

Monitoring building integrated PV-MIPS systems at ECN

Measuring results for a year

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Acknowledgement/Preface

Monitoring described in this report is part of the European Commission PV-MIPS project, within the 6th Framework Programme. The report describes the work carried out by ECN within the Work package 6: Integration of Electrical Interconnection and Mechanical Interface, and Work package 7: Field tests. ECN project number is 7.4992 and ECN project leader is B. Jablonska, M.Sc.

Abstract

Two different types of PV MIPS systems have been mounted on the roof of two research houses at the ECN site in Petten, the Netherlands. The PV-MIPS systems, which consist of AC-modules with an inverter fixed on the rear, have been integrated in sloped roofs. Various types of inverter integration in the module have been applied in order to test the heat load and influence of natural ventilation on the delivered power and durability of inverters.

Prior to installation, outdoor tests of the HV CIS PV-MIPS systems have been done in order to detect defects on a system level. Exchange of failed inverters of AC-modules integrated in sloped roofs is supposed to be labour-intensive and expensive. Two IWES/Steca inverters failed outdoor test and were returned for reparation.

Measuring period was 15 months for HV CIS modules with IWES/Steca inverter and 12 months for a-Si modules with Delta inverter. Apart from one of the 24 a-Si modules, both combinations of modules and inverters have been operating without problems.

No clear influence of the mounting of the inverter can be seen on electricity output and module temperature. For the inverter temperature, influence is small as well, i.e. inverter temperature is a bit lower if mounted on a support. On the other hand, *temperature gradients* for outdoor inverters are much larger than for inverters installed indoor. A much more detailed indoor laboratory test setup of a complete PV-MIPS system would be needed to reveal the connection between PV system performance and all these system and ambient aspects.

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Summary

Two different types of PV MIPS systems have been mounted on the roof of two research houses at the ECN site in Petten, the Netherlands, both for getting information on building integration of AC-modules with an inverter fixed on the rear of a module in sloped roofs and for measuring the electricity output of the systems and temperatures of modules and inverters. This report is on energy performance of the PV systems and integration.

For one series of systems, HV CIS modules were combined with 3-phases IWES/Steca inverters; the other series consist of a-Si modules with 1-phase Delta Gridfit 250 inverters. For both system types, 3 systems have the inverter glued directly on the rear of the module, 3 systems have the inverter on a support at 20 mm distance from the rear of the module and 2 systems have the inverter indoor as usual. The HV CIS systems have been installed on the support frame of the Schletter mounting system. Directly on the roof, vertical bars for good ventilation and sufficient distance from the roof have been added to the system. For the a-Si systems, vertical bars have been used as well. On these bars, horizontal profiles were fixed in a form that does not accumulate water and dirt. Manufacturer has supplied the modules already equipped with connecting clips on the rear of the modules, to be clicked on the horizontal bars. The various ways of integration of an inverter with module and the integration of the systems in the roof as mentioned above have been tested.

Prior to installation, outdoor tests of the HV CIS PV-MIPS systems have been done in order to detect defects on a system level. Exchange of failed inverters of AC-modules integrated in sloped roofs is supposed to be labour-intensive and expensive. Two IWES/Steca inverters failed outdoor test and were returned for reparation.

Measuring period for the HV CIS systems was 15 months and for the a-Si systems 12 months. Apart from one of the 24 a-Si modules, both combinations of modules and inverters have been operating without problems.

Following conclusions can be drawn from the field tests for both PV system types:

1. There is no significant influence of the mounting of the inverter on the electricity output and on the temperature of the PV module. This can be the result of the optimally designed integration of the systems in the roof, with sufficient ventilation between the roof and the modules.
2. For the measuring period, inverters glued directly on the module backside reach the highest temperature i.e. about 60°C, followed by inverters on support. However, differences in temperature between these two inverter mounting types are small. Inverters in the attic get the lowest maximum temperature, however, mean temperature is higher than for the inverters placed outdoors.
3. Temperature gradients for outdoor inverters are much larger than for inverters installed indoor. For the measuring period, temperature differences within the hour can reach 15 K and over the day up about 50 K. The effect is largest for the inverters glued directly on the module backside.
4. Average temperature difference between inverter and PV module is 1 - 2 K, both for glued inverters and inverters on support. The spreading in temperature difference is somewhat larger for PV systems with inverter on support than for systems with glued inverters.
5. Performance ratio of HV CIS systems is somewhat higher than for the a-Si systems. Degradation of a-Si systems during the first hour of use, differences in type of inverter and in way of roof integration may be reason for that.
6. A much more detailed indoor laboratory test setup of a complete PV-MIPS system would be needed to reveal the connection between PV system performance and all these system and

ambient aspects. In a laboratory (like a climate chamber), unlike under unpredictable conditions outdoor, the boundary conditions can be set. For prototypes of PV-systems that are still under development, the laboratory tests should be done first in order to detect the defects and get detailed information on performance and mutual influence factors.

7. When integrating PV-MIPS systems in sloped roofs, special attention should be given to the suitable support construction which allows ventilation of inverters fixed at the rear of the modules. In case of a large roof system, the recommended air gap between roof and inverter is 5 cm, and therefore an air gap between roof and the module of 5 cm + inverter thickness.
8. Large HV-CIS systems are less easy to install since two workers must be present and a crane must be used. This means higher installation costs, too. Modular a-Si systems with a click fixing to the profiles can be installed by one worker and without crane.
9. In case of a large-scale application on roofs (for example by a housing association on rental houses or in a newly built residential area), the costs can be lowered substantially.
10. For a better accessibility of inverters in case of a failure, the inverters could be placed at the edges of the modules.
11. The visibility of the module grid should be as much as possible eliminated. The mounting clips and sealing rubber strips of the HV CIS systems disturb the module grid too pronounced.

Findings 1 - 5 above both hold for the HV CIS systems and a-Si systems.

Observation 4 leads to the recommendation of durability testing of inverters in the laboratory. Clear test conditions can be derived from these measurements in practice.

1. Introduction

Within the framework of the European PV-MIPS project, demonstration with prototypes of AC-modules has been carried out.

The field tests and the monitoring have been divided in the following phases:

- A. Phase 0 – State-of-the-art of reference systems (completed)
- B. Phase 1 – Demonstration and field tests with 1st version of PV-MIPS systems (completed)
- C. Phase 2 – Demonstration and field tests with 2nd improved version of PV-MIPS systems (ongoing)
- D. Phase 3 – Demonstration, field tests and large-scale market introduction of the 2nd version of the PV-MIPS systems (ongoing)

Up till now, the field tests have been carried out by the following partners: IWES (location Kassel, Germany), MVV-Energie (location Mannheim, Germany) and ECN (location Petten, the Netherlands).

In 2011, the Phase 2 field tests will be carried out by IWES, MVV-Energie, AIT (location Vienna, Austria) and Steca (location Memmingen, Germany).

At ECN, two types of building integrated PV-MIPS systems have been tested during 2009 and 2010:

- a. high voltage CIS modules with 3-phases IWES¹/Steca inverter;
- b. a-Si modules with 1-phase Delta inverter (Gridfit 250).

In September 2009, PV-MIPS systems mentioned under (a) were installed on the so-called Ecobuild house A; see Figure 1.1, most left house. In December 2009, PV-MIPS systems indicated under (b) were mounted on the roof of the Ecobuild house D, i.e. the most right house.

The objective was to monitor the effect of module integration of inverters on the delivered power of the PV-MIPS systems and on inverter and PV-MIPS module temperatures. Inverters have been mounted on the modules in different ways. Choice of the integration way of inverters in modules and PV-MIPS systems in roofs and assessment of ease of installation of PV-MIPS modules are other objectives.

The report describes the monitoring of both PV-MIPS systems during the period reaching from the middle of December 2009 to the middle of December 2010. Use of the same monitoring period enables comparison between both types of PV systems.

¹ Formerly ISET.



Figure 1.1 *HV CIS modules on the roof of the most left Ecobuild house A, and a-Si modules on the roof of the most right Ecobuild house D [ECN]*

Section 2 describes the integration considerations of the inverters in modules and PV-MIPS systems in roofs, and gives the evaluation of the PV-MIPS systems by an architect, as well as the ease of installation and costs.

Section 3 presents the set-up of the PV systems with different inverter integration modes. Measuring and data acquisition method have been described in Section 4 and the monitoring results themselves including analysis in Section 5. Finally, Section 6 gives conclusions and ideas for further evaluation.

2. Design considerations

2.1 Integration in sloped roofs

Within the PV-MIPS project [1], ECN made the decision to integrate the PV-MIPS modules in roofs. This decision was made based on the facts that (1) IWES and MVV were already carrying out tests of free-standing modules, (2) building integration increases the average temperature of these modules, submitting them to more severe conditions, and (3) in the Netherlands, building integrated PV is seen as the most important potential market for AC-modules.

First, an inventory was made of the different locations at which these modules could be mounted on the premises of ECN. Among the examined options were the Ecobuild research houses at the ECN site, the ECN office building 71, a test-roof dedicated for PV and collector testing and dedicated test racks in which the thermal effects of building integration could be simulated (by creating a façade-like construction at the rear of the modules). The choice was made to mount the modules on the Ecobuild research houses because of the test infrastructure available, the demonstration aspect and the realistic building integration. In particular, the Ecobuild research houses have sloped roofs, which is the most common type of roof in the Netherlands. The systems have been installed with 30° inclination. The main disadvantage that was foreseen at that time was the fact that it would be very difficult to replace faulty inverters. Fortunately, during the field tests not many inverter problems occurred. Finally, the CIS modules were located at Ecobuild house A (leftmost of the row) and the a-Si modules at Ecobuild house D (rightmost of the row), see Figure 1.1.

The aim of the tests was to monitor the performance of the PV-MIPS modules under typical operating conditions. Therefore, the configuration design aimed at a suitable but realistic (not fully optimised) configuration as could be applied in real domestic installations. In general, the temperature of the PV as well as the air gap between the PV and the roof is strongly influenced by the local wind speed, which in the built environment generally has a large degree of unpredictability due to the influence of the surrounding buildings, as well as turbulence generated e.g. at the edges of the roof. If there is no wind, natural convection flow will occur at the rear of the module, contributing to the cooling of the PV. The integration of inverters and modules in the roof has been optimised in order to ensure sufficient ventilation under the PV-roof under both windy and windless conditions, such as a sufficiently large air gap and a frame that would not obstruct the airflow. On the other hand, the inverters were positioned on the module centre without trying to minimise the distance between the inverter and the module edge, in order to obtain a realistic impression of the functioning of these modules under building integrated conditions.

The height of the modules above the roof was chosen according to the following guidelines found in the literature with respect to spacing between PV and roof:

- In the EU project PV cool build [2], the recommended airspace between PV and roof is 2.5 cm per meter along roof slope (so for 5 m slope that results in 12.5 cm), independent of roof slope. However, calculations with the PV coolbuild calculator for different air gaps showed very little effect of using a smaller air gap.
- In the Dutch norm NVN 7250:2007 [3]: Zonne-energiesystemen - Integratie in daken en gevels - Bouwkundige aspecten it is recommended to use 1 cm/meter along the slope of the roof. Communication by B. van Kampen (TNO) [4].
- In the EurActive roofer project [5], in order to remove moisture, a minimum distance of 2 cm is given, while the recommended distance is 5 cm.

At ECN, the roof length along the slope is 5 m. Taking into account the above considerations of a minimum distance of 1 cm/m, it was decided to have an air gap between roof and inverter of 5 cm, and therefore an air gap between roof and PV of 5 cm + inverter thickness (distance C in the Figure 2.1). The inverter thickness for CIS is about 3 cm, and for a-Si about 5 cm, resulting in a PV-roof distance of respectively 8 cm for CIS, and 10 cm for a-Si.

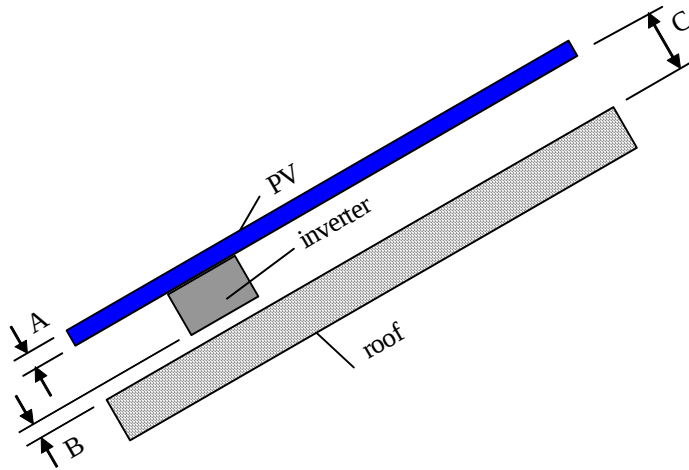


Figure 2.1 *Definition sketch of roof spacing distances used at ECN in the PV-MIPS project*
[ECN]

The mounting frame was chosen based on the consideration that the natural convection flow below the modules (upward flow of heated air) should be hindered as little as possible. Therefore, the choice was made for a mounting frame using vertical mounting bars. For the large CIS modules, a system was found with connecting clips that can be fixed directly to the vertical mounting bars (the Schletter mounting system) [6]. For the small a-Si modules, a different system was chosen [7] because the manufacturer supplied these modules with connecting clips for horizontal mounting bars at the rear side. The choice was made to attach thin horizontal bars to the vertical mounting system and connect the modules with the clips that were already glued to the rear of the modules by the manufacturer. In this way both the manufacturer specified clips could be used and the obstruction of the natural convection flow was kept to a minimum.



