SSTM

Scalable Shade Tolerant Modules

Final report

Project details

Projectnumber:	TEID215030
Project title:	Scalable Shade Tolerant Modules - SSTM
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Partners:	Universiteit Utrecht
	Optixolar
	Heliox
	Solned
	Rimas
	Expice Hoorn
Project period:	16 September 2015 – 31 December 2018

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Subsidy

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Inhoud

Summary

Photovoltaic (PV) modules are mainly available in one standard size , which means that full roof coverage of PV modules asks for expensive tailor-made modules. Besides that, the interconnection between the cells in a standard module is very sensitive to partial shade on the module, where a small shadow can already result in a substantial drop of the produced power. E.g. when 1% of module area is shaded, the resulting drop in power can be as high as 33%. Both issues hamper further rapid growth of PV in the built environment.

The project aim was to determine the feasibility of scalable, shade tolerant modules based on the criteria of manufacturability, industrialization, lifetime and LCOE. The project thereby contributes to the PV program line, especially by lowering the LCOE of modules applied under non-optimal circumstances and thereby opening up new application possibilities.

ECN and Utrecht University have developed the TESSERA (prototyping) and SMART (proof-of-concept) module technologies. Industrial partners are involved to industrialize and market the technologies, focussing on specific parts of the development. Rimas and Optixolar cooperate with Rofin and Eurotron to optimize cell cutting and handling of mini-cells. Solned develops flexible patterned backsheets for the MWT TESSERA module designs and collaborates with Expice to integrate diodes. Heliox develops micro-inverters matching the designed modules. Exasun is involved to determine manufacturability and market readiness / system integration of the modules.

Besides a benchmark report on currently available technologies on system and module level, two concepts have been developed, resulting in a lab-tested proof-of-concept of a SMART module and prototyping and field testing of a TESSERA system. For the TESSERA system manufacturing methods such as cell cutting, diode integration in backsheets, and specific micro-inverters were investigated, showing that the concept is very interesting with respect to shade tolerance, but still needs improvements in the manufacturability.

Final report

This report concerns the final report of the subsidy project Scalable Shade Tolerant Modules (hereinafter referred to as "SSTM") as carried out with subsidy by the Ministry of EZ, Topsector Energie – Subsidy Energie en Innovatie (SEI). The following reports address the substantive objectives and final results. In addition, a number of project changes are described.

Preface

PV modules have significantly dropped in price, due to standardization and mass production. This resulted in a boost in their installation. The far majority of these installations is for residential application (around 80%). However, modules are available in one size only and partial shade on a solar cell can result in a drop of the produced power. This means that when 1% of module area is shaded, the resulting drop in power can be as high as 33%. Both issues hamper further rapid growth of PV in the built environment. In this environment, shade is often present and various sizes are required. Both for building applied PV (BAPV) to be able to cover entire surfaces, but especially for building integrated PV (BIPV), as building elements come in a large variety of sizes. Especially in The Netherlands, field space is limited and in order to achieve our renewable energy goals, installation of PV in the built environment is needed. Solutions to re-design the solar panel in order to allow better shade performance AND scalability of the module at the same time are on-going.

One of these is the TKI project, INHYPE, in which partners ECN, Eurotron and Heliox developed a shade tolerant module3, 4. The electrical interconnection of the cells is altered and smaller cells are used to allow nearly 100% shade linearity. Results are positive. The design is scalable, and shade performance calculations prove very promising, up to 92% shade linearity has been demonstrated for shade cases where conventional modules only show 38-66% shade linearity4, 5, 6. Feedback from international parties on the concept is also positive. The module concept has been named TESSERA, as this means 'the building block of a mosaic'.

Another shade tolerant solution, the "SMART" module, can be based on standard cell sizes. The module uses back contact solar cells connected through a conductive backsheet and can be placed between other "normal" modules on locations that suffer from shading. The cells are divided in groups (granularity will be determined later) which are connected to a central smart integrated circuit (IC). The IC will perform maximum power point racking (MPPT) per group of cells and convert the current of shaded groups to match that of unshaded groups. A switching circuit will ensure that only shaded groups are converted, which minimizes conversion losses and allows shaded groups to contribute to power generation. This power would otherwise be lost when using bypass diodes.

For both TESSERA and SMART a good comparison is needed on system level (including inverters, system configuration aspects), in terms of yield, lifetime of components, maintenance and system costs (LCOE).

Goal and purpose

The project aim was to determine the feasibility of a scalable, shade tolerant modules based on the criteria of manufacturability, industrialization, lifetime and LCOE. The activities to achieve this aim are summarized in the figure below:

TESSERA
- Process of laser scribing and breaking/handling mini-cells
- Process and reliability of in-laminate diodes
- Development of cell process to allow diode free module
- Flexibility in foil structuring for various sizes
- Yield
- Full size lifetime

SMART Module
- Standard size solar cells
- Development and reliability of cell mppt tracker and dynamic switching circuit
- Flexibility in foil structuring for various sizes
- Yield
- Full size lifetime

Project Outcome
Feasibility of scalable and shade tolerant modules based on manufacturability, industrialisation, lifetime and LCOE

Fig 1: activities in the project related to the TESSERA and SMART module.

The project consisted of the following tasks: :

- Overview of SMART module concepts and techniques to enhance scalability and shade tolerance;
- SMART module and TESSERA module conceptual designs;
- Component design of structured foils, diodes, micro-inverters, and so on for application in intelligent PV module and system applications;
- Process design for cutting PV cells into mini-cells and handling those mini-cells;
- Feasibility / proof-of-concept of the developed SMART and TESSERA concepts;
- Prototyping of the TESSERA modules;
- Field testing of TESSERA modules;
- Lab testing of SMART modules;
- Techno-financial model and business cases of developed components and concepts, comparing their performance to available technologies.

Working procedures

The objective of this innovation project was to develop, compare and demonstrate two systems including a feasibility study for better performance in shaded conditions, that include the desirable properties: higher yield, longer lifetime of components and acceptable maintenance and system costs (LCOE).

The project was divided into six work packages. Each work package focused on a separate innovation that was needed to reach the end goal:

WP1: Concept design: Building of a simulation model to test concepts designs of the SMART module and TESSERA module for determining optimal granularity and shade tolerance of the different topologies. Furthermore, both modules have been developed and benchmark analyses have been executed by ECN → TNO.

WP2: Materials and enabling technologies: In this work package the components and control algorithm for the SMART module have been developed by UU with four focus areas: 1) solar module and solar cells, 2) MPPT, 3) DC-DC converters and 4) IC and control logic. Expice has performed a study on the integration of electronics in backsheets including various methods of applying conductive glue and solder for adhesion purposes and processing. Solned has developed a structured backsheet specified to the desired pattern. The cells in the TESSERA modules are 1/sixteenth of a standard 6 inch cell, and cutting and handling of these mini-cells processing is an issue. ECN, Rimas and Optixolar have researched the possibilities in cell cutting, handling and processing in the production line.

WP3: Prototyping and feasibility: The concept designs of WP1 and the material and process designs of WP2 need testing before full-scale prototyping can occur for the TESSERA modules. In this activity, material and cell suitability were verified on small modules. Mini-modules were manufactured at ECN using backsheets from Solned . Process compatibility, as well as power output performance (IV measurements) and module quality (using EL and DLIT imaging to check interconnection and cell quality after lamination) have been determined. Furthermore, reliability tests have been executed to determine potential failure mechanisms. Rimas and Optixolar have perform tests with cell cutting and handling processes. This resulted in extensive knowledge regarding the feasibility of the cell cutting process. Besides the development of the TESSERA prototypes, UU has developed the (Proof of Principle) prototype of the SMART module for further feasibility testing.

WP4: System design: In this workpackage, this design of the Heliox inverter (originated in the IN-HYPE project) is further industrialized with respect to the MPPT input power stage including MPPT software algorithms. System electronics have been designed for optimal performance of the TESSERA modules in the field. The TESSERA modules have been setup at the SolarBEAT location of the Technical University of Eindhoven. 6 TESSERA modules and 6 standard modules, both with Heliox micro-inverters were compared with a standard system with string inverters. Utrecht University has tested their prototype in a lab setting and further testing of the system will be done on the roof of the University (outside the project).

WP5: LCOE: In work package 2 and 3 the technical feasibility of the developed concepts and components has been determined. In this work package, those results have been translated to an evaluation of the proposed business cases. This has led to a component specific and a system level cost model of the developed concepts.

WP6: Project management: During the project, consortium meetings were organized (once every 8-12 weeks) during which the partners shared the progress of the results. In addition, regular coordination has taken place through a monthly telephone conference. Quarterly the financial status of the partners was requested. These activities have resulted in extensive reporting of meetings, progress reports, etc.

Results

A large number of results have been achieved in this project. The most important results are explained below.

WP 1: Concept design

State-of-the-art PV modules are not suitable for size and shape variation. When going to more shape variations in PV modules there are a few desired properties:

- Fixed voltage: independent of shape or size;
- Current depends on module area;
- Freedom of connection: terminals can be placed at any point;
- Shade tolerant: fixed voltage; current depends on shaded area.

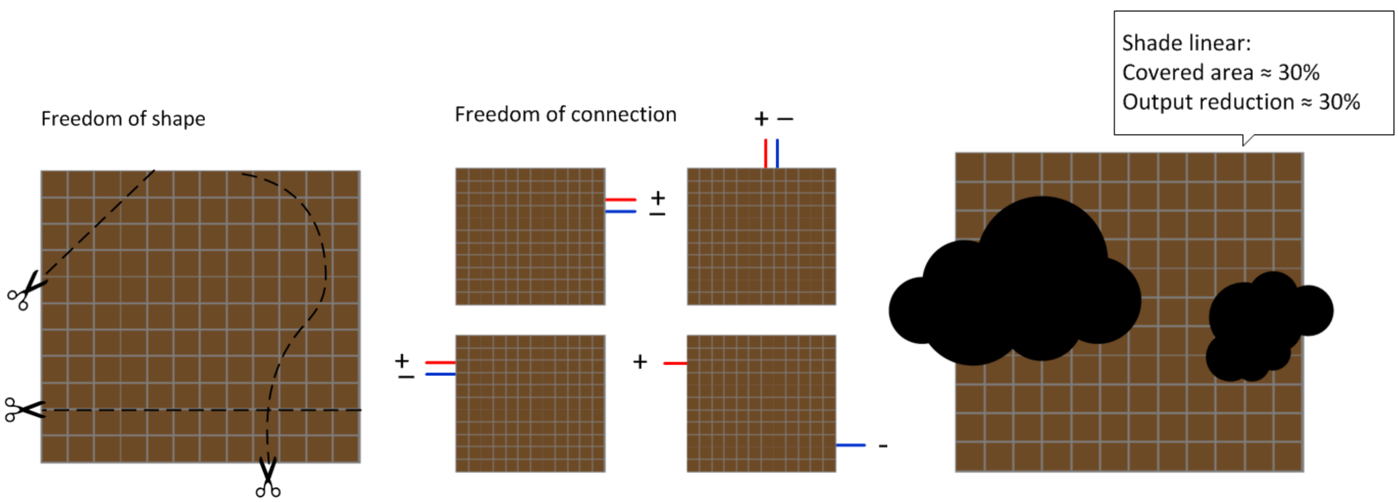


Figure 2: Schematic overview of TESSERA 0.0

Most PV modules today consist of 3 strings, with 20 cells connected in series in the string. The string is protected by a bypass diode. When one cell is shaded by more than 15%, the current of the string is bypassed through the diode and the string output is lost. Hence, one shaded cell can cause 1/3 of the module output to be lost. In other words, the module consists of 3 'pixels'.

