June 2004 ECN-RX--04-073

# Lay-out of Building integrated PV-systems

H.H.C. de Moor
N.J.C.M. van der Borg
B.J. de Boer
H. Oldenkamp (Oké Services)

This paper has been presented at the 5th ISES Europe Solar Conference, 20-23 June 2004, Freiburg, Germany

## Introduction

Building integration is at present the most important market segment for PV [1]. Surely governmental support was important, but especially in Europe it is the first major market to become cost-effective, as the solar electricity has to compete with the relatively high tariffs for private consumers.
A drawback is the usually non-optimal performance due to non-uniform illumination and failures in the modules, wiring and inverters. In this paper it is proposed to go to parallel wiring as this reduces the losses compared to series connected modules.

## 1. LAY-OUT STRATEGY AND PERFORMANCE LOSS

Building integration has a number of implications that may influence the energy performance of the PV-system, such as:

- **partial shading**; if only a part of the PV-array is shaded the energy loss can be over-proportional compared to the loss of incident solar energy
- **multiple orientations**; the PV-array may cover area's with different orientations or more in general non-optimal orientation as the PV modules are part of the building envelope.

As the installation and maintenance is part of the building process two factors have to be taken into account in the system lay-out

- **ease of installation;** the cabling and mounting of the modules most be standardised to avoid costly engineering and allow roofers to install the PV system
- **accessibility**; the system components are often not accessible for inspection or repair requiring a lay-out that is tolerant to system failures

Partial shading and different orientations within one system are especially important in larger buildings [2], but also not negligible in family houses. These differences in the irradiance on the various PV-modules of the total PV-system, cause a loss of power of the array of modules compared to the sum of their potential individual power values. This so-called mismatch effect is the phenomenon that PV-modules connected in parallel or in series cannot operate in their individual maximum power point because their voltage (parallel) or current (series) is forced to be equal.
The maximum power point of the various interconnected modules may differ from each other due to possible individual differences in the modules, due to differences in soiling, module temperature and irradiance.

The amount of annual energy loss due to mismatch can be influenced by the electrical and geometrical layout of the PV-system. Accessibility, determined by the mechanical structure, is also of importance for the system performance. The effect of a non-functioning module might not be restricted to that module itself but it can jeopardise the performance of other modules as well. The effect of a bad module on the amount of annual energy loss depends on the electrical layout of the PV-system; the presence of bypass diodes and the lengths of the strings (series connected modules).

Some possibilities for the electrical layout of a PV-system are the following [3]:

- Central inverter. All the modules are grouped in a number of strings. Each string consists of modules in series and the strings are connected in parallel on the central inverter.
- String inverter. This is the same a central inverter but it is based on one string only, typical in the range between 1 and 2.5 kWp.
- Multi-string inverter. This is a special application of a central inverter in which the various parallel strings are equipped with their own MPP-tracker.

- Parallel connection of single modules.
  In this concept the modules are coupled to a DC-bus. The total DC-power is then converted to AC by a central DC/AC-inverter [4].
  A similar approach was proposed using electromagnetically coupled modules [5].
- AC-Module inverter. In this concept each module has its own inverter [6]. The output of all parallel inverters is fed into the 230 V AC-bus.

The number of modules per string is an important design choice; on the one hand lower ohmic losses (higher voltages) for longer strings, on the other hand higher output for shorter strings (see below) and more simple safety measures due to the lower voltages.
The installation is simple if all the modules are in series or all parallel. A mixed lay-out becomes complex for large systems.

An attempt was made to quantify the effects of multiple orientation (by modelling), of partial shading (by experimenting) and of accessibility (by reasoning). This has been done for realistic but arbitrarily chosen PV-systems. Therefore the results are not generally applicable but they give an indication of the order of magnitude of the addressed effects. Furthermore in the concept choice, stringing and size of inverter, more items play an important role such as the price, efficiency and reliability of the inverters. These items are not addressed in this paper.

