PV-WIREFREE:
RESULTS OF PROOF-OF-PRINCIPLE PROJECT AND FINAL SYSTEM DESIGN

Irene de Jong[1], Henk Oldenkamp[1], Esther Hebly[2], Bart de Boer[3], Hugo de Moor[3], Wim Sinke[3]
[1] OKE-Services, Keizerstraat 121, 2584 BD The Hague, The Netherlands, email: oke@euronet.nl
[2] Oskomera Solar Power Solutions BV, PO Box 5, 5750 AA Deurne, The Netherlands, email: esther.hebly@oskomera.nl
[3] Energy research Centre of the Netherlands, PO Box 1, 1755 ZG, Petten, The Netherlands, email: sinke@ecn.nl

ABSTRACT: The PV-wirefree concept was introduced in October 2002 as a new approach for designing PV-systems, aiming at minimizing BOS costs by minimizing components and material, integrating and combining functions and simplifying PV systems design and installation. Within one (sub)system all modules are connected in parallel, at a DC-voltage of less than 22 V. A PV-wirefree system consists only of PV laminates, click-on dual-purpose clamps, aluminum extrusions and an inverter. No diodes, no cables, no connectors, no junction boxes, etc.
In this paper the final design of the three essential components – PV-wirefree laminate, connector and mounting bus - will be presented. These are not only based on test results and economic considerations, but also on new and adapted views on the PV-wirefree concept, as well as the views of the mentioned PV-standards' experts. Next we will discuss the implications, with leading questions: to what extent can PV-wirefree actually contribute to a cost reduction of PV BOS costs and electricity generated by PV, and what is the impact on reliability and safety.
Keywords: cost reduction, reliability, supporting structures

1 INTRODUCTION

PV-wirefree is based on the concept of combining the functions of support or integration with those of electrical connection and current conduction. Within one (sub)system all modules are connected in parallel, at a DC-voltage of less than 22 V. A PV-wirefree system consists only of pv-laminates, click-on-click-off dual-purpose clamps, aluminum extrusions and an inverter. No diodes, no cables, no connectors, no junction boxes, etc.

The main objective of PV-wirefree is to minimize costs of PV-systems and costs of electricity generated by PV-systems. The latter will not only realized by reducing the actual BOS costs but also by increasing the annual energy yield because the laminates are connected in parallel in stead of in series. Paralleling the PV laminates also improves the system output reliability.

An additional advantage of paralleling the laminates is a maximum open circuit voltage of approximately 22 Volts. Thus the system is inherently touch safe, even under extreme fault conditions, for example, a smashed PV module

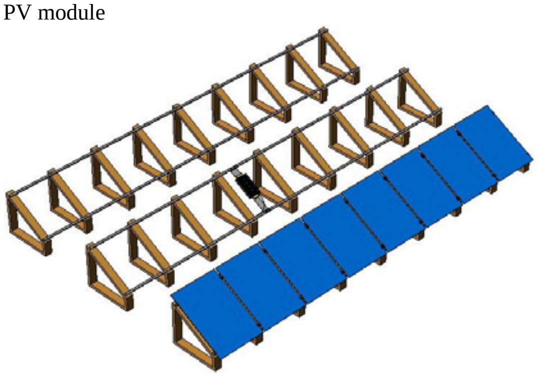

Fig 1: Impression of a PV-wirefree system. First the mounting buses are mounted on a support structure, then the inverter is mounted between the mounting buses, and finally the pv-laminates are clicked onto the mounting buses. All pv-laminates are connected in parallel using a current carrying mounting frame (= mounting bus).

2 PV-WIREFREE COMPONENTS

2.1 Only four components

As explained in paragraph 1, a PV-wirefree system consists of only four components: the laminate, the connector, the mounting bus and the inverter.

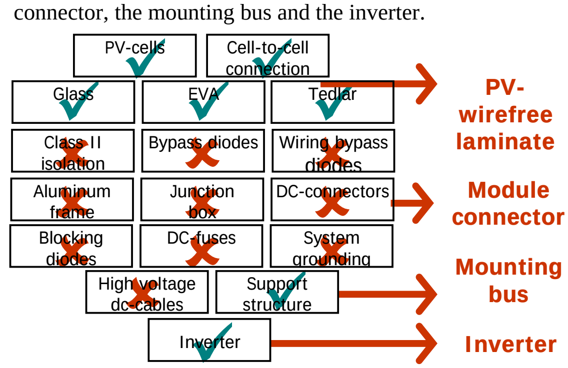

Fig. 2: PV-wirefree consists of only four components

The main reason why so many components can be omitted – compared with a "traditional" PV-system – is that the PV-wirefree laminates are connected in parallel instead of in series. So, firstly no bypass diodes are required anymore, nor its wiring, whereas class II isolation is not needed since the dc voltage remains less than 22 V. Furthermore, the module connector does not only serve as "electrical contact" and junction box, but also as mechanical support for the PV-module, replacing the aluminum frame. Also the mounting bus has more than one function as current carrying mounting frame, replacing both the dc cables and (part of) the support structure.

