EVALUATION OF RENEWABLE ENERGY MODELLING METHODOLOGIES WITHIN DOMESTIC BUILDING DESIGN COMPLIANCE PROCEDURES

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1. Introduction

In response to the ratification of the Kyoto Protocol, the European Union has the target of reducing CO_2 emissions by 20% from 1990 levels by 2012. As part of this obligation, the UK is aiming to reduce its own CO_2 emissions by 34% based on 1990 levels by 2022 (DECC). In order to assess emission reduction compliance from domestic housing, the UK Government have developed a Standard Assessment Procedure for new and existing dwellings, called SAP 2009 (DECC 2010). This document contains key energy performance indicators including energy consumption per unit floor area, energy cost rating (SAP rating), environmental impact rating based on CO_2 emissions (EI rating) and dwelling CO_2 emission rate (DER).

This work involves an analysis of the methodologies by which PV and solar thermal technologies are assessed to contribute to energy generation and carbon reduction projections for domestic dwellings. Using comparative analysis with advanced software simulations along with measured data from field installations, the evaluation is focussed upon the projected energy contributions and CO_2 emission reductions arising from these technologies in the context of dwellings' overall design targets. Specifically, methods used by SAP to estimate solar irradiation are evaluated with potential limitations quantified and described, and comparisons to simulations made using PV-GIS and meteorological data for three locations in the south, midlands and north of England respectively. The annual solar energy available to a solar thermal system predicted by SAP is compared with modelled and measured data for Camborne, Nottingham and Durham. The impact of DHW demand and occupancy of a household on solar input and fuel savings made is then investigated using measured data from (Forward & Roberts 2008) and SAP predicted values.

2. The predicted annual irradiation and yield of photovoltaic systems

The effects of location on irradiation were investigated in order to show the significant differences in the available solar resource depending on latitude. SAP 2009 assumes a constant annual irradiation value, based on Sheffield, throughout the UK. This can lead to inaccurate yield predictions from the solar technologies. To investigate this, the SAP estimate for irradiation in three locations (Camborne, Nottingham and Durham) were compared with PVGIS based estimates and measurements from UK Met Office stations at these sites. As the Met Office stations use a pyranometer in a horizontal inclination the PVGIS and SAP estimates were made using a horizontal inclination also. Following this the variation between measured and modelled irradiation predictions within a region were investigated. The irradiation values for three locations within the Midlands (Loughborough, Sutton Bonington and Nottingham) were compared. The annual yield of a south facing $3.56kW_p$ system with a tilt angle of 30° was predicted using SAP and PVGIS for Camborne, Nottingham and Durham. Finally the effect of shading on power output was evaluated.

2.1. Comparison of annual irradiation between southern, central and northern England

Fig. 1 shows annual global irradiation for Camborne (50°12'N), Nottingham (52°58'N) and Durham (54°47'N) as predicted by SAP 2009 and PVGIS respectively compared with measured values obtained from the UK Met Office. These values represent horizontal plane irradiation values to allow like-for-like comparisons to be made between the estimated and the measured values.

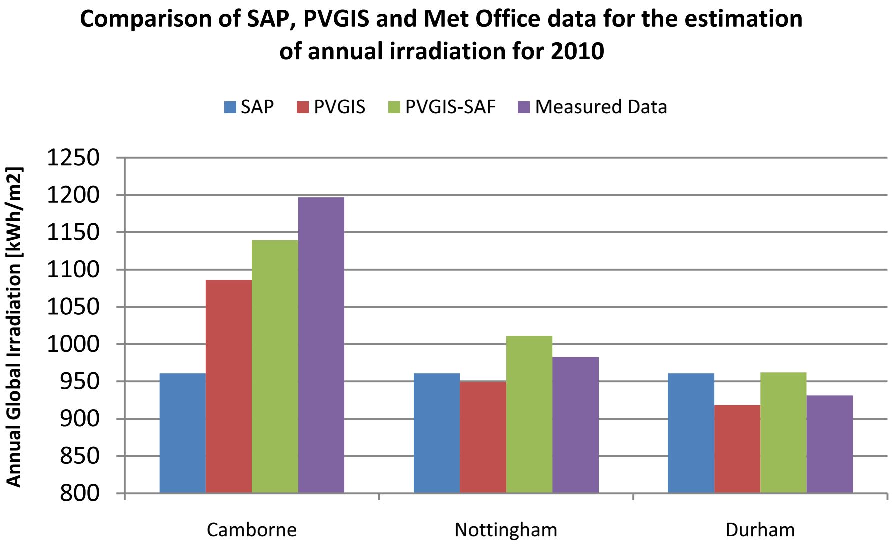


Fig. 1: Annual global irradiation values from SAP 2009, PVGIS and Met Office for southern, middle and northern England

Fig. 1 shows comparisons of SAP estimates for the annual irradiation for Camborne and Nottingham with measured data; deviations are summarised in Tab. 1. These results are corroborated by (Murphy et al. 2009). Fig. 1 also shows a trend of reduced irradiation with increasing latitude, shown by both the PVGIS and measured values.

