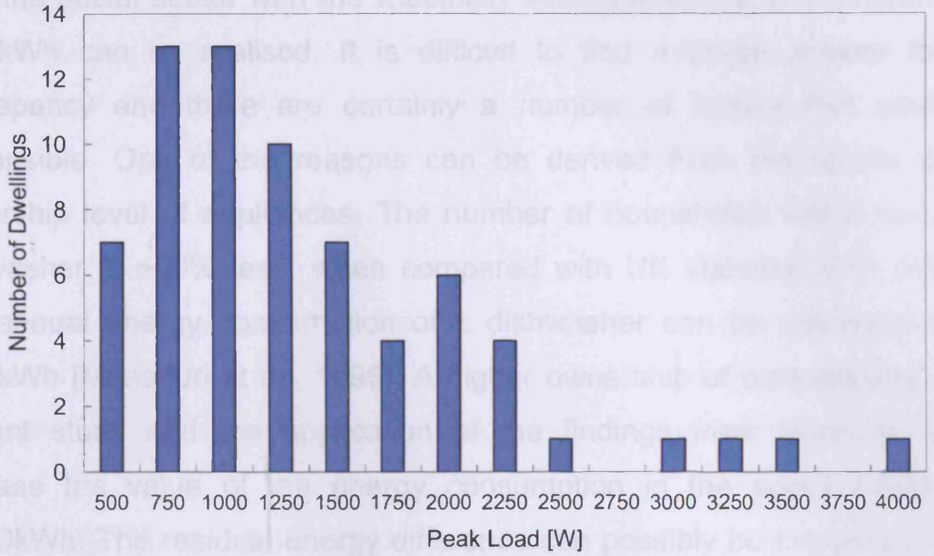


Figure 5-14: Distribution of monthly peak load – winter Weekday data (obtained from the monthly averaged profiles of each dwelling, 5 minute data, 250W bins)

The monthly load factors of these averaged profiles ranges between 0.15 and 0.52 (average 0.34).

The annual total electric energy consumption of the monitored dwellings varies between ~800kWh and ~7800kWh with an average of ~3160kWh.

The electric energy consumption of the domestic sector in the UK amounts to 115TWh per year [DECC, 2004]. The housing stock consists of 24.7 million households [National Statistics, 2004], this results in an annual consumption of around 4650kWh per dwelling. However, this also includes the houses which employ electricity for heating. The Electricity Association [Stokes, 2005] reported a consumption of 3782kWh/year per household, excluding electric heating (unrestricted tariff). National Statistics [National Statistics, 2001b] published an annual consumption of 3489kWh (cooking, lighting and appliances) and 2907kWh (lighting and appliances). The study of Mansouri [Mansouri et al., 1996] estimated the annual consumption for a dwelling excluding electrical heating but with an electric cooker to be 4460kWh/year (based on the obtained ownership level during the study and assuming all appliances are present).

For the present study, the value of the Electricity Association is used as a comparison. This 3782kWh is a measured figure over a large number of households, as oppose to the estimated figures from National Statistics and the Mansouri study. Comparing the average annual energy consumption from the social sector with the Electricity Association result, a difference of ~600kWh can be realised. It is difficult to find a single answer for the discrepancy and there are certainly a number of factors that could be responsible. One of the reasons can be derived from the results of the ownership level of appliances. The number of households which posses a dishwasher is ~50% less, when compared with UK statistics [ECI, 2000a]. The annual energy consumption of a dishwasher can be estimated to be ~570kWh [Mansouri et al., 1996]. A higher ownership of dishwashers in the present study and the application of the findings from Mansouri would increase the value of the energy consumption in the social housing to ~3550kWh. The residual energy difference can possibly be explained by the differing proportion of electric cooking and DHW preparing within the two samples. There are variations in the consumption between the five sites. The differences in consumption and the responsible factors are explained in detail in the next section where site specific results are investigated.

The conclusion drawn from the findings of the load profile study (see figure 5-12) in the social housing sector and the integration of the results from the survey in the social housing sector is that the occupants show a different energy usage pattern (see chapter 4) when compared with the UK average, however as a first estimation a standard approach from the non-social housing will be sufficient. The load profiles from the social housing exhibit a similar shape to profiles obtained from a sample where all social levels are present.

From the parameters annual average of the monthly peak loads and the annual energy consumption a relationship has been derived from the monitoring data. This peak load represents the average of the highest values of each month of each dwelling. This peak load is derived from measured data and then averaged over the 12 month. The results are shown in figure 5-15. These peak load values can occur in a dwelling, oppose to the values shown in figure 5-14. The values from figure 5-14 are based on the averaged profiles and therefore they can be used for a more generalised estimation in conjunction with the monthly average 24 hour profiles from figure 5-12.

The formula, derived from the equation of the linear trendline of figure 5-15, can be used to calculate the peak load from the given annual energy consumption of the dwelling:

peak load=(annual energy consumption/0.4)-1143.3 (5-1)

This linear model shows an error of 2483W for this peak load calculation. This error is calculated by averaging the absolute errors derived from the subtraction of the value of the linear model from the measured values.

Another relationship has been derived from the values of the monthly base load and the annual consumption (see figure 5-16). The values of the base load are the same values used for figure 5-13. These are values for an average winter day, however it can be seen from figure 5-11 that the base load remains similar when comparing summer and winter profiles.

The formula, derived from the equation of the linear trendline of figure 5-16, can be used to calculate the base load from the given annual energy consumption of the dwelling:

base load=(annual energy consumption/9.69)-191,35 (5-2)

This linear model shows an error of 89W for this calculation. The error is calculated by averaging the absolute errors derived from the subtraction of the value of the linear model from the measured values.

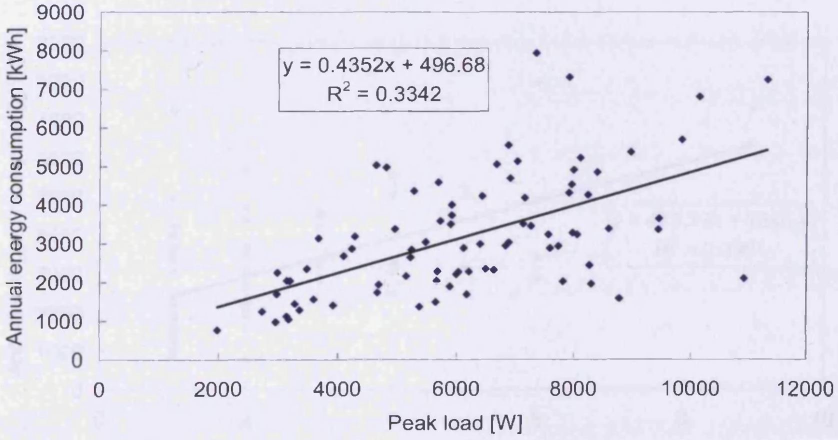


Figure 5-15: The relationship between the peak load (one data point per dwelling represents the average of the highest load values of each month) the annual energy consumption

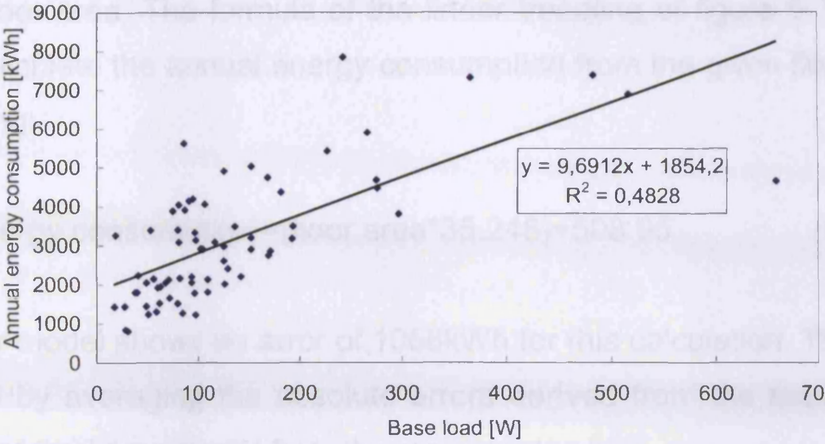


Figure 5-16: The relationship between the base load (one data point per dwelling represents the base load of an average winter day) and the annual energy consumption

Figure 5-17 shows the relationship between the annual energy consumption and the number of tenants. The formula of the linear trendline of figure 5-17 can be used to calculate the annual energy consumption from the given number of tenants in the dwelling:

annual energy consumption =(number of tennants*489.39)+1945.4 (5-3)

This linear model shows an error of 1017kWh for this calculation. The error is calculated by averaging the absolute errors derived from the subtraction of the value of the linear model from the measured values.

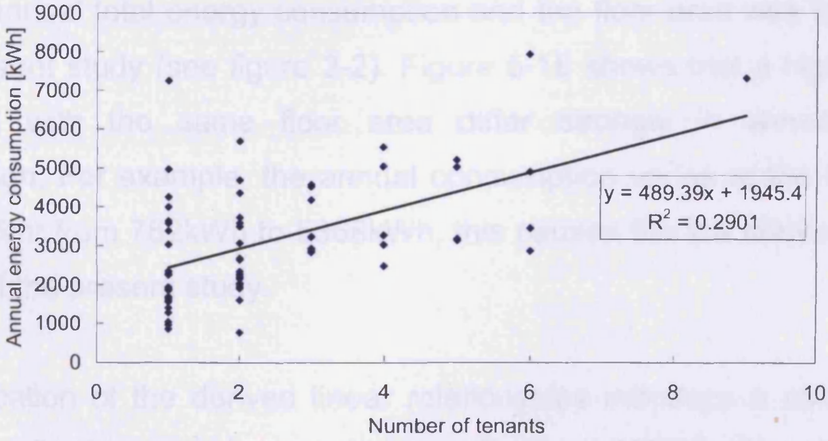


Figure 5-17: The relationship between the number of tenants (obtained during the occupant survey) and the annual energy consumption

Figure 5-18 shows the relationship between the annual energy consumption and the floor area. The formula of the linear trendline of figure 5-18 can be used to calculate the annual energy consumption from the given floor area of the dwelling:

$$\text{annual energy consumption} = (\text{floor area} * 35.248) + 508.95 \qquad (5\text{-}4)$$

This linear model shows an error of 1068kWh for this calculation. The error is calculated by averaging the absolute errors derived from the subtraction of the value of the linear model from the measured values.

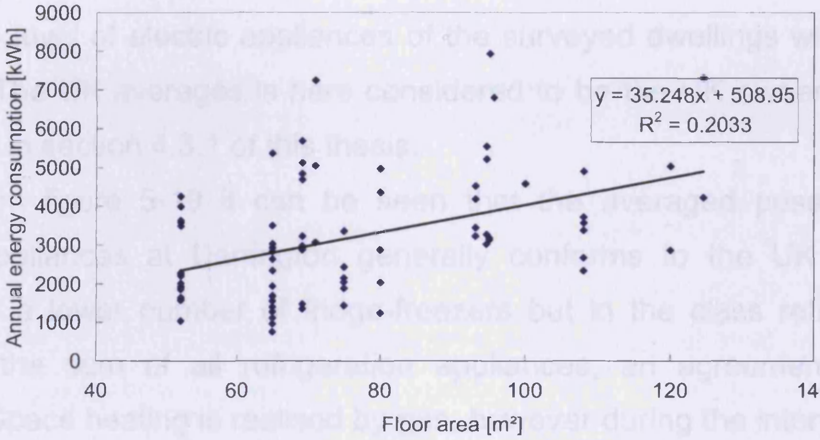


Figure 5-18: The relationship between the floor area and the annual energy consumption

In the study of Yohanis [Yohanis et al., 2007] a stronger linear relation between annual total energy consumption and the floor area was found than in the present study (see figure 2-2). Figure 5-18 shows that a high number of homes with the same floor area differ strongly in annual energy consumption. For example, the annual consumption varies at the floor area point of 65m² from 762kWh to 5368kWh, this causes the low convergence in the data of the present study.

The application of the derived linear relationships introduce a certain error into the results, for example a mean error of around 1000W when the energy consumption is calculated from the floor area, however there must be a starting point for an estimation of the demand. Usually the number of tenants and the floor area are known, and for this situation useful hints can be derived from the here obtained relationships.

5.5. Site specific results

5.5.1. Dartington

As already described in this thesis, the 8 detached houses in Dartington are owner-occupied, the people living there belong to a different socio-economic class than the other occupants in this study (see section 4.2.1).

The first step of the site specific analysis was to compare the ownership level of electric appliances of the surveyed dwellings with the UK average. The UK averages is here considered to be the UK ownership level presented in section 4.3.1 of this thesis.

From figure 5-19 it can be seen that the averaged possession of electric appliances at Dartington generally conforms to the UK average. There are a lower number of fridge-freezers but in the class refrigeration, which is the sum of all refrigeration appliances, an agreement can be realised. Space heating is realised by gas, however during the interviews two of the surveyed households stated that they use additional electrical heating in the winter month. The energy for food preparation and DHW is supplied by a mix of gas and electricity for the corresponding houses. The number of tenants varies from 1 to 6 persons per dwelling, with an average of 2.13 occupants. As already stated (see section 3.2.1), the floor area average is 101m², ranging from 80m² to 108m² (see table 5-2).

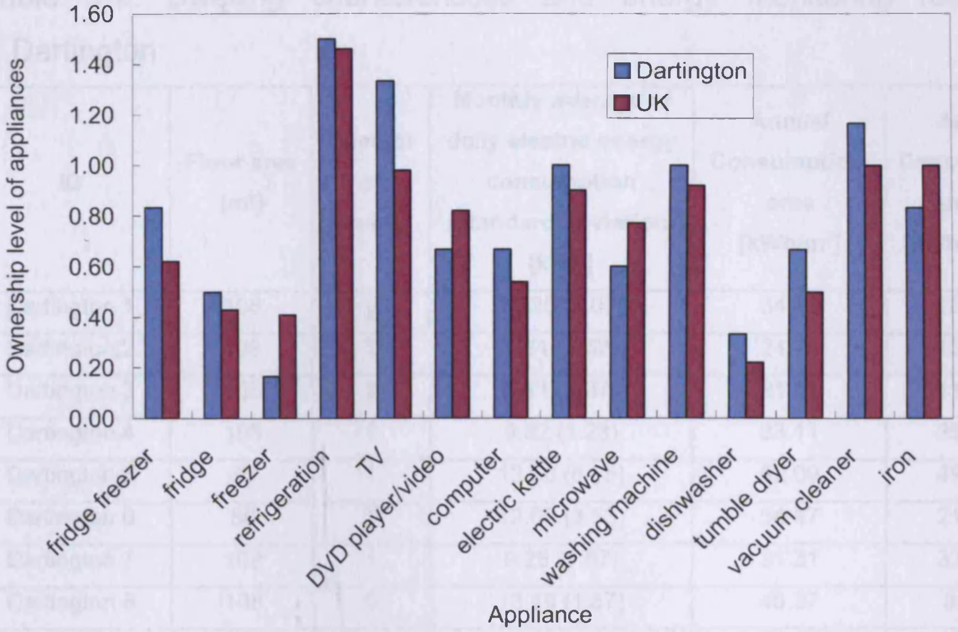


Figure 5-19: Ownership level of appliances at Dartington (obtained during the occupant survey) compared with UK averages [ECI, 2000b] [Mansouri et al., 1996]

The annual average electric energy consumption per dwelling amounts to 3752kWh. This corresponds with the findings from the EA study, reporting a consumption of 3728 kWh/year (assumed also to be a mix of gas and electricity supply for cooking and DHW). The monthly variation in consumption is illustrated in figure 5-20. A difference between the highest (July: 231kWh) and the lowest (March: 438kWh) monthly consumption of 52% can be realised.

The normalisation of the annual consumption per day, floor area and number of tenants results in 10.3 kWh/day, 37.2 kWh/m² and 1761.6 kWh/person. See table 5-2 for detailed information on each dwelling.

Table 5-2: Dwelling characteristics and energy monitoring results of Dartington

ID -	Floor area [m²]	Number of tenants	Monthly average of daily electric energy consumption (standard deviation) [kWh]	Annual Consumption/ area [kWh/m²]	Annual Consumption/ person [kWh/person]
Dartington 1	108	2	10.25 (2.07)	34.49	1862.49
Dartington 2	108	2	7.31 (3.32)	24.76	1336.97
Dartington 3	108	2	6.41 (1.37)	21.61	1167.14
Dartington 4	108	1	9.82 (1.23)	33.11	3575.89
Dartington 5	80	1	13.60 (6.05)	62.09	4967.00
Dartington 6	80	2	12.09 (3.53)	54.47	2178.80
Dartington 7	108	1	9.28 (1.67)	31.31	3381.25
Dartington 8	108	6	13.49 (1.87)	45.37	816.74
Average	*101*	*2.13*	*10.28 (2.64)*	*37.15*	*1761.59*

The analysis, carried out within this site specific results section, is based on 5 minute interval monitoring data.

The monthly averaged peak loads of the site are shown in figure 5-21. This diagram was obtained by averaging the measured maximum peak for each month for each dwelling. In order to derive the site average of this value, the average of this value over all dwellings has been derived. This is an average of 72 values (6 dwellings times 12 month).

Figure 5-21 does not show a seasonal tendency, as there is in the energy consumption, however, March is still the month which shows the highest load peaks. The mean value is 6065W, the peaks range from 5280W to 7084W, which is a variation of around 25%.

The monthly maximum peaks for each house are shown in figure 5-22. The highest peaks were identified to be in the range of 9000W to 10500W. This diagram shows the differences between the dwellings, house 8 with an all electric supply of the DHW and the cooking has an average of around 8000W (data for July to October missing). House 7 shows even higher peaks, however this dwelling was not part of the survey, therefore no information on the appliances can be made.

House 2, representing a house in which gas is used for DHW and the cooker, shows only an annual average of ~4100W of monthly mean peaks.

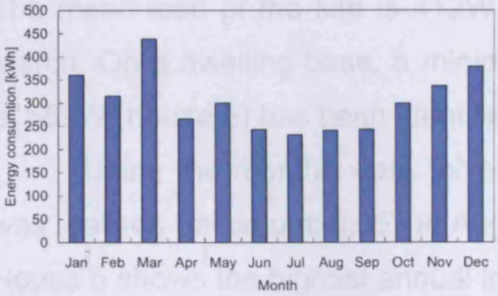


Figure 5-20: Monthly average of the energy consumption per dwelling

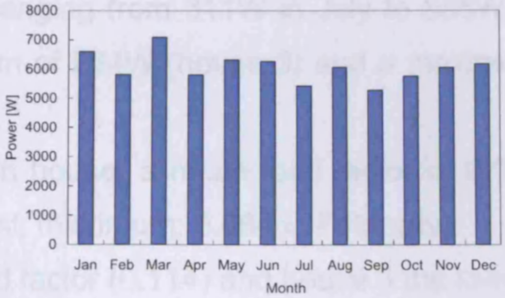


Figure 5-21: Monthly average of the peak power demand occurring in each dwelling

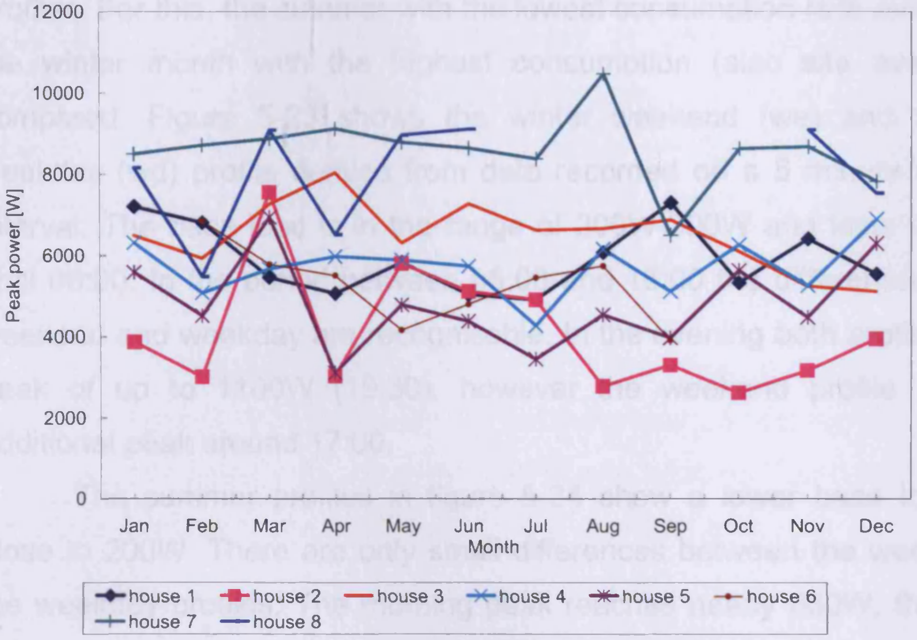


Figure 5-22: Monthly peak power (this peak load is the highest recorded value per month with in the 5 minute data) for each dwelling in Dartington

The mean load of the site is 412W, ranging from 311W in July to 535W in March. On a dwelling base, a minimum of 264W (house 3) and a maximum of 559W (house 5) has been identified.

Using the monthly data for each house, a mean load factor of 0.072 was realised (minimum: 0.057 in August, maximum: 0.084 in February). House 5 shows the highest annual load factor (0.114) and house 3 the lowest (0.042), also derived from monthly calculations. The load factor shows a tendency related to the monthly energy consumption.

The last part of the site specific analysis deals with the electric load profiles. For this, the summer with the lowest consumption (site average) and the winter month with the highest consumption (also site average) are compared. Figure 5-23 shows the winter weekend (we) and the winter weekday (wd) profile derived from data recorded on a 5 minute monitoring interval. The base load is in the range of 200W-300W and lasts from 00:00 until 06:00. In the period between 06:00 and 16:00 the differences between weekend and weekday are recognisable. In the evening both profiles show a peak of up to 1100W (19:30), however the weekend profile shows an additional peak around 17:00.

The summer profiles in figure 5-24 show a lower base load, being close to 200W. There are only small differences between the weekend and the weekday profiles. The morning peak reaches nearly 500W, the evening peaks are up to 680W.

When comparing figure 5-23 and figure 5-24, it can be concluded, that this site shows big differences in the shape of the load profiles in different months. The base load of the summer and the winter profiles shows a similar range (around 200W). As already shown in figure 5-12, there is a difference in the occupancy behaviour, resulting in a different shape of the profile, when winter and summer data are evaluated. People spend more time indoor in the winter month, where due to generally better weather conditions (higher temperature, less rain) in summer more outdoor activities are possible.

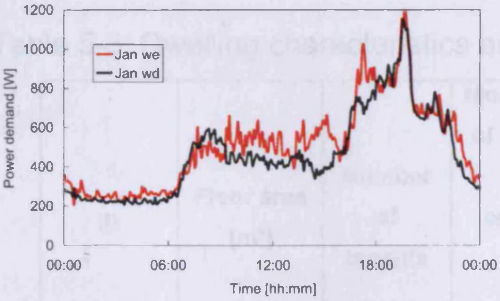


Figure 5-23: Electric load profile for a winter month in Dartington

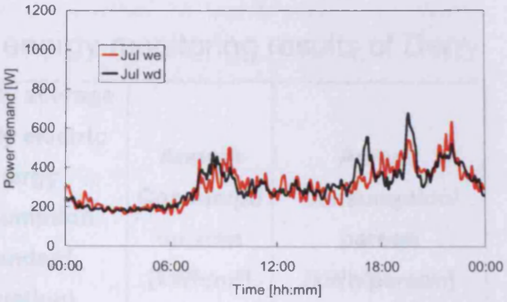


Figure 5-24: Electric load profile for a summer month in Dartington

5.5.2. *Derry*

This site monitoring in Derry contained 21 semidetached houses and bungalows. The ownership level of appliances is illustrated in figure 5-25. The biggest discrepancy can be realised in the ownership level of entertainment equipment. The results from the occupancy survey show, that there is more than twice as many TV and DVD player/Video than the UK average.

The average floor area is 85m² and the mean number of tenants is 3.86 (see table 5-3). The energy for cooking and showering is supplied by electricity, there is no electricity used for space heating. The hot water for the bath is connected to the DHW system and powered by gas.

