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Solar PV Shingle Sunplicity ™

Building integrated PV Element - 100% compatible with conventional roof system

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Photo on the front page:

Figure 1 on the front page shows the test site at Laboratory of Energy, Ecology and Economy (LEEE-TISO), Lugano, the south of Switzerland. Final tests had been performed at this test site because of the excellent infrastructure and the higher solar radiation and ambient temperature.

Content

Summary

SUNPLICITY^{TM} is a new solar building element for tilted roofs. It has been designed, built and successfully tested in a combined effort in an industrial partnership between three Swiss and one US based company. Four test set-ups have been built and evaluated to optimise integration, design and electrical interconnection. The first one in Zürich was to prove feasibility, the second one in Rickenbach was to evaluate potential roofer's concern, the third one in Schwyz to optimise cabling and interconnecting issues and the fourth and final one at LEEE in Lugano to measure and evaluate expected temperatures in comparison with rack mounted PV modules. The temperature histogram over a given period was used to extrapolate expected lifetime of the plastic material and potential energy losses to the particular integration.

SUNPLICITY^{TM} fits in every conventional roof built from fibre cement shingles, which are widely used in northern Europe. Its dimensions are exactly identical to a conventional shingle, not only both in length and width, but also in thickness. The new solar roof shingle is absolutely plane and flat, as is a normal fibre cement shingle. The integration into existing roofs is therefore very straightforward: wherever the roofer wants solar shingles, he replaces conventional shingles with the new solar shingle Sunplicity. Even the electrical connections are in the same plane. A new interconnection design provides safe and reliable cabling of the PV array formed by the solar roof shingles.

Two new polymer materials were used for the roof tiles. These were a non-EVA encapsulant and a backskin material that served as the edging for the tiles and also allowed for integral bonding of the wires from the module. Early problems included delamination of the encapsulant from soldered bus bars, bond strength of the backskin edging to the glass, and forming a secure connection within the module of the internal leads in the module with the external leads that were integrally bonded to the backskin. In work either concurrent with the time of the project or soon afterwards these issues were all successfully addressed. The one remaining question is the cost of the backskin material. This needs to be investigated further.

1. Introduction

The technology for the PV cladding of facades and roofs is well demonstrated. However, much work remains to be done on improving designs for simpler installations, improved aesthetics and reduced costs. The initial reason to use PV in buildings is to generate electricity, and the main driver is the use of renewable solar energy to achieve a sustainable, environmentally benign energy supply. In addition, PV modules in buildings may well serve for other purposes such as shading elements, wall cladding, or roofing material. The use of PV modules for roofing system is especially attractive, because the roof represents an idle support structure for PV. This reports presents the result of an extensive research program, where a very promising building integrated PV Element for roofs had been developed.

Such PV elements are - by the nature of their use - designed and manufactured for outdoor use. PV products are suitable for long term exposure to sun, rain and all the other climatic impacts. And, PV modules generate electricity without any moving parts. This makes PV modules suitable for building integration and offers a huge potential for the PV industry. Still, most PV modules are designed as conventional, aluminium framed glass substrates for a stand-off fixture rather than as building elements that will substitute building skin material in larger quantity.

The roof of a building offers the best options for large scale application of PV module integration in buildings: roofs are mostly exposed to sun, not competing with other usages, and have the highest solar irradiance from all building surfaces. In Switzerland, for example, PV modules mounted on roofs are generating over 30% more energy than when mounted on vertical facades. Further south, the difference is even larger and favours the integration onto roofs. However, cost effective integration of PV modules on roofs is much more difficult than for facades.

1.1 Innovations in conventional building sector

The building sector has, for many years, been rather conservative, and new designs or materials had large difficulties in finding their ways into the building industry. It is only in the last few years that the pace of Innovation has accelerated. This is especially true for building facades, where today, at almost every building material show, new facade systems are presented. On the roof, however, real innovations are very rare. Large scale introduction of steel metal sheets for industrial building roofs has probably been the biggest innovation in the roofing industry in the last century. The question, then, is why are there so many innovations in the facades, whereas the systems on roofs hardly change from decade to decade? Are roofing systems highly optimised, while facades are not?

In terms of costs, this may - to some degree - be true. Table 1 summarises some of the costs for roofing and facade system. Cost figures are estimates, and given in Swiss Francs per m^2 of installed "skin" -material, including labour to install it, but excluding any support structure of the building for fixing this "skin".

Roof	Normal tile	25 - 40	Range comparison
	Fibre cement	50 - 70	
	metal sheet	30 - 40	
	Copper	50 - 70	
	Well Eternit	30 - 40	
	Average		30 - 100
Facade	Normal brick wall	50 - 60	
	bonding plates and plaster	80 - 100	
	Eternit fibre cement	100 - 130	
	Glass	200 - 400	
	Ceramic, Stone, marble	250 - 1000	
	Average		100 - 1000

Table 1 shows estimates for roofing and facade costs for different materials. Roofs are, on an average, roughly 10 times cheaper than facades per m^2. This may also contribute to the fact that innovations in the roof area are exremly rare. Roofs are looking the same from decade to decade (Source W. Müller, Gebr. Müller AG).

Table 1 shows that roofing material is about tenfold cheaper than facades and this suggests several possible implications:

- The possible amount of cost savings through Innovation is much smaller for a roof than for a facade. In fact, the market for facades is about three times as large as that for roofing materials. This makes it more attractive to make innovations in the facade market.

- Facades are more visual and therefore architects pay more attention to them. This is especially true when considering that 1/3 of buildings are flat and another 1/3 of buildings, such as industrial buildings, are not sensitive to visual aesthetics,

- Roofing systems are highly optimised, and the facades are less so.

- Once they have reached the same degree of optimisation as conventional roofing systems, it may eventually be cheaper to install PV systems on the roof, Whatever the reasons may be, it is important for the nascent PV industry that wants to explore the potential for roofs to be aware that the sloped roof field is conservative, and innovations in this market have been rare.

This is also very often reflected by the official authorities, who have to judge the aesthetic appearance. Especially in older towns, this is a sensitive issue. Roofs are well protected, although in most medieval cities in Europe, the old substance on first floor level - where it is most visible for all visitors - has long been replaced by very modern materials that are designed to mostly fulfill the needs for modern shops. It will, however, take a long time before the need for a sustainable energy supply will be strong enough to replace the old roofing material by systems that generate environmentally benign energy.

There is a whole set of specifications for PV roofing systems which should be fulfilled in order to meet cost, building and aesthetic requirements.

2. Requirements for PV roof tiles.

A roof is an important and complex element of a building, and its requirements are very severe. Figure 1 shows an overview of the elements that may impact the design of a future PV roofing design. In the following, these requirements are listed generically.

Weather requirements.

- Waterproof protection against rain, snow, and ice water
- Inclination, water quantity, and velocity
- Damming up water
- Snow, ice, hail
- Heat
- Thermal cycling
- Frost and moisture
- Wind
- UV resistance
- Sunlight reflection
- Wind noise avoidance
- Noise barrier
- Allowance for vented cooling effects

Fire requirements.

