



# **Final report on solar collector and primary circuits developments in WP 3**

Deliverable 3.4 – **Final** – 06 July 2015

MacSheep - New Materials and Control for a next generation of compact combined Solar and heat pump systems with boosted energetic and exergetic performance

Dissemination Level: PU – public

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## Executive Summary

In the MacSheep project two solar collector prototypes have been developed by two groups. These prototypes include breakthroughs which have been identified and analyzed within phase 1 and phase 2 of the project. This document presents the final status and results concerning the solar collector developments at the end of phase 3 of the project.

**ESSA** has developed a new absorber made of ferritic stainless steel with a new selective paint that is applied on the stainless steel coils (coil coating) before the stamping and welding operation. This absorber will be a key component of the new system developed by IWT, SPF & ESSA which uses the unglazed collectors as only heat source for the heat pump.

Two new selective paints have been tested and compared with the benchmark collector. Despite that the new selective paints perform between 11 and 14 % less than the benchmark ESSA product under normal steady state test conditions; they show a very good performance-cost ratio in the particular system concept of IWT, SPF & ESSA.

ESSA tested the new coated collectors in the field at different outdoor conditions (chlorine environment, saline air, gas burner exhaust) under stagnation for durability. After 5 months duration of these exposure tests, the coating of the test samples showed no damage.

**CTU** has developed a new design of a glazed hybrid photovoltaic-thermal (PVT) collector with polysiloxane gel as encapsulation compound for PV cells. PV strings are encapsulated between double glazing with low-e coating and the copper fin & tube absorber into. Polysiloxane gel has been chosen because of its high temperature resistance in combination with other important features such as high solar transmittance, high thermal conductivity, electric insulation, and low modulus of elasticity.

Several different prototypes of glazed PVT collector have been fabricated and tested at outdoor and indoor (sun simulator) conditions. The mathematical model for the glazed PVT collector has been validated. Sufficient electric resistance between PV part and the metal sheet absorber has been achieved to guarantee the electric safety of the product. Based on the experience from the tests and the new encapsulation process, the final design of the glazed PVT collector has been adapted and optimized.



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# 1 Introduction

Within the MacSheep projects, solar thermal and heat pump systems that achieve 25% energetic savings compared to the current state of the art are developed. These developments take place in four different development branches that are carried out by the following groups of partners:

- Energie Solaire SA & HSR-SPF & IWT TUG
- Ratiotherm GmbH & Co. KG & SERC
- VIESSMANN Faulquemont S.A.S., CEA INES
- Regulus spol. s.r.o., CTU

Within the first and second phase of the project in the year 2012, breakthroughs for materials, components and control that lead to higher energetic performance and/or lower cost of the system were analyzed and selected (see Figure 1). The selection was based on an analysis of the cost-effectiveness of the new development. The effect of potential breakthroughs on the energetic performance was determined by annual simulations. The cost difference compared to a system without this breakthrough was estimated based on the experience of the industrial partners on one hand, and on best guess for new products or methods for production on the other hand.

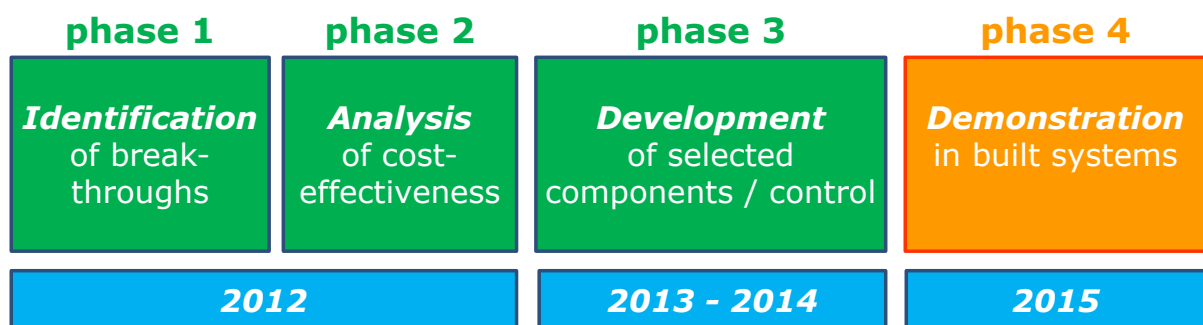


Figure 1: Phases and time-line of the MacSheep project.