Figure 2.2 *Integration of HV CIS modules on the roof* [ECN]



Figure 2.3 *Integration of a-Si modules on the roof [ECN]*

Finally, in order to obtain insight into the full range of temperatures that can be obtained in building integrated PV systems, for the case of the large CIS modules it was decided to close the gaps in between the large CIS modules by black rubber strips, thereby eliminating additional ventilation through the air gaps between the modules. In practise, such measures may be taken for reasons of aesthetics or water tightness of the configuration, but at the same time lead to a reduced ventilation rate and thereby increase the temperature of the modules and, in case of the PV-MIPS modules, the inverters located underneath the modules.

2.2 Architectural aspects, accessibility and costs of PV-MIPS systems and easiness of installation

As mentioned in [1], it is important that architects, users and neighbours accept the PV-MIPS systems as for their integration and aesthetics. An architect employed at ECN has evaluated the PV-MIPS systems, integrated in the roofs of the Ecobuild research houses at ECN, as follows below.

“In principle, both systems are well integrated from the constructional point of view. Both systems are mounted on a water-tight layer (EPDM), on a technically and visually acceptable distance from the roof. However, the module size of the amorphous system (with Delta inverters) fits better the dimensions of the roof. From the architectural point of view, the row of roof tiles at the left side of the HV CIS system (with IWES inverters) should be avoided. Furthermore, there is a too big roof area that is not covered by PV above the HV CIS system.

The mounting clips on both systems should be coated in the colour of the profiles (HV CIS system) or coated in a dull black. Apart from that, even if coated, the mounting clips of the HV CIS system are visually too dominant. The black rubber strips around the modules give a visual accent. Consequently, the design should be adapted to that fact. The mounting clips are disturbing the grid of modules too pronounced.

The grid of the amorphous system is hardly visible, although not fully invisible. In combination with the variety of colour of the various modules, which are intrinsic to amorphous modules, it gives the roof a vivid appearance.”

Furthermore, the easiness ease of the installation is very important. As the HV CIS modules are large and heavy (65 kg each), a crane must be hired for the installation. Costs for a crane for two days, which were needed for the installation of the 8 HV CIS modules, were €1.000. Normally, the costs are often even higher. The scaffolding hired for preparation of the roof and installation of the modules cost €700. Due to the size and weight of the modules and according to the rules, at least two workers must be present. All these aspects increase the total costs of the systems. In case of a large-scale application on roofs (for example by a housing association on rental houses or in a newly built residential area), the costs can be lowered substantially.

The modularity of the HV CIS system is less flexible than the modularity of the amorphous system. In case that an inverter fails, a whole large module has to be removed, due to the fact that the inverter is located in the middle of the module. Here again, two workers must be

present. A solution could be to place the inverter at module edges, in which case, lifting the module up can be enough.

As for the amorphous systems, there was no crane needed for the installation. Because the systems consist of three separate modules connected by one inverter, there is no glass lamination layer used as is the case with the HV CIS modules. The modules can be installed by one person. As with the other system, scaffolding was hired for € 700.

If an inverter of the amorphous system fails, removing just one module is not sufficient. In case that inverters have been mounted on the middle modules of the system, or in case that the PV area is larger, it might be necessary to remove more modules for access. The solution could be, like with the HV CIS systems, to place the inverters on the edges of the modules. Due to the click fixing system, there is always some space above necessary to remove (and install) a module. So, all modules above the given module must be removed in case of repair.

3. Set-up of PV-MIPS systems

Section 3.1 shows the set-up of the HV CIS modules with the 3-phases IWES/Steca inverter on the roof of dwelling A, and Section 2.2 shows the same for the a-Si modules with Delta inverter on the dwelling D roof. Both paragraphs include positioning of modules, positioning of inverters and AC wiring set-up. An overview of the most important features of the systems can be found in the Annex A.

3.1 High voltage CIS modules with IWES/Steca inverter

Figure 3.1 shows mounting of the 8 HV CIS modules on the roof of Ecobuild house A. Gaps between the PV modules have been closed with rubber strips, thereby eliminating additional ventilation through the air gaps between the modules and simulating real-case integration, as it would be carried out in practice, due to the aesthetics.

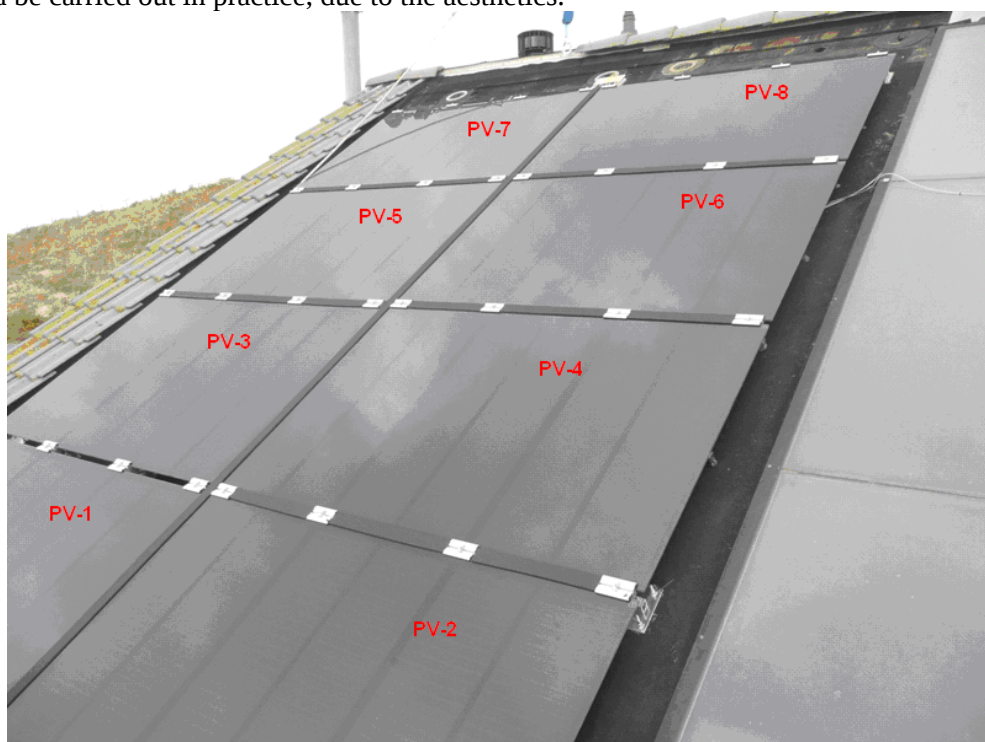


Figure 3.1 *The HV CIS modules on the roof of Ecobuild house A including references [ECN]*

Every PV module consists of 3 sub-modules connected in parallel to an inverter to convert DC into AC power. Module integration of the inverter differs:

- For PV-1, PV-5 and PV-7, location of the inverter is on a support that has been glued on the backside of the PV modules (see Figure 6a). Distance between inverter and module is about 20 mm.
- For PV-3 and PV-4, location of the inverter is conventional: indoor in the attic of house A (see Figure 3.2b).
- For PV-2, PV-6 and PV-8, the inverter has been glued directly on the backside of the PV modules (see Figure 3.2c).

Figure 3.3 gives additional information on location of the inverters and connection of the PV systems to the grid.

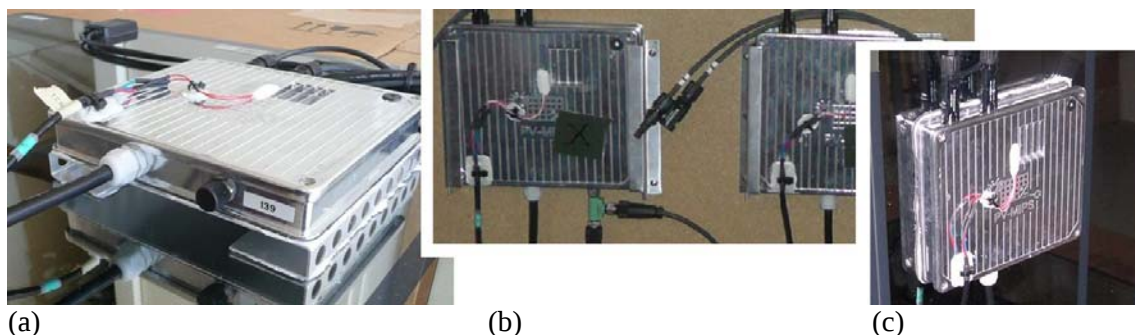


Figure 3.2 Location of the inverters for the HV CIS systems: (a) on a support glued on the backside of the module, (b) in the attic and (c) glued directly on the backside of the module [ECN]

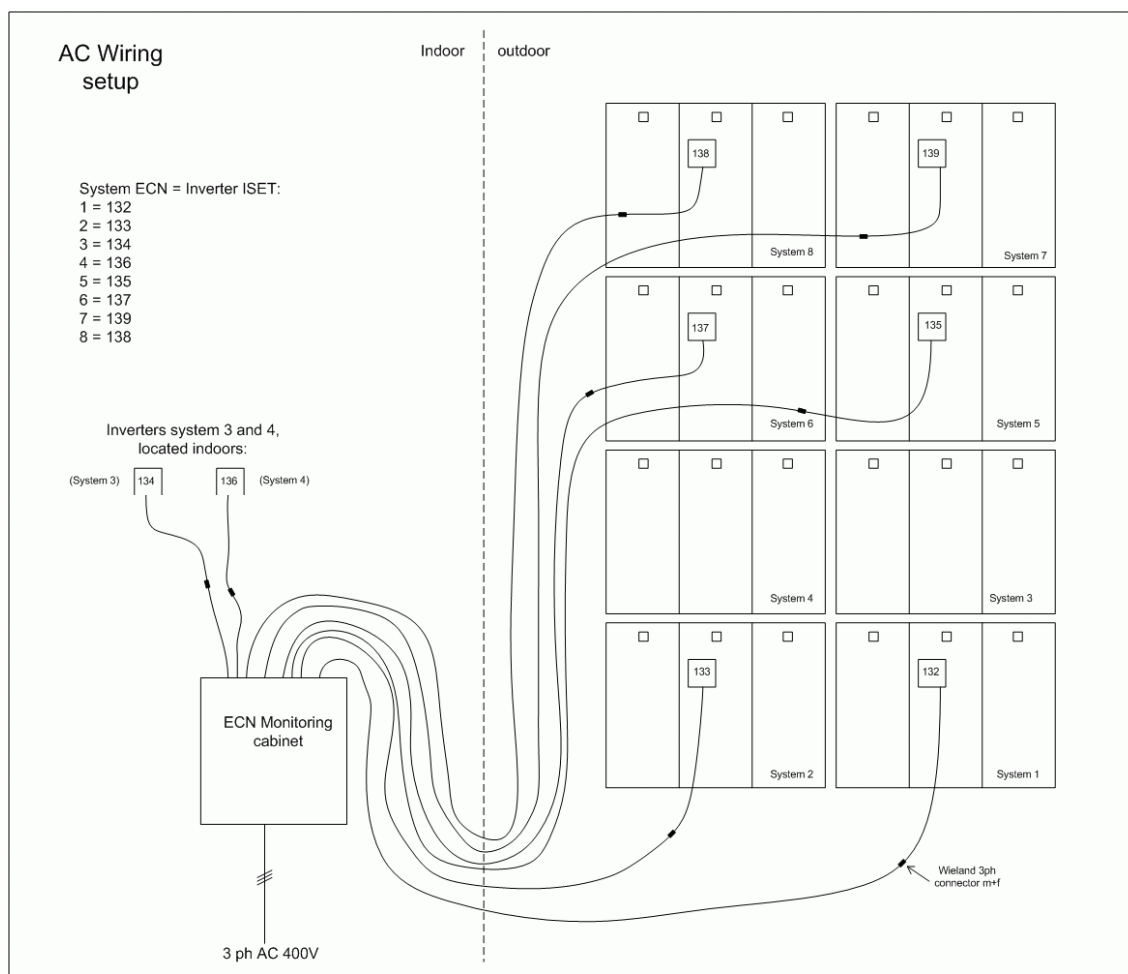


Figure 3.3 Location of the inverters for the HV CIS systems and connection of the PV systems to the grid [ECN]

3.2 A-Si modules with Delta inverter

Figure 3.4 shows the mounting layout of the a-Si PV modules on the roof of Ecobuild house D. Every module consists of three sub-modules connected in parallel to the inverter. The gap between the sub-modules (and modules) is about 5 mm.



