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A Simplified Procedure for Sizing Solar Thermal Systems; Based on National Assessment Methods in the UK and Ireland

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Abstract

Solar heating systems have the potential to be an efficient renewable energy technology, provided they are sized correctly. Sizing a solar thermal system for domestic applications does not warrant the cost of a simulation. As a result simplified sizing procedures are required. The size of a system depends on a number of variables including the efficiency of the collector itself, the hot water demand and the solar radiation at a given location. Domestic Hot Water (DHW) demand varies with time and is assessed using a multi-parameter detailed model. Secondly, the national energy evaluation methodologies are evaluated from the perspective of solar thermal system sizing. Based on the assessment of the standards, limitations in the evaluation method for solar thermal systems are outlined and an adapted method, specific to the sizing of solar thermal systems, is proposed. The methodology is presented for two common dwelling scenarios. Results from this showed that it is difficult to achieve a high solar fraction given practical sizes of system infrastructure (storage tanks) for standard domestic properties. However, solar thermal systems can significantly offset energy loads due associated DHW consumption, particularly when sized appropriately. The presented methodology is valuable for simple solar system design and also for the quick comparison of salient criteria.

Keywords: Domestic hot water; solar thermal systems; aperture area; storage tank

1. Background

The IEA [1] report that over one third of the final energy consumption in Europe can be associated to buildings, more than both transport and industry, with thermal conditioning accounting for the largest portion of operational

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Nomenclature

Qs	Solar input (kWh)
S	Solar radiation (kWh/m^2/day)
Z_{panel}	Overshading factor
A_{ap}	Aperture area (m^2)
h_0	Zero-loss coefficient
UF	Utilisation factor
f_1	Collector performance factor
a_1	Linear heat loss coefficient (W/m^{2}K)
a_2	Second order heat loss coefficient (W/m^{2}K^2)
V_{eff}	Effective solar volume (Litres)
V_d	Daily hot water demand (Litres)
f_2	Solar storage volume factor
D	Hot water demand (kWh)
I	Total solar radiation on a given surface (kWh)
SF	Solar fraction
SE	System efficiency

Abbreviations

DHW	Domestic hot water
Lcd	Litres per occupant per day
SAP	Standard assessment procedure
DEAP	Dwelling energy assessment procedure

energy consumption in buildings [2]. The thermal conditioning of a building can be broken down into heating (hot water and space heating), ventilation and air conditioning. With regard to residential buildings in the UK and Ireland, heating is the primary load. Solar thermal systems can be used to provide for this load. However, in order to design renewable energy systems that provide space heating and DHW, it is paramount to quantify the heat energy consumption of the building in question. There are a large number of variables that dictate the heat energy consumption of a building. Due to the number of variables, sufficiently reliable results may only be obtained if a large database is at the disposal to those concerned [3].

Solar combisystems, which are used for both space and DHW heating, are becoming more prevalent throughout some parts of Europe [4]. However, solar thermal systems are predominantly used for DHW applications. This study focuses on systems that are used solely for DHW purposes. Designing a solar thermal system involves more than just selecting a specific type of technology. The optimum size of a solar thermal system will vary from building to building; hence, the location, the occupancy and the function need to be considered. For retrofit designs, the existing system also needs to be considered.

2. Literature review

This section is divided into three sections, which are the basis for the proceeding sections of this paper. A literature review of the domestic hot water consumption of residential buildings is presented in Section 2.1. Section 2.2 then gives a discussion on the methods currently used to size solar water heating systems with reference to the available literature. Finally Section 2.3 outlines the methods used in current national standards.

2.1. Hot water consumption

Obtaining information on the hot water consumption of buildings allows for solar water heating systems to be sized with greater accuracy. However, obtaining domestic hot water (DHW) consumption data is a difficult task,

resulting in a lack of accurate and available information and, ultimately resulting in systems that are either under or over dimensioned. The main obstacles in obtaining this information arises due to the fact that standard buildings are not equipped with meters to provide flow and temperature, in addition to the difficulty in estimating highly variable parameters such as occupant's behaviour. According to The National Standards Authority of Ireland [6], the DHW consumption of a single occupant of a dwelling can be expressed as a linear function of the total occupancy and lies somewhere between 30 and 50 Litres per occupant per day [6]. Studies in other countries have shown that the actual consumption of residential buildings to be different to the values outlined in national guidelines and depend on more than just the occupancy levels [7]–[12]. Each study assesses the DHW consumption as a function of different parameters, however, it is the study of Lutz et al. [12] that uses the most parameters, therefore has the greatest level of detail.