Reports D3.4, D4.4, D5.4 and D6.4 give details of the developments in the project within the field of collectors, heat pumps, storage and control respectively, while D7.3 gives information about the whole system and energy savings compared to a state of the art reference system.

Within phase 3 of the MacSheep project, the breakthroughs on solar collectors shown in Table 1 were further developed within this work package.

Table 1: Summary of breakthroughs for solar collectors and primary circuits to be further developed during phase 3.

<b>Description</b>	<b>ESSA-IWT-SPF</b>	<b>Ratiotherm-SERC</b>	<b>Viessmann-INES</b>	<b>Regulus-CTU</b>
uncovered collectors with selective paint	X			
covered photovoltaic-thermal (PVT) collector				X

## 2 Development by ESSA, IWT & SPF

Energie Solaire SA (ESSA) is probably the only manufacturer of selective unglazed collectors in the world. These collectors can be used well as a heat pump source directly or in combination with a small / medium ice storage. The omitted glazing leads to a much better heat transfer between collector and ambient air, compared to glazed collectors. Thus, it is possible to use these collectors also as air source heat exchangers when there is little or no sunshine available. The MacSheep system developed by ESSA, IWT & SPF uses the unglazed collectors as only heat source for the heat pump, replacing the traditional ambient air heat exchanger. Thus, the collectors represent a key component of the new system development.

The investigated breakthroughs for this deliverable were:

- Two selective paints that have been selected by ESSA for deeper investigation. These new coatings can be applied directly on coil (before stamping and welding) and bring thus a significant cost advantage compared to the absorber coating that is currently applied for these kind of absorbers;
- Both new coatings allow using more cost effective stainless steel substrates, which leads to a substantial material cost reduction.

The geometric design of the unglazed collector (absorber with cushion geometry and full irrigation) remains the same as for the current ESSA solar collector design.

### 2.1 Description of developed component

The ESSA benchmark consists of an unglazed solar collector made of austenitic (1.4301) stainless steel with a selective coating made of chrome-oxide. The absorbers are made from the stainless steel coils before the coating is applied. First, sheets are stamped with a cushion geometry. Then, both sheets are spot-welded together and a seam is welded on the periphery of the solar absorber. The final production step is the galvanic plating of the selective chrome-oxide coating on the absorber (component coating).

The new developed unglazed collectors are made from ferritic stainless steel coils. These coils are already coated with a selective paint upon delivery at the ESSA plant. The coated sheets are first stamped (see Figure 2) and then welded together. Thus the production process is shorter, leading to cost reductions.



*Figure 2: Ferritic stainless steel coil with new selective paint (after stamping of cushions).*



The production process of the new developed solar absorbers is quite different from the benchmark. The welding process had to be adapted and first absorbers were produced with the new process.

Table 2: Construction parameters of the unglazed collector

Collector	type	ESSA Solar Roof - Ferritic Stainless Steel
	gross area	2.41 m <sup>2</sup>
	aperture area	1.83 m <sup>2</sup>
	connection	15 mm compression ferrule
	max. pressure	3 bar
	fluid	Water without chlorine ions with 40% antifreeze and corrosion inhibitor
	weight	9.8 kg
Absorber	type	ESSA AS Selective Coating
	material	Ferritic stainless steel with selective paint coating
	thickness	8 mm
	area	2.03 m <sup>2</sup>
Glazing		--
Insulation		--
Frame	material	--

The unglazed absorber is fixed on two aluminum profiles on each side, and clamped by EPDM sliders. On the lower side, there is a corrugated panel made of glass reinforced polyester, acting as a double skin system. The absorber plus the mounting system together represent a mounting height of 25 mm, with a weight of 13 kg/m<sup>2</sup>.