Figure 3.4 The a-Si modules on the roof of Ecobuild house D including references [ECN]

The location of the inverters on the a-Si modules is similar to the inverters on the HV-CIS modules:

- For PV-1, PV-5 and PV-7, location of the inverter is on a support that has been glued on the backside of the PV modules (see Figure 3.5a). Distance between inverter and module is about 20 mm.
- For PV-3 and PV-4, location of the inverter is conventional: indoor in the attic of house D.
- For PV-2, PV-6 and PV-8, the inverter has been glued directly on the backside of the PV modules (see Figure 3.5b).

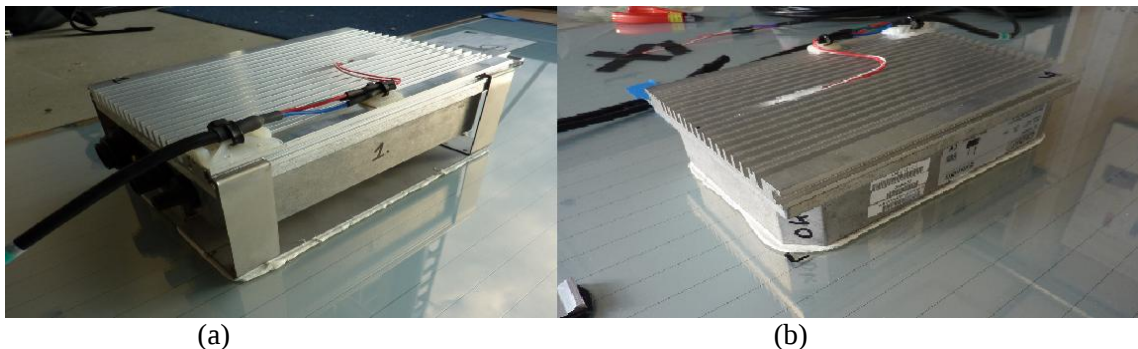


Figure 3.5 Location of the inverters for the a-Si systems: (a) on a support glued on the backside of the module and (b) glued directly on the backside of the module [ECN]

Location of the inverters and connection of the PV systems to the grid is similar to the situation for the systems on house A.

4. Measuring and data acquisition method

4.1 Outdoor tests of the HV CIS systems prior to installation

The HV CIS modules with the PV-MIPS inverters (developed by IWES) were prototypes. The inverters and the modules have been separately tested by the developers in laboratories. ECN decided to test also the combination of the prototypes - the AC PV-system. One of the main reasons was the fact that it is labour-intensive and expensive to exchange failed inverters of AC-modules integrated in sloped roof.

Firstly, all inverters to be glued to the modules directly or on a bracket were fixed to the modules. Outside, all the HV CIS PV-systems were put into operation and measurements have been done while PV-systems were exposed to solar irradiation (see Figure 4.1 below).



Figure 4.1 Outdoor test of HV CIS module [ECN]

Two inverters failed; one to be placed on the attic and one glued on a bracket to a module. This inverter has been removed from the module and both inverters returned to IWES for reparation (see Figure 4.2 below).



Figure 4.2 Measuring device and removing the failed inverter [ECN]

4.2 Sensors and measuring

Table 4.1 *Measuring variables for the PV systems [ECN]*

	Sensor	Type	Unit	Max. inaccuracy
Temperature PV module	PT-100	Minco, type S665	°C	±0.12 °C
Temperature inverter	PT-100	Minco, type S665	°C	±0.12 °C
Power roof A	Power transducer	Camille Bauer, type Sineax M561	W	±0.5 % (Class 0.5)
Power roof D	Power transducer	Camille Bauer, type Sineax M563	W	±0.5 % (Class 0.5)

Moreover, two pyranometers (Kipp&Zonen, type CMP21) measure solar irradiance (in W/m²) in the PV module plain for roof locations A and D separately; maximum inaccuracy: 0.5%. A solar protected PT100 sensor measures outdoor air temperature near the top of the roof of house D. It is assumed that these temperature readings can also be used for roof A.

4.3 Measuring and communication

The data are logged every 10 seconds and processed into 10 minute average values, i.e. for roofs A and D individually. The in total four sets of values are recorded in separate Access data files.

The RS485 connectors of the IWES/Steca inverters have been connected in series to enable communication with IWES; see Figure 4.3. Communication data are not being recorded and analyzed at ECN. There is no specific data communication set-up for the Delta inverters on the roof D.

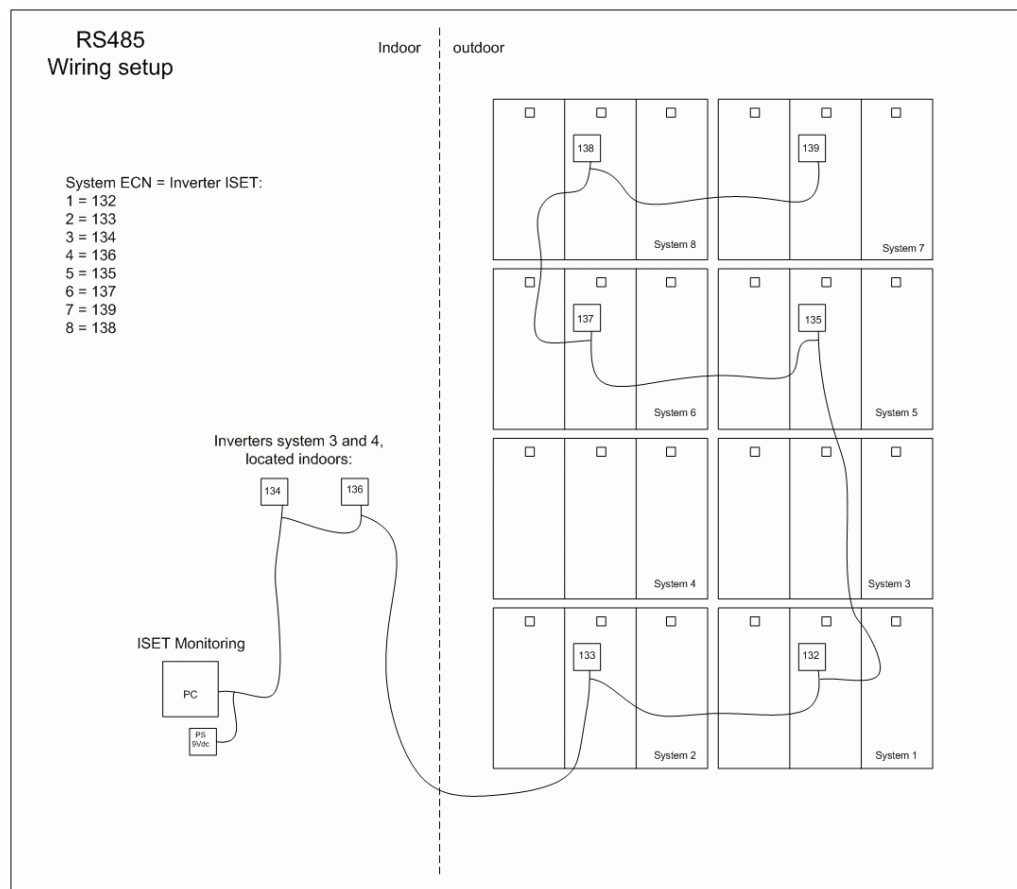


Figure 4.3 *Connection of the inverters for the HV CIS systems [ECN]*

4.4 Data acquisition

For both systems, measuring data have been processed into a table and various graphs:

- PV system electricity output over the whole measuring period for each of the PV systems and average values for PV systems with the same integration of the inverter.
- PV system electricity output per solar irradiance interval of 100 W/m² averaged for PV systems with the same integration of the inverter.
- Performance ratio as function of solar irradiance.

Performance ratio has been determined for each PV system according to:

$$\text{Performance_Ratio} := \frac{\frac{P_{pv}}{P_{pv_stc}}}{\frac{P_{solar}}{P_{solar_stc}}}$$

where:

- P_{pv} is the measured power (W/module);
- P_{pv_stc} is the power for standard test conditions (W/module);
- P_{solar} is the measured solar irradiance (W/m²);
- P_{solar_stc} is the solar irradiance used in standard testing, i.e. 1000 W/m².

Table 2 lists the power for standard test conditions for the 8 HV CIS modules [8] and Table 3 does the same for the 8 a-Si modules [9].

Table 4.2 Power for standard test conditions of the 8 HV CIS modules [ECN]

Ref. PV module	P_{pv_stc} (W/module)		Ref. PV module	P_{pv_stc} (W/module)
PV-1	238.8		PV-5	224.9
PV-2	225.2		PV-6	220.7
PV-3	235.9		PV-7	231.0
PV-4	235.5		PV-8	221.7

Table 4.3 Power for standard test conditions of the 8 a-Si modules [ECN]

Ref. PV module	P_{pv_stc} (W/module)		Ref. PV module	P_{pv_stc} (W/module)
PV-1	169.8		PV-5	168.7
PV-2	169.4		PV-6	170.7
PV-3	170.8		PV-7	168.9
PV-4	170.6		PV-8	169.2

Performance ratio may depend on temperature of the PV module. That is why performance ratio measurements have been distributed over various temperature intervals of module temperature.

- PV module temperature distributed over temperature intervals averaged for PV systems with the same integration of the inverter.
- Inverter temperature distributed over temperature intervals averaged for PV systems with the same integration of the inverter.
- Inverter temperature gradients in one hour and in one day.
- Temperature difference between PV module and inverter.

5. Monitoring results

5.1 HV CIS systems

5.1.1 Electricity output

Measuring period for the data processing ranges from 16 February to 15 December 2010. Table 4 presents the PV system electricity output over this period for each of the PV systems and average values for PV systems with the same integration of the inverter. Values between brackets show the electricity output corrected for differences in power of the individual modules under standard conditions according to Table 4.2, where $P_{pv_stc} = 229.2$ W/module, i.e. the average power of all 8 PV modules has been taken as reference value. It should be noted that electricity output as function of solar irradiance will not be similar for all PV modules, but this approach is assumed to give a good first order correction.

Table 5.1 *Electricity output of the 8 HV CIS PV systems for the monitoring period from 16 February to 15 December 2010; also averaged for PV systems with the same integration of the inverter [ECN]*

Ref. PV system	E_{pv} (kWh)		Ref. PV system	E_{pv} (kWh)
PV-1	199.0 (191.0)		PV-1/5/7 Inverter on support	195.4 (193.4)
PV-5	189.3 (192.9)			
PV-7	197.8 (196.3)			
PV-3	190.6 (185.2)		PV-3/4 inverter in attic	194.3 (188.9)
PV-4	198.0 (192.7)			
PV-2	194.8 (198.2)		PV-2/6/8 Inverter on module	195.4 (201.7)
PV-6	202.1 (209.9)			
PV-8	190.4 (196.9)			

Analysis

Corrected values in Table 5.1 seem to show that electricity output depends on integration of the inverter to some extent. PV systems with inverters glued directly on the modules perform best, followed by those with inverter on support. Systems with the inverter in the attic have relatively lowest performance. It was expected that PV systems with inverter on support would perform better than those with inverter on the module, due to a lower temperature of module and inverter as PV system performance decreases with increasing temperature. Reality is the other way around. Apparently, aspects other than mounting of the inverter have larger influence. Probably, module temperature is likely to be influenced more by local air temperature due to warming up of the PV modules on the roof in combination with cooling by wind. Moreover, there may be differences in the performance of the inverter to influence the system performance. Together, that makes dependency between module temperature and integration of the inverter weaker than expected.

A much more detailed indoor laboratory test setup of a complete PV-MIPS system would be needed to reveal the connection between PV system performance and all these system and ambient aspects. In a laboratory (like a climate chamber), unlike under unpredictable conditions outdoor, the boundary conditions can be set. For prototypes of PV systems that are still under development, the laboratory tests should be done first in order to detect the defects and get detailed information on performance and mutual influence factors. The laboratory tests (like speeded up durability tests of PV systems) can save financial means and time for the developing company. Field tests combined with the monitoring shall be done only with a PV system that has withstood the laboratory tests already.

Hence, no conclusion can be drawn with respect to influence of mounting of the inverter on system performance.

