

Treatment in SAP Appendix Q of a close-coupled store in a FGHRs with an electric immersion heater powered by photovoltaic modules

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1 Introduction

Flue gas heat recovery systems (FGHRs) with close-coupled stores were recently recognised in SAP 2005, Appendix Q. A further request to recognise close-coupled store with a 12V DC, immersion heater powered directly by photovoltaic (PV) cells has recently been received by Zenex. This report describes a procedure necessary for such recognition.

Elements from SAP 2005 Appendix H (solar water heating) and SAP Appendix M (photovoltaic modules) are brought together to devise a procedure for photovoltaic modules powering an immersion heater.

The purpose of this report is to document the procedure and its basis. It is not intended to be used by SAP assessors.

The main assumption is that the immersion heater allows the water to be heated up to 85°C (after which thermal protection then kicks in). If this assumption does not hold the procedure is not valid.

2 Description of system

A close-coupled store in FGHRs is kept warm by the combi boiler and maintained at 65°C by a separate channel that is controlled by a clock.

Electricity produced by the PV module feeds a 12V DC electric immersion heater, inserted into the closely-coupled store subject to a maximum of 85°C. There are no additional pumps and no power conversion to 240V AC. The maximum length of the cable is 10m of standard twin and earth main cable of a specified thickness.

Table 1: Technical specification provided by Zenex

Working voltage:	12v DC
Rated Power:	160w (the single immersion unit contains 2 x 80w elements with thermal protection)
Std Cable length:	10m
Resistance of cable:	7.41Ω per km at 20°C. 2.5mm sq twin-core, sheathed cable, one cable for each heater
PV module:	2 x 80Wp modules

3 The procedure

The parameters required for assessment are shown in table 2 and calculation steps in table 3.

Table 2: Assessment parameters required

<p>Immersion heater and cable Nominal power (W) and Voltage (v) dc Maximum cable length (m) Wire cross sectional area (mm²)</p> <p>Photovoltaic module Peak power (kWp) Voltage at peak power (v) Solar shading factor (heavy, significant, average, modest or none see table H3, SAP 2005) Orientation (one of the eight compass points) Tilt (horizontal, 30, 45, 60, vertical)</p> <p>Others (included in the FGHRs close-coupled store sheet) Close-coupled store volume and daily heat loss at 45K rise above ambient. Floor area (to work out daily water volume Table1 of SAP) Hot water efficiency (set to 91% for conservative estimate FGHRs savings)</p>

Table 3 Calculation steps

1. Lookup: the resistance per m of the cable based on the cross sectional area, the heater's nominal power and voltage, maximum cable length and the module's peak power (in kW) to calculate the fractional power loss (8). For separate circuits note paragraph after (8).
2. Obtain the close-coupled storage volume to calculate the effective volume using 16.
3. Retain the effective volume and obtain the daily volume of water from floor area to calculate the solar storage volume factor using 13.
4. Obtain PV parameters: peak power (kW), orientation and shading factor to calculate the solar-to-load factor (11).
5. Calculate the utilisation factor (12).
6. Calculate the useful solar gain (10) , divide it by the assumed water efficiency (91%) of FGHRs and add the result to the gas savings in appendix Q close-coupled calculations.
7. Calculate the extra heat gains (17) and add the result to the heat loss of the closed-coupled store in Appendix Q close-coupled calculations.

4 Basis of procedure

4.1 Generated power

The electrical power rating of PV modules are specified in terms of output under test irradiance of 1000W/m^2 . This rating is referred to as the peak power. Terrestrial solar irradiation varies throughout the year; from 0 to 950W/m^2 in the southern parts of the UK¹, which is close to the testing standard. And therefore the “peak power” is also approximately the peak power expected in the UK.

The solar irradiance will also vary with angle of tilt and orientation. Tilt and orientation are already accounted for in SAP (see table H1). The day-time average on a horizontal surface is 213W/m^2 (table H2 \div (12 hours \times 365 days)) or about a quarter of the peak.

The electricity generated over a year from the PV module of a given peak power is specified in Appendix M, SAP as:

$$0.8 \times \text{kWp} \times S \times Z_{PV} \quad 1$$

kWp is the peak power of the PV (the peak power corresponds to the rate of electricity generation in bright sunlight, formally defined as the output of the module under radiation of 1 kW/m^2 at 25°C - SAP page 67)

S is the average solar irradiance in the year in kWh/m^2 (table H2 of SAP) for a given angle of tilt and orientation.

Z_{PV} is a shading factor for the module (table H3 SAP)

The *0.8* includes DC to 240C AC inverter power loss of around 5%; giving a factor of *0.84* without the inverter loss.

4.2 Cable power loss

There is no DC to AC power conversion and hence no inverter power loss, but power is dissipated along the cable linking the PV panel to the immersion heater. Figure 1 shows a simplified layout for illustrative purposes only.

¹ 850 (CIBSE A2.27) \div $\sin(63.2^\circ)$. 63.2° is the maximum height of the sun in Plymouth UK, latitude of 50.3° see <http://www.astro.uu.nl/~strous/AA/en/antwoorden/zonpositie.html#v357> for more details.