## 2.2 Laboratory measurements and derived results

Two new selective paints were tested and compared with the benchmark collector. The test has been carried out at the SPF solar institute in accordance with EN 12975-2, under artificial sky (Figure 3).

The collector mounting used for the test was made to replicate a real installation, even if the effect of other panels around could not really be reproduced.



Figure 3: Test collector exposed under the artificial sky at the SPF solar institute.

The optical properties of the tested samples are:

- test sample 1 (benchmark) – collector testn° C970, ESSA coating type C2-80 (AS):  
Optical properties :  $\varepsilon < 16 \%$ ,  $\alpha > 94 \%$ ;
- test sample 2 (selective paint type 1) – collector testn° X300:  
Optical properties :  $25 \% < \varepsilon < 27 \%$ ,  $91 \% < \alpha < 92 \%$ ;
- test sample 3 (selective paint type 2) – collector testn° X297:  
Optical properties :  $44 \% < \varepsilon < 46 \%$ ,  $92 \% < \alpha < 93 \%$ ;

The performance coefficients of the test samples are given in Table 3. The collector efficiency equation according to EN12975-2 is defined as follows:

$$\eta(t_m) = \eta_0 \cdot (1 - b_u \cdot u) - (b_1 + b_2 \cdot u) \cdot \frac{(t_m - t_a)}{G''}$$

With:

$$G'' = G + \frac{\varepsilon}{\alpha} \cdot \sigma \cdot (T_{sky}^4 - T_a^4)$$

Table 3 gives an overview of the collector performance test results and derived efficiencies for  $G = 800 \text{ W/m}^2$ ,  $t_m - t_a = 20 \text{ K}$  and  $32 \text{ K}$ ,  $u = 0$  and  $1 \text{ m/s}$ , and effective sky temperatures that are  $10 \text{ K}$  below ambient ( $t_a = 20^\circ\text{C}$ ).





Table 3: Efficiency data in accordance with EN12975-2 (unglazed collector efficiency). Differences of the efficiency of the new coatings compared to the reference are given in % relative to the reference.

	Benchmark coating Testn° C970	Selective paint type 1 Testn° X300	Selective paint type 2 Testn° X297
$\eta_0$	0.954	0.955	0.957
$b_1$ [W/(m <sup>2</sup> K)]	9	11.96	12.65
$b_2$ [J/(m <sup>3</sup> K)]	3.768	2.904	2.061
$b_u$	0.01	0.038	0.043
$\varepsilon$	0.13	0.26	0.456
$\alpha$	0.953	0.917	0.927
$\eta$ for $u = 0$ m/s, $(t_m - t_a)/G = 0.025$	73 % (ref)	65 % (-11 %)	63 % (-13 %)
$\eta$ for $u = 1$ m/s, $(t_m - t_a)/G = 0.025$	62 % (ref)	54 % (-13 %)	54 % (-14 %)
$\eta$ for $u = 0$ m/s, $(t_m - t_a)/G = 0.04$	59 % (ref)	47 % (-21 %)	43 % (-27 %)
$\eta$ for $u = 1$ m/s, $(t_m - t_a)/G = 0.04$	43 % (ref)	31 % (-27 %)	31 % (-28 %)

The comparison test shows the results for the new absorbers from the indoor collector performance test. The benchmark values of the original coating were taken from an official SPF test report<sup>1</sup>.

For a typical value of  $(t_m - t_a)/G = 0.025$  for the given application the new selective paints perform between 11 and 14 % less than the benchmark product. However, when the new collector performance parameters are implemented in the annual system simulation, the resulting performance difference is only 2 % (2% increase in el. energy used) compared to an annual simulation with the ESSA benchmark collector parameters. The unglazed collectors were simulated with the TRNSYS type 202 by Bertram et al. (2010). For more details regarding the simulation one can find it in the deliverable 7.3.

Selective solar coatings are in general not specifically developed for direct exposure to outdoor weather conditions, since they are usually applied in covered solar collectors where they are protected by the glazing. To our knowledge ESSA is the only company which has developed and applied selective coatings for unglazed collectors.

