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Energy and Buildings 37 (2005) 663–671
ENERGY and BUILDINGS
www.elsevier.com/locate/enbuild

A method of formulating energy load profile for domestic buildings in the UK

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Received 20 July 2004; received in revised form 22 September 2004; accepted 24 September 2004

Abstract

There are varieties of physical and behavioral factors to determine energy demand load profile. The attainment of the optimum mix of measures and renewable energy system deployment requires a simple method suitable for using at the early design stage. A simple method of formulating load profile (SMLP) for UK domestic buildings has been presented in this paper. Domestic space heating load profile for different types of houses have been produced using thermal dynamic model which has been developed using thermal resistant network method. The daily breakdown energy demand load profile of appliance, domestic hot water and space heating can be predicted using this method. The method can produce daily load profile from individual house to urban community. It is suitable to be used at Renewable energy system strategic design stage.

Keywords: Domestic building; Load profiles; Energy-consumption; Appliance; Renewable energy (RE)

1. Introduction

In the UK, the non-domestic building sector contributes 19% and the domestic sector 27% to total UK CO_2 emissions, hence buildings are critically important to the UK national response to climate change [1,2]. Britain will aim for a 60% reduction in carbon dioxide emissions by 2050 as part of efforts to curb global warming, according to government energy white paper [3]. Renewable energy (RE) is expected to play an important role in meeting the target of 60% reduction in carbon dioxide emissions by 2050. Considerable effort is being directed to the deployment of RE technologies in an attempt to mitigate greenhouse gas emissions. The diversity of load demands at macro scale are such that there will always be an intermittent demand ideally matched to the power available from the RE systems. At the macro scale, the power ratings of the installed RE systems are substantially greater fraction of the demand. In this case, the optimum match between demand and supply becomes crucial. Therefore at RE system strategic design stage, a very important element is to determine energy demands based on the consumption patterns of individuals. The other important issue in sizing renewable energy system is the load profile. The varieties of factors will determine the energy demand. The attainment of the optimum mix of measures and renewable system deployment requires a simple method suitable for use at the early design stage.

The aim of this study is to develop a simple method of predicting households daily energy-consumption profile for planning and strategic design of RE system for residential buildings in the UK.

2. Methodology

In order to match load shape to the RE power generated by local RE system, it is essential to identify the pattern of energy uses of a house and to predict domestic load profile. In 2000, 56% of UK domestic energy-consumption was used for space heating, 24% for domestic hot water, 20% for

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doi:10.1016/j.enbuild.2004.09.007

Nomenclature

A	daily appliance energy-consumption per capita (kWh/day)
A_{floor}	floor area of the house (m^2)
C	thermal capacity (W/°C)
C_p	specific heat capacity of water = 4.187 (kJ/kg K)
Eff	luminance efficacy in workplane (Lum/W)
E_a	daily delivered appliance energy-consumption of household
E_{hw}	daily domestic hot water load (kWh/day)
E_l	daily electric lighting energy-consumption (kWh/day)
H	daily hours of lighting on during (Hour/day)
I_{mean}	average luminance level (lx)
N_p	number of the occupants (unit)
N_r	number of rooms in the house (unit)
T_{in}	water temperature inlet the tank (°C)
T_{out}	water temperature outlet the tank (°C)
V	daily volume of hot water consumed for each component (m^3/day)

Greek letters

ρ	density of water = 1000 (Kg/m^3) (kWh/day)
$\Phi_{heat/cool}$	auxiliary heating/cooling (W)
Φ_{cond}	conductive heat transfer (W)
Φ_{vent}	solar gain (W)
Φ_{sp}	internal space gain (W)

lighting and appliance [1]. The use pattern varies depending on the different factors, such as climate, household composition, family income, culture background, and human factor, etc. In order to produce domestic load profile with taking into account various factors, a cluster analysis method has been applied. The energy demand can be categorized into two types of determinants:

(1) Behavioral determinants: This type of energy-consumed has non-related/little-related to climate but strongly related to households human factor. It has a high co-relation to people's habits and may slightly influenced by season, for example, cooker, microwave oven, washing machine, fridge-freezer, kettle, television, dishwasher, etc. The relationship between electricity used in households and the behavior of end uses have been discussed widely [4]. Behavioral determinants, such as the frequency of use per appliance, involve relatively 'flexible' decisions, which are made on an hourly/daily/weekly time scale [4].
(2) Physical determinants: This type of energy-consumed, for example, heating/cooling and lighting energy, has high co-relation to climate and building design, however has low co-relation to people's habits. The physical determinants of energy use, such as dwelling's size, building deign, and its space-heating system are the results of relatively 'fixed' decisions. The use of heating/cooling energy for thermal comfort also related to the occupancy pattern and household income level. For example, most people will set internal comfort temperature low when the house is in unoccupied period and during the night. People preferring warm environment may set higher comfort temperature while the others may set lower.