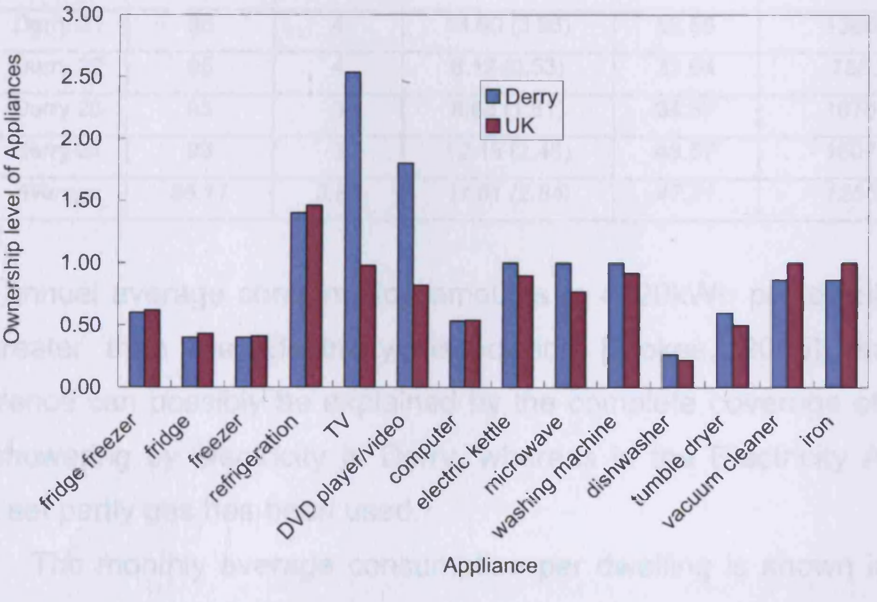


Figure 5-25: Ownership level of appliances at Derry (obtained during the occupant survey) compared with UK averages [ECI, 2000b] [Mansouri et al., 1996]

Table 5-3: Dwelling characteristics and energy monitoring results of Derry

ID	Floor area [m²]	Number of tenants	Monthly average of daily electric energy consumption (standard deviation) [kWh]	Annual Consumption/area [kWh/m²]	Annual Consumption/ person [kWh/person]
Derry 1	69	2	15.29 (4.30)	82.21	2844.54
Derry 2	69	2	12.60 (2.57)	67.75	2344.07
Derry 3	69	3	7.89 (1.77)	42.41	978.32
Derry 4	69		3.66 (1.05)	19.66	
Derry 5	69	3	8.69 (2.07)	46.71	1077.44
Derry 6	69		3.98 (1.59)	21.39	
Derry 7	95	4	8.79 (1.85)	34.55	817.20
Derry 8	95	5	14.02 (3.71)	55.14	1043.33
Derry 9	125	9	19.66 (2.55)	58.73	812.50
Derry 10	125		11.36 (3.25)	33.94	
Derry 14	96		18.28 (4.10)	71.14	
Derry 15	93	6	9.27 (5.43)	37.05	574,92
Derry 16	93	3	11.25 (2.72)	44.94	1394,71
Derry 17	69		13.77 (3.72)	74.03	
Derry 18	69	3	7.74 (0.96)	41.60	959,61
Derry 19	69		13.02 (5.23)	70.00	
Derry 20	69		8.00 (3.96)	43.03	
Derry 21	95	4	14.90 (3.98)	58.58	1385,30
Derry 22	95	4	8.12 (0.53)	31.94	755,36
Derry 23	93	3	8.68 (1.81)	34.67	1075,95
Derry 24	93	3	12.15 (2.48)	48.57	1507,18
Average	*85.11*	*3.86*	*11.01 (2.84)*	*47.21*	*1255,03*

The annual average consumption amounts to 4020kWh per dwelling, which is greater than the Electricity Association [Stokes, 2005] results. The difference can possibly be explained by the complete coverage of hot water for showering by electricity in Derry, whereas in the Electricity Association data set partly gas has been used.

The monthly average consumption per dwelling is shown in figure 5-26, it can be concluded that there is a seasonal effect, with higher figures in winter. The difference between the highest consumption in December (390kWh) and June (265kWh) with the lowest consumption is around 32%. The normalisation of the annual consumption for the day, the floor area and number of occupants gives the following results: 11.0kWh/day, 47.2kWh/m² and 1091.8kWh/person. Detailed information on each dwelling is given in table 5-3.

The monthly averages of the peak power loads for the 21 dwellings are illustrated in figure 5-27. The findings indicate that there is no seasonal tendency in the peak loads. The minimum occurs in June (~6300W) and the maximum in December (~7600W), this is a variation of around 17%.

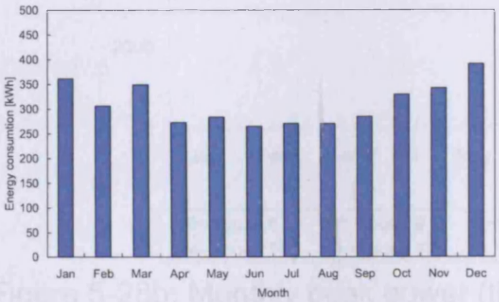


Figure 5-26: Monthly average of the energy consumption per dwelling in Derry

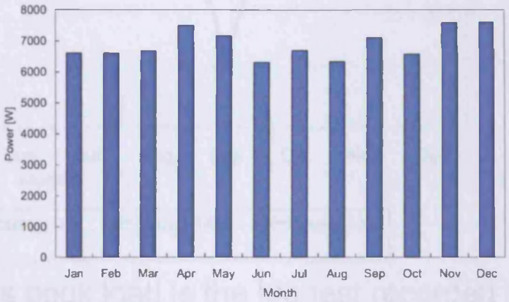


Figure 5-27: Monthly average of the peak power demand occurring in each dwelling in Derry

Figures 5-28a to 5-28c show the monthly peak for each dwelling. The maxima are in the range of 11000W to 12000W. The mean value of the monthly power peaks amounts to 7500W.

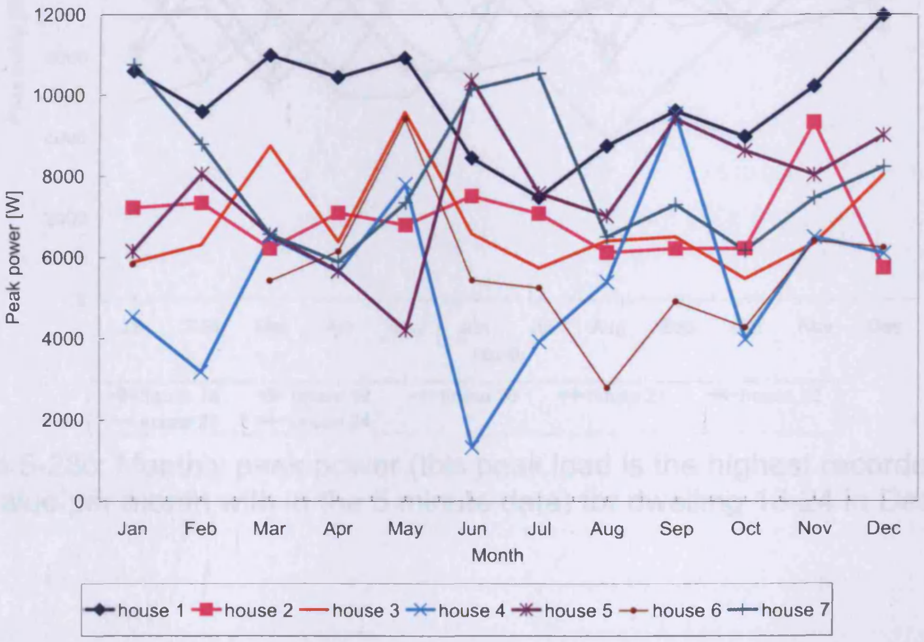


Figure 5-28a: Monthly peak power (this peak load is the highest recorded value per month with in the 5 minute data) for dwelling 1-7 in Derry

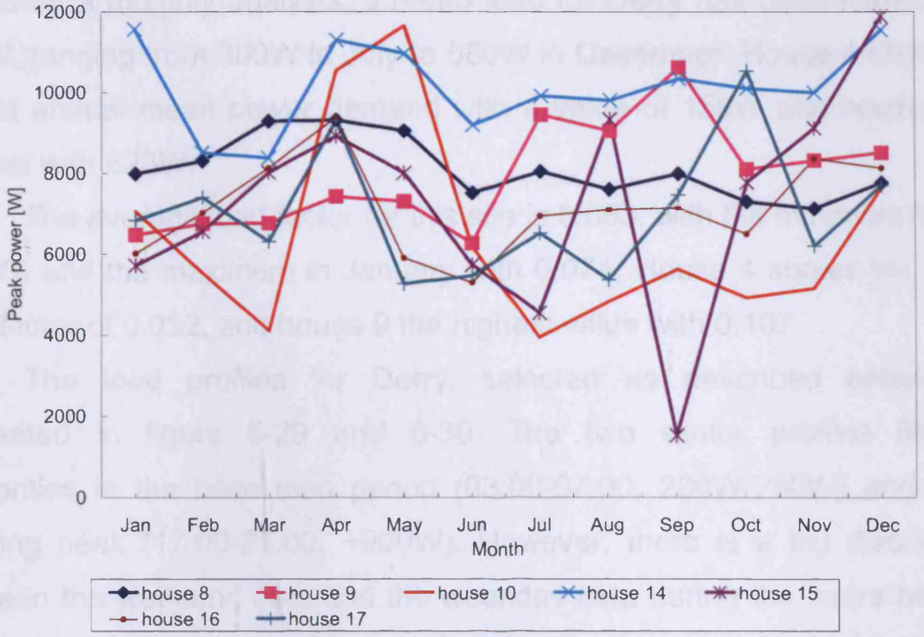


Figure 5-28b: Monthly peak power (this peak load is the highest recorded value per month with in the 5 minute data) for dwelling 8-17 in Derry

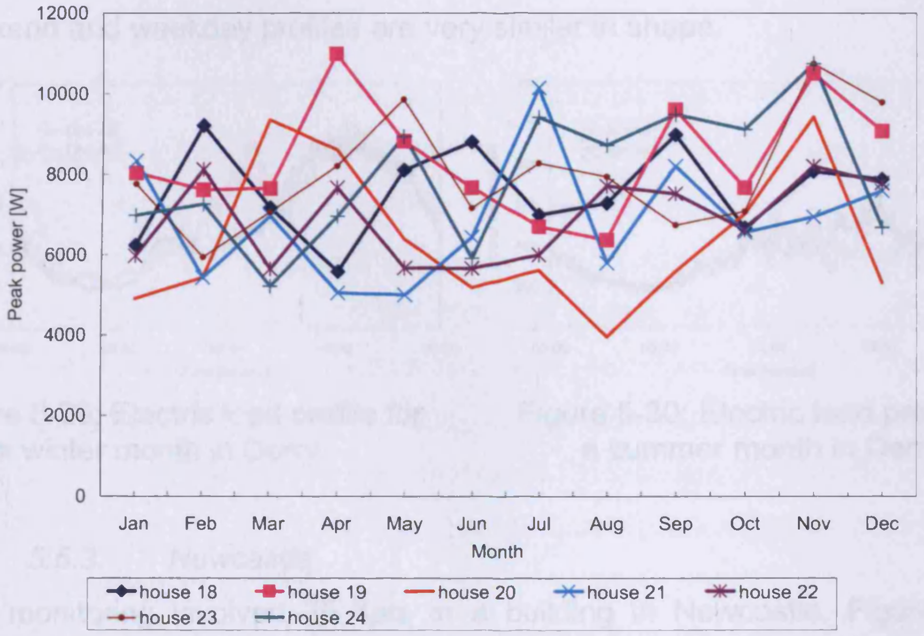


Figure 5-28c: Monthly peak power (this peak load is the highest recorded value per month with in the 5 minute data) for dwelling 18-24 in Derry

Based on a monthly analysis, a mean load for Derry has been identified as 465W, ranging from 390W in July to 580W in December. House 4 shows the lowest annual mean power demand with a value of 150W and house 9 the highest with 823W.

The average load factor for this site is 0.063, with the minimum in June (0.588) and the maximum in January with 0.074. House 4 shows the lowest load factor of 0.032, and house 9 the highest value with 0.107.

The load profiles for Derry, selected as described before, are presented in figure 5-29 and 5-30. The two winter profiles illustrate similarities in the base load period (03:00-07:00, 200W-250W) and in the evening peak (17:00-21:00, ~900W). However, there is a big discrepancy between the weekend data and the weekday data during the hours between 10:00 and 15:00. The weekend profile shows a higher peak, highly likely to be created by food preparation appliances.

The summer profiles have a base load close to the winter data, there is no notable evening peak and no weekend peak around noon. The weekend and weekday profiles are very similar in shape.

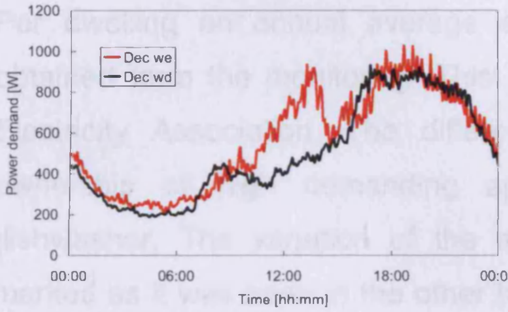


Figure 5-29: Electric load profile for a winter month in Derry

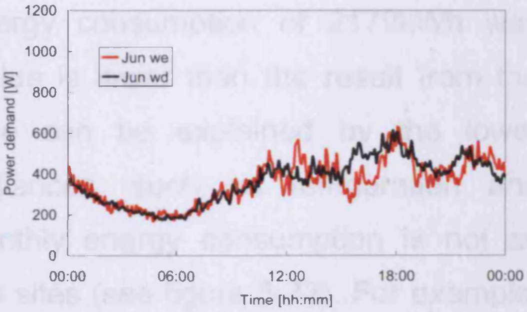


Figure 5-30: Electric load profile for a summer month in Derry

5.5.3. *Newcastle*

This monitoring involved 25 flats in a building in Newcastle. Figure 5-31 shows the results from the occupancy survey. The comparison with the UK average reveals differences in the possession of several electric appliances. The refrigeration group in Newcastle shows a lower level of ownership, here only 26% of the households own a freezer. There is a far higher ownership of entertainment equipment, but fewer personal computers. None of the surveyed dwellings possessed a dishwasher.

The number of occupants per household is 1.6 and the average floor area amounts to 69m², see table 5-4. The energy supply for cooking, heating and the DHW are realised by gas.

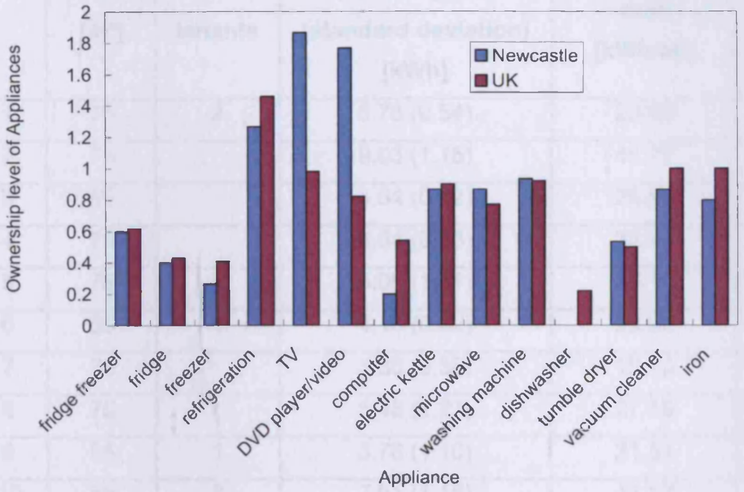


Figure 5-31: Ownership level of appliances at Newcastle (obtained during the occupant survey) compared with UK averages [ECI, 2000b] [Mansouri et al., 1996]

Per dwelling an annual average energy consumption of 2179kWh was obtained form the monitoring. This value is lower than the result from the Electricity Association. The difference can be explained by the lower ownership of high demanding appliances, such as refrigeration and dishwasher. The variation of the monthly energy consumption is not as marked as it was seen in the other two sites (see figure 5-32). For example, in February the consumption is comparable with results obtained during the summer month. The month with the lowest consumption was August with 166kWh, March with 215kWh the highest. The variation between these two energy consumptions is 22%.

Table 5-4 presents the normalised consumptions for day, floor area and number of occupants for each dwelling. The averages were identified as 5.9kWh/day, 30.9kWh/m² and 1336.0kWh/person.

Table 5-4: Dwelling characteristics and energy monitoring results of Newcastle

ID	**Floor area [m^2]**	**Number of tenants**	**Monthly average of daily electric energy consumption (standard deviation) [kWh]**	**Annual Consumption/ area [kWh/m^2]**	**Annual Consumption/ person [kWh/person]**
Newcastle 1	75	2	5.78 (0.54)	28.69	1075.87
Newcastle 2	75		9.03 (1.15)	44.77	
Newcastle 3	65		4.54 (0.42)	25.99	
Newcastle 4	75		6.54 (0.83)	32.44	
Newcastle 5	75	1	5.06 (1.61)	25.10	1882.24
Newcastle 6	65	1	4.18 (0.82)	23.92	1554.66
Newcastle 7	75		3.86 (0.36)	19.13	
Newcastle 8	75		5.48 (1.27)	27.19	
Newcastle 9	65	1	3.76 (1.10)	21.51	1398.04
Newcastle 10	65	3	7.61 (1.15)	43.57	943.95
Newcastle 11	65	2	5.21 (0.97)	29.82	969.00
Newcastle 12	65	2	7.09 (3.08)	40.59	1319.20
Newcastle 13	65		14.43 (1.47)	82.59	
Newcastle 14	65	2	2.05 (1.79)	11.74	381.41
Newcastle 15	65		3.00 (0.75)	17.18	
Newcastle 16	65	3	7.88 (2.15)	45.11	977.47
Newcastle 17	65	1	8.15 (1.05)	46.65	3032.37
Newcastle 18	65	1	3,17 (0.44)	17.80	1157.05
Newcastle 19	65	1	3.44 (0.31)	19.67	1278.64
Newcastle 20	65	1	6.29 (1.88)	36.00	2339.94
Newcastle 21	65	1	4.52 (0.92)	25.84	1679.76
Newcastle 22	80	2	5.47 (0.47)	25.46	1018.33
Newcastle 23	80		3.34 (0.31)	15.52	
Newcastle 24	80		7.73 (1.25)	35.93	
Newcastle 25	65		9.42 (2.09)	53.90	
Average	*69.20*	*1.60*	*5.86 (1.12)*	*30.91*	*1336.81*

The peak loads on a monthly base are presented in figure 5-33, the mean peak load of this site is 5024W, ranging from 4466W in August to 5418W in November (variation of 18%).

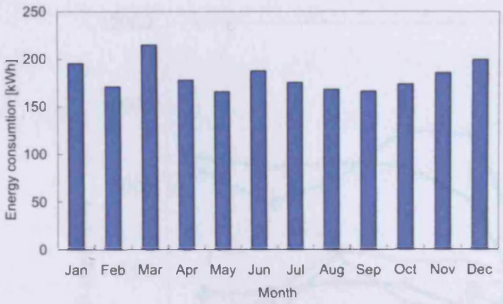


Figure 5-32: Monthly average of the energy consumption per dwelling at Newcastle

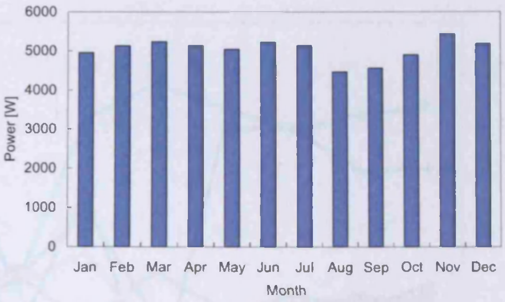


Figure 5-33: Monthly average of the peak power demand occurring in each dwelling at Newcastle

The monthly load peaks for each dwelling are illustrated in figure 5-34a to 5-34c. It can be seen, that the highest peaks are in the range of 10000W and 11000W. The highest annual averaged peak load has been identified in House 2 (9433W, see figure 5-34a) and the lowest in house 14 (1980W, see figure 5-34b). The occupants of this dwelling (house 2) have not been surveyed, it must be assumed, that they either have a particular pattern (for example the usage of the washing and the tumble dryer at the same time) or in this flats there are other high demanding appliances like an electric shower or an electric cooker.

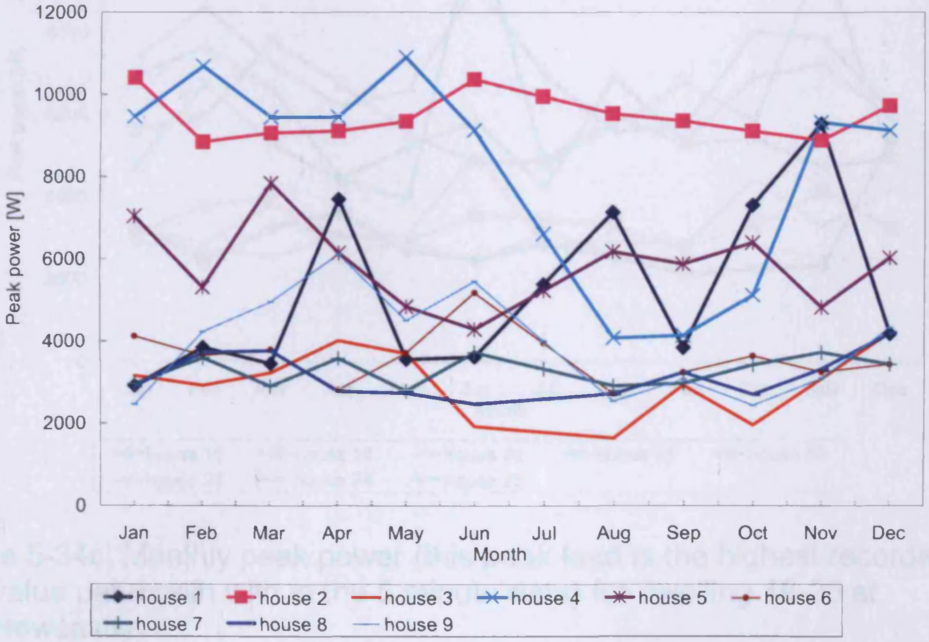


Figure 5-34a: Monthly peak power (this peak load is the highest recorded value per month with in the 5 minute data) for dwelling 1-9 at Newcastle

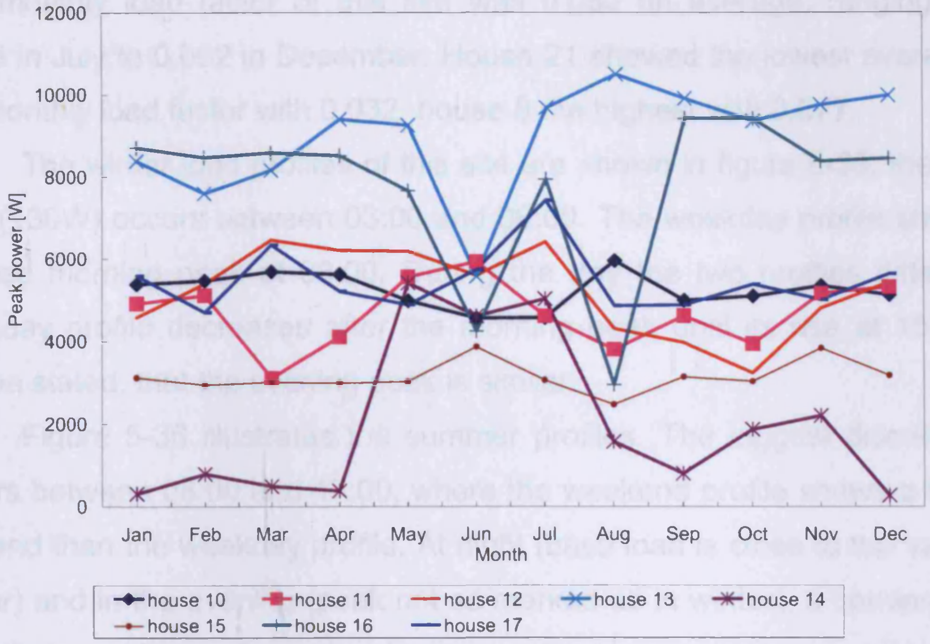


Figure 5-34b: Monthly peak power (this peak load is the highest recorded value per month with in the 5 minute data) for dwelling 10-17 at Newcastle

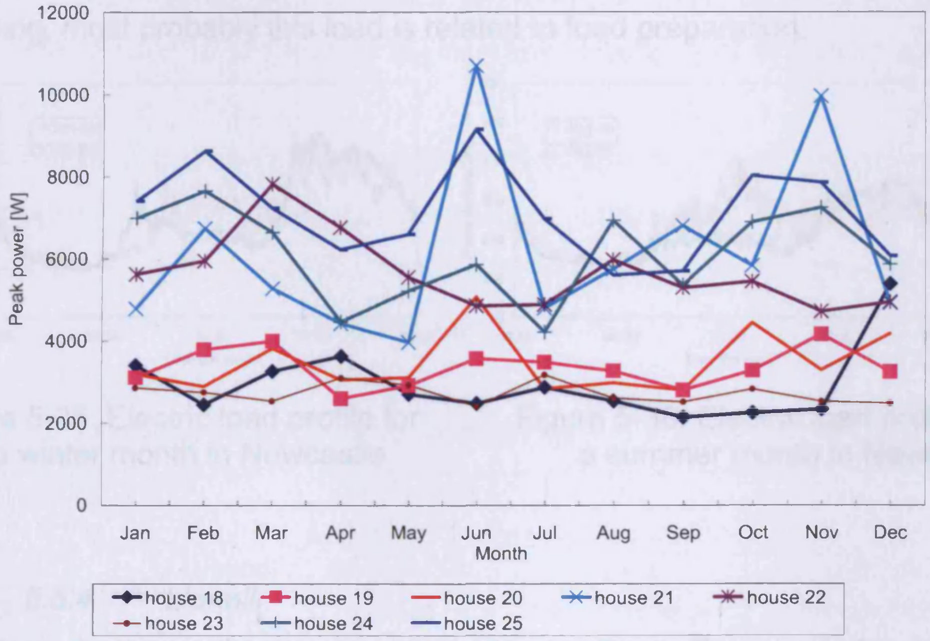


Figure 5-34c: Monthly peak power (this peak load is the highest recorded value per month with in the 5 minute data) for dwelling 18-25 at Newcastle

The mean load of the site Newcastle was 246W, varying from 222W in May to 267W in December. The dwelling based analysis revealed that house 14 had an annual mean load of 86W (minimum of all dwellings) and house 13 an annual mean load of 607W (maximum of all dwellings).

