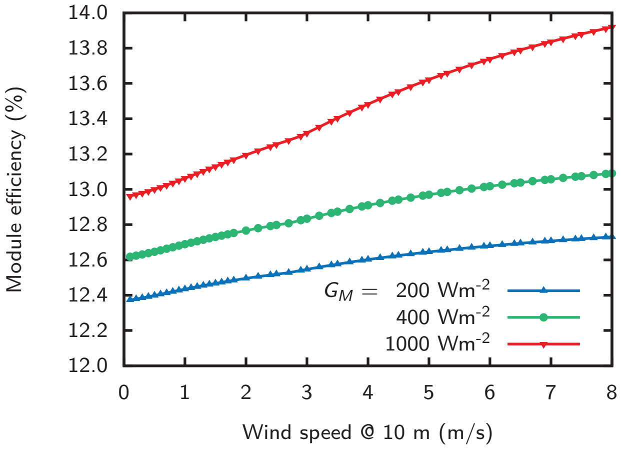

Figure 20.9: The PV module efficiency in dependence of the wind speed at various irradiance levels. The curves were computed using the fluid-dynamic model presented in Appendix G.

20.4 Designing grid-connected PV system

In this section we learn how to design a PV system, based on the *energy balance* paradigm. This means that we design the system such that the generated energy and the consumed energy during one year match. Of course, there are also other ways of designing systems for example based on economic arguments.

For the energy balance we first need to calculate the annual load, which we already explained in Section 20.2. The energy yield at the DC side is given by

$$E^Y_{\mathrm{DC}} = A_{\mathrm{tot}} \int_{\mathrm{year}} G_M(t)\eta(t)\,\mathrm{d}t, \tag{20.30}$$

where A_{tot} is the total module area. It is related to the area of one module A_M via

$$A_{\mathrm{tot}} = N_T \cdot A_M, \tag{20.31}$$

where N_T is the number of modules. The energy balance now writes as

$$E^Y_{\mathrm{DC}} = E^Y_L \cdot \mathrm{SF}, \tag{20.32}$$

where SF is a *sizing factor* that usually is assumed to be 1.1. We therefore can calculate the required number of modules,

$$N_T = \left\lceil \frac{E^Y_L \cdot \mathrm{SF}}{A_M \cdot \int_{\mathrm{year}} G_M(t)\eta(t)\,\mathrm{d}t} \right\rceil, \tag{20.33}$$

where $\lceil x \rceil$ denotes the ceiling function, *i.e.* the lowest integer that is greater or equal than x.

Now it is important to decide how many modules are to be connected in *series* (N_S) and in *parallel* (N_P). Of course,

$$N_T = N_S \cdot N_P. \tag{20.34}$$

Such a PV array hence consists of P strings of S modules each. The N_T determined in Eq. (20.71) does not necessarily need to be a practically divisible number. For example, if $N_T = 11$, one might want to choose $N_T = 12$ panels, because they can be installed as $S \times P$= 12×1, 6×2, 4×3, 3×4, 2×6 or 1×12 strings. In principle, it is preferable to connect as many modules as possible in series since then the currents on the DC side and hence the cable losses stay low. Many modern string inverters have two or more independent string inputs, each having its own maximum power point tracker. This can be important if the installation contains two or more areas with different shading and irradiance, for example on two different sides of a roof. An alternative option is to connect different strings to different inverters, which would mean that the system uses several independent inverters.

As for N_S, a maximum exists since each inverter type has a maximum allowed input voltage. The maximum voltage the PV array can generate is the maximum open-circuit voltage of the array, occurring when the inverter is not operating. The maximum open-circuit voltage is determined by the number of modules in series N_S and the maximum open-circuit voltage of an individual module. Because of the negative value of the temperature coefficient, the maximum open-circuit voltage occurs in the coldest period of the year. There is also a minimum value for N_S. Each inverter has an input voltage window, where the maximum power point tracker operates. If the array maximum power point voltage falls below this voltage window, the maximum power point tracker does not operate any more. The lowest array maximum power point voltage occurs in the hottest period of the year.