From the description of above two types of energy load, we can see that both behavioral determinants and physical determinants related energy-consumption are more or less influenced by people's occupancy pattern.

2.1. Composition of household

Between 1971 and 1991, there was a decline in the average size of household in Great Britain, from 2.91 persons to 2.48. It continued to decline though at a slower rate throughout the next decade, falling to 2.32 by 1998. Since then it has remained fairly-constant. In 2002, the average number of persons per household was 2.31. Since 1971 there have also been changes in the composition of households. In particular, these have included an increase in the proportion of one-person households, and of households headed by a lone parent. Between 1971 and 1998, the overall proportion of one-person households almost doubled from 17 to 31%, and the proportion of households consisting of one-person aged 16–59 tripled from 5 to 15%. Over the last five years, there have been no statistically significant changes in the overall proportion of adults living in one-person households, and among people aged 65 and over the proportion living alone has remained relatively stable since the mid-1980s [5,6]. Table 1 lists the UK composition of households in 2002 [5].

2.2. Occupancy pattern of household

An energy-consumption labeling scheme was introduced for refrigeration appliances in 1995 by the European Community, but the comprehensive list of energy performance data for all major domestic appliances is not published. Discrepancies exist in the published data concerning ownership levels and there is little information on usage patterns for domestic appliances. The utilization of the appliances (e.g. factors influencing the frequency of use) needs to be considered in their culture contexts. Usage

Table 1
Composition of households in the UK 2002

Number of persons in the household	1	2	3	4	5	6 or more
Proportion of households with the specified number of people	31%	35%	16%	13%	4%	2%

Source: http://www.statistics.gov.uk/.

patterns associated with different sections of the population and the variations in consumers' knowledge/attitudes needs to be identified. Possible links between cultural values and energy use should be explored in order to identify feasible means for promoting energy-rational behaviour. The usage pattern is related to the occupied period. For example, when people are not at home, most appliances will not be used. In daily appliance electricity profile, the occupants use virtually little power (stand by and fridge-freezer) during the night, may wake up and have breakfast, vacate the house during the morning and then return around mid-day for lunch, in the evening, the meal is cooked, television is watched, and showers are taken, etc. The different households has different life styles. The total load profile shape will of course vary from day to day and house to house. The factors influencing the occupancy pattern are as follows:

(1) The number of occupants.
(2) The time of the first person getting up in the morning and the last person going to sleep.
(3) The period of the house unoccupied during the day.

It is important to identify the cluster of households when analyze the load profile, because the load profile depends very much on the occupancy pattern. In the case of lack of information about household occupancy pattern, we propose five most common scenarios of household occupancy pattern in the UK.

- Scenario 1: Unoccupied period is from 09.00 to 13.00. One of the occupants in this type of household may have a part-time job in the morning session.
- Scenario 2: Unoccupied period is from 09.00 to 16.00. The occupants in the house all have full-time job.
- Scenario 3: Unoccupied period is from 09.00 to 16.00. The family of this type of household may have a child to look after when school closed.
- Scenario 4: The house is occupied all the time. The family of this type of household may have minor child to look after or is of retired couples and single.
- Scenario 5: Unoccupied period is from 13.00 to 18.00. One of the occupants in this type of household may have a part time job in the afternoon session.

Table 2 lists the scenarios of possible occupied period in domestic house in the UK. In the unoccupied period, most appliances will not be used.

2.3. Energy-consumption of domestic appliance

Domestic appliances can be classed as:

- Brown goods: electronic consumer goods—TVs, VCRs, etc.
- Cold appliances: refrigerators, freezers, and combined fridge-freezer.

Table 2
Occupancy pattern for a three-person household

Scenarios	Type	Unoccupied period
1	Part-time working morning session 1/2	9:00–13:00
2	Full-time working	9:00–18:00
3	Part-time working 2/3	9:00–16:00
4	No working	N/A
5	Part-time working afternoon session 1/2	13:00–18:00

- Cooking appliances: electronic ovens, electric hobs, kettles, and microwaves, etc.
- Wet appliances: washing machines, tumble dryers, and dishwashers.
- Miscellaneous appliances: vacuum cleaners, irons, electric showers, central heating pumps, PCs, etc.