While this study was carried out in the U.S., portraying patterns and consumption levels different to that of other countries, it does highlight the level of detail that can be considered when determining a dwelling's DHW consumption. To this date, a study of similar detail has not been conducted. The study is based on measured data from 110 households in California. A model was produced that predicts the hot water consumption in volume per hour for 8 separate daily time zones (periods of similar consumption levels) for both weekdays and weekends, resulting in 16 empirically derived equations. 11 variables in total are considered, including: occupancy, age, lifestyle (unemployed or not), existence of a dishwasher or clothes washer, outside air temperature, inlet water temperature of the water heater, size of tank, thermostat setting, season, senior citizen only household and whether or not the occupants pay for their energy. This model illustrates the detail that can be applied when estimating the hot water consumption for a given dwelling. An Example of this is illustrated in Fig. 1 for four different dwellings.
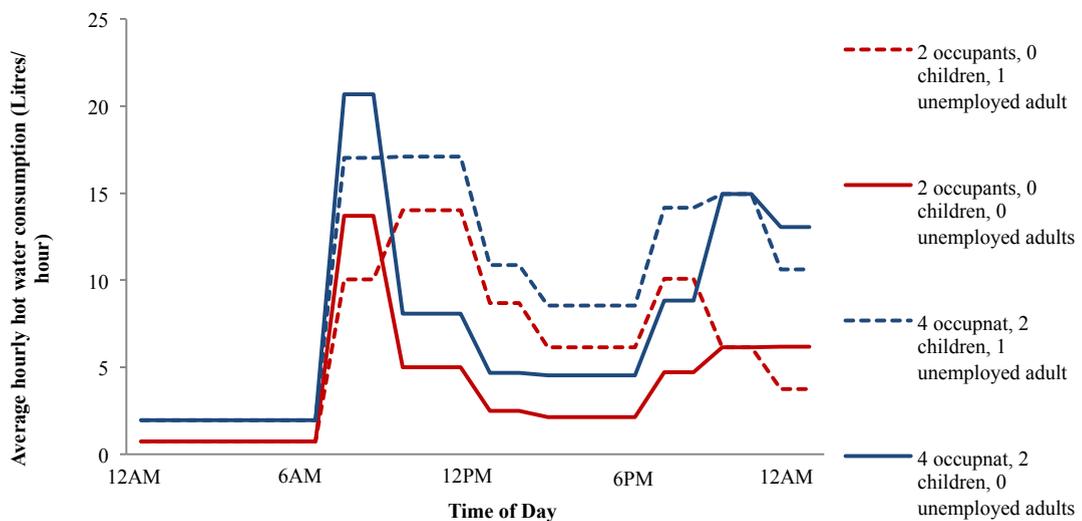

Fig. 1. DHW consumption profiles for four different occupancies, age of occupants and employment status, adapted from [12]

A dwelling with two adults (red) and a dwelling with two adults and two children (blue) are modelled. In addition, a change in profile, in the case that one of the adults was unemployed, is shown for both cases (dashed lines). Three of the eleven variables are altered (occupancy, age and employment status) with all other listed parameters remaining the same. This illustrates the effect these particular variables have on the DHW. DHW is seen to peak in the morning for all cases, but the demand profile is significantly broadened throughout the day given the unemployed status of the occupants. Children lead to an increased overall demand with an evident increase in the evening demand profile, when cooking, bathing and laundry would augment the DHW load.

2.2. System sizing for DHW consumption

The four primary components of the solar thermal system include: the solar collectors, the storage tank, the solar loop and the control system. There is a relationship between the hot water consumption and collector area. Sizing a system will ultimately depend on the hot water consumption, climate and the efficiency of the collectors, which in turn will dictate the area of the solar arrays and the volume of the storage tank. Rules of thumb are often used for the hot water consumption, expressed in litres per occupant per day (Lcd). However, hot water consumption varies greatly per person. Since the solar radiation and hot water demand typically occur at different times, the time difference needs to be bridged. This is typically done by increasing the storage volume and is the reason why solar storage units are larger than the conventional water storage tank [4]. However, large storage tanks have greater heat losses associated to them and are expensive, thus, significantly increasing the capital cost [5].