Unfortunately no standards or official test procedures exist for the qualification of selective coatings for unglazed collectors that are exposed directly to outdoor weather conditions. For this reason ESSA is testing the new coated collectors in the field, where they are exposed in a flat position under outdoor weather conditions.

<sup>1</sup> SPF Homepage, link to the test report C970:  
<http://www.spf.ch/fileadmin/daten/reportInterface/kollektoren/factsheets/scf970de.pdf>

Different cases for harsh outdoor conditions are being tested. Some samples have been placed at a chlorine treated swimming pool (close to the skimmer entrance), directly at the sea side for saline air, and directly at the exhaust of a gas burner.

After nearly 5 months of exposure in stagnation, the coating of the test samples shows no visual damage. The exposure test is hard, since the samples are continuously exposed to high temperature, and, since the samples are positioned flat, rain water and dust cannot easily run off. These durability tests will be carried on as long as possible beyond the MacSheep project. Until now only the samples from the swimming pool exposer test could be measured regarding the alpha and epsilon value. The selective paint type 1 shows no change. The results of the type 2 show an increase in the epsilon value, of about 7 % absolute.

Table 4: Outdoor testing of selective paint coated stainless steel samples.

**Conditions and results after 5 months**

**Figure**

**Sea side exposure:**

- Visual aspect: no damage
- Optical properties:
  - Ongoing test



**Chimney gas exhaust:**

- Visual aspect: no damage
- Optical properties:
  - Ongoing test



**Swimming pool:**

- Visual aspect: no damage
- Optical properties:

	$\alpha$	$\epsilon$
type 1 ref.	92%	26%
type 1 exp.	91%	22%
type 2 ref.	93%	46%
type 2 exp.	93%	53%





### 2.3 Conclusions and outlook

In general, the development of the unglazed collectors is very promising, but some question marks remain concerning the long term durability. Regarding the integration and advantage of the selective unglazed collectors in the new designed system, the simulations show very positive results, more detailed results can be found in Mojic et al. (2013).

Since no general agreed upon ageing test for uncovered selective collectors is available, samples have been placed in especially harsh outdoor conditions, showing no visual degradation until now (i.e. after five months). Optical measurements have been done with the samples from the swimming pool exposer test after five months of exposure. These measurements showed that for the selective paint type 1 there are no significant negative optical changes. For the type 2 the emissivity is about 7 % (absolute) higher compared to samples which were not exposed outside. These outdoor tests will be continued in 2015 and further optical measurements will be done. Depending on the outcome, one of the two new selective paints may replace the current chrome-oxide coating in the production of selective solar absorbers from ESSA.

### 3 Development by CTU

A glazed hybrid photovoltaic-thermal (PVT) collector has been developed in the frame of the MacSheep project. This collector provides heat and electricity simultaneously within the MacSheep solar and heat pump system developed by CTU and Regulus. Heat can be used directly for storage tank charging, electricity can be used both to cover the electricity consumption of the solar heat pump system and for charging the upper part of the storage to temperatures (90°C) by an electric heater.

#### 3.1 Description of developed component

A glazed PVT collector with polysiloxane gel encapsulation of PV strings was developed at CTU. Double glazing with a gap between the glass panes of 30 mm, filled with argon, was used for this collector (see Figure 4). A low-e coating with high solar transmittance and an emissivity of 30 % was applied to the absorber glazing to achieve low heat losses. The main construction parameters of the PVT collector are shown in Table 5.