- Fire resistance
- Satisfying local codes
- Satisfying national codes
- Satisfying international codes

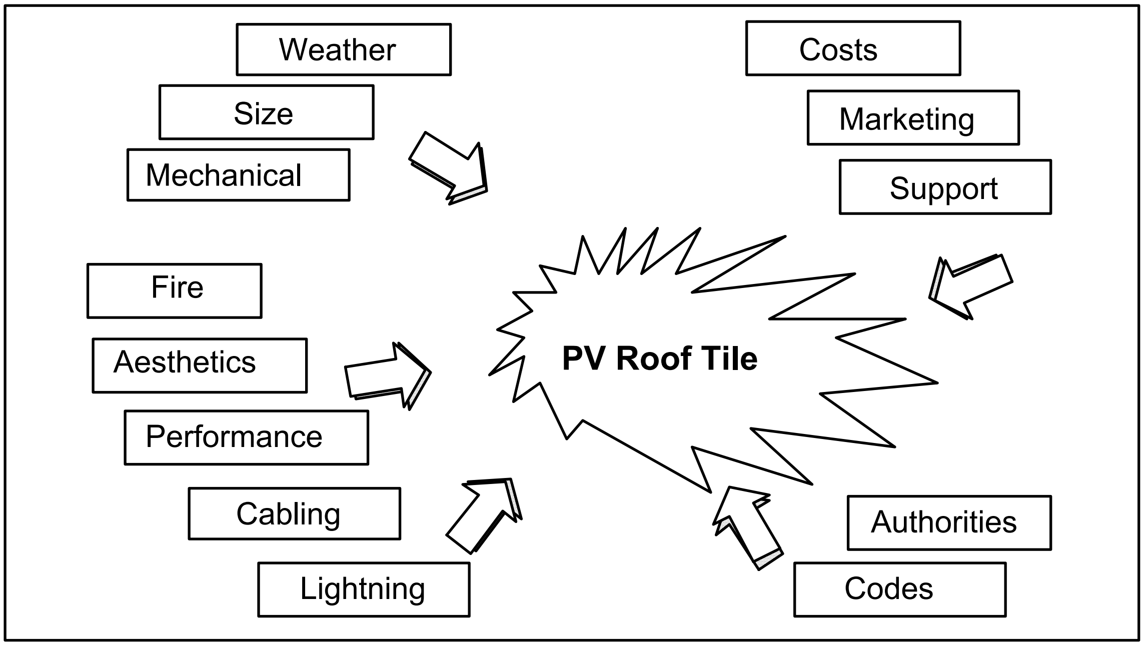


Figure 2 shows the basic elements which are influencing optimised PV Roof designs.

lightning protection requirements.

- Earthling
- Grounding
- Lightning protection
- Frameless/metal framed modules
- Local codes
- National codes
- International codes, IEC

Cabling requirements.

- Number of contacts
- Cumulative series resistance
- Diodes
- Easy installation
- Fail proof
- Easy replacement

Mechanical, Structural requirements.

- Integration
- New building/retrofit
- Replacement of modules
- Interfaces to other parts of roof
- Easy handling, size, weight of each unit
- Structural stability

- Resistance to internal and external loads
- Durablity, low but easy maintenance, Vandal proof

Plastic material.

- Optimal for processing/manufacturing
- Injection mould, casting, etc.
- Weather resistance, UV
- Mechanical strength
- Potential to apply colouring agent, dye
- Fire resistance
- Long-term stability

Performance requirements.

- Shading
- Temperature
- Cable losses, number of contacts
- Mismatch, number of elements

Support requirements.

- Manuals
- Tests
- Training of installers

Marketing and pricing policy requirements.

- Who is going to install (roofer, specialist etc.?)
- Selling channels (PV experts, normal building material?)
- Architects
- Other market forces
- Costs, prices

Visual requirements.

- Aesthetics
- Colours
- Size
- Sunlight reflection
- Optical appearance

Cost requirements.

- Generic roof tile design versus individual solutions
- Standard design versus versus costs for individual engineering
- Labour costs
- Low interfaces costs with other roofing material

3. Design of Sunplicity ™

3.1 Specific requirments for Sunplicity

Sunplicity is designed to be truly roof integrated. Roofing elements are traditionally small by size, and the roof is covered by using literally hundreds of these roofing elements, typically about 10 per square meter. In general, designers of roof PV elements are confronted with this basic issue:

(i) To become truly identical with an existing, market established roof element, the PV roofing element has to be the same small size. And this has implications on manufacturing and inter-cabling costs. On the other hand, the benefit is a PV building element, which requires almost no training of roofers, no planning, and no specialist for PV.

(ii) Or, as a compromise, to use modules which are much larger than normal roofing tiles. This seems to have clear cost advantages, at least for the initial market where volume is still small. With this approach, module sizes are often sized to be a multiple of the existing roof dimensions.

Sunplicity makes no compromises. It is designed to be absolute identical in every dimension and in its mounting and handling features to an existing, market-established fibre-cement shingle, manufactured by the market leader Eternit.

Sunplicity history goes back a long time. However, many elements had first to be developed before being able to finally realize the initial concept:

(i) Conceptual design of Eternit shingle compatible PV roofing element in a design study on behalf of State of Zürich (Draft report Alpha Real, 27. February 1989)

(ii) Rack built proof-of-concept by Alpha Real Ag and Glas Trösch Solar AG in Ursenbach, evaluating the mechanical issues of PV shingles identical to exisiting Eternit roof shingles on a full size test set up, in collaboration with local roofers (Spring 1992).

(iii) First prototypes using Evergreen’s innovative encapsulant techniques. This was the missing element to take the concept from feasibility to reality.

(iv) Project approval for support by the Swiss Federal Office of Energy in May 2000.

(v) Final report in November 2003, with (almost) all elements developed and proven for market entry.

Figure 2 shows the layout of Eternit shingles on a roof. The roof becomes water-tight because the shingles overlap. Since these types of roofs are very robust, they are often used in areas with heavy snow or wind loads, such as in the Swiss Alps. The large fraction of overlapping makes the design somewhat more expensive with competing designs, which do achieve waterproofing by a interconnection design, that requires less overlap. The large fraction of overlap in a purely flat shingle implies that more material is used to make the roof.

This may also contribute to the fact that the fibre-cement shingle is somewhat more expensive than conventional roof clay tiles and therefore has never succeeded in getting a larger market share. We estimate the market share of roof shingles to be around 15% for Switzerland. The manufacturer has tried to overcome this inherent disadvantage of higher initial price structure by adding more to the architectural merits. Furthermore, various designs and different colours for facade systems have been added. Since shingle are by nature flat, the project team from Sunplicity has tried to match this roofing element, because glass covered solar modules are by nature also flat.

In order to achieve the goal and to make a solar roof shingle absolutely identical in dimensions and handling to the existing roof shingle, the following subtasks were formulated and worked upon:

(i) Optimise size of Sunplicity with regard to the shingle size (identical, multiple dimension of actual cement fibre re-enforced shingle used in the marketplace)

(ii) Design and built prototypes, using Evergreen innovative frameless encapsulant method, and also introduce methods of potential mass production methods

(iii) Design a new inter-cabling design, which is suitable for being used in the harsh environment of a roof and is cost effective. That is, an affordable PV shingle that has to compete with systems using larger PV modules. Larger modules use fewer contact elements than that of a roof integrated element, which is based on many small PV elements.

(iv) Build various test set-ups in different environments, to understand the real need for roofers and practicability of the new PV roof shingle. This proved to be extremely helpful in evaluating the low cost inter-cabling design and instruction manual for installation.

(v) Long term test stand at LEEE in Lugano to evaluate temperature and long-term outdoor behavior over one year.