This can be improved by increasing the number of pixels. For example, by combining fewer cells to one diode. Solar cells have a high current (7.5-9 A), so diodes which can carry this current would need to be placed at various positions in the module. This is difficult and expensive.

A better solution is to divide the 6 in. cells in 16 smaller SubCells, with a lower current (the current scales linearly with the cell area). A group of SubCells (SCG, here 16 cells) can then be connected in series to a smaller in-laminate diode. Four of these SCGs are subsequently connected in series into a module building block (MBB). The module interconnection wiring is based on a single layer of conductor foil. The conductor foil is divided in a positive and negative section by an isolation trench in such a way that every unit module has access to the local positive and negative section. The resulting module consists of 15 MBB's in parallel, each containing 64 series connected SubCells.

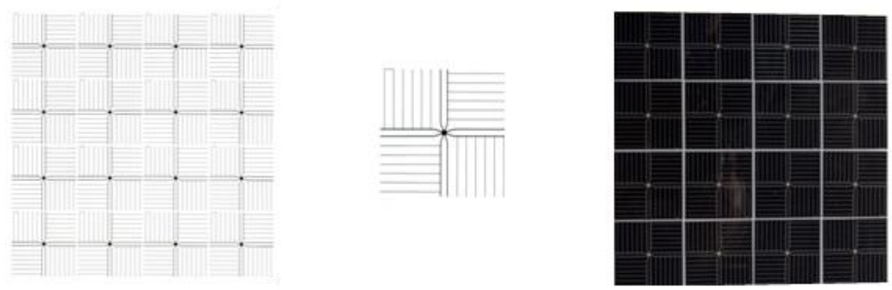


Fig: Series connected subcells

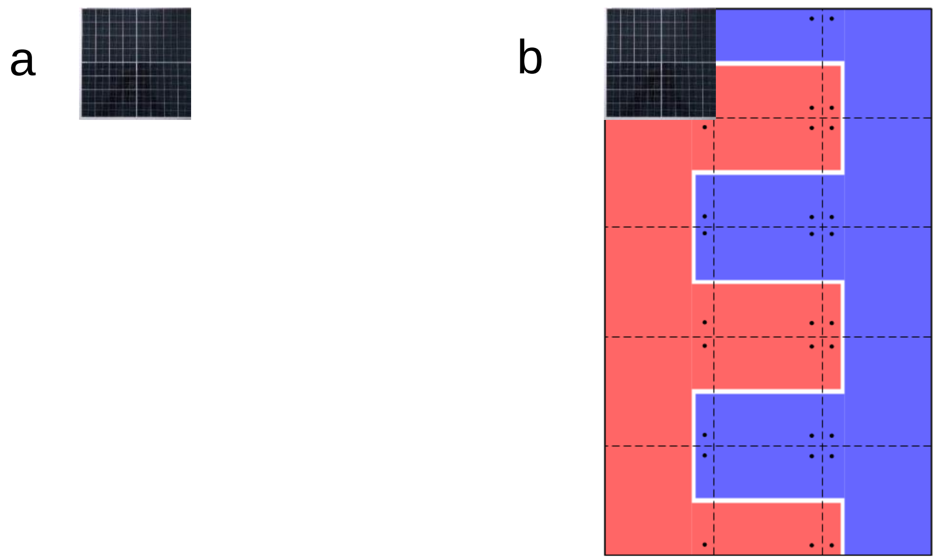


Figure 3: Module building block and full size Tessera module layout

Another benefit of this design is that the voltage is almost independent of the shaded area, which makes tracking of the maximum power point more easy.

The concept has its limitations however when it comes to size tolerance. When cutting the module there is a large possibility that the functionality of the module is harmed as it can easily happen that one of the polarities does not have a contact. For this reason the bridge-foil concept is developed.

Bridge foil

In this concept the positive and negative pathways cross, allowing to cut the module to any form without redesigning the foil. However, in a single layer conductive foil as is used in the Tessera concept, this is not possible. But the cells can make a bridge through their metallization pattern. By adding an extra contact at the rear of the MWT cell, the cell can bridge the crossing. Schematics of the interconnection for full size modules is shown in Fig. 6.

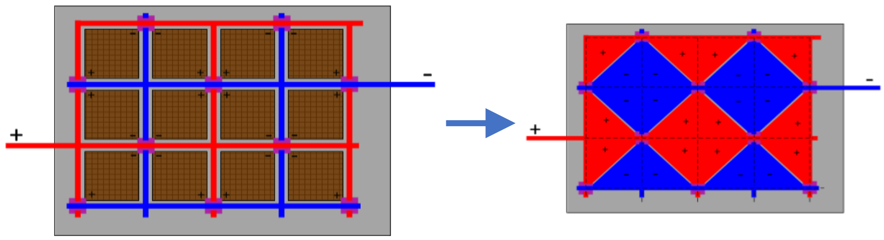
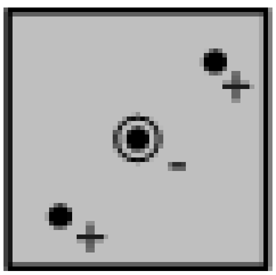


Fig: From standard Tessera foil interconnection to the bridge-foil design



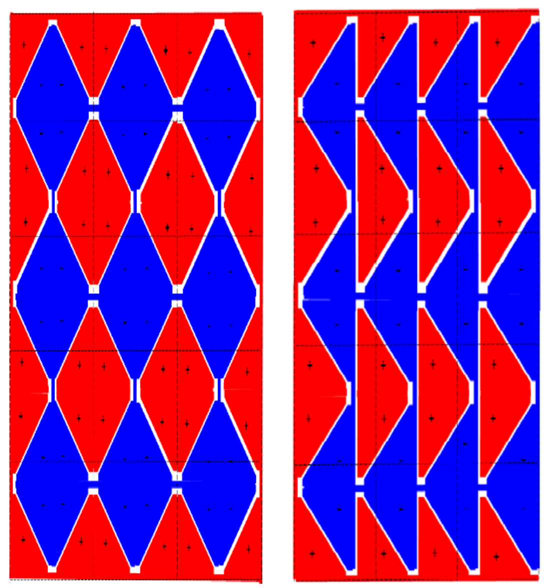


Figure 4: Contacts at the rear of the MWT cell. An extra contact is to allow bridging the crossings and examples of the interconnections in the foil for the bridge-foil concept

Final drawings

These initial schematic drawings have been transferred into the actual patterns that take into account all manufacturing requirements. The resulting drawings are shown:

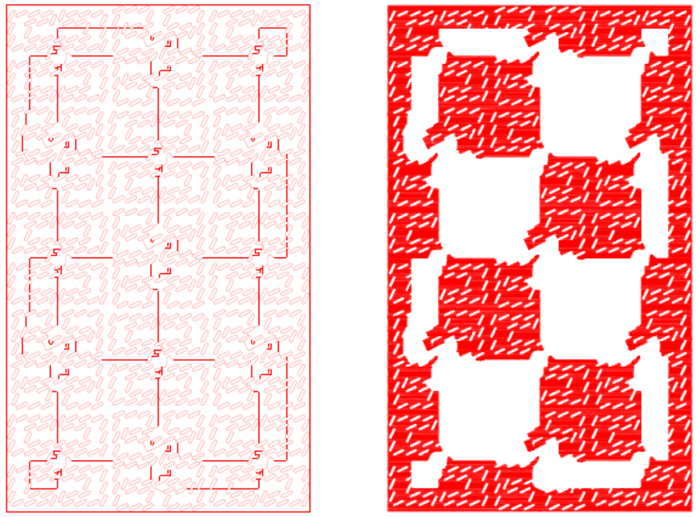


Figure 5: Etch pattern on the left and regions of positive polarity on the right for the final bridge-foil Tessera 0.0

Annual yield model:

During the project yield simulations of an average residential rooftop with modules were executed by ECN → TNO. A reference roof was packed with standard c-Si modules whereas the other modelled roof was packed with Tessera-design c-Si modules.

Module placement was as followed:

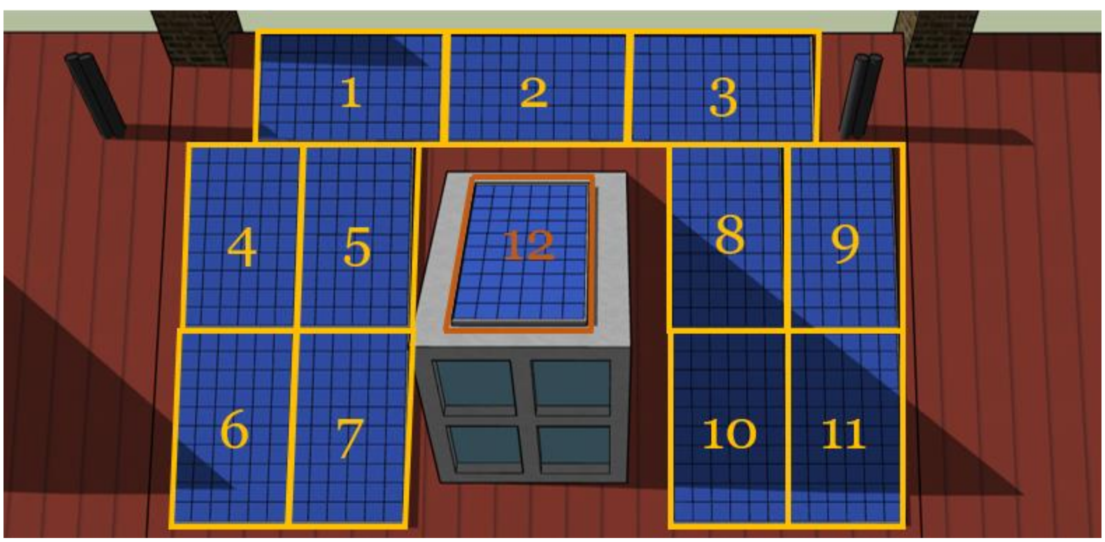


Figure 6: Numbering of Yingli Pandas modules on a full "Standard" house roof. Note that module 12 is colored differently because of its horizontal orientation, while the others are all facing 40° S.