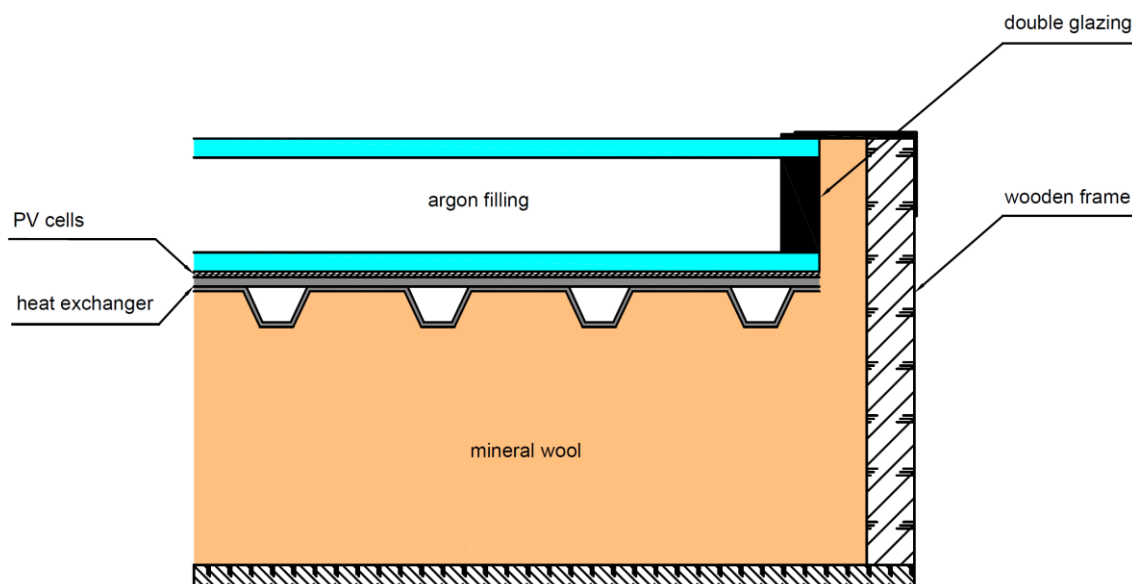


Figure 4: Layout of the glazed hybrid PVT collector.

Polysiloxane gel has been chosen for the encapsulation because of its high temperature resistance in combination with other important features such as high solar transmittance, high thermal conductivity, electric insulation, and low modulus of elasticity. The polysiloxane gel encapsulation machine that is available at the University Centre for Energy Efficient Buildings (Czech Technical University, CTU) was used to produce different glazed PVT collector prototypes. The encapsulation technology is based on low vacuum dosing of the gel into the gap between the glass pane and the flat heat exchanger with immersed strings of PV cells. The encapsulation process is carried out at room temperature. This fact brings a clear advantage for future production of the hybrid PVT collectors.

Large effort has been dedicated to the development of the encapsulation process and to the search for suitable materials for sealing, distance elements between the glass and the absorber sheet, and electric contact sleeves that are compatible with the polysiloxane gel.



Table 5: Construction parameters of final PVT collectors

Collector	type	glazed, PVT
	gross area	1.60 m <sup>2</sup>
	aperture area	1.55 m <sup>2</sup>
	connection	pipe 22 x 1 mm
	max. pressure	1 MPa
	fluid	water, antifreeze
	weight	35 kg
Absorber	type	fin & tube
	material	copper
	thickness	0.2 mm
	area	1.55 m <sup>2</sup>
PV cells	type	monocrystalline 125 x 125 mm
	number of cell, strings	66 cells, 3 strings
	packing factor	70 %
	electric power	160 W
	encapsulation	polysiloxane gel
Glazing	type	low-iron cover low-emittance surface
	cover transmittance	91 %
	thickness	4 mm / 3 mm
Insulation	material	mineral wool
	thickness	40 mm (back side), 10 mm (edge side)
Frame	material	aluminum or wood

The final construction design of the developed glazed PVT collector is based on monocrystalline silicon cells 125 x 125 mm with a nominal efficiency of 17 %. Three parallel strings were used with 66 cells in total (Figure 5). A comparatively low packing factor has been used to eliminate edge shading of the PV cells that may result from the frame of the double glazing.