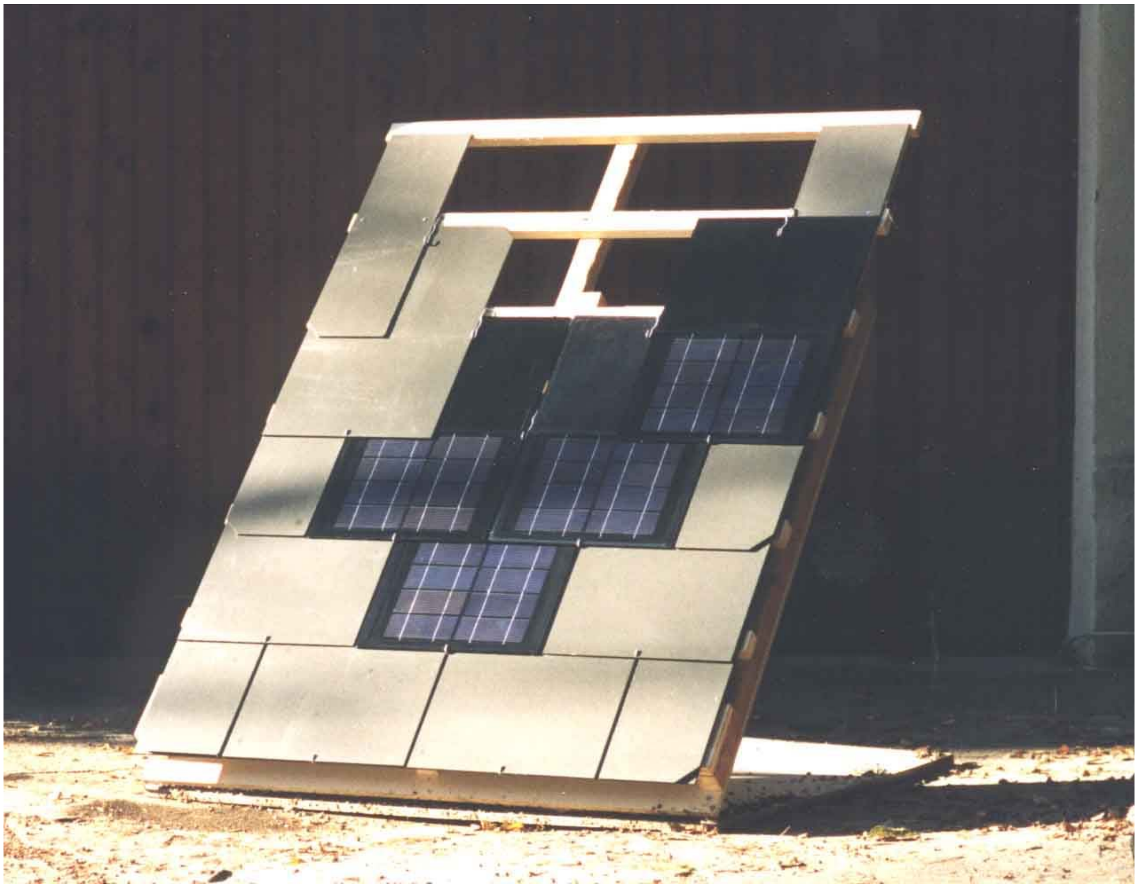


Figure 3 shows the first test stand to demonstrate proof of concept and evaluate the new lamination technique for the PV roof shingle. The PV shingles had no electrical interconnects. The concept was evaluated by architects and roofers to test their reaction. This was very positive and encouraged us to proceed with the project.

In a first phase, an initial design was elaborated. Using this design and concept, Evergreen made prototypes. First goal was to learn whether the new lamination concept together with the design features would result in a PV roof shingle that looks promising both for the roofer as well as for the architect. A first proof of concept test stand was set up.

At this time, no issues on interconnecting wires were considered, and the PV roof shingles were simply just dummy modules that in mechanical and optical characteristics would be as close to the final solution as possible. Figure 3 shows the lay-out of the first test stand, built at the premises of Alpha Real in Zürich. Roofers and architects were invited to comment.

3.2 Layout and size of Sunplicity ™

The market on conventional fibre shingles have various shingle sizes. Eternit, the market leader for such shingles, has for many years promoted the standard size of a shingle which is 40 cm wide and with a length of 60 cm. In mountain areas, where snow and wind loads are extremely high, a smaller standard type of 40 by 40 had been used.

It is clear that the smaller the standard size, the more "hidden" roofing material is overlapped in the roof, which has a direct impact on the roof costs. To make the tile more cost competitive with other clay roof tiles, the market leader Eternit introduced a new size of 72 by 40 cm, thus reducing the overall material used in the roof and therefore also the cost.

The amount of overlap by itself depends on the tilt angle. Steeper roofs need less overlap to make the roof water-tight. Since the overlap ratio directly impacts the material used and hence the costs, a minimal overlap should be achieved, but still maintaining the water-tightness of the roof.

After careful cost evaluation, the dimensions of Sunplicity were fixed at the standard size of 72 by 40 cm. Larger sizes would be favourable in terms of cost, but several roofers expressed their concern in terms of long term durability and stiffness when using the identical roof support structure. The market name for the Eternit shingle to be used in conjunction with Sunplicity is "Linea", with the following data:

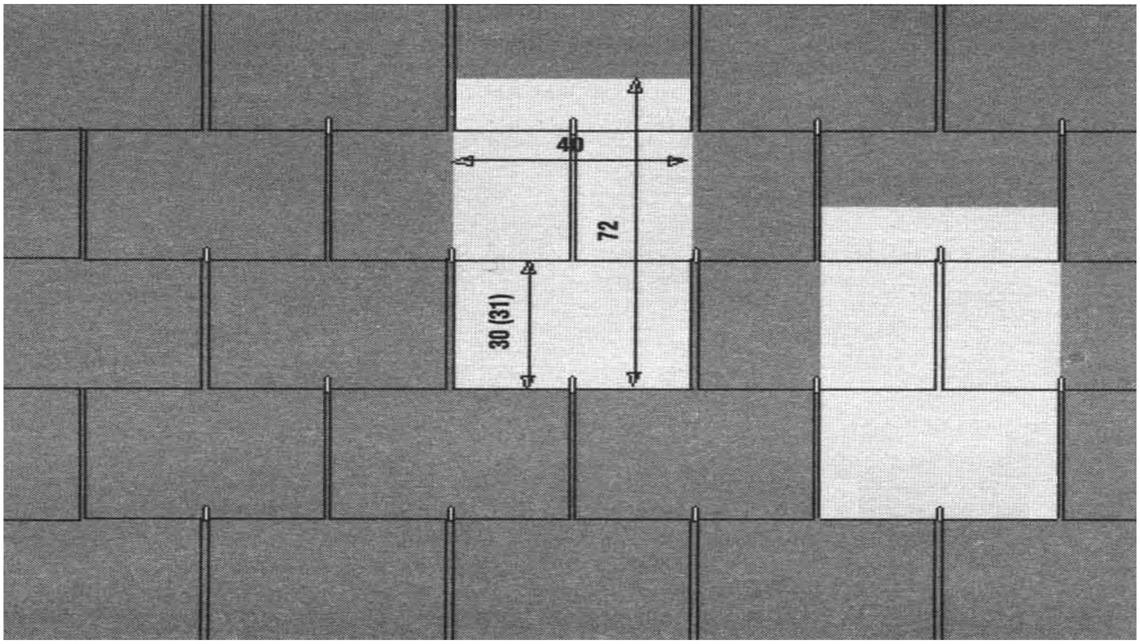
Roof tilt angle	Overlap (cm)	Weight (kg/m^2)	# shingle/m^2	Shingles packing
> 18 Degrees	12	24,3	8,2	300
> 30 Degrees	10	23,7	8,0	300

Table 2 shows the mechanical specifications of the roof shingle which had been adoppetd as the design base case for sunplicity. Sunplicity will be used in conjucntion with or in place of fibre cement conventional shingle of 40 by 72 cm (Source Eternit Instruction Handbook)

One issue which is not an easy one and which has not a straightforward answer is: The amount of surface area of the roof tile actually exposed to the sun. The overlap defines how much "free" space is exposed to the sun, and hence how much free space can be used for the solar cells.

Unfortunately, this is not a fixed value, as can be seen from the table above. The design of Sunplicity has been made for the case for roofs with a low tilt angle. This means less free space to be used, and therefore less power per tile, and hence higher specific costs. In steeper roofs, however, the overlap will become larger, and a 2 cm wide area will not be covered with solar cells.