Figure 5.1 shows electricity output per solar irradiance interval of 100 W/m² averaged for PV systems with the same integration of the inverter. Values have been corrected for differences in power of the individual modules under standard conditions as indicated above for Table 4. Differences in inverter performance and influences of local ambient temperature have not been taken into account in these corrections.

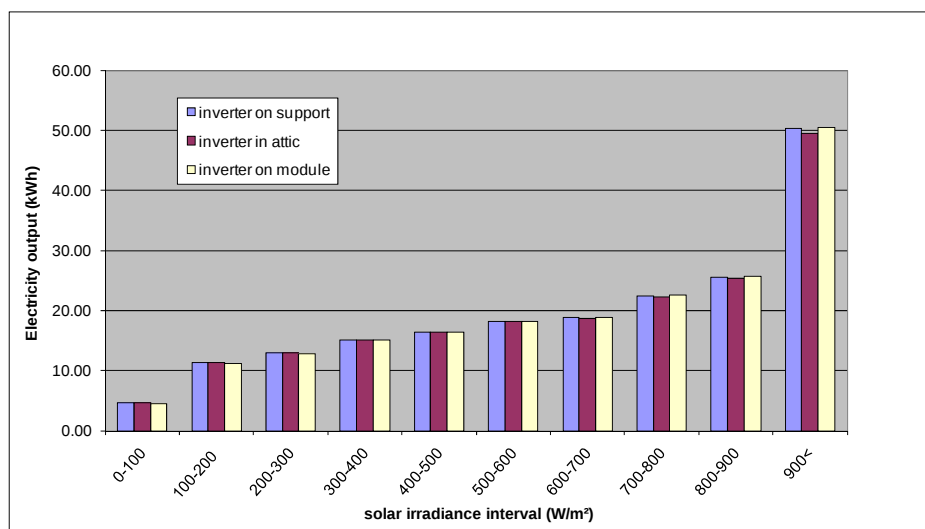


Figure 5.1 *Electricity output per solar irradiance interval of 100 W/m² averaged for PV systems with the same integration of the inverter for the monitoring period from 16 February to 15 December 2010; values corrected for differences in PV module power under standard conditions[ECN]*

5.1.2 Performance ratio

Figure 5.2 presents the performance ratio as function of solar irradiance for all PV systems separately for a period of ten months. Values have been distributed over various intervals of module temperature. Values have been corrected for differences in power of the individual modules under standard conditions. Differences in inverter performance and influences of local ambient temperature have not been taken into account in these corrections.

Analysis

Distribution in Figure 5.2 reflects the overall performance of the values in Table 4: system performance not between brackets (Table 4) can be explained from the shape of the individual 'curves' in Figure 5.2.

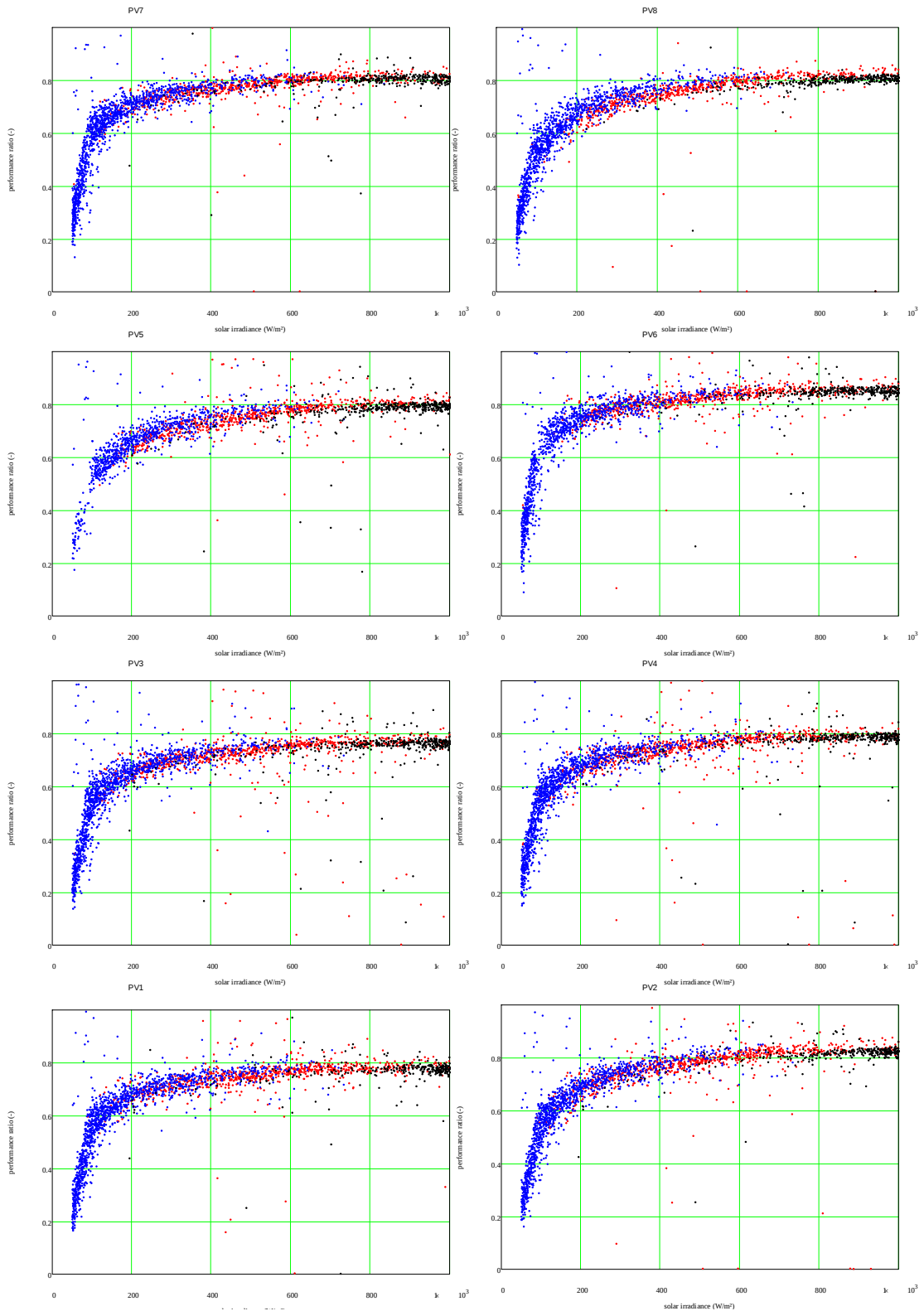


Figure 5.2 *Performance ratio as function of solar irradiance for all PV systems distributed over various intervals of module temperature for the period from 16 February to 15 December 2010; blue = around 15 °C, red = around 30 °C, black = around 45 °C [ECN]*

5.1.3 Module temperature

Figure 5.3 shows module temperatures distributed over 5 K temperature intervals averaged for PV systems with the same integration of the inverter.

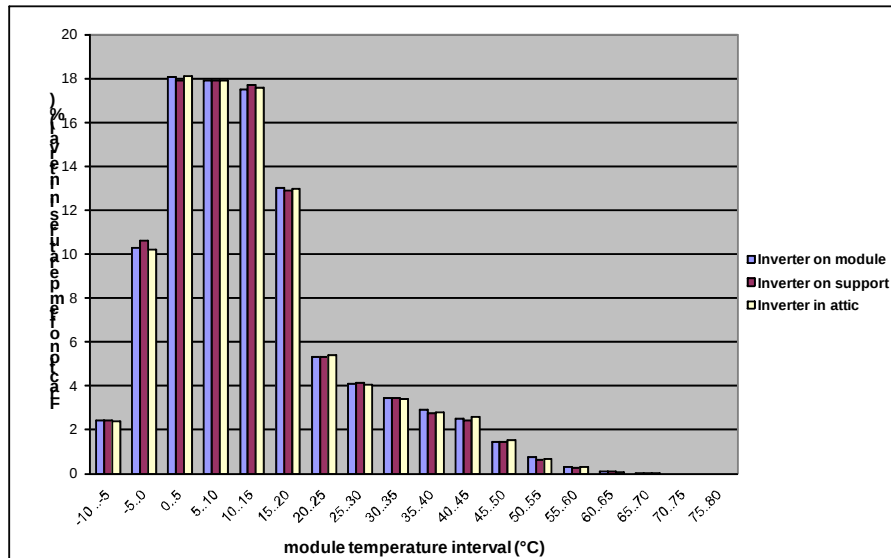


Figure 5.3 *Module temperatures distributed over 5 K temperature intervals averaged for PV systems with the same integration of the inverter for the monitoring period from 16 December 2009 to 15 December 2010 [ECN]*

Analysis

Taking into account accuracy of the temperature measurement, no significant differences in module temperature can be read from Figure 5.3.

Figure 5.4 shows the module temperatures on a sunny day for PV-1 and PV-5 with inverter on support, PV-2 and PV-6 with inverter glued directly on the module backside and PV-3 and PV-4 with inverter in the attic.

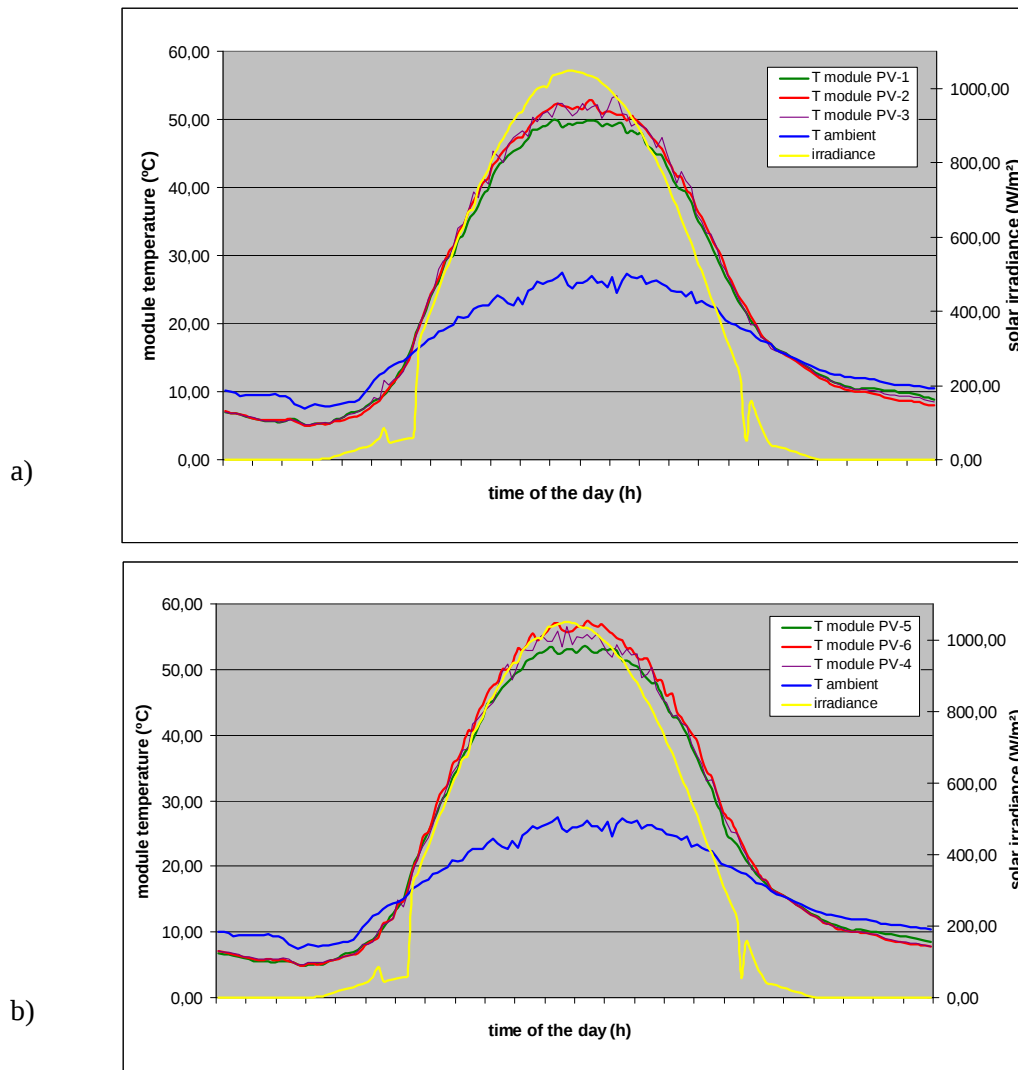


Figure 5.4 Module temperatures during a sunny day (3 June 2010) for (a) PV-1, PV-2 and PV-3 and (b) PV-5, PV-6 and PV-4. Green: inverter on support; red: inverter direct on backside of module; black: inverter in attic; blue: ambient temperature; yellow: solar irradiance [ECN]

Analysis

Distribution in Figure 5.4 shows that, on this day, module temperatures (at about 15 cm from the integrated inverter) get slightly higher for modules with the inverter glued directly on the backside compared to the inverter on support. On this sunny day, highest temperatures differ about 4 K at maximum. The difference in temperature may (partly) be caused by the influence of the inverter nearby the module temperature sensor: access of wind to the module around the inverter on support is better than for the inverter glued directly on the backside of the module and, therefore, may result in a lower temperature. Module temperature for modules with the inverter in the attic is in the same range.

