Modelling PV electricity generation and calculating self-consumption within the Home Energy Model

A technical explanation of the methodology

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Contents

Background to the Home Energy Model

What is the Home Energy Model?

The Home Energy Model (HEM) is a calculation methodology designed to assess the energy performance of homes, which will replace the government's Standard Assessment Procedure (SAP).

The Home Energy Model is still under development and its first version will be implemented alongside the Future Homes Standard (FHS) in 2025. We are publishing information about the model while it is still at a formative stage to enable industry to participate in the ongoing development process.

Where can I find more information?

This document is part of a wider package of material relating to the Home Energy Model:

Home Energy Model technical documentation (e.g. this document)

What: This document is one of a suite of technical documents, which go into further detail on the methodology and the validation exercises that have been carried out. We intend to update and produce further technical documentation throughout the model development process.

Audience: The technical documentation will be of interest to those who want to understand the detail of how the Home Energy Model works and how different technologies are treated.

The Home Energy Model consultation

What: The Home Energy Model consultation, which explains the overhaul to the SAP methodology and seeks views on the approach taken by the new Home Energy Model.

Audience: The Home Energy Model consultation will be of interest to those who want to understand the proposed changes to the SAP methodology and wider SAP landscape.

The Home Energy Model reference code

What: The full Python source code for the Home Energy Model and the Home Energy Model: FHS assessment has been published as a Git repository. This code is identical to that sitting behind the consultation tool. We are currently considering whether the open-source code could serve as the approved methodology for regulatory uses of the Home Energy Model.

Audience: The reference code will be of interest to those who want to understand how the model has been implemented in code, and those wishing to fully clarify their understanding of the new methodology. It will also be of interest to any potential contributors to the Home Energy Model.

Related content

Other relevant technical papers include:

- HEM-TP-03 External conditions (for description of the solar radiation data)
- HEM-TP-08 Solar gains and shading (for explanation of shading calculations)

To understand how this methodology has been implemented in computer code, please see:

src/core/energy_supply/pv.py

src/core/energy_supply/energy_supply.py (for calculation of instantaneous self-consumption and surplus available for battery and diverter)

src/core/energy_supply/elec_battery.py

src/core/heating_systems/storage_tank.py (for PV diverter)

Methodology

Photovoltaic (PV) systems generate electricity which can be used in the dwelling or exported to the grid. The amount of electricity generated will depend on the characteristics of the PV system and the solar radiation incident upon it. The latter of these is dependent on the location, orientation, and tilt of the array and any shading upon it, and the shading calculation is dependent on the array's height, width and base height (i.e., height of the lowest part of the array from the ground). More than one array can be specified with different characteristics, and the generation from all the arrays will be summed at each timestep.

The amount of the generated electricity that is used in the dwelling or exported to the grid is also dependent on the electricity demand within the dwelling and the extent to which this occurs at the same time as generation by the PV system.

1. PV generation

The energy output of a PV system is calculated using the hourly procedure ('Method 6') given in BS EN 15316-4-3:2017.

For each time step, the electrical energy E_{out} delivered by the PV modules in kWh per m2 is:

$$E_{out} = Solar\ energy \cdot\ efficiency\ at\ STC\ \cdot system\ performance\ factor$$

or

$$E_{out} = E_{sol} \cdot \frac{P_{pk}}{I_{ref}} \cdot f_{perf}$$

where

E_{sol} is the solar irradiation energy on the modules in the time step per m2 (kWh/m2)

P_{pk} is the peak power of the PV system per m2 at standard test conditions[1] (irradiance of $1kW/m^2$, 25°C cell temperature, a solar spectrum corresponding to direct normal radiation with an air mass[2] of 1.5, that is, with a tilt angle of 37° and a solar zenith angle of 48.19°)

I_{ref} is the reference solar irradiation under standard test conditions

f_{perf} is the system performance factor of the PV system

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[1] PD IEC/TS 61836:2016 Solar photovoltaic energy systems - Terms, definitions and symbols

[2] National Renewable Energy Laboratory, 'Reference Air Mass 1.5 Spectra' at https://www.nrel.gov/grid/solar-resource/spectra-am1.5.html

For further details see *6.2.4.7 Calculation procedure* in BS EN 15316-4-3:2017.