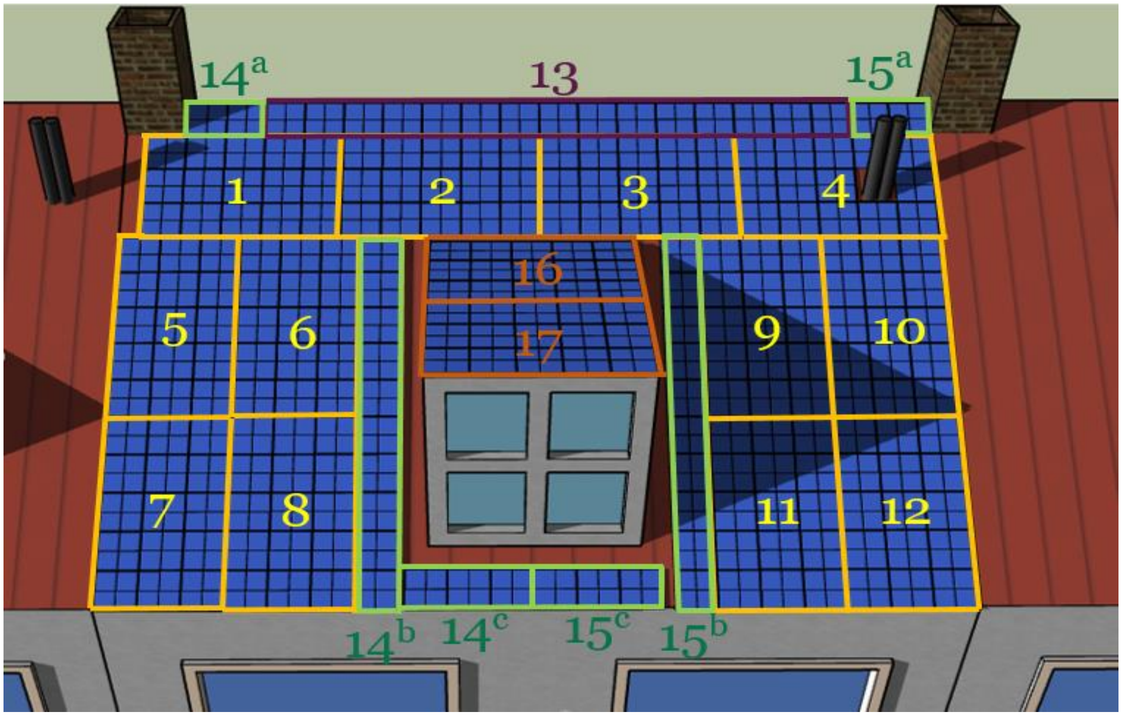


Figure 7: Numbering of TESSERA modules on a full "Tessera" house roof. Notes: module 4 contains 14 branches instead of 15; module 13 is elongated; modules 14 and 15 are built up from three pieces each; modules 16 and 17 are oriented horizontally instead of facing 40° S.

The chosen lay-outs result in system characteristics as specified in table below. Note that the relative system capacity is stated relative to the nominal capacity of the full "standard" house roof.

Parameter	Full standard house roof	Full Tessera house roof
Module type	Yingli Pandas 265	TESSERA (ECN)
Number of modules	12	16 + (14/15)
Rated module capacity	263 W_p	241 W_p
Nominal system capacity	3.15 kW_p	4.08 kW_p
Relative system capacity	100.0	129.3
Cells per module	60	960
Substrings per module	3	-
Blocks per module	-	60
Branches per module	-	15

Table: Layout of the system characteristics in simulations

Based on the relative positions of all objects covered in this section, shading tables are constructed to model partial shading throughout a typical meteorological year (TMY). The set location is Eindhoven (HTC) throughout this study.

Below are the results of the simulations regarding the DC outcome and AC outcome. Please note that all simulations conducted here include all shading objects (in other words: no shade-less results have been generated). The figure below shows that the DC yield benefits of using a full roof Tessera lay-out exceed the difference in relative rated capacity. This means that the difference in yield is larger than the difference in rated capacity. The increased shade tolerance of the Tessera system is the cause for the difference in DC yield. A third aspect highlighting the excellent Tessera shade performance is the fact that the extra modules (compared to the standard system) are generally closer to neighbouring shading objects. Despite all this, the yield offset when using Tessera modules is more-than-proportional.

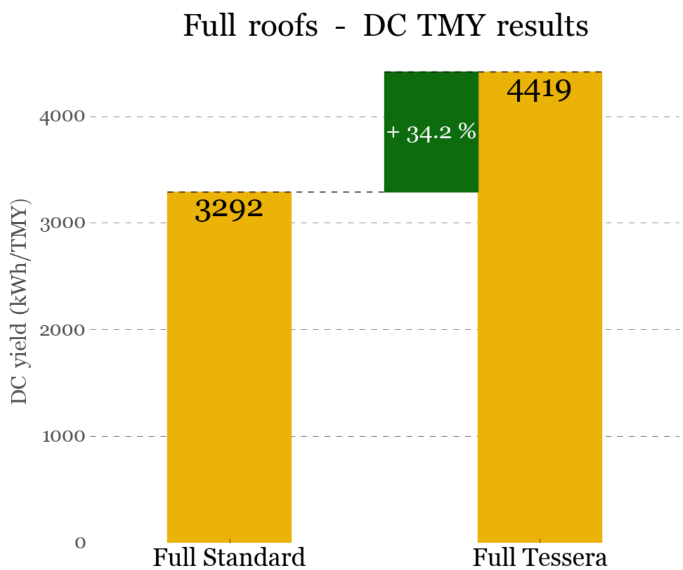


Figure 8: TMY DC yield in kWh for both scenarios studied. The green bar illustrates the additional system DC yield when using a full roof of c-Si Tessera modules instead of a full roof of standard c-Si modules.

In short, there is a clear DC advantage of packing the studied roof with Tessera-based modules:

- About 30% more yield due to increased packing density;
- About 5% yield bonus due to increased shade tolerance;
- Despite some of the modules being located closer to neighbouring shade objects.

For the AC simulations, the PV systems were integrated using either micro-inverters (MIs) or power optimizers (POs). The yield results of these simulations are shown below:

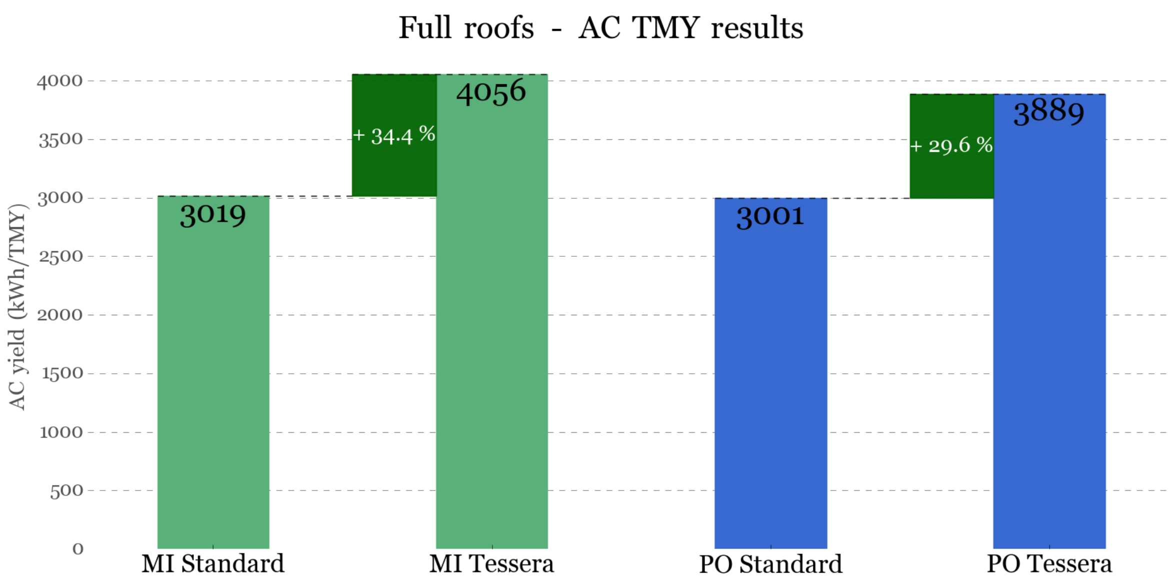


Figure 9: TMY AC yield in kWh for both scenarios and power electronic configurations studied. The green bars illustrate the additional system AC yield when using a full roof of c-Si Tessera modules instead of a full roof of standard c-Si modules.

The yield benefits of Tessera-based systems on a packed roof compared to those of a roof packed with standard c-Si modules are evident. However, some aspects are not fully considered in the simulation. Firstly, ideal by-pass diode (BPD) behavior is assumed. However, it is not expected that this will cause substantial additional losses in the standard full-roof PV system, as the amount of BPDs per module is limited. The effect due to this simplification on the Tessera-based system is expected to be modest as well. This is because the system design is such that it requires extremely irregular shading patterns for BPDs to be activated. Secondly, cable losses are not considered. This could lead to additional losses in the Tessera-based system in particular – because the modules that are built up by separate module parts (14 and 15) are separated from each other by several meters. However, these cabling losses are not expected to exceed a few percent of the total annual yield. In fact, the key messages of this section are still expected to hold if these factors would have been fully considered.