The monthly load factor of this site was 0.052 on average, ranging from 0.045 in July to 0.062 in December. House 21 showed the lowest average of the monthly load factor with 0.032, house 8 the highest with 0.077.

The winter load profiles of this site are shown in figure 5-35, the base load (130W) occurs between 03:00 and 06:00. The weekday profile shows a marked morning peak at 08:00. During the day the two profiles differ, the weekday profile decreases after the morning peak until its rise at 15:00. It can be stated, that the evening peak is similar.

Figure 5-36 illustrates the summer profiles. The biggest discrepancy occurs between 08:00 and 17:00, where the weekend profile shows a higher demand than the weekday profile. At night (base load is close to the value in winter) and in the evening (peak not as marked as in winter), a convergence of the two graphs can be realised.

In both figures a small load peak at 06:00 is visible. This is caused by flat 19, here nearly every morning at the same time a load of ~400W occurs. From the survey it is known that a working female person is living in the dwelling, most probably this load is related to food preparation.

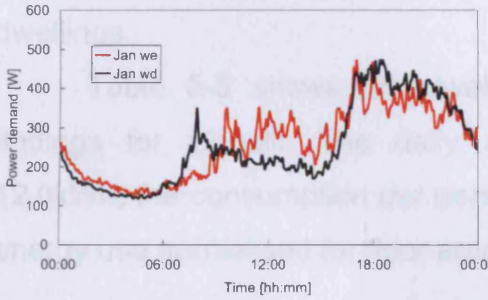


Figure 5-35: Electric load profile for a winter month in Newcastle

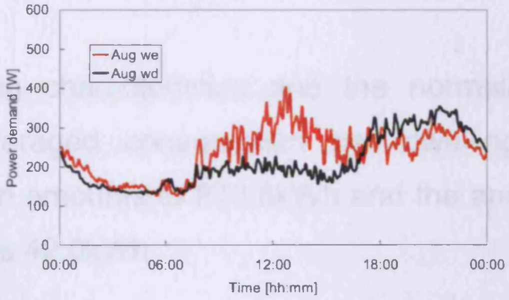


Figure 5-36: Electric load profile for a summer month in Newcastle

5.5.4. Llanelli

The Llanelli site monitoring consisted of 6 dwellings. The ownership level of appliances and the UK average are compared in figure 5-37. There are three appliances that differ strongly from a typical UK household, the entertainment equipment and the dishwasher. A far higher possession of TV's and DVD/Video player in the surveyed houses can be realised. On the other hand there are no dishwashers present. Smaller differences have also been realised with the refrigeration appliances and the tumble dryer. The floor area is 104m² on average and the mean number of occupants per dwelling amounts to 5. Cooking, space heating and DHW preparation at this site is realised by gas.

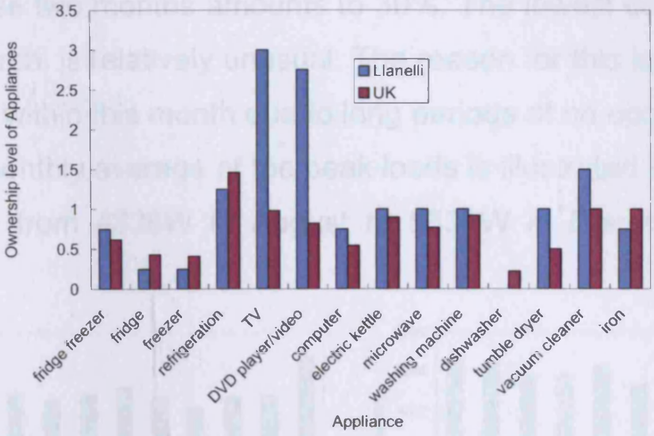


Figure 5-37: Ownership level of appliances at Llanelli (obtained during the occupant survey) compared with UK averages [ECI, 2000b] [Mansouri et al., 1996]

The averaged annual consumption per household is 4370kWh, which is higher than the comparable results of 3782kWh [Stokes, 2005]. The obtained high consumption is affected by the number of occupants and the size of the dwellings.

Table 5-5 shows the dwelling characteristics and the normalised findings for Llanelli. The daily averaged consumption per dwelling is 12.0kWh, the consumption per person amounts to 873.8kWh and the annual energy use normalised for floor area is 42.0kWh.

Table 5-5: Dwelling characteristics and energy monitoring results of Llanelli

ID	Floor area	Number of tenants	Monthly average of daily electric energy consumption (Standard deviation)	Annual Consumption/area [kWh/m²]	Annual Consumption/person [kWh/person]
Llanelli 1	100	3	12.31 (0.78)	45.80	1526.67
Llanelli 2	95	6	21.32 (4.49)	83.49	1321.90
Llanelli 3	95	5	8.43 (3.79)	33.00	627.05
Llanelli 4	120	6	7.69 (2.66)	23.83	476.64
Llanelli 5	120	5	13.51 (2.09)	41.88	1005.18
Llanelli 6	95	5	8.55 (5.22)	33.47	635.89
Average	*104.17*	*5.00*	*11.97 (3.17)*	*41.94*	*873.81*

The variation of the monthly consumptions in Llanelli is presented in figure 5-38. The month with the lowest consumption is March (319kWh) and the one with the highest consumption is December (452kWh). The difference between these two months amounts to 30%. The lowest consumption, which occurs in March, is relatively unusual. The reason for this is that house 4 only used 70kWh within this month due to long periods of no occupancy.

The monthly average of the peak loads is illustrated in figure 5-39. The peaks range from 4338W in August to 5334W in December (variation of 19%).

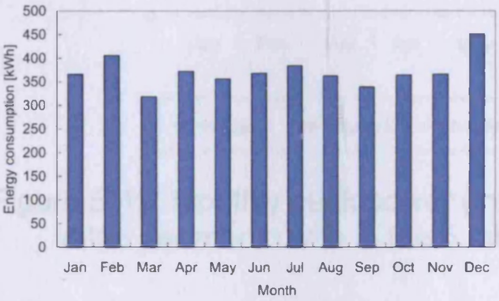


Figure 5-38: Monthly average of the energy consumption per dwelling at Llanelli

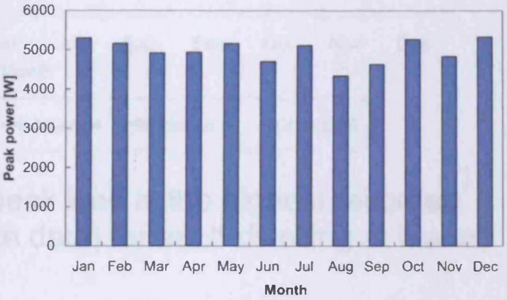


Figure 5-39: Monthly average of the peak power demand occurring in each dwelling at Llanelli

The results from the dwelling based peak load analysis are shown in figure 5-40. It can be concluded that the maximum peak of this site is around 9000W created by house number 2, the mean peak value is 4975W.

House 3 showed the lowest average of the monthly peaks loads with 3670W, house 2 the highest with 7346W.

The mean load of the site 508W, ranging from 428W in March to 606W in December. The household based findings show that house 4 has a mean load of 326W (minimum of this site) and house 2 has a mean load of 907W (maximum of this site). The average monthly load factor for this site is 0.099, varying from 0.080 in March to 0.112 in February. House 4 showed the lowest mean of the monthly load factors with a value of 0.076 and house 5 the highest with 0.124.

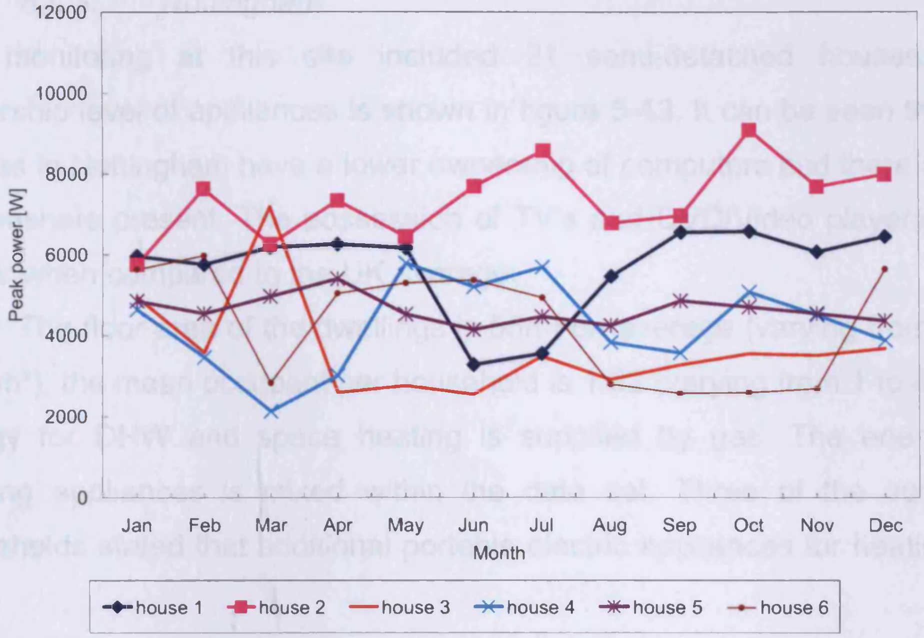


Figure 5-40: Monthly peak power (this peak load is the highest recorded value per month with in the 5 minute data) for each dwelling at Llanelli

The winter load profiles for Llanelli are shown in figure 5-41. The base load of ~200W occurs between 04:00 and 00:70. The weekend profile shows a slightly higher base load at night, possibly more occupants are active on the weekends. The weekday profile shows a marked morning peak of ~700W at 08:15. During the day the two profiles differ strongly, however from 17:00 onwards the profiles start to converge. The evening peak reaches more than 1000W. The summer profiles, shown in figure 5-42, show less difference between weekend and weekday. Still, there is the morning peak of the weekday profile and the higher demand of the weekend profile during the day. The base load is similar to the values in winter.

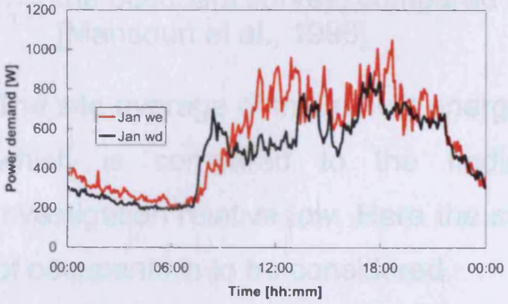


Figure 5-41: Electric load profile for a winter month in Llanelli

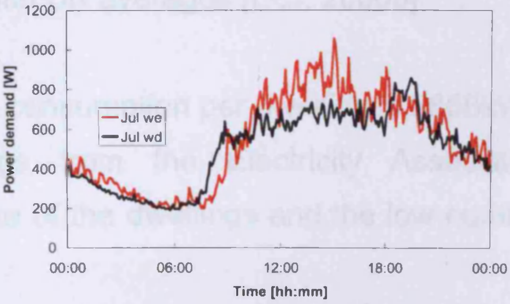


Figure 5-42: Electric load profile for a summer month in Llanelli

5.5.5. Nottingham

The monitoring at this site included 21 semi-detached houses. The ownership level of appliances is shown in figure 5-43. It can be seen that the houses in Nottingham have a lower ownership of computers and there are no dishwashers present. The possession of TV's and DVD/Video players is far higher when compared to the UK average.

The floor area of the dwellings is 55m² on average (varying from 52m² to 71m²), the mean occupant per household is 1.52 (varying from 1 to 4). The energy for DHW and space heating is supplied by gas. The energy for cooking appliances is mixed within the data set. Three of the surveyed households stated that additional portable electric appliances for heating are used.

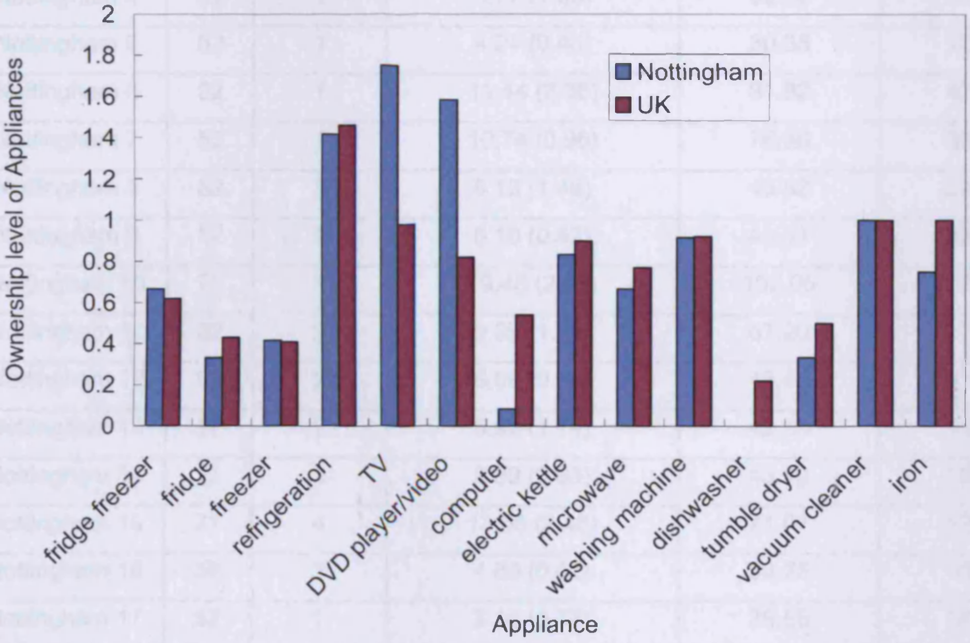


Figure 5-43: Ownership level of appliances at Nottingham (obtained during the occupant survey) compared with UK averages [ECI, 2000b] [Mansouri et al., 1996]

The site average of the annual energy consumption per dwelling is 2865kWh, which is compared to the findings from the Electricity Association investigation relative low. Here the size of the dwellings and the low number of occupants is to be considered.

Figure 5-44 shows the variation of the averaged monthly energy consumption. The minimum occurring in June is 212kWh and the maximum occurring in December is 282kWh. This results in a variation of 25%.

The normalised values of the annual consumptions amount to 7.9kWh/day, 52.4kWh/m^2 and 1885.0kWh/person, see table 5-6 for a detailed, dwelling based presentation of the results.

Table 5-6: Dwelling characteristics and energy monitoring results of Nottingham

ID	**Floor area [m^2]**	**Number of tenants**	**Monthly average of daily electric energy consumption (standard deviation) [kWh]**	**Annual Consumption/ area [kWh/m^2]**	**Annual Consumption/ person [kWh/person]**
Nottingham 1	52	1	2.79 (1.26)	19.94	1037.09
Nottingham 2	52	2	5.40 (1.59)	38.66	1005.28
Nottingham 3	52	1	6.03 (0.78)	43.17	2244.79
Nottingham 4	52	1	9.77 (1.00)	69.90	3634.79
Nottingham 5	52	1	4.24 (0.40)	30.35	1578.44
Nottingham 6	52	1	11.44 (2.36)	81.82	4254.38
Nottingham 7	52	1	10.74 (0.96)	76.80	3993.73
Nottingham 8	52	1	6.13 (1.49)	43.82	2278.80
Nottingham 9	52	1	6.10 (0.42)	43.61	2267.90
Nottingham 10	71	1	19.48 (2.28)	102.05	7245.21
Nottingham 11	52	2	9.39 (1.20)	67.20	1747.30
Nottingham 12	52	2	6.08 (0.64)	43.46	1130.08
Nottingham 13	52	2	5.92 (1.74)	42.35	1100.99
Nottingham 14	71	2	8.99 (0.63)	43.19	1533.16
Nottingham 15	71	4	13.56 (2.46)	71.07	1261.50
Nottingham 16	52	2	4.69 (0.62)	30.75	799.44
Nottingham 17	52	1	5.44 (0.73)	35.66	1854.08
Nottingham 19	52	2	5.58 (0.71)	36.58	951.18
Nottingham 20	52	2	11.55 (1.44)	68.86	1790.26
Nottingham 21	52	1	5.29 (0.56)	31.55	1640.52
Nottingham 22	52	1	6.24 (1.07)	37.19	1933.68
Average	*54.71*	*1.52*	*7.85 (1.16)*	*52.37*	*1885.03*

Figure 5-45 shows the monthly based analysis of the peak loads recorded on the households. The mean of the data is 6633W, ranging from 5776W in August to 7530W in December (variation of 23%).

The dwelling based peak load analysis is presented in figure 5-46a to figure 5-46c, it has been found, that the maximum peaks are in a range of 11000W to 13000W. In figure 5-46c there is one data point with a value of more than 15000W (house 20, 16/12/2002, 19:30). Initially it was believed that this was an error in the measurement system, but the values in this period show a high demand generally. It is difficult to derive which appliances are used in this event. However, this household is one that stated in the survey to use additional heating. Thus it can be assumed that this very high peak load is possibly related to a heating demand in connection with other high consuming appliances.

The mean load obtained from this site amounts to 332W, ranging from 294W in June to 379W in December. The investigation revealed that house 1 has the lowest mean load of 118W and house 10 the highest with 822W. The load factor for this site is 0.054, varying from 0.048 in June to 0.059 in September. The household based calculation showed that house 5 has the lowest annual average of the monthly load factor (0.021) and house 3 highest (0.089).

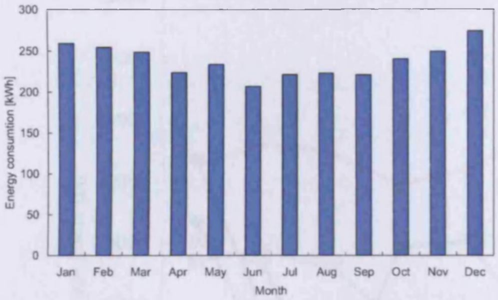


Figure 5-44: Monthly average of the energy consumption per dwelling at Nottingham

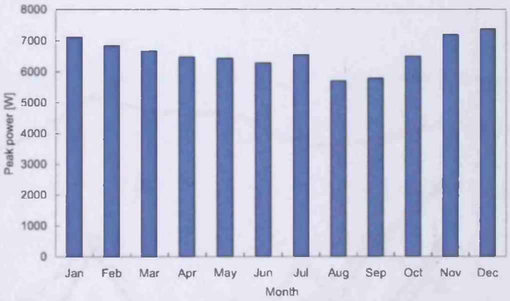


Figure 5-45: Monthly average of the peak power demand occurring in each dwelling at Nottingham

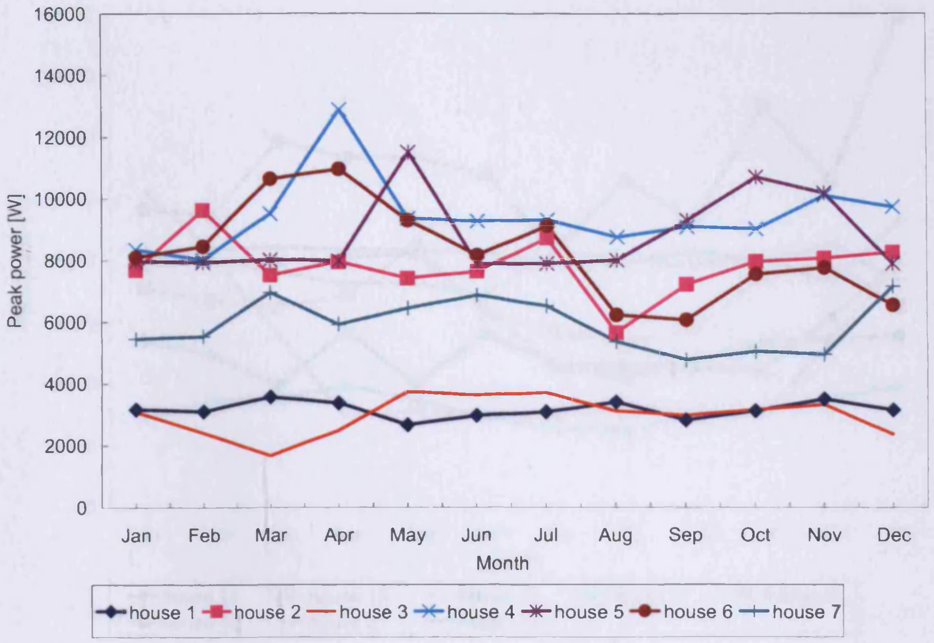


Figure 5-46a: Monthly peak power (this peak load is the highest recorded value per month with in the 5 minute data) for dwelling 1-7 at Nottingham

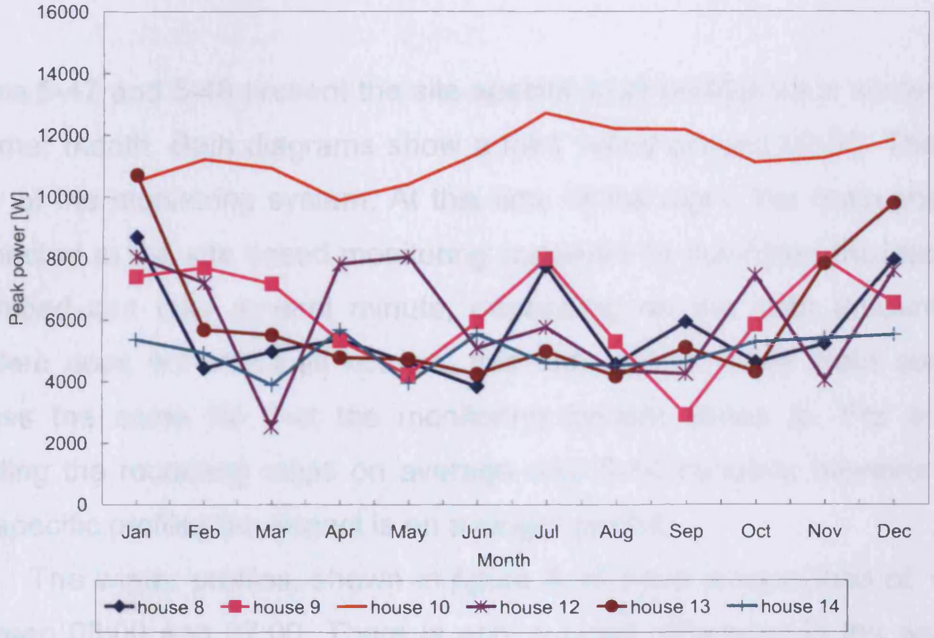


Figure 5-46b: Monthly peak power (this peak load is the highest recorded value per month with in the 5 minute data) for dwelling 8-14 at Nottingham

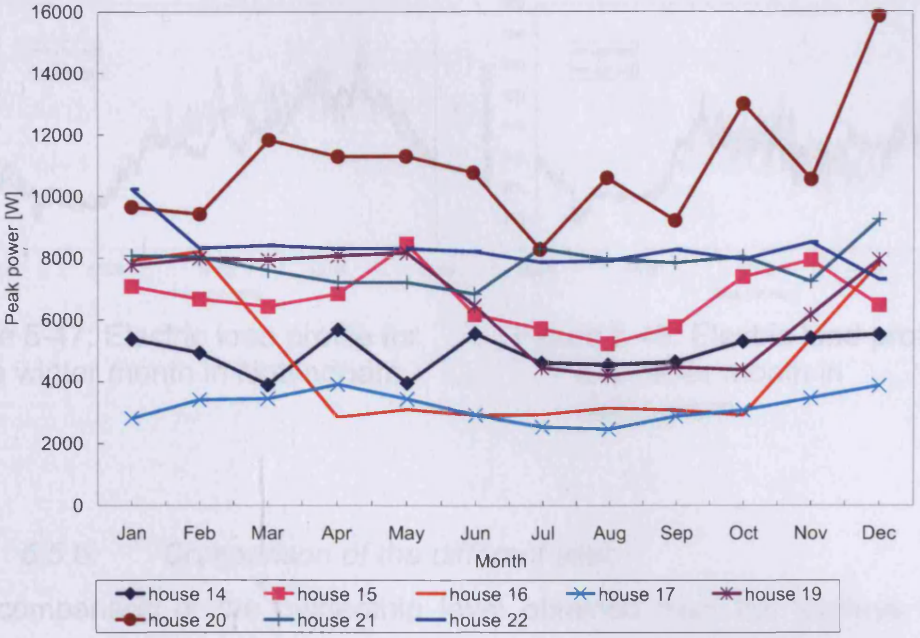


Figure 5-46c: Monthly peak power (this peak load is the highest recorded value per month with in the 5 minute data) for dwelling 15-22 at Nottingham

Figure 5-47 and 5-48 present the site specific load profiles for a winter and a summer month. Both diagrams show a load valley around 02:30. This is an error of the monitoring system. At this time of the night, the main computer connected to the site based monitoring computer to download the data. The download can take several minute, depending on the data amount. This problem does not affect all houses, this only occurs if the main computer access the same file that the monitoring system writes to. For a single dwelling the recording stops on average only 5-10 minutes, however in the site specific profiles the impact is on a longer period.