In 2000, electricity-consumption by brown goods accounted for 14.3%, cold for 22.2%, wet appliances for 16.5%, cooking appliances for 18.8%, lighting for 22.6%, and miscellaneous appliances for 5.6% [2]. At present, British consumers are poorly informed with respect to the energy-consumption of domestic appliance. Mansouri carried out the research on energy-consumption on UK domestic and supplied the average daily energy-consumption of each appliances [4,7]. Mash has collected some information of domestic household appliance energy-consumption from various resources [8].

(1) Electric cooker: A survey (carried out in South East England in 1994) reveal that, on average, an electric hob and oven were used for approximately 60 and 30 min/day respectively, corresponding to a predicted annual electricity-consumption of approximately 670 kWh per household [4,7]. Usage of hobs and ovens varied between different households, indicating that consumption ranged from 260 to 1800 kWh/year per household. Further analysis indicated that the number of persons in the household was the clearest indicator of usage for all appliances including cooking appliance [4]. Cranfield Survey of more than 500 households in Peterborough in 1997 (Bennet, 1998) indicated similar overall usage patterns for cooking appliances: hobs and ovens being used on average for approximately 58 and 36 min/day per household [7].
(2) Refrigeration appliance: Multiple ownership of refrigeration appliance has become common in the UK. Shopping patterns have been changed during the last decade, because working patterns have diversified. The associated reduction in the frequency of food shopping has encouraged the purchase of refrigeration appliances. The households may have separate freezer for storing the chilled food.
(3) Television sets and video recorders: Ownership level for black-and -white television sets have decreased, as they have been replaced gradually by colour-television sets. According to Mansouri's survey, colour-television sets

were owned by 97% of the respondents. Video recorders owned by 75%. The utilization period of television varies by household's lifestyle. According to Mansouri's survey, the average total viewing time per household is 5.17 h for colour-television and 1.5 h for video recorder [4].

(4) Wet appliance: The national ownership level of clothes-washing machine, tumble driers and dish washers is 88, 49 and 16%, respectively. Mansouri's survey is 93, 54 and 42%, respectively. It is slightly lower than the national level due to regional variations. The frequency of utilization of wet appliances depends on the number of persons in the household. According to Mansouri's report, the highest average number of wash cycle per week was 8 cycles per household. The greatest tumble dryer usage pattern is 3.4 cycles per week in winter and autumn. The highest average use of dishwasher is 0.95 cycles per day [4].

(5) Artificial lighting: Unlike domestic appliances, artificial lighting energy-consumption is highly influenced by season. The following equation can be used to calculate electric lighting energy-consumption:

$$E_1 = \left(\frac{I_{\text{mean}}}{Eff}\right) \times H \times A_{\text{floor}} \times \left(\frac{N_{\text{p}}}{N_{\text{r}}}\right) \quad (1)$$

where E_l is the daily electric lighting energy-consumption (KWh/day); I_{mean} the average luminance level, domestic building is 150 lux; H the hours of artificial lighting on; Eff the luminance efficacy in workplane (lum/W); A_{floor} the house floor area (m^2); N_{p} the number of occupants; N_{r} the number of rooms in the house.

The electric lighting on/off pattern also depends on daylight and occupancy pattern. If the internal required lighting level less than the available daylight illuminance level then artificial lighting will be switched on, when the room is occupied. In winter, people get up in the morning and need the lights on for the activities but in summer no lighting required due to the daylight. Daily lighting energy-consumption can be calculated using the above equation.

(6) Others: The other electricity appliances are kettle, iron, and vacuum cleaner, etc. The usage pattern of this kind of appliances also depends on the household occupancy pattern and lifestyle.

By reviewing the previous statistic work, the information of daily average end use electric appliance energy consumption for an average size household, per capita daily energy-consumption and the ownership level are listed in Table 3. The daily appliance energy-consumption for different sizes of household can be calculated based on the per capita daily energy-consumption data.

2.4. Energy-consumption of domestic hot water

Domestic hot water (DHW) accounts for about 20% of the total primary energy-consumption by housing. It is used within a house for a variety of different purposes such as, drinking, washing, laundry, etc. The components of domestic hot water are as follows:

- bath/shower: the traditional method of personal hygiene in the UK;
- wash hand basin: for personal hygiene;
- dish washing: by hand and machine;
- clothes washing: wash machine.