While the general goal is to maximise solar input (Q_s), care should be taken not to oversize the system. Oversized systems are unnecessarily expensive and have poor annual efficiencies as a result of the diminishing returns in solar input as the collector area and storage tank increase. Also oversized systems have greater periods of stagnation resulting in the possible reduction in service life [4]. Hence, there is an optimum size of solar storage tank and collector area for a given application that maximises solar gain while adhering to the economic, efficiency and durability constraints.

The sizing process can be carried out with varied level of rigour and detail, from simple rules of thumb to the use of detailed dynamic simulation software. While transient modelling software, have been successfully used to provide highly accurate results for modelling solar thermal systems, in the case of residential buildings the scale of a project generally does not warrant the cost of a simulation [13], creating a requirement for a simplified procedure that can produce reasonable results. As a result standards [6], [14] and [15]; as well as a number of studies [16]–[18], have produced simplified procedures that can be used to estimate the size of a solar thermal system for a given location and application.

2.3. Standard procedures for dwelling assessment

The UK and Ireland use the Standard Assessment Procedure (SAP) for the energy rating of dwellings [19]. In Ireland the procedure is known as the Dwelling Energy Assessment Procedure (DEAP) which is drawn heavily on SAP. The equations used by SAP for calculating the energy performance of a building are set out in a workbook format that uses reference tables. Eq. (1) outlines the method of calculation of the solar input.

$$Q_s = S \times Z_{panel} \times A_{ap} \times h_0 \times UF \times f_1 \times f_2 \times h_1 \tag{1}$$

Where Q_s is the solar input (kWh/year), S is the total solar radiation shining on the collector (kWh/m²/year), Z_{panel} describes the over shading factor for the solar panel, A_{ap} is the aperture area of collector (m²), h_0 is the zero-loss collector efficiency, UF is the utilisation factor, $f1$ denotes the collector performance factor, a_1 is the linear heat loss coefficient of collector (W/m²K), a_2 is the second order heat loss coefficient of collector (W/m²K²), f_2 is the solar storage volume factor and is related to V_{eff}, the effective solar volume (litres) and V_d, the daily hot water demand (litres).

The solar fraction is equal to the solar input divided by the DHW energy demand (i.e. Q_s/D). The system efficiency is equal to the solar input divided by the total solar energy incident on the collector (i.e. Q_s/I).

This procedure is the means for rating the energy performance of dwellings in the UK and Ireland and hence requirements must be achieved based on this procedure.

3. Adapted procedure for sizing solar thermal systems

While SAP has been designed to assess the building's energy performance, it can also be useful in early stages of a design process. This study aims at adapting solar thermal descriptions in SAP/DEAP so that it can be used for sizing domestic solar thermal installations. Currently, if using the SAP/DEAP procedure as a guide for solar thermal installation sizing, a reiterative approach must be undertaken, where the aperture area and volume of the storage

tank are calculated using a trial and error approach to meet a desired solar fraction.

The adapted procedure relies on two inputs for area (starting size and modular increment) and volume (starting size and modular increment) and documents solar fraction and system efficiency for a range of sizes. Graphical representations of the solar fraction (*SF*) and seasonal efficiency (*SE*) are obtained as a function of aperture area (A_{ap}) for different storage volumes (*V*). Similar to the procedure undertaken by Raffenel et al. [16] for the sizing of a combisystem. The solar fraction and efficiency are plotted on the same graph to show the trade off between the two (e.g. Fig. 2 and Fig. 3). The aperture area for the optimum balance between solar fraction and efficiency can then be identified from these plots.

Furthermore, SAP describes occupancy as a function of floor area, resulting in fractional occupancies. In the adapted model, the input parameter is changed from floor area to occupancy so that systems can be sized for DHW with respect to the number of occupants in the home rather than the size of the building. In this situation it assumed that the solar thermal system supplies hot water applications only, and not space heating.

A standard, market available flat plate solar collector was considered for this analysis. The collector considered has an aperture area of 2.3 m^2; therefore, the system is sized based on 2.3 m^2 modular intervals. Storage tank volumes vary by manufacturer. In this study 250 Litre intervals were considered for the volumetric increments. The lower limits are represented by a 0.5 m^2 collector area and a 100L storage volume. An optimally orientated solar collector located in Dublin (53°North) was assumed for these figures (i.e. maximum yearly solar radiation of 1135 kW/m^2) [20].