Tab. 1: Percentage difference in annual irradiation between measured and predicted values (positive values indicate an under prediction and negative values indicate over prediction in comparison to measured data)

Location	SAP [%]	PVGIS [%]	PVGIS-SAF [%]
South	24.57	10.22	5.08
Midlands	2.26	3.54	-2.80
North	-3.11	1.41	-3.22

Tab. 2: Variations in irradiation for the Midlands and the North compared to the South

Location	Measured [%]
Midlands	21.81
North	28.56

PVGIS irradiation values also show the same trend, namely a SAP over-prediction of irradiation in the North and an under-prediction in the South in comparison to measured data.

2.2. Comparison of annual irradiation between locations within central England

To facilitate a higher resolution local evaluation of irradiation trends, annual irradiation data was collected for three locations within central England; Sutton Bonington (52°50'N), Loughborough (52°47'N) and Nottingham (52°58'N). The measured data was collected from 2007 to 2010 and has been averaged. Fig. 2 shows the level of local variation within this local region.

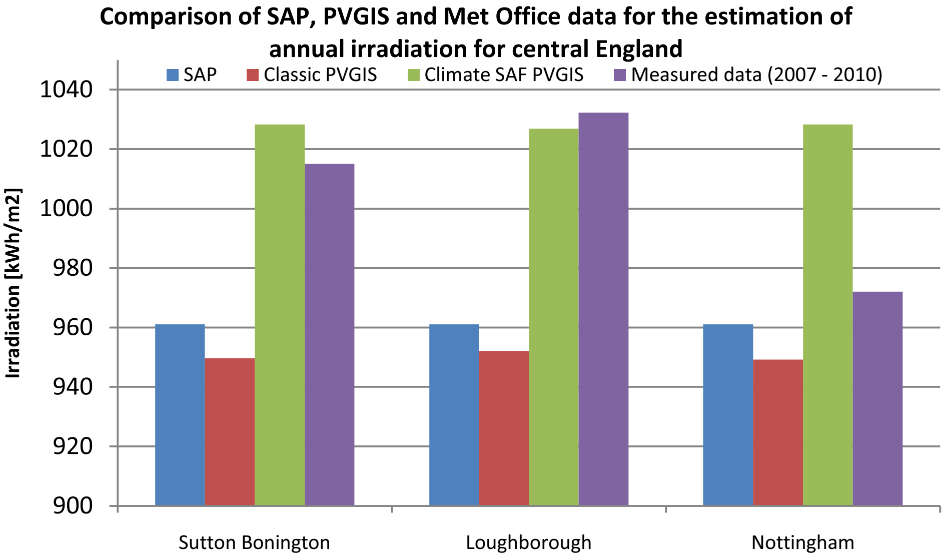


Fig. 2: Comparison of the annual irradiation for central England obtained from measured and predicted sources

The results indicate that SAP values are low in comparison with measured data. In particular, SAP values are low for the southern the region. It appears that the further away from Sheffield the irradiation measurement is taken the greater the deviation SAP has from the measured value.

Tab. 3**Error! Reference source not found.** shows the percentage difference between the irradiation values for measured and modelled data.

Tab. 3: Percentage difference in annual irradiation between measured and predicted values (positive values indicate an under prediction and negative values indicate over prediction)

Location	SAP [%]	PVGIS [%]	PVGIS-SAF [%]
Sutton Bonington	5.63	6.89	-1.28
Loughborough	7.41	8.41	0.52
Nottingham	1.15	2.41	-5.46

2.3. Annual PV output prediction

The following is a comparison of the SAP 2009 and PVGIS annual output predictions of a 3.56kW$_p$ system with a south-facing orientation and a tilt angle of 30°. Fig. 3 shows the annual output that would be expected on a south-facing module at a tilt angle of 30°. SAP 2009 provides the annual irradiation value for this scenario whereas PVGIS allows this to be modelled by changing the tilt angle in the model. Detailed information about how the PVGIS model works can be found in (Suri & Hofierka 2004) and (Šúri et al. 2005). In order to calculate the irradiation at an angle of 30° using measured data the beam and diffuse components are required as in the Telecom method (Wenham et al. 2008). Alternatively a method described by (Olmo et al. 1999), (Muzathik et al. 2011) and (Evseev & Kudish 2009) allows the irradiation incident on a tilted surface to be calculated using only the horizontal irradiance. However the UK Met Office do not provide beam or diffuse components nor do they provide irradiance measurements only irradiation. In order to convert from horizontal irradiation to horizontal irradiance, to calculate the clearness index as in the Olmo et al. method, time values are required. This again was not provided only daily totals for irradiation at the three locations. Therefore measured data for irradiation incident on an inclined plane at 30° is not included in the comparison.