From far, the visual impact will be almost zero, but the 2 cm represent a 7% loss in unused space. Once market volume will pick up, however, this could be easily adapted by introducing two different models of PV roof shingle: one for roof tilt angles above and one for below 18 degrees. In Figure 4 are shown some of the key dimensions for a roof tile installation.



Figur 4 shows the layout of the shingle in a roof. The design default used for further work is 40 by 72 cm fibre cement shingles. Overlapp is 12 cm, which allows covering roofs with all tilt anlges (Source Eternit Handbook).

3.3 Inter-cabling

Inter-cabling refers to the electrical circuit needed to interconnect all the individual solar PV shingles to a combiner box or an inverter. Each module has a power level of only roughly 10 watt, which makes it hard to come up with a cost effective and reliable solution. Various test runs with roofers under actual installation situation demonstrated that only a simple, fail-safe inter-connection could be envisaged.

The low power generated per plug, and also the fact that the plug most likely will never be used more than once for the initial installation, makes plugs just too expensive. An ideal tool would be something that would permanently solder or crimp the two wires together. Unfortunately, this tool does not yet exist, but it is maybe just a question of time until such a tool will be developed.

The new lamination procedure from Evergreen Solar allows also the integration of pig- tails. Pig-tails refer to a wire or wires that come from the module and are integrally bonded to the module in the lamination step. In close cooperation, an interconnecting system had been developed based on the following points:

(i) The cable connection to the shingle is of a "pig tail" type. This avoids expensive module inter-connection or even worse: junction boxes.

(ii) The cable outlet will be at the top of the module. There, the module is protected against water and other environmental influences from the outside overlapping shingle. The pig tail will come out horizontally in order to avoid droplets of moisture moving along the cable.

(iii) The two pig tails are close enough to allow the inter-connection with the bypass diode. Such a diode had been evaluated and tested.

(iv) Six shingles are interconnected into a mini-string. Each side of such a mini-string is coupled to the next one by means of a plug.

(v) The mini-string is factory assembled, and packed in an easy to handle package. Various tests, in simulation on test stands and once on a roof, confirmed the practicability of the concept. The speed in installing the roof is comparable with that of conventional cement-fibre shingles.

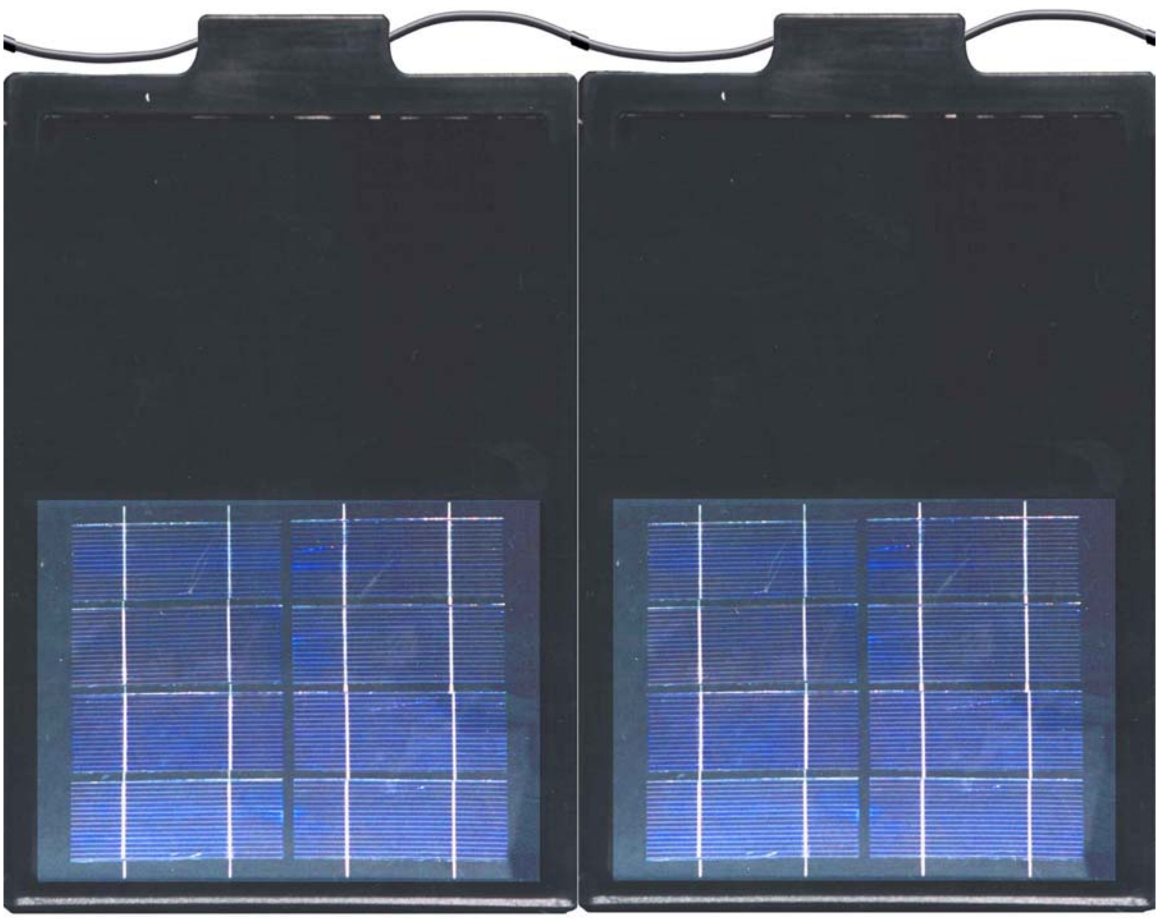


Figure 5 shows two solar shingles Sunplicity. Clearly visible is the upper, overlapping part, and the lower section, which allows for integrating the solar cells. Furthermore, the integration of the entire shingle is shown, using Evergreeen Solar advanced encapsulant procedure. Of particular interest is the construction detail of the pig tail inlet. The pig tail is on top of the module in order to avoid water infiltration. The interconnection, on the photo still shown with a factory made crimp, will be replaced by a single cable.

The interconnection design with pre-wired strings was then tested on a 2nd generation test stand. Here, not only mechanical and optical properties were evaluated, but also the inter-cabling issues. Figure 5 illustrates two roof tiles with pig tails.

3.4 Replacing broken PV roof shingles

Although broken PV roof shingles are most likely to be rare, it is essential that the design and the cabling allows for a procedure to replace non-functioning roof shingles with new ones. The following procedure was developed and evaluated :

(i) Open hook at the bottom. The roofer has a special tool to do this, and it is a common procedure. It was impressive to see how the roofer works with the hammer close to the PV solar shingle. But this must be expected if the new solar roof tile design is to allow actual construction procedures, with not much more attention than is given to other materials on a construction site.

(ii) Slide down the module. To do so, the cable length between the shingles has to be 105 cm long. This long cable looks untidy when in place, because there is more cable than is used for a straight inter-connection, and hence the cable makes large loops, visible from under the roof.

(iii) Cut inter-connecting cable.

(iv) Replace new module, splice cables, for example with crimps. Since it is expected that this replacement procedure will be seldom used, a somewhat more elaborate connecting procedure would be allowed here.

(v) Slide module back, using a flat, specially formed metal sheet to avoid that cables get twisted with roof battens.

(vi) Restore hook, or even better, replace by a new hook before sliding back.

The procedure had been successfully tested various times. Replacing broken solar shingles is not only feasible, but even fast and easy. However, this needs some instruction, more than the normal installation of the Sunplicity shingles.

Installation is straightforward and not different for the roofer than if he were installing Eternit roof shingles. Replacement is also basically identical to the replacing of normal cement shingles, except for the cable. This needs special attention to the following issues:

(i) The sliding down is easy, because the cable is long enough to slide down. But the roofer has to know when he has to stop, and not just keep pulling when the module is almost down.

