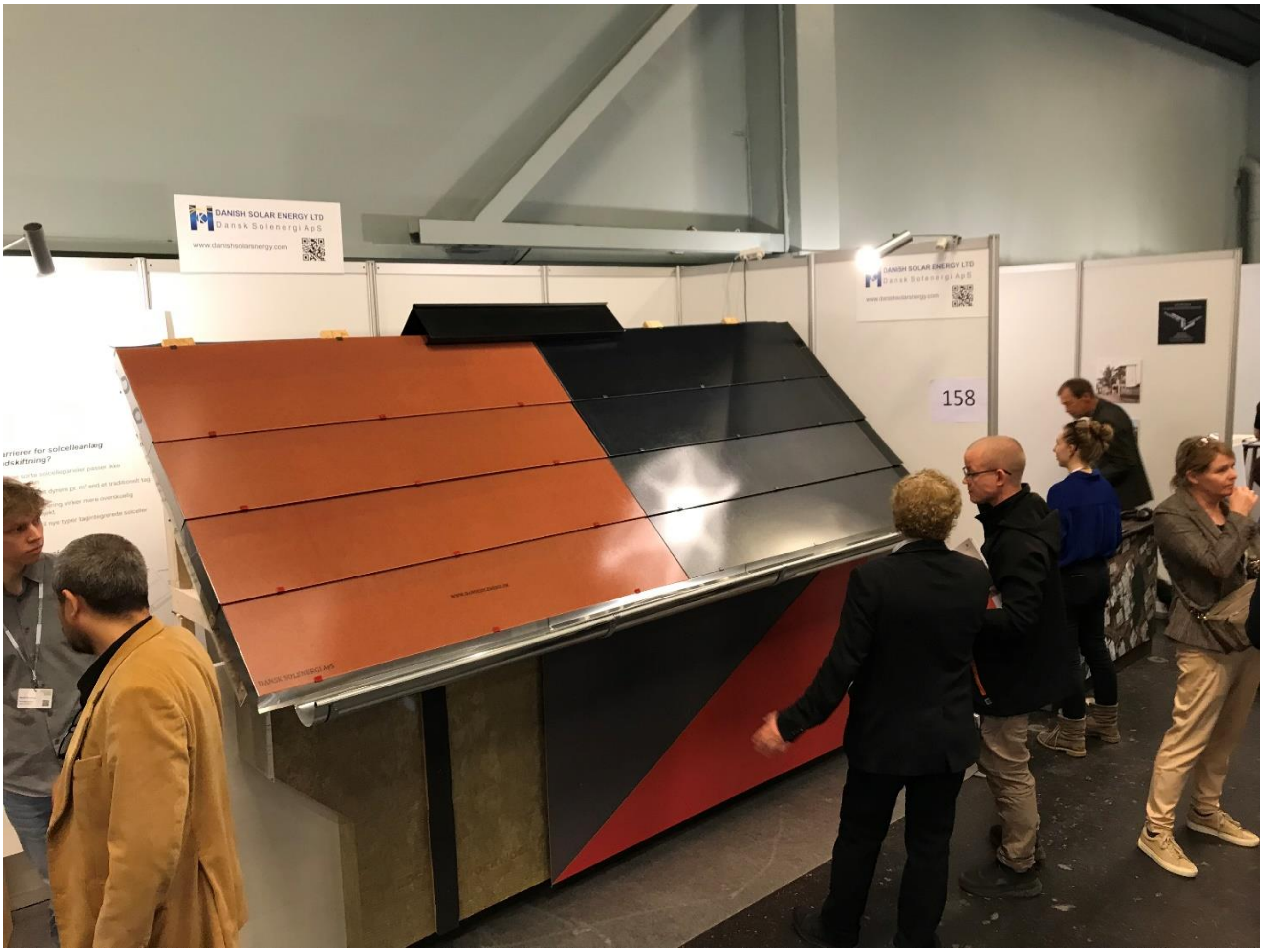
PV-ROCK-ROOF

Final report
January 2023



Title:
PV-ROCK-ROOF

EUDP project number
64019-0029

Project partners
Danish Technological Institute (project coordinator)
DTU Fotonik
ROCKWOOL
Dansk Solenergi
EFFEKT
Solar City Denmark
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January 2023

Front page
Photo from Building Green exhibition in Copenhagen 2021

Table of Contents

1. Project details 4
2. Summary 5
2.1 English summary 5
2.2 Danish summary 5
3. Project objectives 6
4. Project implementation 7
5. Project results 9
5.1 WP2 Building envelope design 9
5.1.1 Market and cost analysis 13
5.2 WP3 Colored BIPV module R&D 19
5.3 WP4 Optimization of module manufacturing 32
5.4 WP5 Module test and verification 34
5.5 WP6 Full system demonstration 35
5.6 WP7 Dissemination of results 37
6. Utilisation of project results 40
7. Project conclusion and perspective 42
8. Appendices 43

1. Project details

Project title	PV-ROCK-ROOF
File no.	64019-0029
Name of the funding scheme	EUDP
Project managing company / institution	Danish Technological Institute
CVR number (central business register)	56 97 61 16
Project partners	• ROCKWOOL • DTU Fotonik • Dansk Solenergi • Mernild Byg • Tegnestuen EFFEKT • Solar City Denmark
Submission date	31 January 2023

2. Summary

2.1 English summary

Existing buildings in Denmark contribute to the total energy consumption with about 40 %, and a reduction of their demand is one of the most cost-effective ways to fulfil the goal of 100 % renewable energy in 2050. Furthermore, the environmental footprint of buildings is becoming more and more important when selecting construction materials. By combining stone wool with active BIPV modules, the energy for construction can be wholly or partly offset by the electricity produced.

The objective of the PV-ROCK-ROOF project is to develop a cost-effective, aesthetical, and energy saving roof-cover where a new type of photovoltaic (PV) module is attached to the insulation without the need for any further weather protection. Dansk Solenergi has developed a novel method for manufacturing colored PV modules without major impact on performance, and these modules will be further refined and verified as a part of the project. Finally, the entire system has been demonstrated on a full-scale roof. The project aims at:

1. Development and demonstration of a new cost-effective building envelope with integrated PV modules – “PV-ROCK-ROOF”.
2. Research and development of materials and methods for a cost-effective exterior thermal insulation of large roof areas.
3. Research in translucent colored layers and surfaces for aesthetical PV modules that can replace the ordinary roof membrane.
4. Preparation for marketing (Certification needs for PV elements and the entire system. Safety, energy, and environmental standards/ratings).
5. Dissemination of results by Solar City Denmark (Video/visualization).

2.2 Danish summary

Eksisterende bygninger i Danmark bidrager til det samlede energiforbrug med omkring 40 %, og en reduktion af dette forbrug er en af de mest omkostningseffektive måder at opfylde målet om 100 % vedvarende energi i 2050. Derudover bliver bygningers miljømæssige fodaftryk til stadighed mere og mere vigtigt, når der skal vælges byggematerialer. Ved at kombinere stenuld med aktive BIPV-moduler kan energien til byggeri helt eller delvist opvejes af den producerede elektricitet.

Formålet med PV-ROCK-ROOF-projektet har været at udvikle et omkostningseffektivt, æstetisk og energibesparende tagelement, hvor en ny type PV-modul fæstnes til isoleringen uden behov for yderligere vejrbeskyttelse. Dansk Solenergi har udviklet en ny metode til fremstilling af farvede PV-moduler uden større indvirkning på ydeevnen, og disse moduler vil blive yderligere raffineret og verificeret som en del af projektet. Endelig vil hele systemet blive demonstreret på et fuldskalatag. Projektet sigter mod:

1. Udvikling og demonstration af en ny omkostningseffektiv klimaskærm med integrerede PV-moduler – "PV-ROCK-ROOF".
2. Forskning og udvikling af materialer og metoder til en omkostningseffektiv udvendig varmeisolering af store tagflader.
3. Forskning i gennemskinnelige farvede lag og overflader til æstetiske PV-moduler, som kan erstatte den almindelige tagmembran.
4. Forberedelse til markedsføring (Certificeringsbehov for PV-elementer og hele systemet. Sikkerhed, energi og miljøstandarder / ratings).
5. Formidling af resultater ved Solar City Denmark (Video / visualisering).

3. Project objectives

The PV-ROCK-ROOF project aimed at:

1. Development and demonstration of a new cost-effective building envelope with integrated PV modules – "PV-ROCK-ROOF".
2. Research and development of materials and methods for a cost-effective exterior thermal insulation of large roof areas.
3. Research in translucent colored layers and surfaces for aesthetical PV modules that can replace the ordinary roof membrane.
4. Preparation for marketing (Certification needs for PV elements and the entire system. Safety, energy, and environmental standards/ratings).
5. Dissemination of results by Solar City Denmark (Video/visualization).

The project has succeeded in development and demonstration of a combined roof renovation solution for heat savings and local electricity generation with PV modules. The system can also be used in new buildings and offers a new construction method which is simpler and faster to implement than traditional roofs. The exterior roof insulation forms a continuous layer and connects to facade insulation without thermal bridges. The appearance can be adjusted to the color and style of the adjacent roof material.

Figure 1: Photo of one of the experimental mockups showing different PV colors.

4. Project implementation

Like many other activities in the period 2020-22, the project was affected by restrictions due to the COVID-19 pandemic, in particular travels and physical meetings were restricted.

Regarding the technical ideas and product development, the project evolved as planned. However, some of the original ideas were modified during the process:

- The glued lamination of PV and stone wool was given up due to the disassembly requirements that would be important in a future where circular economy becomes more and more important. This is a key selling point for tomorrow's construction materials.
- The product development on a flat-roof solution was interrupted in the middle of the project because the partners concluded that the commercial perspectives would be better for sloped roofs where the product is more visible, and house owners are willing to pay extra for aesthetics.

On the organizational level, the project group was changed after some time, as it turned out that the partnership between SolarTag and Danish Solar Energy could not continue as planned, and SolarTag had to leave the project. This was partly due to a successful marketing of SolarTag´s own products that would – to some extend - compete with the PV-ROCK-ROOF solution. After some time, Mernild Byg replaced SolarTag and took over the obligations regarding construction of mockups and evaluation of the developed solutions.

The main technological risk identified in the project was if the temperature of the PV cells would become critically high, which could harm encapsulation materials and reduce lifetime. Another important risk was if it was not possible to find a host for demonstration of the final system. Fortunately, Rockwool proposed that they could become the host and the systems could thus be successfully demonstrated at the end of the project.

The milestones have generally been met, however with some delay and complications:

<u>Milestones</u>

M1 Prototype finished: This milestone is more than fulfilled. Several different prototypes and models have been constructed and evaluated, and many drawings have been generated in the work process.

M2 Semi-automatic production (20 units): This milestone is more than fulfilled. Danish Solar Energy (DSE) has produced a lot more in the project period with semi-automatic equipment. The machines used for this were rebuilt as a part of the project.

M3 Critical PV tests passed: Milestone fulfilled. UV tests and performance tests showed no degradation of the colored PV modules. A complete module test according to IEC61215 was initiated in the project period, and the preliminary results from TÜV show that the first tests (Gate 1) are successfully passed. The last results are pending by December 2023.

M4 Critical system tests passed: Milestone fulfilled. A combined rain and wind load test was performed in one of DTI's laboratories, and long-term outdoor testing was conducted as a supplement to this. The results showed no sign of rain penetration or thermal damage.

M5 Optical model: This milestone is fulfilled and refers to the advanced color model developed based on the angular reflected light from the colored solar modules.

M6 Demosystem established: Milestone fulfilled. A complete rooftop system has been constructed at Rockwool in Hedehusene. The system comprises 60 modules from DSE mounted with the newly developed method. The roof is mounted with sensors for humidity and temperature as well as power monitoring equipment. Rockwool will follow the system performance beyond the project period.

Research Milestones

RM1 Review of available BIPV products (Publication 1: P1): Milestone fulfilled. A summary of the available coloring technologies for BIPV was given in the master thesis entitled *Degradation study of colored building integrated photovoltaic modules* by Marco Marcellan.

RM2 BSDF and PV power analysis: Milestone fulfilled by measuring the angular resolved power output of several different colored modules. Additionally, the optical setup at DTU Fotonik was extended with a spectrometer enabling the angular resolved color measurements by the BSDF technique.

RM3 BIPV Characterization Model (Publication 2: P2): Milestone fulfilled linking color theory and measurements from RM2 The modelling was extended into including also glare. The fundamentals were published in the master thesis entitled *Experimental characterization of angular dependent color perception of colored PV samples in combination with IAM measurements targeting building integrated photovoltaic products* by Markus Babin. The work led to four international peer reviewed publications, and the glare model is proposed in the IEA PVPS TASK 15 as a physical metric for assessing glare from BIPV systems.

RM4 DSE Concept characterization: Milestone fulfilled by BSDF and power characterization in laboratory setups and furthermore outdoor exposure to sunlight logging the power.

RM5 Color lifetime tests: Milestone fulfilled and published in RM1 publication.

RM6 Comparison of BIPV technologies: Milestone fulfilled and published in RM1 publication.

Commercial milestones

CM1 Draft business plan ready: Milestone fulfilled. The business plan consists of user cases and calculations of the cost per m2 using traditional and PV-ROCK-ROOF renovation.

CM2 Patent application issued: Not fulfilled. For strategic reasons, the commercial partners have decided to continue their work without issuing a patent application.

CM3 Presentation seminar: Milestone fulfilled. A webinar was held in the first part of the project period, and a final public meeting was held at the end of the project (8 December 2022). Photos and videos from the events are presented at the project web site.

Unexpected problems

The project faced some unexpected problems, mainly COVID-19 related, but also difficulties and delays concerning the testing and certification of the modules from DSE. Furthermore, the change of one partner with another was not foreseen and caused a significant delay. The construction of the demo plant was affected by supply chain problems related to the global market situation and could therefore not start until very late in the project.

5. Project results

No project follows exactly the way it was planned to, and so with PV Rockroof. During the project many different ideas and concepts were discussed and tried in practice under the different work packages:

- WP2 Building envelope design. This WP developed technical and architectural solutions as preparation for the test and demonstration of the system.
- WP3 Colored BIPV module R&D. This WP was centered around the work done by a PhD student at DTU and resulted in improved methods for characterization of colored PV modules.
- WP4 Optimization of module manufacturing. This WP resulted in an improved production line at Danish Solar Energy.
- WP5 Module test and verification. In this WP the first generation of modules and system solutions were tested and documented.
- WP6 Full system demonstration. A demonstration system was constructed in this WP.
- WP7 Dissemination of results. The results include a variety of articles, videos and exhibitions.

Important results from the work packages are presented in the following.