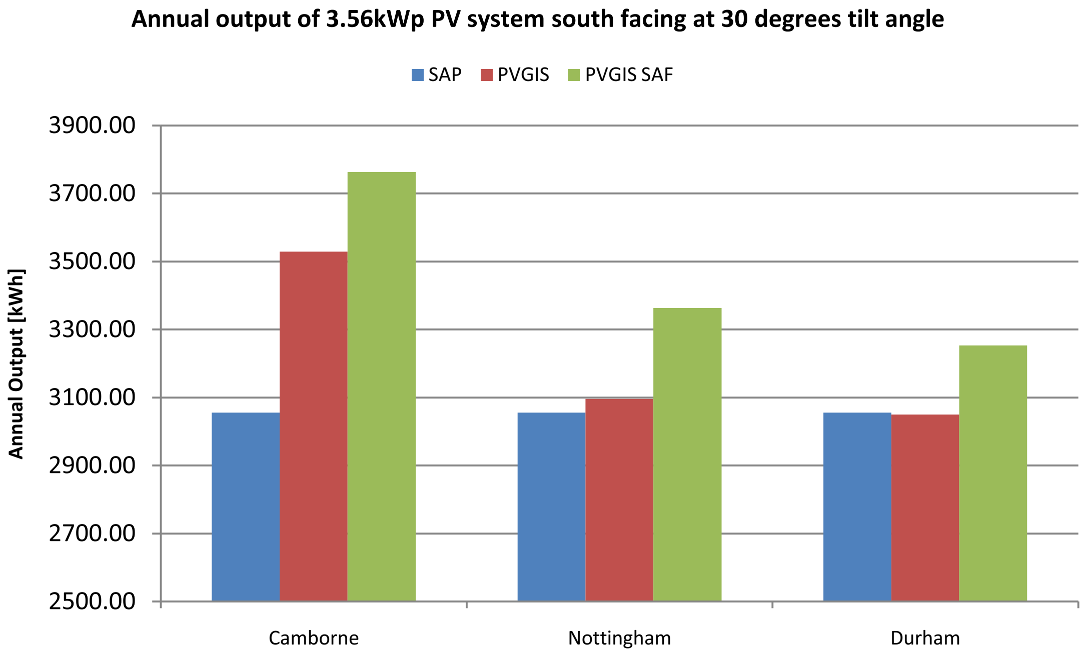


Fig. 3: Annual output of a 3.56kW$_p$ system with a south facing orientation at 30° tilt angle

It is shown that in comparison with PVGIS, SAP gives closer approximations for central and northern England but underestimates the solar resource in the south of England to a greater extent. This agrees with the suggestion by (Murphy et al. 2009) that SAP underestimates the solar resource under favourable conditions. It seems that for PV systems, the location of the dwelling can have significant impacts on the predicted annual yield also seen by (Munzinger et al.). The use of central England data may not be suitable as locations such as Camborne are much further away from Sheffield than the very north of England. This leads to greater underestimation of the solar resource in southern areas as the distance from Sheffield increases. Using a fixed annual irradiation value regardless of location also gives poor approximations to annual yield of PV systems. Areas in the north are overestimated and thus erroneous predictions in cost and emissions savings may result; future work would include validating this hypothesis with comparisons of annual yield from a number of Northern installations. For areas in the south, the converse applies, and basing potential investment in PV systems on SAP benchmarks could deter potential investors as the annual yield can be up to 23% greater than the SAP prediction as shown in Tab. 4.

Tab. 4: Percentage difference in annual output between measured and predicted values (positive values indicate an under prediction and negative values indicate over prediction)

Location	PVGIS [%]	PVGIS-SAF [%]
Camborne	15.47	23.14
Nottingham	1.30	10.06
Durham	-0.20	6.46

2.4. Effects of shading on PV output

The effect of shading was investigated using measured data from previous work (Martínez-Moreno et al. 2010). As stated in this study, shading is often unavoidable and must be considered when analysing PV system output. Advanced shading modelling often uses current-voltage curves, which though accurate, can lead to long computation times. (Martínez-Moreno et al. 2010) developed a model that uses direct power outputs from the PV system. In the current work, experimental data from this study is used to compare the measured effects of shading against the SAP model used to assess the impact of shading. Martínez-Moreno et al. include the effect of different PV module shading geometries, whilst SAP makes no allowance for this and bases its annual yield on a simple shading factor. This is used as a correction factor to estimate any negative effects of shading on the annual yield. This correction factor is calculated by estimating the percentage of the sky blocked by obstacles and assigning a corresponding over shading factor.