The winter profiles, shown in figure 4-46 have a base load of ~170W between 03:00 and 07:00. There is only a small difference in the weekend and weekday profile, notably in the period 09:00 to 16:00. The weekend also shows a higher evening peak (680W) than the weekday (570W) profile.

The summer profiles, figure 5-47, converge until 16:00, from here on the weekday profile shows a more equilibrated demand than the weekend profile.

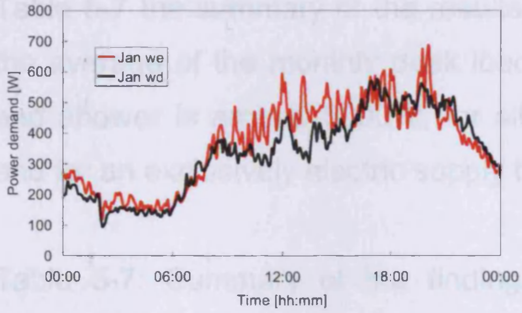


Figure 5-47: Electric load profile for a winter month in Nottingham

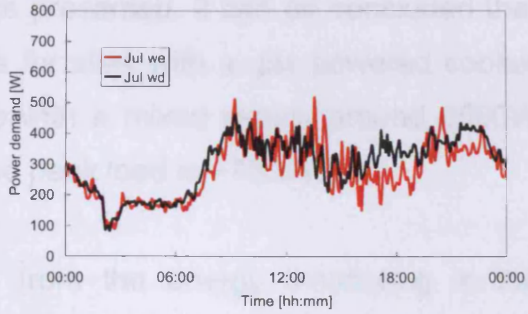


Figure 5-48: Electric load profile for a summer month in Nottingham

5.5.6. *Comparison of the different sites*

The comparison of the ownership level obtained from the surveys in the different sites generally shows a good agreement in the most appliances class. However, there are appliances where discrepancies occur (TV, DVD/Video player, computer, dishwasher and tumble dryer). The ownership level of dishwasher showed the biggest differences, in some sites none of the households possessed this electric appliance (see figure 5-49).

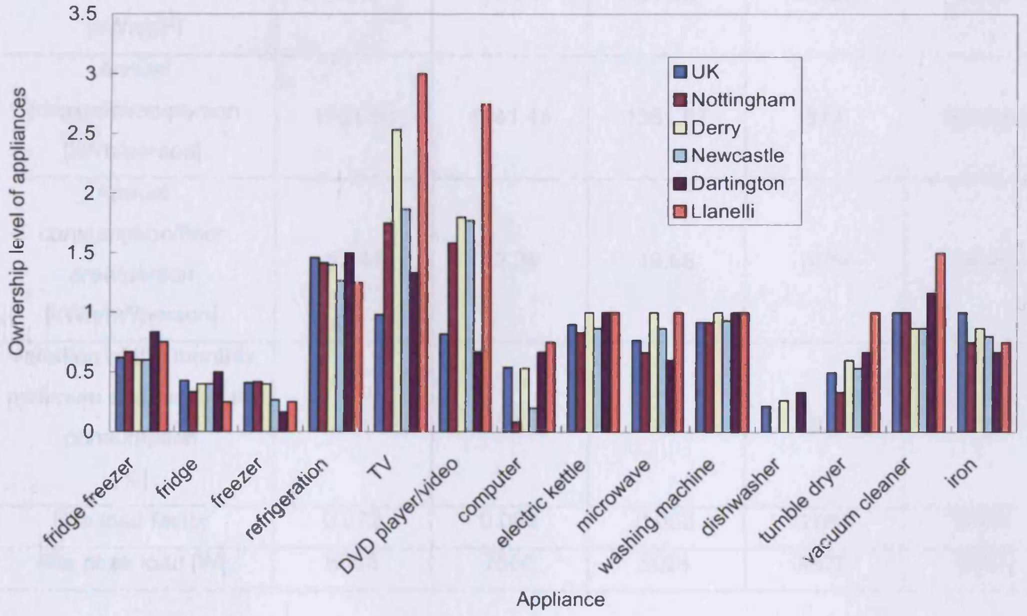


Figure 5-49: Comparison of the site specific ownership level of appliances (obtained during the occupant survey) compared with UK averages [ECI, 2000b] [Mansouri et al., 1996]

The findings from the energy consumption monitoring are difficult to compare since the characteristics of the sites and the occupants type are varying. In

Table 5-7 the summary of the results is presented. It can be concluded that the average of the monthly peak loads for sites with a gas powered cooker and shower is around 5000W, for site with a mixed supply around 6500W and for an exclusively electric supply the peak load is ~7500W.

Table 5-7: Summary of the findings from the energy monitoring in the dwellings

	Dartington	Derry	Newcastle[6]	Llanelli	Nottingham
Average floor area [m²]	101	85.11	69.20	104.17	54.71
Average number of occupants	2.13	3.86	1.60	5.00	1.52
Cooker powered by	gas/electric	electric	gas	gas	gas/electric
Shower powered by	gas/electric	electric	gas	gas	Gas
General characterisation of the occupants	Couples and one person households (middle aged people)	Lone parents and families	Lone parents and one person households	Lone parents and families	Mainly elderly people
Annual consumption [kWh]	3752	4020	2179	4370	2865
Annual consumption/floor area [kWh/m²]	37.15	47.23	31.49	41.95	52.37
Annual consumption/person [kWh/person]	1761.50	1041.45	1361.87	874	1884.86
Annual consumption/floor area/person [kWh/m²/person]	17.44	12.24	19.68	8.39	34.45
Variation of the monthly minimum and maximum consumption [%]	52	32	22	30	25
Site load factor	0.072	0.063	0.052	0.099	0.054
Site peak load [W]	6065	7500	5024	4975	6633

The assessment of the shape of the winter weekday load profiles (see figure 5-50) shows that all sites have a typical curve with a base load

---

[6] Here to be considered as a site with only gas powered cookers and showers.

(variation between the site specific profiles is only 200W), a morning peak (8:00 to 09:00, ranging from 350-700W), a lower period during the day (Llanelli and Nottingham show an additional peak) and an evening peak (varying between 460W and 1150W).

From the comparison of all site specific summer weekday profiles (see figure 5-51) it can be derived, that the variation between the curves is generally less (up to ~300W), only Llanelli shows a high demand, comparable with the winter profile of this site. There is no marked separation of the daily profile into morning peak and evening peak as it can be seen in the winter weekday profiles.

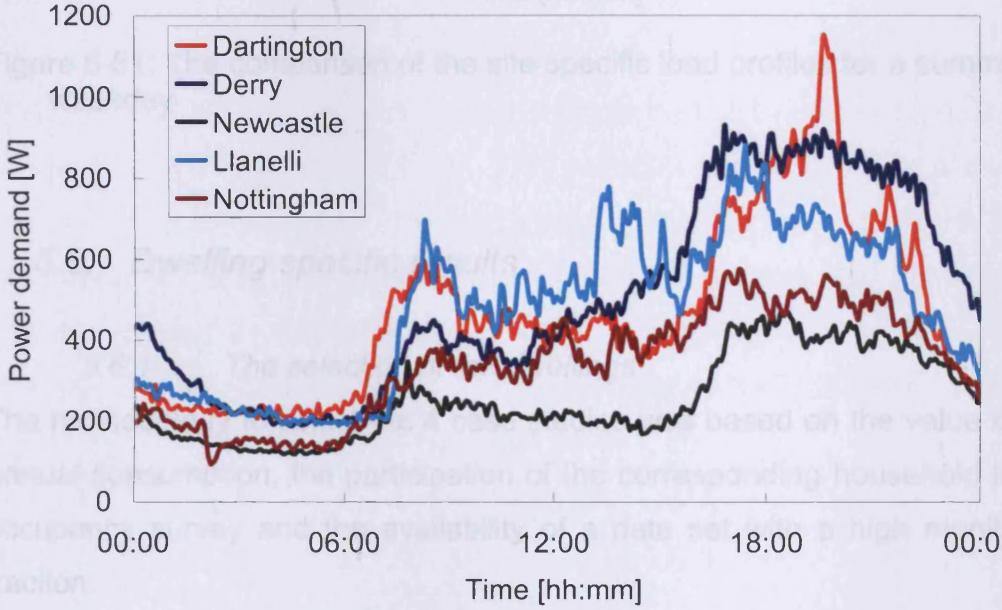


Figure 5-50: The comparison of the site specific load profiles for a winter weekday

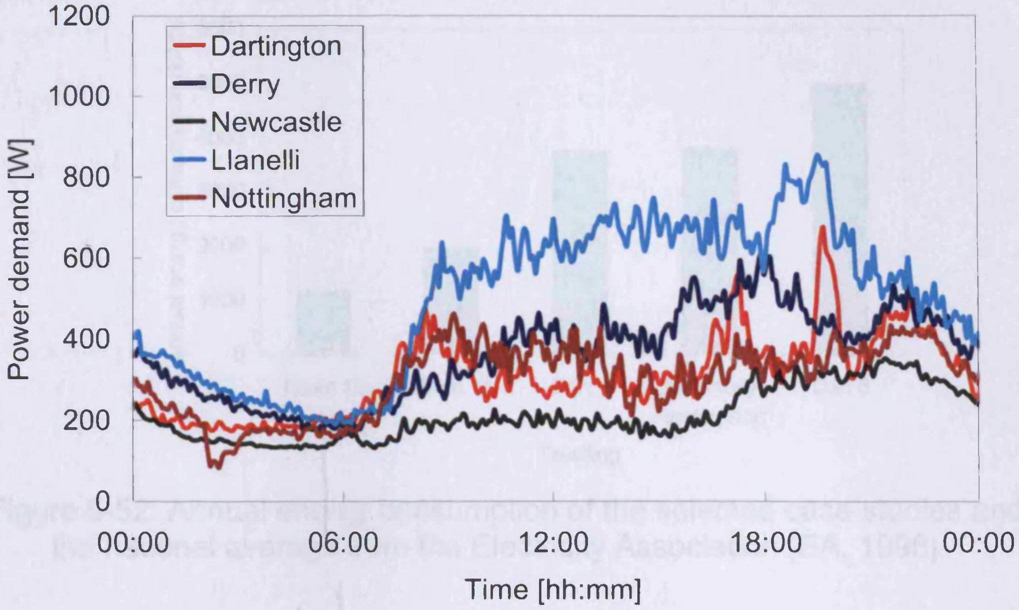


Figure 5-51: The comparison of the site specific load profiles for a summer weekday

5.6. *Dwelling specific results*

5.6.1. *The selection of the dwellings*

The methodology to select the 4 case studies was based on the value of the annual consumption, the participation of the corresponding household in the occupancy survey and the availability of a data set with a high monitoring fraction.

Figure 5-52 illustrates the annual consumptions for the 4 case studies, ranging from 1155kWh to 4967kWh, and the national average from the Load Research Group of the Electricity Association [Stokes, 2005]. The value from house 1 in Dartington (Dart 1) is nearly equal with the data from the Load Research Group (2% difference). House 5 of Dartington presents in this investigation a dwelling with higher consumption than the national average (25% above the national average).

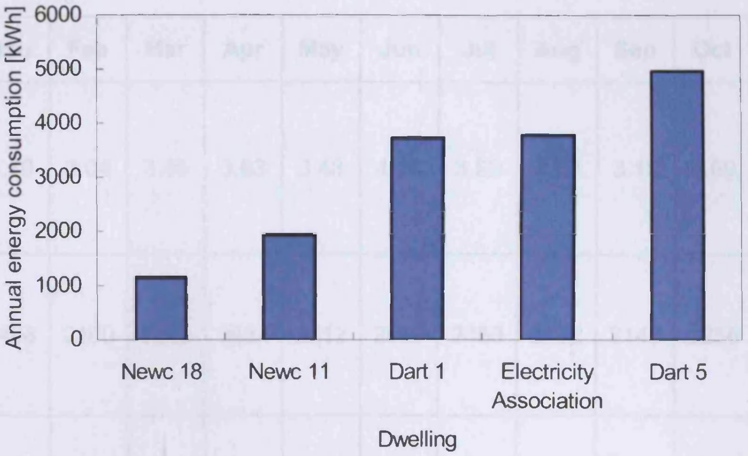


Figure 5-52: Annual energy consumption of the selected case studies and the national average from the Electricity Association [EA, 1998]

5.6.2. *Case study 1 – Newcastle 18*

The first case study is represented by a single person household located in a dwelling with a floor area of 65m². This person does not posses a washing machine or a tumble dryer, the appliances that have been identified during the survey are a fridge freezer, a TV, a computer, a kettle and a microwave. The energy supply for DHW and cooking is realised by gas. The annual electric energy consumption for this dwelling amounts to 1155kWh, varying from 74kWh in November to 123kWh in June.

Table 5-8: Energy consumption and load parameters for Newcastle 18

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean daily consumption [kWh]	2.79	3.04	3.46	3.63	3.43	4.10	3.22	3.00	3.18	2.69	2.48	2.98
Peak load [W]	3408	2460	3276	3624	2712	2556	2880	2592	2148	2256	2388	5424
Mean load [W]	116	127	144	151	143	171	134	125	133	112	103	124
Load factor	0.034	0.052	0.044	0.042	0.053	0.067	0.047	0.048	0.062	0.050	0.043	0.023

Table 5-8 presents the results from the analysis of the monitoring data. The annual mean of the monthly peak load (monthly peak load is the highest value of the recorded load of the month) amounts to 3000W, varying from 2148W in September to 5424 in December. The annual mean load is 131W raging from 103W (November) to 170W (June). The load factor analysis resulted in an average load factor of 0.047, based on the monthly results where December is the lowest with 0.023 and June the highest load factor with 0.067.

The tendency of a lower consumption during the summer month and a higher consumption during the winter month, as it can be seen on the average domestic energy consumption in the UK, is not recognisable. This case study shows the opposite effect. Due to the absence of other high consuming appliances it can be assumed that this effect is caused by the higher demand of the fridge freezer in the summer month. Saidur [Saidur et al, 2002] has concluded that the ambient temperature has the biggest effect of the energy consumption of fridge freezers. From a laboratory test it was derived that the energy consumption will increase by ~20% when the room temperature increases by 4°C. In the CIEL study [Sidler, 1997] a difference of 37% between the consumption in summer and the consumption in winter has been identified (mean annual consumption of the sample in the Sidler investigation was 581kWh). The average external temperature in June in Newcastle has been recorded at 14°C, in November it was only 7°C.

Certainly, the room temperature will not change as much as the external temperature, however there is a correlation.

The difference of around 1kWh/day (comparing December and June in table 5-8) can also be estimated from the recorded data in the dwelling. The load data shows that the fridge freezer uses around 140W for 30% of the time in winter (0.140kW*0,3*24h=1kWh) and 140W for around 60% of the time in summer (0.140kW*0,6*24h=2kWh). This is a doubling of the consumption, Sidler has obtained an average difference between summer and winter of 37%, however assuming an older model of a fridge freezer this is a possible result.

Other factors may affect the monthly energy consumption of this household (for example, changes in the occupancy pattern), nevertheless it can be concluded that households with a low annual consumption are more sensitive to the increasing demand of refrigeration appliances in a month with a higher room temperature. In the following the summer month with the lowest monthly consumption and the winter month with the highest consumption are compared. This methodology has been applied to identify the discrepancies in the occupancy pattern between power demands in periods of different meteorological characters. Comparing the power demand over the course of a complete winter and summer month (figure 5-53 and 5-54) it can be stated that two graphs do not vary very much.

The only marked difference is the period of non occupancy and the peak of more than 5000W in December. The amplitude of the peaks are generally very similar.

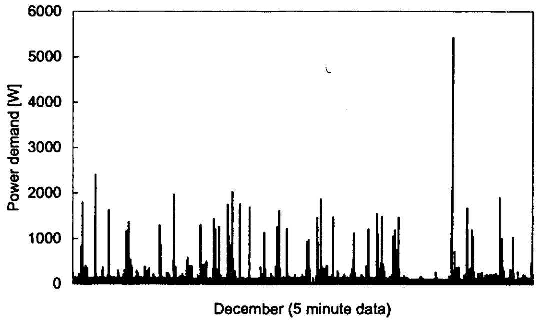


Figure 5-53: Power demand over the course of a winter month (Newcastle 18)

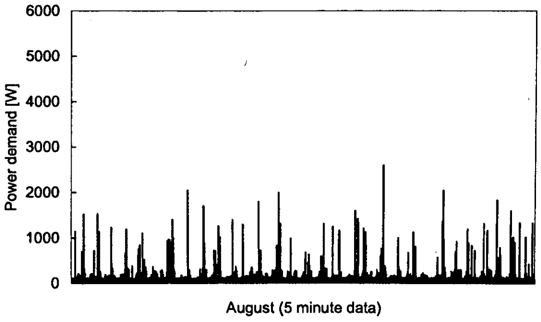


Figure 5-54: Power demand over the course of a summer month (Newcastle 18)

The electric load profile for a winter and a summer month are compared in figure 5-55 and figure 5-56. It can be seen that the summer month shows more peaks in the profile and that the winter profile has a more constant evening peak, however the profiles are similar. It appears as if the occupant was active also during the early morning hours, especially figure 5-56 shows a higher load around 02:15.

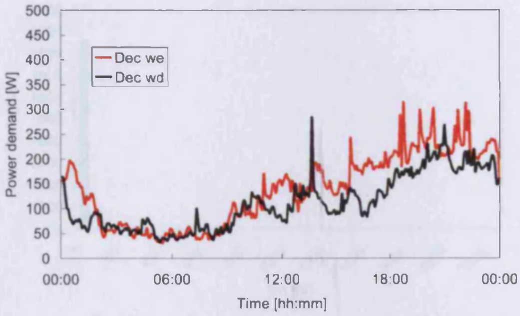


Figure 5-55: Electric load profile for a winter month (Newcastle 18)

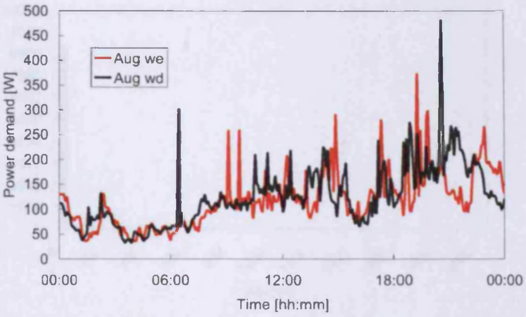


Figure 5-56: Electric load profile for a summer month (Newcastle 18)

For the sizing and the integration of on-site systems (for example the usage of a fuel cell as a storage of PV-energy) it is required to know what load levels commonly occur in the household, as this can help to optimise the system. Figure 5-57 and 5-58 show the distribution of loads for a summer and a winter month. It can be seen that the distribution changed between the months. In December the majority of the demands are in the range of 100W to 200W, in August between 200W and 300W. This effect can be explained by the lower energy consumption values in Winter. It can be concluded that most of the loads in this case study vary between 0W and 500W, there is only a small number of data above this range.

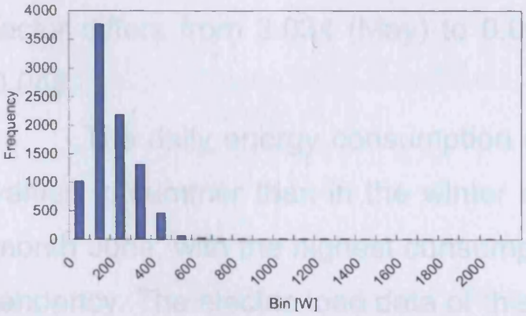


Figure 5-57: Distribution of the power demand for December (Newcastle 18, 100W bins)

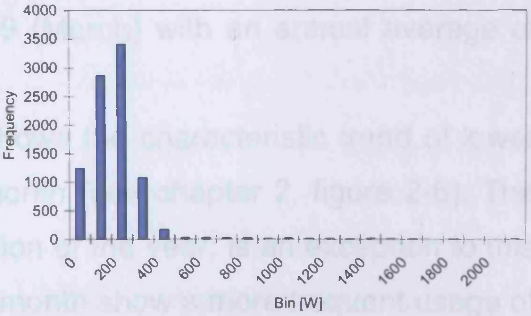


Figure 5-58: Distribution of the power demand for August (Newcastle 18, 100W bins)

Figure 5-59 and 5-60 are produced in order to gain knowledge of the variation of the electric demand; the on-site system has to be capable to follow these changes when a high load coverage or an autarkic schedule is desired. It can be concluded that the changes in load do not vary when summer and winter of this household is compared. The majority lie in the range of 0W to 100W.

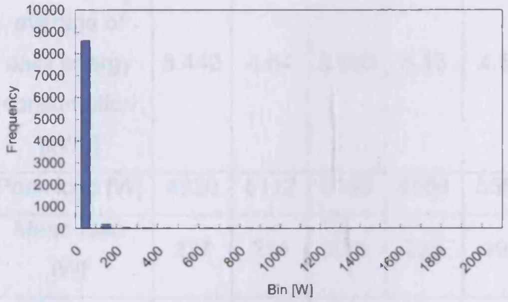


Figure 5-59: Absolute values of the load changes for December (Newcastle 18, 100W bins)

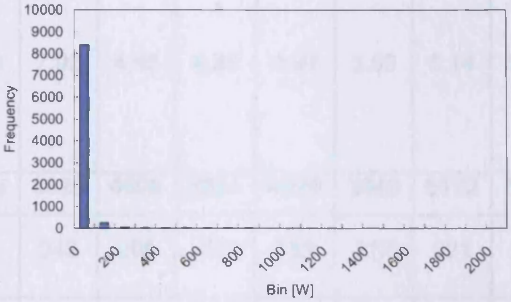


Figure 5-60: Absolute values of the load changes for August (Newcastle 18, 100W bins)

5.6.3. *Case study 2 – Newcastle 11*

This case study represents a lone parent family living in a 65m² dwelling in a building in Newcastle. The electric appliances present in the household are: a fridge freezer, two TV's, two DVD/Video players, a kettle, a microwave, a washing machine, a vacuum cleaner and an iron. DHW and cooking is realised by gas. The annual consumption of this dwelling amounts to 1938kWh, ranging from 132kWh in August to 246kWh in June.

The results from the monitoring of this household are shown in table 5-9. The mean monthly peak load is identified as 4683W, with the minimum of 3108W in March and the maximum of 5928W in June. The annual mean load is 219W, varying from 178W (August) to 342kWh in June. The monthly load factor differs from 3.034 (May) to 0.069 (March) with an annual average of 0.048.

The daily energy consumption shows the characteristic trend of lower values in summer than in the winter month (see chapter 2, figure 2-6). The month June, with the highest consumption of the year, is an exception to this tendency. The electric load data of this month show a more frequent usage of appliances with a power demand of ~3500W. In Newcastle the data for June were obtained from the monitoring in 2006 (see section 3.41.), due to the higher monitoring fraction. It is possible that the possession of appliances in this household changed from 2005 (the year when occupant survey took place) to 2006, this would explain the higher consumption.

Table 5-9: Energy consumption and load parameters for Newcastle 11

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Monthly average of daily energy consumption [kWh]	5.442	4.64	5.686	5.18	4.58	7.95	4.95	4.26	4.31	5.09	5.14	5.27
Peak load [W]	4920	5112	3108	4104	5556	5928	4608	3804	4620	3948	5172	5316
Mean load [W]	227	214	215	223	191	342	206	178	186	212	221	220
Load factor	0.046	0.042	0.069	0.054	0.034	0.058	0.045	0.047	0.040	0.054	0.043	0.041

The plots of the power demand for a winter month and a summer month are presented in figure 5-61 and 5-62. It can be derived that January shows higher peaks than August, but due to the different mean loads, the load factor is similar (see table 5-9). A marked difference between the two months can be concluded, it appears as if in the winter month the washing machine, as the only high demanding appliance in the household, is used more frequent. Furthermore, the superposition of several loads can be assumed.

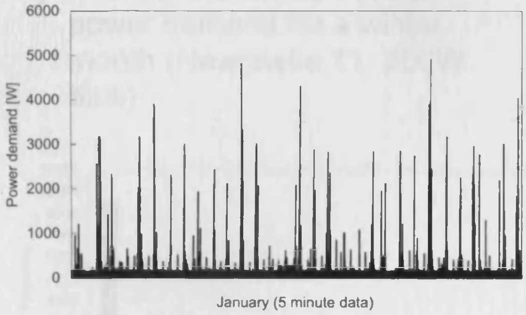


Figure 5-61: Power demand over the course of a winter month (Newcastle 11)

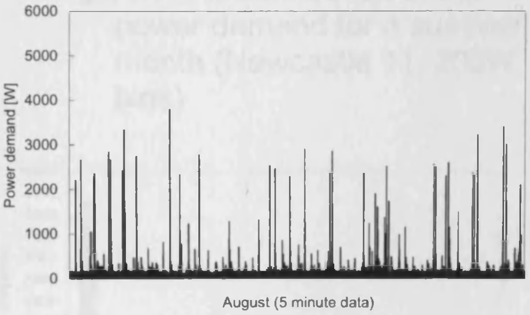


Figure 5-62: Power demand over the course of a summer month (Newcastle 11)

The load profiles (see figure 5-63 and 5-64) are characterised by a very smooth base load from 00:00 to ~06:00. The winter weekday profile shows a morning peak at 06:00 and the evening peak (maximum ~820W) starting at

15.15. In the winter weekday profile more activity during the day is recognisable, the evening peak (maximum 820W) begins at 15:30.