5.1 WP2 Building envelope design

This work package got a lot of attention in the beginning, and several ideas and solutions were tried in practice, both sloped roof and flat roof solutions. Some of this material is confidential and not published. The tangible results of this work package are the WP2 report (Annex A) and the mockups that were developed during the project:

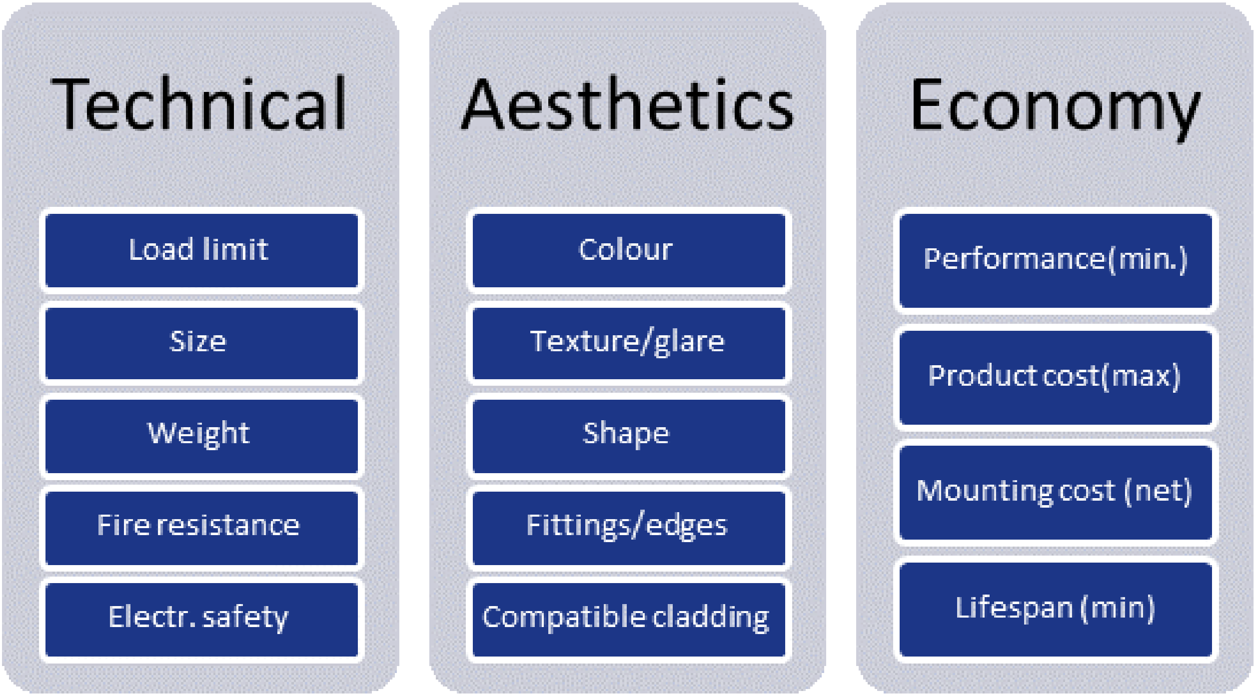
1. Mockup#1 for raintest
2. Mockup#2 made for the Building Green and Intersolar exhibitions
3. Mockup#3 made for outdoor testing at DTI.

Furthermore, sketches and presentations of architectural solutions have been produced. A calculation tool for economic assessment was also made and some of the results are shown later in this section.

General requirements for the BIPV

The process began with identifying a list of questions and desired properties of the system. PV laminates are developed in their basic form by DSE (Danish Solar Energy) but need redesign. Some of the obvious questions are:

- One size or multiple? Elements for fixation and water proofing need to be integrated.
- Mounting methods: Do the PV laminates need to be glued, or should they be dismountable? What should be the maximum weight or size? Are the elements intended for new buildings or renovation?
- Technical requirements: Fire resistance, durability, water tightness, temperature.
- Economical constraints: Added value vs. added cost. What would the reference cost of a traditional solution be?
- Aesthetic requirements: Should the solution fit to Copenhagen roofs? Reduction of glare (comparison of different glass types).



In the beginning of the project there was focus on two roof types, each with specific challenges.

Pitched roof solution requirements:

1. Should it be mounted from the top and down or the opposite?
2. Should the design fit existing roofing materials?
3. Which type of roof construction should the solution fit to?

The advantage of the pitched roof solution is that it addresses a huge market of single-family houses where roofs need replacement in the near future and where the design element is more important than by flat roofs where the PV is less visible.

Flat roof solution requirements:

1. Should the elements be “traditional” warm roofs or inverted roofs?
2. Can edges be made of roofing felt, so it fits to the rest of the roof?
3. As aesthetics are less critical for the flat roof, what is the added value of integrating PV elements? Multifunctional use of the roof? Easy upgrade of the roof for both insulation and energy generation?

The most promising concept was found to be a construction where the PV area is located on elevated areas, whereas the lower areas in between are used as service paths and collection of rainwater. In this way, the PV elements are protected from physical overload and will not be soaking in water.

The flat roof PV systems are hardly seen from the surroundings, and any type of standard PV could be used without visual impact as opposed to sloped roofs. The following figure shows the concept that is believed to be most realistic for large flat roofs.

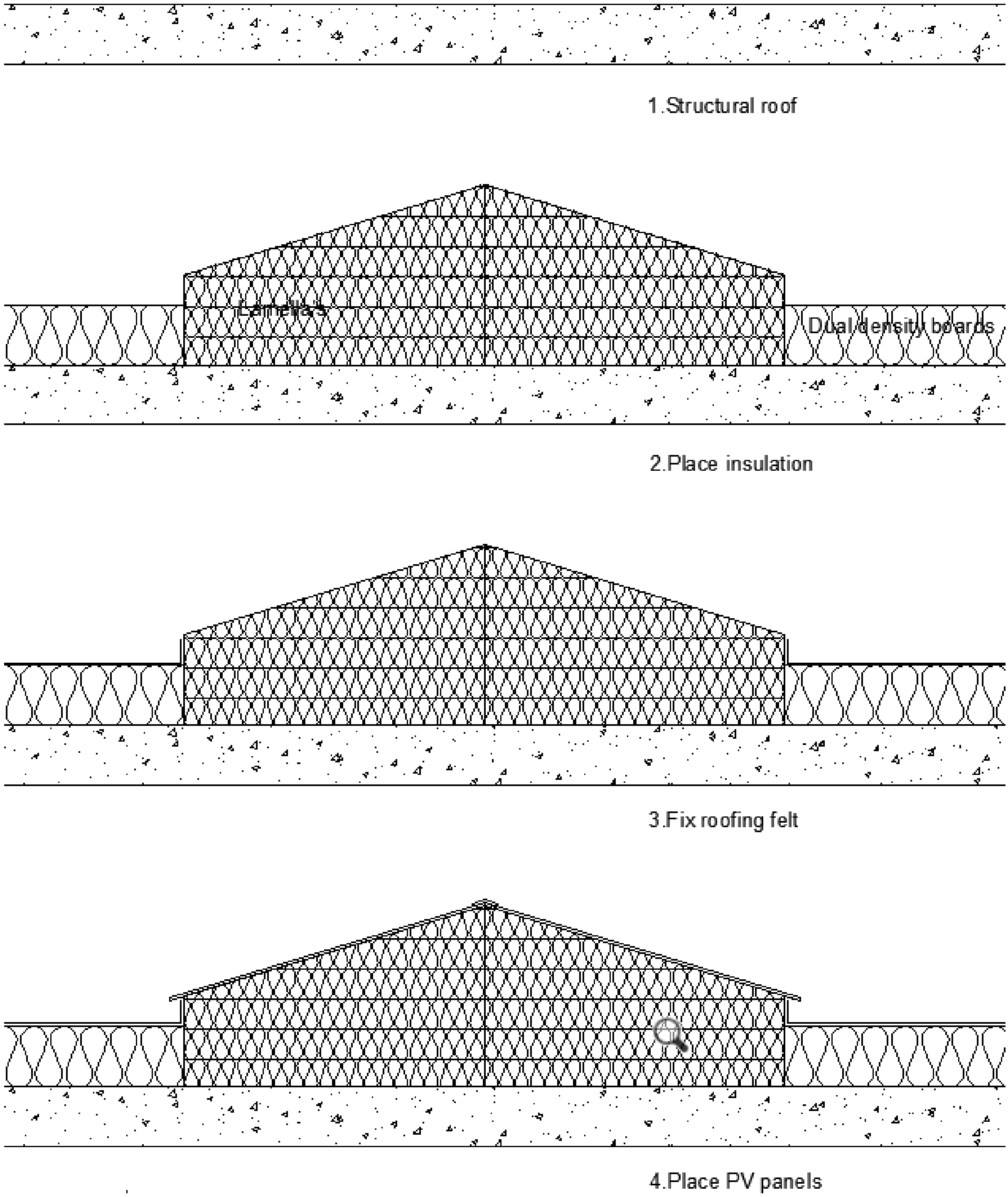


Figure 2: Final solution for a flat roof concept combining PV and insulation.

The final solution for the flat roof was a combination of lamellas with PV panels glued on them and with traditional stone wool insulation in between. The reasoning was that the maintenance around the PV panel is usually more impact full on the insulation (walking) than the load of the panels itself. So, in the final idea, standard flat roof insulation that has been proven for this application is used in between the PV elements.

This had the following advantages:

- Water proofing can be made with traditional materials.
- Optimal orientation towards the sun can be arranged.
- No separate materials, like aluminum, required to make a slope.
- The weight of the insulation can be optimized with heavy density insulation for the walkable areas and lamellas for the PV elements.

The development was only continued with the pitched roof solution because of the added value of special appearance and/or color.

In case of the sloped system, the project group based the mounting principles on the so-called REDAir facade renovation system developed by Rockwool, which is very easy to mount as external insulation and any type of light weight facade cover.

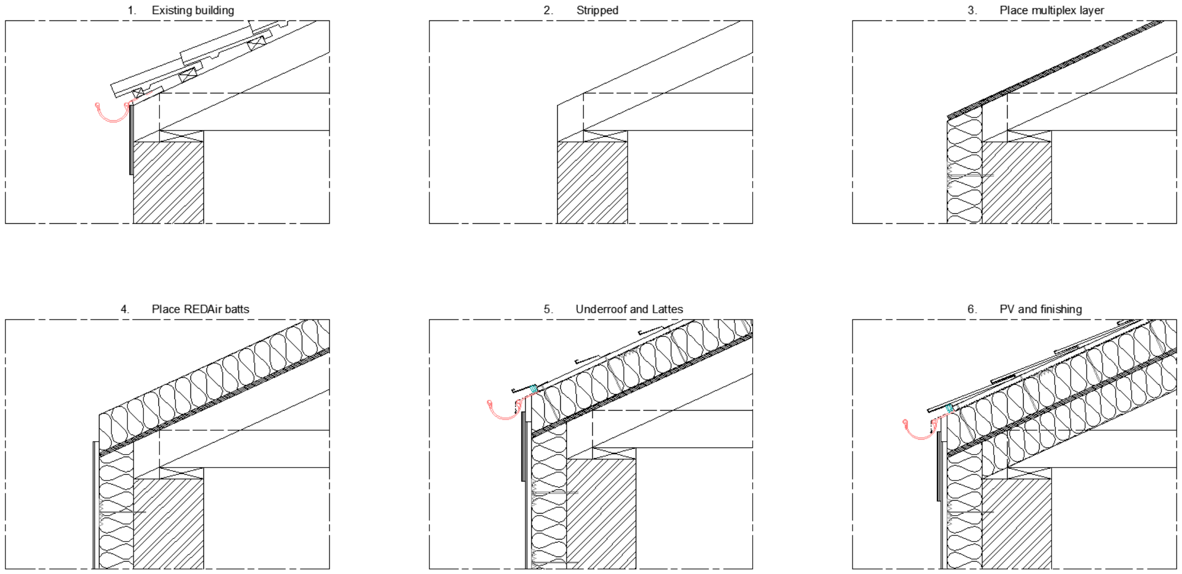


Figure 3: Final solution for sloped roof solution based on Rockwool´s REDAir facade insulation system.

The argumentation for the pitched roof solution is as follows:

- The insulation can be put directly on an OSB board on the rafters and prevent the downwards sliding.
- Standard insulation (produced online) can be used and is as such not tied to a special format.
- By using the LVL lath from the REDAir system, we will create a ventilation gap behind the PVs and by this increase their effectiveness.
- The installation is business as usual for the carpenter.
- A watertight underroof can be placed under the PVs and REDAir system lath.
- As there is no mechanical demand for the insulation in this solution, a product with better insulation value can be used.
- The hooks for the PVs are so much smaller and can be fixed directly to the laths. Or PV overlay can be fixed directly or put on a rail.
- No need for gluing PVs to the wool.

The pitched roof design was first tried in a mockup built by Rockwool, and later it was moved to DTI for instrumentation and weather exposure.

Figure 4: Photo of one of the mockups showing metal hooks and overlapping areas between the modules.

A full explanation of the design process and results are given in Annex A.

5.1.1 Market and cost analysis

PV Rockroof

As a first step in the project, a screening of the Danish building stock was made. The purpose was to check which types of buildings and which roofing materials would be potentially interesting as end user market for a PV Rockroof solution. Because the product is new, it was natural to go for the home market first.

Not surprisingly, the building boom in the 1960-70ies still dominates the building stock so it would be interesting to have a closer look on these. Many of the roofs from that period need to be replaced with another material, since the once popular asbestos cement is now forbidden

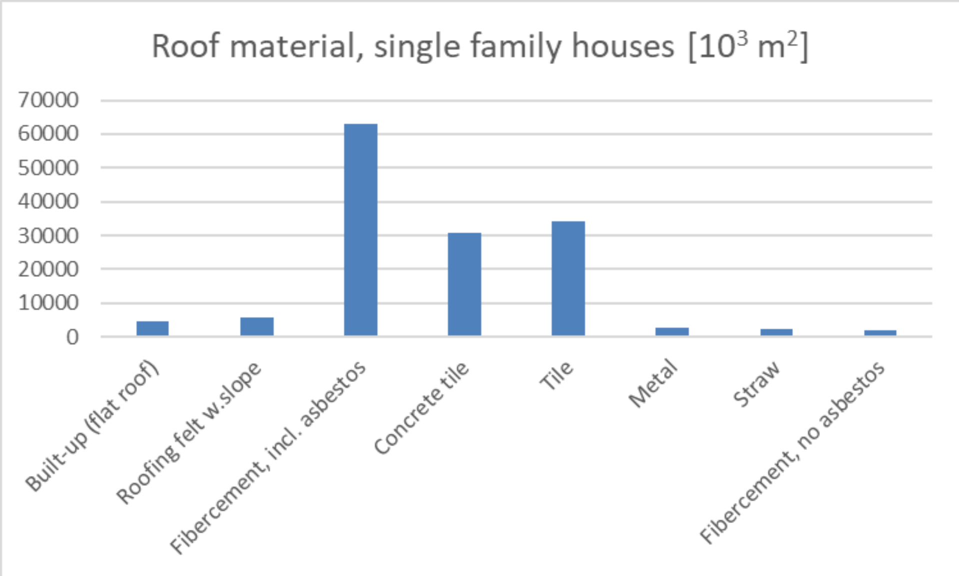


Figure 5 Distribution of roof type on single family houses in Denmark

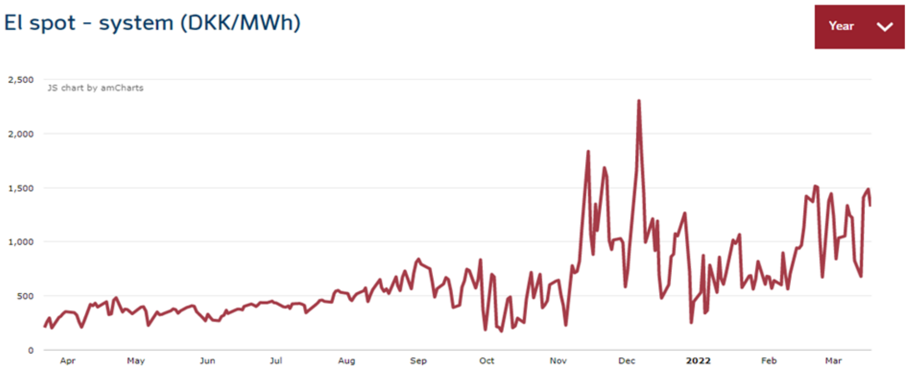
With 60 mill m² old fibre cement roof and an estimated exchange of 5% per year the annual area to be refurbished in this segment alone is around 3 mill m² per year.