(ii) Cutting the cable and splicing the new one is delicate, because here the work is carried out under live voltage. Strings must be isolated from the rest of the installation, which requires an electrician, or an otherwise well instructed person. If string voltage is high, and cutting and splicing the cable is needed, then this is working under live voltage and requires an electrician.

(iii) Replacing the modules by shifting it up is a little bit more complex because it requires a metal sheet, which needs some instruction in how to handle it. It is easy for a roofer to understand, but it is not self-explanatory.

In the case where the nominal voltage is high, or working under live voltage conditions is not feasible because no such trained person is available or ready to go onto the roof, an entire string may be replaced by just using the normal plugs at the end of each string. These plugs are touch proof, as it will be defined in the new IEC draft 62093.

A new test stand was chosen for this purpose in order to involve new roofers, with different inputs and different comments. Figure 6 shows the test installation where the major issues of the interconnection optimisations were studied.

Figure 6 shows the test stand at the premisis of the roofer Georg Acherman in Schwyz. The test set up was to evaluate changes and the interwiring concept. The shingles were modified to the choosen size of 40cm by 72cm. The test stand allowed easy checking of the cabling at the back side of the modules (Source G. Achermann, roofer, Schwyz)

3.5 Module temperatures

The module temperature is different from that of free- standing rack mounted modules. This is important for two reasons:

(i) The higher module temperature has a negative impact on energy production, as it is now well understood and documented in various publications and international (draft) standards.

(ii) The higher temperature can potentially have a negative impact on service life time of the plastic materials used for the encapsulation of the solar PV shingle Sunplicity. However, extensive in—house testing at Evergreen Solar using an environmental chamber under thermal cycling of +90°C to –40°C has indicated that the polymers used should hold up well. Also, long term U.V. exposure tests have indicated that the encapsulant will have a very long service life.

Temperature has been measured at the test site at LEEE in Lugano, which has a test stand well equipped to do such measurements. The temperatures are recorded every few minutes. The precision is +/- 1 degree C.

Five temperature sensors have been incorporated at different areas in the test array. LEEE did sent their sensors to the shingle manufacturer Evergreen to incorporate them into the roof shingles during the fabrication of the prototypes. The sensors are not directly in contact with the backs of the cells, but bonded onto the backskin on the inside of the modules. The difference is estimated to be max 2 degrees from state of the art integration of such temperature sensors, which normally contact directly the rear of the cells. Results are shown in Figure7.

The following results are derived form the measurements:

(i) Histogram of temperatures over one year. This histogram gives an indication, of how many hours such an installation would run on a given temperature for a site such as Lugano. These values are plotted for various temperature sensors incorporated at different locations on the array. The differences between such different locations of temperature sensors are very small, as can be seen on the figure, and can be neglected. On the other hand, the difference with a free standing rack mounted module is also plotted. Note that there is a difference.

(ii) This data are compared with data given from NREL on a similar test stand, given also as histograms in the appendix. As a worst case, a test set up with high thermal isolation on the back is shown as a reference.

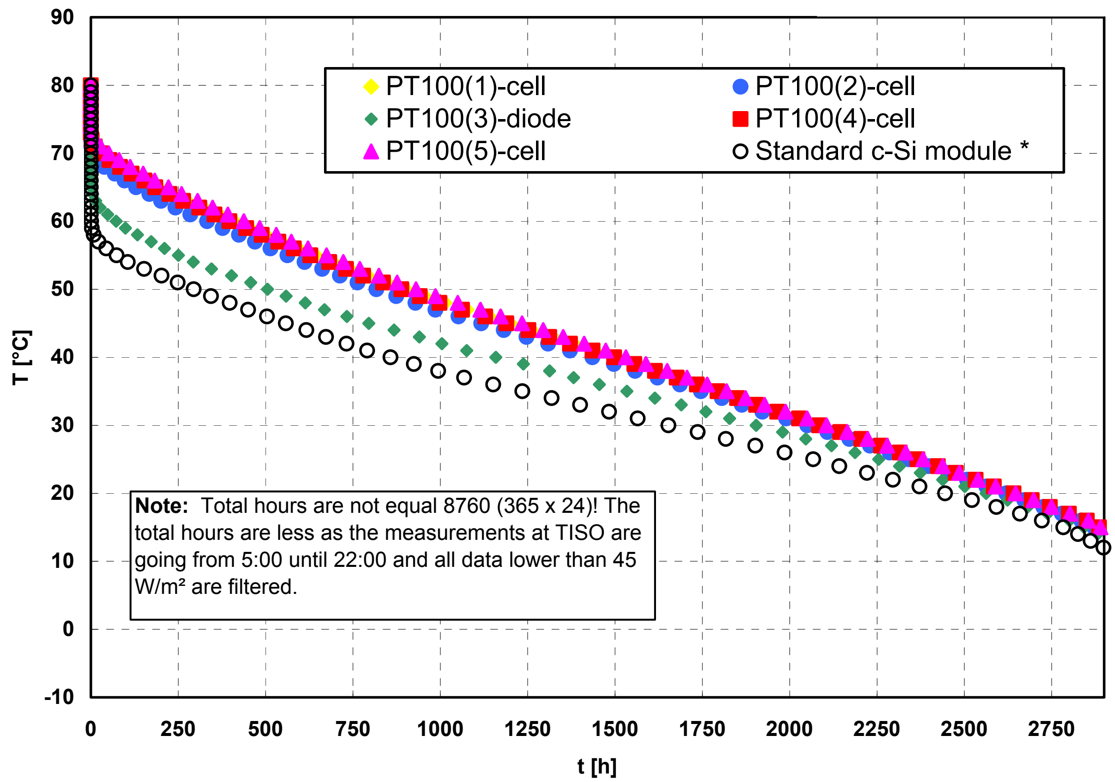


Figure 7 shows the temperature histogram of measured temperature over one year period for different places in the sunplicits shingle array, as well as for reference the temperature of an free standing well vented standard module. In terms of stress and yearly loss of energy production due to elevated temperature, there are just a few hours per year where shingle temperature is at maximum of 83°C (Source D. Chianese, LEEE).

3.6 Module performance

Module performance and power output alteration over the test period was not within the objectives of the project. However, since LEEE is well equipped and even accredited to ISO 25 for indoor IV Curve measurements, the performance analysis was carried out by LEEE. Two major effects were monitored over the 12 month test period:

(i) Some delamination did occur around the solar cells. This is principally due to the new, non- EVA encapsulant formula used by Evergreen. Below is a discussion of this issue and how it can be fixed.

(ii) There was a performance degradation of around 7% over the entire test period. It is assumed that part of this degradation may be explained with the effect of the delamination around the bus bars on the solar cells, which may impact cell performance.

In August of 2001 the roof tiles for the project were shipped from Evergreen to Switzerland. Since that time, work on improving the materials and process used in making these roof tiles has continued.

Here is a summary of this work:

(i) *Delamination of the transparent encapsulant at the encapsulant-solar cell interface.* - This problem occurs along the bus bars of the cell. Prior to sending the roof tiles, Evergreen had seen indications of this problem when accelerated environmental tests were conducted on modules made using our new encapsulant. This effect is due to both the properties of the encapsulant which is used and the high points due to the soldered wires on top of the bus bars.

(ii) Evergreen has since found a solution to this problem that consists of rapidly cooling the module following lamination. The encapsulant material Evergreen is using is not EVA but a new encapsulant that Evergreen has developed itself. The reason Evergreen is using this new encapsulant instead of EVA is that it has demonstrated better UV-stability under extended sunlight exposure, it can be laminated in a non-vacuum process such as hot roll lamination, and that it has a much wider processing window than EVA.