1.1 System performance factor

The system performance factors (f_{perf}) used are from a bespoke national annex as permitted in Section 6.2.2.7 of the BS EN standard. Re-arranging the equation above, f_{perf} is defined as:

$$f_{perf} = \frac{Actual\ energy\ out}{Solar\ energy \cdot\ efficiency\ at\ STC} = \frac{E_{out}}{E_{sol} \cdot \frac{P_{pk}}{I_{ref}}}$$

The table below shows the default informative values provided in Table C.4 Annex C of the standard, and the updated values proposed for HEM, which are based on monitored performance data for UK systems.

According to research from the University of Sheffield's Sheffield Solar research group[3], the median performance factor of domestic solar systems in the UK during the monitored period was 0.85. It was assumed that the median performance factor corresponds to the value for moderately ventilated modules. The other figures from Table C.4 were increased by the same proportion (0.85 / 0.8).

Table 1 – System performance factors

Type of ventilation of the photovoltaic modules	Informative value (Table C.4)	f_{perf} used in HEM
Unventilated modules	0.76	0.81
Moderately ventilated modules	0.80	0.85
Strongly or forced ventilated modules	0.82	0.87
Free-standing (not integrated)	n/a	0.87

Section 6.2.4.7.2 of the BS EN standard states that if modules are not "integrated" (rear surface free) then the performance factor is equal to 1.0. This is assumed to mean that the PV system is not integrated (BIPV) or attached (BAPV). This appears to be an unrealistic value, given that cell temperatures would usually be higher than 25°C, and there are also other system losses such as inverter losses which need to be included (see Annex A – System

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[3] J Taylor, J Leloux, L Hall, A Everard, J Briggs & A Buckley (September, 2015). 'Performance of Distributed PV in the UK: A Statistical Analysis of Over 7000 systems', *31st European Photovoltaic Solar Energy Conference and Exhibition.* Hamburg, Germany, 14-18 September 2015.

performance factor). For these systems, a value of 0.87 is proposed as it is assumed that they will have similar performance to strongly or forced ventilated modules. In the Sheffield University study of domestic solar systems in the UK, very few PV installations exceeded 0.92, while 0.87 did occur frequently. In Germany, the Fraunhofer Institute found in 2012 that the best performing solar installations had a performance factor around 0.87. Of the top 10 best performing of the 100 systems they studied, 8 out of 10 were also free-standing[4].

1.2 Shading

Note that the output of the PV system is limited by the incoming solar irradiance on the panels. The direct solar irradiance on the PV panel may be reduced by shading due to distant objects (e.g., neighbouring buildings). The reduction factor is calculated as described in the “distant shading” section of the technical paper HEM-TP-08 Solar gains and shading.

1.3 Limitations

The system performance factor is assumed to be constant throughout the year. However, it will vary from minute-to-minute because solar irradiance, air temperature, and wind speed affect the temperature of the module. The actual solar PV output in each timestep could therefore vary by +/- 10% to the predicted value because of the temperature variation and the temperature coefficient.

There are various parameters which could influence system performance in a given timestep which are currently accounted for in HEM in the annual average performance factors listed in Table 1. Accounting for these parameters separately and calculating their effects in each timestep could result in a more accurate prediction of overall performance. Table 2 below lists some key parameters, and the impact on the accuracy of energy output predictions.

Table 2 – Parameters affecting system performance

Temperature co-efficient	The temperature coefficient of the maximum output power of PV modules is typically in the range -0.3% / °C to -0.5% / °C[5]. Modules with lower temperature coefficients will have better system performance factors. There are also separate temperature coefficients for open-circuit voltage and short-circuit current, which may need to be accounted for separately.