## 2. MULTIPLE ORIENTATIONS

To quantify the performance effect of multiple orientations within one PV-array, performance calculations were carried out for a rather extreme situation: a house with a double-sided roof facing east and facing west (both slopes 45°). The calculations were performed with PVSYST V3.21 [7] for a sunny summer day in the Netherlands (52° north latitude). The results are given in figure 1. This figure shows the in plane irradiance on the two array parts, the sum of their individual maximum power values and the maximum power value of both parts connected in parallel. The figure shows that parts of an array with different orientations can be connected in parallel without a significant loss of power.
From this it can be concluded that multiple orientations within one PV-array are acceptable as long as the modules within a string have the same orientation; the parallel strings may have different orientations. The effect of multiple orientations of modules within a string has not been modelled since it is common practice to avoid these situations.

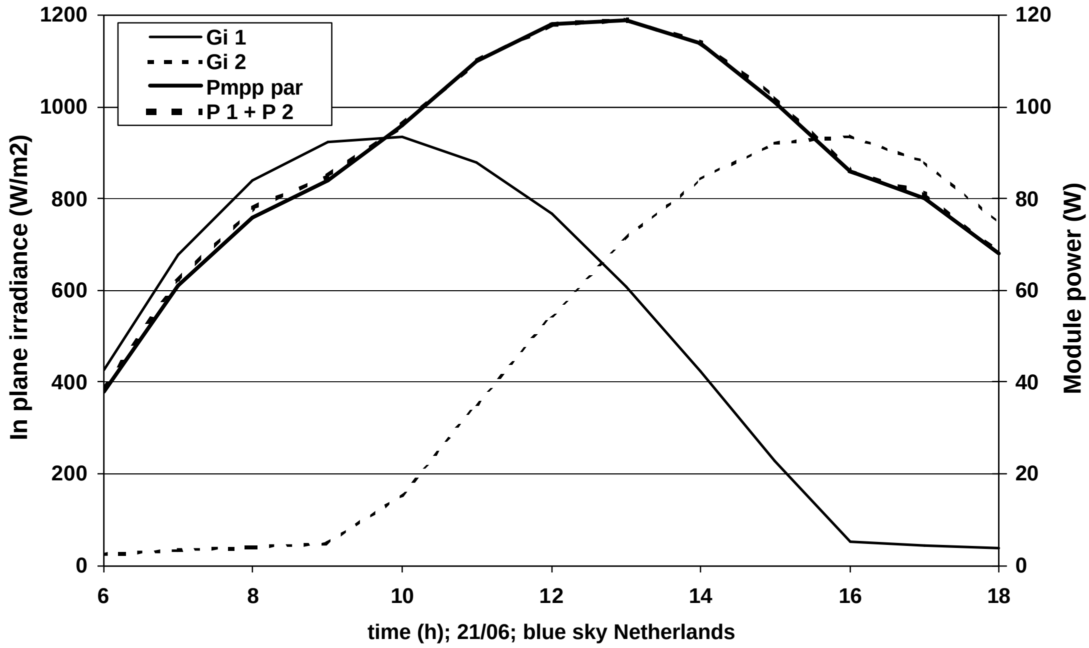


*Figure 1 Parallel connection of an array facing west and an array facing east (slope 45°)*

# 3. PARTIAL SHADING

To quantify the difference between the mismatch loss in partially shaded PV-modules connected in parallel and in series, experiments were conducted with nine modules alternately connected in parallel and connected in series. The measurements were done with the very same modules under virtually identical conditions, which excludes other influences on the array power than the mismatch effect.

Experiments were performed with 9 modules on sheds on a horizontal roof. The orientation of the sheds is depicted in figure 2. Figure 3 shows which 9 modules of the second shed were used for the experiments.

The 9 modules were chosen arbitrarily from the total set of modules and were not cleaned prior to the experiments. The modules have their original two bypass diodes (1 diode per string of 18 cells).

With a specially designed relay-switchbox the 9 modules were alternately connected in parallel and connected in series. During the measurement campaigns the IV-curve of the modules with the parallel connection and with the series connection were measured alternately. The pairs of IV-curves were used to calculate the corresponding pairs of maximum power point values.

Next to the PV-arrays some slim poles (5 x 6 cm) are situated with horizontal wires (6 mm). The width of the PV-cells is 12.5 cm. At the time of the measurements these poles cast a shadow over some of the 9 modules mainly in the morning period. In the afternoon this happens only sporadically. The wire always casts a shadow over the modules. The following picture shows the shadows on the modules at 10:40h. The shadow of the wire is too thin to be seen on the picture.