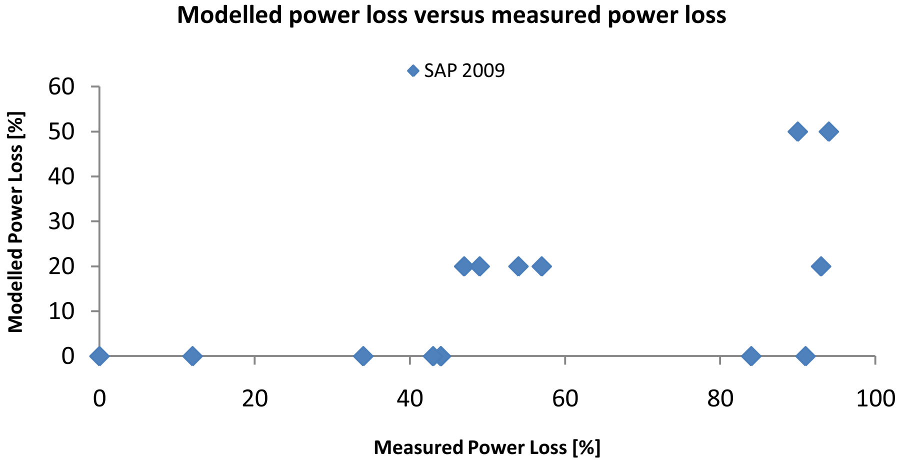
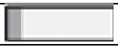


Fig. 4: SAP modelled power loss versus measured power loss (Martínez-Moreno et al. 2010)

Fig. 4 shows the SAP modelled power loss versus the measured power loss for modules with different shaded geometries as shown in Tab. 5 (Martínez-Moreno et al. 2010)

Tab. 5: Shadow geometry, percentage shaded and corresponding power loss (Martínez-Moreno et al. 2010)

Shadow geometry	Horizontal shading [%]	Vertical shading [%]	Total shading [%]	Power loss [%]	SAP power loss [%]
	0	0	0	0	0
	100	9	9	84	0
	100	18	18	91	0
	100	36	36	93	20
	4	64	2.56	12	0
	17	45	7.65	44	0
	29	27	7.83	44	0
	50	9	4.5	43	0
	13	100	13	34	0
	25	100	25	47	20
	38	100	38	49	20
	50	100	50	54	20
	58	82	47.56	57	20
	75	73	54.75	90	50
	92	64	58.88	94	50

It can be seen in Fig. 4 that SAP tends to underestimate the amount of power loss shading can produce. In addition Tab. 5 indicates that SAP makes no allowance for the amount of power lost due to different shading geometry

3. The prediction of annual solar energy available and fuel savings made for a solar thermal system

3.1. Comparison of annual irradiation between southern, central and northern England

The solar energy available, Q_{solar}, to the solar thermal system is a function of the annual irradiation. This parameter determines the contribution the solar thermal system makes to DHW heating (Q_s) shown by (eq. 1) found in SAP 2009 (DECC 2010):

$$Q_s = (Q_{solar})(UF)f\left(\frac{a_1}{\eta_0}\right)f\left(\frac{V_{eff}}{V_d}\right)$$

(eq. 1)

Where UF is the utilisation factor, $f(a_1/\eta_0)$ is the collector performance factor (a_1 being the linear heat loss coefficient of the collector and η_0 being the zero loss efficiency) and $f(V_{eff}/V_d)$ is the solar storage volume factor (V_{eff} being the effective solar volume and V_d being the daily DHW demand). The annual solar energy was calculated using the (eq. 2) given in SAP 2009 (DECC 2010) with the irradiation values from SAP, PVGIS and measured data, using horizontal plane irradiation values.

$$Q_{solar} = A_{ap}\eta_0 S Z_{panel}$$

(eq. 2)

Here A_{ap} is the aperture area, η_0 is the zero loss efficiency, S is the annual irradiation and Z_{panel} is the over shading factor.

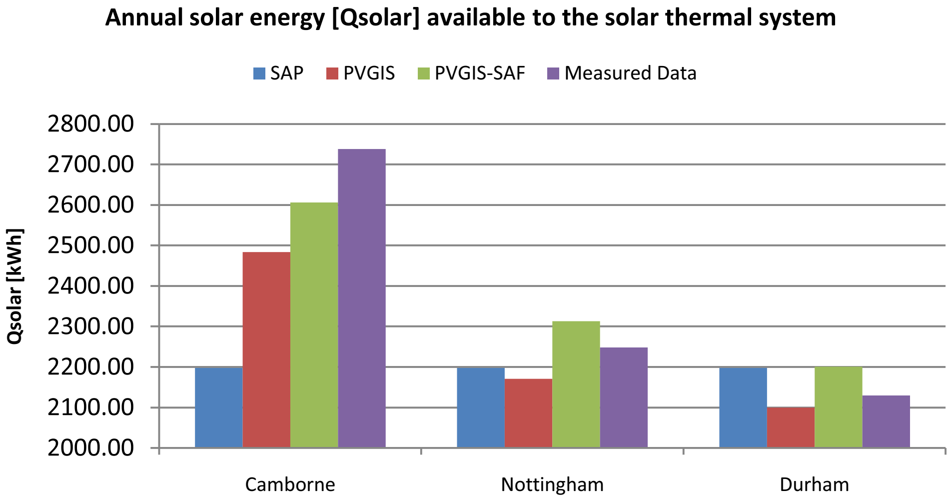


Fig. 5: Annual solar energy available to the solar thermal system for the three locations