Not considered here but still particularly relevant (for future commercialization) are the economic aspects. The full roof TESSERA system will of course be more expensive than the standard system.

Comparing a Tessera-based full roof PV system to a standard full roof PV system:

Economic advantages	Economic disadvantages
+ Higher energy yield, therefore increased value (of energy) generated.	- Costs per module are higher for Tessera
+ More effective use of space on the roof.	- 17 module equivalents required instead of 12
+ Potential integration of Tessera PV modules in roof design (may save costs for roof tiles).	- 17 POs and MIs required instead of 12
+ more esthetically pleasing	- Additional cabling costs

Benchmark

The growth of smart and AC modules is inevitable. MLPE suppliers all point to integrated smart and AC modules as part of their long term roadmap. As the MLPE market matures, it is expected that increasingly reliable power electronics will find their way into embedded PV modules. The market is projected to see a gradual growth in the sales of smart and AC modules rather than a tipping point. The biggest challenge for the smart and AC modules remains the business model and not the technology. Module vendors will be helped considerable by showing to their customers embedded modules as a cost effective solution rather than a premium product. There is room for more MLPE vendors to enter the market especially at the power optimizer segment. The window for new entrants is narrow but the existence of only 3 major DC optimizer vendors means there is room for competitors. The most likely entrants are major inverter vendors.

The forecasts for both smart and AC module shipments are very encouraging. For the SSTM project this means that industrialization of such solutions should be implemented fast and come in a small cost overhead from standard module designs. In the case of TESSERA and micro inverter (AC module) forecasts show a price of around 0,7 Euros/Wp by 2020. Taking into account the 3-4% extra yield provided by the TESSERA module and micro inverter combination a markup of 3-4% in selling price makes perfect sense.

WP 2: Materials and enabling technologies:

SMART MODULE

In this package the components and control algorithm for the SMART module were developed by UU. There were four focus areas: 1) solar module and solar cells, 2) MPPT, 3) DC-DC converters and 4) IC and control logic. The bill of materials for the SMART module is as follows:

- Back contact module with electrical wiring for groups of solar cells in series with connections to the centre of the back of the module.
- Solar cells are used for small scale demonstration purposes.
- MPPT per group of cells, Heliox provided input to UU on the MPPT algorithm and components.
- DC-DC converters for required I-V levels, Heliox provided input to UU on converter technology.
- Switches
- Sensors and components for safety.
- Control logic.

Simulation results

The described model is implemented to simulate the behaviour of the smart module as well as the other described architectures under different shading patterns. To understand which architecture is more shade-resilient, the harvested energy during a certain period is computed and compared for all architectures. To this end, experimental irradiance data is used as our model input, which is acquired at the Utrecht Photovoltaic Outdoor Test facility (UPOT) at Utrecht University campus in the centre of the Netherlands. Irradiation measurements are done using four EKO MS-802 pyranometers (EKO Instruments, Tokyo, Japan), one EKO MS-401 pyranometer and one EKO MS-56 pyrheliometer; the measurement time is dependent on light intensity and varies from 10 milliseconds to 5 seconds. With these facilities, many variables are being measured every day like irradiation, temperature, humidity, etc.. For this research available data are (i) global irradiation level; (ii) direct irradiation level; and (iii) diffuse irradiation level for four months, i.e., January, March, June and September 2016. The following steps are followed in the analysis:

1. Figure 10 below shows recorded data from UPOT at 7 September 2016. Three different time frames of 15 min in length are chosen to be discussed in this section and are pointed out in the figure.

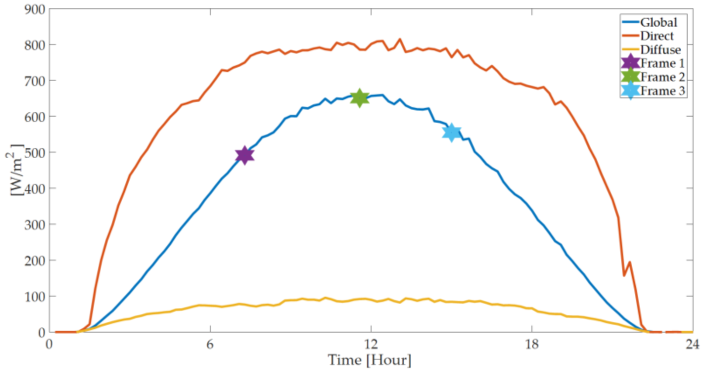


Figure 10. Global, Direct and Di

2. Generate the shading patterns: two types of shadow must be generated. Figures below show different shading patterns and their effect on groups of PV cells for different architectures.

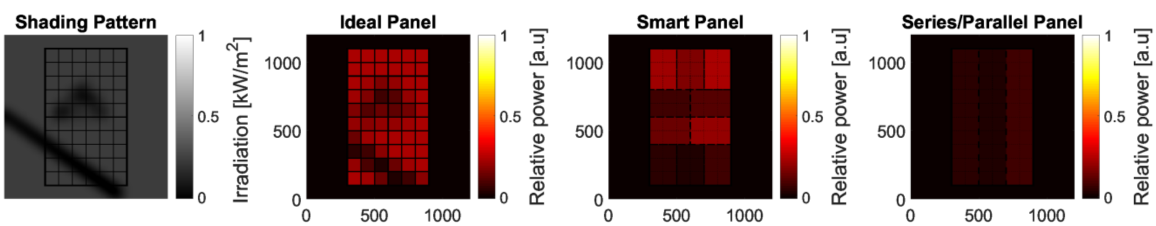


Fig. Combined pole and random shading pattern and effect of that on different architectures at time frame 1

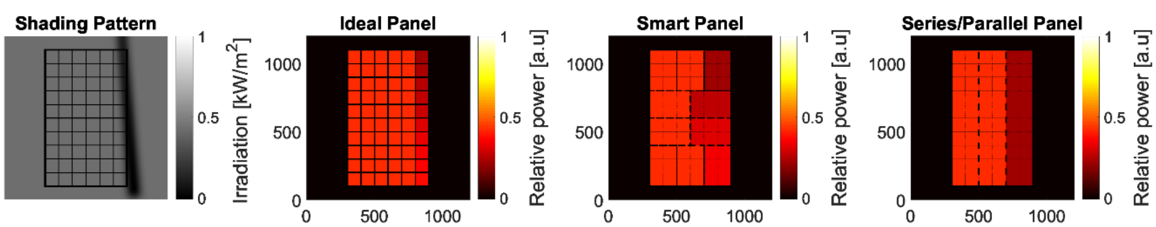


Fig. Pole shading pattern and effect of that on different architectures at time frame 2.

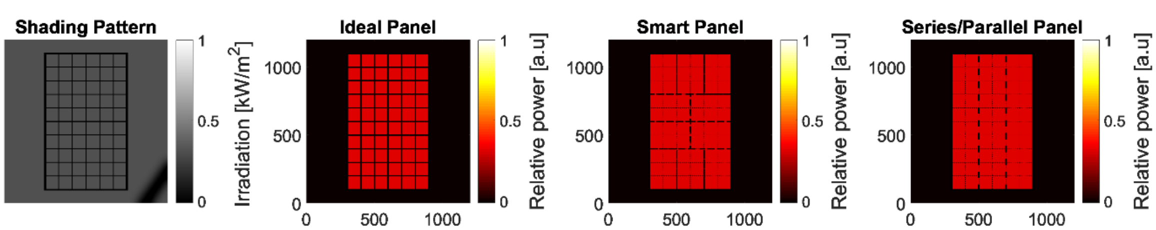


Figure 11. Pole shading pattern and effect of that on different architectures at time frame 3. Note that the shade is not cast on the panel

3. Analysis of the effect of shading patterns on different architectures and cell groups. In this step the effective irradiation level for each group of cells in different architecture is computed precisely.
4. Maximum power output at each time frame is calculated.

5. Each time frame simulates 15 min of the real world with the assumption of having a constant value of irradiation variables.

Figure 12 below depicts the output energy from different module architectures for different months of the year 2016.

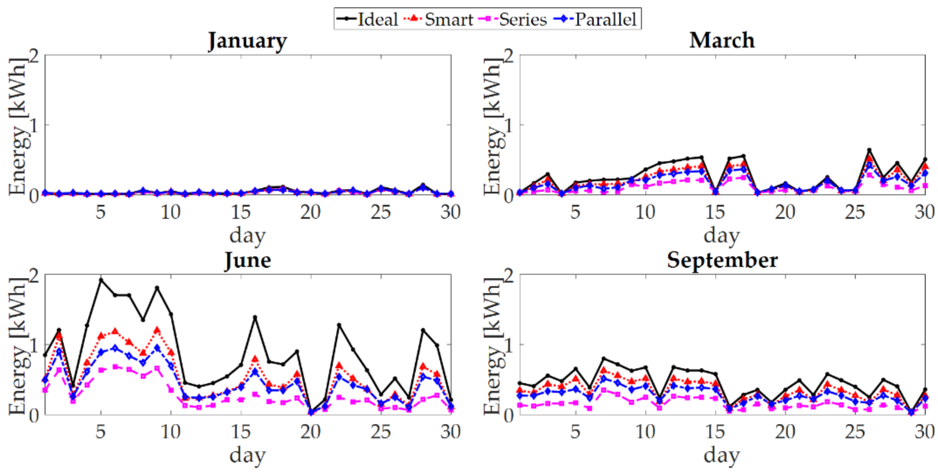


Figure 12. Harvested energy at four different months of the year 2016.

The summation of output energy and the average RE(%) for the whole year 2016 are depicted in Figure 13.

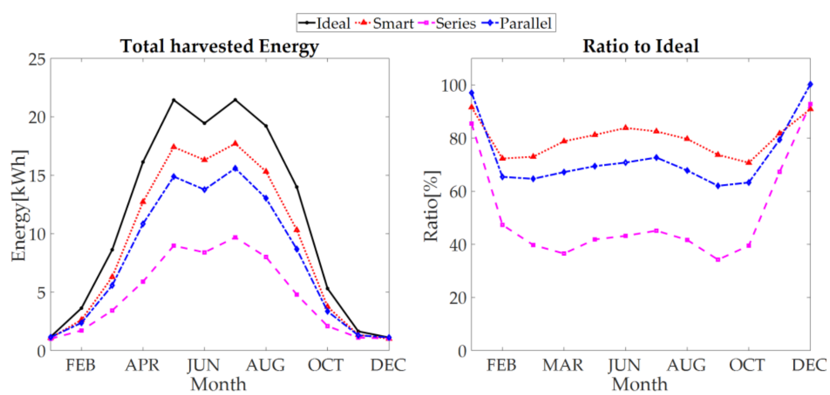


Figure 13. Perspective of total harvested energy during different months in 2016.