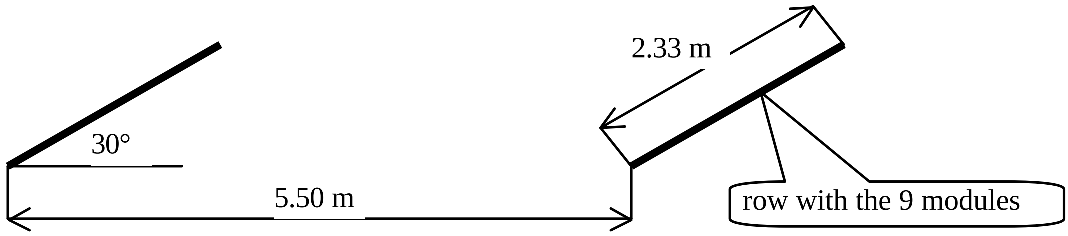


Figure 2: Sketch of the orientation of the sheds

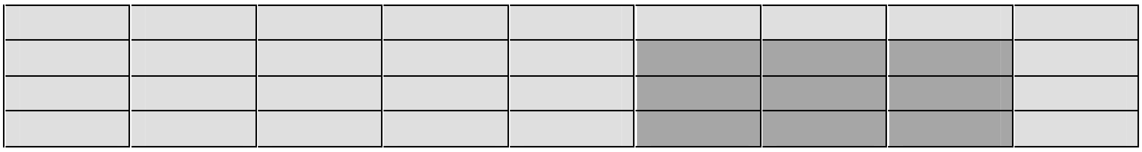

*Figure 3: sketch of the shed with 9 x 4 modules.*
*The 9 modules chosen for the experiment are indicated with the dark-grey filling.*

*Figure 4: Part of the PV-array with some shadows (13/10/03; 10:40h)*

The results of the measurements on a sunny day (17/11/2003) are shown in figure 5. It shows that in the afternoon, when there is practically no shading, the parallel concept produces marginally more power than the series concept. However in the morning, when there is only little shading, the parallel concept produces significantly more.
Of course the difference between both concepts depends very much on the shading conditions and consequently no general conclusions can be formulated on the annual energy gain by the parallel concept. However the results do show that PV-systems in the built environment, which are virtually always subject to some shading, will profit by the parallel concept.

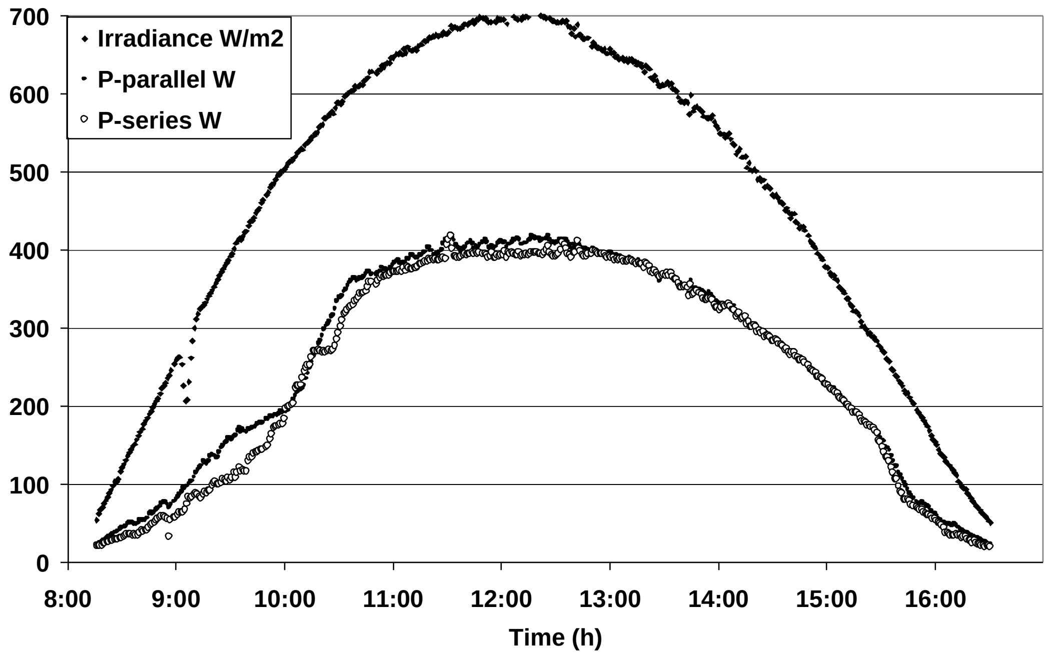


Figure 5:Output of the 9 modules alternately series and parallel connected

# 4. ACCESSIBILITY

PV modules are poorly accessible when being part of a building. Usually scaffolding must be put up to replace defective modules. As this is costly it is good to consider what are the effects of a defect in the system.