The energy used for domestic hot water depends on many factors, such as the required water temperature, the volume requirement per person, and the household size. Individual households have a wide variation in consumption, though household size has been shown to be a factor. Mash adapted the results from Hall and Butler and obtained delivered figures of the hot water consumption per person per day [8]. They are listed in Table 4. We use this figures for the calculation of DHW energy profile. The daily energy-consumption can be calculated using the following equation:

$$E_{\text{hw}} = \frac{C_{\text{p}} \rho V (T_{\text{out}} - T_{\text{in}})}{3600} \quad (2)$$

where E_{hw} is the domestic hot water load (kWh/day); C_{p} the specific heat capacity of water (4.187 kJ/kg K); ρ the density of water (1000 kg/m^3); V the daily volume of hot water consumed for each component (m^3/day); T_{out} the water

Table 3
Average energy-consumption of appliances in the UK

Appliance	Average annual consumption per household (kWh/day)	Average annual consumption per capita (kWh/day)	Ownership level (%)
Electric hob	1.33	0.39	37
Electric oven	0.74	0.22	56
Microwave oven	0.23	0.07	74
Refrigerator	0.82	0.33	53
Fridge-freezer	1.9	0.56	58
Freezer	1.9	0.55	55
Colour-television set	0.91	0.27	97
Video recorder	0.3	0.09	76
Clothes-washing machine	0.8	0.20	88
Tumble-drier	0.78	0.28	49
Dishwasher	1.72	0.48	16
Electric kettle	0.78	0.28	5
Iron	0.3	0.09	100
Vacuum cleaner	0.15	0.04	100
Miscellaneous	1.1	0.33	100

Table 4
Domestic hot water consumption in the UK household

Appliance/use	DHW consumption (l/capita day)	Water temperature (°C)
Bath/shower	10.6	40
Wash hand basin	15.8	35
Dish washing	14.9	55
Clothes washing 50%	11.7	60
Clothes washing 50%	11.7	10

Table 5
Energy-consumption for domestic hot water of a three-person family

Appliance/use	DHW load consumption (KWh/day)
Bath/shower	1.1
Wash hand basin	1.4
Dish washing	2.3
Clothes washing 50%	2.0
Clothes washing 50%	0

output temperature (°C); T_{in} the water input temperature (10 °C) (Table 5).

2.5. Method of generating domestic load profile

To model appliance energy-consumption profile for a typical household, we need to get the information of daily usage of each appliance. That is:

- daily energy-consumption for each appliance;
- ownership of each appliance;
- occupied period.

The calculation of daily energy-consumption of each appliance can use the following equation:

$$E_a = N \times \sum A \quad (3)$$

where E_a is the daily delivered appliances energy-consumption of household; N the number of occupant; A the appliance energy-consumption per capita.

The UK statistical data of daily appliance energy-consumption of average household and of per capita are listed in Table 4.

2.5.1. Specific profile

The above section introduced the way of obtaining/generating daily average end use energy-consumption of an ordinary household in the UK. To model the daily energy load profile of appliance, we consider the worse case that means all the appliance are supposed to be used in this day. Season influence is not considered for appliances. Random profile of each appliance for the specific scenario can be generated using Random Number Generator technique. The aggregation of all appliances' random profiles will generate a daily electric appliances load profile for a stated scenario. This profile is called Specific Profile because it is relevant to a specific occupancy scenario. For each scenario, the daily load profile can be different from day to day and peaky. Computer random operation repeats 20 times for each scenario and the aggregated random profile appears as a relatively smooth curve throughout the day. Fig. 1 shows the framework of generating specific appliance load profile.

In Fig. 1, $A_1, A_2, \ldots, A_n$: name of appliance; $E_1, E_2, \ldots, E_n$: average daily energy-consumption of each appliance; $P_1, P_2, \ldots, P_n$: random profile for each appliance; P_{si}: specific profile for each occupancy scenario.

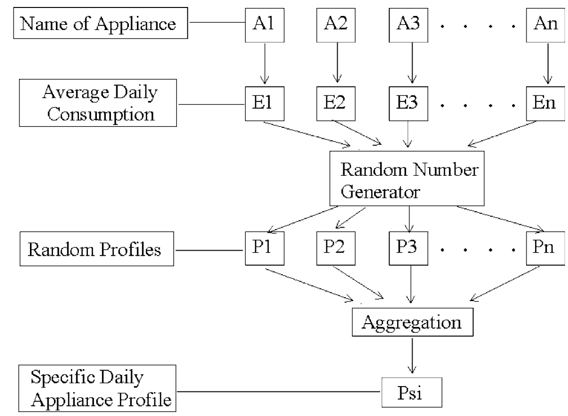

Fig. 1. Framework of generating specific scenarios profile.

