Hybrid PV-Thermal collector development: concepts, experiences, results and research needs

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Abstract

This paper highlights research on aspects underlying PVT collector development, from which possible design concepts and development paths are determined. Test results from several performance improvements to PVT collector prototypes are presented, culminating in a thermal performance in open circuit mode which is similar to that of a good solar thermal collector. This collector prototype incorporates the required ‘fail-safe’ stagnation protection feature. Remaining material and construction research and development needs are also indicated.

1. Introduction and motivation

The size of annually installed solar thermal (ST) collector area in Europe has been left far behind that of PV, for example: by 2012 in Germany alone 16.5 million m² ST collector area was installed compared to 32.4 GW (or ca. 230 million m²) PV [1]. Partly driven by an increasing competition for suitable roof area, the integration of the two technologies may create new market opportunities for the solar thermal industry [2]. PVT collector research and development is thus potentially an important development path for the solar thermal industry.

Photovoltaic (PV) modules generally absorb much of the available solar radiation, but only a relatively small part is converted into electricity (see Fig. 1: Left); the rest is converted into heat and purposely dissipated to the

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Another benefit of PVT collectors is their ability to capture cascading energy qualities: first electricity with high exergy and most of the remaining energy, as heat, with low exergy. The total available exergy captured from such a surface is potentially much larger than what is possible when only capturing a single energy quality. Our simulations show that significantly more energy can be captured from the same area with PVT collectors than with PV modules or ST collectors. See Tab. 1 for a comparison of simulated energy yields using a PV module, a solar thermal collector and thermal performance values from a prototype PVT collector from 2010.

For example, in Essen, for a typically sized domestic hot water system and a typically sized combi system the simulated total energy yield of a system with performance characteristics of a PVT-prototype developed in 2010 at Fraunhofer ISE is: 2289 kWh/a (1767 kWhth + 522 kWhel) and 3522 kWh/a (2490 kWhth + 1032 kWhel), respectively, which is more than that from the PV and ST systems only.

Tab. 1: Comparison of simulated energy yields from PV modules, PVT collectors and solar thermal collectors for domestic hot water systems with 6 m² collector aperture area (left) and combi-systems (DHW and space heating) with 12 m² collector aperture area (right). Bold values are the absolute references for the relative quantities in the same row. Note: The PV module and PVT collector parameters given in the tables show that a slightly idealized PVT module is used as the performance characteristics are the same as for the PV module and the PVT collector. In a real PVT collector both \( \eta_{STC} \) and the packing factor are likely to be lower than that of a standard PV system which uses a similar PV construction. The influence of different PV operating temperatures is taken into account in the simulation.

<table>
<thead>
<tr>
<th></th>
<th>PV Module</th>
<th>ISE PVT2010</th>
<th>Solar Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domest. Hot Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Essen</td>
<td>0</td>
<td>0%</td>
<td>1767 81%</td>
</tr>
<tr>
<td></td>
<td>522</td>
<td>100%</td>
<td>522 100%</td>
</tr>
<tr>
<td>Passau</td>
<td>624</td>
<td>100%</td>
<td>624 100%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combi System</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Essen</td>
<td>0</td>
<td>0%</td>
<td>2490 73%</td>
</tr>
<tr>
<td></td>
<td>1044</td>
<td>100%</td>
<td>1044 99%</td>
</tr>
<tr>
<td>Passau</td>
<td>0</td>
<td>0%</td>
<td>2947 99%</td>
</tr>
</tbody>
</table>

For market-focused PVT collector development to commence many questions need to be answered. Many of the relevant aspects to be addressed were mentioned in the PVT Roadmap: A European guide for the development and market introduction of PV-Thermal technology by Zondag et al. [3] (Fig. 1: Right).
In this paper we try to clear some of the complexity surrounding PVT collector development by showing some of the insights we have gained from functional requirements and important design parameters and by using the collector thermal insulation as a key aspect in PVT collector development. This analysis then ultimately leads to the proposal of three possible PVT collector concepts, each with very different implications.

2. Functional requirements and key design parameters

Photovoltaic (PV) and solar thermal (ST) technologies and manufacturing have evolved driven by different functional and technical requirements, they deliver different outputs (electricity or heat) and serve different demands (in size and temporally). Both have contrary thermal insulation requirements: low for PV and high for ST. Each technology was optimized separately with respect to efficiency, cost effectiveness, reliability and durability, which resulted in different constructions and materials being applied and also in different standards and tests to be complied with.

New products are often compared side-by-side to existing products, especially when they are a combination of existing products. Costs are an important aspect for comparison, and because costs can be offset against gains, performance is an important aspect for a comparison.