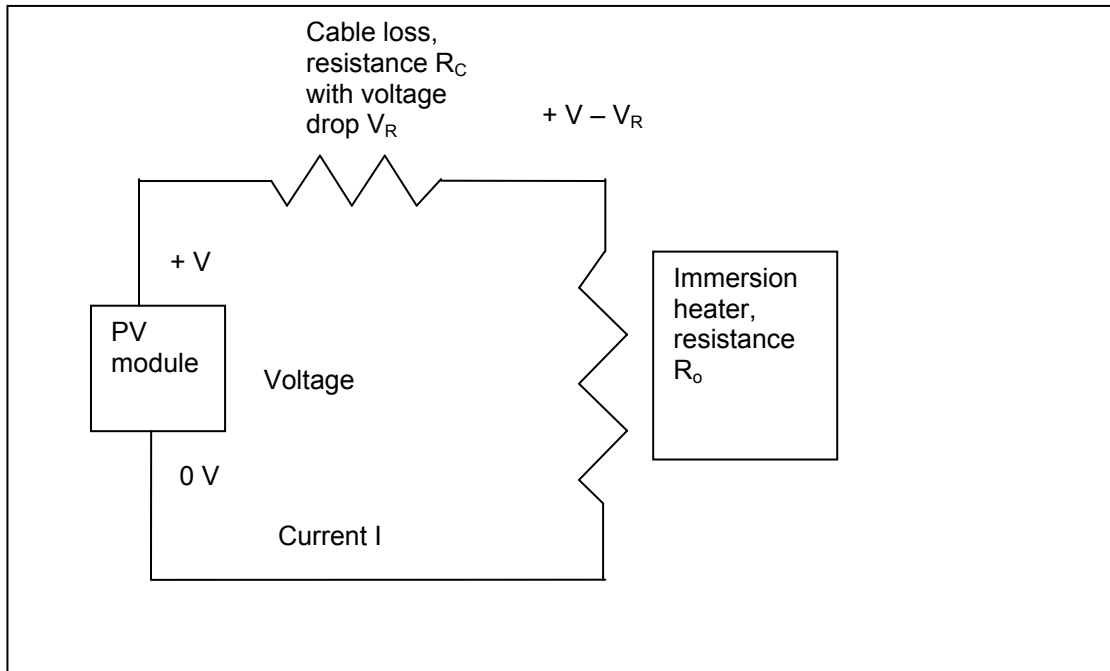


Figure 1 – Simple electrical schematic illustrating cable and heater resistance.

An electrical current, I , generated by the photovoltaic module at voltage, V , is related to the power generated, P , by:

$$P = I \times V \quad 2$$

And Ohms' law also states voltage is related to current and electrical resistance by:

$$V = I \times R \text{ or } I = V/R \quad 3$$

The electrical resistance in the heater is therefore:

$$R_0 = V_w^2 / P_w \quad 4$$

where P_w is the nominal power rating and V_w the nominal voltage of the heater.

From 2 and 3, the power of the circuit is:

$$P = I^2 \times (R_0 + R_c) \quad 5$$

The power dissipated along the cable due to its electrical resistance is:

$$\text{Power loss} = I^2 \times R_c \quad 6$$

And the fractional power loss in the cable C_c is

$$C_c = (I^2 \times R_c) / (I^2 \times (R_0 + R_c)) = R_c / (R_0 + R_c) \quad 7$$

Using 4 to eliminate R_0 and defining the resistance of the cable in terms of its length, L , and resistance per unit length, R_L , gives:

$$C_c = (2 \times R_L \times L) / (V_w^2 / P_w + 2 \times R_L \times L) \quad 8$$

Recalling that:

- V_w is the nominal voltage of the heater (V)
- P_w is nominal heater power (W)
- L is the length of cable in m
- R_L is resistance of the cable in Ω/m
- $x 2$ is for a positive and negative wire.

There is the added complication that some systems may consist of two separate but identical circuits of PV module, cable and heater. In this case, calculate the C_C value based on one circuit and use the total peak power for both circuits in 9 below.

Incorporating the fractional cable power loss into 1 gives the annual energy consumed by the heater as:

$\text{Energy consumed} = 0.84 \times \text{kWp} \times S \times Z_{pv} \times (1 - C_C)$	9
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4.3 Useful energy

For solar water heating, SAP 2005 (appendix H), states that the useful solar heating contribution is:

$$Q_s = S \times Z_{panel} \times A_{ap} \times \eta_0 \times UF \times f(a_1/\eta_0) \times f(V_{eff}/V_d) \quad (H1)$$

where

Q_s = solar input, kWh/year

S = total solar radiation on collector, kWh/m²/year

Z_{panel} = overshadowing factor for the solar panel

A_{ap} = aperture area of collector, m²

η_0 = zero-loss collector efficiency

UF = utilisation factor

a_1 = linear heat loss coefficient of collector, W/m²K

$f(a_1/\eta_0)$ = collector performance factor = $0.87 - 0.034 (a_1/\eta_0) + 0.0006 (a_1/\eta_0)^2$

V_{eff} = effective solar volume, litres

V_d = daily hot water demand, litres

$f(V_{eff}/V_d)$ = solar storage volume factor = $1.0 + 0.2 \ln(V_{eff}/V_d)$ subject to $f(V_{eff}/V_d) \leq 1.0$

In the case of the PV module, the zero loss efficiency (η_0) and the collector performance factor do not apply. The aperture A_{ap} is also unnecessary as the peak power is specified and the not peak power per square metre of the PV module. Equation H2, SAP 2005, for PV modules then reduces to (10).