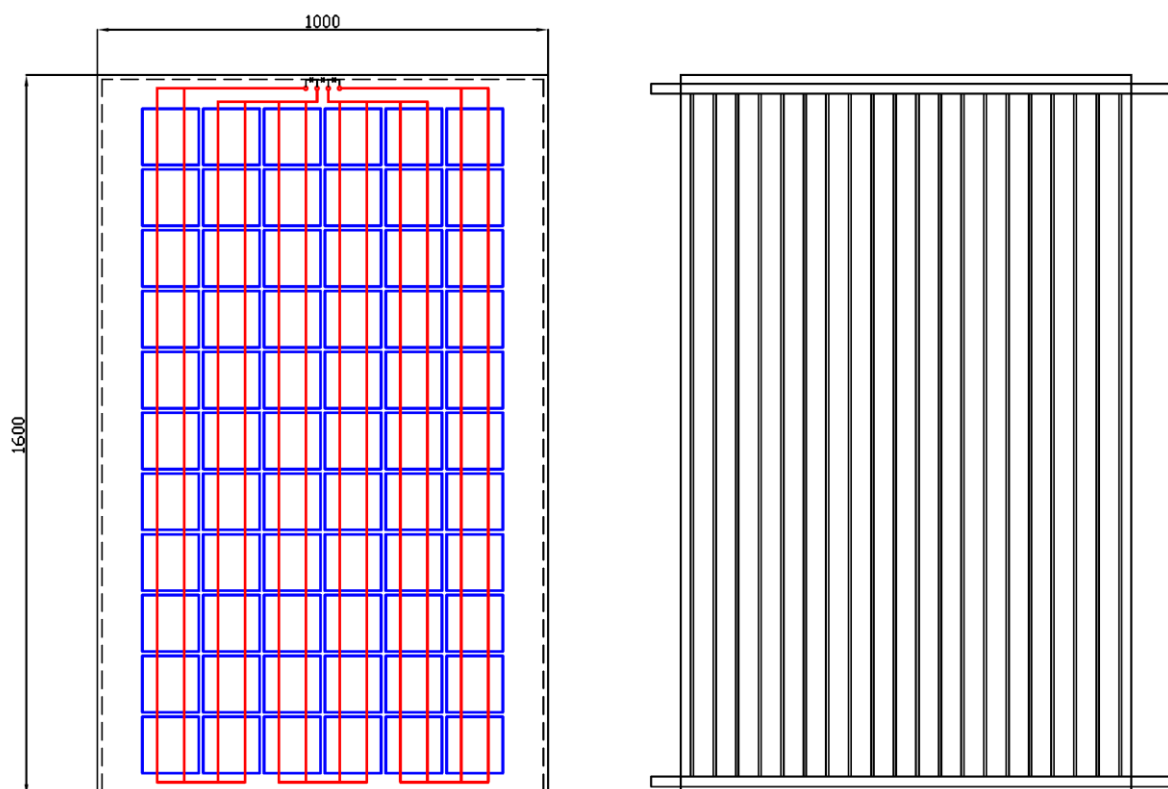


Figure 5: Geometry, PV strings and heat exchanger.

## 3.2 Laboratory measurements and derived results

### 3.2.1 Thermal performance

In the frame of the PVT collector development, two main prototypes, a nonselective and a selective one, have been fabricated and tested. Mathematical model of glazed PVT collector was validated and the collector design was verified.



Figure 6: Glazed nonselective PVT collector at outdoor testing, glazed selective PVT collector at indoor testing.

Glazed solar PVT collector prototypes have been tested under outdoor conditions at the Faculty of Mechanical Engineering, Czech Technical University in Prague, and under conditions of artificial sun at University Centre for Energy Efficient Buildings, Bustehrad (see Figure 6). Tests have been performed in accordance with EN ISO 9806 for the open circuit

mode. A double glazing, consisting of two solar glass panes, has been used for the spectrally nonselective alternative of the final PVT collector. The spectrally selective PVT collector has been fabricated from double glazing with a standard coating with low-emissivity in the infrared part of the spectrum and reduced transmittance in the near infrared region of solar radiation.

Figure 7 shows the comparison of the thermal performance characteristics for original glazed PVT collector prototypes (selective, nonselective). The comparison has confirmed the excellent properties of the polysiloxane gel encapsulation. The high zero-loss efficiency for the nonselective prototype confirms the good heat transfer from the PV absorber into the heat transfer fluid, and the high transparency of the polysiloxane layer. On the other side, the high radiative heat loss reduces the thermal performance of the nonselective PVT collector at high temperatures.