2.5.2. Typical profile

Specific profile only represents one of five scenarios of occupancy pattern, and it could not reflect the general situation of an average household. In order to get a general shape of load profile, a typical domestic household electric appliance profile can be generated by aggregating these five specific profiles. Fig. 2 is the framework of generating a typical household electric appliance load profile.

In Fig. 2, P_{s1}, P_{s2}, …, P_{s5}: specific profile of each scenario; P_T: typical profile for an average household.

2.5.3. Urban context profile

To get a regional/national load profile, information of the composition of household in the region/nation is essential. The UK national composition of household is listed in Table 1. Fig. 3 illustrates the framework of generating regional/national load profile.

In Fig. 3, P_{n1}, P_{n2}, …, P_{n6}: typical profile for different composition of household, e.g. 1-person, 2-person,…, 6-person family profile; N_1, N_2, …, N_6: percentage of stated number of people in household in the region; P_A: regional load profile.

3. Heating load

Load profile for space heating depends on the building thermal characteristics, orientation, internal air temperature

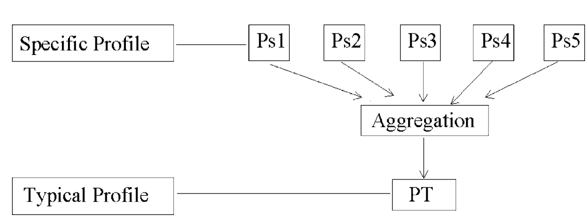

Fig. 2. Framework of generating typical profile.

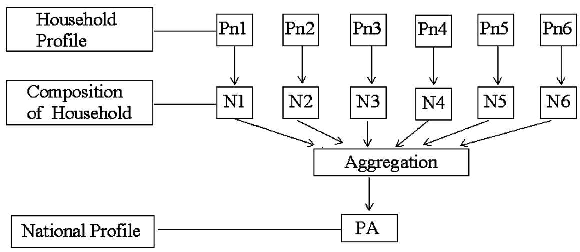

Fig. 3. Framwork of generating regional profile.

control, and local climate, etc. The space heating load has been simulated using thermal resistant method based on the energy balance [9,10]. The equations can be illustrated as follow:

$$C\,\frac{\mathrm{d}T}{\mathrm{d}t} = \Phi_{\mathrm{heat/cool}} + \Phi_{\mathrm{cond}} + \Phi_{\mathrm{vent}} + \Phi_{\mathrm{solar}} + \Phi_{\mathrm{sp}} \tag{4}$$

C is the thermal capacity of the stated node, $\Phi_{\mathrm{heat/cool}}$ the auxiliary heating/cooling energy of the room, Φ_{cond} the conductive heat transfer through the building envelope (wall and window); Φ_{vent} the ventilation heat transfer through the building, Φ_{solar} the solar gain, Φ_{sp} the internal gain from electrical lighting, people and appliance. The detail simulation equation was illustrated in the reference paper [9,10]. This model was validated with the popularly used thermal simulation tool esp-r.

To calculate domestic heating load, four typologies of houses are selected, which are flat, semi-detached, detached, and mid-terraced house. In order to take into account occupant's habits, control algorithm related to occupancy pattern has been embedded within the thermal model. For this case study, we select a floor area of 80 m^2, south–north orientated medium weight dwelling. The control strategy for this example is that the heating set point is 19 °C, when occupied and 15 °C when unoccupied and during sleeping period. Computer simulation has been performed to generate hourly dynamic load profile. The greatest energy-consumption occurred in January. For each typology of dwelling, there are five specific load profiles of five occupancy scenarios. A typical load profile for one typology of dwelling can be produced by aggregating the load profile of five occupancy scenarios. A large scale of load profile for the urban context can be produced based on the typical profiles by taking into account the proportion of each typology of dwelling in the region.

4. Example of UK average household

An example of a typical load profile for UK average size household has been performed using the method presented above. The daily energy-consumption load profiles of electric appliance, DHW and space heating have been calculated for a winter weekday case.

Fig. 4 shows the modeling results of a UK average household appliance load profiles. The thin line represents

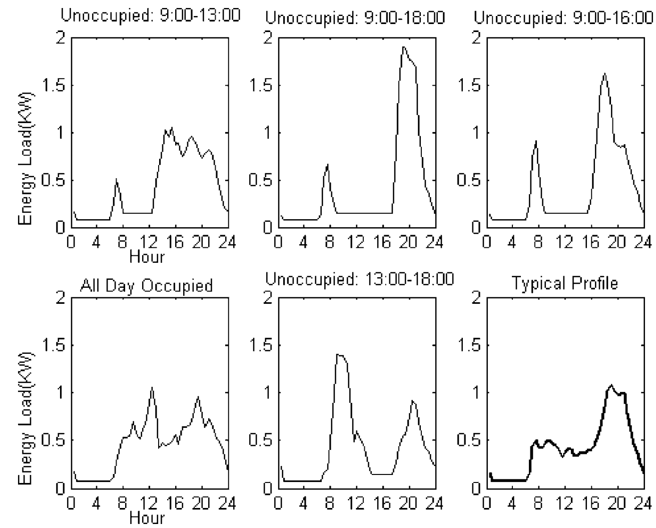

Fig. 4. Typical appliance load profile of an average size domestic household.