Economic analysis and user cases

The future market and sales of the developed PV Rockroof concept is highly depending on the actual production cost as well as the development in consumer prices on heat and electricity. It has never been the intention to develop a product that could compete on the bare square meter cost, rather it should offer an aesthetic and green alternative to traditional roof renovation. This report indicates cost ranges and sensibility for changes in boundary conditions with background in Danish climate and prices.

Energy cost

Consumer tariffs on heat and electricity have risen dramatically in 2022 and even before the war in Ukraine shaked the markets. In Denmark energy taxes and transport fees constitutes a significant part of the electricity bill, which dampens the relative fluctuations of market prices. The oscillations make it extremely difficult to calculate the payback time of energy related investments. On top of that the initial insulation standard and consumption pattern can vary very much, which also affects payback time.



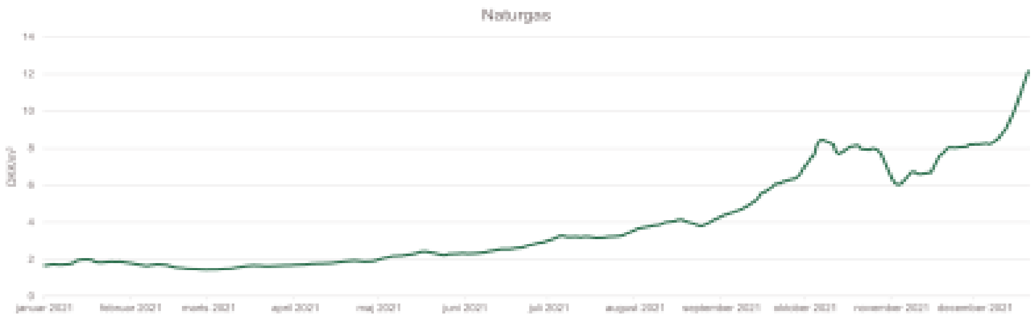


Figure 6 Market price for electricity and gas (Energinet.DK)

Analysis of thermal energy savings

As a producer of insulation Rockwool has extensive experience and documentation on the effect of added thermal insulation of buildings. As basis for the current analysis the brochure *ROCKWOOL GUIDE- efterisolering June 2022* was used as it contains values for annual savings of a typical dwelling. The values are calculated for added loft insulation, but they will not differ much if the insulation is on top of the roof, provided the attic is not ventilated to the outside.

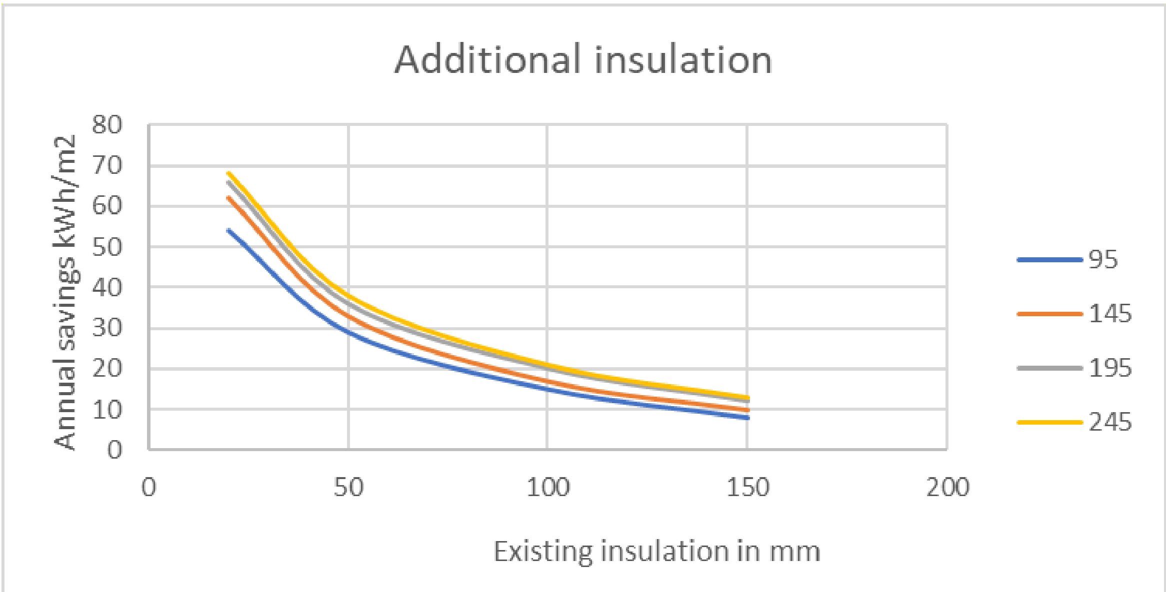


Figure 7 Annual savings for added insulation of the roof

In case the attic is converted from unheated to heated part of the building there will likely not be any savings, but the inhabitable area will be significantly increased. The economic value of this expansion should to be assessed from case to case.

The effective variable cost of heating per kWh (including all taxes) can be very different and depends on the source. Some indicative figures in DKK/kWh for private Danish households as of mid-2022 are:

Gas: 2, Heat pump: 1.2, District heating: 0.6-1.2

The savings in DKK per m^2 insulated surface can be found from the following table:

Annual savings DKK/m2	Heating tariff DKK/kWh									
kWh saved pr m2	0,25	0,5	0,75	1	1,25	1,5	1,75	2	2,25	2,5
10	2,5	5	7,5	10	12,5	15	17,5	20	22,5	25
20	5	10	15	20	25	30	35	40	45	50
30	7,5	15	22,5	30	37,5	45	52,5	60	67,5	75
40	10	20	30	40	50	60	70	80	90	100
50	12,5	25	37,5	50	62,5	75	87,5	100	112,5	125
60	15	30	45	60	75	90	105	120	135	150

In many Danish houses there is already a relatively thick layer of minimum 100 mm on the roof(ceiling), so the two upper lines are most likely to reflect reality.

<u>Analysis of electricity savings</u>

The analysis of electricity savings is more complicated due to various facts:

- Tariffs for buying from the grid and exporting from PV are not the same
- Tariffs differ from hour to hour
- Transport fee is higher in peak load periods
- Reduced energy tax for electrical heating

In the following table the tariff for sale to the grid is calculated on basis of the buy tariff deducted VAT 25%, energy tax DKK 0,88 and transport tariffs DKK 0,30.

The self-consumption is the part of the PV production that is immediately consumed, whereas the rest is exported. The self-consumption is typically less than 30% in households but significantly higher in commercial buildings. The bigger PV plant the less fraction is self-consumed.

PV income per produced kWh

Buy tariff DKK	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6
Sell tariff DKK	0,1	0,5	0,9	1,3	1,7	2,2	2,6	3,0	3,4	3,8
Self consumption ratio										
0,2	0,36	0,79	1,22	1,66	2,09	2,52	2,96	3,39	3,82	4,26
0,3	0,50	0,94	1,38	1,82	2,27	2,71	3,15	3,59	4,03	4,47
0,4	0,64	1,09	1,54	1,99	2,44	2,89	3,34	3,79	4,24	4,69
0,5	0,79	1,24	1,70	2,16	2,62	3,08	3,54	3,99	4,45	4,91
0,6	0,93	1,39	1,86	2,33	2,79	3,26	3,73	4,19	4,66	5,13
0,7	1,07	1,55	2,02	2,50	2,97	3,45	3,92	4,40	4,87	5,35
0,8	1,21	1,70	2,18	2,66	3,15	3,63	4,11	4,60	5,08	5,56

Investment

Looking at the construction costs it is possible to compare the PV Rockroof system with traditional renovation. Mernild Byg has calculated the difference in mounting time and costs on basis of their experience with the mock-ups built in the project.

In traditional renovation the thickness(profile) of the rafters must be increased in order to reach the required insulation values, whereas in the Rockroof system extra insulation is placed on top of the original rafters. This saves time on the construction site as stipulated in the table below. In this calculation the assumption is an average family house that is 12 meters long and 8 meters wide. The roof pitch is 45 degrees and there are 14 rafters on the building. The original construction will then be insulated with 300 mm.

The steps in the process where there is no difference between the two assembly systems are completely omitted from calculation. It covers, for example, scaffolding, demolition, insulation between existing rafters, covering the eaves, etc

Reference roof renovation	PV Rockroof renovation
32 hours to raise rafters 16 hours laying out track material and clamping strips 19 hours for insulation between rafters As well as materials for the above. Estimated price 10500 DKK	0 hours to Setup 24 hours for laying out etc 10 hours for insulation 8 hours for installation of steel clamping strips As well as materials for the above. Estimated price 8300 DKK

This is roughly a 21% reduction in construction costs. On top of that there is a reduced time the construction is exposed to rain and the total structure is 30mm thinner as the rafters are covered by insulation and thus reducing thermal bridges.

Installation time for the PV-panels is roughly the same as with traditional roofing material and mono-crystalline PV-panels. Material cost is higher but the new panels are designed to be more aesthetically pleasing and better integrated into the built environment.

Mono-crystalline panels	PV Rockroof panels
1200 DKK	2000 DKK

It is possible to apply different roofing materials on the Rockroof system, which gives architects and building owners a high degree of freedom in the visual expression. EFFEKT has developed a large number of drawings and visualizations showing typical roof types with PV Rockroof. (Annex E+F).

The following benchmark calculations show renovation cases in the traditional way versus PV Rockroof. The result shows that for typical cases, the value of the PV production exceeds the savings on heating costs. For the multi storey house, it will often be possible to add extra living space du to the new roof insulation, in the case study 64 m2. The commercial value of this will far exceed the energy related aspects.

The roof area per inhabitant is highest in the detached house (parcelhus) so if the entire area is used for PV there will be a lot of excess electricity that is sold to the grid at a less favorable cost than in the case of self-consumption where the value includes all tariffs and taxes.

The excel calculation tool used for this is available from the project web site.

Standard roof renovation cases						
PV RockRoof project December 2022			Overføre data fra geometriark			
Multi Tenant house	**Before renovation**	**Traditional renovation**	**PV Rockroof**	**Units**	**Comments**	
(Per entrance)	**No PV**	**New roof+240mm flat**	**BIPV+340mm sloped**			
Roof cladding	**Any**	**Tile**	**BIPV**			
Slope	**48**	**48**	**48**	**degrees**		
Footprint	**169**	**169**	**169**	**m2**	**13x13**	
Storeys	**5**	**5**	**6**		**New top floor**	
Appartments	**10**	**10**	**11**			
Added living space after renovation		***0***	***63,765***	***m2***	***From geometry sheet, 10% deduct***	
Electricity cons. Appartments.	**27200**	**27200**	**29920**	**kWh**	**1,7 inhabitants per appartment**	
Elec.cons.common areas	**5440**	**5440**	**5984**	**kWh**	**Own estimate 20%**	
Total annual electricity consumption	**32640**	**32640**	**35904**	**kWh**		
Max roof surface with PV			**126,3**	**m2**	**southern part of roof only**	
Power density			**0,14**	**kWp/m2**		
Specific production			**950**	**kWh/kWp**	**BIPV reduced due to colour and**	
Annual production			**16796**	**kWh/year**		
Production/consumption			**46,8**	**% see self consumption sheet**		
Part of production consumed directly			**50,5**	**% Very user dependent**		
Buy tariff			**3**	**DKK/kWh**		**link til vindstoed etc**
Sell tariff			**1,3**	**DKK/kWh**		**link til vindstoed etc**
Value per produced kWh			**2,2**	**DKK/kWh**		
Value of PV production			***36250,2***	***DKK/year***		
U value of the roof	**0,41**	**0,12**	**0,12**	**W/m2K**	**Calculations from Rockwool**	
Heat looses through the roof	**28,60**	**8,37**	**8,37**	**kWh/m2**	**2906 degree days**	
Effective area	**169**	**169,0**	**252,6**	**m2 for roof heat losses**		
Annual heat loss	**4832,6**	**1414,4**	**2113,8**	**kWh**		
Heat savings		**3418,2**	**2718,8**	**kWh**		
Marginal cost of heat	**1,0**	**1,0**	**1,0**	**DKK/kWh**	**Gas boiler**	
Value of heating savings		***3418,2***	***2718,8***	***DKK/year***		
Total savings	**0**	**3418,2**	**38968,9**	**DKK/year (ex value of added living space)**		
Cost of BIPV modules			2500	DKK/m2 (Danish Solar Energy)		
Cost of tile/dummies		500	500	DKK/m2 Varies depending on type		
Other expenses		1000	1500	DKK/m2 Varies on local conditions, height etc.		
		1500,0	3000	DKK/m2 renovated		
Investment		**378850**	**757700**	**DKK for entire renovation**		

Parcel house	**Before renovation**	**Traditional renovation**	**PV Rockroof**	**Units**	**Comments**
	No PV	**New roof+240mm flat**	**BIPV+340mm sloped**		
Roof cladding	**Any**	**Tile**	**BIPV**		
Slope	**25**	**25**	**25**	**degrees**	
Footprint	**16,4 x 8,2**	**16,4 x 8,2**	**16,4 x 8,2**	**m**	**135,6**
Storeys	**1**	**1**	**1**		
Appartments	**1**	**1**	**1**		
Added living space after renovation		***0***	***0***	***m2***	***not used in case of low slope***
Electricity cons. Appartments.	**4000**	**4000**	**4000**	**kWh**	**Avg. Consumption**
Elec.cons.common areas	**0**	**0**	**0**	**kWh**	**Own estimate 20%**
Total annual electricity consumption	**4000**	**4000**	**4000**	**kWh**	
Max roof surface with PV			**74,8**	**m2**	**southern part of roof only**
Power density			**0,14**	**kWp/m2**	**DSE module data**
Specific production			**900**	**kWh/kWp**	**BIPV reduced due to colour and**
Annual production			**9426**	**kWh/year**	
Production/consumption			**235,6**	**% see self consumption sheet**	
Part of production consumed directly			**14,5**	**% Very user dependent**	
Buy tariff			**3**	**DKK/kWh**	
Sell tariff			**1,3**	**DKK/kWh**	
Value per produced kWh			**1,5**	**DKK/kWh**	
Value of PV production			***14575,7***	***DKK/year***	
U value of the roof	**0,41**	**0,12**	**0,12**	**W/m2K**	**Calculations from Rockwool**
Heat looses through the roof	**28,60**	**8,37**	**8,37**	**kWh/m2**	
Effective area	**135,6**	**135,6**	**149,6**	**m2 for roof heat losses**	
Annual heat loss	**3877,5**	**1134,9**	**1252,2**	**kWh**	
Heat savings		**2742,6**	**2625,3**	**kWh**	
Marginal cost of heat	**1,0**	**1,0**	**1,0**	**DKK/kWh**	**Gas boiler**
Value of heating savings		***2742,6***	***2625,3***	***DKK/year***	
Total savings	**0**	**2742,6**	**17201,0**	**DKK/year (ex value of added living space)**	
Cost of BIPV modules			2500	DKK/m2 (Danish Solar Energy)	
Cost of tile/dummies		500	500	DKK/m2 Varies depending on type	
Other expenses		1000	1500	DKK/m2 Varies on local conditions, height etc.	
		1500,0	3000	DKK/m2 renovated	
Investment		**224427**	**448854**	**DKK for entire renovation**	

5.2 WP3 Colored BIPV module R&D

A methodology for characterizing the angular dependence of visual appearance of BIPV products has been presented. Measurements of the single-plane spectral BRDF of single cell BIPV devices have been performed allowing a description of angular dependent color appearance using the CIELAB color space. A schematic diagram of the improved optical setup realized in the project is shown below.