It shows that the smart module harvested almost 79.5% of the energy that the ideal module harvests; the series connected harvested 42.2% and parallel connected yield 68.8% of total module capacity under the same shading patterns. The method discussed and improved in this study is based on the fact that even small amounts of power that can be produced by cells should be harvested. In other feasible architectures, series and parallel, there is always some energy loss due to the electrical connections.

Results from prototype

To investigate the feasibility of the smart module we tested the module under a partial shading condition at the PV lab at Utrecht University campus, and recorded data for about one hour. In Figure 14, the variation of shadings is roughly depicted in three TWs of $t_1 \in$ [0; 20] min, $t_2 \in$ [20; 40]min, and $t_3 \in$ [40; 60] min over the panel surface during the data logging. The maximum irradiation level measured on the panel surface within the one hour data logging is 350W/m^2, as measured with a pyranometer, located on the top of the module. It should be taken into consideration that Figure 14 shows only the starting point of the TWs, while the solid and pole shadows move during each TW to reach the next frame.

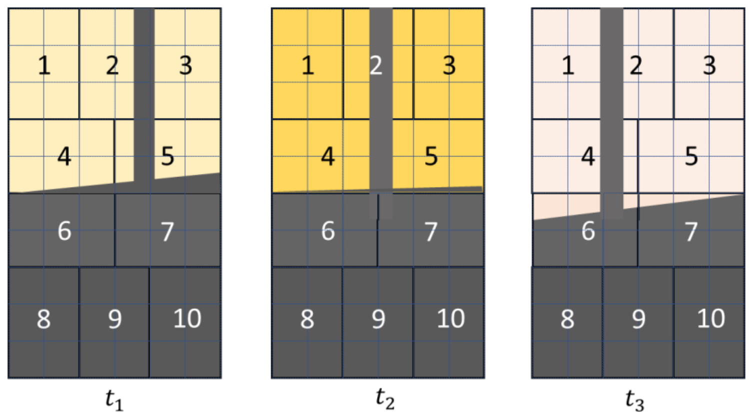


Figure 14. Shades move in three time windows

Figure 15 shows the output power from each group of cells.

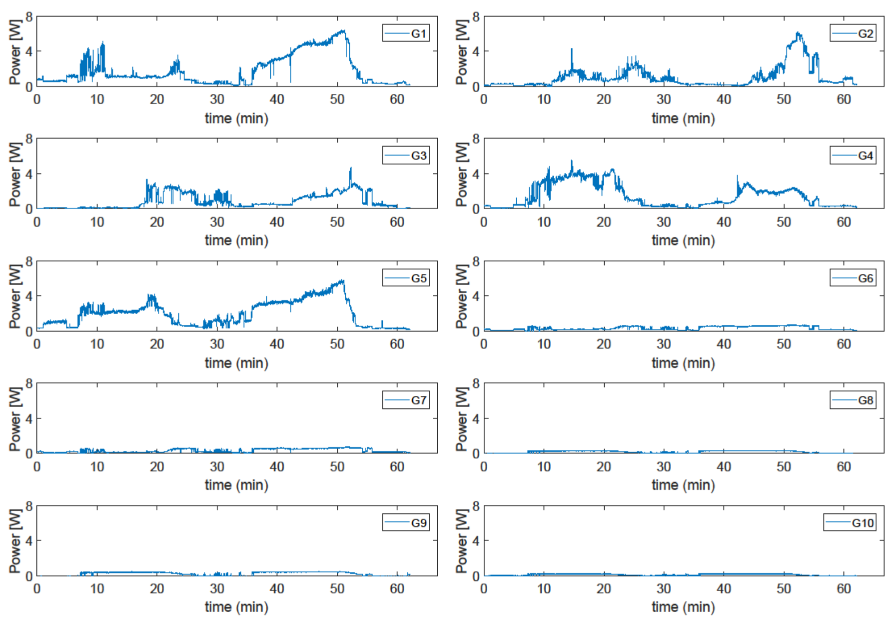


Figure 15. Output Power from the smart panel

TESSERA MODULE

The improved TESSERA module design is based on two developments: a structured backsheet with specific patterning and integration of diodes in the backsheet. ECN designed the desired backsheet patterning. Solned developed a process that can be used for flexible backsheet patterning which enables any desired pattern and developed the production method needed for this patterning. In addition, together with Expice, the integration of diodes on the backsheets was investigated.

Expice has performed a study on the integration of electronics in backsheets. This involved research into various methods of applying conductive glue and/or solder to adhere the components with respect to processing at relatively low temperatures and durability at operating temperatures. Integrating the electronic diodes in the backsheets ended up being quite challenging as the diodes could stop working due to shunting in the lamination process or the diodes could crack the cells. Several tests were executed:

Test 1: Gluing the diodes to the backsheet

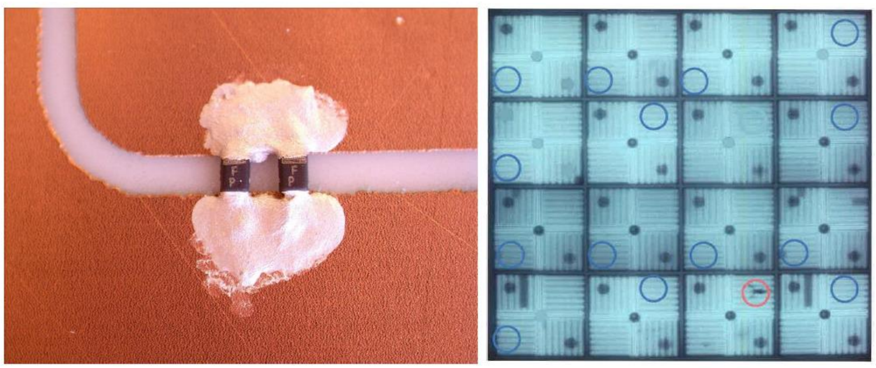


Figure 16: (left) - diodes glued to the backsheet and (right) - cracks in cells due to height of the used diodes (400 microns)

Test 2: Lasering small bins in the adhesive & PET/PVDF/PP layers of the conductive backsheet.

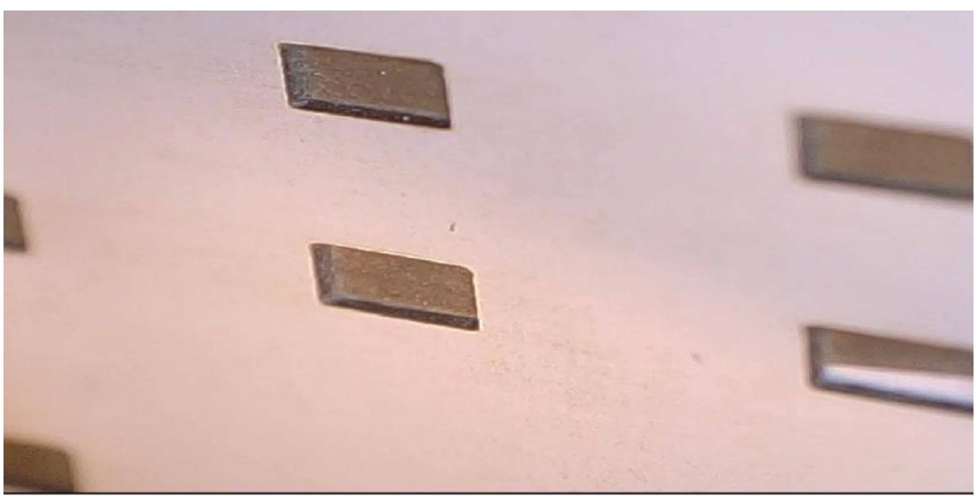


Figure 17: Lasered small bins in backsheet in order to lower the height of the diodes.

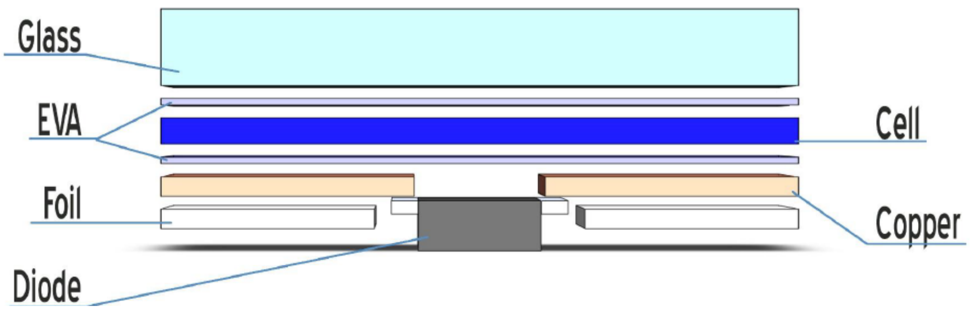


Figure 18: Schematic overview of diodes placed in small bins.

Test 3: Similar to test 1, however the diodes were placed beside the mini cells:

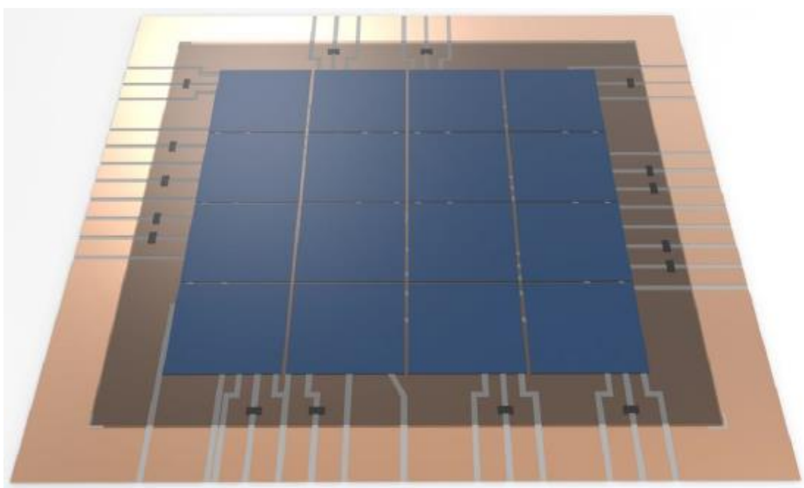


Figure 19: Diodes placed at the side of the mini cells.