The comparison of the summer profiles indicates a higher activity on weekends, however the weekend profile and the weekday profile differ only slightly. The differences of the summer and the winter month in the changes in load analysis (figure 5-67 and 5-68) are very small, the winter month shows a slightly higher proportion of this parameter in the range of 400W to 600W.

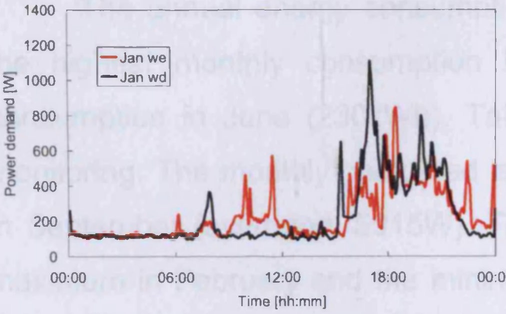


Figure 5-63: Electric load profile for a winter month (Newcastle 11)

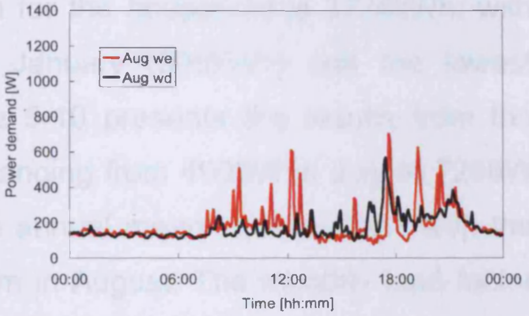


Figure 5-64: Electric load profile for a summer month (Newcastle 11)

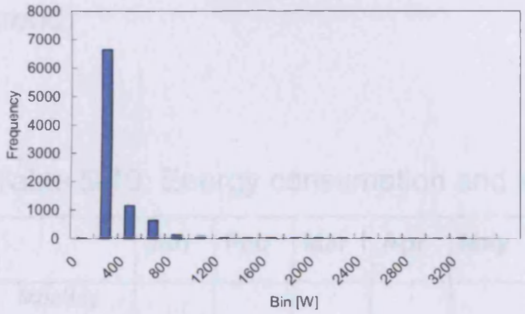


Figure 5-65: Distribution of the power demand for a winter month (Newcastle 11, 200W bins)

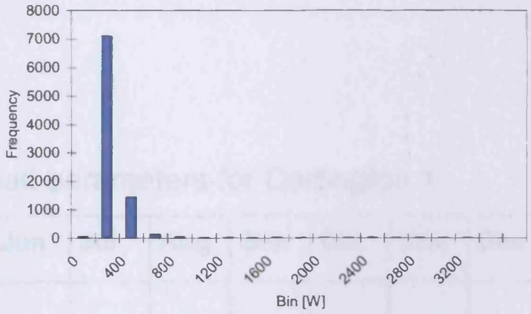


Figure 5-66: Distribution of the power demand for a summer month (Newcastle 11, 200W bins)

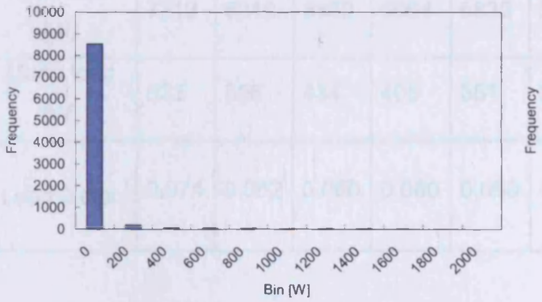


Figure 5-67: Absolute values of the load changes for a winter month (Newcastle 11, 200W bins)

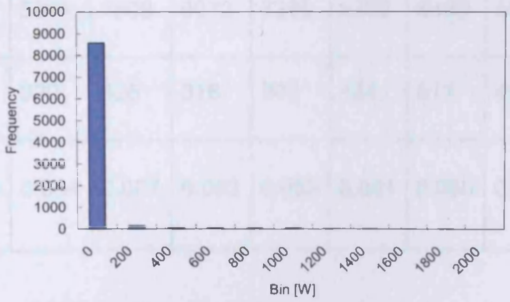


Figure 5-68: Absolute values of the load changes for a summer month (Newcastle 11, 200W bins

5.6.4. Case study 3 – Dartington 1

This case study represents a couple, where the man is retired and the woman is still working. They life in a 108m² house in Dartington. According to the survey, the following appliances are present in the household: one fridge freezer, one TV, one computer, one HIFI, one kettle, one washing machine, one dish washer, one tumble dryer, two vacuum cleaners and one iron. In winter additional electrical heating is used when necessary. DHW and the energy for the cooker is supplied by gas.

The annual energy consumption for the household is 3724kWh, with the highest monthly consumption in January (396kWh) and the lowest consumption in June (230kWh). Table 5-10 presents the results from the monitoring. The monthly peak load is ranging from 4908W in July to 7296W in September (averaged: 5915W). The annual mean load is 422W with the maximum in February and the minimum in August. The monthly load factor varies from 0.052 to 0.090 with an average of 0.072. The daily energy consumption shows the typical trend of lower energy consumption in winter than in summer. The monthly load factor of this dwelling also follows this trend.

Table 5-10: Energy consumption and load parameters for Dartington 1

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Monthly average of daily energy consumption [kWh]	12.79	13.35	11.47	9.73	8.40	7.69	7.84	7.88	9.20	10.41	12.26	11.93
Peak load [W]	7212	6816	5460	5064	5832	5040	4908	6072	7296	5328	6408	5544
Mean load [W]	533	556	434	405	351	320	326	318	383	434	511	497
Load factor	0.074	0.082	0.080	0.080	0.060	0.064	0.067	0.052	0.053	0.081	0.080	0.090

Comparing the plots of the power demand in figure 5-69 and 5-70 it can be stated that peaks in the summer are lower. Generally shows the winter figure a higher daily energy consumption with a complete daily profile (see figure 2-1).

In figure 5-70 is a period of ca. two days where only the base load is present, probably the occupants were not home.

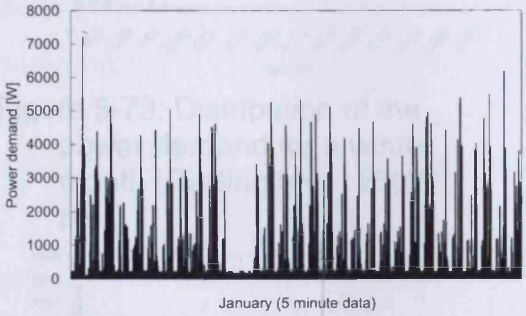


Figure 5-69: Power demand over the course of a winter month (Dartington 1)

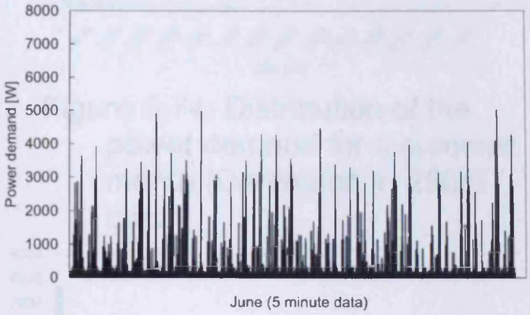


Figure 5-70: Power demand over the course of a summer month (Dartington 1)

The load profiles of figure 5-71 and 5-72 show a base load of around 100W. Significant is the load peak of 2500W to 3500W around 19:30, this could be created by the electrical shower.

The weekend and weekday profile in summer are very similar, the two winter profiles differ between the morning and the evening peak.

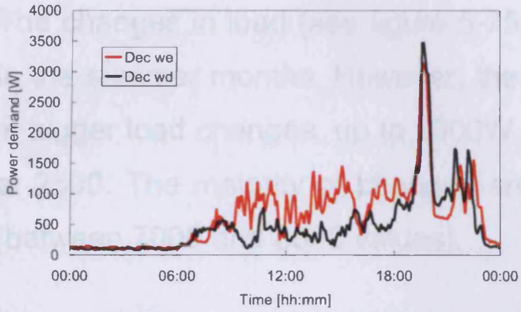


Figure 5-71: Electric load profile for a winter month (Dartington 1)

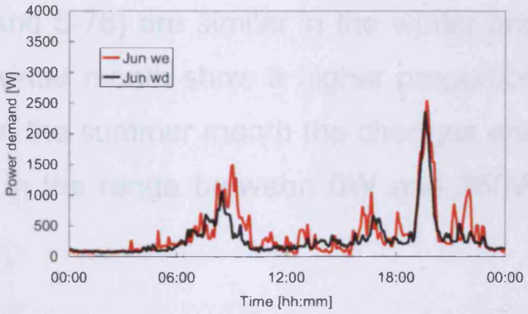


Figure 5-72: Electric load profile for a summer month (Dartington 1)

The distribution of the power demand is shown in figure 5-73 and 5-74. The majority of the load is between 0 and 750W. Whereas the summer month has a higher number of values between 0 and 250W.

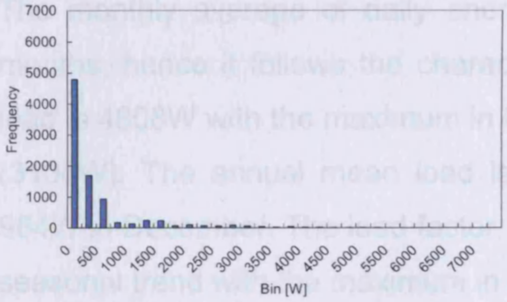


Figure 5-73: Distribution of the power demand for a winter month (Dartington 1, 250W bins)

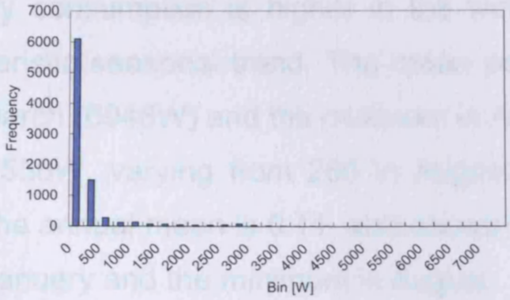


Figure 5-74: Distribution of the power demand for a summer month (Dartington 1, 250W bins)

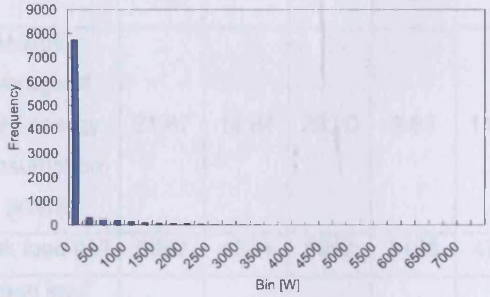


Figure 5-75: Absolute values of the load changes for a winter month (Dartington 1, 250W bins)

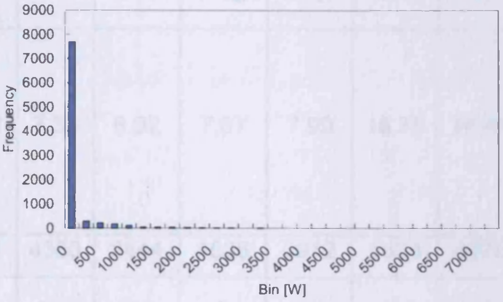


Figure 5-76: Absolute values of the load changes for a summer month (Dartington 1, 250W bins)

The changes in load (see figure 5-75 and 5-76) are similar in the winter and in the summer months. However, the winter month show a higher proportion in bigger load changes, up to 3000W. In the summer month the changes end at 2500. The majority of changes are in the range between 0W and 250W (between 7000 and 8000 values).

5.6.5. Case study 4 – Dartington 5

This case study presents a single person household with an annual energy consumption above the average. The tenant of this 80m² semi-detached dwelling is female and retired. The survey resulted in the following ownership level of appliances: one fridge freezer, one TV, one DVD player, one computer, two hi-fis, one kettle, one toaster, one washing machine, one tumble dryer and one vacuum cleaner. The oven is powered by electricity, the hob as well as the heating for DHW is powered by gas. The annual consumption of electric energy is 4967kWh, ranging from 214kWh in August to 717kWh in December.

The monthly average of daily energy consumption is higher in the winter months, hence it follows the characteristic seasonal trend. The mean peak load is 4808W with the maximum in March (6948W) and the minimum in April (3108W). The annual mean load is 556W, varying from 285 in August to 964W in December. The load factor, the annual mean is 0.11, also shows the seasonal trend with the maximum in January and the minimum in August.

Table 5-11: Energy consumption and load parameters for Dartington 5

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Monthly average of daily energy consumption [kWh]	21.87	14.84	20.20	9.63	11.01	7.38	6.92	7.07	7.99	16.75	16.43	23.15
Peak load [W]	5592	4524	6948	3108	4788	4380	3444	4536	3972	5628	4476	6300
Mean load [W]	911	618	765	401	460	308	288	285	333	698	685	964
Load factor	0.163	0.137	0.11	0.129	0.096	0.07	0.084	0.063	0.084	0.124	0.153	0.153

There is a remarkable difference in the power demands and the load profiles between summer and winter (see figure 5-77 to 5-80). Also from table 5-11 it can be seen that the monthly energy consumption triples from summer to winter. The tenant uses in winter an electrical radiator for space heating, which possibly explains the high demand in this period.

The value of the energy consumption of an electrical radiator can be roughly estimated to 10kWh (2kW radiator operating for 10 hours and the thermostat is closed for 50% of the time, 2kW*5h=10kWh). Considering this calculation, it is possible, that the higher consumption in winter is caused by an electrical radiator.

Due to this behaviour, the distribution of the power demand (figure 5-81 and 5-82) shows a very different shape in winter than in summer. The winter distribution shows a large number of loads above 1000W, where the majority values of the summer distribution lie in the range from 0W to 1000W (maximum from 250W to 500W).

The changes in load (figure 5-83 and 5-84) correspond to this result with higher load changes in winter, with the majority lying in the range from 0W to 750W.

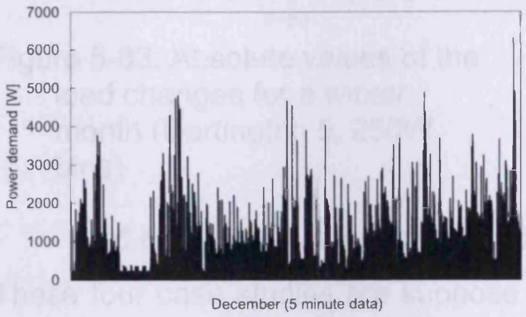


Figure 5-77: Power demand over the course of a winter month (Dartington 5)

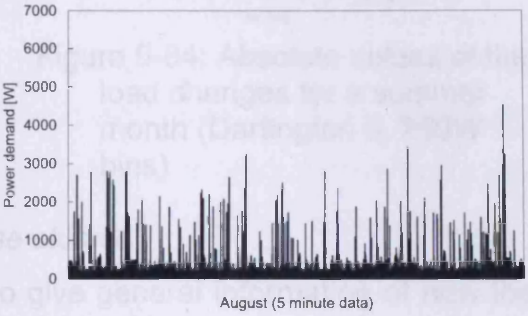


Figure 5-78: Power demand over the course of a summer month (Dartington 5)

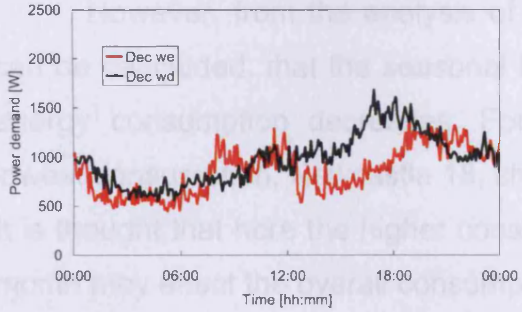


Figure 5-79: Electric load profile for a winter month (Dartington 5)

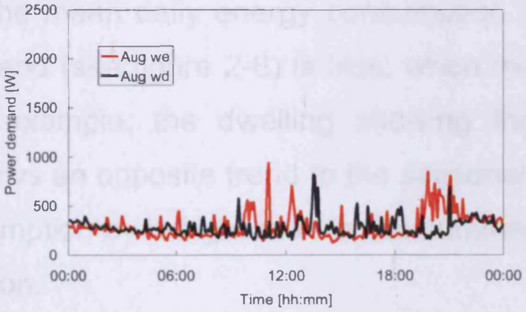


Figure 5-80: Electric load profile for a summer month (Dartington 5)

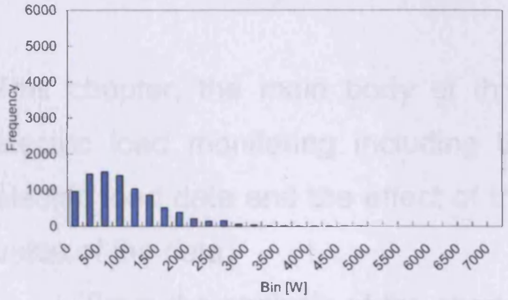


Figure 5-81: Distribution of the power demand for a winter month (Dartington 5, 250W bins)

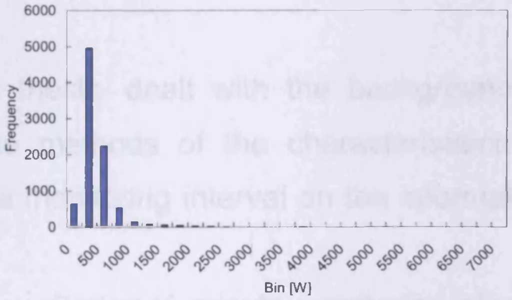


Figure 5-82: Distribution of the power demand for a summer month (Dartington 5, 250W bins)

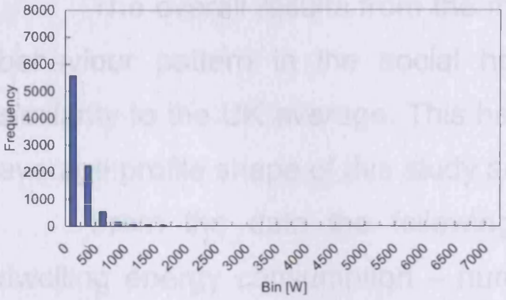


Figure 5-83: Absolute values of the load changes for a winter month (Dartington 5, 250W bins)

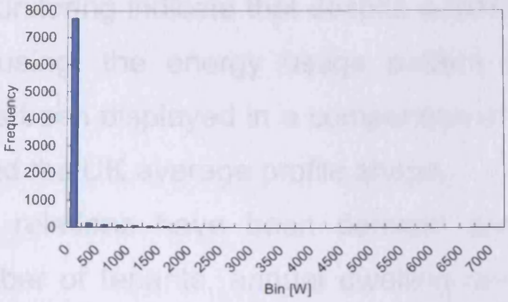


Figure 5-84: Absolute values of the load changes for a summer month (Dartington 5, 250W bins)

5.6.6. *Evaluation of the 4 case studies*

These four case studies are suppose to give general information of how the characteristic of the electrical parameters with the annual energy consumption vary. The comparison of the four studies is difficult; the studies are rather seen as an independent source of information.

However, from the analysis of the mean daily energy consumption it can be concluded, that the seasonal trend (see figure 2-6) is less, when the energy consumption decreases. For example, the dwelling showing the lowest consumption, Newcastle 18, shows an opposite trend to the seasonal. It is thought that here the higher consumption by refrigeration in the summer month may effect the overall consumption.

5.7. *Summary*

This chapter, the main body of this thesis, dealt with the background of electric load monitoring including the methods of the characterisation of electric load data and the effect of the monitoring interval on the information value of the data.

From the analysis of the short monitoring (1 minute monitoring interval recorded over the period of 1 week in 6 houses) it can be concluded that the usage of 5 minute data ignores peaks of up to 4500W in the load. The average undetected power peaks with in the data have been determined as 1300W (calculated by subtracting the average of the peak load of the 1 minute data from the average of the peak load data of the 5 minute data).

The overall results from the monitoring indicate that despite a different behaviour pattern in the social housing, the energy usage pattern was similarity to the UK average. This has been displayed in a comparison of the average profile shape of this study and the UK average profile shape.

From the data the following relations have been derived: annual dwelling energy consumption – number of tenants, annual dwelling energy consumption – floor area of the dwelling, annual dwelling energy consumption – peak loads as well as and annual dwelling energy consumption – base loads. Even with a fairly low correlation between the two parameters, the findings are useful to find the first approach of describing the character of the electric load in the dwelling.

The site specific analysis revealed the differences of each project in terms of possession of appliances and consumption. From the investigation of the peak loads of the 5 different sites it can be generalised that sites that use only gas to power the cookers and the showers have a monthly peak load of around 5000W, sites with a mix of gas and electric show peak loads of 6500W and sites which are a purely electric powered have loads up to 7500W.

In the dwelling specific investigation it could be shown how a single household power demand varies on the 5 minute interval by using histograms for the changes in the load. This is valuable information when the, for example, on-site generation or a storage system has to follow the load steps.

6. Load modulation by BIPV

6.1. Introduction

This part of the thesis deals with the options of reducing the electric load in a domestic dwelling by building integrated photovoltaic systems. For this, the findings from the previous chapters on the characteristics of the dwelling and the energy consumption (5 minute data) are combined with results from a simulation of photovoltaic energy generation patterns. During the PVDFT of the DTI irradiances and PV-generation data were recorded, however not all needed data for this simulation were part of the monitoring campaign. Therefore, a certain part of the required data for the present study had to be modelled. However it is explained within the following sections when recorded or simulate data is utilised.

This investigation on the modulation of the electric load by BIPV uses the consumption data of the Dartington and Newcastle. The Dartington site was chosen because the average annual consumption of this site (3752kWh) was the closest to the results from the Electricity Association (3782kWh). This case study represents the UK average regarding the annual consumption.

The simulation for Dartington has been carried out using a two step approach, where first the irradiance (west and south orientated) and second the energy production of a photovoltaic system was obtained. For each flat the influence of two different sized PV-systems (1.36kWp and 2.04kWp) is investigated.

The second investigation was carried out with the consumption data of Newcastle. This site was chosen because it is a typical building of the social housing sector with an annual average consumption of 2179kWh per flat. For Newcastle the irradiance data (south and west orientated) were available (recorded during the PVDFT) so only the energy generation by BIPV had to be simulated. Due to the limited available space on the roof of the building (see figure 3-3) only the influence of a 1.36kWp PV-generator (ca. 10m^2) was investigated.

For this analysis the data of a south-facing (30° inclination) generator and a west-facing (30° inclination) generator is simulated onto the power demand data of the dwellings. A photovoltaic system orientated towards west

produces less power than a south-facing, however this generation is shifted to the later hours when the evening peak on the load profiles occurs.
This investigation also considers a possible future grid configuration with small networks connected to a larger on-site generation system. Therefore the dwellings of each site are seen as one grid, still connected to the electric supply and the sum of each photovoltaic system as one large generator. This increase the coverage since the overall electric demand looses the characteristic peaks and valleys and a more balanced load profile occurs. A small network will still have the same technical configuration like the present one. The PV-system can be still integrated into the roof of the building. However, the building internal wiring regarding the connection of the PV-system to the dwellings would change.

In the following sections the term “reduction of domestic load” will be used. This term is defined as the reduction within the domestic dwelling, not on the public grid. This investigation has been carried out from the point of view of the occupant. The usage of the PV-energy directly within the building will reduce the losses on the grid, therefore this strategy should be the favourite one in most cases.

6.2. The simulation of the photovoltaic generation profiles

The generation of a south and a west facing photovoltaic generator are described in the following. For the simulation of the irradiance in plane of array, the Integrated Simulation Environment Language [INSEL, 2007] [Luther and Schumacher-Grühn, 1991] was utilised. This program, well known in the German research of renewable energy, has been used since it provides the required skills and the author had known this software from several other projects. The inputs are the irradiance on the horizontal (recorded during the PVDFT), the latitude and longitude of the location as well as the albedo value. The albedo is defined as the ratio of the radiation reflected from the surface and the radiation incident on the surface [Iqbal, 1983]. It depends on the characteristic of the surface. Since the PV systems are located in an urban environment, a value of 0.2 for weather beaten concrete was chosen [Quaschning, 1998]. For the site Newcastle, the desired irradiance (30° west and 30° east) was recorded during the monitoring campaign of the DTI and no modelling was needed.

The basic principle of the written INSEL program is that the diffuse irradiance is calculated from the horizontal irradiance, the position of the sun and the irradiance outside the atmosphere. The diffuse irradiance, the horizontal irradiance and the albedo are then used to obtain the irradiance on the tilted surface.