Fig. 5 shows the annual solar energy available to the solar thermal system for the three locations. As the solar energy available is a function of irradiation and all other parameters (UF, $f(a_1/\eta_0)$ and $f(V_{eff}/V_d)$) in (eq. 2) are kept the same for each of the locations the trends are identical to the annual irradiation plot. It is shown that again SAP has low values for the solar resource in the south and higher values in the north. SAP as stated before bears no consideration to the effects of location on the solar resource estimating 2198kWh/year of solar energy available to the solar thermal system. Using measured data it is shown that Camborne and Nottingham receive 24.57% and 2.27% more irradiation than predicted respectively.

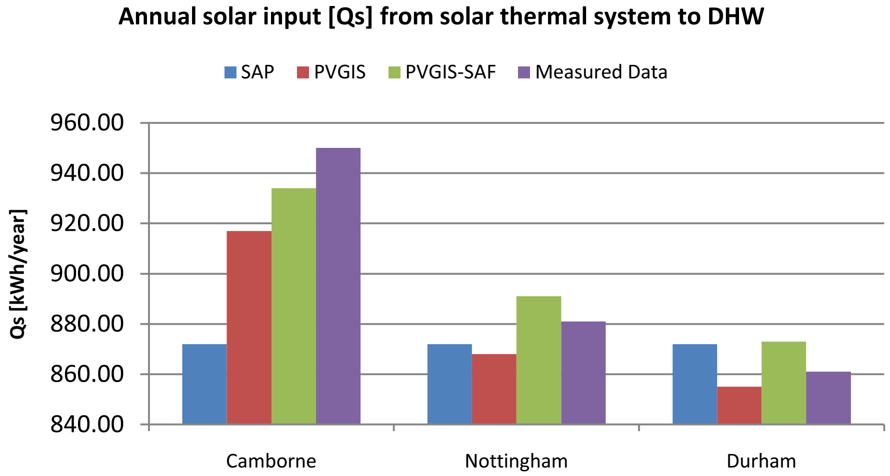


Fig. 6: Annual solar input from the solar thermal system to DHW heating

Fig. 6 shows SAP approximations to solar thermal DHW input for the Midlands and the South are lower than the measured values. The converse is seen for the north..

Tab. 6 shows the percentage differences between the solar input for predicted values and measured approximations. This indicates that for solar thermal systems SAP mainly underestimates systems in the south compared to measured data. A reason for this could be that Sheffield is not strictly the dead centre of England as Camborne is much further away than anywhere in the north. A greater distance from Sheffield seems to produce less accurate SAP approximations.

Tab. 6: Percentage difference in annual solar input between measured and predicted values (positive values indicate an under prediction and negative values indicate over prediction)

Location	SAP	PVGIS	PVGIS-SAF
Camborne	3.31	1.37	0.68
Nottingham	0.36	0.57	-0.45
Durham	-0.52	0.24	-0.54

3.2. The impact of occupancy and DHW demand on fuel savings made through solar thermal system

Using data obtained from a field trial of solar thermal systems (Forward & Roberts 2008) the effects of occupancy and DHW demand on solar thermal yield were compared with that predicted by SAP 2009.

In the field trial, six houses were monitored, each with a total floor area of 85m^2 and varying occupancies consisting of both adults and children. The solar thermal system of aperture area 3.05m^2 had a dedicated solar store of 55L and a total storage volume was 180L. Gas boilers with efficiencies of 90% were used to provide any extra heating required. The daily DHW demand was measured along with any fuel savings resulting from the solar thermal systems. Fig. 7 shows occupancy for these dwellings, ranging from 2 to 5 adults and children.

SAP-based calculations were then carried out for an equivalent dwelling of 85m^2 total floor area. It should be noted that SAP makes no allowances for occupancy variations, and uses a simple floor area conversion factors to predict occupancy, in this case 3 persons.