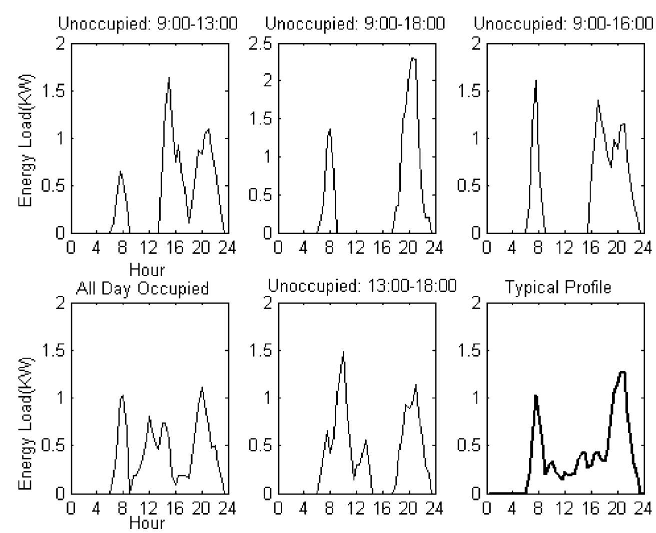

Fig. 5. Typical DHW load profile of an average size domestic household.

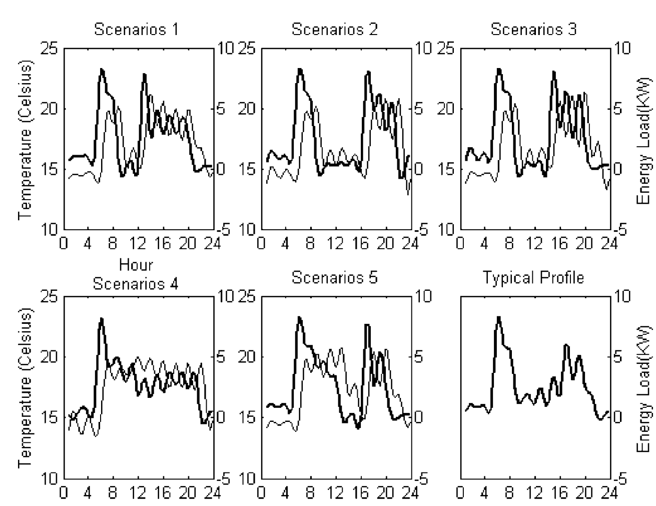

Fig. 6. Temperature and load profiles of semi-detached house.

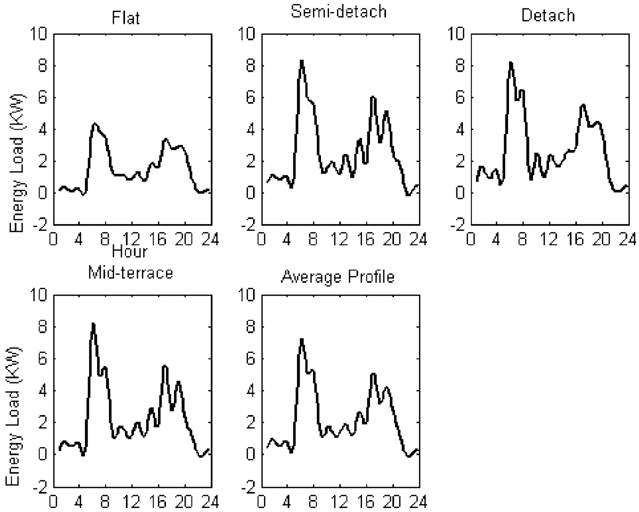

Fig. 7. Typical heating load profile of a tipical dwelling.