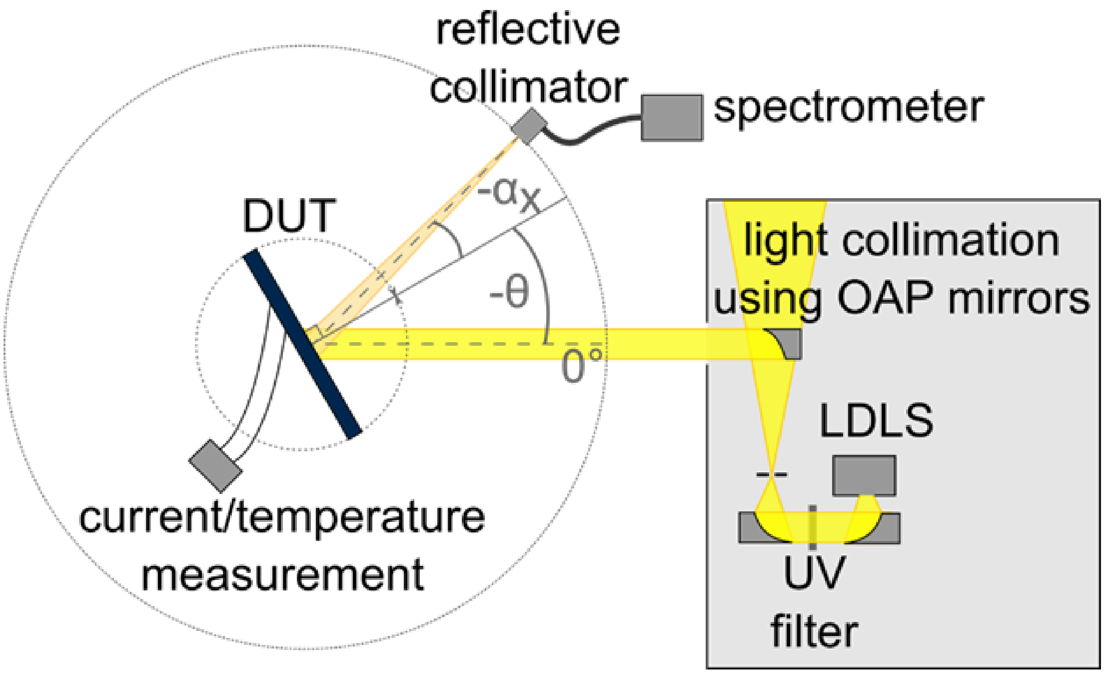


Figure 8: Schematics of experimental measurement setup for single-plane spectral BRDF: α_x denotes the view angle, and θ denotes the incidence angle of light.

The light source is a broadband laser-driven light source (LDLS), Energetiq EQ-99X. The light output source is a high brightness 100 µm size Xe plasma in the range from 170 to 1700 nm. The light is collimated using three offaxis parabolic (OAP) mirrors and a pinhole. An UV filter cutting light below ~320 nm is included to achieve a spectrum closer to that of the sun. The maximum spot size is 38 mm in diameter at the sample plane and can be reduced to fit within the size of the solar cell at all measured angles.

Spectra are acquired through independent rotation of a reflective collimator (Thorlabs RC04SMA-F01) around the sample, collecting reflected light, which is transferred to an Ocean Optics QE65000 spectrometer using a 600 µm optical fiber. The reflective collimator is mounted at a distance of 28 cm from the sample and is adjusted to be situated 4° below the plane of irradiance so as not to occlude the incoming light, allowing measurements of the single-plane spectral BRDF.

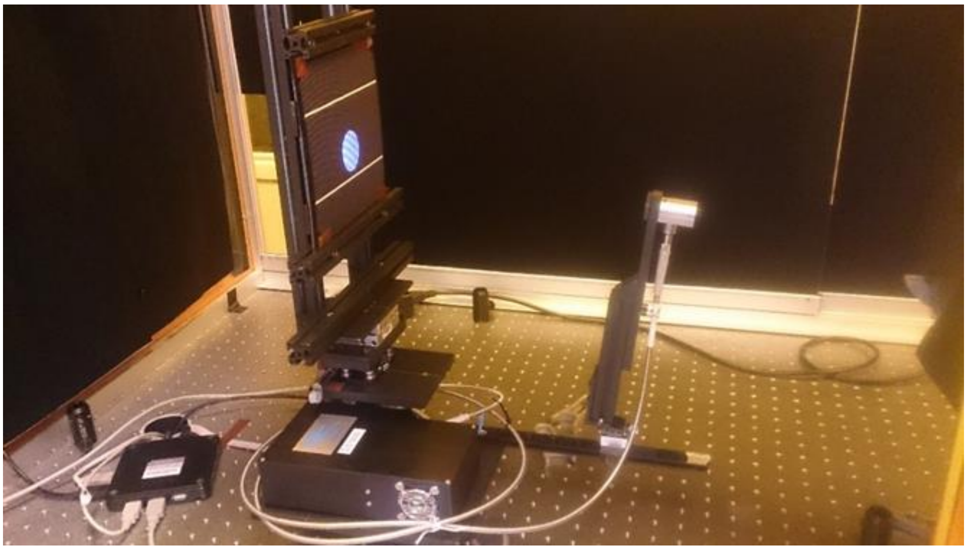


Figure 9: Photo of experimental BRDF setup.

In order to understand the optical properties and the perceived visual aspect of samples under illumination, it is important to obtain measurements of the light reflected from the sample and to quantify changes in intensity and spectrum shape. This allows the translation of these quantities into perceived color changes and specular and diffuse reflected intensity. Measurements obtained at different view angles allow the geometrical distribution of these acquired parameters.

For this purpose, multidirectional reflectance measurements are performed in this work to compute the bidirectional reflectance distribution function (BRDF). Studies of BRDF have been used in a wide range of industries and laboratories to improve the understanding of the bidirectional reflectance characteristics of either natural or man-made surfaces.

The general formulation of the BRDF as defined by (F. E. Nicodemus, Directional reflectance and emissivity of an opaque surface, Applied Optics 4 (1965) 767-775) is as follows:

$$B(\phi_i, \theta_i, \phi_r, \theta_r) = \frac{\mathrm{d}L_{\Omega,r}(\phi_r, \theta_r)}{\mathrm{d}E_i(\phi_i, \theta_i)}$$

The BRDF is defined as the ratio between the reflected radiance $L_{\Omega,r}$ and the incident irradiance E_i on the sample. The angles φ_i and θ_i refer to the incident light, while φ_r and θ_r refer to the reflected light. A laboratory setup for the measurement of the single plane spectral BRDF was developed. It consists of a collimated light source and a gonioreflectometer, which allow variation of incidence angle and measured reflectance angle on the sample surface. The sample is mounted on a motor allowing variations in incidence angle (θ). Below in the same rotational axis, an independent motor rotates a mechanical arm that holds the input optics to a spectrometer. Measurements are obtained on a single axis in the range of +/- 90 degrees of input optic relative to the sample, and a set of angular data per each sample/light source angle is obtained. The BRDF setup is shown in Figure 8 and Figure 9 above.

In addition to the angular dependent optical characteristics of each of the different samples, it is also of interest how they impact the power performance. Therefore, measurements of DUT short circuit current (I_{sc}) and temperature (T_{DUT}) are carried out during simultaneous rotation of the sample respect to the incident light to compute the incidence angle modifier (IAM). For the particular case of our measurement setup, all the incident light is contained within the samples at all angles, and no cosine factor is required, resulting in the following equation:

$$IAM(\theta) = \frac{I_{sc}(\theta)}{I_{sc}(0°)}$$

IAM measurements are carried out using the same setup, but Isc and TDUT are acquired using a National Instruments NI 9213 acquisition system with a 24-bit ADC. Isc is acquired by measuring the voltage across a 0.5 Ω precision shunt resistor, and each measurement is an average over 20 acquired samples to reduce electrical noise variations. Device temperature is measured at the back of the sample with a J-type thermo-couple and averaged over 3 measurements at each angle.

As a final electrical performance characterization, IV curves at STC conditions are performed on all the sam-ples using a PASAN class AAA flash solar simulator for cells. Temperature is measured at the base plate, and the voltage sweep is performed with a 4-quadrant electronic load.

The analysis of color appearance variations is carried out by calculating coordinate values mapped within the CIELAB color space.

The measured spectral BRDF is used to calculate the XYZ tristimulus values for each measurement point in the CIE 1931 color space via color matching functions and the D65 standard illuminant. Using a measured white reference sample (Spectralon), these coordinates are then transferred to CIELAB color coordinates, yielding device independent values. Coordinates in the CIELAB color space can be interpreted as functions of Hue (h°), Chroma (colorfulness, C*) and Lightness (L*), as represented in Figure 10.

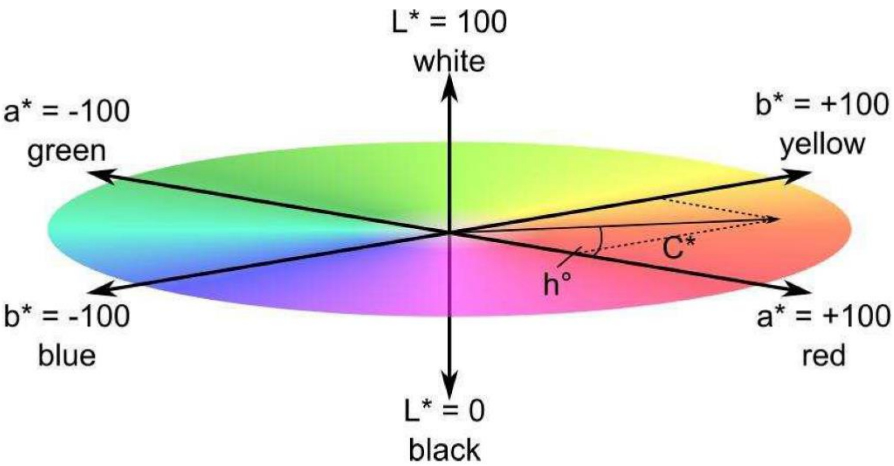


Figure 10: CIELAB color space.

Chroma (C*) in the CIELAB is defined as the Euclidean distance to a point on the a*-b*-plane, while the hue (h°) is described using the 4-quadrant arctangent of the a* and b* coordinates. This results in the following equations:

$$C* = \sqrt{a^{*2} + b^{*2}}$$

$$h° = atan2(a*, b*)$$

CIELAB color coordinates can further be translated to the CIELUV color space which also defines a saturation parameter $s_{uv} = C^*_{uv} / L^*$, where C^*_{uv} is the chroma in the CIELUV space, and L* is the lightness parameter.

Optical losses in electrical performance were studied performing IAM and IV curve measurements. Using this methodology, samples of three coloring technologies were measured.

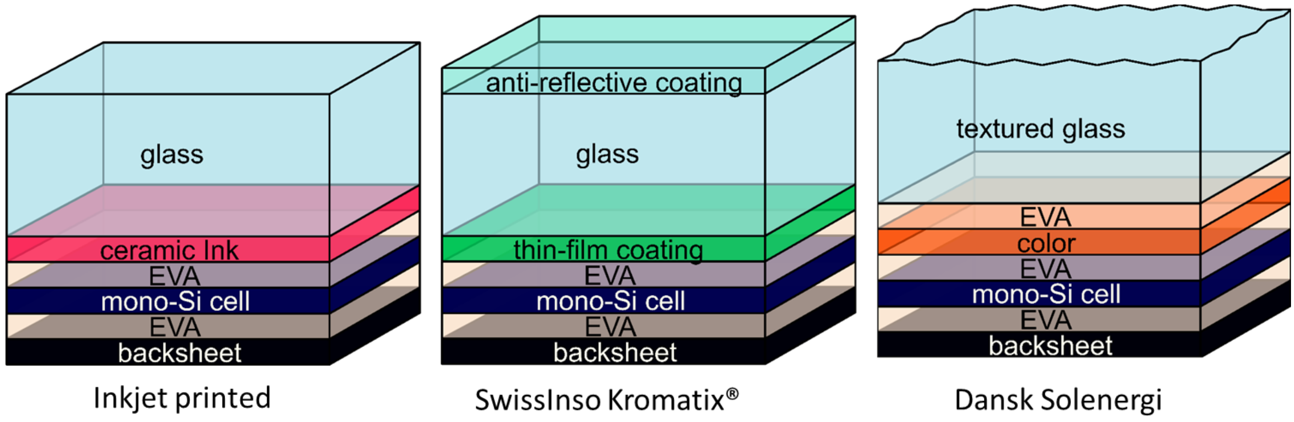


Figure 11: Conceptual drawings of the different colored technologies measured in the setup.

Figure 14 shows the BRDF measurement results for the Injet printed (printed ceramic inc – PCI) samples. The spectral BRDF at the center position ($\alpha_x = \theta = 0°$) highlights the large differences in reflectance spectra between colors. Additionally, the total BRDF with changing view angle is shown, with the peak at $\alpha_x = 0°$ giving an indication of the amounts of specular reflections. While most samples show very little specularity, the blue sample shows significant specular reflections, followed by the red and white sample.

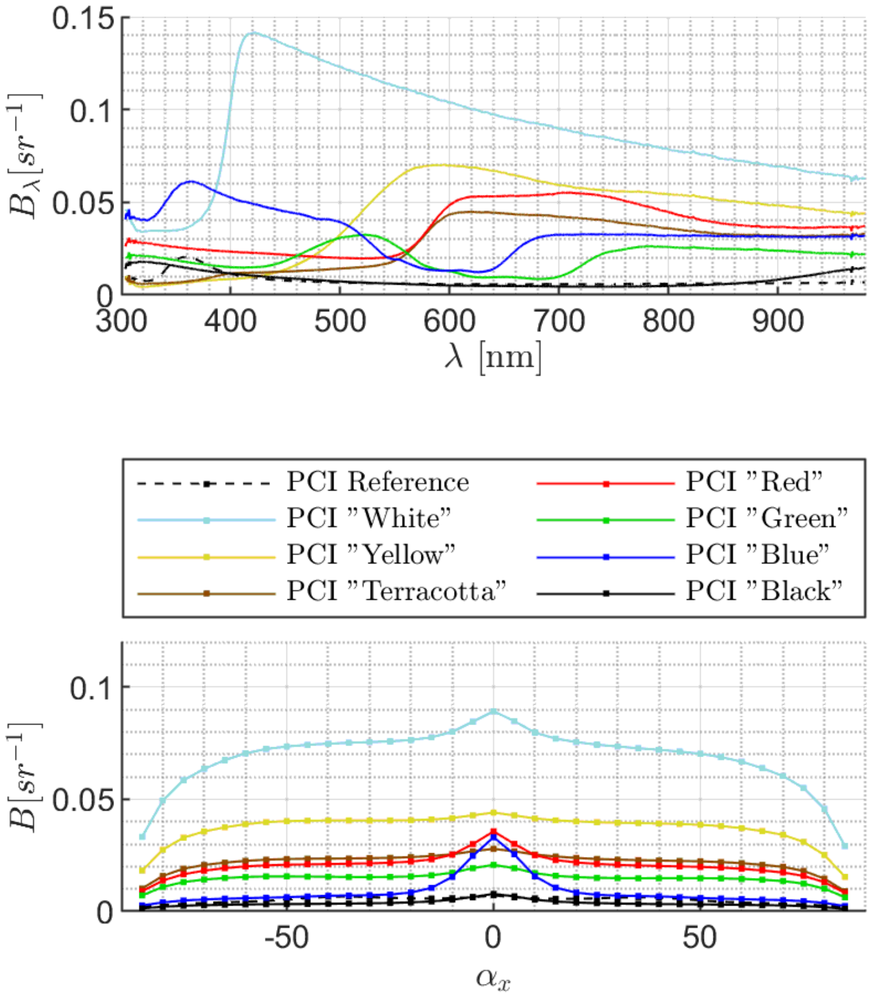


Figure 12: Spectral BRDF at αx = θ = 0° (top), total BRDF at θ = 0° (bottom) for PCI samples.