$Q_s = 0.84 \times \text{kWp} \times S \times Z_{pv} \times (1 - C_c) \times UF \times f(V_{eff}/V_d) \quad \text{kWh per year}$	10
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UF and f are a utilization factor and solar storage volume function defined in part 4.3.1 (11) and 4.3.2 (12) respectively these are PV description parameters

4.3.1 Utilization factor

To calculate a unitization factor (10) used in SAP appendix H2, the solar-to-load ratio is required and is defined as:

solar-to-load ratio = $0.84 \times \text{kWp} \times S \times Z_{pv} \times (1 - C_c) / (\text{box39} + \text{box40})$	11
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For solar-to-load ratio >0 $UF = 1 - \exp[-1/(\text{solar-to-load ratio})]$	12
For solar-to-load ratio = 0 $UF = 1$	

4.3.2 Solar storage volume factor

The solar storage volume factor, f , in SAP Appendix H depends on the *effective* solar storage volume and is given by:

$f(\text{V}_{\text{eff}}/\text{V}_d)$ solar storage volume factor = $1.0 + 0.2 \ln(\text{V}_{\text{eff}}/\text{V}_d)$	13
subject to the constraint $f(\text{V}_{\text{eff}}/\text{V}_d) \leq 1.0$	

where

V_{eff} is the effective solar storage volume and
 V_d is the daily volume of hot water (SAP table1).
 $\ln()$ is the natural logarithm of the expression in the brackets.

The effective solar storage volume in appendix H is applicable to stores that warm the hot water by approximately 50K. So the amount of solar heat that can be stored is:

$$Q_s = \text{V}_{\text{eff}} \times 50 \times 4.2$$

(4.2 is the specific heat capacity of water in kJ/k/litre)

The amount of solar heat that can be stored in a close-coupled store is only the amount over and above that already provided by the boiler which is:

$$Q_s = \text{CCvol} \times (85 - T_s) \times 4.2$$

where

T_s is the temperature of the store averaged of 24-hours that is achieved by the boiler alone (i.e the average temperature of store with no solar input).

85°C is the assumed maximum temperature of the store when the immersion heater(s) cut(s)-out

CCvol is the volume of closed-couple store

Equating the last two equations and rearranging to obtain the effective solar volume gives:

$$\text{V}_{\text{eff}} = \text{CCvol} \times (85 - T_s) / 50K \quad 14$$

The 24-hour average temperature of the close-coupled store with no solar input (T_s) can be calculated from knowledge of the average temperature difference between the store and its

surroundings, which are defined in SAP. For a conventional indirect cylinder, this equates to 50K multiplied by a store temperature factor (table 2b, SAP). Here 50K is the temperature difference between the cylinder temperature and its surrounding during testing. A temperature factor of 0.54 is used ($0.54 = 0.6 \times 0.9$; the 0.6 is from table 2b of SAP and 0.9 is specified in the footnote of SAP, table 2b). The average temperature difference between a cylinder and its surroundings calculated by SAP is therefore $50K \times 0.54 = 27K$.

If the average inside house temperature is taken as 20°C , then $T_s = 20^{\circ}\text{C} + 27^{\circ}\text{C} = 47^{\circ}\text{C}$

The effective solar storage volume assuming a maximum temperature of 85°C is therefore:

$V_{\text{eff}} = (85 - 47)/(50K) = 0.76 \times \text{CCvol}$ (litres)	16
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4.4 Extra store heat loss

The hotter store will increase the heat loss. The extra heat loss is not a penalty because it is produced from solar energy and may partly offset the space heating.

Extra store heat loss = $0.8 \times (\text{total solar input} - \text{useful solar input})$

0.8 is the utilization factor in SAP 2005 (box 52). Assuming the store temperature will not rise above 85°C , the maximum extra store heat loss is:

$$\begin{aligned} \text{Maximum extra solar gain} &= \text{CCloss (box 41)} \times ((85-39.3)/(60-15)) \times 365 \\ &= 370.7 \times \text{CCloss (kWh/day)} \text{ kWh/year} \end{aligned}$$

where CCloss is daily heat loss figure (in kWh) required to maintain the store at 45K above ambient conditions.

The additional heat loss is therefore:

Additional store gains heat gains	
$= 0.8 \times 0.84 \times \text{kWp} \times S \times Z_{\text{pv}} \times (1 - C_c) \times (1 - (\text{UF} \times f(\text{Veff}/\text{Vd}))$	17
Subject to a maximum of $\times 370.7 \times \text{CCloss}$ (box 41) kWh per year,	