In a conservative assumption, the power on the DC side at STC now is given as

$$P_{\mathrm{DC}}^{\mathrm{STC}} = N_T \times P_{\mathrm{MPP}}^{\mathrm{STC}}. \tag{20.35}$$

The inverter must be chosen such that its maximal power $P_{\mathrm{DC,\,max}}^{\mathrm{inv}}$ is above the maximal PV output,

$$P_{\mathrm{DC,\,max}}^{\mathrm{inv}} > P_{\mathrm{DC}}^{\mathrm{STC}}. \tag{20.36}$$

Further, the nominal DC power of the inverter should be approximately equal to the PV power at STC,

$$P_{\mathrm{DC}_0} \approx P_{\mathrm{DC}}^{\mathrm{STC}}. \tag{20.37}$$

In practice, the nominal DC power of the inverter is selected slightly below the PV power at STC, up to 10%, depending on the climate zone, because of the different irradiance distributions. Also, for $P_{\mathrm{DC}_0} < 5$ kWp, *single-phase* inverters are used while for $P_{\mathrm{DC}_0} > 5$ *three-phase* inverters are advised.

The inverter efficiency is dependent on the input power and voltage. A model discussing the inverter efficiency is presented below.

20.4.1 Inverter efficiency

As we already discussed in Chapter 19, modern *inverters* fulfil two major functions: First, *maximum power point tracking* (MPPT), and secondly, the actual inverter function, *ie* converting the incoming direct current (DC) to alternating current (AC) that can be fed into the electricity grid.

In order not to waste electricity produced by the PV array, an inverter should always work as close as possible at its maximum achievable efficiency. However, the inverter efficiency strongly depends on the DC input voltage as well as the total DC input power as well as on the DC input voltage of the system. The inverter efficiency η_{inv} with respect to the input DC power at various DC voltage level is usually given at the data sheet, at least for some values. Sometimes, only a peak value is given as a single value.

Weighted efficiencies

A more reliable way of expressing the inverter efficiency in a single number is to use *weighted efficiencies*, which combine the inverter efficiencies over a wide range of solar resource regimes [168]. Two different weighted efficiencies are commonly used. First, the *European Efficiency*, which represents a low-insolation climate such as in Central Europe, and the *California Energy Commission* (CEC) efficiency, which represents the PV system performance in high-insolation regions such as in the southwest of the United States [168]. They are given by

$$\begin{aligned}\eta_{\text{Euro}} = {} & 0.03\,\eta_{\ 5\%} + 0.06\,\eta_{10\%} + 0.13\,\eta_{20\%} + \\ & 0.10\,\eta_{30\%} + 0.48\,\eta_{50\%} + 0.20\,\eta_{100\%},\end{aligned} \tag{20.38a}$$

$$\begin{aligned}\eta_{\text{CEC}} = {} & 0.04\,\eta_{10\%} + 0.05\,\eta_{20\%} + 0.12\,\eta_{30\%} + \\ & 0.21\,\eta_{50\%} + 0.53\,\eta_{75\%} + 0.05\,\eta_{100\%},\end{aligned} \tag{20.38b}$$

where $\eta_{x\%}$ denotes the efficiency at x% of nominal power of the inverter. Note that the CEC efficiency contains a 75% value that is not present in the European efficiency.

Even though the weighted efficiencies represents a more accurate approximation of the effective yearly working performance of the inverter compared to the mere peak efficiency, it still only is an approximation of the average performance of a system in the European climate.

If a better estimate of the *real time energy yield* of an extended PV system is needed, a more accurate representation of the instantaneous inverter performance at every level of input power and voltage must be developed, for example the model discussed below.

Sandia National Laboratories (SNL) model

Due to lack of detailed data from inverter manufacturers, many research institutes around the world have published extended data, which are publicly available online. These data present efficiency curves for a large range of inverters as a function of a several characteristic parameters. One database that can be used is the one provided by the Sandia National Laboratories [170].