2.2. PV-wirefree laminate with a 4-points connection

In order to minimize the costs (and energy payback time) of the PV-wirefree laminate it was decided to replace the aluminum frame by a four-points-connection [3, 4]. The question that needed to be answered was, assuming a 4-points connection was feasible, whether it would not have negative (cost) effects for other components. Would for example a 4-points connection imply using thicker glass?

From the general requirements regarding wind loads and maximum stress in glass the following design requirements were defined. First the PV-wirefree laminate should be able to withstand a wind load of 2400 Pa (IEC 61215), while the stress of the glass should not exceed 80 N/mm^2, implying 50 N/mm^2 at a wind load of 1500 Pa. Preferably the weight of the laminate should not exceed 10 kg, which corresponds with an area of about 1 m^2 when using 4 mm glass.

In order to find out whether such a 4-points connection can meet these requirements, as well as to define possible (additional) requirements, extensive Non-linear Finite Elements Analysis (FEA) were executed by Femto. These simulations showed the maximum stress in the PV laminate remains below 78 N/mm^2 at a wind load of 2400 Pa, provided:

- Using mechanically optimized connectors and
- Locating these at the optimum position. The optimum distance between the mounting buses is 51% of the laminate length.

The FEA also showed that an optimal PV-wirefree laminate with 4 mm glass thickness can be realized for most types of crystalline cell dimensions:

- 125 x 125 mm^2 → 5 x 7 cells → 0,632 m^2 → 87 Wp @ 16%
- 150 x 150 mm^2 → 5 x 7 cells → 0,889 m^2 → 126 Wp @ 16%
- 200 x 200 mm^2 → 4 x 5 cells → 0,893 m^2 → 128 Wp @ 16%
- 125 x 125 mm^2 → 6 x 8 cells → 0,854 m^2 → 150 Wp @ 20%

To verify and validate the results of the FEA, laboratory tests are executed by ECN, which proved that the bending of the laminate predicted by the FEA matches closely to the results of the laboratory tests.

So, based on the FEA analysis and the laboratory measurements, it can be concluded that indeed a 4-points-connection is feasible, and can replace the aluminum frame without increasing the thickness of the glass.

Fig. 3: Photo of laboratory test setup at ECN to verify and validate laminate bending predicted by FEA

2.3 Connector

The PV-wirefree module connector replaces the junction box and the PV-module frame. So it should provide mechanical support for the 4-points connection, be strong enough to withstand the wind loads at the PV-laminates, and electrically connect the PV-laminates to the mounting bus.

Tha main concern regarding the connector was the electrical contact. Could a reliable electrical contact be made between the aluminum mounting bus and the PV-laminate with a lifetime of at least 20 years? It should be noted that aluminum is a difficult material for establishing an electrical contact.

However, Multi-Contact developed a solution which was tested both in the laboratory and during a 5 months period at the ECN test site. The results are presented in figure 4 and show that the contact resistance remains stable, which implies that indeed the contact meets the set requirements.

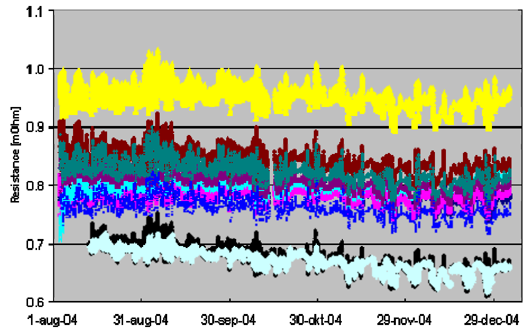

Fig. 4: Contact resistance of tested contacts over a 5 months period

2.4 Mounting bus

The mounting bus – short for current carrying mounting frame - replaces the high voltage dc-wiring and the support structure. So, the mounting bus should be strong enough to carry the weight of the PV-laminates and the wind load on the PV-mdoules and at the same time have a cross area sufficient to carry the current of the PV-wirefree subsystem. The material should be suitable to provide a reliable electrical contact.