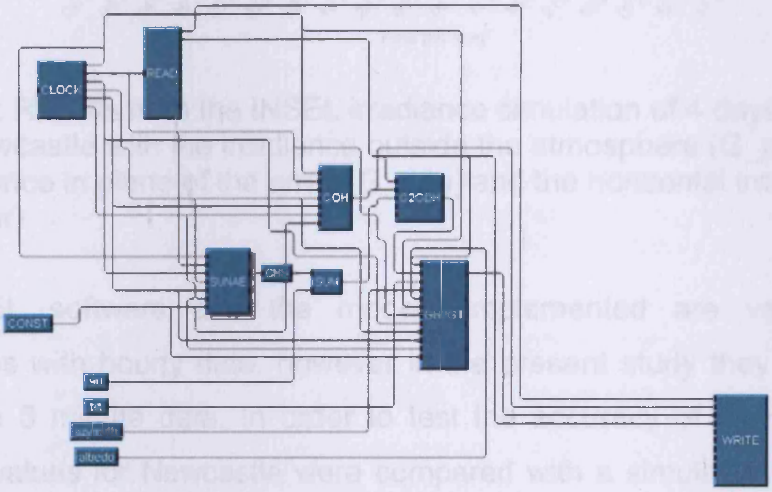


Figure 6-1: Screenshot of the graphical programming language INSEL (Integrated Simulation Environment Language) [INSEL, 2007] [Luther and Schumacher-Grühn, 1991], showing the different modules used for the simulation

Figure 6-2 illustrates four days of simulation in August, the results show the irradiance outside the atmosphere G_{oh}, the irradiance in the plane of array (tilted surface irradiance) G_{poa} and the horizontal irradiance G_{hor}. Day two shows that irradiance in plane of array is greater than the irradiance outside the atmosphere. In August, it is possible that due to reflections a higher irradiance can occur on a horizontal surface than outside the atmosphere.

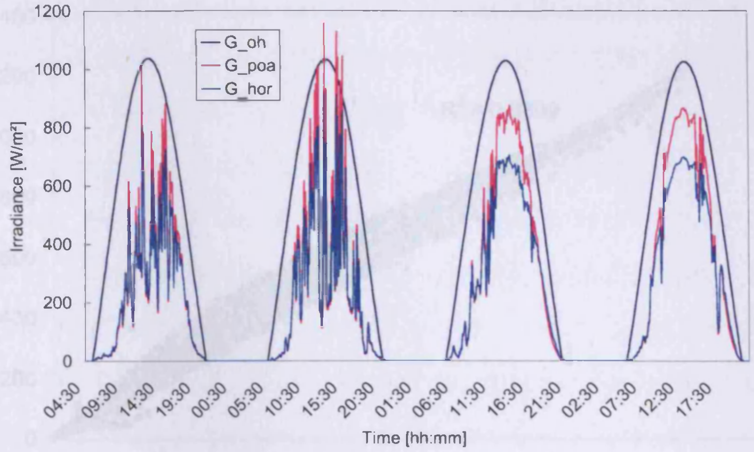


Figure 6-2: Results from the INSEL irradiance simulation of 4 days in August at Newcastle with the irradiance outside the atmosphere (G_oh), the irradiance in plane of the array (G_poa) and the horizontal irradiance (G_hor)

The INSEL software and the models implemented are validated for calculations with hourly data, however in the present study they have been applied on 5 minute data. In order to test the accuracy of the results, the recorded values for Newcastle were compared with a simulation carried out for this site. Figure 6-3 shows the comparison of the simulated and measured data of irradiance for August. The red line presents a perfect model, the green line the linear trend of the modelled data. The coefficient of correlation is close to 1. The monthly measured irradiation was 113.49kWh the simulated irradiation 109.65kWh.

From figure 6-3 it can be seen that the model overestimates the irradiance in the range between ~200W/m² and ~700W/m². In higher ranges (1000W/m²) the model underestimates the irradiance. The model shows an average error of 18W/m² across the whole range when compared with the measured irradiance. This error is calculated by averaging the absolute errors derived from the subtraction of the value of the irradiance model from the measured values.

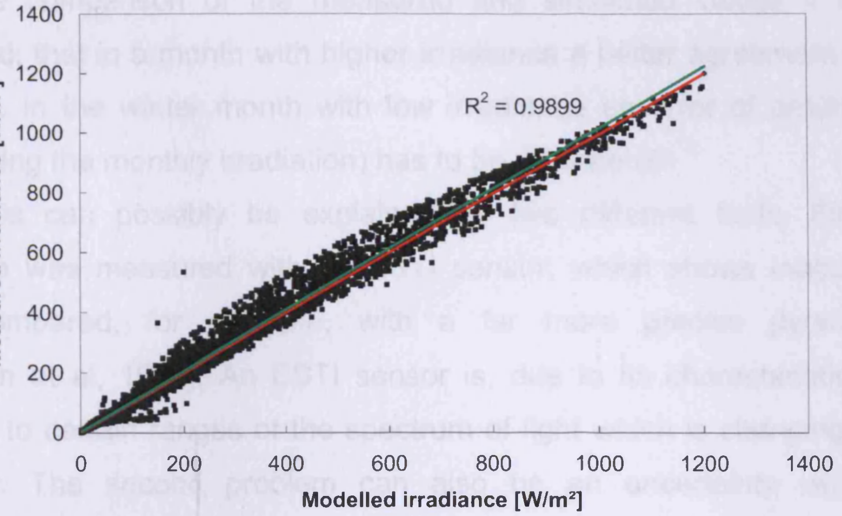


Figure 6-3: Comparison of measured and simulated results of irradiance in plane of array for August in Newcastle (the red line presents a perfect model, the green line presents the trend of the modelled data)

Figure 6-4 shows the results for the simulation in January (the red line presents a perfect model, the green line the linear trend of the modelled data). The measured irradiation amounts to 36.15kWh the simulated irradiation was 31.20kWh. The coefficient of correlation is 0.93, which is less than in the month August. The irradiance data show an average error of 34W/m² across the whole range when compared with the measured data. This error is calculated by averaging the absolute errors derived from the subtraction of the value of the irradiance model from the measured values.

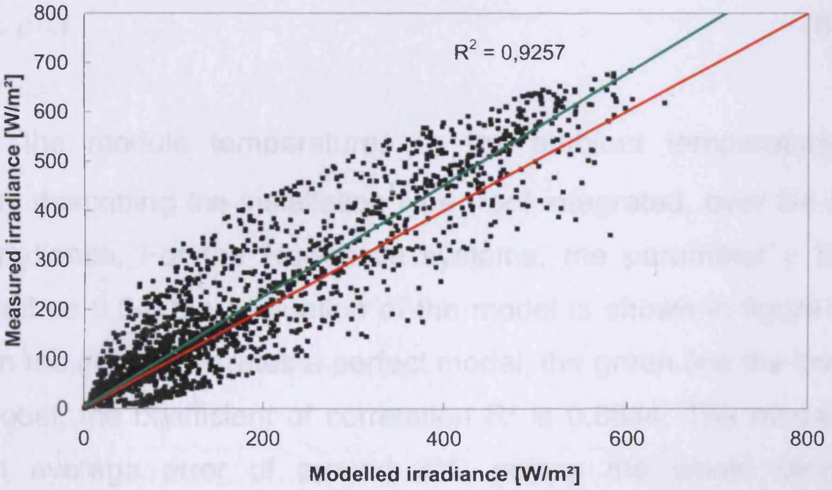


Figure 6-4: Comparison of measured and simulated results of irradiance in plane of array for January in Newcastle (the red line presents a perfect model, the green line presents the trend of the modelled data)

From the comparison of the measured and simulated values it can be concluded, that in a month with higher irradiance a better agreement can be expected. In the winter month with low irradiance an error of around 10% (considering the monthly irradiation) has to be considered.

This can possibly be explained by two different facts. First, the irradiance was measured with an ESTI sensor, which shows inaccuracies when compared, for example, with a far more precise pyranometer [Heaberlin et al, 1995]. An ESTI sensor is, due to its characteristics, less sensitive to certain ranges of the spectrum of light which is changing during the year. The second problem can also be an uncertainty within the irradiance model, which also has to cope with the variation of the characteristic of light during the year.

For each site a roof integrated photovoltaic system with BP585 modules (16 modules for the 1.36kWp system and 24 for the 2.04kWp system) and an SMA inverter (1100W for the 1.36kWp system and 1700W for the 2.04kWp system) is simulated. The models, described in chapter 3 to correct the photovoltaic data, were applied to obtain the AC output of the inverter.

As described in chapter 3, the MPP model requires the module temperature as an input. This parameter was simulated with the following model [Prignitz, 2005]:

$$T_M = T_A + c \cdot G \qquad (6\text{-}1)$$

with T_M the module temperature, T_A the ambient temperature, c the parameter describing the installation type (roof integrated, over tile etc.) and G the irradiance. For the Newcastle systems, the parameter c has been determined as 0.04, the evaluation of the model is shown in figure 6-5. The red line in the graph illustrates a perfect model, the green line the linear trend of the model, the coefficient of correlation R^2 is 0.8844. The modelled data show an average error of around 3°C across the whole range when compared with the measured data. This error is calculated by averaging the absolute errors derived from the subtraction of the value of the irradiance model from the measured values. From this test it can be concluded that the modelled data shows a good agreement with the measured data.

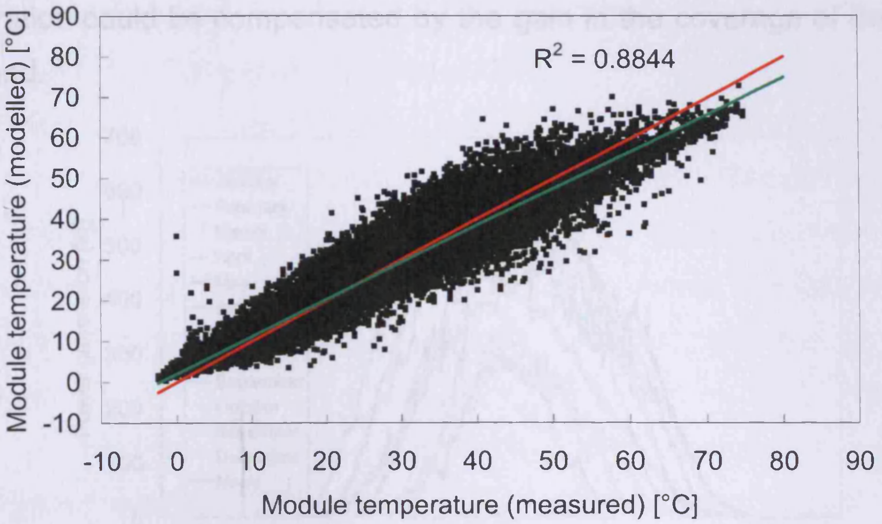


Figure 6-5: Comparison of measure and modelled module temperature at Newcastle (the red line presents a perfect model, the green line presents the trend of the modelled data)

Table 6-1 gives a summarising overview of each step of the simulation to obtain the PV-energy pattern for the different sites. The table also includes the input and output parameter, as well as the sources for the models.

Table 6-1: Summary of the steps of the simulation in order to obtain the inverter output data

Simulation	Source	Input	Output
Irradiance	INSEL (various models)	Horizontal irradiance, recorded during the PVDFT	Irradiance on a south and west facing generator with an inclination of 30°
Module temperature	[Prignitz, 2005]	Ambient temperature (recorded during the PVDFT) and irradiance in plane of array	Module temperature
Solar generator	[PVSAT2, 2006], [Beyer et al., 2004]	Irradiance in plane of array, module temperature	DC output of the PV-generator
Inverter	[Eicker, 2001]	DC power of the generator	AC output of the PV-generator

The figures 6-6 and 6-7 show the results from the simulation of a south and west facing 1.36kWp PV-generator. As it can be expected, the generated energy from the south orientated systems is higher, however the peak of the west profile shifted towards the evening, where the peak of the demand usually occurs. In the following it was investigated whether this loss in generation could be compensated by the gain in the coverage of the electric demand.

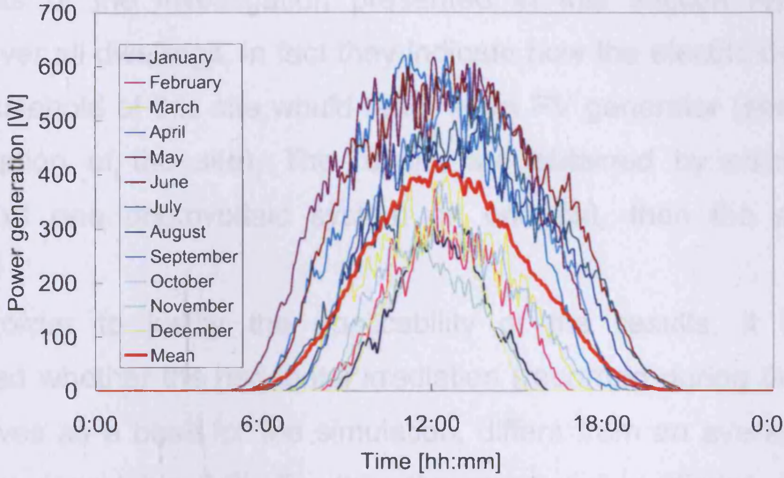


Figure 6-6: Modelled monthly average of a generation profile for a 1.36kWp PV-system (orientation south, 30° inclination) obtained with the Newcastle meteorological data

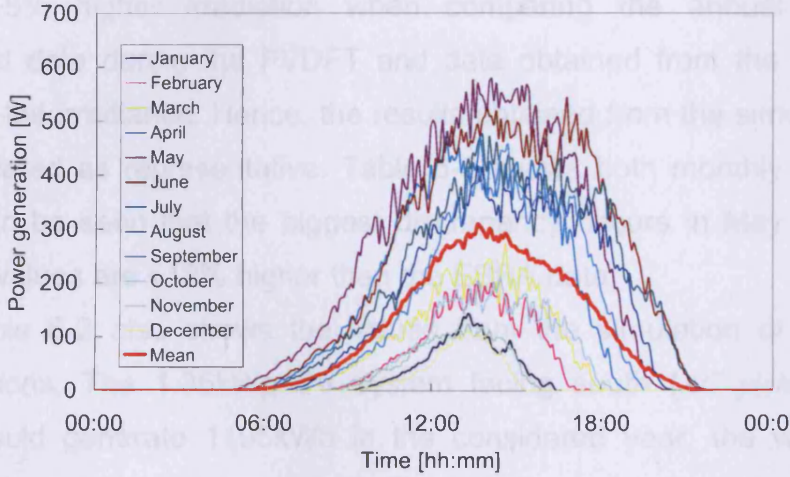


Figure 6-7: Modelled monthly average of a generation profile for a 1.36kWp PV-system (orientation west, 30° inclination) obtained with the Newcastle meteorological data

6.3. Electric load and its modulation by BIPV: results

6.3.1. Case study 1 – Dartington

The results of the investigation presented in this section represent an average over all dwellings, in fact they indicate how the electric demand of a typical household of this site would react to an PV generator (see chapter 5 for description of the site). The results are obtained by calculating the influence of one photovoltaic system on one flat, then the outcome is averaged.

In order to justify the applicability of the results, it has to be investigated whether the horizontal irradiation (recorded during the PVDFT), which serves as a base for the simulation, differs from an average year for the location (see table 6-2). For this, the measured irradiation (H_{hor_meas}) is compared with the data from ESRA (H_{hor_ESRA}) [ESRA, 1998] which represents an average of 10 years. The measurements of Dartington show only a ~5% higher irradiation when comparing the annual summary (measured data during the PVDFT and data obtained from the data base ESRA) of the irradiance. Hence, the results obtained from the simulation can be considered as representative. Table 6-3 shows both monthly data sets, here it can be seen that the biggest discrepancy occurs in May, when the recorded values are ~12% higher than the ESRA data.

Table 6-2 also shows the values from the simulation of the 4 PV configurations. The 1.36kWp PV system facing south (*AC yield (1.36kWp south)*) would generate 1195kWh in the considered year, the west facing 1025kWh (*AC yield (1.36kWp west)*). The third and the fourth configuration would produce 1818kWh (*AC yield (2.04kWp south)*) for the south facing 2.04kWp system and 1556kWh (*AC yield (2.04kWp south)* for the west facing system (see also figure 6-8, *E_ac_south* and *E_ac_west*). The annual final yield of the simulation for Dartington, located in the south of England, is around 880kWh, which is higher than the UK average of 707kWh/kWp. However this value is close to the maximum value of 833kWh/kWp for the UK, representing the south of England [Šúri et al., 2007].

Considering first the smaller 1.36kWp system, it can be concluded that the south facing generator produces around 15% more energy than the west facing generator. However, as it can be seen in figure 6-8, the months

February, May and June show a lower resulting energy consumption (*E_resulting_south* and *E_resulting_west*) when using a west facing generator (the resulting energy is the energy used in the dwelling, excluding the energy exported to the grid).

The west facing generator shows a higher value of the direct use fraction (*fd_south* and *fd_west*) (see figure 6-8), which is due to the fact that PV occurs closer to the evening peak (the direct use fraction is the ratio between the direct consumed energy and the generated PV energy). The annual average of this parameter for a south facing generator is 60% and for a west facing generator 70%.

Table 6-2: Comparison of measured irradiation ($H_{hor,\ meas}$) during the PVDFT and statistical based irradiation ($H_{hor,\ ESRA}$) [ESRA, 1998] and results from the PV simulation of Dartington for the 4 different configurations (AC Yields)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Sum**
H_{hor_meas} [kWh]	24	41	77	125	157	163	165	137	94	53	29	18	1083
H_{hor_ESRA} [kWh]	24	44	80	111	127	161	161	132	98	48	28	18	1032
AC Yield (1.36kWp south) [kWh]	36	65	115	125	151	160	143	153	118	67	39	23	1195
AC Yield (1.36kWp west) [kWh]	20	40	99	106	147	155	134	141	101	47	22	12	1024
AC Yield (2.04kWp south) [kWh]	54	95	175	192	231	244	218	234	180	101	58	34	1816
AC Yield (2.04kWp west) [kWh]	30	61	150	160	224	236	205	214	154	71	33	18	1556

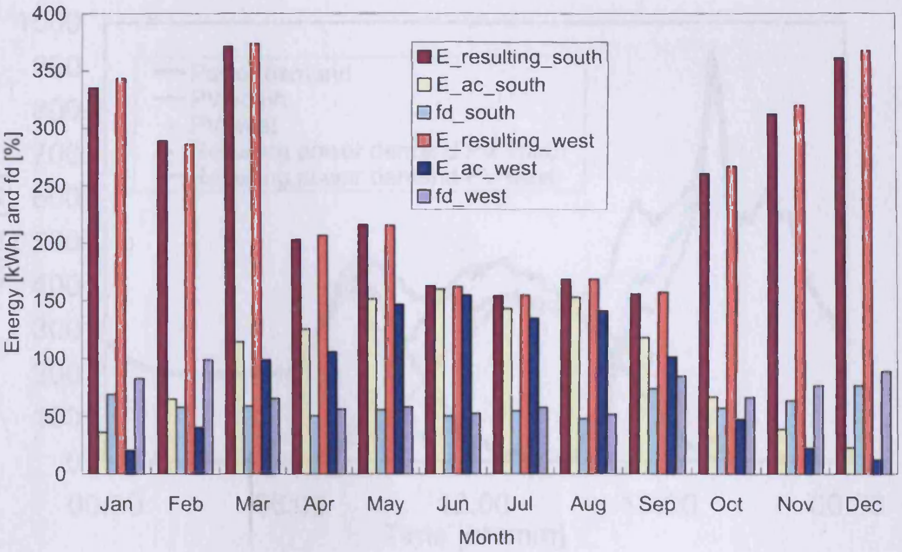


Figure 6-8: Comparison of the monthly values of the remaining energy consumption of the dwelling (E_resulting), the generated PV-energy (E_ac) and the direct use fraction (fd) for a 1.36kWp PV-system with the orientations south and west at Dartington

From this case study it can be concluded, that there is no significant difference in the annual resulting energy consumption regarding the orientation of the PV generator (considering west and south). A south facing PV system would reduce the consumption from 3752kWh to 2988kWh (20% reduction) and a west facing PV system to 3022kWh (19% reduction). The energy generated and exported to the grid is less with a west generator, on the other hand a better reduction of the evening peak can be achieved. This effect is illustrated in figure 6-9. The graph shows that the PV energy of a west facing generator occurs around 1 hour later. This results in a marked decrease of the evening demand, at least in the early hours of the peak. At 18:00, for example, the resulting power demand with the west orientated system shows a value of 370W, the resulting power is 450W for the south orientated system. When a south facing system is used the resulting power demand will be 0W for around 4 hours. The west PV-configuration shows a much shorter period in which no power is needed (ca. 2 hours).

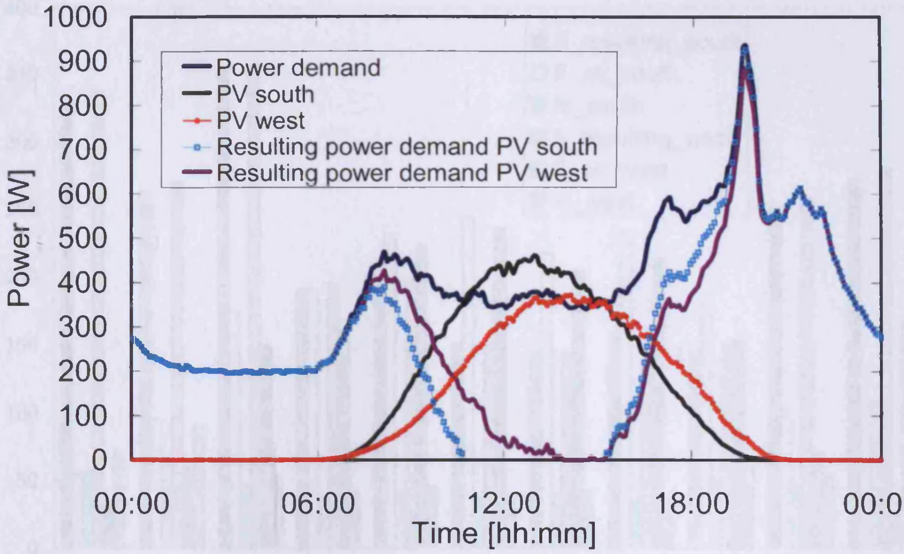


Figure 6-9: Annual average load profile (Power demand), 1.36kWp PV generation profiles (PV) with two orientations and the resulting load profile (Resulting power demand) for Dartington

Considering the 2.04kWp PV-system configuration, the difference in the energy generation between a west facing and a south facing PV system is also 15% (see table 6-2). The same effect occurs as with the 1.36kWp configuration, the months May, June, July and August show a lower resulting consumption *(E_resulting)* with a west facing PV system (see figure 6-10). This is due to the high value of exported energy, and in this case unused energy by the south facing system.

The annual direct use fraction for the south facing system amounts to 53% and 66% for the west facing, respectively. A south facing 2.04kWp generator would reduce the annual energy consumption from 3752kWh to 2827kWh (reduction of 25%), a west facing generator to 2869kWh (reduction of 24%). Also here no significant difference in the load reduction can be realised when the west and south PV-configuration is compared.

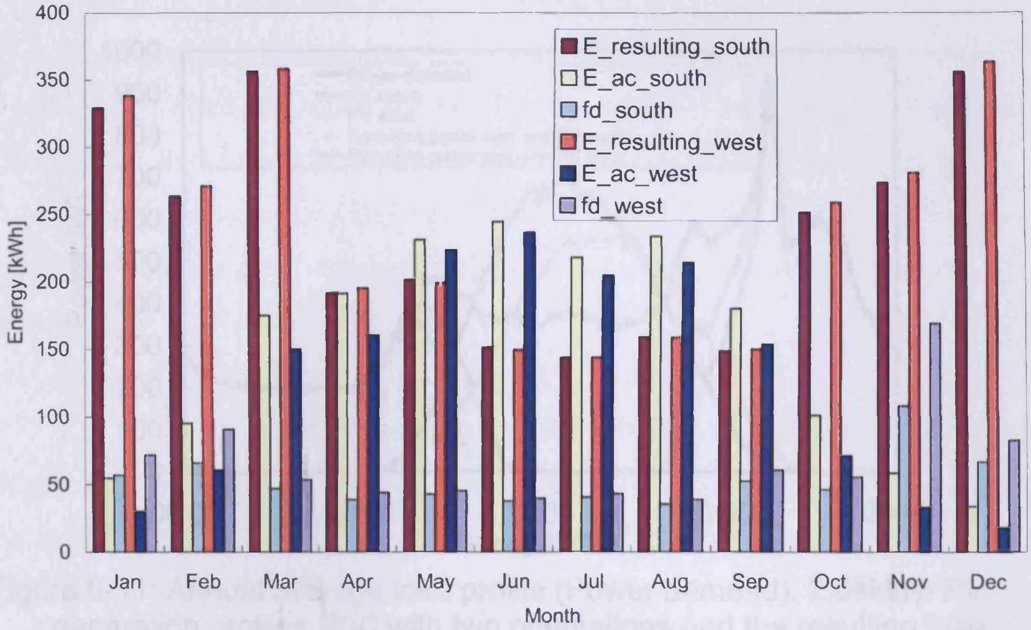


Figure 6-10: Comparison of the monthly values of the remaining energy consumption of the dwelling (E_resulting), the generated PV-energy (E_ac) and the direct use fraction (fd) for a 2.04kWp PV-system with the orientations south and west at Dartington

Figure 6-11 shows the power profiles on an annual base, there is a considerable difference in the amplitude of the PV profiles when compared to the smaller 1.36kWp system. The annual average of the 2.04kWp system power generation profile is 40% higher than the 1.36kWp system. The larger PV configuration leads to longer periods of no import of energy, the south facing system would create a period of 6 hours and the west facing around 5 hours, respectively. At 18:00, for example, the difference in the power demand would be 280W (PV west) to 400W (PV south).