The BRDF measurements of the SwissInso Kromatix consisting of a thin-film coating (TFC) samples are shown in Figure 10. The “Terracotta” seems misnamed, as it appears green-yellow with high iridescence. The samples can be separated into several groups according to spectrum shape. For one, these are the blue, green, and terracotta samples, which all show two distinct peaks within 300-600nm. Secondly, the gold and bronze samples show an almost identical spectrum with a higher reflectance at longer wavelengths. Lastly, the gray sample shows only one peak at~360nm, from which the reflectance declines almost linearly for longer wavelengths. While differences between colors in a group are most likely caused by differences in coating thickness, differences between groups are most likely due to different coating materials.

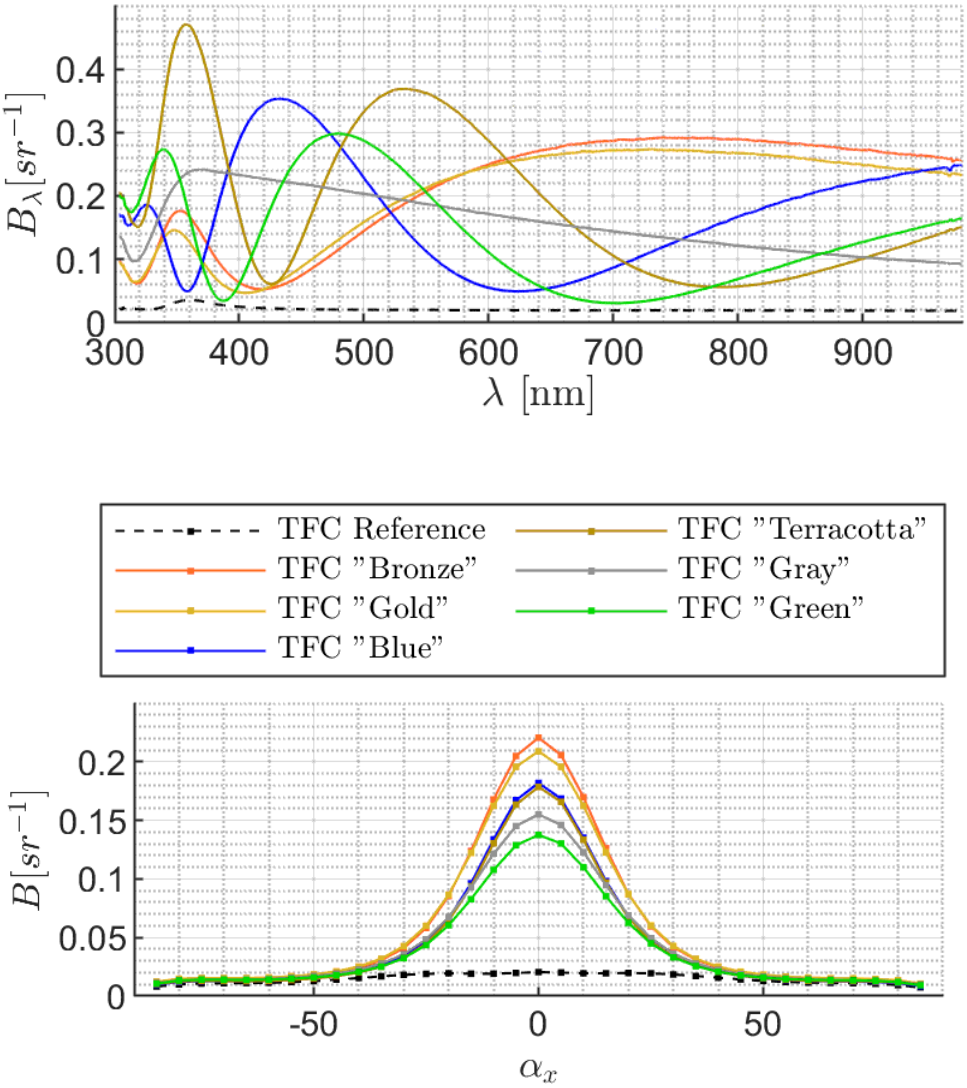


Figure 13: Spectral BRDF at $\alpha_x = \theta = 0°$ (top), total BRDF at $\theta = 0°$ (bottom).

The BRDF graphs of the colored solution developed by Dansk Solenergi based on colored interlayers (CIL) samples are shown in Figure 11. The flat shape of the reflectance spectra indicates low color saturation for the samples studied.

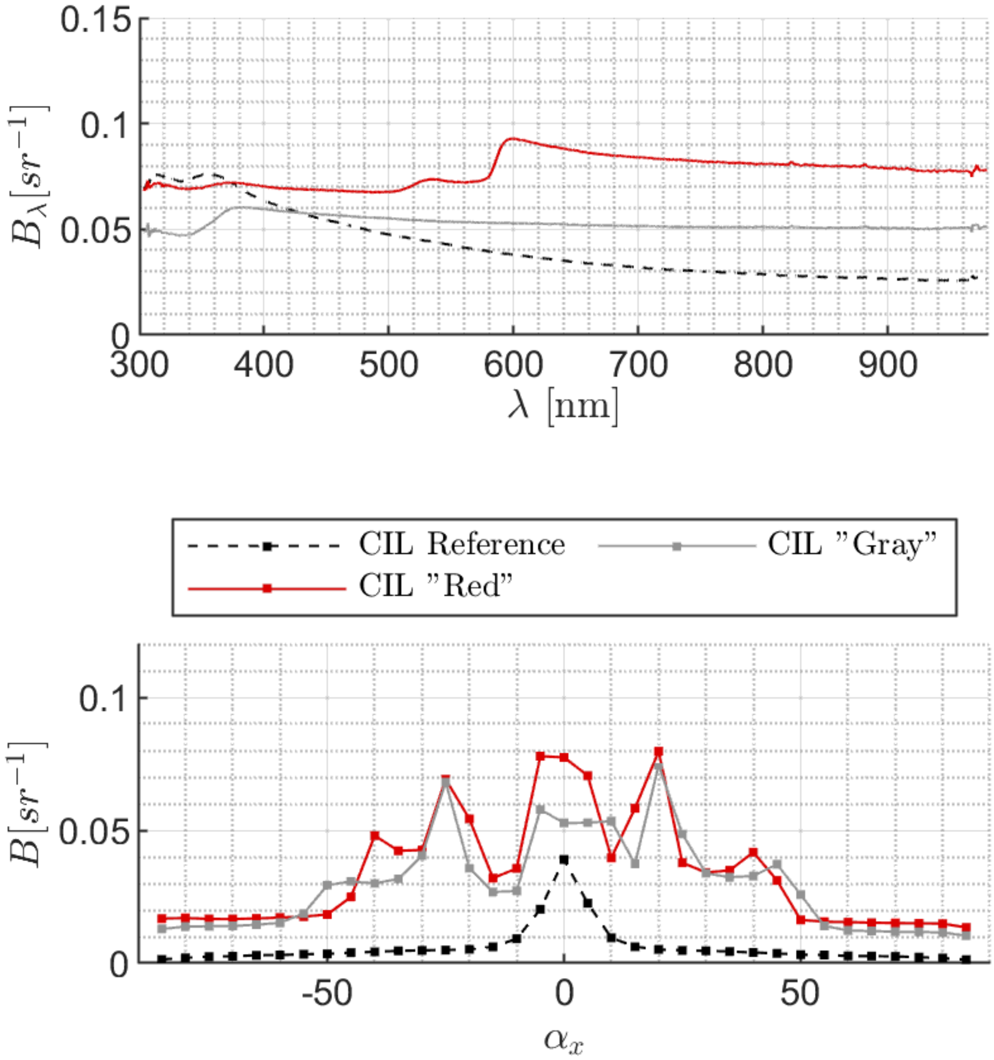


Figure 14: Spectral BRDF at αx = θ = 0° (top), total BRDF at θ = 0° (bottom) for CIL samples.

In the total BRDF plot, irregular changes in total BRDF values with view angle are observed, and this effect can be mainly attributed to the textured glass surface. This observation is reinforced by the measurement of the reference sample, which has a non-textured glass, as its total BRDF shows a shape more similar to the other technologies.

Colorimetry calculations are performed for two selected PCI samples, namely PCI "Blue" and PCI "Terracotta", with photographs shown in Figure 15.

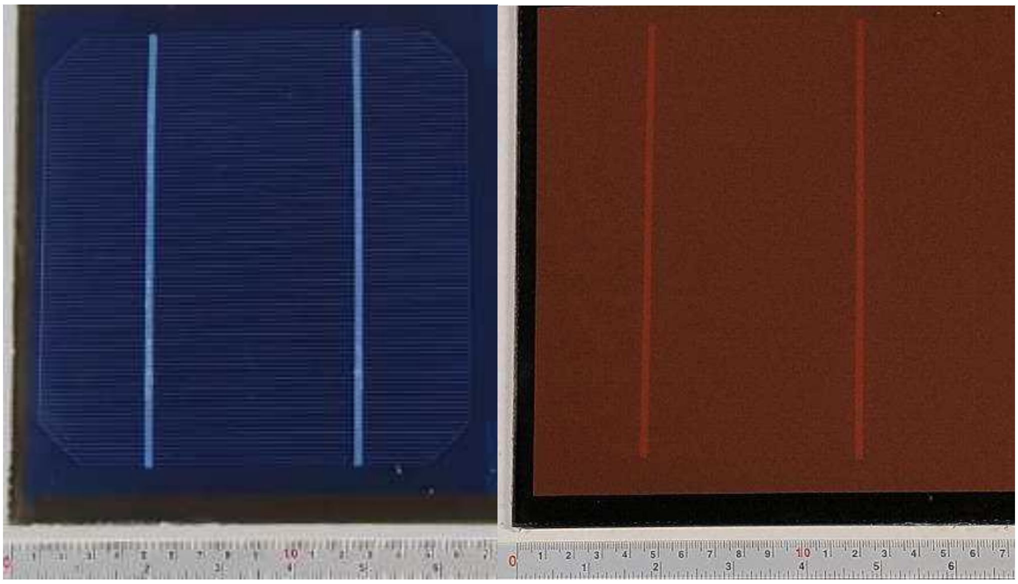


Figure 15: Photos of PCI “Blue” and PCI “Terracotta”.

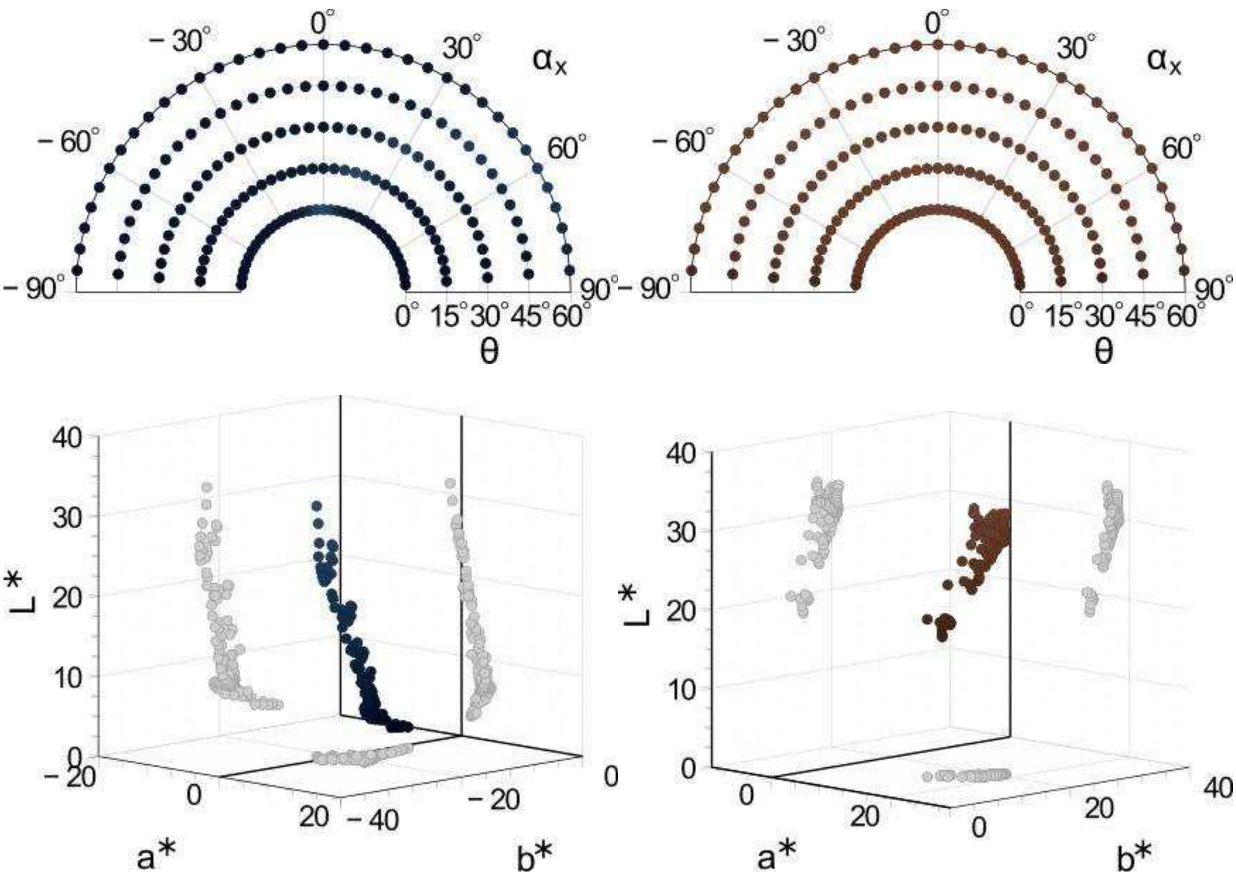


Figure 16: PCI “Blue” (left) and PCI “Terracotta” (right) in angular color representation and CIELAB color space.

The PCI samples appear visually uniform from all angles with changing lightness for samples with high specular reflections, as shown in Figure 16. For the terracotta sample, the CIELAB coordinates are clustered closely together with only slight variations in chroma and lightness, indicating high color constancy. The PCI “Blue” sample shows the highest amount of specular reflections, resulting in a less uniform angular appearance due to very low lightness outside of specular reflection angles ($\alpha x = \theta$).

For the TFC samples, again two selected samples are analyzed in greater detail. Photos of the samples, TFC “Blue” and TFC “Gold”, are shown in Figure 17.

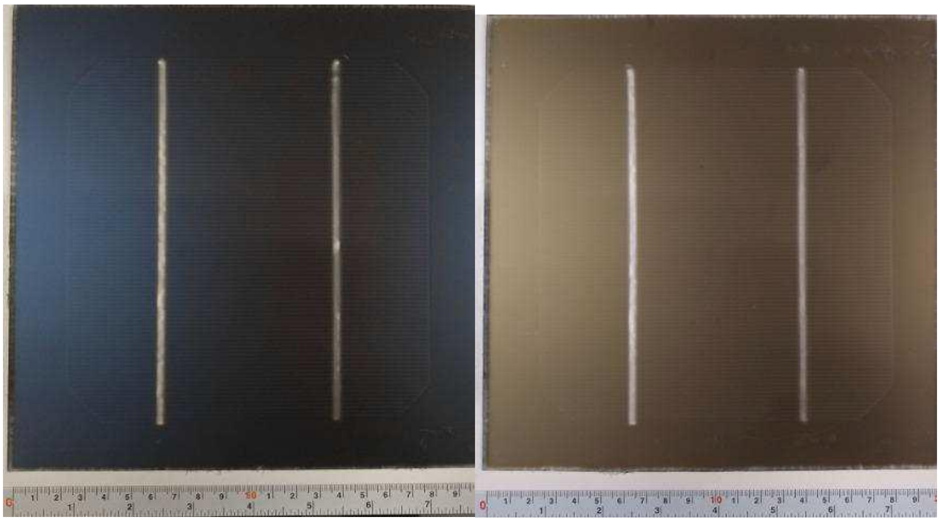


Figure 17: Photos of TFC “Blue” and TFC “Gold”.