Figure 20.10 shows an example of an inverter efficiency curve. For the graph, field test measurements were taken during a period of 13 days with changing weather condition. While the relationship between the AC and DC power appears to be linear at first, a closer look to the graph reveals that this is not entirely the case, as shown in Fig. 20.11. The power consumption of the inverter itself together with the electrical characteristics of the switching modes and circuits at different power levels results in a degree of non linearity between AC and DC power at a given DC voltage level. Assuming that the inverter efficiency is a

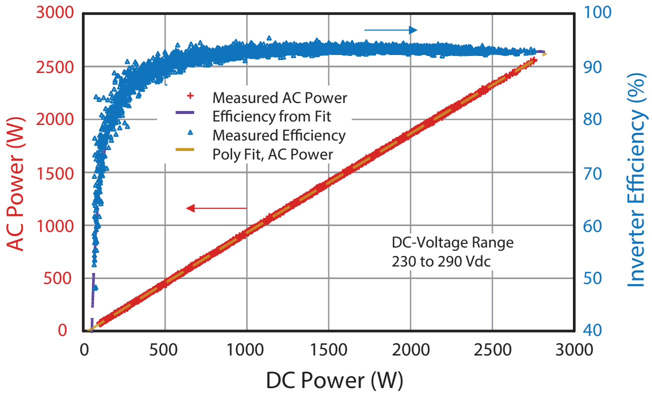

Figure 20.10: The measured AC power and inverter efficiency for a 2.5 kW Solectria PVI2500 inverter recorded during a period of 13 days at Sandia National Laboratories (figure reproduced with kind permission from Sandia National Laboratories) [169].

constant value throughout the whole DC power range is equivalent to assuming a linear relationship between DC and AC power, which has been shown not to be the case.

The dependency of the inverter efficiency on the DC input voltage is a very complex phenomenon. The differences between the different inverter types can partially be explained by different types of switches used. Figure 20.12 shows the voltage dependent inverter efficiency for different inverter types. These curves were determined with the SNL model that is described in the next paragraph.

In the Sandia National Laboratory model the relationship between P_{AC} and P_{DC} is given by [169]

$$P_{\mathrm{AC}} = \left[\frac{P_{\mathrm{AC}_0}}{A-B} - C(A-B)\right] \cdot (P_{\mathrm{DC}} - B) - C(P_{\mathrm{DC}} - B)^2, \tag{20.39}$$

where the coefficients A, B, and C are defined as

$$A = P_{DC_0}\left[1 + C_1\left(V_{\mathrm{DC}} - V_{\mathrm{DC}_0}\right)\right], \tag{20.40a}$$

$$B = P_{S_0}\left[1 + C_2\left(V_{\mathrm{DC}} - V_{\mathrm{DC}_0}\right)\right], \tag{20.40b}$$

$$C = C_0\left[1 + C_3\left(V_{\mathrm{DC}} - V_{\mathrm{DC}_0}\right)\right]. \tag{20.40c}$$

Several of the parameters are depicted in Fig. 20.11. The parameters are [169]:

$P_{\mathbf{AC}}$: AC-power output from inverter based on input power and voltage, (W).

$P_{\mathbf{DC}}$: DC-power input to inverter, typically assumed to be equal to the PV array maximum power, (W).

$V_{\mathbf{DC}}$: DC-voltage input, typically assumed to be equal to the PV array maximum power voltage, (V).

$P_{\mathbf{AC}_0}$: Maximum AC-power "rating" for inverter at reference or nominal operating condition, assumed to be an upper limit value, (W).

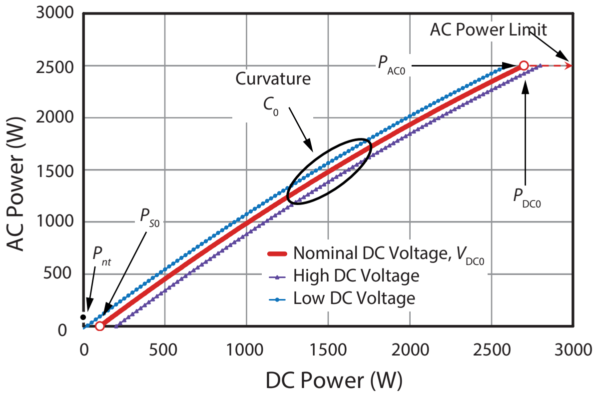

Figure 20.11: A closer look on to the relationship between DC input and AC output power for an inverter and the definition of the parameters used in the *Sandia Inverter Perfomance Model* (figure reproduced with kind permission from Sandia National Laboratories) [169].

P_{DC_0}: DC-power level at which the ac-power rating is achieved at the reference operating condition, (W).

V_{DC_0}: DC-voltage level at which the ac-power rating is achieved at the reference operating condition, (V).