Unfortunately the first two tests did not results in a working procedure. The third test did work, but needs more space between the cells to fit the diodes.

The mini-cells for the TESSERA modules were created by cutting the back contact cells. In the TESSERA concept cells are cut into 16 pieces. This leads to challenges in terms of unwanted side-effects of cell cutting/breaking such as reduction of mechanical strength of the cell and the occurrence of microcracks which, in turn, will negatively impact module lifetime and efficiency. Therefore, a suitable cell cutting process with proper handling of the mini-cells was jointly researched by Optixolar and Rimas.

Rimas and Optixolar have researched the cell cutting process together with Rofin-BAASEL (laser scribing expertise), Eurotron (cell handling in combination with the MWT module production process) and other (international) parties. A concept for safe handling of the mini-cells was created and a feasibility study was conducted to determine the optimal lasering process. The following extra production steps are needed in order to produce the SSTM panel:

- Cell lay-up 1: cells need to be taken from a box/tray/carrier and put into the line
- Laser cutting: the standard MWT cell needs to be cut into 16 pieces

- Cell re-orientation: The cell pieces need to be centred again or the robot needs to identify what the position of the cell pieces are
- Cell piece lay-up 2: The cell pieces need to be put into the Eurotron line.

If the cell pieces were to be handled as single pieces, than a pick & place would need to handle around 25 cell pieces / second. This is not feasible with such a product. If 16 cell pieces are prepared as a “normal” cell in a tray this can be solved. However, this will shift the problem to preparing the trays.

Cutting speeds of around 800 meter per hour are needed. Unfortunately, after multiple studies and tests, it turned out that this cutting process would be too expensive to apply in a production line setting due to the amount of lasers that would be needed to perform the actual cutting of the cells. Using less lasers would increase the production time substantially making the process too slow. Also cell handling of the small minicells is, at this moment, too expensive.

WP 3: Prototyping and feasibility:

TESSERA CONCEPT

Previously the TESSERA concept was developed within the project INHYPE and the functionality and lab-scale manufacturability were proven, despite some setbacks during manufacturing.

Durability

One of the aspects that was not tested was the durability of different bill of materials (BoM). This was tested in the current project .

16 cells mini modules were built for the durability tests. Within this experiment backsheets of four different suppliers were tested for which the remaining BoM is based on the full size Tessera module:

- Isovoltaic (group reference)
- Eppstein (group a)
- Coveme (group b)
- Solned foil A and B (group c and d)

Based on the foil comparison there are two promising candidates: Eppstein and foil A of Solned. Unfortunately Eppstein, and meanwhile also Isovoltaic, cannot be ordered anymore.

Modules built using foil A show only less than 5% loss in efficiency after damp-heat and thermal cycling testing, see Fig.20, which is less compared to other foils. This is the reason to use foil A for builing the full size modules.

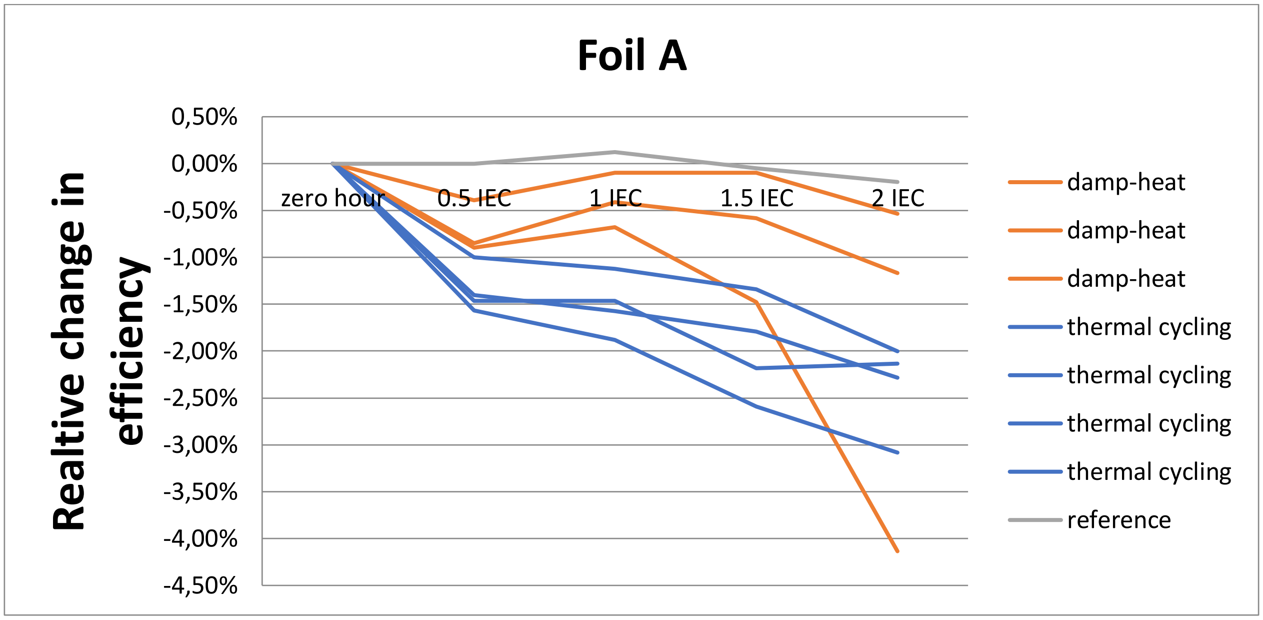


Figure 20: Expected relative loss in power. Leftl for a standard 3-string module and right for a TESSERA module. The colors and numbers indicate the amount of the loss; blue = low, red = high. The black dots are specific reported losses to a TESSERA module

The success of the TESSERA concept was proven by the build of one full size module and performing multiple shadow tests with the Pasan IIIb Flashtester at ECN. The results are shown in Fig. 21 on the right. The black dots indicate the measurements. As can be seen the loss is linear with the shade fraction is much more lineair compared to a standard 3 string panel as shown on the left in Fig. 21. The TESSERA module did not have any bypass diodes. The shadow linearity can be improved further by adding one bypass diode over 16 mini cells. Therefore the in-laminate diodes will be tested under the mini cells in this experiment.

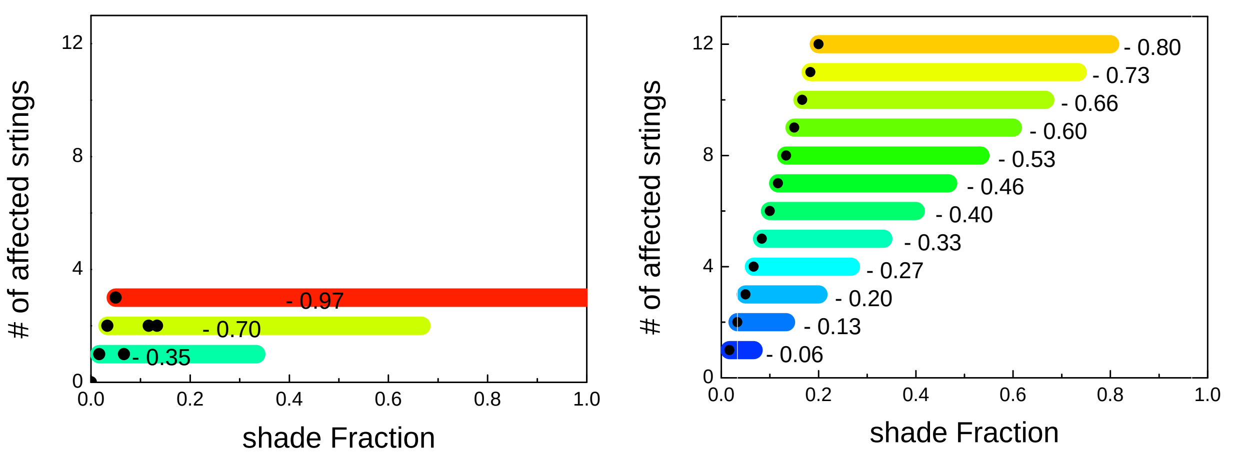


Figure 21: Shade response of a TESSERA full size module

Diode-free concept

The integration of in-laminate diodes is difficult and costly. Therefore it is interesting to see if a diode-free concept is feasible. This might be possible by tuning the electrical reverse characteristics of the mini MWT cell or a mini IBC cell in such way that the conducted current in shaded conditions is substantial better than the original back contact mini cell. This was studied for MWT and IBC cell types. The results of hot spot testing show that the IBC cells are well suited for the diode-free concept, as the module temperature upon blocking the incident light remained below 65 ^{o}C. The modules with MWT cells showed temperatures above 115 ^{o}C.

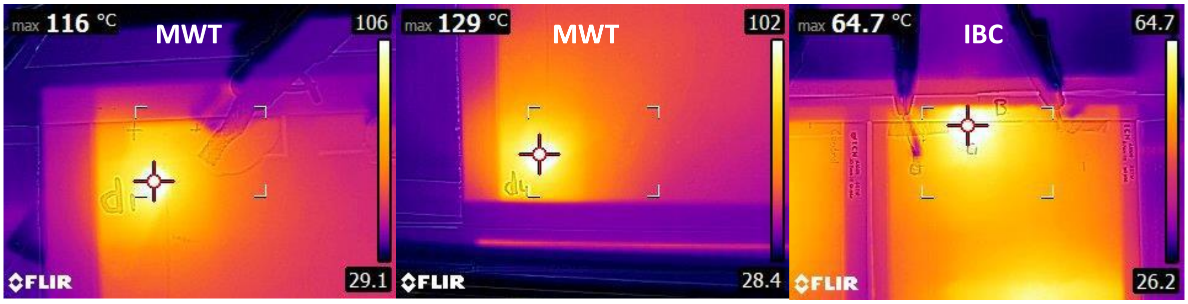


Figure 22: Hot spot test results for back contact modules with MWT and IBC mini cell.

After the feasibility tests, the partners created six TESSERA modules for outdoor pilot testing in Eindhoven. Solned provided backsheet. Due to excessive costs, cell cutting/delivery for the TESSERA prototype was done by FillFactory. Due to delays in the production of the modules by Fill Factory, the project got delayed up to six months. The actual prototypes were produced by Exasun.