<table>
<thead>
<tr>
<th>PV Performance</th>
<th>ST Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross/aperture area ratio</td>
<td>Gross/aperture area ratio</td>
</tr>
<tr>
<td>Optical efficiency</td>
<td>Optical efficiency</td>
</tr>
<tr>
<td>Packing factor</td>
<td>Heat removal construction (HRC, $F'$)</td>
</tr>
<tr>
<td>PV operating temperature</td>
<td>Thermal insulation</td>
</tr>
</tbody>
</table>

When aiming for an electrical performance of a PVT collector similar to that of a PV module the requirements for gross/aperture area ratio, optical efficiency, packing factor, and PV operating temperature are also similar. When aiming for a thermal performance which is similar to that of a good solar thermal collector then the requirements for gross/aperture area ratio, optical efficiency, heat removal construction (HRC) and thermal insulation are also similar. These influential design factors of the PV and ST performances are listed in Tab. 2.

Fig. 2: Illustration of differences in gross and aperture area, ‘depth’ of the cell in the collector and shading from the frame onto the cells and the need for an enlarged cell-free zone around the strings in covered PVT collectors.

The influences of geometric factors (gross/aperture area ratio and packing factor) can be understood easily as marginal changes in these factors lead to proportional changes in the yield per square meter. For PVT collectors in comparison to PV modules a more solid frame and possible thermal side insulation may likely take up some of the available area. In the case of a PV module, a cell-free edge around the strings is needed to prevent shading from the
frame onto the outer cells. The cell-free edge may need to be wider when the cells lie ‘deeper’ in the collector, this is especially the case for a covered absorber (Fig. 2).

A possible stagnation protection mechanism (see later) may also require some of the available area or may have an effect on the optical efficiency of the collector cover and cell cover.

PV as well as thermal performances are proportional to the optical efficiency, expressed in $\tau \alpha_{\text{eff}}$ [5]. Thus any benefits of a measure that reduces the optical efficiency, e.g. a low-$\epsilon$ coating, should be carefully weighed against the loss of both electrical and thermal yield.

Tab. 3: A comparison of optical parameters of a PV module and a thermal collector with selective coating.

<table>
<thead>
<tr>
<th>Component</th>
<th>Characteristic</th>
<th>PV</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover</td>
<td>$\tau$ (transmittance)</td>
<td>0.98</td>
<td>0.96</td>
</tr>
<tr>
<td>Absorber</td>
<td>$\alpha$ (absorptance)</td>
<td>0.89</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon$ (emittance)</td>
<td>0.92</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Legend: Glass cover — PV cell — Selective absorber

A comparison of optical parameters of a typical PV module and a typical ST collector with selective absorber coating shows that the differences in transmittance and absorptance between the two are not very large and pose no significant issues for using a PV as a thermal absorber. But the differences between the thermal emittance of the cell cover, which is usually a glass sheet or a polymer, is much higher, around 0.92, than the thermal emittance 0.05 of a selective absorber. As part of one of our research projects on PVT collectors the department Coatings – Technologies and Systems (BTS) of Fraunhofer ISE developed a transparent low-emissivity coating specifically optimized for PVT applications. A thermal emittance of around 0.15 was achieved, but with that the solar transmittance (for c-Si PV and AM 1.5) was reduced to 0.82. This compromise was the result of an optimization which included weighing the effects of optical characteristics on the electrical and thermal performances.

![Fig. 3: Illustration of a simple model of a PVT collector (derived from [4]), showing the incoming radiation, removed PV electricity and two thermal resistances: one between the PV cells and the environment ($R_{\text{insul}}$) and one between the PV cells and the heat removal fluid ($R_{\text{HRC}}$).](image)

Regarding the heat removal construction of a solar thermal collector, whose purpose is to conduct the heat from the absorbing surface to the heat removal fluid efficiently and effectively, a simple analysis which includes the collector thermal insulation shows its importance in different collector constructions. Equation 1 is the linear efficiency formula for ST collectors [5]. Equation 2 is the collector efficiency factor $F'$, adopted from [5], but expressed in the thermal resistances $R_{\text{insul}}$ and $R_{\text{HRC}}$ of the simple PVT collector model in Fig. 3. From equation 2, it can be seen that possible values for $F'$ are in the range between 0 and 1. The ideal value for this parameter is close to 1. A low thermal resistance between absorber and heat removal fluid (a low $R_{\text{HRC}}$) and a high thermal resistance between the collector and the environment ($R_{\text{insul}}$) are thus beneficial for the thermal efficiency. In addition, a low $R_{\text{HRC}}$ is also beneficial for the PV efficiency because it brings the PV cell temperature closer (down) to that of the heat removal fluid. It can also be seen that when the thermal collector insulation is high, for example for covered
collectors with low-ε absorbers, the influence of the HRC thermal resistance is relatively low; and when the thermal collector insulation is low, for example for non-covered collectors, then the influence of the HRC is relatively large. The latter shows that especially for good thermal performance of non-covered collectors, an efficient heat removal construction with low thermal resistance between absorber and fluid is essential.