To select a proper material three options – copper, steel and aluminum - were compared regarding costs, energy content, etc. Though at first glance steel seemed to be a good choice, aluminum showed to be far better since its costs per amount of conduction is lower than that of steel and copper, while also its energy content per amount of conduction is lower than of steel. Moreover, aluminum is a common building material and can easily be extruded in virtually any shape. Therefore aluminum was selected as material for the PV-wirefree mounting bus.

The profile should be rugged and thick enough to withstand mechanical loads from the PV-modules.. Calculations and tests have shown a cross section of approximately 120-150 mm^2 aluminum is strong enough to carry the PV modules and to safely conduct hundreds of amperes. Using this profile the maximum PV-wirefree subsystem size is approximately 3-4 kW for the 5 x 7 cells laminates and 1 kW for the 4 x 5 cells laminates. The aluminum used is 0.67 kg per module, resulting in a energy payback time of 2 months (5 x 7 cells, 150 mm) at 1000 kWh/year/m^2.

3 STANDARDS

3.1 Introduction

In an earlier stage of the PV-wirefree project it was already concluded meeting existing PV-standards might become a problem, simply because PV-standards do not include the option of paralleling large numbers of PV-laminates. Therefore it was decided to approach UL and TÜV and ask for their opinion about the concept, and especially regarding which standards and/or PV-wirefree components they perceived contradictions, and thus possible future problems.

3.2 UL

In first instance UL was rather skeptical which is illustrated by the following quote from the UL report “Preliminary investigation of PV-wirefree system” of 11 December 2003:

> *“It appears that the nature of the PV-wirefree system will not satisfy some of the most basic construction, bonding and grounding requirements of UL 1703, UL 1741 and the conventions of the NEC [USA’s National Electricity Code].”*

But after discussions by email, in which the concept in more detail was explained, UL redefined their statement. The Updated UL report “PV-wirefree system” of October 2004 states:

> *[...] it was initially determined that compliance with these standards [UL 1707, NEC en UL 1741] was not likely without major changes. However, following the in-dept study of the PVWFS and similar concepts, we have determined that UL can provide Listing under the category QHYZ, AC modules or QIJL for Photovoltaic Power Units.*

3.2 TÜV

On 6 September 2004 a workshop was held at TÜV Rheinland, Köln in Germany, in which the PV-wirefree concept was extensively discussed as well as possible discrepancies with existing PV-standards. TÜV concludes in its report “Statement on PV- System Concept PV-Wirefree” of 6 December 2004:

> *To summarize it can be established that, under consideration of the restrictions stated [..], there are no fundamental reservations or objections to the utilization of the PV-wirefree system.*

The mentioned restriction(s) are that both the mounting buses should be isolated (e.g. painted or coated), and of course, the separate components should meet the applicable standards

4 OTHER ADVANTAGES OF PV-WIREFREE

4.1 Increase of energy yield

In order to verify whether the assumption that parallel connected systems (like PV-wirefree) will produce more energy due to less influence of partial shading, extensive tests were executed. A test rig was set up where, by means of relays, the module interconnection could be changed from parallel to series instantly. An automatic measuring system continuously measured and logged the complete I-V curve of the system and a web cam was used to provide pictures of the actual shading conditions. Measurements were executed over a period of several months under different shading conditions varying from virtually unshaded to partially shaded. The results show a significant increase of output ranging from 2 to even 400 % for the parallel connection. An overview of the results are presented in Table 1, and for more details we refer to the paper presented at 19th EPSEC, June 2004, Paris [5].

Condition	Very lightly shaded	Lightly shaded	Moderately shaded
Energy gain minimum	2-5	10-20	10-50
Energy gain practical	5-25	10-40	30-400

Table I: Increase of energy yield [%] parallel connection compared with series connection.

Besides the higher output PV-wirefree offers additional advantages for inverters. First of all, inverters can have a significantly narrower input voltage window. The reason is that in a PV-wirefree system the inverter input voltage does not depend on the number of PV-modules on one mounting bus, while the string voltage increases proportionally with the number of modules in the string.

Additionally a PV-wirefree system has a clear well defined maximum power point which is more or less independent of the shading conditions while the maximum power point voltage of the string will vary considerably under partial shading conditions. Moreover, under these conditions the string will usually show multiple local maxima. Therefore the MPP tracking efficiency of a PV-wirefree system will always be better than this efficiency in a comparable PV-string. Note that inverters with a narrower input voltage range can either be more efficient or can be more cost effective.