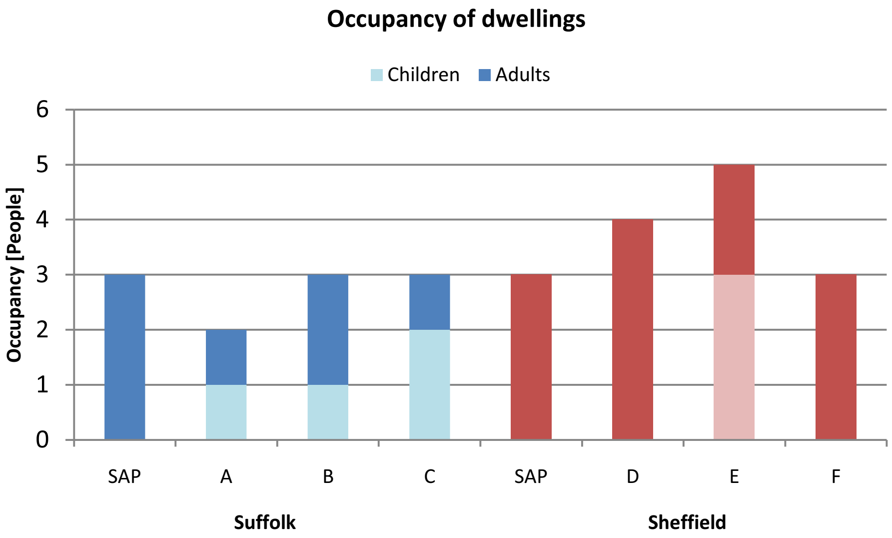


Fig. 7: Measured and predicted occupancy of 85m^2 houses based in Suffolk (blue) and Sheffield (red). Light shades refer to children and dark shades refer to adults [(Forward & Roberts 2008)**]**

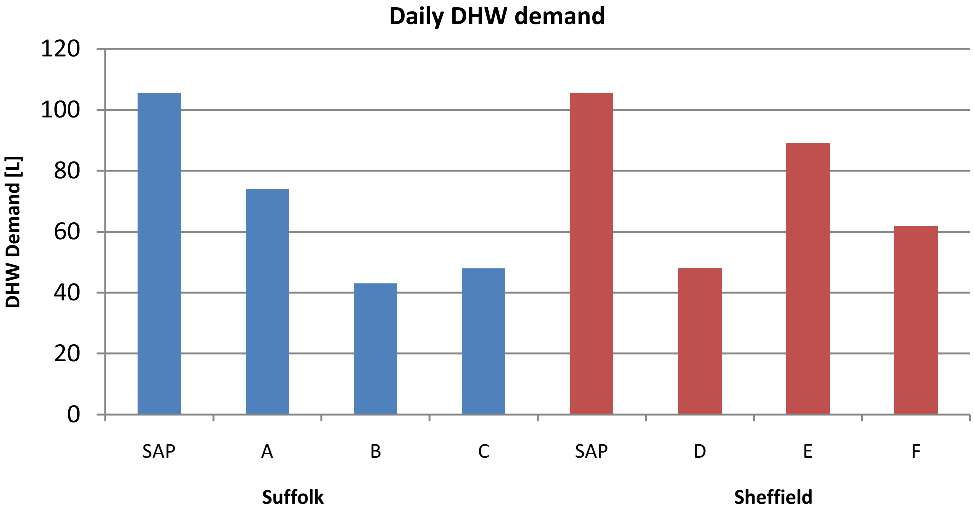


Fig. 8: Measured and predicted daily DHW demand

SAP uses the total floor area to predict occupancy which can vary greatly for houses with the same floor area as shown in Fig. 7. SAP also uses the occupancy to predict the average daily hot water demand. This means that effectively the daily hot water demand for a household is based on the total floor area. As can be seen above in Fig. 8, in reality, dwellings with the same total floor area can have quite different DHW demands. This is partly due to the occupancy; house E with five people uses the most. However there is no apparent correlation between occupancy and DHW demand. For example, house D contains four people but uses the same amount as house C with three people, and less water than A and F with two and three people respectively. The SAP estimates for daily DHW demand are greater than the measured data in all cases. It exceeds the measured demands of houses with 85m^2 even those with over the predicted three occupants. The result of an over predicted DHW usage is that the predicted solar input decreases and the fuel required by the auxiliary heating system increases. This leads to underestimations in the fuel saving that can be made by installing a solar thermal system.