(iii) *Materials costs* - The polymers used to make the roof tiles, particularly the backskin, were higher in cost than what was desired. The backskin material has already passed many of the qualification tests required by the standard PV module qualification laboratories. Subsequent work has indicated that Evergreen can use a backskin material that is likely to meet all the qualification requirements but at about 40% lower cost than the original material, but further work on this is needed.

(iv) *Manufacturing Process* - This work is still ongoing and not complete but there are already excellent indications of successful methods to simplify the manufacturing process for making roof shingles. One method involves an easier way to assemble the polymer components of the module, including the external wiring that is bonded directly into the backskin.

The other method allows to inter-connect the cells in the module using wrap-around contacts and a conductive adhesive that is printed on the backskin material. Evergreen calls this a monolithic module construction.

		Pn	Pa	P0	P15		delta Pa-P15
String 1	row 6	54	51.1	51.1	47.4		-7.24%
	row 5	54	51	51.0	47.3		-7.25%
	row 4	54	51	51.0	47.4		-7.06%
		162	**153.1**	**153.1**	**142.1**		
String 2	row 3	54	50.7	50.7	47.2		-6.90%
	row 2	54	50.7	50.7	47.3		-6.71%
	row 1	54	51.1	51.1	47.7		-6.65%
		162	**152.5**	**152.5**	**142.2**	**Media=**	**-6.97%**

Table 3 summarizes the degradation measured over time. Pn: nominal power, Pa: initial power, P0: power after first degradation assuming an average degradation of aprox. -3.53%, P15: power after 15 months. The 7% value amy be due to the observed delamination around bus bars of the newly tested non EVA encapsulant material.

4. Cost analysis

Of course it is difficult to estimate final production costs of the PV roof shingle, but the estimation made during the project phase is based on the following consideration:

Since the functionality of the roof shingle is based on overlapping parts, the cost of the overlapping material may be significant, as indeed it is also for the fibre cement shingle. This part consists mainly of three different materials: Glass, backskin material, and encapsulant material. Therefore it is important that these three materials are, on a unit area basis, cost effective. Evergreen has spent considerable effort in finding low cost materials that are likely to pass all the qualification tests. Evergreen's patented backskin material as well as non- EVA encapsulant had been used.

In terms of the glass, there is a trade-off between two options: (i) Low iron, higher cost glass with about 4% higher electrical output versus (ii) low cost, normal float glass with higher iron content and hence slightly reduced electrical performance. In order to bring initial cost down, and based on the trade off, the normal float glass is the more cost effective solution, simply because the actual glass surface is about 65% higher than the fraction which actually is covering the solar cells.

The other otimisation was made on the inter-connection system. It became obvious that a plug system based on today's plug will not pay for small shingles, which are only about 10 Watts in power. Therefore, the new design explained in chapter 3 is based on a pig- tail solution, and a pre-wiring string of several PV solar shingles. These provide several advantages: the costs come down because of fewer connectors, reliability increases, and ohmic resistance is minimised. Furthermore, this pre-wiring can be made in the factory, and therefore any errors can be made minimal.

The optimal handling package was evaluated during hands-on installations on roofs, to simulate the actual working conditions. Handling constraints, cabling issues and speed of placing and mounting the shingles were evaluated. The result was a pre-packaged string of 6 PV shingles. Based on the above considerations, the cost figures look quite promising. However, it has to be mentioned, that these are material cost figures only, and manufacturing and overhead are not included. Hence, these figures do not represent the final market price. Of course, manufacturing cost depend very much on production volume. Several different ways to manufacture the shingles had already been discussed, but final decision how to manufacture will depend on market demand.

The actual prototypes had a power output of around 8.5 Watt per shingle, or 51 Watt per string. The optimisation of available space of the shingle exposed to the sun, and the improved efficiency performance of the newer cells allows power output per shingle of 12 Watt, or 72 Watt per string.

The required glass area for each individual shingle is 0.28m^2. From this the following material cost figures can be derived and shingle cost been estimated, although final market price will be some 40% higher considering manufacturing cost and overheads.

Solar cells	per Watt	2.00	24.00
Glass	per sqm	8.65	2.42
Encapsulant	per sqm	5.00	1.40
Backsin	per sqm	8.65	2.40
Frontskin	per sqm	4.40	0.90
Edging	per m	1.00	2.20
Connectors per shingle	per 6 shinglestring	3.00	0.50
Cost per 12 Watt PV Shingle Sunplicity			33.82
Material Cost per Watt			2.82

Table 4 shows the cost figures for the roof shingle material. Manufacturing and overheads are not included. This transforms to about 300US$/sqm material cost, compared to fibre cement price of roughly 15 $/sqm. Please note that at the moment cost are compared with prices, two very different things, but since mfg costs are still unknown, the figures are an important indication. And it has to be restated, that installations costs of conventional fibre cement shingles and PV Sunplicity is roughly the same.

5. Conclusions

Innovations in the roof have not kept pace with the innovations that can be observed in facades. To adapt to market practice, PV roof systems should therefore be as compatible with existing roofing systems as possible.

Taking costs figures from facades and roofs, the area related integration cost of PV will be smaller in the roof than in the facade. Combined with the fact that the performance of PV systems is generally higher on the roofs than on facades, makes the opportunity for the PV industry even more attractive.

On the other hands, architects tend to be more innovative in the facades, because this part of the building is more visible. The architect may therefore choose the facades to start promoting PV. And in fact, this can be observed in the actual marketplace: project driven by costs such as the Solarstrombörse from the utility of Zurich are realised on the roofs, but in more prestigious projects architects have chosen the facade wishing to make a statement with PV. Is therefore the facade less resistant to innovations?

Requirements on the roof may be higher, and the challenge to meet the low cost figures of conventional roofing material is much harder than in the facade. The facade is more forgiving in terms of waterproofing, water shedding, snow and wind loads, UV, heat etc. Nevertheless, when considering the option to contribute not only to a merging niche market, but to contribute to a new energy paradigm based on renewables, the roof will ultimately play a more important role. Several studies indicate that the market for roofing systems in countries like Switzerland are in the range of 20sqm per capita. This represents a huge market, which certainly justifies the efforts the PV industry to develop innovative new products and systems for the roofs. The new design Sunplicity fulfills these criteria.

6. Outlook

The developed roof tile concept offers many advantages over aluminum-framed PV modules built onto or integrated with some other features into the roof. The advanced plastic frame is a pre-requisite for the market success and offers in the long run the potential for the mass production of the roof tile.

The polymers used to make the roof tiles were demonstrated to be able to hold up under accelerated environmental conditions. The roof tiles were made in a basically manual process, but no impediments to developing a manufacturing process could be seen. For purely strategic business reasons, Evergreen Solar is not pursuing the development of such a manufacturing process at this time.

Earlier problems with the two polymers used were solved with later work. Annex 5 contains a discussion of the work done and the results in solving these problems. A remaining issue is the cost of the backskin but a fuller investigation of cost reduction possibilities here was not done, due to lack of time.

Annex 1: List of references

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6. Arbeitsgemeinschaft Ziegeldach im Bundesverband der Deutschen Ziegelindustrie e.V., Web page 10/24/2000 http://www.ziegeldach.de/themen/i1304.html,

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8. M. Schalkwijk, F. Leenders, "Prescript Task 1, survey of building codes" Published by ECOFYS E 2109 B1

9. BDA Damakadivies B.V.,Avelingen West 33, Postbus 389, NL-4200 AJ Gorinchem, Fax Regarding"Systemtest" Ref. NCVDP 00-0686

10. IEC 1215:1993-04, Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval

11. Michael Benner, Diplom Thesis:2000, "Solarstromanlagen auf Gründächern, Entwicklung eines geeigneten Montagesystems", Fachhochschule Köln (Germany), Fachbereich Maschienentechnik

12. J.J. Bloem, R. van Dijk, "The PV Module considered from an energy flow perspective" Published by JRC Renewable Energies, Special Publication Nº S.P.I.00.52

13. COPPER IN ROOFING - DESIGN AND INSTALLATION, 28th of November 2000: http://www.cda.org.uk/megab2/build/tn32a/default.htm

Annex 2: Example of project work items
exemplified on a project Action Item List, Project Solarshingle Sunplicity, during project work meeting.