\[ \eta = F'(\tau \alpha)_{\text{eff}} - F'U_L \frac{\Delta T}{G} \]  \hspace{1cm} (1)

\[ F' = \frac{R_{\text{insul.}}}{R_{\text{insul.}}} + \frac{R_{\text{HRC}}}{\rho_T} \rightarrow 1 \]  \hspace{1cm} (2)

The next design parameter is the PV operating temperature. But first some operating assumptions need to be made: For typical PV and ST systems it is commonly assumed that:

- PV electricity is always usefully removed and applied whenever there is solar radiation available on the module area, but ...
- Solar thermal operation is further limited by collector performance, heat demand and storage capacity.

In the near future the first assumption may be unrealistic in times of excess electricity available from PV and wind renewable sources. At these times it may not be possible to feed (all) electricity into the grid. Other end-use applications, such as direct heating with electricity or done via a heat pump, or not removing the electricity from the collector (i.e. ‘open circuit’ mode PV operation) or even dumping the electricity elsewhere may then be considered. The implications of any new operating assumptions still need to be researched.

Combining the two assumptions, the potential synergetic effect from actively cooling the PV cell below the usual PV module temperature is only possible when the thermal collector loop is operating, i.e. heat is actively removed, and the fluid temperature is relatively low compared to the ambient temperature. The resulting net annual balance compared to that of a standard PV module depends in particular on the size of the heat store capacity and the collector field area, the temporal balance of demand for and supply of heat and on the level of collector insulation.

The temperature coefficient of the electrical performance of common PV materials is rather low (-0.45 %/°C for c-Si cells and lower for many thin film materials including -0.13 %/°C for single junction a-Si [6]). This means for example that with an effective cooling of 10 K the yield increases with 1.3 % (for a-Si) or 4.5 % (for c-Si).

Simulations show that the potential synergy does not occur in typical systems (see Fig. 4). Typical collector areas for DHW and combi systems in Germany are: 6 and 12 m² respectively. A small net annual effect of cooling of the PV cell only occurs when the PVT collector area is undersized. The annual fractional energy savings (f_{sav}, i.e. the energy saved by the solar thermal system as compared with the energy needs of a conventional (none solar) system) of the systems with small PVT collector fields is also relatively low.

The graphs also show the much larger PVT collector areas needed to achieve the same f_{sav} as that of a system with good ST collectors (red line starting from black curves at 6 m² and 12 m² respectively). A better thermal performance of the collector results in much less collector field area needed to achieve the same f_{sav}. The drop-off of the electrical yield of the PVT collectors with increasing PVT collector field area is caused by increasing stagnation periods and increased temperatures in the thermal store.
Fig. 4: Simulation results showing the influence of thermal collector performance parameters and collector area on $f_{\text{env}}$ (left axis, continuous lines) and electrical yield per unit of area (right axis, dotted lines) of PVT systems for a typical DHW (left graphic) and a typical combi system (right graphic) in Essen. Note: The electrical performance parameters of the PV module are the also those for all of the PVT collectors, so that only the effect of the PV operating temperature on the PV performance is taken into account, and not any difference in optical performance nor differences in packing factor. The thermal performance parameters are from actual measurements on PVT prototypes (see Fig. 6). System yields are simulated with TRNSYS software.

With the requirement for high thermal collector performance comes the need for good thermal insulation of the collector and thus elevated stagnation temperatures. Elevated temperatures may accelerate aging of the cell encapsulant and cells, and large thermal cycling ranges may cause thermo-mechanical stress in cells, cell connections and the laminate. In one of our prototypes the cell connection was shown to be the weak point for thermal cycling.

Not only does the operation of PVT collectors come with different boundary conditions than those for systems with ST collectors, their effects are also different. A PVT system is thus not just a ST system with PVT collectors, but it needs to be designed and optimized for PVT operation in a specific location and climate.

The collector thermal insulation and the PV operating temperature are considered to be the two key factors in design decisions for the PVT collector development as well as for the system design.

Using a simple energy balance, at an irradiation of 1000 W/m² and ambient temperature of 30 °C, a heat loss of 25 W/m²K is needed to reduce the stagnation temperature to around 70 °C. This can be achieved through passive cooling, but only when applying the same level of insulation as in a PV module, i.e. none, not at the front and not at the back of the module, so also no roof integration. The front and back surfaces are both needed fully for passive cooling.