Comparison of Figure 5.4a and Figure 5.4b reveals that the modules higher up the roof have a higher temperature, probably due to uprising of heated air between PV modules and the under-roof.

5.1.4 Inverter temperature

Figure 5.5 shows inverter temperatures distributed over 5 K temperature intervals averaged for PV systems with the same integration of the inverter.

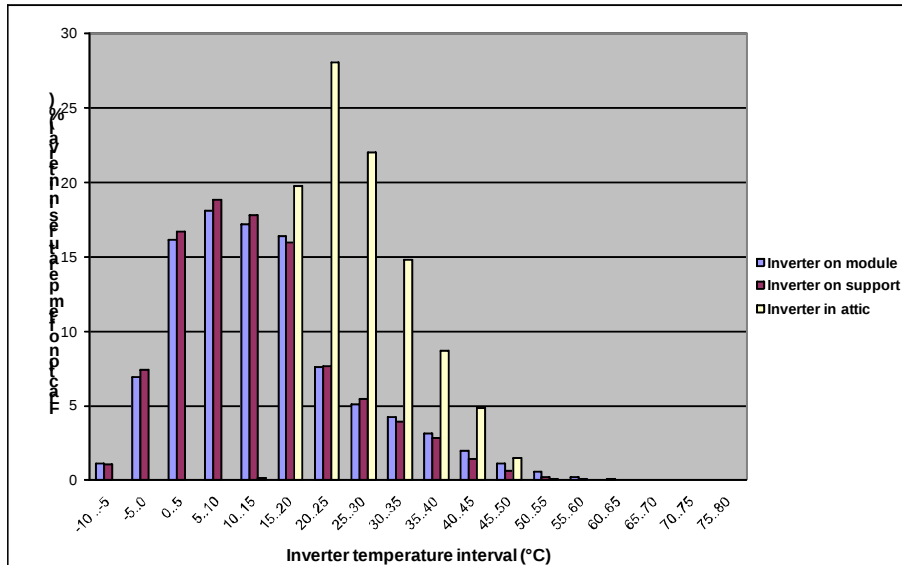


Figure 5.5 *Inverter temperatures distributed over 5 K temperature intervals averaged for PV systems with the same integration of the inverter for the monitoring period from 16 December 2009 to 16 December 2010 [ECN]*

Analysis

Figure 5.5 indicates that inverters placed outdoors may reach higher temperatures than inverters in the attic. For the outdoor inverters, application on support has better cooling.

Figure 5.6 shows the inverter temperatures on a sunny day for PV-1 and PV-5 with inverter on support, PV-2 and PV-6 with inverter glued directly on the module backside and PV-3 and PV-4 with inverters in the attic.

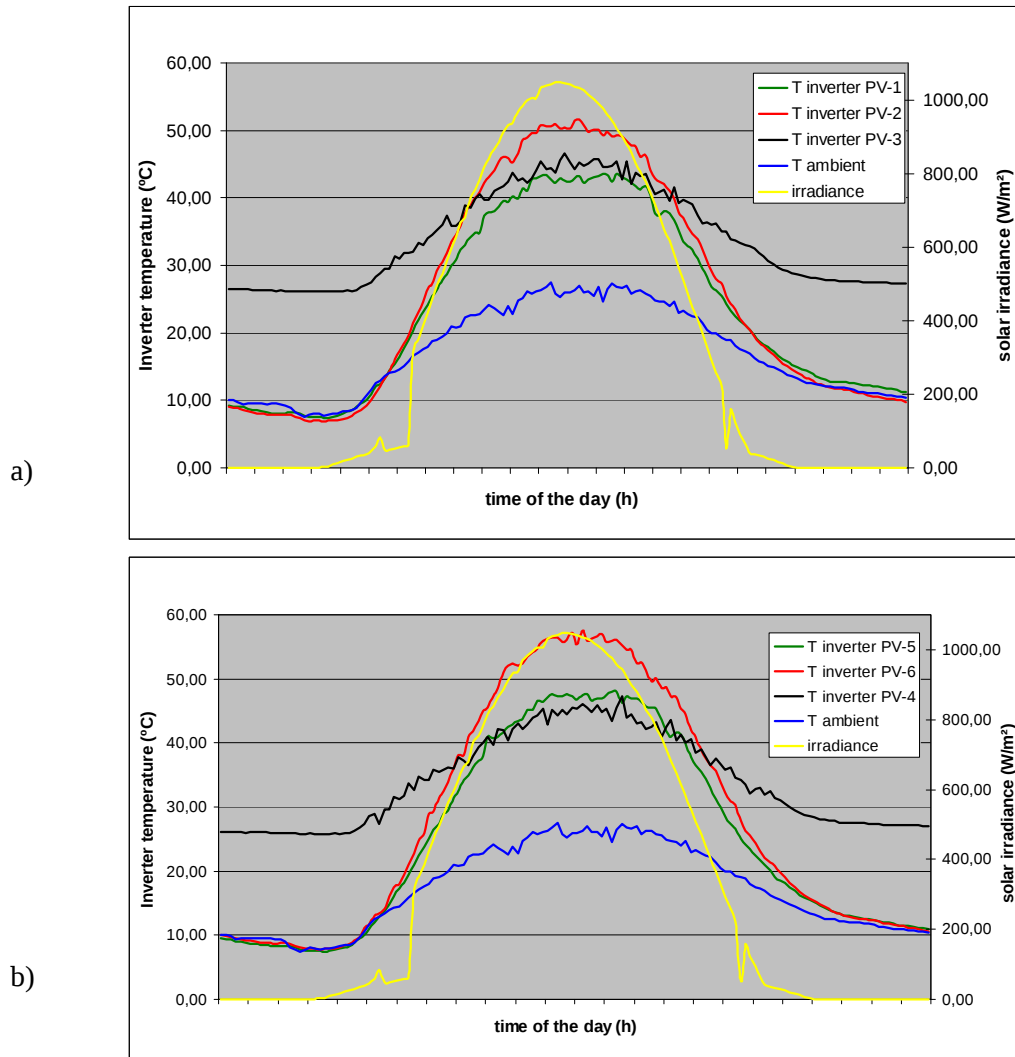


Figure 5.6 Inverter temperatures during a sunny day (3 June 2010) for (a) PV-1, PV-2 and PV-3 and (b) PV-5, PV-6 and PV-4. Green: inverter on support; red: inverter direct on backside of module; black: inverter in attic; blue: outdoor temperature; yellow: solar irradiance [ECN]

Analysis

Distribution in Figure 5.5 shows that, on sunny days, inverters glued directly on the modules get highest temperatures. The highest temperatures of the inverters on support remain a bit lower. For the inverters in the attic, on the other hand, the mean temperature is higher than for those outdoors. Figure 5.6 nicely explains what happens:

- The inverter temperature increases due to electricity production and solar irradiation. This effect is highest for the inverter glued on the backside of the module.
- The inverter temperature decreases due to heat loss to the environment. This effect is highest for the inverter on support in the lowest location on the roof.

Figure 5.6 shows the net results of warming up and cooling for the various types of inverter integration.

Comparison of Figure 5.6a and Figure 5.6b reveals that the inverters higher up the roof have a higher temperature, probably due to uprising of heated air between PV modules and the roof, as for the PV modules. End result is that the inverter for PV-6 reaches the highest temperature, i.e. more than 10 K higher than the temperature of the inverters in the attic. Inverter temperature for PV-2 remains about 5 K lower.

Inverter temperature gradients

Lifetime of the inverter may not only depend on absolute temperatures (causing emission of vapors from electronic components), but also on gradients in temperature (causing mechanical stresses). In Figure 5.7, distinction has been made between temperature gradients (a) over the hour and (b) over the day.

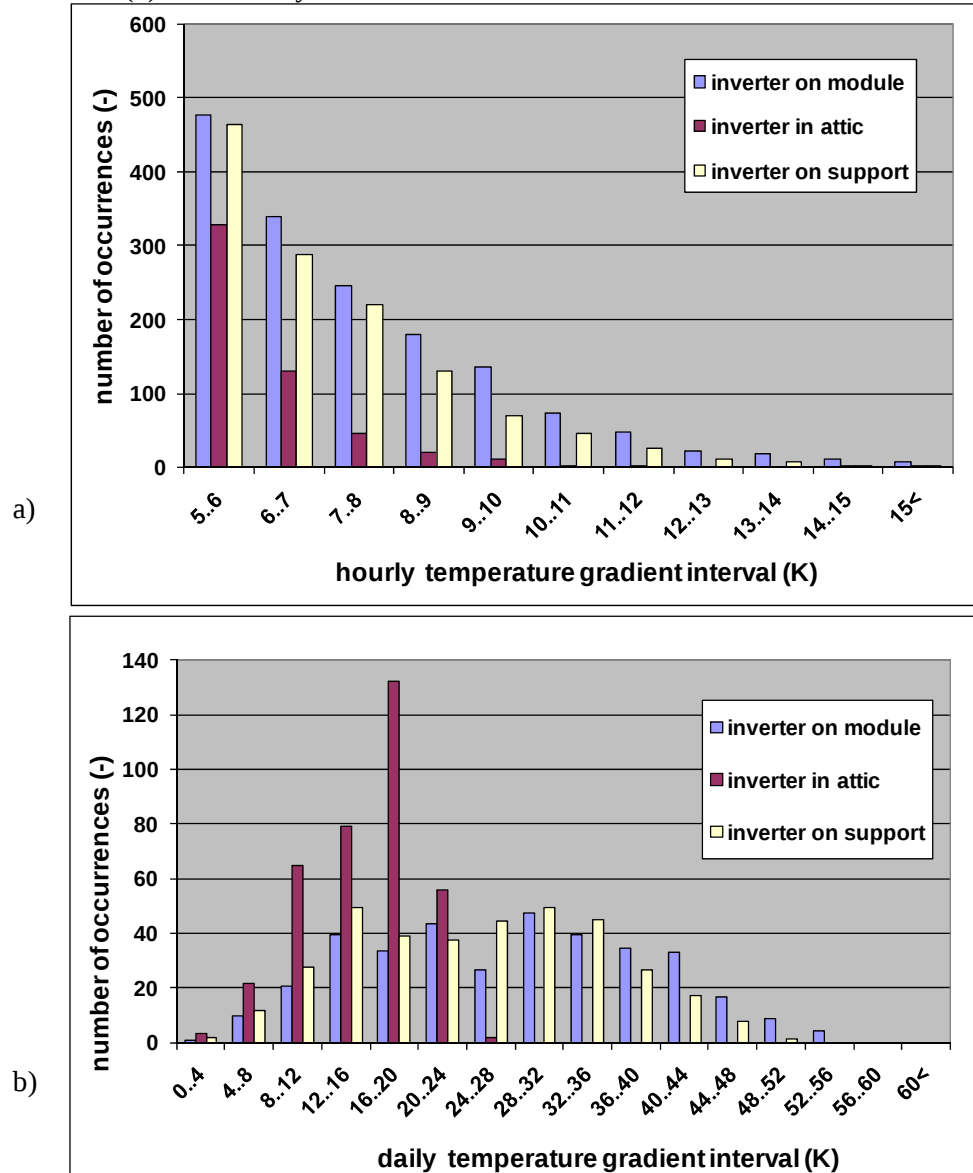


Figure 5.7 Temperature gradient (a) over the hour and b) over 24 hours for the monitoring period from 16 December 2009 to 15 December 2010 [ECN]

Analysis

Figure 5.7 shows that temperature gradients for outdoor inverters are much larger than for inverters installed indoor. The effect is largest for the inverters glued directly on the modules backside.

Temperature difference between module and inverter

Figure 5.8 presents temperature differences between module and inverter distributed over 1 K temperature difference intervals averaged for PV systems with the same integration of the inverter.