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[4] Reich, N.H., Mueller, B., Armbruster, A., Van Sark, W.G., Kiefer, K. and Reise, C., 2012. Performance ratio revisited: is PR> 90% realistic?. *Progress in Photovoltaics: Research and Applications*, 20(6), pp.717-726.

[5] Eco-GreenEnergy. Temperature Coefficient of Solar PV Module

Normal Operating Cell Temperature (NOCT)	NOCT can vary from 45°C to 49°C[6]. Modules with lower NOCT will have better system performance factors.
Degradation rate	Degradation rates can vary from 0.1% to 1.1% per year[7]. Modules with lower degradation rates will produce more total energy over their lifetime.
Inverter efficiency	Higher inverter efficiencies will improve the system performance factor. Inverter efficiency also typically varies depending on the ratio of actual PV power output to the maximum power output that the inverter can handle, with lower efficiencies occurring at lower power output.

2. Use of generated electricity in the dwelling ("self-consumption")

Since HEM has sub-hourly modelling, it can account for near real-time variations in PV supply and in electricity demand in the home. This improves the accuracy of predictions of self-consumption, with closer matching of available PV power to the electrical demand in the home in each time step. Further explanation is given below.

2.1 Priority assumptions

Generated electricity is allocated in order of priority to:

1. Instantaneous demand from the dwelling
2. Battery storage
3. PV diverter
4. Grid export

Electricity demand within the home is assumed to be met from the following sources (in order of priority):

1. Self-generated electricity
2. Battery storage
3. Mains electricity (grid import)

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[6] Muller, M., 2010. Measuring and Modeling Nominal Operating Cell Temperature (NOCT),'Conclusions and Continuing Work'. National Renewable Energy Laboratory.

[7] Deline, C. et al., 2022. PV Lifetime Project-2021 NREL Annual Report. National Renewable Energy Lab.

2.2 Instantaneous self-consumption

Instantaneous electricity demand in a timestep is summed from various components of electricity used during that timestep by:

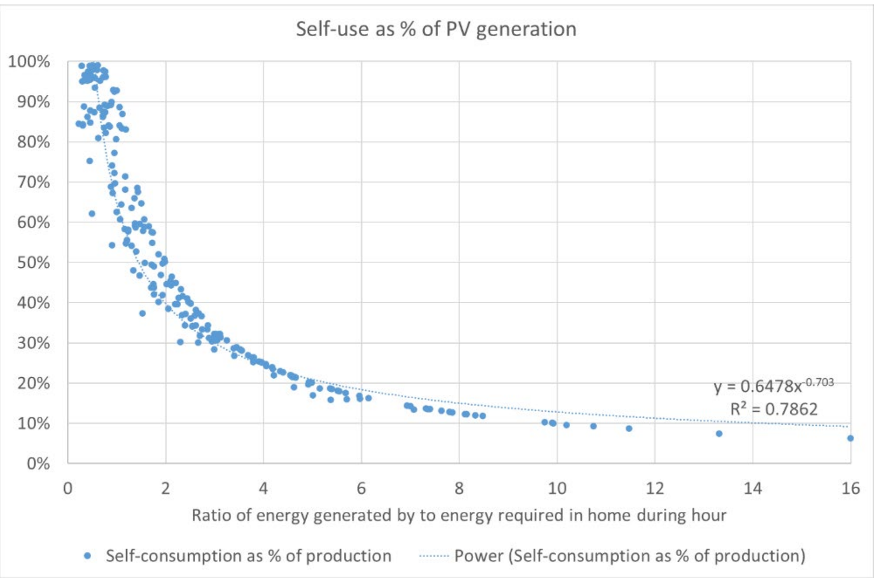
Space heating/cooling and hot water systems (including electric showers)
Ventilation systems
Appliances, cooking, lighting etc. (electricity use at each timestep is user input or defined in wrapper)

Note that this does not include electricity used to charge a battery or to top-up thermal storage such as a hot water cylinder in response to surplus generation. This is handled later in the calculation.