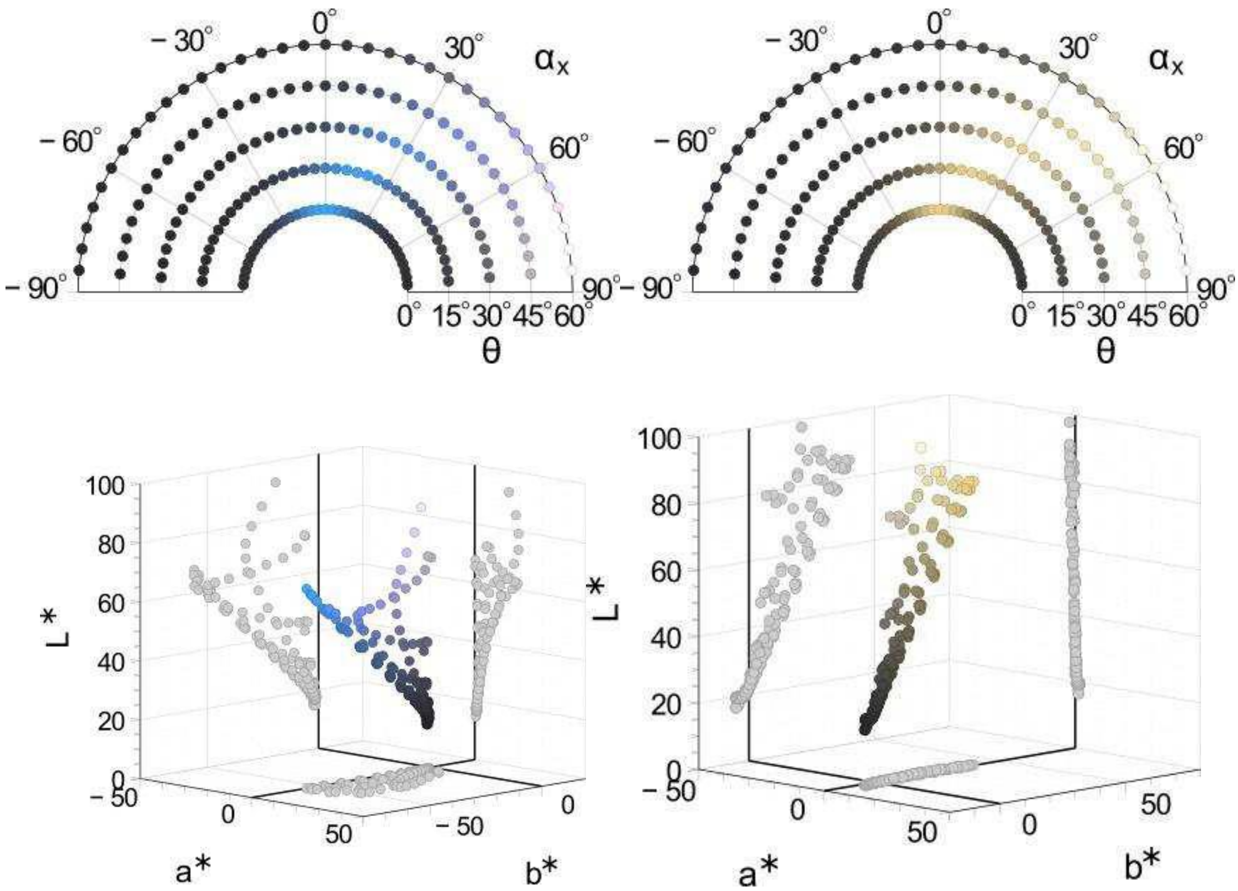


Figure 18: TFC “Blue” (left) and TFC “Gold” (right) in angular color representation and CIELAB color space.

Angular color representations and CIELAB color coordinates are shown in Figure 15. While both samples show significant angular dependency of appearance, the blue sample appears iridescent, while the gold sample does not. Similarly, iridescence can be observed for the green and terracotta samples, but not for bronze and gray, though not shown here. Iridescence therefore follows the separation into groups as described earlier. The iridescent nature of the TFC "Blue" sample is shown in more detail in Figure 19. With increasing incidence angles, the color shifts towards magenta with the specific color depending on the view angle. This is observed with the gradual shift of the points towards more positive values in the a* axis as incidence angle increases. The difference between positive and negative view angles similarly increases with incidence angle.

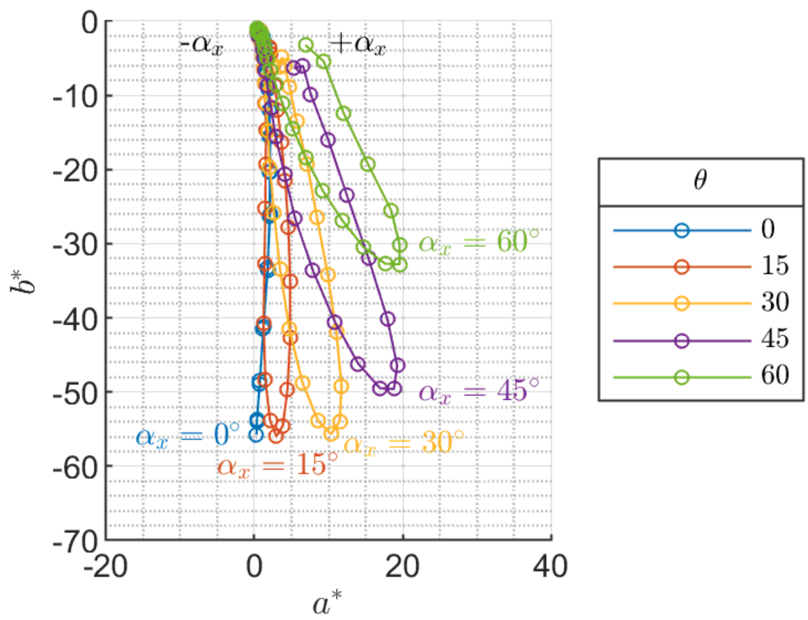


Figure 19: TFC "Blue" color coordinates in a*-b*-plane with changing angles.

Photographs of the two CIL samples, CIL "Gray" and CIL "Red", are shown in Figure 20. Compared to the photographs of other sample groups, irregular reflections caused by the textured surface glass are visible.

Figure 18: Photos of CIL "Gray" and CIL "Red"

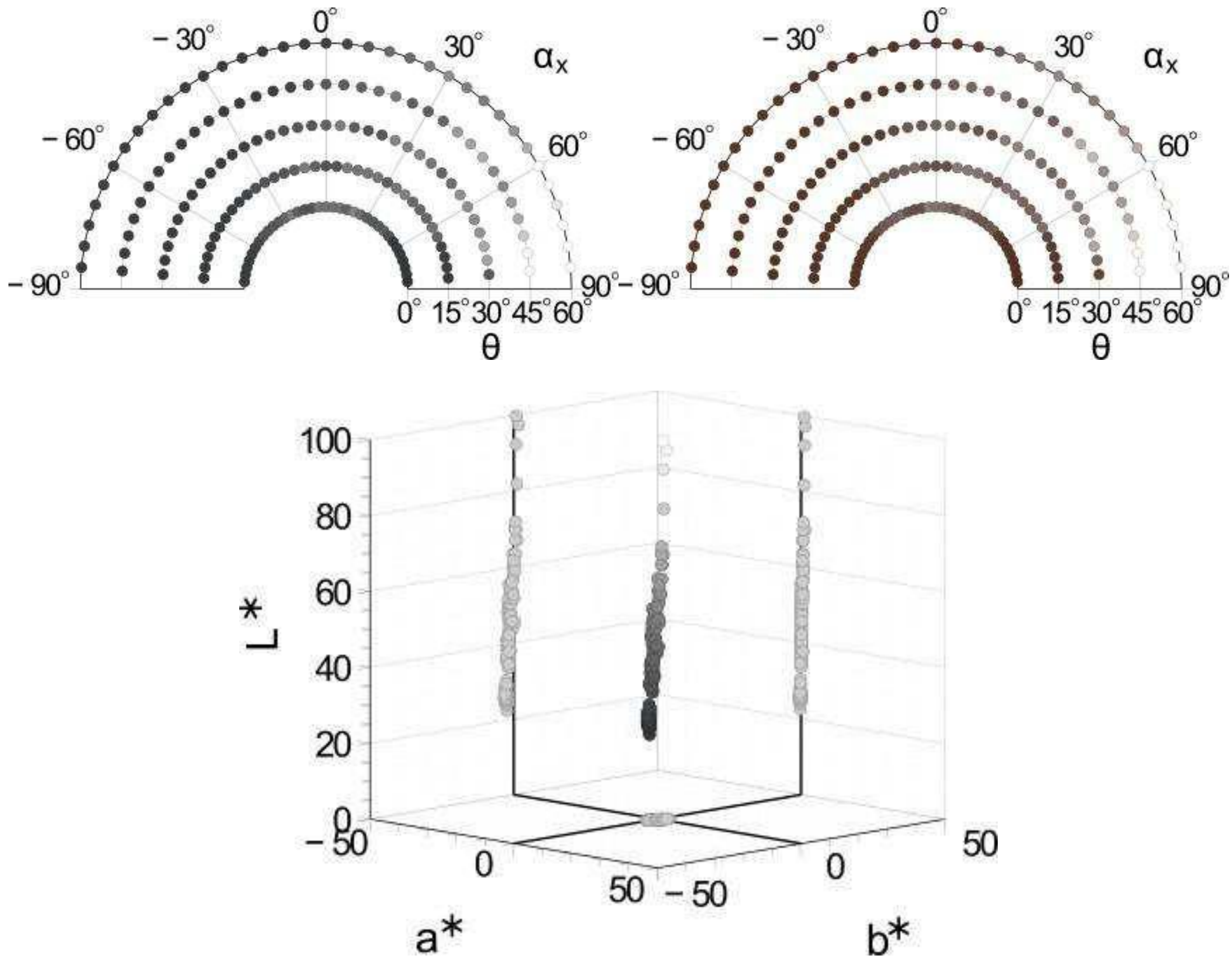


Figure 19: CIL “Gray” (left) and CIL “Red” (right) in angular color representation and CIELAB color space.

Figure 21 shows a representation of the angular dependent color and the CIELAB color coordinates for the CIL samples. Due to the irregular reflections caused by the textured glass surface, the apparent sample color varies with view angle, showing an intermediate average color saturation.

Opposed to the other sample groups, CIL samples show lower chroma at specular reflection angles ($\alpha_x = \theta$), while both PCI and TFC samples show increasing chroma at specular reflection angles. This can also be observed in the CIELAB color space, where the measurement points for the CIL “Red” sample form an asymptotic curve with high chroma (increasing away from the axis origin) at low lightness, while the other sample groups show measurement points that can be extrapolated to cross the origin. This results in lower average color saturation for the CIL samples and is most likely a consequence of the textured glass surface.

Figure 22 shows the IAM for the PCI samples. The primary observation is that apart from the black colored sample, all samples show a similar IAM curve. Additionally, the IAM for all colored samples is below that of the reference sample. Secondly, there is a relationship between IAM and the amount of specular reflections: For colors with higher specular reflections (blue, white, red), a higher IAM is measured compared to samples with few specular reflections.

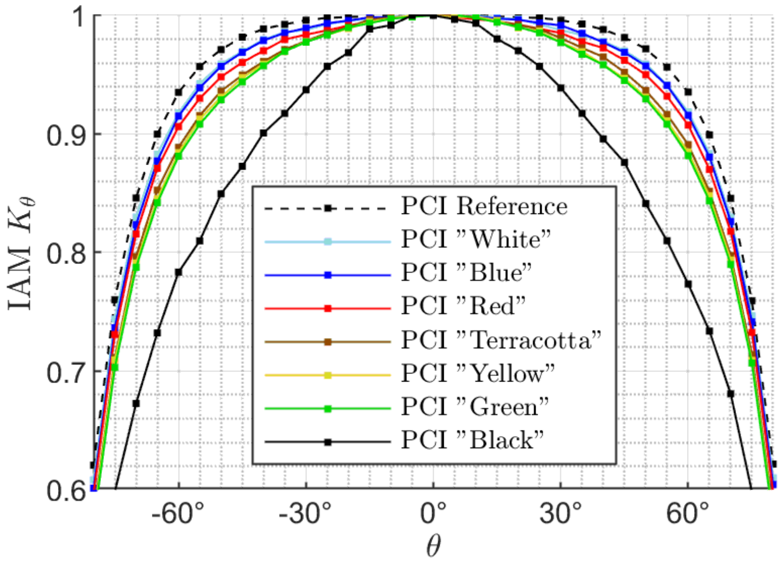


Figure 20: IAM for PCI samples.

The IAM of the TFC samples is shown in Figure 20. Due to the ARC, all samples show a high IAM compared to the other sample groups. Despite also having an ARC, the reference sample shows a significantly reduced IAM. Differences in IAM between colors follow the sample groups shown earlier: The non-iridescent samples (gray, gold, bronze) show a higher IAM than the iridescent samples (blue, green, terracotta).

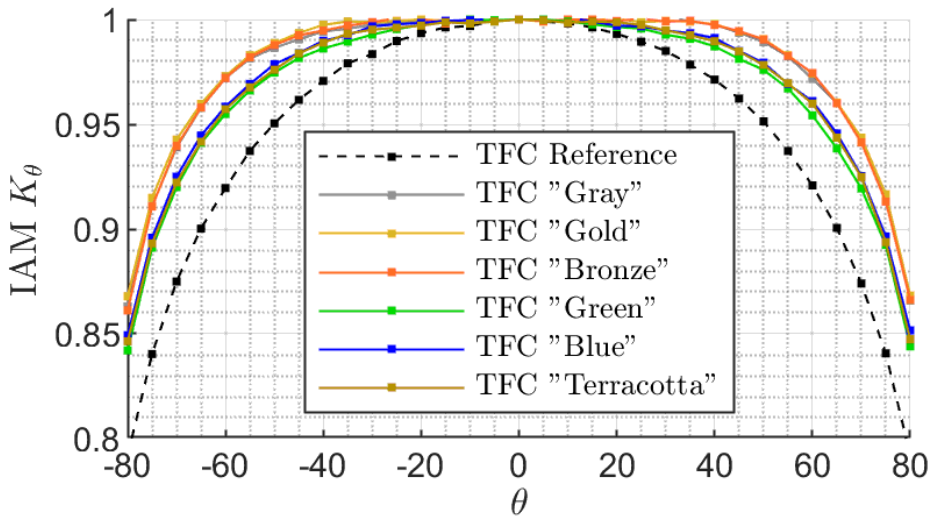


Figure 21: IAM for TFC samples.

IAM measurements of the CIL samples are shown in Figure 21. They present a generally lower IAM compared to other sample groups, with the red sample achieving a slightly higher IAM than the gray sample. It can be observed that this lower IAM characteristic is mainly an effect of the textured glass, as evidenced when compared to the reference sample, which uses a flat glass.