P_{S_0}: DC-power required to start the inversion process, or self-consumption by inverter, strongly influences inverter efficiency at low power levels, (W).

C_0: Parameter defining the curvature (parabolic) of the relationship between AC-power and DC-power at the reference operating condition, default value of zero gives a linear relationship, (1/W).

C_i: Empirical coefficient allowing P_{DC_0} to vary linearly with DC-voltage input, default value is zero, ($i = 1, 2, 3, 1/\mathrm{V}$).

The model takes the following losses into account [171]:

- Self consumption of the inverter. This value corresponds to the DC power required to start the inversion process.
- Losses proportional to the output power due to fixed voltage drops in semiconductors and switching losses.
- Ohmic losses

The accuracy of the model depends on the data available for determining the performance parameters. An initial estimate can be performed using the little information provided by the manufacturer. Using all the required parameters will provide a model with an error of approximately 0.1% between the modelled and measured inverter efficiency [171].

All the parameters required for handling Eq. (20.39) are given in the SNL database where a full list of a wide range of inverters with nominal powers from 200 W up to 1 MW are covered [170]. This model therefore uses the instantaneous value of P_{DC} and V_{DC} produced by the entire PV array to evaluate the AC power output and inverter efficiency.

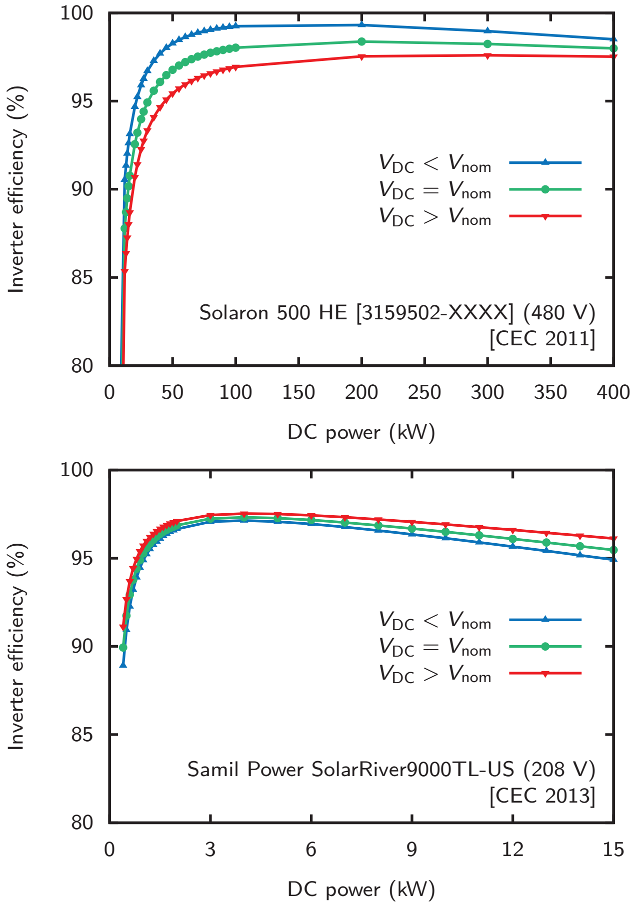

Figure 20.12: Variation in the inverter efficiency with DC input voltage for two different inverters.

Maximum power point tracker and additional losses

The efficiency of the MPPT has not been included explicitly in the SNL performance model. This is because the efficiency of most MPPT used in the inverters ranges between 98% and nearly 100% at every level of input power and the voltage provided is within the accepted minimum and maximum window for the MPPT to function correctly. A decrease of 1% in the system performance has therefore been used to take the MPPT losses into account.

An additional decrease of 3% in the system performance can be considered to cover losses caused by mismatch between modules (-1.5%), ohmic cable losses (-0.5%) and soiling (-1%) [167], if the cable losses are not determined as described in Section 19.5.