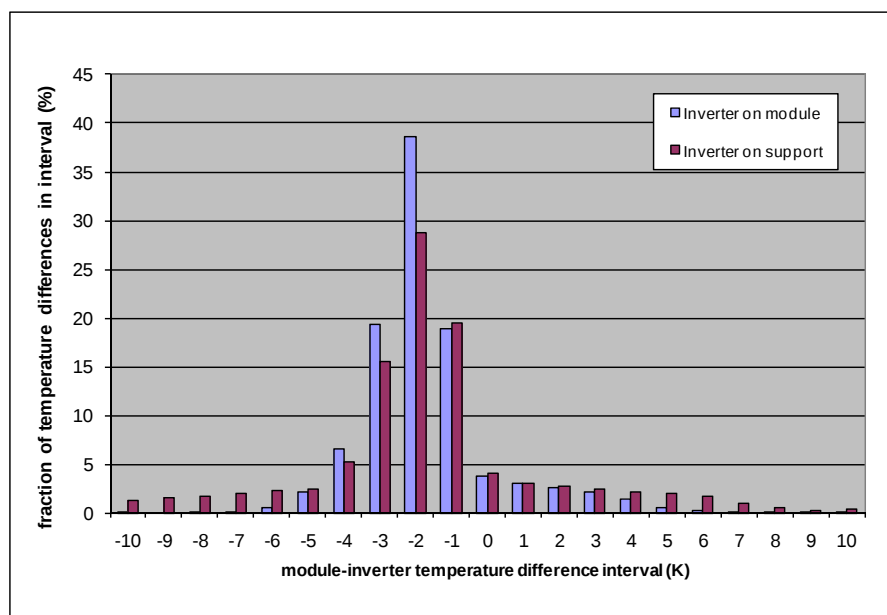


Figure 5.8 *Temperature differences between module and inverter distributed over 1 K temperature difference intervals averaged for PV systems with the same integration of the inverter for the monitoring period from 16 December 2009 to 15 December 2010 [ECN]*

Analysis

Figure 5.8 shows that on average inverter temperature is 1-2 K higher than module temperature, i.e. for both inverter mounting types. The spreading in temperature difference is somewhat larger for PV systems with inverter on support than for systems with glued inverters. Wind influence may be the reason for that.

5.2 A-Si systems

5.2.1 Electricity output

Measuring period for the data processing of the a-Si systems on the roof of Ecobuild House D ranges from 16 February to 15 December 2010.

Table 5 presents PV system electricity output over this period for each of the PV systems and average values for PV systems with the same integration of the inverter. Values between brackets present the electricity output corrected for differences in power of the individual modules under standard conditions according to Table 4.3, where $P_{pv_stc} = 169.8$ W/module, i.e. the average power of all 8 PV modules, has been taken as reference value. It should be noted that electricity output as function of solar irradiance will not be similar for all PV modules, but this approach is assumed to give a good first order correction.

Table 5.2 *Electricity output of the 8 a-Si PV systems for the monitoring period from 16 February to 15 December 2010; also averaged for PV systems with the same integration of the inverter [ECN]*

Ref. PV system	E _{pv} (kWh)		Ref. PV system	E _{pv} (kWh)
PV-1	139.3 (139.3)			
PV-5	85.2 (85.8)		PV-1/7 inverter on support	139.8 (140.2) ²
PV-7	140.4 (141.1)			
PV-3	132.8 (132.0)		PV-3/4 inverter in attic	135.6 (134.9)
PV-4	138.5 (137.8)			
PV-2	134.3 (134.6)		PV-2/6/8 inverter on module	135.2 (135.2)
PV-6	140.1 (139.4)			
PV-8	131.2 (131.7)			

Analysis

First of all, Table 5.2 shows that system PV-5 does not work properly. Probably, one of the three modules has broken down or there is a problem with the connections. Visual inspection did not give an explanation. In the average value of electricity output for inverters on support, PV-5 has been left out.

The corrected values in Table 5 seem to show that the electricity output depends on integration of the inverter to some extent. PV systems with inverters on support perform better than those with the inverter in the attic or glued directly on the module. However, as analyzed in the section 5.1.1 for HV CIS systems, aspects other than mounting of the inverter should be considered as well. Module temperature is likely to be influenced more by local air temperature due to warming up of the PV modules on the roof in combination with cooling by wind. Moreover, there may be differences in the performance of the inverter to influence the system performance. Together, that makes a strong dependency between module temperature and integration of the inverter unlikely. A much more detailed indoor laboratory test setup would be needed to reveal the connection between PV system performance and all these system and ambient aspects. Hence, no conclusion can be drawn with respect to influence of mounting of the inverter on system performance.

Figure 5.9 shows electricity output per solar irradiance interval of 100 W/m² averaged for PV systems with the same integration of the inverter. Values have been corrected for differences in power of the individual modules under standard conditions as indicated above for Table 5.2. Differences in inverter performance and influences of local ambient temperature have not been taken into account in these corrections.

² Electricity output of PV-5 has been left out of this average value.

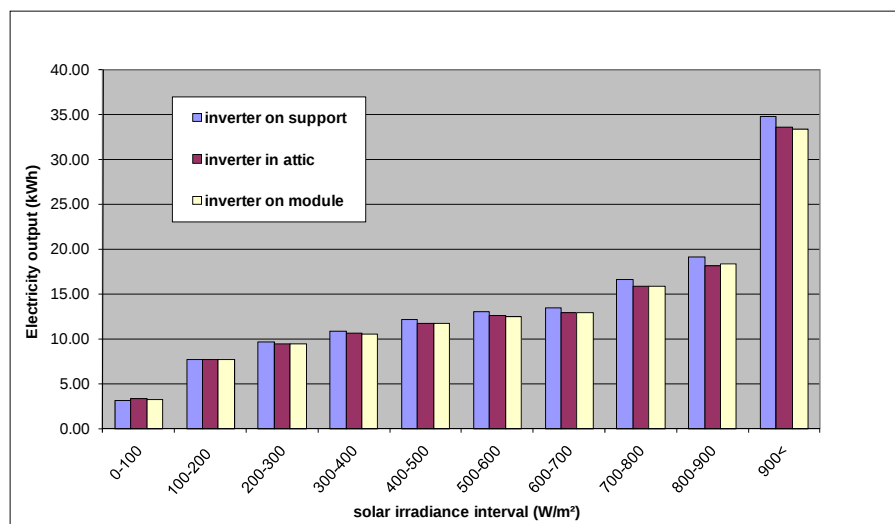


Figure 5.9 Electricity output per solar irradiance interval of 100 W/m² averaged for PV systems with the same integration of the inverter for the monitoring period from 16 February to 15 December 2010; values corrected for differences in PV module power under standard conditions [ECN]

5.2.2 Performance ratio

Figure 5.10 presents performance ratio as function of solar irradiance for all PV systems separately. Values have been distributed over various intervals of module temperature. Values have been corrected for differences in power of the individual modules under standard conditions. Differences in inverter performance and influences of local ambient temperature have not been taken into account in these corrections.

Analysis

Distribution in Figure 5.10 reflects the overall performance of the values in Table 5: system performance not between brackets (Table 5) can be explained from the shape of the individual ‘curves’ in Figure 5.10. The performance ratio for the PV-5 system deviates due to improper operation of one of the modules. Comparison with performance ratios of the HV CIS systems in Figure 5.2 reveals somewhat lower performance for the a-Si systems. An explanation may be found in lower efficiency of the inverter (due to the transformer), a higher module temperature and/or degradation during the first hour of use of the PV modules³.

³ For a-Si modules, major degradation (in the order of 10%) appears during the first hour of solar exposure. Flash testing should be performed after initial exposure. This initial exposure should be checked in order to find out whether or not initial degradation is part of the lower performance ratio.

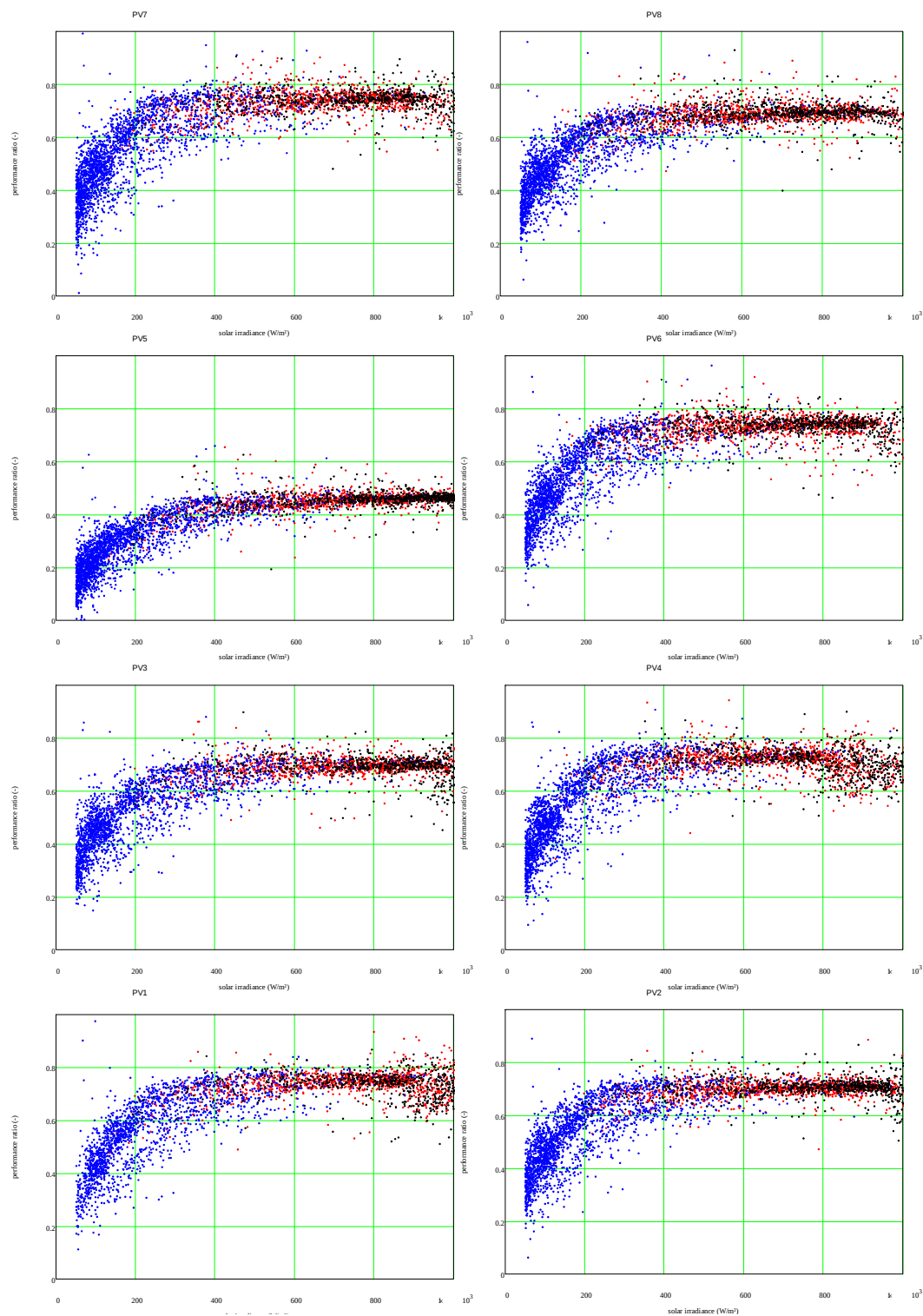


Figure 5.10 *Performance ratio as function of solar irradiance for all PV systems distributed over various intervals of module temperature for the period from 16 February to 15 December 2010; blue = around 15 °C, red = around 30 °C, black = around 45 °C [ECN]*

5.2.3 Module temperature

Figure 5.11 shows module temperatures distributed over 5 K temperature intervals averaged for PV systems with the same integration of the inverter.

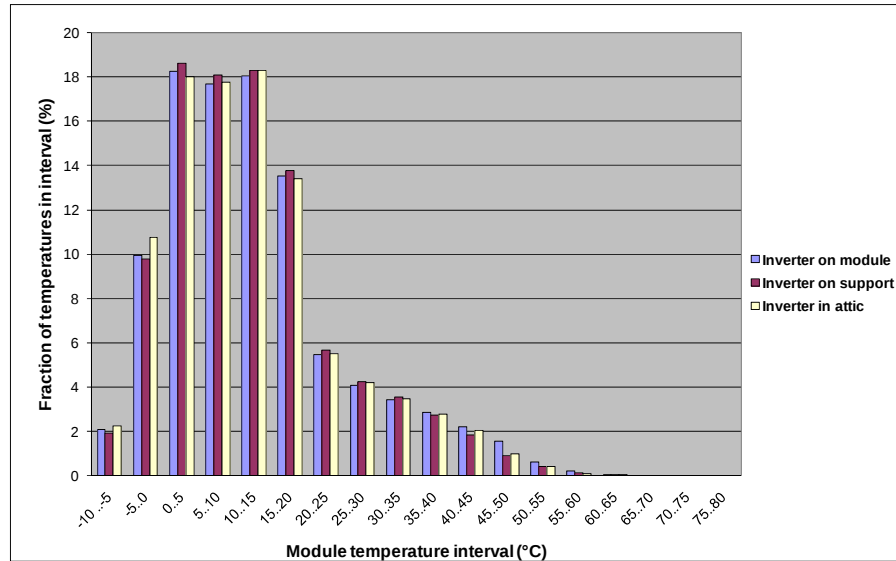


Figure 5.11 *Module temperatures distributed over 5 K temperature intervals averaged for PV systems with the same integration of the inverter for the monitoring period from 16 December 2009 to 15 December 2010 [ECN]*

Analysis

Only minor differences in module temperature can be read from Figure 5.11. For modules with inverter glued directly on, temperatures get somewhat higher than for modules with the inverter on support or in the attic.