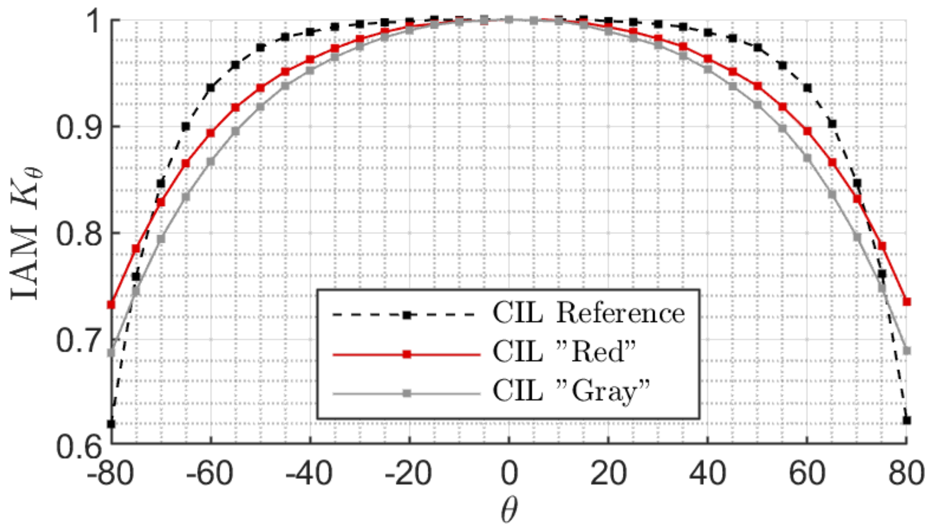


Figure 22: IAM for CIL samples.

IV-curve measurements of the colored samples in relation to their specific reference samples result in the relative short circuit currents shown in Figure 25 giving an indication of transmission losses caused by the coloring technology.

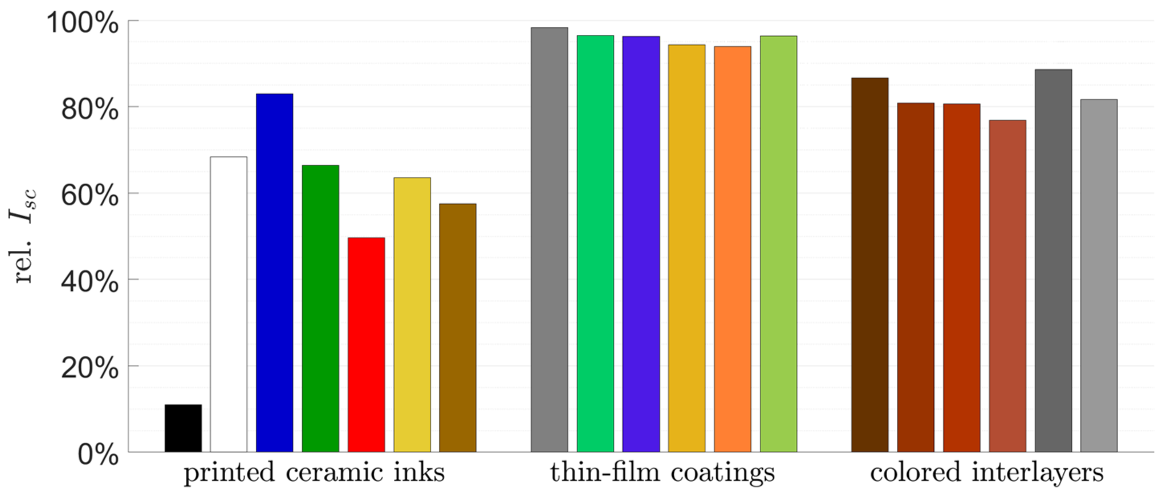


Figure 23: Short circuit measurements relative to a non-colored one cell PV module.

The colored PV solution developed in the PV-ROCK-ROOF project has an impressive high efficiency (low loss) close to the thin-film coatings which are the most efficient colored solutions in the market.

Samples with printed ceramic ink show the highest color constancy and saturation but also the highest losses in short circuit current. Additionally, a clear correlation can be observed between specularity of reflection, IAM and angular constancy of appearance. Samples with thin-film coatings show higher average efficiency with high angular dependency. For the blue, green and terracotta samples, iridescence is observable. Additionally, samples can be separated into two groups with similar IAM and angular dependency. This leads to the conclusion that for thin-film coatings, the choice of layer material, affecting the number of reflectance and transmittance peaks in the visible range, is of high importance for the angular dependency of both appearance and efficiency.

Samples with colored interlayers (The PV-ROCK-ROOF solution) show intermediate color saturation and transmission losses. Contrary to the other technologies, these samples also show decreased color saturation at specular reflection angles due to the textured glass surface.

The presented optical characterization and modelling methodology allows accurate determination of angular dependent sample color. Differences between coloration technologies and individual samples highlight the need for further research to obtain highly efficient BIPV coloration technologies. As the individual coloration technologies could not be directly compared to each other, due to differences in sample structure, further measurements with new sample batches of more uniform composition will be performed. This should allow direct comparison of color saturation and thus coloration efficiency between technologies.

<u>Glass types</u>

It was also studied how different glass surface treatments influence the angular dependent reflectance and the visual appearance:

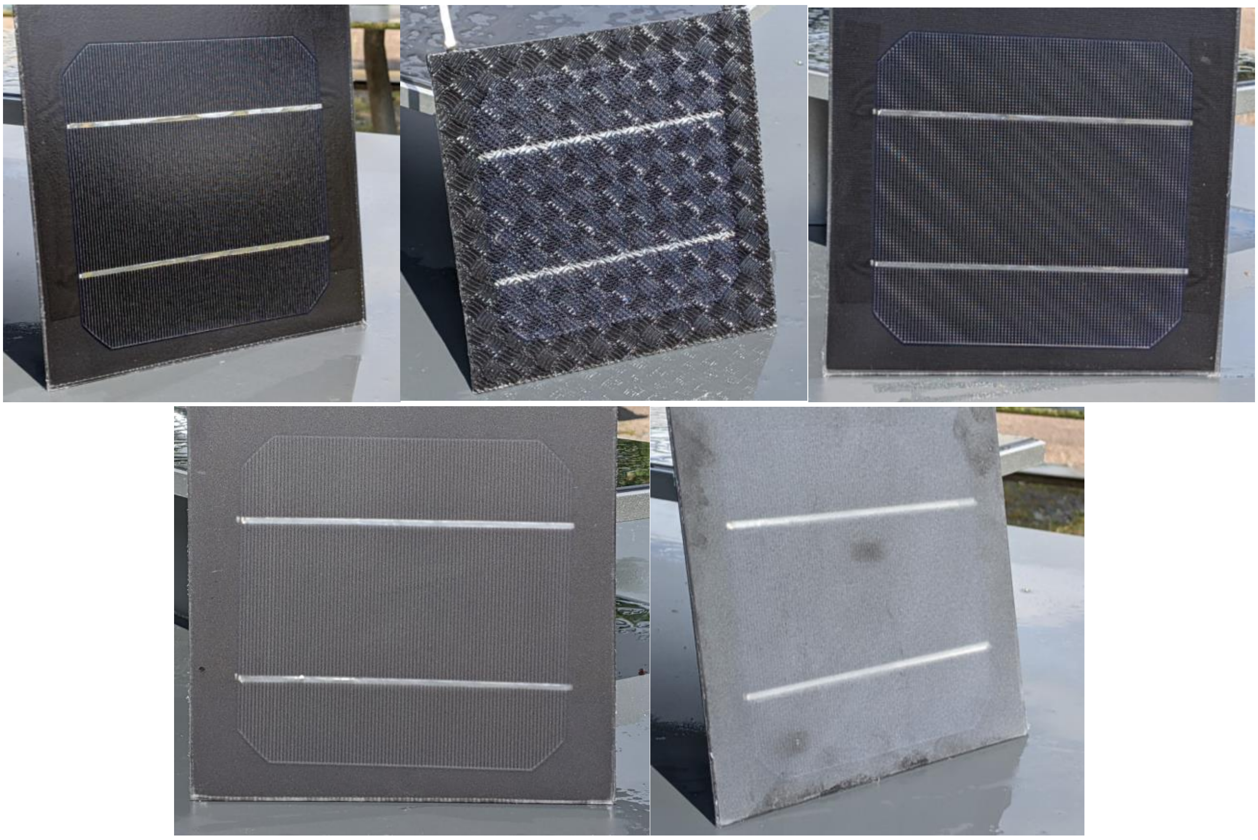


Figure 24: Visual comparison of different glass types: Reference, textured1, textured2, etched, sand blasted.

5.2 WP4 Optimization of module manufacturing

This work package was largely conducted by Danish Solar Energy (DSE) as they own and run the PV manufacturing plant in Holeby. At first, the entire project group was invited to the factory to see how the machines and processes worked at the beginning of the project. The most important machines in the production line are:

1. Stringer for electrical connection of individual solar cells
2. Color mixer and application apparatus (defining color intensity and layers on composite mats)
3. Laminator for “baking” of the PV laminates including intermediate colored layer
4. Flash tester for performance control.

The original stringer machine was set up to solder series connections of traditional PV cells with busbars on the front. This is the traditional method used by the majority of module manufacturers, but it is not optimal for BIPV modules where it is preferable to avoid shiny busbars on the front of the module for aesthetic reasons. In order to hide the metallic busbars, they are either covered by colored plastic strips or painted which is a manual and difficult process. To overcome this problem, it was decided to shift to IBC solar cells, which do not have busbars on the front but are fully black. It is so-called back contact cells, where both plus and minus terminals are on the rear side. These cells are also significantly more efficient than the old cells used by DSE. To be able to use this cell type, the stringer machine had to be modified and adjusted accordingly, which was a delicate process. The automatic picking up, positioning and interconnection of cells was realised by means of an optical recognition system that is able to detect the cells from the packaging material and pick them up with a robot arm.

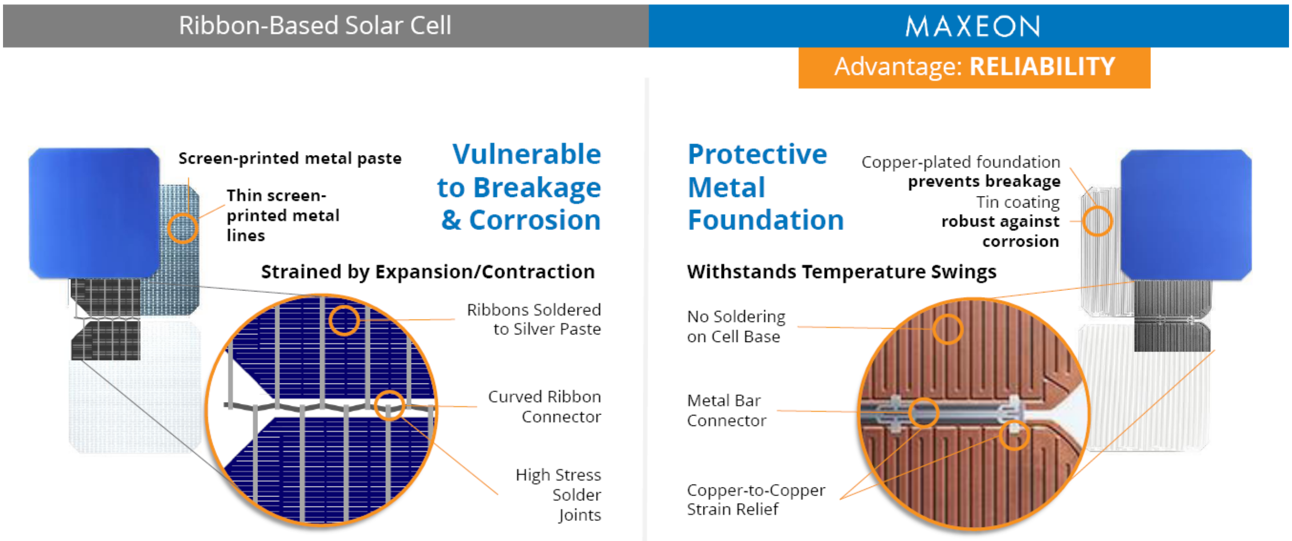


Figure 25: Advantages of the back-contacted cells according to Maxeon

The dimensions of the individual solar cells determine which size the final module can have though there is some flexibility on edges. The current module design from DSE use 24 cells in series, resulting in a modular size of approximately 160 cm x 30 cm.

Figure 28: PV stringer at DSE and red/brown PV sample to the right.

The color machine is used to mix the different pigments so that the correct RAL color can be achieved. This is a key element in the practical use of special knowledge and IPR of Danish Solar Energy. In the project, this machine was refined and is now able to apply color in the correct intensity and mixture for any variety. Samples of colored laminates have been produced for evaluation. The most popular colors are red-brown or grey, but many others have been produced and displayed on the mockups made in the project. The flexibility of the machine and choice of pigments is important because roof materials are found in many different appearances, and they even change color over time.

Development processes:

- Cassette feeding process of Maxeon Me3 cells as an alternative to the 6" cells with which the machine is born.

- Automated camera system that can distinguish paper from the solar cells. Since the new solar cells come with a protective layer of paper between the solar cells, it has been a big challenge to find a solution to automate this process. This was solved with a camera taking pictures which are then image processed so that it can recognize paper from solar cells. Then we have programmed the feed part for the string and put the paper in an extra cassette and only lead the solar cells to the soldering process. For this, the solar cells should also be supplied with flux on the new solder areas.

- Rebuilding solder heads has also been a great challenge in terms of finding a solution to go from traditional long threads that are soldered on the front and back of solar cells of approx. 20 cm to now a completely different contact shape, which is only soldered on the back, and where the connections are only 0.8 cm. We have solved this by rebuilding a completely new automatic wire supply, including wire supply, cutting, placement on matrix, fetch with vacuum heads and placement on solar cell and holding sticks to keep contact during hot air soldering.

A number of experiments have been done to further optimize color reproduction in relation to performance. Here, we have found some new solutions that can reduce color intensity and almost preserve color, and we have produced some modules that are delivered to Danish Technological Institute (DTI) who performs measurements on these.

5.4 WP5 Module test and verification

This WP included internal testing at Rockwool and DTI as well as external test house. The tests took place as follows:

1. Rain penetration test of mockup at DTI Aarhus. The test report can be seen in Annex D.
2. Outdoor performance test of mockup at DTI Taastrup. The test report can be seen in Annex C.
3. UV test of PV samples at DTI Taastrup.
4. Test (partly completed) at TÜV Rheinland according to IEC 61215-1:2021 Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1: Test requirements.

The minimum requirement for marketing of PV modules in the EU is CE marking stating conformity with the Low Voltage Directive and the harmonized standard IEC 61730 Photovoltaic (PV) module safety qualification. In practice the testing is combined with the standard IEC 61215, which has more focus on product durability and lifetime. TÜV Rheinland was contracted for this specific test as they are a well reputed independent test house not too far from Danish Solar Energy. Due to logistic problems related to Covid-19 the test is not yet completed but step 1 is successfully passed.

The other tests were set up internally as laboratory or outdoor tests. The results achieved during the project period do not indicate any kind of general problem with the product. The electric performance in the last generation of modules was measured to 65 Wp which is very close to specifications. The long-term energy measurements showed a slightly reduced performance due to elevated temperature but no damage nor signs of water penetration/condensation in the construction.

There was a small issue with shadows from the edge of the roof on the outer cells, and in the final solution it is therefore mandatory that carpenters refrain from using the usual cover profile. Instead, they should use the integrated metal strips, which can be bent and form a weather resistant edge.

Figure 29: Outdoor mockup being instrumented.