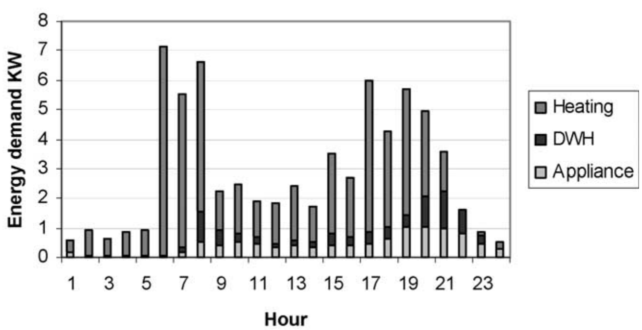

Fig. 8. Typical daily energy demand profile in January.

specific appliance load profile of each occupancy scenario and the thick line represents the typical appliance load profile.

Fig. 5 shows the modeling results of DHW load profile. The thin line illustrates the specific DHW load profile of each occupancy scenario. The dark line illustrates the typical DHW load profile of this average size household.

Fig. 6 illustrates the daily space heating load profiles in winter for a semi-detached house. Profile1 to Profile5 are specific profiles of five occupancy scenarios. The thin line represents the internal air temperature. The thick line represents the energy demand. Typical profile represents the space heating profile of this type of house. Using the same method, four typical space heating load profiles of four types of houses have been produced (see Fig. 7). In Fig. 7, the average profile stands for the regional daily space heating profile.

Fig. 8 is the breakdown daily energy-consumption in January for an average size household. This result will be very useful for the RE system planning and strategic design.

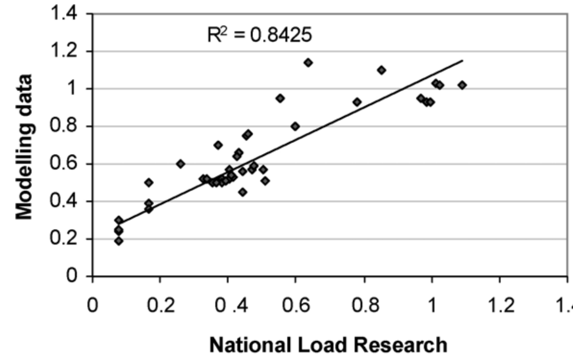

Fig. 9. Co-relation of model method and statistic method.

5. Validation

5.1. Thermal model

The space heating load profile was produced using the thermal model developed at the Martin Centre [9,10]. The model has been validated by the well-validated simulation software Esp-r.

5.2. Appliance model

The UK Electricity Associate Load research Team carried out load profile research and the results are based on the sample of 1300 customers. We take a 3-person winter weekday profile to compare with the model method proposed in this paper. The regional electric load profile of a 100 households in a proposed community has been produced. There is a good agreement between the load profile using simple method (SMLP) proposed in this paper and the statistical profile by UK Electricity Associate Load Research (see Fig. 9). The correlation coefficient of these two profiles is 0.84. Fig. 10 is the comparison of the two profiles. The grey line is produced by SMLP, and the dark line is provided by UK Electricity Associate [11]. The daily electricity-consumption from modelled data is about 10 KWh in the winter for an average family, and about 13 KWh from a national load profile. The national profile result is slightly higher than the model data due to the different resources. This is because national profile data includes a proportion of electricity

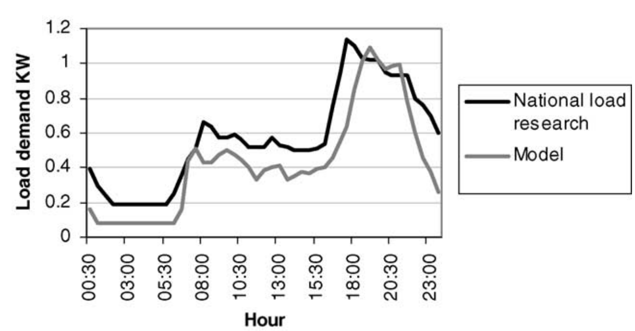

Fig. 10. Comparison of load profiles.