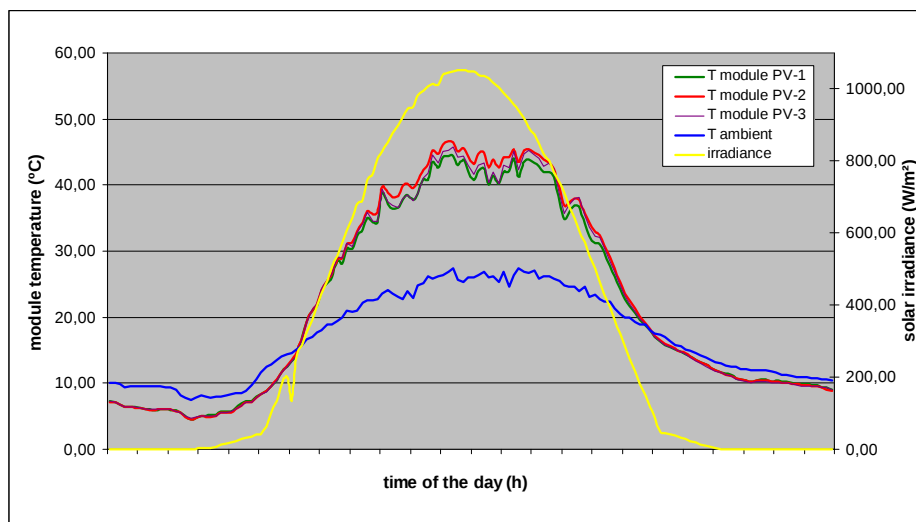
Figure 5.12 shows the module temperatures on a sunny day for PV-1 and PV-5 with inverter on support, PV-2 and PV-6 with inverter glued directly on the module backside and PV-3 and PV-4 with inverter in the attic.

Analysis

Distribution in Figure 5.12 shows that, on this day, module temperatures (at about 15 cm from the integrated inverter) get slightly higher for modules with the inverter glued directly on the backside compared to the inverter on support. On this sunny day, highest temperatures differ about 3 K at maximum. These findings correspond with the analysis of Figure 5.11. The difference in temperature may (partly) be caused by the influence of the inverter nearby the module temperature sensor: access of wind to the module around the inverter on support is better than for the inverter glued directly on the backside of the module and, therefore, may result in a lower temperature. Module temperature for modules with the inverter in the attic is in the same range.

Comparison of Figure 5.12a and Figure 5.12b reveals that the modules higher up the roof have a higher temperature, probably due to uprising of heated air between PV modules and the under-roof.

a)



b)

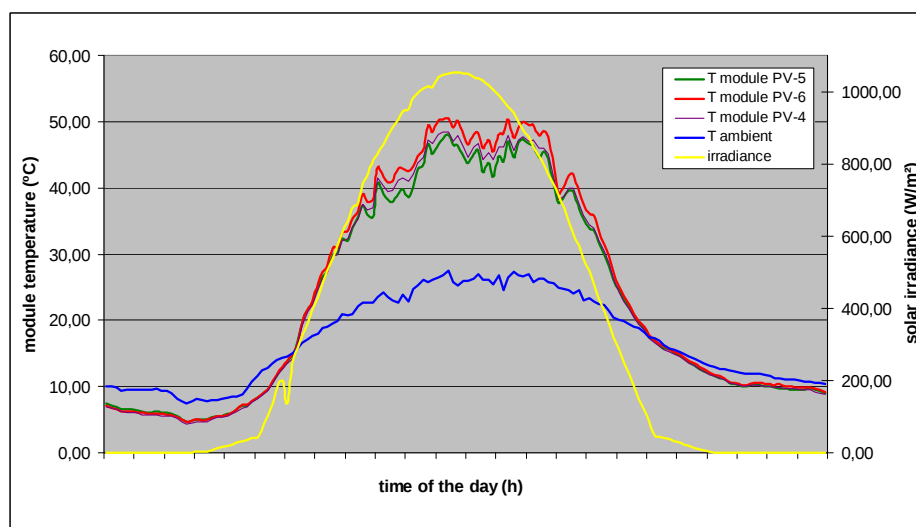


Figure 5.12 *Module temperatures during a sunny day for (a) PV-1, PV-2 and PV-3 and (b) PV-5, PV-6 and PV-4. Green: inverter on support; red: inverter direct on backside of module; black: inverter in attic; blue: ambient temperature; yellow: solar irradiance [ECN]*

5.2.4 Inverter temperature

Figure 5.13 shows inverter temperatures distributed over 5 K temperature intervals averaged for PV systems with the same integration of the inverter.

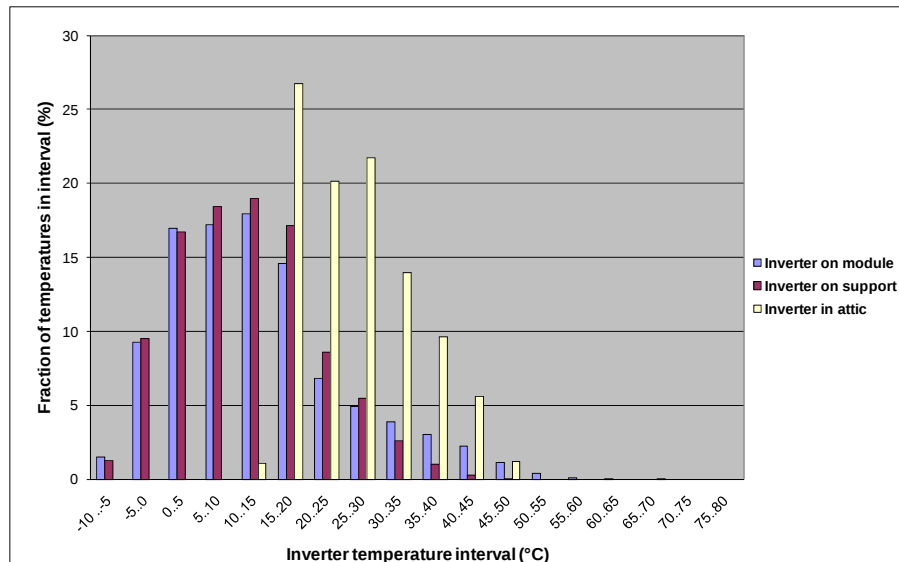


Figure 5.13 *Inverter temperatures distributed over 5 K temperature intervals averaged for PV systems with the same integration of the inverter for the monitoring period from 16 December 2009 to 15 December 2010 [ECN]*

Analysis

Figure 5.13 shows that inverters on support remain lower in temperature compared to those glued directly on the modules and those placed in the attic. Glued inverters reach the highest temperatures.

Figure 5.14 shows the inverter temperatures on a sunny day for PV-1 and PV-5 with inverter on support, PV-2 and PV-6 with inverter glued directly on the module backside and PV-3 and PV-4 with inverters in the attic.

Analysis

Distribution in Figure 5.13 shows that, on sunny days, inverters glued directly on the modules and installed in the attic get highest temperatures. Figure 5.14 nicely explains what happens:

- Inverter temperature increases due to electricity production and solar irradiation. This effect is highest for the inverter glued on the module backside.
- Inverter temperature decreases due to heat loss to the environment. This effect is highest for the inverter on support.

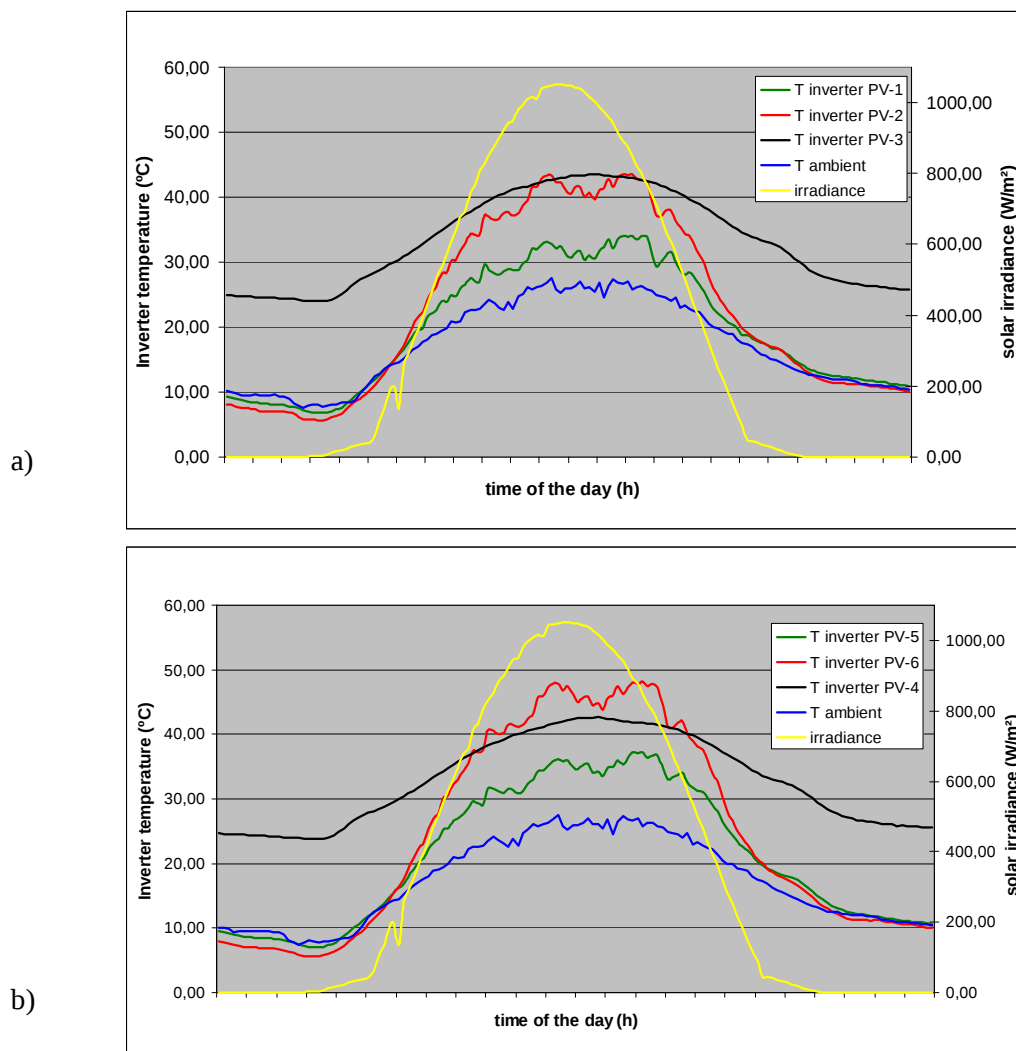


Figure 5.14 Inverter temperatures during a sunny day for (a) PV-1, PV-2 and PV-3 and (b) PV-5, PV-6 and PV-4. Green: inverter on support; red: inverter direct on backside of module; black: inverter in attic; blue: outdoor temperature; yellow: solar irradiance [ECN]

Figure 5.14 shows the net results of heating and cooling for the various types of inverter integration.

Comparison of Figure 5.14a and Figure 5.14b reveals that the inverters higher up the roof have a higher temperature, probably due to uprising of heated air between PV modules and the under-roof, as for the PV modules. End result is that inverter for PV-6 reaches the highest temperature, i.e. higher than the temperature of the inverters in the attic. Inverter for PV-2 gets about the same temperature as the inverters in the attic.

Inverter temperature gradients

Lifetime of the inverter may not only depend on absolute temperatures, but also on gradients in temperature. In Figure 5.15, distinction has been made between temperature gradients (a) over the hour and (b) over the day.