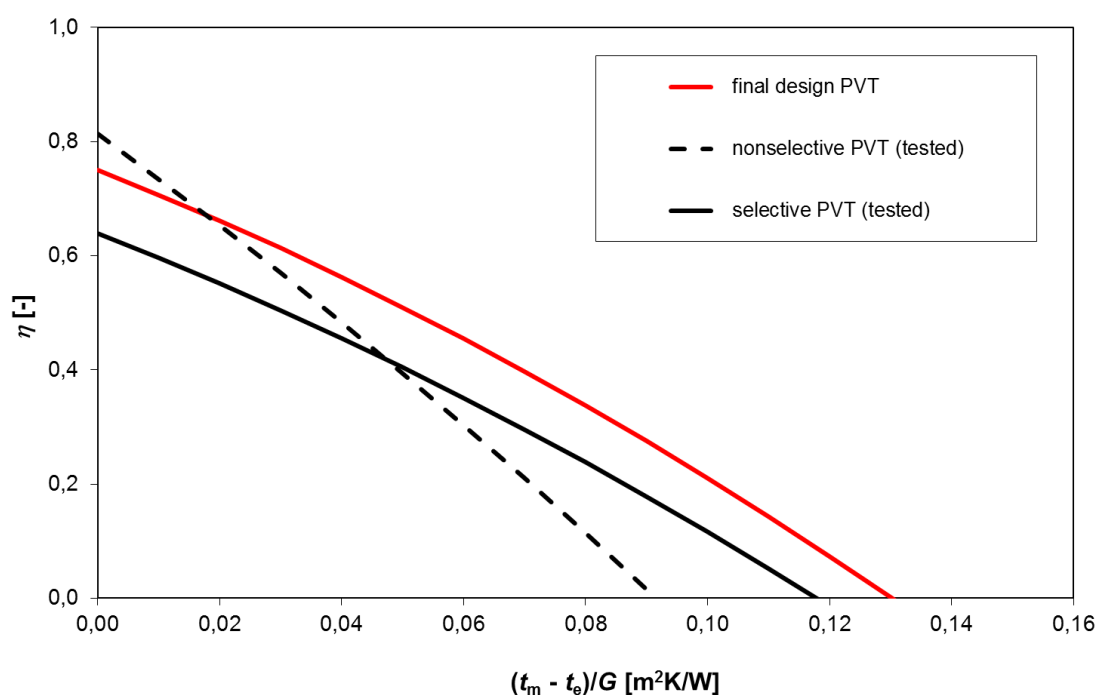


Figure 7: Thermal efficiency characteristics for developed glazed PVT prototypes (open circuit)

Results for the selective PVT collector prototype have confirmed the assumption of high reflection losses in the near infrared radiation region due to the low-e coating applied to the absorber laminate glass.

Table 6: Performance indicators of the glazed PVT collector (final design).

Mode	$\eta_0$ [-]	$a_1$ [W/m <sup>2</sup> K]	$a_2$ [W/m <sup>2</sup> K <sup>2</sup> ]
glazed PVT collector (open circuit)	0,75	4.20	0,012
glazed PVT collector (MPPT)	0,65	3,30	0,012

Based on the results for the prototypes, the selective covered PVT collector has been chosen for the MacSheep system. The resulting performance indicators for both modes of operation (with and without electricity use) are shown in Table 6.

### 3.2.2 Electric safety

Since PVT collectors are electric devices, the electric safety has been in the focus from the beginning of the development. Several designs of PV encapsulation with painted copper sheet absorbers have shown to be electrically safe components. The distance between PV cells (and metal contacts) and metal absorber is guaranteed by a glass fiber grid, and the electric resistance is given by the polysiloxane gel. The wiring sleeves through the copper sheet were made from the silicone compound and connected to the junction box at the outer surface of the collector box. The electric resistance was tested by 1 kV applied between the copper absorber and the electric wiring of the PV cells, and a value  $> 200 \text{ M}\Omega$  was measured. This result is common for standard PV modules on the market.