	Action item	Reference	remarks
1	Diodes. Evergreen will perform tests with laminated diodes. What is the temperature rise, does the backskin material support this	Meeting at Evergreen 12.5. 2000	Evergreen will perform temperature tests
2	Diodes: Evergreen presents new diodes, which can be laminated into the backskin. Only solution. Every module needs a diode, otherwise external wiring would be required, which would kill the economics. Real proposes to just add forward current with power supply, 3A , if you don't burn your finger, it is OK.	Meeting at Evergreen, 4. Mai 2001	Evergreen will perform temperature tests, power supply, 3A, indication of temperature rise
3	Tiso LEEE will send temperature sensor TP100 to evergreen. 4 pieces to measure temperature at i) cell temperature, 2 different locations ii) back skin temperature iii) diodes temperature, 2 pieces, at 2 diodes, thermally coupled, but electrically decoupled	Meeting at TISO LEEE 15. 6. 2001	LEEE will send 5 thermocouple to Evergreen
4	Hanoka will send electrical cell characteristic to Alpha Real in order to evaluate potential configuration, to match inverter product available on the market and optimise electrical design of roof shingle with respect to size and power output.	Evergreen will perform temperature tests	done
5	Alpha Real will make new trial with new prototypes with roofer, final fine tuning for intercabling and handling issues.	Tiles shipped to Switzerland 8. Mai 2001	Done, see minutes
6	Alpha Real will file patent on inter-cabling of tiles at Swiss patent office. Evergreen will have then one year to decide whether it will proceed with the filing the patent.	Several phone calls with Jack Hanoka	done
7	Alpha Real will design demo layout	Meeting at TISO LEEE	done15. 6. 2001
8	Evergreen will re-evaluate cost figures for production of roof tiles, by end of August 01	Meeting at Evergreen, 4. Mai 2001	done
9	Glas Trösch will evaluate cost figures for production in Europe, based on lamination technologies from GT in BRD		done

Annex 3: Temperature Histograms for PV systems at NREL

Temperature histograms on 3 PV systems that have been installed at National Renewable Energy Laboratory NREL in Golden, Colorado. System 1 is a roof type system and has insulation on the back of the modules to increase their temperature and promote thermal annealing of amorphous silicon. The other Roof systems 2 and 3 are installed on a well ventilated attic. This data is only valid for our location (Golden, CO). The maximum recorded air temperature is 40°C. In Phoenix, AZ the maximum recorded air temperature is 50°C. So one would expect the modules to run about 10°C hotter in Phoenix.

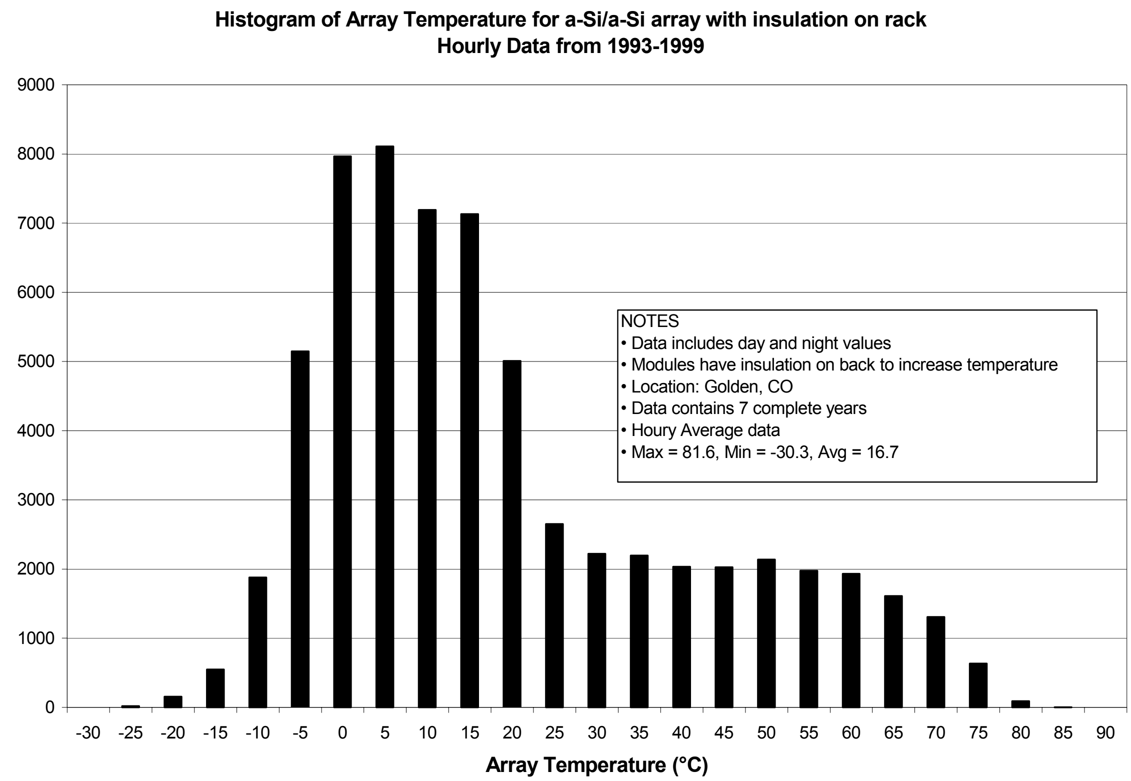

Figure A3-1. This array is mounted on an open rack, but the modules do have insulation on the back to promote thermal annealing of the amorphous silicon.

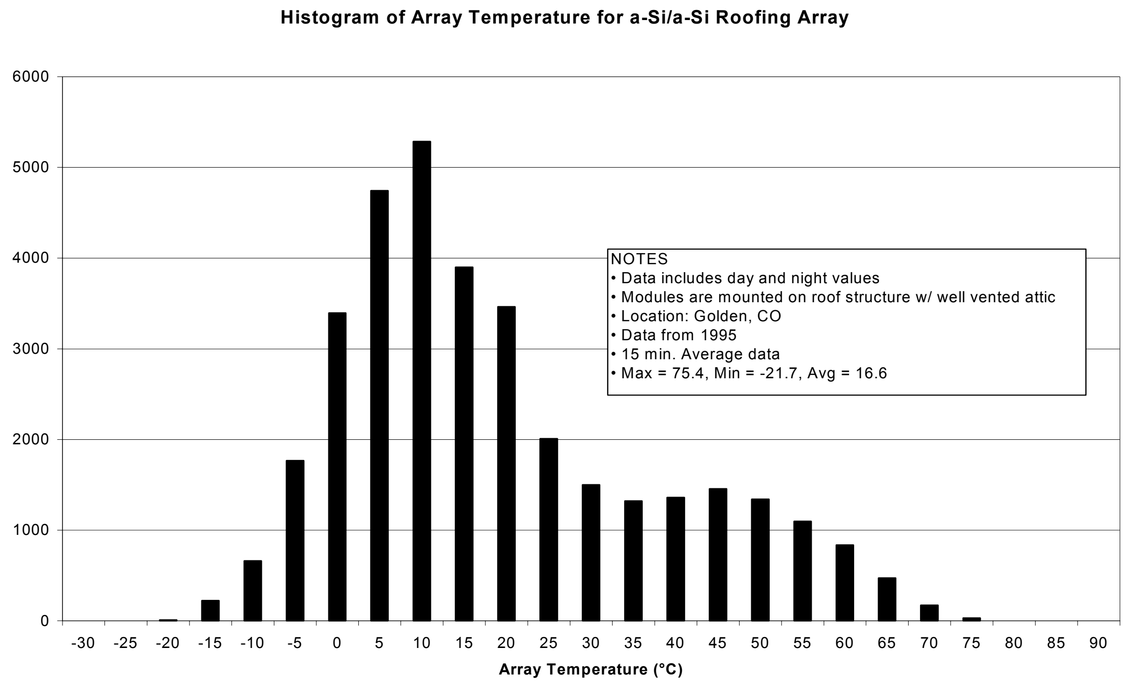

Figure A3-2. This array is mounted on a simulated roof structure with a well ventilated attic. These modules were mounted directly to the roof surface.