The fraction of the energy generated on site that is used instantaneously within the dwelling is commonly known as the self-consumption factor. The equation used to determine the self-consumption factor is based on a small field data sample[8] of UK dwellings which all had gas boilers. Four of these had hourly data which was used to derive the formula, while 15 had monthly data, which was used to check the results from applying the formula to typical generation and demand profiles. The fraction of self-consumption is calculated as a function of the ratio of PV energy available to the electricity demand (the 'demand ratio') during the time step, based on the field data (see graph below):

$$demand\ ratio = \frac{PV\ energy\ supply}{electricity\ demand}$$

$$\textit{self-consumption factor} = \min(0.6748\ \times\ demand\ ratio^{-0.703}, 1)$$



A literature review was undertaken to look at relevant aspects of PV generation and self-consumption. The literature review found similar relationships from other datasets. This equation gives a slightly different result to merely dividing the demand by the available supply,

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[8] The data is owned by two product manufacturers, so it is not possible to share this more widely.

which accounts for the fact that both demand and supply will vary within each hour. For example, if demand and supply are equal, the expected self-consumption factor will be less than 1, because for parts of the timestep the demand may be higher than the supply and for other parts the supply may be higher than the demand. Using this equation therefore captures sub-hourly effects (on an averaged basis).

The predicted self-consumption factor should not be greater than 1/demand ratio, otherwise HEM would potentially predict the demand fulfilled by local generation to be greater than total demand, so this further limit is applied.

2.3 Electric batteries

Electric batteries are simply modelled using a user input of the round-trip efficiency and maximum capacity, with no consideration of the discharging rate currently, although this could be developed in future. It is assumed that the charging efficiency and discharging efficiency are equal, i.e., each is equal to the square root of the round-trip efficiency. Within the model, batteries can only be charged by surplus electricity generation and not from the grid. It is assumed that the battery will be charged by surplus energy first before being discharged. Degradation of the battery capacity over time is not currently modelled.

2.4 PV diverters

It is currently only possible to model PV diverters connected to an immersion heater within a hot water tank. If there is surplus energy after instantaneous demand is met within the dwelling and battery storage is filled, the excess capacity for energy storage within the hot water tank is calculated based on the set point and the position of the immersion heater thermostat connected to the diverter. The surplus generation is used to heat the tank up as much as possible within this limit. The amount of energy that can be diverted is also limited by the maximum capacity of the immersion heater and how much of this capacity for the current timestep has already been used.

Normally battery storage is preferable to prioritise over the PV diverter, since the value of stored electricity is 3 to 4 times greater than the value of stored hot water. Changing the priority order is currently not possible in HEM. However, some householders might wish to prioritise the PV diverter over battery storage. This may be due to various reasons, for example they want hot water quickly, the battery charge rate is lower than the surplus PV power, or if the battery storage has a higher cut-in threshold power than the PV diverter.

Note that there is no cut-in threshold for PV surplus power, which may result in a minor over-prediction of diverted PV when small surpluses occur, and the installed PV diverter would not have cut in that low available power.

Future development

Future development of the PV generation calculation may include accounting for the effect of different inverter types, tracking systems, module efficiency, temperature co-efficients, Normal Operating Cell Temperature (NOCT), degradation rate, changes in hourly system performance factors, module-level power electronics, and bifacial solar modules.

Bifacial solar modules are able to absorb radiation on both sides, increasing energy yield relative to monofacial solar modules. While the benefits of bifaciality on domestic pitched roof installations are expected to be minor, they can be more significant for systems mounted on flat roofs, or small ground mount systems. An east-west setup could for example be mounted vertically, increasing PV output at peak times of the day.

There is potential to make the priority order of the assignment of generation more flexible to account for different system and control configurations that may be able to respond to incentives such as time-of-use import/export tariffs. This includes decisions whether to prioritise instantaneous demand, battery storage, PV diverter, or grid export. The priority could also be made configurable with preferred priority schedules set up in the HEM input file.