20.4.2 Performance analysis

Now we will put all concepts together that we discussed earlier in this section. The *instantaneous power output* on the AC side can be described with

$$P_{\mathrm{AC}}(t) = A_M\, G_M(t)\, \eta_M(t)\, \eta_{\mathrm{inverter}}(t)\, \eta_{\mathrm{MPPT}}(t)\, \eta_{\mathrm{other}}. \tag{20.41}$$

The system efficiency then is given as

$$\eta_{\mathrm{system}}(t) = \frac{P_{\mathrm{AC}}(t)}{A_{\mathrm{tot}}\, G_M(t)} \cdot 100\%, \tag{20.42}$$

which leads us to the *instantaneous AC-side yield* (also known as *performance ratio*),

$$Y_{\mathrm{AC}}(t) = \frac{P_{\mathrm{AC}}(t)}{P_{\mathrm{STC}}} \cdot 100\%. \tag{20.43}$$

Then, the *yearly energy yield at the AC side* can be calculated with

$$E^Y_{\mathrm{AC}} = \int_{\mathrm{year}} P_{\mathrm{AC}}(t)\,\mathrm{d}t; \tag{20.44}$$

it is given in Wh/year. Another important parameter is the *annual efficiency* of the system

$$\eta^Y_{\mathrm{system}} = \frac{E^Y_{\mathrm{AC}}}{E^Y_{i,\,\mathrm{sys}}} \cdot 100\%, \tag{20.45}$$

where $E^Y_{i,\,\mathrm{sys}}$ is the solar energy incident on the PV system throughout the year. It can be calculated with

$$E^Y_{i,\,\mathrm{sys}} = A_{\mathrm{tot}} \int_{\mathrm{year}} G_M(t)\,\mathrm{d}t. \tag{20.46}$$

The last parameter we look at is the *yearly electricity yield*

$$Y_E = \frac{E^Y_{\mathrm{AC}}}{N_S N_P \cdot P_{\mathrm{STC}}}, \tag{20.47}$$

which is given by Wh/(year kWp).

At the end of the design phase it is important to check whether the system really fulfils the requirements. If the yearly energy yield exceeds the annual load, the system is well designed. Otherwise, another iteration has to be done in order to scale up the system. However, as stated earlier, for a grid-connected system it also can be a choice not the require the whole load to by covered by PV electricity.

Table 20.3: The specific annual yield and the various losses in a typical Dutch grid-connected PV system with modules made of crystalline silicon solar cells. The irradiation data used are for Delft, The Netherlands. Ohmic losses are according to IEC standard, while MPP tracking losses can retrieved from inverter suppliers.

	Annual loss	Loss factor
Soiling [167]	1.0%	0.990
Reflection [172]	4.0%	0.960
Module mismatch losses [172]	1.0%	0.990
Module temperature losses [173, 174]	6.0%	0.940
Module irradiance losses [173, 174]	4.5%	0.955
Ohmic losses	1.0%	0.990
Inverter conversion losses	5.0%	0.950
Inverter MPP tracking losses	1.0%	0.990
Performance ratio		0.786
Global horizontal irradiation (kWh/m^2)		999
In plane irradiation (kWh/m^2)		1146
Specific annual energy yield (kWh/kWp)		901

20.4.3 Annual losses in grid-connected PV systems

In Table 20.3 an overview of all the system losses that occur in a typical Dutch grid-connected PV system with modules endowed with crystalline silicon solar cells is given. The modules are roof-integrated with reasonable ventilation and a tilt angle of 36° being the optimal tilt angle for the Netherlands. The losses are given on an annual basis and by a corresponding loss factor as well. The product of all the loss factors is the performance ratio.

- The reflection losses arise because the peak power of modules is determined at perpendicular incidence whereas the modules are illuminated by the whole hemisphere under operational conditions. For crystalline silicon solar modules the spectral mismatch losses with respect to the AM1.5 spectrum are small (at most 1% on an annual basis).

- The module temperature losses are the losses occurring because the actual cell temperature is deviating from the 25°C cell temperature at STC (see section 20.3.2). The temperature loss given in Table 20.3 is for a roof-integrated system in Delft. In case of a free-standing array in Delft the temperature loss would be 2-3%, whereas in southern Europe about 6-7%.

- The module irradiance losses are the losses occurring because the cell efficiency at the actual irradiance deviates from the cell efficiency at the 1000 W/m^2 irradiance at STC (see section 20.3.3).

- The ohmic losses on an annual basis are always lower than the ohmic loss at STC, because of the irradiance distribution over the various irradiance classes. The product of the performance ratio and the in-plane irradiance gives the specific annual energy yield.