3.1. Procedure for using the adapted method

The adapted procedure for sizing solar thermal systems for hot water consumption can be described by the following key steps:

- The user should input local radiation data, collector efficiency (as documented by the manufacturer) and the occupancy into the model.
- An initial aperture area and storage volume should be input (it is recommended to begin with small size systems e.g. an aperture area of 0.5m^2 and a storage volume of 50L).
- The user should then input the modular intervals based on the aperture area of a single collector. For example, if the collector being considered has an aperture area of 2m^2, then 2m^2 intervals should be used.
- Likewise, the user should input modular intervals for the storage volume. For example, 100L intervals.
- Once this information is input into the program two graphical images are obtained.
- From these resulting graphs, an aperture area should be selected that is greater than the cross over between the system efficiency and solar fraction curves (The cross over point represents the collector area for which the solar irradiance (*I*) is equal to the hot water demand (*D*)). This chosen value will be a multiple of the modular interval as these are the panels that are available.
- Based on the selected aperture area, select a storage volume to provide for a desired solar fraction from the second graph, i.e. the bottom plots in Fig. 2 and Fig. Fig. 3 that do not display the efficiency curve.
- An additional step would allow the payback period for the sized system to be calculated. A quote may be obtained from a supplier and the payback period could then be calculated by dividing the capital cost by the yearly potential savings on energy bills.

With this tool designers can size a solar thermal system to abide by the increasingly stringent building regulations without having to carry out a trial an error process. For example, if a designer knows that, for a given dwelling, in order to conform to the increasingly stringent building regulations, a dwelling must achieve a 50% solar fraction, they can dimension the collector area and storage volume accordingly.

4. Results

Using the adapted method of solar thermal system sizing based on the SAP/DEAP methodology, optimum collector and tank sizes are here evaluated. The results are plotted for different domestic occupancies (Fig. 2, 2 person occupancy; Fig. 3, 4 person occupancy). The optimum aperture area can be approximated using the point of

intersection of the solar fraction and efficiency. The discrete module sizes are described by markings on the graph and in the case of the optimum aperture, the module size that is one or two intervals up from the intersection point is chosen. The graphs on the bottom of Fig. 2 and Fig. 3 are used to estimate the storage volume based on the aperture area selected and solar fraction desired. Trade-offs can be made between the storage volume and aperture area. For example, if there is limited space for the storage tank, a larger aperture area could make up for a smaller storage volume.
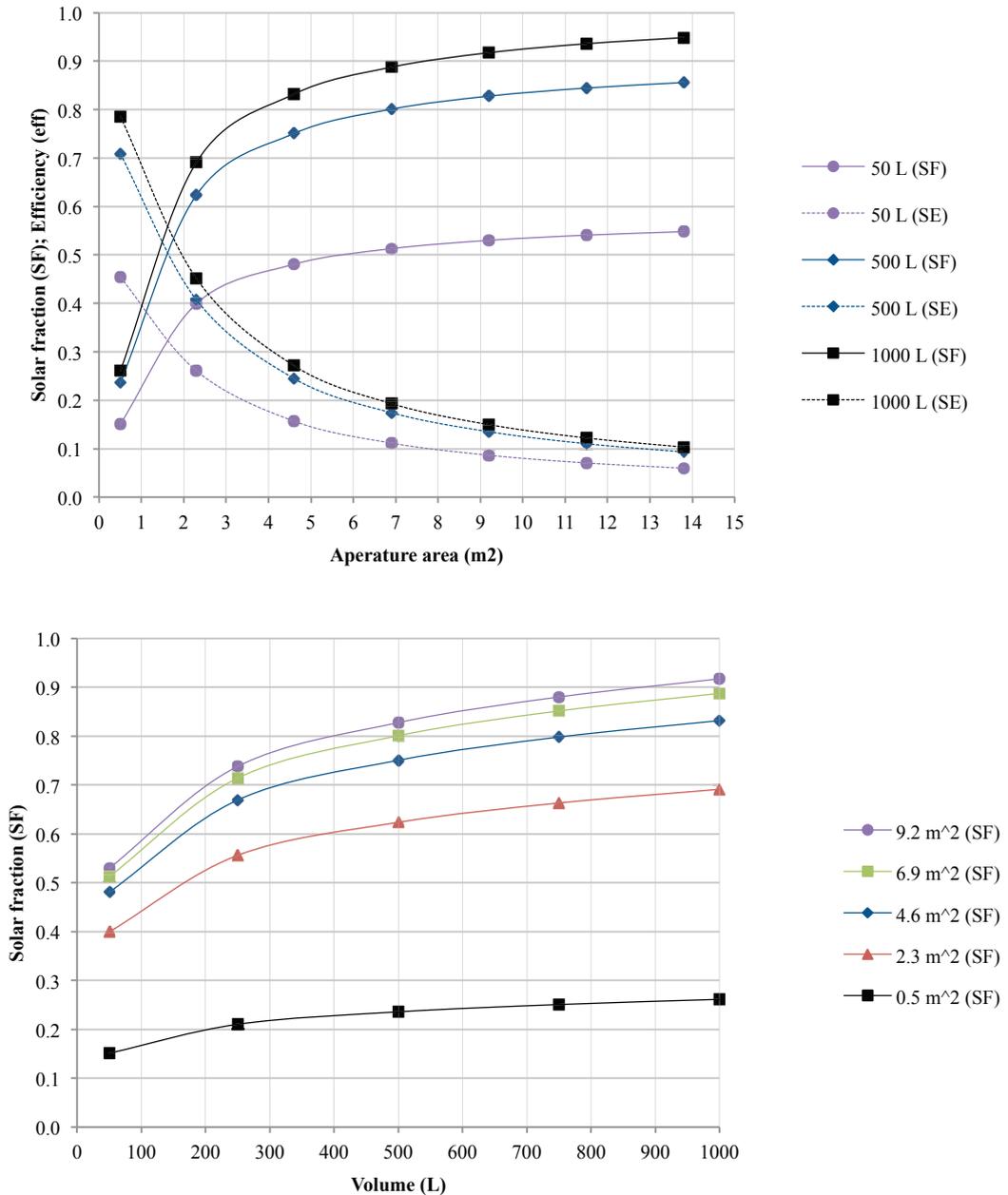