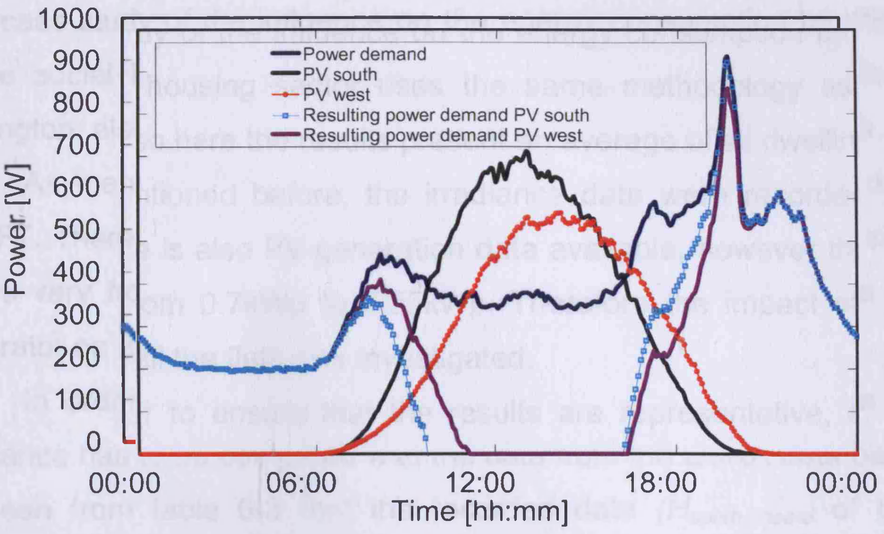


Figure 6-11: Annual average load profile (Power demand), 2.04kWp PV generation profiles (PV) with two orientations and the resulting load profile (Resulting power demand) for Dartington

Comparing the effect of the two different sized PV generators on the annual energy balance of this average dwelling in Dartington, it can be stated that the smaller one reduces the energy consumption by around 550kWh per installed kWp PV power. The larger system reduces the energy consumption only by ~440kWh/kWp. For this case it is obvious, the larger the solar system the smaller the percentage of its energy is used in the dwelling. This is illustrated very well in figure 6-9 and 6-11.

If the single PV-systems of each house are connected to one large system and then fed into one network, created by all the houses, a better coverage by the solar energy can be achieved. In this case study the resulting annual energy consumption of the 8 houses connected to a 10.88kWp (8*1.36kWp) generator can be reduced from 3752kWh to 2770kWh (reduction of 26%) per dwelling, which is around 250kWh less than the former investigated configuration (one house connected to one 1.36kWp PV system).

Considering a 16.32kWp generator (8*2.04kWp), embedded into the electrical network of the 8 houses, the consumption may be decreased from 3752 to 2640kWh (reduction of 30%) per year and dwelling, this is an improvement of 208kWh when compared with the single 2.04kWp PV-house option.

6.3.2. Case study 2 – Newcastle

This case study of the influence on the energy consumption by photovoltaic in the social housing sector uses the same methodology as the one of Dartington, also here the results present an average of all dwellings.

As mentioned before, the irradiance data were recorded during the PVDFT. There is also PV-generation data available, however the size of the arrays vary from 0.7kWp to 2.55kWp. Therefore the impact of a 1.36kWp generator on all the flats was investigated.

In order to ensure that the results are representative, the recorded irradiance has to be compared with the data from the ESRA data base. It can be seen from table 6-3 that the recorded data (H_{south_meas}) of the south orientation is 4% less than the ESRA data (H_{south_ESRA}). The measured data from the west orientation (H_{west_meas}) is around 6% less than the ESRA data (H_{west_ESRA}) base records.

The results from the simulation of the PV-generator are also presented in table 6-3. The south facing generator produces 1034kWh per year (see the last column), which is around 760kWh/kWp. Compared to the results from Šúri [Šúri et al., 2007] (707kWh/kWp) this means that the simulated results are ca. 7% higher than the one from the data base.

The 1.36kWp PV-system oriented towards west generates 244kWh (around 23%) less than the PV-system facing south. If one compares this result with result from the Dartington (west facing PV-generator produces 15% less then the south facing one), it can be seen that there is a difference. It must be assumed that in Newcastle, with lower irradiation due to the location further north (see figure 3-1), the inverter works longer periods in the part load and therefore with a lower efficiency (see figure 3-16).

Still, the overall results of the PV-simulation and the recorded irradiation data are in a range that can be accepted and applied for this study.

Table 6-3: Comparison of measured irradiation ($H_{south, meas}$) during the PVDFT and statistical based irradiation ($H_{south, ESRA}$) [ESRA, 1998] and results from the PV simulation of Newcastle for the 2 different configurations (AC Yields)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Sum**
H_{south_meas} [kWh]	36	43	72	130	150	161	124	113	109	58	34	36	1066
H_{south_ESRA} [kWh]	38	55	94	119	148	145	147	133	107	70	39	21	1117
H_{west_meas} [kWh]	18	28	49	104	137	145	120	97	80	37	19	14	848
H_{west_ESRA} [kWh]	18	34	67	99	136	135	137	114	80	47	22	12	899
AC Yield (1.36kWp south) [kWh]	35	42	68	127	151	149	120	109	109	56	33	36	1034
AC Yield (1.36kWp west) [kWh]	13	24	47	99	137	132	114	92	77	32	14	9	790

Figure 6-12 shows the results of the load modulation by BIPV simulation. From this case study it can be seen that the south facing PV-generator is the best option to reduce the load. The parameters *E_resulting_south* is smaller in all the month than *E_resulting_west*, the shifting of the PV-generation did not improve the energy consumption in the dwellings.

The direct use fraction of the west facing generator is higher in the winter month due to the smaller amount of energy produced by the PV-system, the annual average of the parameter *fd_south* is 54% and of the parameter *fd_west* is 51%.

The south facing 1.36kWp PV-system can lower the energy consumption of the average flat of this building in Newcastle from 2179kWh per year to 1763kWh, this is a reduction of 416kWh and 19%. The west facing PV-generator can reduce the consumption to 1822kWh, this is a reduction of 357kWh and 16%.

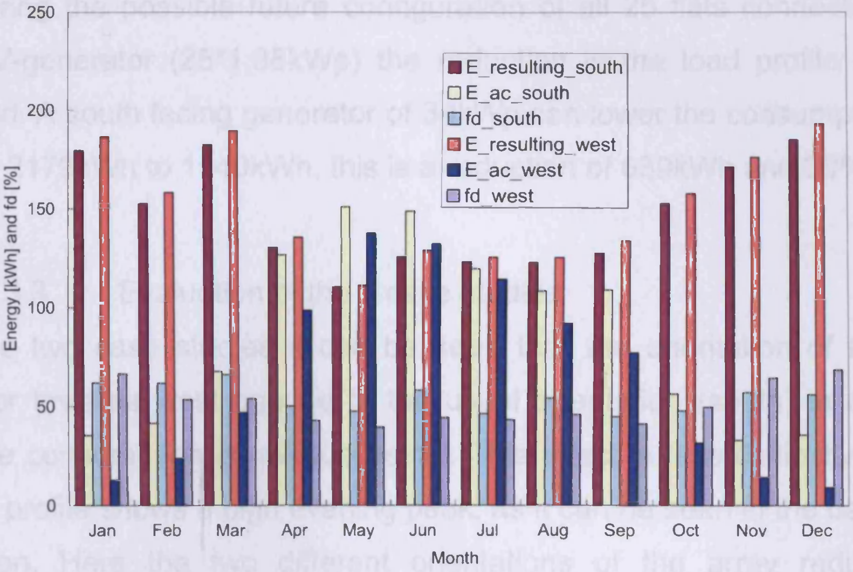


Figure 6-12: Comparison of the monthly values of the remaining energy consumption of the dwelling (E_resulting), the generated PV-energy (E_ac) and the direct use fraction (fd) for a 1.36kWp PV-system with the orientations south and west at Newcastle

Figure 6-13 shows the reason for the lower reduction of the consumption by the west facing PV-system. The PV-generation is shifted towards the evening peak, however the load profile does not show a very strong peak at this time of the day. Another explanation is that the PV-generation profile peak of the west facing occurs, when there is even a valley of the consumption profile (ca. 14:00).

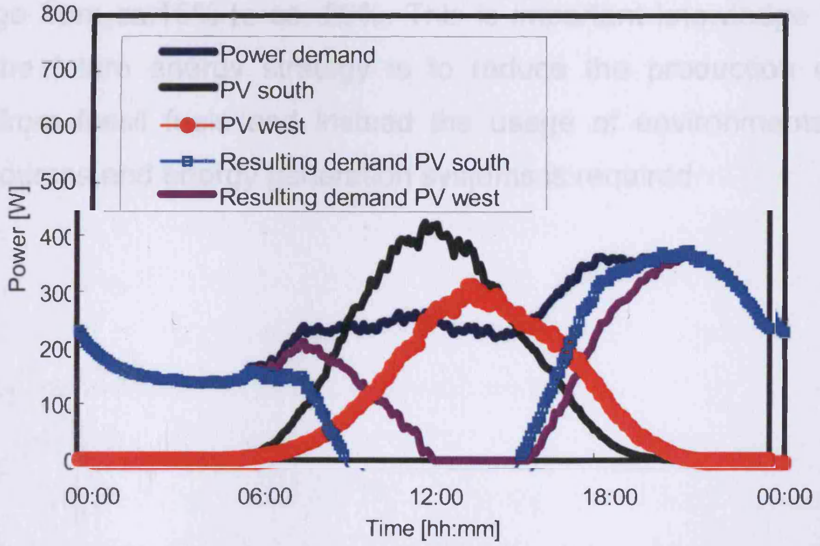


Figure 6-13: Annual average load profile (Power demand), 1.36kWp PV generation profiles (PV) with two orientations and the resulting load profile (Resulting power demand) for Newcastle

Considering the possible future configuration of all 25 flats connected to a large PV-generator (25*1,36kWp) the reduction in the load profile can be optimised. A south facing generator of 34kWp can lower the consumption per flat from 2179kWh to 1540kWh, this is a reduction of 639kWh and 30%.

6.3.3. Evaluation of the 2 case studies

From the two case studies it can be seen that the orientation of the PV-generator towards west oppose to the usual orientation (south) in order to lower the consumption is not successful. This effect is less distinctive when the load profile shows a high evening peak, as it can be seen in the data from Dartington. Here the two different orientations of the array reduce the consumption on a similar level.

The energy consumption of the investigated case studies Dartington and Newcastle can be reduced in a range of 20% to 25%. Assuming one large PV-generator and a small grid instead several separated dwellings, the reduction in the consumption can be increased to around 30%.

The results from the case study Newcastle, Dartington and other studies of the UK are compared in table 6-4. It can be concluded, that the results of the different studies do not differ much from the present study.

Therefore it can be generalised, that the annual energy consumption of a UK dwelling can be reduced by a medium sized PV-system (1 to 2kWp) in a range from ca.15% to ca. 20%. This is important knowledge when the aim of the future energy strategy is to reduce the production of energy derived from fossil fuels and instead the usage of environmental friendly energy sources and energy generation systems is required.

Table 6-4: Comparison of the results of the present study and the results of different UK studies regarding the reduction of domestic load by BIPV

Study	**PV-system size [kWp]**	**Annual energy consumption [kWh]**	**Reduction of consumption [%]**
Present study: Dartington	2.04	3752	25
Present study: Dartington	1.36	3752	20
Present study: Newcastle	1.36	2179	19
Bahaj [Bahaj and James, 2006]	1.53	4400	17
Munyati [Munyati et.al., 2001]	2	3953	21
Munyati [Munyati et.al., 2001]	1	3953	13

6.4. Summary

This chapter investigated the modulation of the electric load by a photovoltaic system. Therefore the methodology of the simulation of parts of the irradiance data and the PV-generation profiles were described.

Two sites were chosen, where one represents an UK average of electric energy consumption and the second one a typical building from the social housing sector, to investigate which level of reduction of the electric consumption can be achieved. The results of the two case studies show, assuming a realistic sized PV-generator, that the energy consumption load can be reduced in the range of 20-25%.

The best load match can be realised when all flats are connected to a large PV-generator oppose to the connection of one flat to one small PV-system, which can be seen as one of the future configurations of PV and buildings. The reduction of load is here around 30%.

The investigation of the different oriented PV-arrays has shown, that the best solution is the south facing, even if the peak of the west facing is moved towards the evening peak of the electric load.

The size and effectiveness of a PV system can also be seen to be strongly influenced by how the PV electricity generated is used. If the electricity can only be used within one house then, assuming no storage solutions are used, the smaller system tested makes more economic sense. However, if favourable feed-in tariffs are provided then it makes sense for the homeowner to export all the electricity produced into the public grid.

7. Conclusions

7.1. Main conclusions

This thesis has described the long term, high resolution monitoring campaign of 81 dwellings on 5 different sites in the domestic sector of the UK as well as the data processing and the data analysis. The data were obtained during Department of Trade and Industry Photovoltaic Domestic Field Trial. 46 of these dwellings were also the subject of an occupancy survey whose results are also reported here. Based on the consumption data of the dwellings an investigation on the possibilities to reduce the electric load by BIPV has been carried out.

It can be concluded, that this research has proven to solve the research problem defined in chapter 2:

- This work has added to the body of knowledge a new set of measured domestic electricity load profiles.
- The thesis has characterised the electric load profiles statistically and by connecting the data from an occupant survey to the energy consumption data.
- This research was able to provide a solid base to the innovative research field of load modulation by BIPV.

Part of this work has also been used in IEA – Energy Conservation in Buildings and Community Systems Annex 42 to help provide a unique set of data profiles suitable for use in assessing micro-generation plant sizing for European domestic properties.

The error found in a certain part of the photovoltaic data sets (2 out of 5 sites) was corrected by the application of a model with meteorological input data, also recorded during the PVDFT. This model is described and the results of the correction were validated against available data sources. This successful correction of the erroneous data was essential to this research since it was needed to calculate the consumption data of the dwellings.

It can be summarised, that the correction of the erroneous data was successful and the errors are in a range that can be accepted.

The overall quality of the recorded and the simulated data used in this research has been evaluated and presented in this work. An error analysis in order to determine the overall accuracy has been carried out, it can be concluded that the data is reliable and therefore useable for further research.

The methodology and the results of an occupant survey in 46 households of the social housing sector are presented in this study. The survey was designed and carried out by the author.

The findings were compared to two available surveys from the UK regarding the ownership level of appliances. The conclusion that can be drawn from the survey is, that the ownership level of TV's in the social sector is twice as much as the UK average. It can also be stated, that the ownership of dishwashers is only half of the national average and that there are 30% less computers to be found in the social housing sector. Other findings from the survey are the usage frequency, the usage duration and the usage pattern of the electric appliances covered by the survey.

The effect of the monitoring interval on the overall findings has been investigated by analysing 7 days of very high resolution energy consumption monitoring (1 minute) of 6 houses and comparing the data against the 5 minute average. The finding of this study is that there can be undetected spikes in the load data of up to 4500W, when using 5 minute data (compared to the 1 minute data). The average undetected peak in the monitored period was 1300W (calculated by subtracting the average of the peak load of the 1 minute data from the average of the peak load data of the 5 minute data). Still, it can be concluded, the usage of 5 minute data can be considered as sufficient for the purposes of describing domestic energy use as most high energy consuming appliances present in a household will exceed the period of 5 minutes.

A new set of high resolution electric load profiles grouped in different seasons, weekdays and weekend days exclusively from the data of the social housing were derived and presented in this work.

From the results it can be concluded, that the social housing load profile does not differ much when compared with the national standard profile, despite the different behaviour pattern obtained from the occupant survey.

The monthly averaged load profile does not exceed 700W for a winter month, for a summer month the maximum of the profile is around 450W.

The analyses also suggest that a rough estimation of the annual consumption of a dwelling can be made from the number of tenants (annual energy consumption=(number of tennants/489.39)+1945.4) and the floor area (annual energy consumption =(floor area/35.248)+508.95).

Estimations of the peak load (peak load=(annual energy consumption/0.4)-1143.3) and of the base load (base load=(annual energy consumption/9.69)-191,35)) to be expected in a dwelling, can be obtained from the annual consumption. Conversely, short term monitoring of the base load, or knowledge of the peak loads, can be used to estimate the annual demand. The derivation of these results has shown, that the convergence in the data is fairy low, however in the absence of any further information that could help to predict load parameters, these estimations are a good starting point.

Each site has been analysed separately regarding the ownership level of appliances, the annual and monthly energy consumption, the peak load and the electric load profile.

The different sites were compared and it can be stated, that the ownership level of appliances shows in general a good agreement. The annual consumption varies from site to site, due to the different dwelling characteristics. The average monthly peak load varies, depending on the way the cooker and showers are powered. Gas powered sites have a monthly peak load of 5000W, gas and electric powered sites have a average peak load of 6500W and purely electric powered sites have 7500W average peak loads. The monthly load profiles of the different sites show in general a similar shape, however the peaks differ strongly.

In order to give a first approach on the characteristic of the electric load of a single dwelling, four case studies have been carried out. This investigation included the monthly energy consumption, peak load, the load profiles, the analysis of the distribution of the load as well as the changes in the load.

The consumption data of the monitoring campaign were employed to investigate the impact of building integrated photovoltaic generators on the electric load and the annual energy consumption. Here the electrical output of different orientated generators was modelled against average sets of load data from the Dartington site and the Newcastle site. It can be concluded, that the orientation of the photovoltaic system towards the west, in order to increase the coverage of the evening peak, does not improve the reduction on the domestic load.

It could be shown that the reduction of the annual energy consumption by a PV-system connected to one dwelling is in the range of 20-25%, depending on the chosen size of the array, which is limited by the space available on the roof.

This research has shown that the reduction of the energy consumption of one dwelling can be increased to around 30% when the dwellings are seen as one small grid, connected to a larger PV-generator.

7.2. Contribution of the research

One of the components of improving the integration of renewable energy resources within buildings is the ability to predict the electrical demand as precisely as possible. However, from the review it can be established, that there is a lack of real long term data, describing the electric load of domestic buildings in the UK.

This research fills this gap by adding a new set of measured publicly available (available from the IEA website, see below) electric load profiles to the body of knowledge. The well described data sets are presented on a 5 minute interval and they cover an entire year. This data can be used for the purpose of computer modelling in different fields of research.

This study also presents the results from a detailed analysis of the electric energy consumption data. This unique information is of use when the value of a specific parameter of electric load, for example peak load or base load, is needed.

In order to support and improve the scientific value of the results of the energy consumption analysis, an occupant survey in the monitored dwelling has been carried out.

The outcome of the survey, like the ownership of appliances, can be utilised to improve existing load models, especially to fine tune the representation of the social housing sector.

A very useful information obtained during the survey is the time of use and the frequency of use of high demanding appliances like the washing machine. This can be the base for an investigation on the options of load shifting, for example, towards the period of solar energy.

This research also contributes to the body of knowledge in the field of load modulation by BIPV in the domestic sector. For the UK there are only a limited number of small scale studies regarding this research field available.

This study presents the generalised results from two different sites with a total number of 33 investigated dwellings. The findings give information to which level the domestic load can be reduced by connecting different sized and oriented PV-systems to theses dwellings. This can be of use when it is required to use the PV-energy directly in order to reduce the losses on the public grid.

This work presents results of a simulation of a possibly future configuration, where a grid of dwellings is connected to large PV-system rather than each dwelling to one PV-system.

The outcome of this research gives detailed information about the energy balance in a dwelling with a PV-system. This means, that the results show how much of the energy PV-system is used directly and how much is exported to the grid. This knowledge can be utilised to size storage systems in order to run the dwelling on a autarkic schedule.

The work published related to the modulation of the domestic demand is listed in appendix D.

A certain part of the electric load profiles of this study were used in the International Energy Agency – Energy Conservation in Buildings and Community Systems Annex 42. This project investigated the integration of Fuel Cells and Cogeneration systems into residential properties. The data sets and the description of the dwellings used in this reseach are downlodable from the Annex 42 website at http://cogen-sim.net/.

The work published related to the International Energy Agency project is listed in the appendix D.

7.3. Suggestions for future work

Based on the recorded consumption data sets of this study a deeper investigation on the optimum size and orientation of photovoltaic systems for the domestic sector can be carried out. This study covered two sites and two different size photovoltaic systems, this investigation could be extended.

The consumption data could also be used to study the possible future configuration of micro grids and the integration of different renewable sources. A micro grid or a building with several flats could be created by combining different dwelling consumption data sets.

Based on the modulation of the electric load by photovoltaic research, the integration of energy storage by, for example, batteries or fuel cells in order to improve the direct use of solar energy could be analysed. The costs for energy storage are still relatively high, however the costs of electrical energy generated by the present fossil sources will increase dramatically.

The findings from the occupancy survey in the dwellings of the social housing could be used to improve the available energy consumption models for this sector. These refined models could then be tested against the real measured consumption data and depending on the results, further improvement could be carried out.

Bibliography

[ACORN, 2006] ACORN – geodemographic tool http://www.caci.co.uk/ACORN/whatis.asp

Accessed 07.12.2006

[AMPY, 2006] AMPY Electrical Meters http://universalmeterservices.co.uk/store/index.php?main_page=popup_image&pID=52&zenid=51e885aea1fc90ef6fe066dce2d814a0

Accessed 23.12.2009

[Advantec, 2006] Advantec Industrial Automation http://www.advantech-uk.com/products/RS-485-I-O-Modules-ADAM-4000/sub_1-2MLKHT.aspx

Accessed 23.12.2009

[Aydinalp et al., 2001] Aydinalp, M., Ferguson, A., Fung, A. and Ugursal, V.I. (2001) *Characterization of Load Profiles in Housing – Literature Review,* Canadian Residential Energy End-Use Data and Analysis

[Aulenback et al, 2001] Aulenback A., Fung A., Ferguson A., Ugursal V.I., (2001) *Standby power requirements for household appliances,* Canadian Residential Energy End-Use Data and Analysis

[Bahaj and James, 2006] Bahaj, A.S., James, P.A.B., (2006) Urban energy generation: the added value of photovoltaics in social housing, *Renewable and Sustainable Energy Reviews,* Vol. 11, Issue 9, pp. 2121-2136

[Beyer et al., 2004] Beyer, H.G., Heilscher, G., Bofinger, S. (2004) A Robust Model for the MPP Performance of Different Types of PV-Modules Applied for the Performance Check of Grid Connected Systems *EUROSUN 2004 (ISES Europe Solar Congress)* Freiburg, 20.6.-23.6.