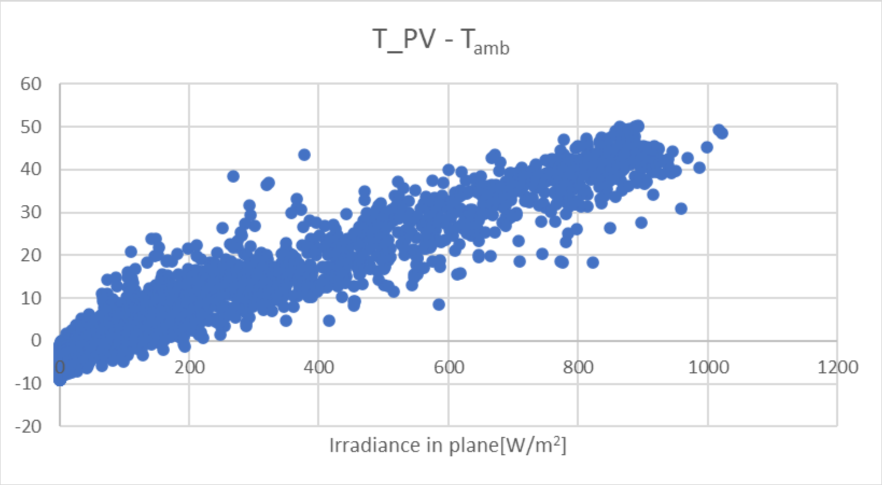


Figure 30: Measured correlation between panel overtemperature and solar intensity.

The temperature rise due to limited ventilation is clearly visible and measurements up to 85°C was measured at full irradiance, high ambient temperature and no wind. As long as it is for limited time this is acceptable though not desired.

As a supplement to the above-mentioned tests, some experiments were carried out on bypass diodes, because it would be beneficial to use diodes with low heat dissipation due to limited cooling on the module rear side. After some searching such a special type of diode was found and tested. The heat release was approximately 1/3 of a normal Shottky diode but due to the higher cost DSE decided to continue with traditional diodes in their modules. These measurements are attached as Annex B.

5.5 WP6 Full system demonstration

The project objectives have been obtained as test and demonstration of the system were technically successful.

The original idea was to have the system installed in a multi-family house in Copenhagen, and therefore some potential renovation projects were contacted. In one case, it has resulted in an order to Dansk Solenergi on the developed red PV modules, but the entire roof construction including Rockwool could unfortunately not be realized within the time frame of the project. Therefore, Rockwool suggested to build the demo system internally as a part of a new pavilion on their premises in Hedehusene. The technical data of the demonstration system are:

Module supplier	Dansk Solenergi ApS
PV modules	RHEM600 24BCM5, GR60/65W
Inverter	Fronius Symo Inverter 3.7-3-M
Installed power	3.7 kW
Total area	29 m2
Roof slope	40 °

Figure 31: Southern roof surface before mounting of the PV modules.

As a supplement to the demonstration house in Hedehusene, another site offered the opportunity to use and demonstrate the colored PV modules as part of a building renovation case in Frederiksberg (Fuglebakkevej 88). The architect wanted an appearance close to the flat tiles that can be seen in the lower part of the roof. Danish Solar Energy commissioned the system in December 2022. The size of the system is 14 kWp.

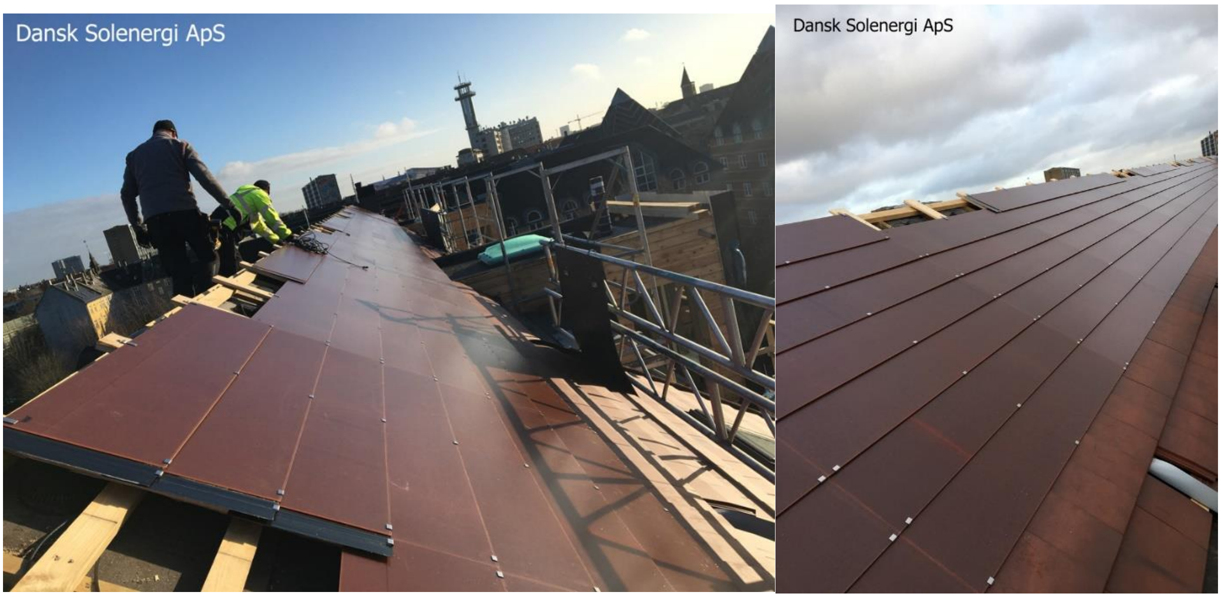


Figure 32 Renovation project with DSE modules in a flat tile roof construction

The demo house in Hedehusene is instrumented so that Rockwool can follow the electrical and thermal performance in the future.

5.6 WP7 Dissemination of results

This work package was led by SolarCity Denmark who arranged several events during the project period. Besides that, Danish Solar Energy participated in Danish and international fairs, where the system was on display. Finally, DTU published relevant scientific results on conferences.

Commercial results are limited, the most important being case studies and cost calculations for typical buildings. The replacement of solar cells with IBC cells was not expected to be a part of the project, but it turned out that Danish Solar Energy would have many benefits from the shift to back contact solar cells. First of all, a more uniform appearance and no need to cover the visible silver tab strings with paint or laminate but also higher efficiency and easier string assembly. On the downside is a higher cost per area.

Target groups:

Construction companies and roof specialist are the most relevant target groups, but also housing associations, architects and building administrators should be interested.

As a part of the project, EFFEKT and DTI have sketched and calculated two different renovation cases that reflect much of the Danish building stock:

- Detached house (parcelhus) with low slope roof. Here, the PV-ROCK-ROOF solution can allow more space and light by opening the ceiling.
- Multi-tenant building with high slope roof. Here, the PV-ROCK-ROOF solution can add a new top floor apartment.

The two cases show that there is a significant overproduction of PV electricity in the first case, which means that a large fraction will be exported to the grid. Before the Ukraine war, this was poorly paid, but currently it is not so bad due to the high spot market price of electricity. In the latter case, the roof area is relatively lower per inhabitant, and production is a smaller fraction of demand. Most of the power is therefore consumed internally, and savings are significant.

In both cases, the thermal energy savings are much lower than the power production, but nevertheless both contributions are profitable given that roof renovation must be done anyway. For the case where livable space is added, the m^2 value alone can be a driver for the renovation, and energy will be a by-product.

A selection tool for planners / architects are available on the project web site.

<u>Dissemination events</u>

1. Webinar, April 2021, DTU (See web site for presentations).
2. Building Green, November 2021, Copenhagen
3. Intersolar, May 2022, Munich
4. Seminar at Rockwool, December 2022 (See web site for presentations).

Figure 33 Building Green, November 2021, Copenhagen

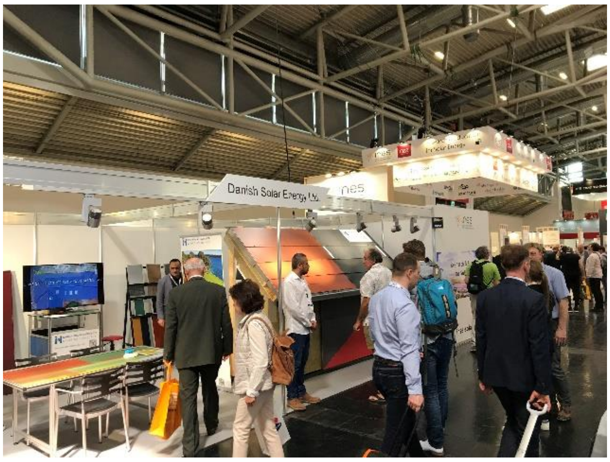


Figure 34 Intersolar, May 2022, Munich

Publications:

- HVAC Magasinet nr. 13 pp 18-22: ”Farvede solceller til byggeriet – muligheder og begrænsninger” https://ipaper.ipapercms.dk/TechMedia/HVACMagasinet/2022/13/?page=18

- Babin, M., Thorsteinsson, S., Santamaria Lancia, A. A., Poulsen, P. B., Thorseth, A., Dam-Hansen, C., & Jakobsen, M. L. (2022). Dependency of IAM Losses in Colored BIPV Products on the Refractive Index of Colorants. In Proceedings of 38th European Photovoltaic Solar Energy Conference and Exhibition (pp. 583 - 588). EU PVSEC. https://doi.org/10.4229/EUPVSEC20212021-4BO.4.2

- Babin, M., Thorsteinsson, S., Jakobsen, M. L., & Spataru, S. V. (2022). Glare potential evaluation of structured PV glass based on gonioreflectometry. IEEE Journal of Photovoltaics, 12(6), 1314 - 1318.

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- Babin, M., Santamaria Lancia, A. A., Thorseth, A., & Thorsteinsson, S. (2020). Characterisation of Angular Dependent Optical Properties of Different Coloring Technologies Employed in BIPV Products. In Proceedings of 37th European Photovoltaic Solar Energy Conference and Exhibition (pp. 1136-1142) https://doi.org/10.4229/EUPVSEC20202020-4AV.2.32

6. Utilisation of project results

The developed system is appropriate for new or existing houses with sloped roofs or buildings with flat roof where a new top floor is added.

By date of project closure, Danish Solar Energy is already selling the colored BIPV modules to individual projects, mainly the tile red type. However, this is with traditional mounting. The full integration with Rockwool's concept will take some time to mature, but the partners are going on with this, and there is no hindrance that carpenters and roofers can use the system already now.

The commercial partners (Rockwool and Danish Solar Energy) will continue to work on the cost and the profitability. An Excel model/tool has been developed, so that building owners or project planners can assess different system sizes and solutions for specific situations. The tool is available from the project web site

Construction companies and roof specialists are the most relevant target groups for PV-ROCK-ROOF, but also housing associations, architects and building administrators should be interested.

The exposure of the project at the Building Green and Intersolar conferences has generated a lot of interest and boosted sales of colored PV modules from DSE.

At the moment of writing, there is an unprecedented need for renewable energy and energy savings in Europe due to the missing gas supply from Russia. The market for PV, and hereunder BIPV, is therefore expected to grow substantially.

Solar Power Europe's report Global Market Outlook For Solar Power 2022-2026 says: "The Europe region continued its positive solar trajectory, achieving 31.8 GW of additional solar capacity – representing 33 % growth and notably only a 0.1 GW difference to our 2021 Global Market Outlook projections. The impact of the Russian war on Ukraine and the accompanying energy security challenges, alongside EU climate goals, are driving the continent's renewable transition – with 25 of 27 EU member states set to install more solar in 2022 than 2021".

Although small rooftop systems, and in particular BIPV, produce electricity at a higher cost than very large central PV plants, the consumer owned plants benefit from exemption from transport fees or energy taxes. Therefore, market projections foresee parallel growth of the two segments.

The PV-ROCK-ROOF product is special because it does not only compete with other PV solutions but also with the thermal insulation market. It is also a cladding material that will be compared with other construction materials in terms of cost, aesthetics and CO2 footprint. The latter is also an element of the new building regulations, as there are requirements on the CO2 emission burden from the construction phase. Rockwool and Danish Solar Energy are aware of this and offer documentation of their specific products to the building sector.

The "solar rooftop initiative" will see new regulations making it mandatory to install solar panels on any new public, commercial and residential buildings by 2029. The plan would also see the EU bring online 320 GW of solar photovoltaic energy by 2025, increasing to 600 GW by 2030. Currently solar energy only delivers 5 % of the total EU electricity generation, so to reach the 2030 target, the EU must install at least 45 GW of solar capacity per year. The EU believes that rooftop PV can not only provide 25 % of the EU's electricity consumption, but that the technology can be deployed rapidly to protect consumers from record high energy prices.

Competition

There are many new and old PV companies entering the BIPV business, but none with an integrated roofing solution including thermal insulation. The most successful BIPV providers in Denmark are SolarTag and Ennogie.

The main barrier is that the solution involves expertise from two traditionally separate sales channels, namely the construction sector and the electricity/energy sector. For building owners or developers, there should be a one stop shop where they can get a tested, reliable and uncomplicated roof solution. The cooperation between Rockwool International and Danish Solar Energy provides the specialist knowledge that must be merged and disseminated in common sales brochures and other promotion material. Rockwool is already ongoing with two internal follow-up projects and plans to include BIPV in their solution catalogues for energy renovation.

Since the beginning of the project, the political focus and need for a robust and versatile energy system has been sharply increasing due to the war in Ukraine and continued climate crises. The timing of the project is therefore in sync with current market trends, showing rising gas and electricity costs and a renewed interest in rooftop solar PV systems.

Use of R&D results

One Ph.D. student has worked on the project for a little more than half of the project. The research results from this still ongoing Ph.D. project has ben disseminated in several DTU courses BIPV course (course number 41461), the Photovoltaic systems (course number 34552) and the Applied Photovoltaics course number 34553. The results have been particularly useful in the BIPV course, where there has been emphasize on glare and color measurements and in the applied PV course where students have performed measurements on the developed laboratory setups.

7. Project conclusion and perspective

The project has shown that the basic ideas from the PV ROCK-ROOF application could be realized, and most of the technical challenges could be solved. The most important technical conclusions from the project are:

- The integration of thermal insulation and a power producing building skin is possible without major loss of energy due to poor ventilation of the PV modules. In the Danish climate, the production loss is less than 3 % compared to a free-standing PV system.
- The coloring technique developed by DSE shows a good stability and angular independent color appearance, which is an important architectural quality.
- The module efficiency compared to an uncolored PV reference was not better nor worse than competitors.
- The untraditional roof construction with OSB sheets as a fast to establish rain screen and external insulation was verified as a robust and compact way to integrate thermal insulation and BIPV without risk of excessive humidity or temperature damage.
- The non-combustible insulation right beneath the cables and PV modules minimize the risk of ignition of combustible building parts in the event of electric arcs or hot spots in the PV system.
- The thermal insulation without thermal bridging around key junctions gives the highest utilization of the insulation material and a uniform indoor surface temperature.

An important lesson learned concerns the interaction between different sectors involved in building renovation, mainly PV/electrical and carpenter/roofer who must understand and respect each other´s way of workflow and expertise. A good mounting guide is essential.

The flat roof solution was found to be the most difficult one to finish and bring to the market, as the complexity of the product (watertight joints) is relatively high compared to current standard add-on roof PV solutions. The developed sloped roof product is very relevant where building owners want to invest more in aesthetics than in usual PV installations or when building owners need to replace existing roof tile due to wear and tear. There could also be cases where building owners wish to improve indoor conditions and have a holistic and sustainable renovation.

The results and drawings are freely available on the web site, and the authors therefore encourage the construction sector to adapt the PV-ROCK-ROOF concept in building renovation and new buildings. DSE will continue selling the colored PV panels from the project.

The project results constitute yet another step in the green transition of the energy system and implementation of energy savings in the building sector. With the developed solution and the adaptation of PV module color to the surrounding built environment, it will be hard to find arguments against PV in our cities.

8. Appendices

Annex A WG2 summary report

Annex B Diode experiments

Annex C Mockups and test results

Annex D Rain test report

Annex E Rockwool Roof References (drawings)

Annex F Design considerations

Annex G Articles etc.

Project home page: PV-ROCK-ROOF - Teknologisk Institut https://www.teknologisk.dk/41425