Fig. 2. Top: Solar fraction (SF) and system efficiency (SE) as a function of aperture area. Bottom: solar fraction as a function of storage volume for a dwelling with 2 occupants.
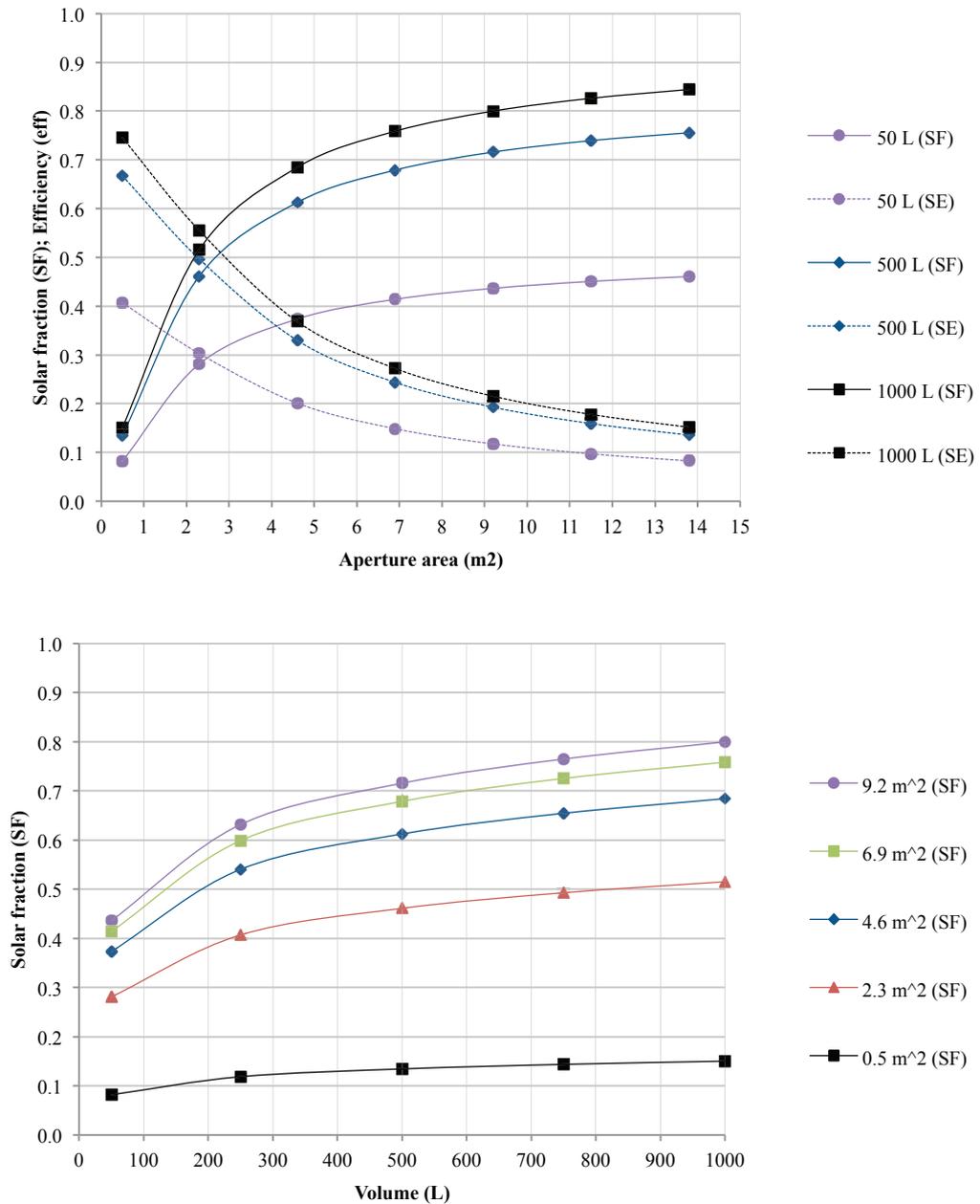
Fig. 3. Top: Solar fraction (SF) and system efficiency (SE) as a function of aperture area. Bottom: solar fraction as a function of storage volume for a dwelling with 4 occupants.