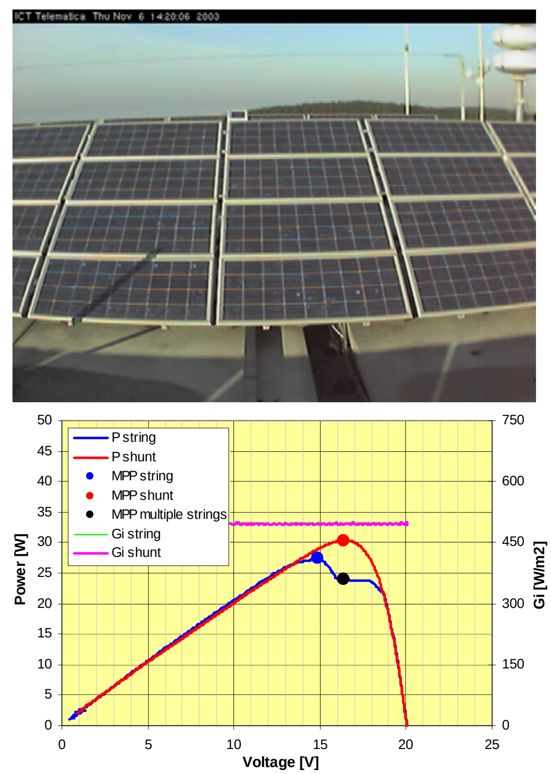

Fig. 5: Photograph and P-V curves of lightly shaded PV-system. The blue line represents the P-V curve of a system in which the PV-modules are connected in series, the red one of a PV-wirefree system in which the PV-modules are connected in parallel. Note that the P-V curve of a string has more local maxima.

4.2 Improved system output reliability

In order to explain the difference in system output reliability of a PV-wirefree system and a PV-system in which the PV-modules are connected in series, we refer to a generally known example: Christmas tree lights. A PV string system is comparable with "Christmas tree lights": if one fails, none of the lights will glow, and it is hard to find which one has gone. So, if any single PV-module in a string system fails, the entire string will not deliver its power to the grid. And it is tough to find which PV-module is not working properly. If a single PV-module in a PV-wirefree system fails, it will not affect the output of the other PV-modules.

So, though the failure rate of the individual PV-modules is the same, the impact is dramatically reduced, and is calculated at a factor 8-25, depending on the size of the strings that are being used.

4.3 Decrease of energy pay back time

A study into the energy pay back time was executed by Erik Alsema of the Utrecht Centrum voor Energieonderzoek (UCE), The Netherlands [6]. In this report an environmental Life Cycle Assessment (LCA) is made of advanced production technologies for crystalline silicium modules in comparison with the existing production technology. Among the investigated technologies are Solsilc solar-grade silicium, Ribbon-Growth-on-Substrate and Edge-defined Film-fed Growth. Also an assessment is made of new solar inverter types and novel roof-integration concepts, like PV-wirefree. Based on these analyses potential improvements in the environmental profile of photovoltaic systems are evaluated. Also energy pay-back times and CO_2 emissions of the considered PV systems are calculated. One of the conclusions of the study is that the energy pay back time of a PV-wirefree system is 15%-20% less than of a comparable 'conventional' PV-system.

5 CONCLUSIONS

The PV-wirefree project has shown that PV-wirefree is not only feasible, but actually can "be made". So, a considerable reduction of the number of components is possible. And thus also a considerable cost reduction can be achieved.

The BOS cost reduction (excl inverter) is estimated at € 1025 - € 1200 per kW, which agrees with:

- 68% - 80 % of BOS costs (excl inverter)
- 17% - 20% of total system costs (2003, Nld)

Besides the BOS costs reduction PV-wirefree also offers:

- Increased energy yield: 5% – 20%
- Improved system output reliability: factor 8-25
- Decreased energy pay back time: 15-20%

And last but not least – probably most important – despite the perceived conflicts with existing standards, PV-wirefree is acceptable for TÜV and UL.

6 REFERENCES, PARTNERS, INFORMATION AND ACKNOWLEDGEMENTS

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6.2 Partners of the PV-wirefree project

In the PV-wirefree project partners from different background participated: Bear Architects, Energy research Center of the Netherlands, OJA-Services, OKE-Services, Oskomera Solar Power Solutions BV and TNO Bouw. Multi-Contact is developing the PV-wirefree connector.

6.3 Information

For more information visit www.pv-wirefree.com, with nice animations of shading effects on the P-V curves of shunt and string systems.

6.4 Acknowledgements

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