[BMU, 2009] Bundesministerium für Umwelt http://www.bmu.de/erneuerbare_energien/erneuerbare-energien-gesetz/doc/42894.php

Accessed 23.12.2009

[BRE, 1998] Building Research Establishment (1998) *Photovoltaics in Buildings: Testing, Commissioning and Monitoring Guide, ETSU Report No. S/P2/00290/REP*

[BUND, 2009] BUND Regionalverband Südlicher Oberrhein http://vorort.bund.net/suedlicher-oberrhein/energievorraete-energiereserven.html

Accessed 23.12.2009

[Capasso et al., 1994] Capasso, A., Grattieri, W., Lamedica, R., Prudenzi, A. (1994) A bottom-up approach to residential load modelling, *IEEE Transactions on Power Systems*, Vol. 9, Issue 2, pp. 957-964

[Decade, 1995] DECADE (1995) , *Domestic Equipment and Carbon Dioxide Emissions*, First year report, Environmental Change Unit, University of Oxford

[DECC, 2004]	Department of Energy and Climate Change Annual tables: 'Digest of UK energy statistics' (DUKES) http://www.decc.gov.uk/en/content/cms/statistics/source/electricity/electricity.aspx Acceseed 14.12.2009
[DECC, 2005]	Department of Energy and Climatechange Monthly Tables http://www.decc.gov.uk/en/content/cms/statistics/source/electricity/electricity.aspx Acceseed 23.12.2009
[Dichter, 1999]	Dichter, E.(1999) *Dusch- und Badeverhalten. Bericht zu einer Repräsentativumfrage,* Eidgenössische Drucksachen- und Materialzentrale (in German)
[Ditch et al, 2001]	Ditch J., Lewis A., Wilcox S., (2001) *Social housing, tenure and housing allowance: an international review*, Department Work and Pensions, United Kingdom
[DTI, 2002]	Department of Trade and Industry and National Statistics, (2002) *Energy Consumption in the UK*
[DTI, 2005]	Department of Trade and Industry, (2005) *New and Renewable Energy Program*, Annual Report

[DTI, 2006] Department of Trade and Industry, (2006) *UK Energy Sector Indicators,* A Supplement to the second annual report on the Energy White Paper "Our Energy Future – Creating a low Carbon Economy

[EA, 1998] Load Research Group of the Electricity Association http://www.electricity.org.uk

Accessed 16.08.2006

[EA, 2003] *G83/1 Recommendations for the connection of small-scale embedded generators (up to 16A per phase) in parallel with public low voltage distribution networks*, September 2003, Electricity Association

[ECI, 2000°] Fawcett T., Lane K., Boardman, B., (2000) *Lower Carbon Future Report,* Environmental Change Institute

[ECI, 2000b] Environmental Change Institute (2000), *Lower Carbon Future Report*, Appendix Country pictures-UK

[EETS, 2006] Energy Equipment Testing Service Ltd. http://www.eets.co.uk

Accessed 01.07.2009

[EIA, 2007] Energy Information Administration
Official Energy Statistic from the U.S. Government
http://www.eia.doe.gov/oiaf/ieo/highlights.html

Accessed 27.06.2009

[Eicker, 2001] Eicker, U., (2001) *Solare Technologien für Gebäude.* B.G. Teubner, Stuttgart /Leipzig / Wiesbaden, 1. Auflage
(in German)

[ESRA, 1998] ESRA (1998) European Solar Radiation Atlas is an atlas made on behalf of the European Commission (Brussels, Belgium), available through Les Presses de l'Ecole des Mines de Paris

[EST, 2006] Energy Saving Trust
http://www.est.org.uk/myhome/generating/types/solarpv

Accessed 25.07.2006

[Firth, 2006] Firth, S. (2006) *Rising efficiency in Photovoltaic Systems: High Resolution Monitoring and Performance Analysis*, Ph.D. thesis, Leicester, UK, De Montfort University

[FSA, 2008] Financial Service Authority
http://www.fsa.gov.uk/financial_capability/pdfs/PDT_OPF.pdf

Accessed 24.12.2009

[Global Cooling, 2009] Global Cooling
Maestro CP20 AR Air Condition data
http://www.global-cooling.com/product_info.php?cPath=98&products_id=712

Accessed 25.12.2009

[Heaberlin et al, 1995] Haeberlin, H., Blaesser, G., Jantsch, M. (1995) Comparison of Pyranomter and SI-refernce Cell Solar Irradiation Data in long Term PV Plant Monitoring, *13. European Photovoltaic Solar Energy Conference*, Nice, France

[Herman, 2002] Herman, R., (2002) Load models for mixed -class domestic and fixed, constant power loads for use in probabilistic LV feeder analysis, *ELECTRIC POWER SYSTEMS RESEARCH*, Vol. 66, Issue 2, pp. 149-153

[INSEL, 2007] Integrated Simulation Environmental Language
http://www.insel.eu/

accessed: 03.29.2007

[IEA, 2007] International Energy Agency
http://www.iea-pvps.org/trends/download/2007/Table%202.pdf

accessed 27.06.2009

[Iqbal, 1983] Iqbal M., (1983) *An Introduction to Solar Radiation.* Academic Press, New York

[Isaacs et al., 2005] Isaacs, H., Camilleri, M., French, L., Pollard, A., Saville-Smith K., Fraser, R., Rossouw, P., Jowett, J. (2005) *Energy use in New Zealand households, Report on the Year 9 analysis for the household energy end-use project (HEEP)*

[Itpower, 2003] IT Power http://www.itpower.co.uk/pvish/Going%20Solar%20-%20Guide%20to%20PV%20in%20Social%20Housing.pdf#search=%22g83%20ac%20isolator%20uk%20pv%22

Accessed 29.09.2006

[Kreutzer et al., 2002] Kreutzer, N., Beyer, H.G., Rüther, R. (2002) Abschätzung spezifischer kWh/kWpeak Erträge unterschiedlicher Solargeneratortechnologien für tropische Standorte am Beispiel Brasiliens, *17. Symposium PV Solarenergie,* Staffelstein, Germany
(in German)

[Lampaditou and Leach, 2005] Lampaditou, E. and Leach M., (2005) Evaluating Participation of Residential Customers in Demand Response Programs in the UK, *European Council for an Energy Efficient Economy,* Summer Study, pp. 1271-82

[Lebot et al., 1997] Lebot, B., Lopes, C., Waide, P. and Sidler, O. (1997) Lessons Learned from European Metering Campaign of Electrical End Uses in the Residential Sector, *European Council for an Energy Efficient Economy,* France

[Luther and Schumacher-Grühn, 1991] Luther, J. and Schumacher-Gröhn, J.: INSEL-A simulation systems for renewable electricity supply systems, *10. European Photovoltaic Solar Energy Conference*, Lisbon, 1991

[Manning et al., 2005] Manning, M., Leban, C., Swinton, M. (2005) *International Energy Agency Annex 42- Random Profile Generator*, Internal Report

[Mansouri and Newborough, 1999] Mansouri, I. and Newborough, M., (1999). Dynamics of energy use in UK households: End-use monitoring of electric cookers. *Summer Study of the European Council for an Energy Efficient Economy*, 1999, paper no. 3–8.

[Mansoury et al., 1996] Mansouri, I., Newborough, M., Probert, D. (1996) Energy Consumption in UK Households: Impact of Domestic Electrical Appliances, *Applied Energy*, Vol. 54, Issue 3, pp. 211-285

[Markvart and Castaner, 2003] Markvart, T. and Castaner, L., editors (2003) *Photovoltaics - Fundamentals and Applications*, Kidlington Oxford: Elsevier Science Ltd., pp. 750

[Michalik et al., 1997] Michalik, G., Khan, M.E., Bonwick, W.J., and Mielczarski, W., (1995) Structural Modelling of Energy Demand in the Residential Sector: Development of Structural Models. *Energy*, Vol. 22, pp. 937-947

[Muneer et al., 2003] Muneer, T., Asif, M., Kubie, J., (2003) Generation and transmission prospects for solar electricity: UK and global markets. *Energy Conversion and Management,* Vol. 44, pp. 35-52

[Munyati et al., 2001]	Munyati, E., Pearsall, N.M. and Haydon, R. (2001) The Effect of Short-Term Storage on the Matching of PV Supply to Load Demand in Houses in Edinburgh. Proc. *17th European Photovoltaic Solar Energy Conference*, Munich, Germany, pp. 2617-2620
[Newborough and Augood, 1999]	Newborough, M., Augood, P. (1999) Demand-side management opportunities for the UK domestic sector, *IEE Proceedings - Generation, Transmission and Distribution*, Vol. 146, Issue 3, pp. 283-293
[NI, 2006]	National Instruments http://www.ni.com/labview/ Accessed 10.12.2006
[National Statistics, 2001a]	National Statistics Tenure: by economic status of household reference person http://www.statistics.gov.uk/StatBase/ssdataset.asp?vlnk=6397&Pos=3&ColRank=2&Rank=240 Accessed 23.12.2009
[National Statistics, 2001b]	National Statistics, Domestic Energy Consumption per Household http://www.statistics.gov.uk/STATBASE/ssdataset.asp?vlnk=7287 Accessed 24.12.2009

[National Statistics, 2002]
National Statistics
Living in Britain – the 2002 General Household Survey social trends 35
http://www.statistics.gov.uk/downloads/theme_compendia/lib2002.pdf

Accessed 11.12.2009

[National Statistics, 2004]
National Statistics
Statistics on households and families
http://www.statistics.gov.uk/cci/nugget.asp?id=1162

Accessed 11.12.2009

[National Statistics, 2007]
National Statistics
Social Trends
http://www.statistics.gov.uk/downloads/theme_social/Social_Trends37/Social_Trends_37.pdf

Accessed 24.12.2009

[National Statistics, 2009]
National Statistics, 2009
http://www.statistics.gov.uk/hub/index.html

Accessed 23.12.2009

[OKSOLAR, 2006]
OKSOLAR
www.oksolar.com/pdfiles/Solar%20Panels%20bp_585.pdf

Accessed 10.11.2009

[Parker, 2002] Parker, D.S. (2002) Research Highlights from a Large Scale Residential Monitoring Study in a Hot Climate. *Energy and Buildings*, Volume 35, pp. 863-876

[Peacock and Newborough, 2004] Peacock, A. and Newborough, M. (2004) *The 40% House Project, Task four: power and Demand, Heriot Watt University*, Edinburgh, UK

[Pratt et al., 1993] Pratt, R.G., Corner, C.C., Cooke, B.A. and Richman, E.E. 1993. Metered End-Use Consumption and Load Shapes from the ELPAC Residential Sample of Existing Homes in the Pacific Northwest. *Energy and Buildings*, Vol. 19, pp. 179-193

[PVSAT2, 2006] Intelligent Performance Check of PV System Operation based on Satellite Data http://pvsat.de/pvsat2_paper548.pdf

Accessed 07.11.2006

[Prignitz, 2005] Prignitz, O., *Begleitung der Testphase des Projektes PVSAT-2 Exemplarische Analyse der Verwendbarkeit von Datenblattangaben und Kennlinien nach Herstellerangaben zur laufenden Ertragsberechnung von Photovoltaikanlagen,* Diploma Thesis, Magdeburg, Deutschland, University of Applied Science (in German)

[Quaschning, 1998]	Quaschning V., (1998) *Regenerative Energiesysteme: Technologie- Berechnung – Simulation, Carl Hanser Verlag München Wien* (in German)
[Saidur et al, 2002]	Saidur, R., Masjuki, H.H., Choudhury I.A.,(2002) Role of ambient temperature, door opening, thermostat setting position and their combined effect on refrigaration-freezer energy consumption. *Energy Conversion and Management,* Vol. 43, pp 845-854
[Shimoda et al., 2003]	Shimoda, Y., Fujii, T., Morikawa, T.,Mizuno, M., 2003 Development of Residential Energy End-Use Simulation Model at City Scale, *8. International IBPSA Conference*, Netherlands
[Sidler, 1997]	Sidler, O., (1997) Demand Side Management: End-Use Metering Campaign in the Residential Sector - *Cabinet SIDLER for the Commission of the European Communities,* Final Report, contract N° 4.1031/Z/93-58, ADEME and EDF. Translated by PW Consulting
[SMA, 2006]	SMA Solar Technology AG http://www.sma.de accessed 12.11. 2006
[Stokes, 2005]	Stokes, M. (2005) *Removing barriers to embedded generation: a fine-grained load model to support low voltage network performance analysis,* PhD thesis, Leicester, UK, De Montfort University

[Stoecklein et al., 2001]	Stoecklein, A., Pollard, A., Camilleri, M., Tries, J. and Isaacs, N. (2001) The Household Energy End-Use Project: Measurement Approach and Sample Application of the New Zealand Household Energy Model. *CIB World Building Congress*, Wellington, New Zealand
[Šúri et al., 2007]	Šúri M., Huld T.A., Dunlop E.D. Ossenbrink H.A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. *Solar Energy*, Vol. 81, pp 1295–1305
[Timeanddate, 2006]	Time and date Rising and setting times for the sun http://www.timeanddate.com/worldclock/astronomy.html?n=136 Accessed 13.07.2007
[UNFCCC, 2006]	United Nations Framework Convention on Climate Change http://unfccc.int/2860.php Accessed 13.07.2007
[Upmystreet, 2006]	Up My Street http://www.upmystreet.com/ Accessed 07.12.2006
[Vowles et al., 2000]	Vowles, J., Boardman, B. and Lane K., (2001) Suspecting standby? Domestic levels and the potential for household level reductions in the UK, *ECEEE Summer Study*, Mandelieu, France

[Weather, 2006] The Weather Channel Interactive, Inc. http://www.weather.com/weather/climatology/monthly/UKXX0085

Accessed 07.12.2006

[Wright and Firth, 2006] Wright, A., Firth, S., (2006) The nature of domestic electricity-loads and effects of time averaging on statistics and on-site generation calculations, *Applied Energy*, Vol. 84, Issue 4, pp. 389-403

[Yao and Steemers, 2004] Yao R., Steemers, K.A. (2005) A method of formulating energy load profiles for domestic buildings in the UK, *Energy and Buildings*, Vol. 37, Issue 6, pp. 663-671

[Yohanis et al., 2008] Yohanis, G. Y., Mondol D. J., Wright, A., Norton, B., (2008) Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use, *Energy and Buildings*, Volume 40, Issue 6, pp. 1053-1059

Appendix A. Description of the monitoring system

The monitoring specifications were defined by the Building Research Establishment [BRE, 1998]. In table A-1 the accuracy and the monitoring interval of the data are shown.

The data from the monitoring system was stored on site using PC's designed to withstand expected monitoring conditions on site. Data was downloaded automatically every night from the on-site computer to the main computer in Energy Equipment Testing Service Ltd office. Here the records were checked for faulty values and gaps in the data.

Table A-1: Domestic field trial monitoring specification [BRE, 1998]

Measured parameter	**Symbol**	**Accuracy**	**Unit**	**Measurement interval**
Irradiance on the horizontal surface	G_{hor}	±5%	W/m^2	10s
Irradiance in the plan of array	G_I	±5%	W/m^2	10s
Ambient Temperature	T_{amb}	±0.5%	°C	1min
Module Temperature	T_{mod}	±0.5%	°C	1min
Energy imported to the building	E_{imp}	±2%	Wh	Continuously integrated
Energy exported from the building	E_{exp}	±2%	Wh	Continuously integrated
DC energy output of array	E_A	± 4%	Wh	Continuously integrated
AC output of inverter	E_{IO}	±2%	Wh	Continuously integrated

During the monitoring for this work, the acquisition of the import and export energy data has been achieved with the same monitoring technique at all sites. The energy meters installed at each site were two single watt hour meters with pulse output and a resolution of 1Wh [AMPY, 2006]. Figure A-1 shows the electrical connection of the meters and the data cable.

The pulse is read by a counter [Advantech, 2006]. These counters, as shown in figure A-2, are linked to an RS 485 network, which allows long distance communication. This network is connected to the serial port of the on-site monitoring computer using an RS 485 to RS 232 converter

[Advantech, 2006]. The conversion is necessary since PCs work with the RS 232 standard.

Figure A-2 shows several counter modules, the power supply, the wiring and the housing utilised during the projects.

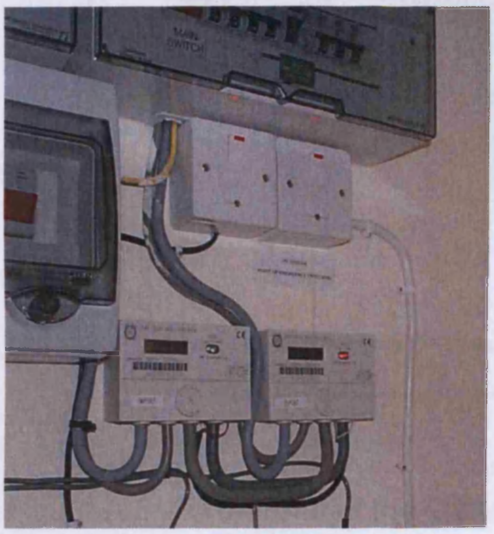


Figure A-1: Installation of electrical meters for the measurement of the import and export of energy at Llanelli [AMPY, 2006]

Figure A-2: Counter modules used in the monitoring [Advantech, 2006]

The addressable modules are read by a program that steps through a main sequence of 5 minutes, as shown in figure A-3. The data is then saved with a time and date tag on the hard disk of the on-site computer. Afterwards, the memory of the counters are reset and new pulses for the following 5 minute period are registered.

The monitoring program is written in LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench), a platform and development environment for a visual programming language from National Instruments [NI, 2006], which is commonly used for data acquisition, instrument control, and industrial automation.

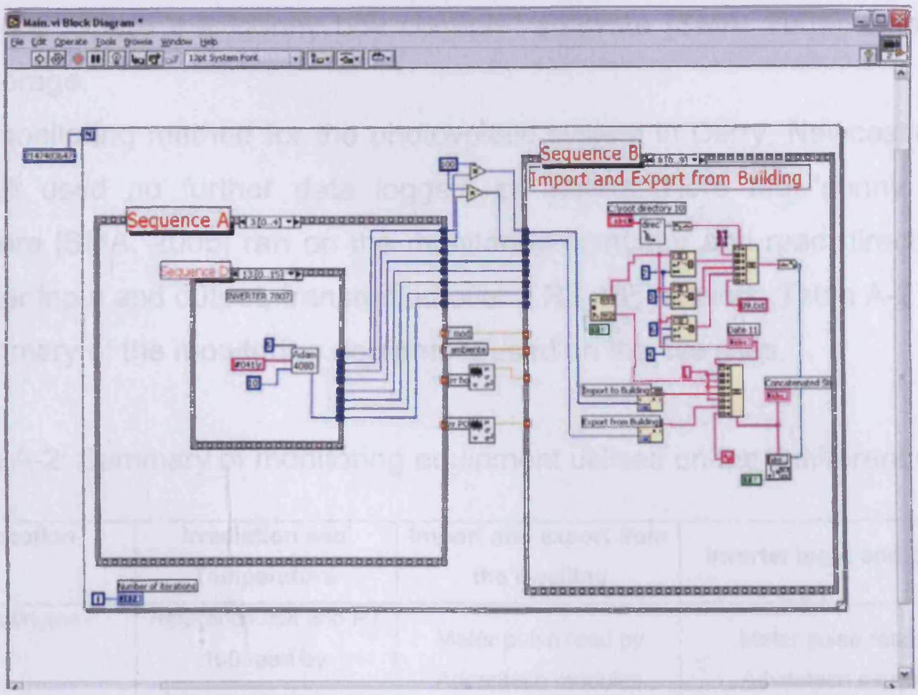


Figure A-3: Screenshot of the LabVIEW code for a monitoring program used on the monitoring computer

The temperatures and irradiations in Dartington, Derry, Llanelli and Newcastle are read by an analog input module, which converts the measured parameters into digital values [Advantech, 2006c]. These analog input modules are connected to the same network and read by the same monitoring program, but with a higher frequency (according to table A-1). During the Nottingham project, a “sunny boy control+” [SMA, 2006] is used to obtain the temperature and irradiation. This data logger has been developed to monitor sunny boy inverters, but it also has analog and digital interfaces where reference cells or temperature sensors can be connected.

The monitoring of the photovoltaic systems was realised using three different techniques. In Dartington, the output of the array and the output of the inverter is measured with meters. The pulses are transmitted to counters and sent to the monitoring computer. This is a similar principle as the import and export data acquisition; only here one meter measured the DC energy.

In the Nottingham project, the “sunny boy control” data logger [SMA, 2006] is used to monitor the DC-input (the DC-input of the inverter is considered to be the output of the array, the losses of the DC cables are ignored) and the AC-output of the inverters; data is then sent via RS485 network to the monitoring computer where the "sunny boy control+" software [SMA, 2006] organised the storage.

The monitoring method for the photovoltaic system in Derry, Newcastle and Llanelli used no further data loggers or meters. Here the "sunny data" software [SMA, 2006] ran on the monitoring computer and read directly the inverter input and output, transmitted over a RS 485 network. Table A-2 gives a summary of the monitoring equipment used on the five sites.

Table A-2: Summary of monitoring equipment utilised on the 5 different sites

Location	**Irradiation and Temperature**	**Import and export from the dwelling**	**Inverter input and output**
Dartington	Reference cell and PT 100 read by Advantech modules	Meter pulse read by Advantech modules	Meter pulse read by Advantech modules
Derry	Reference cell and PT 100 read by Advantech modules	Meter pulse read by Advantech modules	DC-energy and AC-energy read by Internal inverter system
Newcastle	Reference cell and PT 100 read by Advantech modules	Meter pulse read by Advantech modules	DC-energy and AC-energy read by Internal inverter system
Llanelli	Reference cell and PT 100 read by Advantech modules	Meter pulse read by Advantech modules	DC-energy and AC-energy read by Internal inverter system
Nottingham	Reference cell and PT 100 read by Sunny Boy Control+	Meter pulse read by Advantech modules	DC-energy and AC-energy read by Internal inverter system

Appendix B. SMA inverter model

This table presents the complete set of efficiencies over the range of normalised input power for different SMA inverters (inverter models from 700W to 2500W). This has been developed during the PVSAT2 project [PVSAT2, 2006].

	700W	**850W**	**1100W**	**1700W**	**2500W**
Pin/Pnom	**model**	**model**	**model**	**model**	**model**
	η	η	η	η	η
0.010000	0.462023	0.425842	0.489406	0.410231	0.4442
0.020000	0.625295	0.598577	0.651137	0.577988	0.6087
0.050000	0.792237	0.789214	0.810725	0.765219	0.7818
0.100000	0.867000	0.879000	0.880000	0.856400	0.8620
0.150000	0.892837	0.910121	0.903298	0.890517	0.8910
0.200000	0.904556	0.923801	0.913499	0.907600	0.9050
0.250000	0.910290	0.930002	0.918181	0.917337	0.9127
0.300000	0.912941	0.932336	0.920034	0.923245	0.9171
0.350000	0.913803	0.932427	0.920250	0.926906	0.9195
0.400000	0.913541	0.931115	0.919443	0.929139	0.9207
0.450000	0.912531	0.928876	0.917956	0.930409	0.9212
0.500000	0.911000	0.926000	0.916000	0.931000	0.9210
0.550000	0.909096	0.922675	0.913709	0.931095	0.9204
0.600000	0.906918	0.919025	0.911174	0.930819	0.9195
0.650000	0.904535	0.915140	0.908456	0.930257	0.9184
0.700000	0.901995	0.911081	0.905603	0.929471	0.9171
0.750000	0.899335	0.906893	0.902646	0.928508	0.9156
0.800000	0.896583	0.902613	0.899610	0.927402	0.9141
0.850000	0.893758	0.898265	0.896514	0.926180	0.9124
0.900000	0.890879	0.893870	0.893373	0.924861	0.9107
0.950000	0.887956	0.889444	0.890199	0.923464	0.9089
1.000000	0.885000	0.885000	0.887000	0.922000	0.9070
1.050000	0.882020	0.880547	0.883784	0.920481	0.9051
1.100000	0.879022	0.876093	0.880558	0.918915	0.9032
1.150000	0.876011	0.871646	0.877326	0.917309	0.9012
1.200000	0.872993	0.867210	0.874091	0.915670	0.8992

Appendix C. Survey form

Domestic Energy Consumption – Questionnaire

The information will be treated confidentially and ONLY be used for scientific purposes.

Date: ....
Time: ....

Dwelling:
House Type..............................
Location..............................
Street..............................
Floor Area [m2] ....
High of dwelling.........................
Hob powered by..........Gas/Electric......
Cooker powered by......Gas/Electric......
Shower powered by......Gas/Electric......

Appliances:

1. Do you own a fridge freezer (No.)? ....
2. Do you own a fridge (No.)?..........
3. Do you own a freezer (No.)? ....
4. Do you have a TV (No./usage weekday[h]/usage weekend[h])....../....../.......
5. Do you have a DVD player/video (No./how many movies do you watch from Mo to Fr /How many do you watch on the weekend?........./......./........
6. Do you have a computer (No./usage weekday[h]/usage weekend[h])....../....../.......
7. Do you have a hi-fi (No./usage weekday[h]/usage weekend[h])....../....../.......
8. How often do you use the cooker per day and when (wd/we)?.......(...........)/..........(...........).
9. How often do you use your electric kettle per day and when (wd/we)?.......(.............)/..........(............).
10. How often do you use your toaster per day and when (wd/we)? ......(...........)/.......(..........).
11. How often do you use the microwave per day and when (wd/we)? .....(.........)/..........(........).
12. Do you have a washing machine (usage per week/when)? ....(..........)
13. Do you have a dishwasher (usage per week/when)? ....(..........)
14. Do you have a tumble dryer (usage per week/when)? ....(..........)
15. How often do you use the vacuum cleaner per week (when)? ....(..........)
16. How often do you use the iron per week (when)? ....(..........)
17. Do you use additional electrical heating in winter (when)? ....(..........)

Tenant:

18. When did you move into the dwelling.........
19. Number of Tenants ....
20. Number of children (age?) ....(.................)

	Occupant	Hours unoccupied on weekdays	Hours unoccupied on weekends
1			
2			
3			
4			
5			
6			

Water:

21. How often is the shower in use per week?...........................
22. How often is the bath being used per week? ....

....
....
....

Appendix D. Published work

Knight, I., Kreutzer, N., Manning, M., Swinton, M., Ribberink, H., *Residential Cogeneration Systems: European and Canadian Residential non-HVAC Electric and DHW Load Profiles, Report of Subtask A of FC+COGEN-SIM, The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems*, Annex 42 of the International Energy Agency, Energy Conservation in Buildings and Community Systems Programme, 2006

Kreutzer, N., Beyer, H.G., Knight, I., The Modulation of Electric Load Profiles In Domestic Dwellings With Building Integrated Photovoltaic Systems – An Investigation For The United Kingdom, *14th Sede Boqer Symposium on Solar Electricity Production*, Israel, 19-21.02.2007

Kreutzer, N., Beyer, H.G., Knight, I., Der Einfluss gebäudeintegrierter Photovoltaikanlagen auf den elektrischen Lastgang in Wohngebäuden – eine Untersuchung für Groß Britannien, *22.Symposium Photovoltaische Solarenergie*, Germany, 07-09.03.2007

Kreutzer, N., Beyer, H.G., Knight, I., The Modulation Of Electric Load Profiles In Domestic Dwellings By BIPV And Options To Maximise The Load Match - An Investigation For The United Kingdom, *3. Photovoltaic Science, Applications and Technology Conference*, United Kingdom, 28-30.03.2007

Knight, I., Kreutzer, N., European non-HVAC Residential Electrical and DHW demands, *First International Conference and Workshop on Micro-Cogeneration Technologies and Applications - Micro-Cogen*, Canada, 29.04-01.05.2008