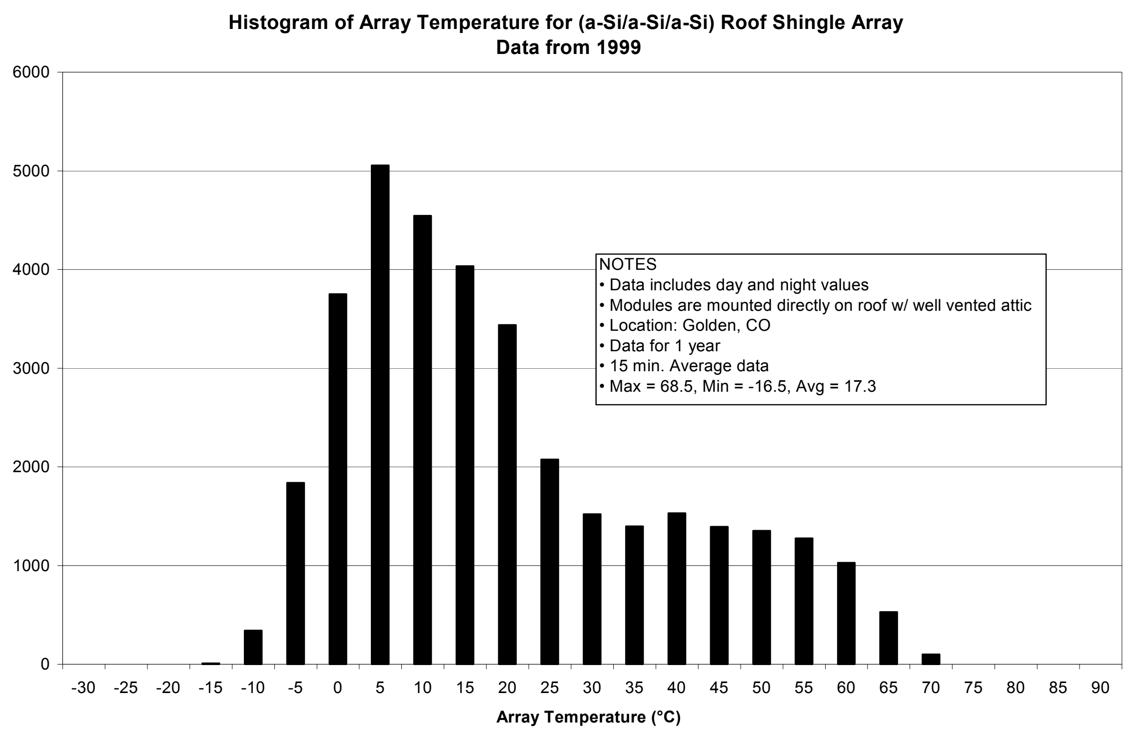

Figure A3-3. *This array is mounted on a simulated roof structure with a well ventilated attic. These modules were mounted directly to the roof surface. These modules are designed as shingles and have a slight overlap onto non-active areas.*

Annex 4: Example of test protocol of LEEE I-V curve measurements

Misura della caratteristica corrente – tensione a 1000 W/m^2 e 25°C di dispositivi fotovoltaici con simulatore solare a impulso

secondo la norma IEC 60904-1

Fornitore dispositivi: Evergreen

Data di consegna: 24.08.2001 Numero di campioni: 6

Data di esecuzione della prova: 28.08.2001 Operatore: NC

Risultati della prova

Codice ID	*P_{max} [W]*	*V_{Pmax} [V]*	*I_{Pmax} [A]*	*V_{oc} [V]*	*I_{sc} [A]*	*FF (%)*
Row1	51.1	16.40	3.12	21.43	3.65	65.4
Row2	50.7	16.01	3.17	21.38	3.61	65.7
Row3	50.7	16.16	3.14	21.41	3.64	65.2
Row4	51.0	16.37	3.11	21.42	3.64	65.3
Row5	51.0	16.38	3.11	21.38	3.64	65.5
Row6	51.1	16.37	3.12	21.43	3.63	65.8
090-07-01	8.6	2.71	3.19	3.56	3.70	65.7
090-07-02	8.9	2.72	3.28	3.58	3.75	66.4

Errori di misura

P_{max} : ± 2.0%
V_{oc} : ± 1.0%
I_{sc} : ± 1.4%

Osservazioni:

090-07-01 and 090-07-02 single shingles

Annex 5 – Description of results in solving the earlier problems with the polymers used in the roof tile project.

As mentioned in the report, there were two principal problems related to the polymers used for the roof tiles. (1) delamination of the encapsulant from the soldered bus bars, and (2) bond strength of the backskin edging to the glass.

A5.1 Delamination of the encapsulant from the soldered bus bars

The solution to this problem consisted in recognizing that Evergreen's encapsulant tends to shrink a good deal when it becomes more crystalline – a general phenomenon associated with polymers that can be either amorphous and crystalline depending on their rate of cooling. So, by quenching the module after it is formed, this keeps the encapsulant more amorphous and shrinking less on cooling. The hypothesis was that excessive shrinkage resulted in de-lamination.

The quenching experiments verified this. It was also found that when the delamination problem still existed, it could be revealed more quickly by cooling the modules to very low temperatures. The standard thermal cycle test for PV modules requires cycling the module between +90^{o}C and –40^{o}C.

The table below lists a number of modules made (test modules -not roof tiles) and the thermal cycles and humidity freeze (H.F.) cycles they were subjected to. It can be seen that no delamination was seen after this quenching procedure was employed. We are now confident that this problem is solved.

Module #	# of Thermal Cycles	Delamination
012902-1	251 (w/ 3 H.F. cycles)	none
012802-1	" "	"
012402-1	" "	"
012802-2	" "	"
012802-3	" "	"
012502-1	182 (w/ 3 H.F.cycles)	none
021302-1	"	"
020502-1	127	"
021402-1	58	"

A 5.2 Bond strength of the backskin edging to the glass

The procedure used to form a strong bond of the backskin edging to the glass involves the application of a very thin layer of a silane coupling agent to the glass surface. This is primarily a question of the right silane at the right pH. The earlier, non-reproducible results are now believed to be due to inadequately satisfying these two requirements. Some further work on finding the optimal pH and the right silane was very successful.

A principal test for the bond strength of such a bond is its so-called hydrolytic stability – this means how well it holds up under hot water. Three briefcase-sized modules made with the backskin material and edging were immersed in 85^{o}C water for from 3 to 6 days. This is a very severe test and and there was no evidence of the edging – glass bond weakening. The initial evaluation in this case consists of seeing if a razor blade can be inserted under the edging. Earlier work had shown that this was a very fast, qualitative test of the bond strength. It could not be inserted, indicating a strong bond.

A rule of thumb from Pluedemann[1], a world authority on silane coupling agents, is that if the bond strength holds up under 70 ^{o}C water for a week, such a bond should last for 75 years. Since this was done at 15 ^{o}C higher than this and one such module has already seen 6 days of immersion, it is likely that we have a very strong bond here.

[1] (*Silane Coupling Agents,* E.P. Pluedemann, Plenum Press, 2nd edition, 1991)