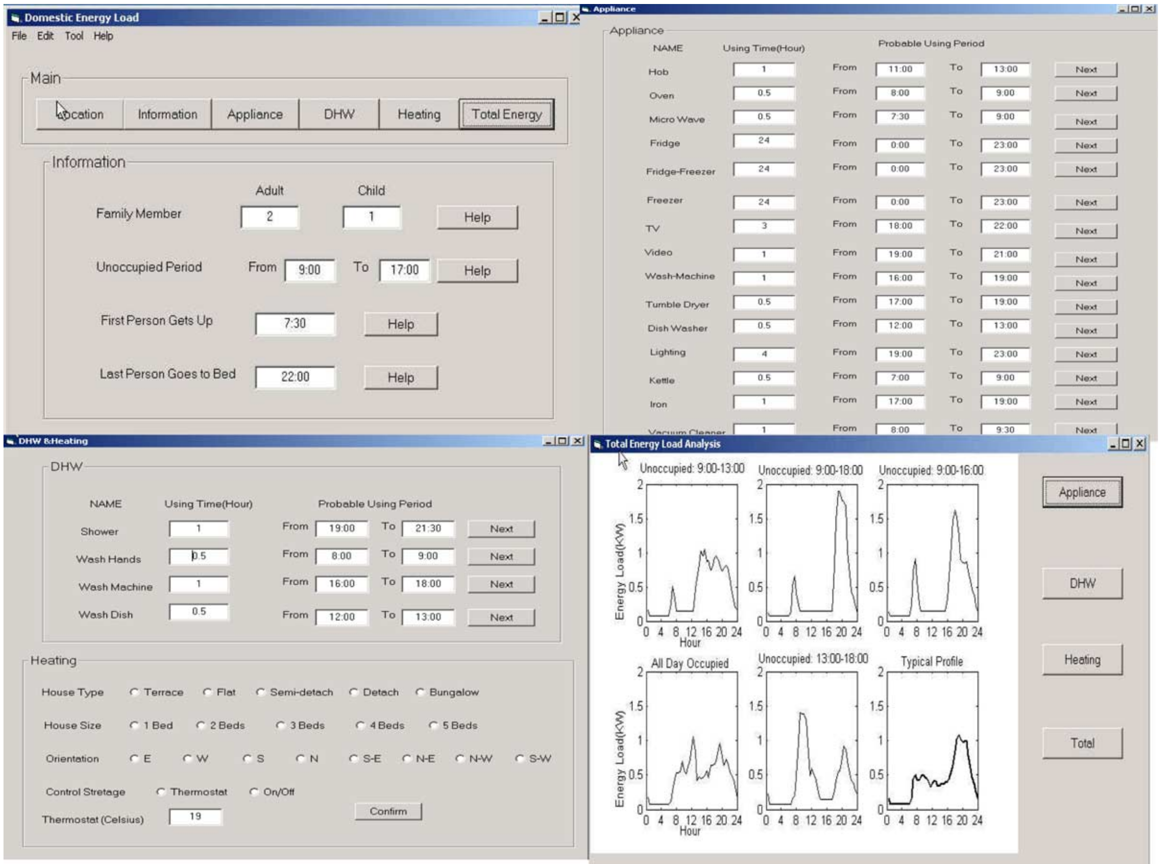

Fig. 11. Interface of the input and output.

heating during the night. However the modelled data is just related to the domestic appliance.

6. Interface

In order to make the method to be used easily and feasible to any users, the computer interface has been developed (see Fig. 11). This will enable the designers to predict individual house, community or regional electricity load profile so that for the RE system planning and design.

The input data are categorized as:

- Location of the community.
- Domestic households information, such as the number of persons in the family, un-occupied period, activity period, etc.
- Appliance usage information, such as items of the appliance, usage hours, and period, etc.
- House information, such as building types, orientation, size, etc.

The program can provide breakdown domestic energy-consumption for any specific period. The simulation time serials interval can be set on 1, 5, 15 min, and half-hour interval, which depends on the design requirement.

7. Conclusion

This paper introduced a simple method of prediction of daily load profile (SMLP). Cluster analysis method has been applied based on the proposed scenarios of occupancy patterns. The method can be applied at both macro (national, regional) and micro (individual houses) levels. To calculate the electric appliance load profile, the required input data are daily average end-use energy-consumptions. To calculate domestic hot water profile, the required input data is daily average hot water consumption of the household. Therefore it is important the accuracy of this information. The season factor will influence the average daily-consumption for each component. This paper illustrates a method and makes an example for winter case. The method can extend to other seasons by alert average daily-consumption of related seasons. A three-person household has been selected as an example of the implication of this method. For the heating load calculation, the thermal resistant method has been used with integration of occupancy pattern control algorithm. A regional load profile for a 100 households has been generated and the load trend is very close to the national statistic data. SMLP method can be used at the RE system early design stage. It can also help the electricity supplier to predict the likely future development of electricity demand in the whole sector of the community.

Acknowledgements

The work of this paper is originally based on the project 'Microgrids—Distribution on-site Generation' funded by the UK Tyndall Centre. The further development of computer-based version is funded by Cambridge-MIT Institute 'Sustainable Building Design' project. The authors appreciate the administrative support from Samantha Lawton and the assistant from visiting Ph.D. student Mr. Qing Luo.

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