Apart from the very small dataset being used, the application of the instantaneous self-consumption curve (based on hourly data) to half hourly timesteps may also be introducing some degree of error (most likely a slight underestimate of the self-consumption factor, as less variation would be expected within a half-hourly timestep than an hourly one). This area would certainly benefit from further study in future, particularly to check that the relationship is also representative of electrically heated dwellings, which were absent from the data set used.

The electric battery calculation could be further developed to account for charge and discharge rates and the effect of temperature on battery performance. Further development may also allow, for example, modelling of electric batteries charging from the grid. Since battery capacity will degrade over time, the capacity loss could be included to ensure effective capacity is not overstated.

There is scope to develop diverters further in future to allow them to power additional systems, such as heat pumps. The heat pump could for example store surplus generation as hot water. Modelling of other forms of “smart” controls which schedule demand to match times of surplus generation may also be developed in future.

Some PV diverters have a cut-in threshold, and do not divert until a threshold PV power is reached, say 100 W. Therefore, a configurable cut-in threshold could be added to the calculation.

Annex A – System performance factor

The performance factor is usually less than 1.0. This is due various factors including[9]:

1. Power losses due to temperature of the PV cells rising above the standard cell temperature of 25°C
2. Inverter losses, when converting from DC to AC current
3. Degradation due to age
4. Soiling of panels
5. Other system losses such as wiring resistance

An open-mounted PV module will lose approximately 10% of its rated efficiency, when ambient temperature is 20°C, solar irradiance is 800 W/m2, wind speed is 1 m/s and with air mass of 1.5. These conditions are used to assess the Normal Operating Cell Temperature (NOCT) of a solar panel, and this value is usually included in the product datasheet for a specific solar PV panel. Typically, the normal operating cell temperature will be around 46°C, and not 25°C as at standard test conditions. Normal operating cell temperatures have been measured experimentally by the National Renewable Energy Laboratory, which found a range of 45°C to 49°C for free-standing solar PV panels under these conditions[10].

The actual cell temperature in use depends on the ambient air temperature, and the amount of solar irradiance. The equation to predict cell temperature in use is:

$$T_{cell} = T_{air} + \frac{NOCT - 20}{800} \cdot S$$

where T_{cell} is the cell temperature, T_{air} is the ambient air temperature, *NOCT* is the Normal Operating Cell Temperature, and *S* is the solar irradiance[11].

A typical solar panel has a typical temperature coefficient of power of 0.5% per °C, causing a 10% drop in power if the solar panel is 20°C higher than standard test conditions (25°C).

For solar panels mounted on a roof, the PV cell temperatures become even higher due to restricted ventilation. This causes a further reduction in efficiency and power output, and Table C.4 from the BS EN standard indicates that overall system losses can reach up to 24% for unventilated modules.

If solar irradiance is 800 W/m2, a cell temperature of 25°C will occur only at ambient air temperatures around 0°C. If solar irradiance is instead 400 W/m2, a cell temperature of 25°C can occur at ambient air temperatures around 12°C. Periods of high solar irradiance in the UK, when the highest solar generation occurs, are associated with higher ambient temperatures

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[9] Walker, H.A., Desai, J.D. and Heimiller, D.M., 2020. Performance of Photovoltaic Systems Recorded by Open Solar Performance and Reliability Clearinghouse (oSPARC), '7.4 Performance Ratio and Balance-of-System Efficiency Combined'. National Renewable Energy Laboratory.

[10] Muller, M., 2010. Measuring and Modeling Nominal Operating Cell Temperature (NOCT),'Conclusions and Continuing Work'. National Renewable Energy Laboratory.

[11] QPV Research Group, 2019. How Does Air Temperature Affect Photovoltaic Solar Panel Output? University of New South Wales in Australia

than 12°C, and often above 20°C. This means that a free-standing PV module in the UK usually has performance losses due to a raised cell temperature when compared to standard test conditions.

This publication is available from: https://www.gov.uk/government/publications/home-energy-model-technical-documentation