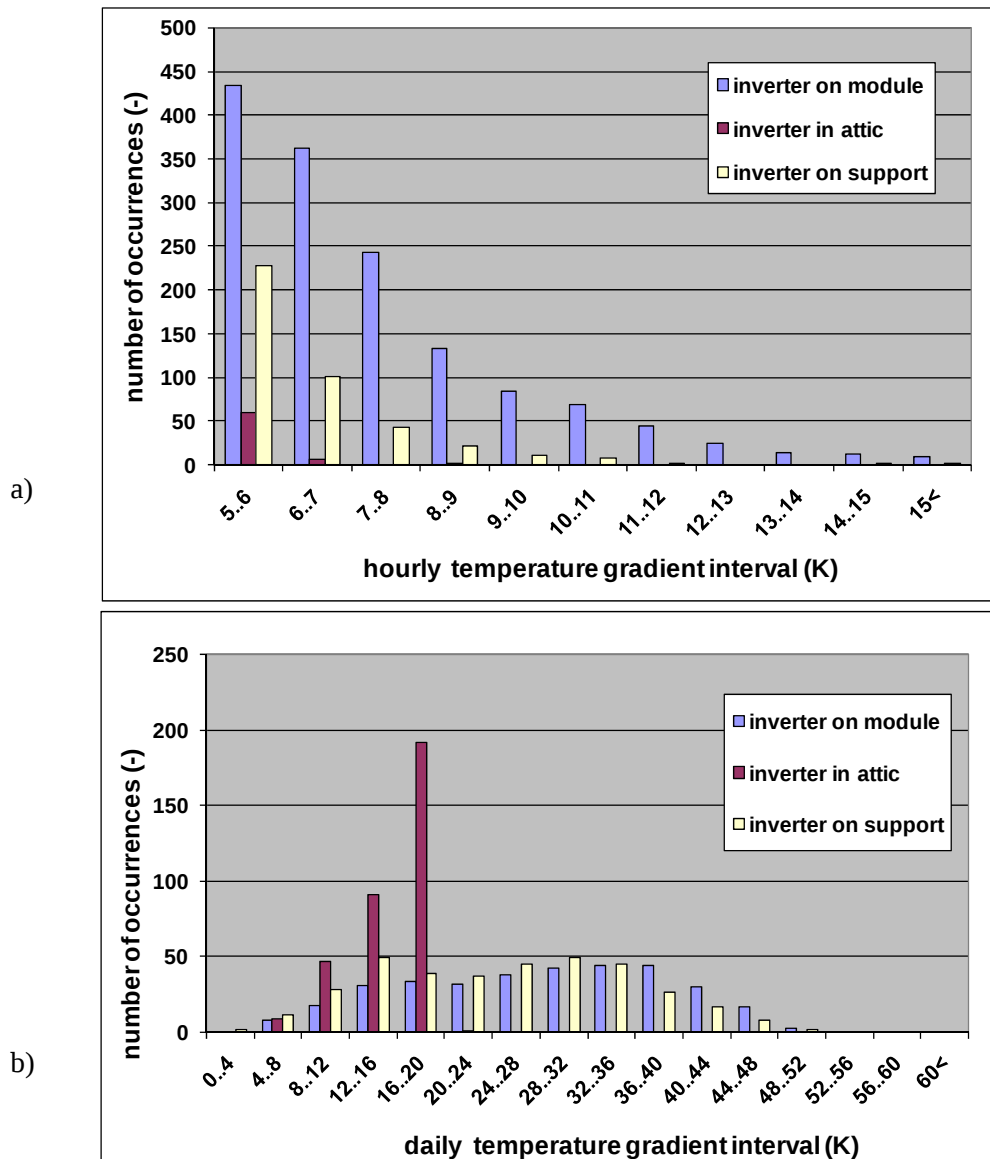


Figure 5.15 *Temperature gradient (a) over the hour and b) over 24 hours for the monitoring period from 16 December 2009 to 15 December 2010 [ECN]*

Analysis

Figure 5.15 shows that temperature gradients for outdoor inverters are much larger than for inverters installed indoor. The effect is largest for the inverters glued directly on the modules backside.

Temperature difference between module and inverter

Figure 5.16 presents temperature differences between module and inverter distributed over 1 K temperature difference intervals averaged for PV systems with the same integration of the inverter.

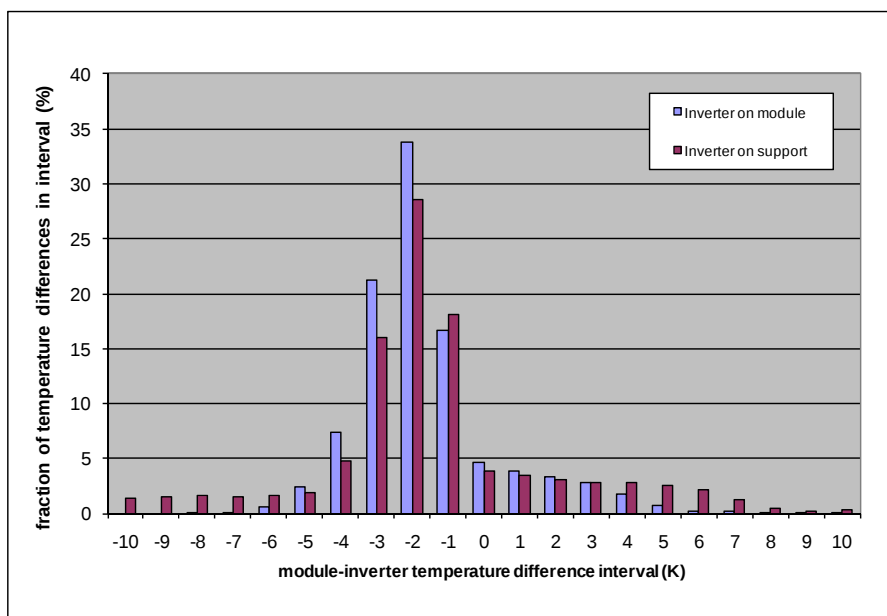


Figure 5.16 *Temperature differences between module and inverter distributed over 1 K temperature difference intervals averaged for PV systems with the same integration of the inverter for the monitoring period from 16 December 2009 to 15 December 2010 [ECN]*

Analysis

Figure 5.16 shows that on average inverter temperature is 1 K higher than module temperature, i.e. for both inverter mounting types. The spreading in temperature difference is somewhat larger for PV systems with inverter on support than for systems with glued inverters. Wind influence may be the reason for that.

6. Conclusions and recommendations

Two different types of PV MIPS systems have been mounted on the roof of two houses at the ECN premises in Petten, the Netherlands, both for getting information on building integration and for measuring the electricity output of the systems. This report focuses on energy performance of the PV systems.

For one series of systems, HV CIS modules were combined with 3-phases IWES/Steca inverters; the other series consist of a-Si modules with 1-phase Delta Gridfit 250 inverters. For both system types, 3 systems have the inverter glued on the backside of the module, 3 systems have the inverter on a support at 20 mm distance from the backside and 2 systems have the inverter indoor as usual.

Measuring period for the HV CIS systems was 15 months and for the a-Si systems 12 months. Apart from one of the 24 a-Si modules, both combinations of modules and inverters have been operating without problems.

Following conclusions can be drawn from the field tests for both PV system types:

1. There is no significant influence of the mounting of the inverter on the electricity output and on the temperature of the PV module. This can be the result of the optimally designed integration of the systems in the roof, with sufficient ventilation between the roof and the modules.
2. Additional, not reported infrared pictures show that there may be a few degrees temperature difference from one module to another due to wind influence. Therefore, accuracy of module temperature measurement should be used with care as only one module temperature sensor per PV system has been installed.
3. For the measuring period, inverters glued directly on the module backside reach the highest temperature i.e. about 60°C, followed by inverters on support. However, differences in temperature between these two inverter mounting types are small. Inverters in the attic get the lowest maximum temperature, however, mean temperature is higher than for the inverters placed outdoors.
4. Temperature gradients for outdoor inverters are much larger than for inverters installed indoor. For the measuring period, temperature differences within the hour can reach to 15 K and over the day up to about 50 K. The effect is largest for the inverters glued directly on the module backside.
5. Average temperature difference between inverter and PV module is 1 - 2 K, both for glued inverters and inverters on support. The spreading in temperature difference is somewhat larger for PV systems with inverter on support than for systems with glued inverters.
6. Performance ratio of HV CIS systems is somewhat higher than for the a-Si systems. Degradation of a-Si systems during the first hour of use, differences in type of inverter and in way of roof integration may be reason for that.
7. A much more detailed indoor laboratory test setup of a complete PV-MIPS system would be needed to reveal the connection between PV system performance and all these system and ambient aspects. In a laboratory (like a climate chamber), unlike under unpredictable conditions outdoor, the boundary conditions can be set. For prototypes of PV systems that are still under development, the laboratory tests should be done first in order to detect the defects and get detailed information on performance and mutual influence factors. The laboratory tests (like speeded up durability tests of PV systems) can save financial means and time for the developing company. Field tests combined with the monitoring shall be done only with a PV system that has withstood the laboratory tests already.

8. When integrating PV-MIPS systems in sloped roofs, special attention should be given to the suitable support construction which allows ventilation of inverters fixed at the rear of the modules. In case of a large roof system, the recommended air gap between roof and inverter is 5 cm, and therefore an air gap between roof and the module of 5 cm + inverter thickness.
9. Large HV-CIS systems are less easy to install since two workers must be present and a crane must be used. This means higher installation costs. Modular a-Si systems with a click fixing to the profiles can be installed by one worker and without crane.
10. In case of a large-scale application on roofs (for example by a housing association on rental houses or in a newly built residential area), the installation costs per system can be lowered substantially (compared to this unique field test).
11. For a better accessibility of inverters in case of a failure, the inverters could be placed at the edges of the modules.
12. The visibility of the module grid should be eliminated as much as possible. The mounting clips and sealing rubber strips of the HV CIS systems disturb the module grid too pronounced.

Findings 1 - 5 above both hold for the HV CIS systems and a-Si systems.

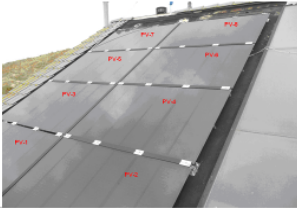
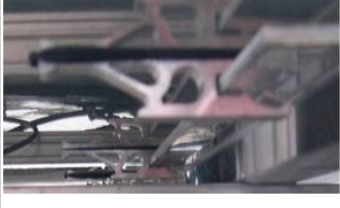
Observation 4 leads to the recommendation of durability testing of inverters in the laboratory. Clear test conditions can be derived from these measurements in practice.

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Appendix A

Overview of the 1st phase field tests at ECN [1]

		PV-MIPS: Phase 1	
Systems at partners:		ECN-1	ECN-2
Technical description	Module type	HV-CIS (3 modules laminated by glass pane in one)	a-Si
	Module designer & manufacturer	Wuerth Solar	EPV
	Inverter (type and version)	3-phases IWES/Steca; version: PCB II	1-phase Delta Gridfit 250 (market version)
	Inverter designer & manufacturer	IWES & Steca	DELTA
	Integrated in (e.g., flat, roof sloped roof)	Building integrated in sloped roof	Building integrated in sloped roof
	Orientation	South	South
	Degree of inclination	30°	30°
	Number of systems	8	8
	Power of the systems	225 Wp	150 Wp
	Total installed power	1800 Wp	1200 Wp
	Photo of systems		
	Integration of inverter / mounting of inverters	3 inverters are on supports that have been glued on the backside of the PV modules, 2 inverters are in attic and 3 inverters have been glued directly on the backside of the PV modules.	3 inverters are on supports that have been glued on the rear of the PV modules, 2 inverters are in attic and 3 inverters have been glued directly on the backside of the PV modules.
	Photo of mounted inverters		
	Wattpeak per inverter	225	250
Monitoring	Mounting system for modules	http://www.click-fit.nl/	http://www.click-fit.nl/
	Installed by	Besseling installation company	partly modules had own brackets already Besseling installation company
	Photo of mounting system		
Measurement results	Temperature sensor	PT-100, Minco type S665, ± 0.12 °C	PT-100, Minco type S665, ± 0.12 °C
	Sensor DC	-	-
	Sensor AC	Power transducer, Camille Bauer,	Power transducer, Camille Bauer,
	Pyranometer	Kipp&Zonen, type CMP21	Kipp&Zonen, type CMP21
Monitoring	Position temperature sensor	Inverter: between cooling rib, PV-module: on back of the module	Inverter: between cooling rib, PV-module: on back of the module
Measurement results	Monitoring period	16-09-2009 to 31-12-2010	15-12-2009 to 31-12-2010
	Failures?	no	one module failed (out of 24 modules)
	Temperature range modules (per installation methode)	Inverter on module: -14,2 - 65,5°C, Inverter on support: -14,2 - 65,9°C, Inverter in attic: -13,6 - 64,1°C	Inverter on module: -12,9 - 64,4°C, Inverter on support: -13,0 - 62,5°C, Inverter in attic: -13,1 - 60,1°C,
	Temperature range inverter (per installation methode)	Inverter on module: -12,4 - 64,3°C, Inverter on support: -11,7 - 59,9°C, Inverter in attic: 15,8 - 52,1°C,	Inverter on module: -12,1 - 62,5°C, Inverter on support: -11,1 - 49,9°C, Inverter in attic: 11,1 - 49,7°C,