SMART MODULE CONCEPT

The goal of the UU was to develop a Proof of Principle of the SMART module With a focus on component integrating (see bill of materials, WP2) and algorithm. UU has developed the main design, development and integration of components into smart circuit, and has development of the algorithm. Expice provided advice and assistance on integration of components in the SMART module. ECN and Heliox have been involved to deliver specific components or provide capacity for prototype production.

The developed Proof of Concept is shown below:

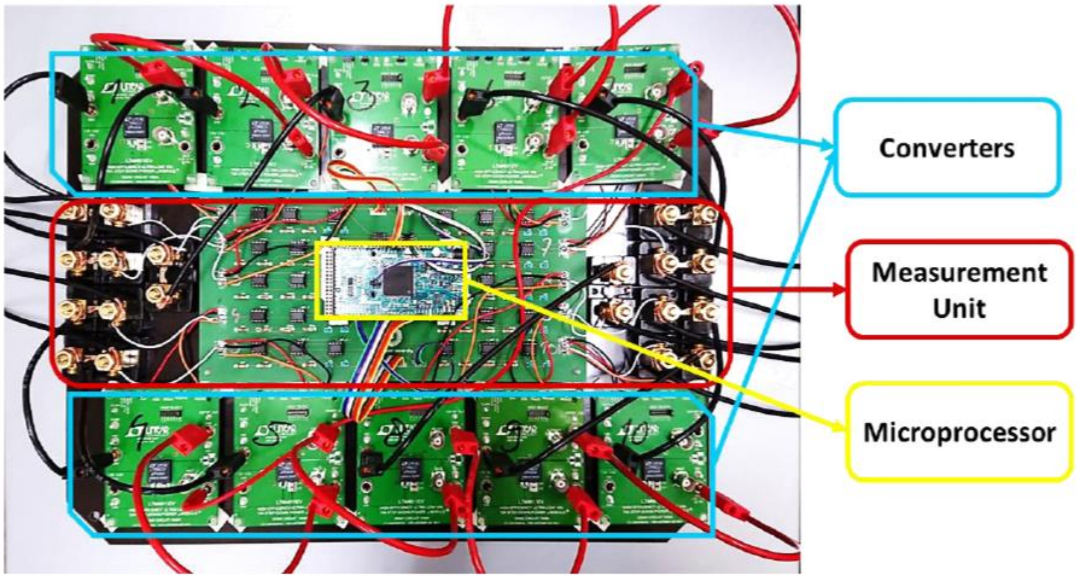


Figure 23: Proof of Concept SMART module – UU.

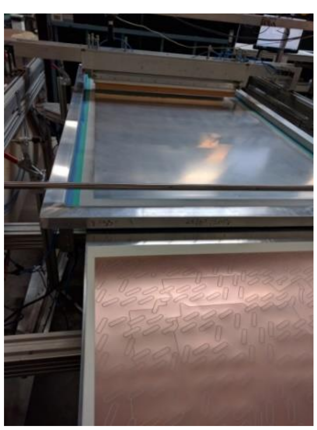
WP 4: System design

TESSERA CONCEPT

Heliox was involved in the INHYPE project in which it conceptually designed a dedicated micro-inverter for the TESSERA module. In this project, this design was further industrialized with reference to the MPPT input power stage including MPPT software algorithms. System electronics were designed for optimal performance of the TESSERA modules in the field.

According to the project plan 6 full size TESSERA modules were planned to be made at Eurotron. However at the time the order had to be placed, Eurotron was stopping all PV activities. As an alternative Exasun was asked to make the modules. They normally make glass-glass MWT modules so their production had to be adapted. Also for the handling and placing of the mini-cells.

The first module that was made looked good from a visual perspective, but it did not work. After careful inspection it was noticed that a corner of a cell was punching trough the encapsulant. By opening the rear, the problem was solved and the module worked properly. In the end, 6 working modules were produced.



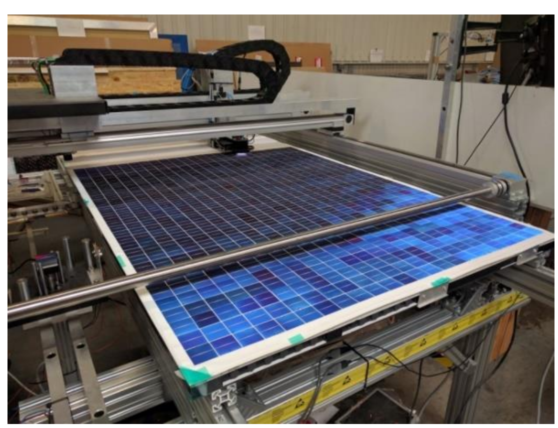


Figure 24: Production of the TESSERA module.

Figure 25: Produced TESSERA modules.

The TESSERA modules have been equipped with micro inverters from HELIOX. An additional system serving as a reference (reference 1) has been installed next to the TESSERA system with standard 60 cell (three substrings of 20 cells). The same micro inverters have been used for the reference system. An additional reference system (reference 2) consisting of 6 series connected standard solar modules is also installed in front of the Tessera system. This system is connected to a string inverter from Mastervolt (1500 WEB)

The systems are fully monitored in terms of electricity production for the DC and the AC part with high accurate power analysers. Moreover temperature sensors are deployed and a secondary standard pyranometer in the plane of the solar modules to measure the irradiance. Data is synchronized providing for all data points the same time stamp. Data points were acquired every second and then averaged for every minute.

Figure 26. Picture of the TESSERA system. A pole is casting shade on several modules

The TESSERA modules have a steady voltage output regardless of the partial shading conditions. When partial shading occurs only a portion of the current is reduced. In this way the power electronics can work more efficiently. In figure 27 the relation of voltage, power output and inverter efficiency can be seen. The data set includes more than six months of data. It can be seen that indeed the voltage output stays in a certain range which is only affected by the module temperature and not by partial shading.

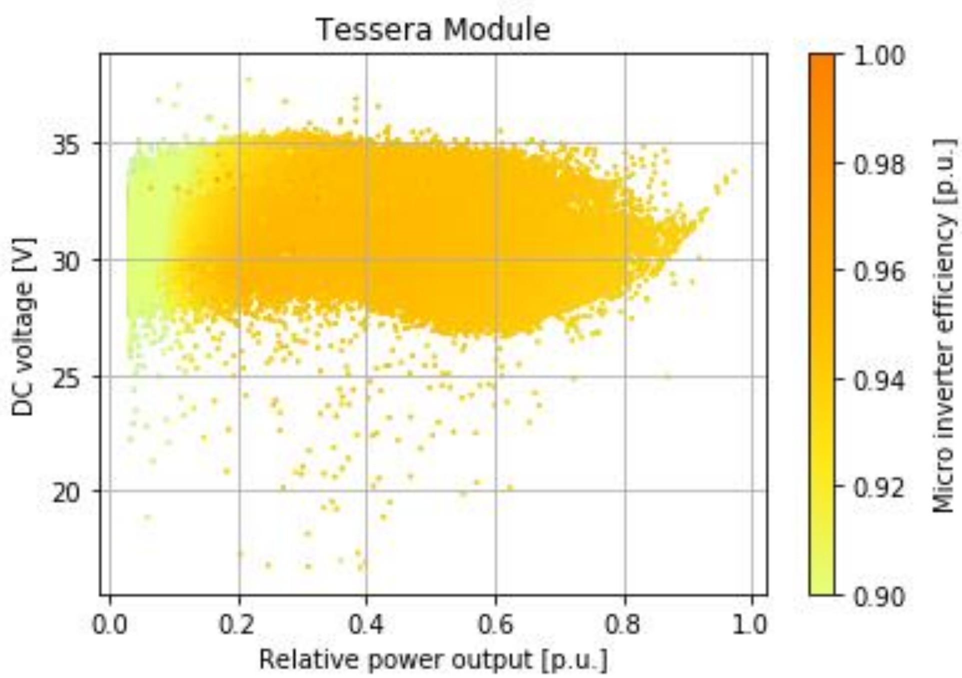


Figure 27. Correlation of Vmpp, power output and micro inverter efficiency of the TESSERA module

DC Performance ratio per month for the three systems

PV System	Feb	Mar	April	May	Jun	Jul	Aug	Sep
TESSERA	0.96	0.94	0.90	0.89	0.88	0.86	0.81	0.89
Reference1	0.94	0.94	0.89	0.85	0.91	0.86	0.78	0.87
Reference2	0.80	0.89	0.85	0.82	0.88	0.82	0.72	0.82

AC Performance ratio per month for the three systems

PV System	Feb	Mar	April	May	Jun	Jul	Aug	Sep
TESSERA	0.91	0.88	0.85	0.84	0.83	0.81	0.76	0.84
Reference1	0.88	0.87	0.83	0.80	0.85	0.81	0.73	0.82
Reference2	0.76	0.84	0.81	0.77	0.84	0.78	0.68	0.78

SMART MODULE CONCEPT

The prototype of the SMART module with realistic current levels (8-9 amps) has been manufactured. These modules were tested in a steady state solar simulator.

WP 5: LCOE

In work package 2 and 3 the technical feasibility of the developed concepts and components have been determined. In this work package, the project plan stated that these results should be translated to an evaluation of the proposed business cases. Due to the costly production of the TESSERA modules SEAC was forced to create an overview of accurate market prices based on interviews with installers and calculate what the highest price of the TESSERA module could be compared to regular modules.

	Residential (5kWp)	Small Commercial (100kWp)
Modules	0,48	0,435
Inverter	0,16-0,3	0,07
Mounting	0,1	0,126
DC cabling	0,02	0,043
Grid connection	0,05	0,025
Labor	0,2	0,1
	1,1 – 1,15	0,8

In the previous chapters the Tessera module technology has been evaluated in terms of annual yield benefit for a residential system of 5KWp. While the Tessera system outperforms the standard technology under partial shading conditions, a full economic analysis is needed to compare the initial investment for a Tessera system versus a standard system. To do this a price for Tessera modules has to be determined.

Taking into account the complexity of the Tessera module and the fact that to come up with a price per Wp a whole production line has to be designed, including all the associated costs. The first impressions of such calculations are that the adaptation of an automated standard production line for c-Si modules will not be economically viable. This is due to the high costs needed for cutting the 6 inch MWT cells into 16 mini cells. At the moment there are production machines that can cut full cells into 2 or 4 pieces. There is not an of the self-production machine that can cut 16 mini cells out of a full size cell. Moreover , picking and placing the mini cells in the module assembly is very difficult due to the small size of the cells. Glass selection is also difficult due to the larger size of the Tessera module. This is because the mini cells have a certain distance between them and as a result the Tessera module is significantly larger than a standard c-Si module.