Most PV-modules are equipped with one or more bypass diodes to prevent thermal destruction of cells due to hot spots in case of partial shading. Another function of bypass diodes is that failing modules in a string are bypassed and that the remaining modules of the string can still produce power. This situation however may lead to additional mismatch loss in the case of a central inverter with parallel strings. This is caused by the differences in the MPP voltage of the strings with a different number of active modules. It is also possible that the cabling that interconnects the modules fails. In these situations one failing module in a string results in the loss of the complete string. This happened recently in a Dutch BIPV system in which 6 modules out of about 400 failed. The modules were part of strings with a length of 13 modules. The 1.5% of failing modules resulted in a loss of 10% of the strings. Since energy loss of 10% was considered unacceptable the failing modules had to be replaced. Because of the low accessibility of the roof this could only be done at high costs. In case the strings would have been shorter (ultimately with a length of one module), the energy loss would have been acceptable and no repair would have been needed.

As in the previous two paragraphs this is merely an example of what can happen. It is hard to quantify the over-proportional energy loss on annual basis as averaged over all BIPV installed. Nevertheless it is recommended to use short strings in BIPV system due to limited accessibility for repairing.

It is also recommended to have a system layout that enables to mount the modules simply.

An identical connection of all modules is preferred, favouring a fully parallel or series connection. In addition the mounting system must allow simple and easy installation and maintenance.

## 5. CONSEQUENCES

In the previous chapters arguments are given for application of short strings in building integrated PV-systems. The arguments are based on the energy yield of the array. The effects of price, efficiency and reliability of the inverters were not taken into account.

The shortest possible string is a string consisting of one module. This leads to the parallel connection of many modules. Possible concepts for applying many modules in parallel are:

- All modules directly DC-connected via a low resistance cable to a central inverter (low voltage DC-bus). In the Wirefree concept [4] this cable is omitted by the dual use of metal strips for mechanical support and electrical connection.
- All modules equipped with their own module (AC-modules) with an AC-bus.
- All modules equipped with an individual maximum power point tracker:
    - DC/DC module inverter connected to a high voltage DC-bus and a central DC/AC inverter
    - DC/AC module inverter connected to a high voltage AC-bus and a central AC/AC inverter

## 6. CONCLUSIONS

In the design of a BIPV system it is necessary to take partial shading, especially at low altitudes of the sun, possible different orientations within the system and the chance of component failures into account. These factors lowering the energy output must be offset to the system cost, including engineering and maintenance cost.
In many cases a parallel connection of modules is favourable especially if it can be combined with lower component costs, such as the Wirefree concept.


## 7. ACKNOWLEDGEMENT

This work was supported by the Netherlands Agency for Energy and Environment Novem (project number: 2020-02-11-11-003).


## 8. REFERENCES


[1] Report IEA-PVPS T1-12:2003 Trends in Photovoltaic Applications Survey
Report of selected IEA countries between 1992 and 2002
[2] N.J.C.M. van der Borg, M.J. Jansen: Energy loss due to shading in a BIPV application,WCPEC-3 (May 2003) Osaka
[3] Achim Woyte: Design issues of photovoltaic systems and their grid interaction;
Thesis University of Leuven, December 2003; ISBN 90-5682-451-1
[4] Henk Oldenkamp et al: "PV-wirefree: redesigning and innovating grid-connected
PV-stems" Proceedings PV in Europe, 7-11 October 2002, Rome; pp. 757 - 760
[5] I. Weiss et al: "A new PV system technology-The development of a magnetic power transmission from the PV module to the power bus"; 16th European Photovoltaic Solar Energy Conference, 1 - 5 May 2000, Glasgow; pp, 2096 - 2099
[6] Henk Oldenkamp et al: "PV-Wirefree: Bringing PV-systems back to their essentials"; WCPEC-3 (May 2003) Osaka
[7] PV-syst: http://www.pvsyst.com/