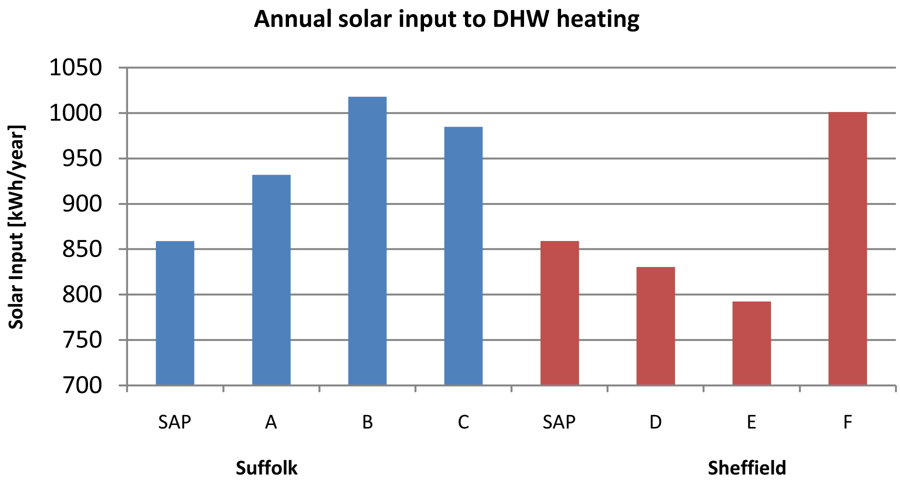


Fig. 9: Measured and predicted annual solar input to the DHW heating system

Fig. 9 shows the annual solar input to the water heating system for the SAP prediction, based on DHW demand, along with measured data. As can be seen for the southern location of Suffolk, SAP consistently under values the solar input for all dwellings. This under prediction of southern locations agrees with previous irradiation measurements and by (Murphy et al. 2009). This could be due to the under prediction of annual irradiation combined with the over prediction for DHW demand, which both cause a drop in predicted solar input according to SAP. For Sheffield it would be expected that SAP provides very close approximations due to the potentially closer irradiation approximations. However SAP shows an underestimation of the solar input for house F, even though this dwelling matches the SAP prediction closely with regards to occupancy. The underestimation could be due to SAP's over prediction of DHW demand for this house giving a low solar input due to a low f(V_{eff}/V_d) term (eq. 1). It could also be that House F receives more irradiation than the other houses in Sheffield. SAP predictions and measured values for House D are very close, which is expected due to location but an underestimation would be expected when observing that SAP over predicts the DHW demand. This may be due to usage pattern as explained in (Forward & Roberts 2008) house D used more DHW in winter when the solar system made very small contributions therefore the solar input would have been higher if DHW use was more uniform throughout the year. Houses E and A could have greater solar input, however the occupants fired the boiler in competition with the solar thermal system negating any benefit from the system.

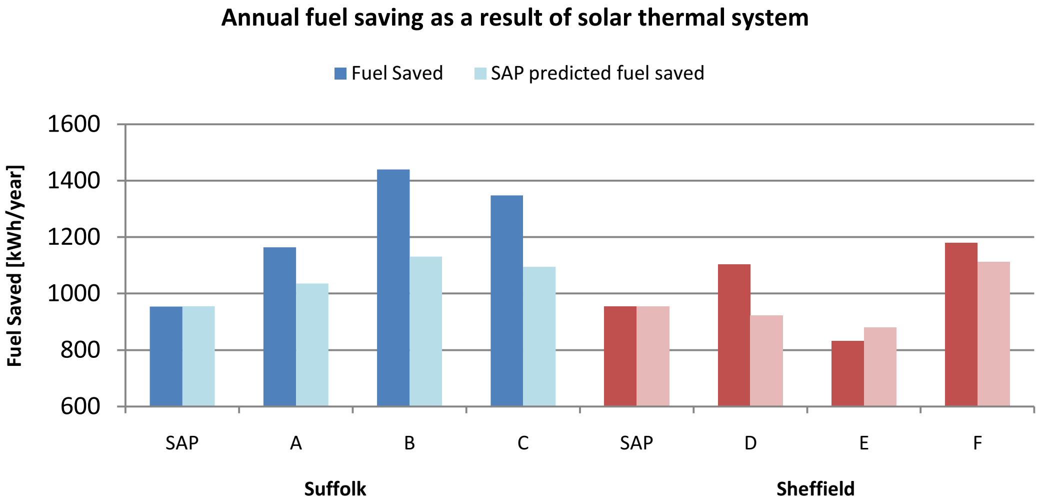


Fig. 10: Measured (dark shade) and predicted (light shade) fuel saved due to solar thermal system

Fig. 10 shows actual and SAP-predicted annual fuel saved. This shows that the predicted fuel saving each year is considerably less than that which is actually saved. In this case SAP therefore underestimates the savings that can be made by installing a solar thermal system. The predicted fuel saved follows the solar input trend closely whilst the correlation of measured fuel savings follows the trend of the solar input to a lesser extent. However greater savings would be expected from house F as it has a similar solar input to houses B and C. This could be due to a greater knowledge of energy management in houses B and C, in which residents are said to have manually fired the boiler when needed thus maximising the effect of the solar thermal system. Houses F (and D) used the boiler programmer to heat water up to temperature before use, though not after. Houses A and E are relatively underperforming, as indicated by the relatively low solar fraction. It is suggested that this is not due to high water use (which leads to higher water energy and greater fuel required to heat it), but because the boiler was fired at the same time as the solar thermal system is heating the water. As the boiler heated section of the tank is at maximum temperature the dedicated solar part of the storage is reduced. A high temperature cylinder will also incur more losses which are met by the boiler system rather than the solar system (Forward & Roberts 2008). Fig. 11, below shows the consequence of effective control of a solar thermal system on the solar contribution. The figure shows the result of a MATLAB simulation where a control system was modelled. The control system calculates the temperature at which the water in the store should be in order to exactly satisfy peak loads. As can be seen the solar contribution is increased with effective control of the system indicating the benefits that can be made by educating people about effectively controlling their solar thermal systems.