The results from WP2 and WP3 have been combined with the results generated by lab and field testing. Subsequently, the SEAC techno-financial model is applied. Based on the information at hand, the TESSERA module can cost up to 9,2% more when comparing standard modules vs TESSERA modules with a micro inverter. Taking into account the extra production costs such as laser cutting the cells and pick and place robots for the mini cells, it doesn't seem feasible to manufacture the TESSERA module at reasonable cost. In order for the TESSERA module to be produced more cheaply, development on cell cutting and handling is needed.

WP 6: Project management

The partners have hired Chematronics to coordinate overall planning between the work packages and organizes quarterly consortium meetings. Continuous monitoring ensured that adaptations were made when necessary in discussion with the project partners, RVO and the TKI Solar Energy. Furthermore, possible activities with third parties are coordinated centrally.

During the project, progress on content and financial progress have been monitored on a quarterly basis. Chematronics has reported progress and anomalies to the steering committee and when needed to the TKI Solar Energy and RVO. When needed, project changes are implemented and formally approved.

Follow up activities

SSTM has managed to achieve a large number of results of which some will have a follow-up after the end of the project. This project has produced unique results for both ECN → TNO and UU.

Taking into account the SSTM project deliverables, two distinct approaches will be evaluated. One is categorized as a AC modules (TESSERA module and attached micro inverter). The other is the proof of concept for the SMART module (DC optimization).

The growth of smart and AC modules is inevitable. MLPE suppliers all point to integrated smart and AC modules as part of their long term roadmap. As the MLPE market matures, it is expected that reliable power electronics will find their way into embedded PV modules. The market is projected to see a gradual growth in the sales of smart and AC modules rather than a tipping point. The biggest challenge for the smart and AC modules remains the business model and not the technology. Module vendors will be helped considerable by showing to their customers embedded modules as a cost effective solution rather than a premium product. There is room for more MLPE vendors to enter the market, especially in the power optimizer segment. The window for new entrants is narrow but the existence of only 3 major DC optimizer vendors allows room for competitors. The most likely entrants are major inverter vendors.

The forecasts for both smart and AC module shipments are very encouraging. For the SSTM project this means that industrialization of such solutions should be implemented fast and come in a small cost overhead on standard module designs. In the case of TESSERA and micro inverter (AC module), forecasts show a price of around 0,7 Euros/Wp by 2020. Taking into account the 3-4% extra yield provided by the TESSERA module in combination with a micro inverter, a mark-up of 3-4% in selling price makes perfect sense.

From a geographical standpoint, Europe will continue to dominate the power optimizer market. AC module shipments will also grow but in a slower pace. Till today, there is no distinguish between integrated and standard modules in EU legislation and thus the minimum import price enables suppliers to sell integrated modules with the artificial module price increase converting a portion or all the DC optimizer or micro inverter costs. This creates a strong incentive to integrate the MLPE products in the manufacturing stage rather than in the field. US serves as the base of MLPE shipments worldwide with strong long term prospects for the residential sector. Legislation in the US encourages the use of MLPE while changes in NEC code in 2017 will include rapid shutdown on the module level and thus create additional incentives for AC and smart modules.

All in all the PV industry and market are hungry for solutions that simplify labour, eliminate redundancy and lower overall costs. It seems that all of these objectives can be accomplished with smart and AC modules.

Discussion, conclusion and recommendations

SSTM was an ambitious project with a large number of innovative objectives. Most objectives have been achieved and all experiences and results have led to further insights for the partners. For some results there was a deviation from the original project plan for strategic, product or market technical reasons, but relevant additional results have been achieved. The table below gives an overview of results achieved.

WP 1: Concept design Category: Industrial Research		
D1.1	Simulation model for shade tolerant concepts	University Utrecht
D1.2	Optimal topology and granularity determined through testing of numerous shading scenarios	University Utrecht
D1.3	SMART module concept design	University Utrecht
D1.4	Improved TESSERA concept design	ECN→TNO
D1.5	Annual yield model TESSERA module	ECN→TNO
D1.6	Benchmark shade tolerance techniques	ECN→TNO

WP2: Materials and enabling technologies Category: Industrial Research		
D2.1	Design of SMART components	University Utrecht
D2.2	Design of TESSERA backsheet alternatives	Solned
D2.3	Design of diode integration process in TESSERA backsheet	Expice
D2.4	Mni-cell design for TESSERA module based on MWT cells	ECN→TNO
D2.5	Concept design mini-cell cutting and handling process in module production line	Rimas

WP3: Prototyping and feasibility Category: Industrial Research/Experimental Development		
D3.1	Feasibility tests Optixolar	Optixolar
D3.2	Feasibility tests mini-modules TESSERA at ECN	ECN→TNO
D3.3	Feasibility test of foil structuring	Solned
D3.4	Feasibility test of diode integration	Expice
D3.5	Feasibility test of diode free TESSERA module	ECN→TNO
D3.6	Small scale prototype available of Smart module	University Utrecht
D3.7	Full sized prototypes available of TESSERA module	ECN→TNO

WP4: System design Category: Experimental Development/Experimental Development		
D4.1	Micro-inverter design for TESSERA concept	Heliox
D4.2	System design for TESSERA modules	Stafier
D4.3	Field test installation of TESSERA modules	ECN→TNO
D4.4	Field test results TESSERA modules	ECN→TNO
D4.5	Lab test results of SMART modules	ECN→TNO

WP5: LCOE Category: Experimental Development		
D5.1	Component level cost models	ECN→TNO
D5.2	System level costs model	ECN→TNO
D5.3	Techno-financial model	ECN→TNO
D5.4	TESSERA LCA	University Utrecht
D5.5	SMART module LCA	University Utrecht

WP6: Project management Category: Industrial Research		
D6.1	Minutes of consortium meetings	ECN→TNO, Chematronics
D6.2	Financial reports	ECN→TNO, Chematronics
D6.3	Progress reports	ECN→TNO, Chematronics
D6.4	Minutes of Review Board meeting	ECN→TNO, Chematronics

The complexity of the project has created various challenges during the execution process and thus affected the project. Therefore, some recommendations and remarks.

- Cooperation between partners, each with their own ambitions, experiences and objectives, requires continuous coordination of strategic and operational interests. By completing the project management from an independent party, all interests were taken into account with successful results for various partners. In addition, this offers the possibility of engaging in an open collaboration with each other even in risky and even potentially competitive activities. The agreement of commercial exclusivity in advance in projects where the uncertainty is still great, hampers cooperation rather than intensifying it.
- Multiple industries that do not have much in common create constantly changing conditions that influence the market perspective of innovations.
- Building modules the TESSERA and SMART module way can result in higher efficiency in shaded conditions, however, due to the handling costs, it currently is too expensive to produce the modules. With regards to the TESSERA module, cutting regular cells into quarter or half cells can be interesting to lower handling costs and cell cutting costs.
- One of the results (D4.2) was linked to a party that was not part of the project partners in this consortium which made collaboration more difficult.
- Working with a review board with representatives of the market was challenging. In order to gain insight into the decision criteria of such parties, it is necessary to get representatives involved at the right level of these organizations. It appears to be difficult to retain this involvement when the commercial interest in the short term is not yet completely clear. As the developments in this project are not yet market ready, collaboration with the review board is of more importance in a follow up project.
- The ambitions were high and the diversity of innovations was large. On the one hand this generates broad knowledge sharing and a focus on aspects in the system. On the other hand, this has caused some delay in achieving some results. A clear project phasing with jointly agreed milestones and decision moments is necessary to maintain project progress and to keep track of the status of the various developments in relation to the agreed goals.

In conclusion, the project partners look back on a challenging project that ultimately led to positive results for those involved.

Project implementation

The project has had various challenges. These have resulted in the need of more time to achieve the project results and a slight deviation regarding the application of the coatings. These are explained further below.

Technical, organizational challenges and project changes

There have been several technical challenges which are explained below:

- Due to a late approval of the project, the activities in the project were initiated later than the start date.
- Cell cutting of the solar cells: Cutting the solar cells into 16 separate mini cells was both difficult and costly. Multiple lasers are needed in order to cut the cells precisely. Furthermore, pick-and-place equipment needs to be able to handle 16 mini-cells at a time. Current technology uses one large suction cup per solar cell. Having a production line that is able to pick-and-place 16 mini cells was either too challenging or costly.
- Based on the yield of the TESSERA module, the price of a module can (only) be 9,2% higher than standard reference modules which means this technology is currently not viable for market introduction.

Organisationally, one important change has taken place:

- Request for project extension of 6 months – approved on 28 February 2018 by RVO;

In addition to the above technical and organisational challenges and associated changes, no further substantive changes have occurred. All significant changes were reported to RVO during the project and approved where necessary.

Dissemination

Dissemination activities have aimed to promote non-confidential results obtained within the project as swiftly and effectively as possible to benefit the whole community and avoid duplication of R&D efforts. Multiple publications were done:

5-4-16	Scalable Shade Tolerant Module project kicks off	SEAC newsletter
9-6-17	Towards new module and system concepts for linear shading response	IEEE Conference Proceedings
5-3-17	Shade response of a full size TESSERA module Shade response of a full size TESSERA module Shade response of a full size TESSERA module Shade response	Jap Journ of Appl Phys; PVSC conference proceedings
25-9-17	An Adaptive PSO-Based Approach for Optimal Energy Harvesting in PV Systems	University Utrecht, S.Z. Mirbagheri Golroodbari, W.G.J.H.M van Sark
2-10-17	New module concept for aesthetic PV integration with better shadow performance	Proceedings Adv. building skins Conference
13-12-17	Improvement of Shade Resilience in Photovoltaic Modules Using Buck Converters in a Smart Module Architecture	MDPI - University Utrecht
24-9-18	Design and Simulation for a Shade Resilient Smart Module	University Utrecht, S.Z. Mirbagheri Golroodbari, W.G.J.H.M van Sark
24-9-18	EUPVSEC: Outdoor performance characterization of a novel shadow tolerant module.	SEAC, K. Sinapis

PR project en verdere PR mogelijkheden

The project partners would like to be approached for any further publicity activities and would like to contribute to public activities of the Rijksdienst voor Ondernemend Nederland or the TKI.