### 3.3 Component simulation models

The detailed mathematical model PVT-NEZ (Matuska, 2010; Matuska & Buchta, 2011), originally developed for unglazed PVT collector performance modeling based on detailed optical, thermo physical and electrical parameters of the absorber, has been extended for glazed PVT collectors. The validation has been done for the thermal efficiency characteristics (Figure 8).

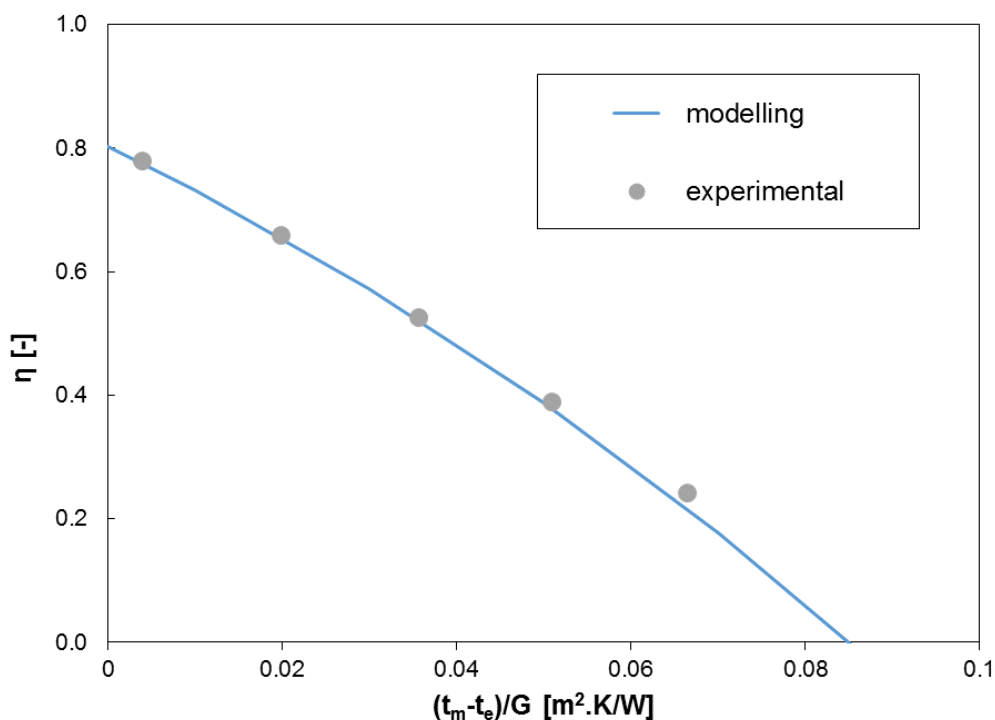


Figure 8: Experimental validation of modelled nonselective PVT collector performance (open circuit).

A model for the glazed PVT collector for TRNSYS (type) is under development. For the time being, TRNSYS Type 50b was used in combination with Type 832 for PV yield and solar thermal heat output respectively for MacSheep system simulations. The influence of the thermal heat extraction (cooling) on PV yield as well as the reduction of heat output resulting from PV production in MPP mode were considered.





### **3.4 Conclusions and outlook**

Despite that the development of the glazed PVT collector has started within the MacSheep project from level zero, the designed and manufactured product seems to be promising not only for solar and heat pump systems. While other attempts for glazed PVT collector developments failed with the use of the standard EVA encapsulation, the polysiloxane gel compound offers all the necessary features in order to reach both durability and affordability of this new product.

## **4 Conclusion**

Within the MacSheep project two quite different solar collector prototypes were developed by two different groups. These solar collectors will be used in the MacSheep systems developed by these two groups.

The prototypes include breakthroughs which have been identified and analyzed within phase 1 and phase 2 of the project – the unglazed solar collector (absorber) with a new spectrally selective coating, and the glazed photovoltaic-thermal collector for simultaneous production of heat and electricity.

The prototypes of solar collectors have been tested and performance indicators have been derived. In addition to performance testing, the unglazed absorbers have been tested also for long term durability in extreme environments and showed no degradation up to now. The glazed PVT collectors have been checked for sufficient electric resistance between PV cells and metal absorber and have passed this test.



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