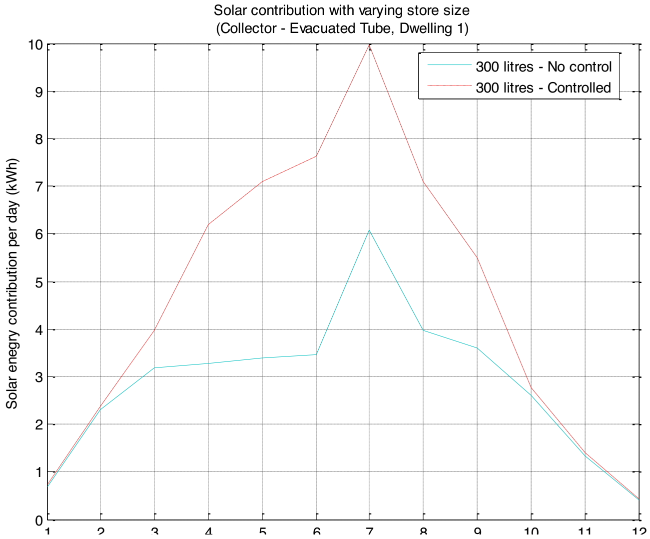


Fig. 11: Comparison of soalr energy contribution for controlled and uncontrolled systems

From this it is clear that use of total floor area gives very poor approximations of occupancy. For the sample in question, the number of people living in a house of similar sizes varies greatly from the predicted value. The DHW demand based on total floor area and occupancy is also very inaccurate. The DHW demand is a complex relationship of human factors such as size of household, mixture of adults and children, household occupation, age, energy consciousness and so on. For example house B and C seem to be the most energy conscious due to low DHW demand and the understanding of the solar thermal system. SAP under values the solar input in the south, which could be due to low irradiation and high DHW demand values in comparison to measured data. Usage patterns can have a greater effect than the amount of water used (Forward & Roberts 2008). The solar input is also affected by when the water is heated, water heated in the winter has very little contribution from the solar thermal system and so solar input is reduced. The solar input is also affected by the knowledge of the occupants. Houses A and E fired the boiler when the solar thermal system was working thus reducing the solar input. Though this cannot be predicted and cannot realistically be included in SAP, a simple awareness strategy could be implemented educating people about solar thermal systems. The fuel saved is a function of the solar input but it is also affected by DHW usage patterns and knowledge of the system. Effective control of solar thermal systems is shown to improve the performance and therefore the fuel savings.

In summary to improve the effectiveness of solar thermal systems education of users is important, as a key impact on performance of solar thermal systems are human factors (Forward & Roberts 2008), (Allen et al. 2010). Educating people about DHW usage patterns and how they affect solar input and fuel savings as well as not forcing the system to compete with auxiliary heating systems could greatly improve the performance of solar thermal systems.

4. Conclusion

With regards solar irradiation estimation in England, SAP consistently under predicts in the south and over predicts in the north compare to measured data. This trend exists even within a region and the further the distance from Sheffield the poorer the irradiation approximation seems to get. It might be preferable to divide the country into regions and approximate irradiation values based on the region the dwelling is located.

The shading of a PV system is not considered in enough detail and is overly optimistic. Reductions in power output can be drastically affected by shading geometry. Again this introduces uncertainty and risk into investment into PV systems.

With regards to solar thermal systems the same trend can be seen for SAP predicted solar energy available as irradiation in the PV case. That is an underestimation in the south and an over estimation in the north. This is expected due to the solar energy available being a function of irradiation.

It is shown that based on measured data, albeit a small sample, the total floor area gives a very rough approximation for occupancy. The total floor area and occupancy give very poor approximations of DHW demand, overestimating in most cases.

The solar input is poorly predicted in SAP as is the fuel saving. They are based mainly on the DHW demand and solar energy available which as discussed above are also predicted to a low level of accuracy. The fuel saved and solar input are dictated by mainly human factors, as opposed to PV systems which are typically controlled by technological issues. The understanding that the user has of the solar thermal system as well as their energy consciousness means that they can maximise the effect of the solar thermal system as in houses B and C. Poor understanding of the system can lead to poor control and poor performance as in houses A and E. The pattern of DHW usage also has an effect on the solar input and fuel saved as in houses D and F.

To increase performance of solar thermal systems it is advisable to educate users in the effects of DHW usage patterns and effective control of the system. (Cortese 2003) suggests that the role of the education system should include teaching people about sustainability and thus helping to alter behaviour to that, which should prompt energy consciousness. Recommendations made by (Munzinger et al.) include educating installers, householders and other users of PV systems in the effective operation of such systems.

5. References

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