5. Discussion

Fig. 2 evaluates optimum sizing of a solar thermal system for what might be assumed to be a domestic couple. For a desired solar fraction of, for example 0.4, the aperture area is 2.3 m^2. For the same desired solar fraction, the

tank volume would be 80L. A commercially available storage tank that has a volume nearest to the resulting volume, based on this method, should be selected for installation. This is the case, since storage tanks do not come in custom-built sizes. For the standard family of four occupants, (two adults, two children) illustrated in Fig. 3, achieving a 40% solar fraction would result in a 4.6m2 aperture area and a 100L storage tank. Example values for two and four person occupancy, given different desired solar fractions, are documented in Table 1.

Table 1. Associated aperture area and storage volume for given solar fractions

Solar fraction	Occupancy	No. Collectors (2.3m^2 each)	Aperture area (m^2)	Storage volume (L)
0.6	2	2	4.6	180
	4	3	6.9	250
0.4	2	1	2.3	80
	4	2	4.6	100

The results illustrated in Table 1 are guidelines for designers. Increasing the aperture area and reducing the storage volume, or vice-versa, can also achieve the solar fractions. For example, in a dwelling where the occupants do not have the space for a large storage tank, the same solar fraction may be achieved by increasing the aperture area. Thus, providing the necessary solar fraction required to comply with the current building regulations.

6. Conclusion

Sizing a solar hot water system accurately requires a large amount of input data that is not always available to designers. To achieve a high level of detail, hourly input data should be used; however, as mentioned previously, this is not always possible. From the hot water consumption model employed [12], it was shown that employment status and occupancy have a significant impact on the DHW consumption. National standards generally model DHW consumption as a function of occupancy; however, this model emphasises the number of other factors, for accurate calculation. Limitations were identified in SAP with regards to the sizing of solar thermal systems. One limitation observed was the fact that they use floor area as the primary input parameter to obtain the DHW consumption. The reason for this is because SAP was not designed specifically for solar thermal applications, but rather for whole building energy assessments. Also, the methodology requires a trial and error process to size a solar thermal system for a desired solar fraction. The proposed adapted model, which is based on the same methodology allows for quick and simple optimal sizing of solar thermal systems using graphical results. One of the changes of the adapted model is to use occupancy as the input parameter instead of floor area. It is proposed that this parameter is more pertinent when considering solar thermal systems for domestic applications. Different objective solar fractions were considered. For larger families, achieving a high solar fraction may have issues of practicality since the storage tank volume may be too large for standard housing. The proposed methodology could be a useful tool for solar thermal system design for domestic properties allowing for the quick comparison of salient parameters. Additionally, since the method is based on the standard energy assessment procedure, a trial and error process is no longer required when conforming to building regulations. Instead, a required solar fraction, for a given dwelling, is determined and the system is dimensioned accordingly.

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