Compliance tests for PV modules (IEC 61215 and IEC 61646) include repeated exposure to temperatures varying between -40 and 85 °C, notably in the Thermal Cycling and Humidity Freeze tests as well as the Damp Heat test. Parts of the PV module may become hotter than this during the Bypass Diode Test and Hot-spot Endurance Test, but these tests expose only parts of the collector to varying, self-induced, high temperatures, and these tests are repeated numerous. This means that the test limit of 85 °C can be taken as a reasonable upper limit for repeated exposure to high temperatures while maintaining some indication about durability and functional reliability.

Applying the maximum PV test temperature of 85 °C in the same energy balance as above, a minimum heat loss of 18 W/m²K needed. Simulations on a simple thermal model of an irradiated object in its environment (see Fig. 5) show that this is roughly the passive cooling capacity of only the front surface of a PV module, not taking into account any thermal bridge between the outer surface of this object and the PV cells: so neither with additional cover nor with air gap. This can thus only be achieved for a ‘non-covered’ collector. The thermal annual performances of non-insulated and non-covered solar thermal collectors are relatively low compared to typical, well insulated thermal collectors.
Obviously for good solar thermal performance much more insulation is needed. For common solar thermal collectors the overall loss factor is between 0.4 W/m²K for a good evacuated tube collector and 7 W/m²K for lesser insulated flat plate collectors with non-selectively coated absorbers. However, these high levels of thermal insulation lead to stagnation temperatures above 170 °C, which would damage standard PV modules when subjected to these temperatures for longer periods or repeatedly.

Using standard PV modules in PVT collectors has some obvious cost and time advantages over the development of modified or new PV constructions, but it also puts a limit on its operating temperature and thus the thermal insulation that can be applied.

3. Possible PVT collector concepts and their implications

The PVT collector classification used by Zondag et al. [3] is based on the criteria: air/water, concentrating/flat-plate and glazed/unglazed. The criteria apparently relate to: the heat removal medium, the level of irradiation and the level of collector insulation. This classification makes sense from a market or application point of view. From the point of PVT collector development we suggest using the level of thermal insulation as a distinguishing classification.

With the functional requirements and design parameters and their implications from the previous section in mind, the challenge arising from the correlation between improved insulation and increased stagnation temperature leads to three possible basic collector concepts:

- Concept 1: Apply such a low level of thermal insulation that this inherently limits stagnation temperatures in the collector below any damaging level for standard PV modules.
- Concept 2: Apply a high level of thermal insulation to achieve good thermal performance but prevent collector from overheating when needed.
- Concept 3: Apply a high level of thermal insulation but this time in an inherently high temperature resistant PVT collector using high temperature resistant PV components and constructions.

The level of thermal insulation differentiates concepts based on the stagnation temperature and stagnation resistance, and differences in the level of standardization of the PV construction used (standard or new/modified). Some of the direct differentiations between the concepts are shown in Tab. 4.
Tab. 4: Table of basic classification of PVT concepts with direct distinguishing features.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Concept 1: LT-Resist</th>
<th>Concept 2: HT-Protect</th>
<th>Concept 3: HT-Resist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functional</td>
<td>Standard PV</td>
<td>Good solar thermal (ST) performance</td>
<td></td>
</tr>
<tr>
<td>Requirements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Criterion:</td>
<td>None</td>
<td>Switchable</td>
<td>High</td>
</tr>
<tr>
<td>Collector insulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performances</td>
<td>Low ST</td>
<td>High ST, Improved PV</td>
<td>High ST, Reduced PV</td>
</tr>
<tr>
<td>Stagnation</td>
<td>Low</td>
<td>Actively limited</td>
<td>High</td>
</tr>
<tr>
<td>temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Research focus</td>
<td>Optimal Heat Removal Construction (HRC)</td>
<td>'Fail-safe' stagnation protection ‘switch’</td>
<td>Resistant PV encapsulation and construction</td>
</tr>
</tbody>
</table>

The level of thermal collector insulation leads to different consequences for many of the aspects mentioned in the PVT Roadmap (Fig. 1: Right). Tab. 5 gives a first glance of many of the distinctions on some of these aspects. The range of aspects mentioned is wide, with many mutual influences. Much depends on the specific solutions and constructions that are applied, but also on the system, the application and the environment it operates in. The remarks are thus ‘indicative-only’. However, it can be seen that each concept is strategically a very different path for a company pursuing the development of any of the PVT collector concepts.

From the point of development effort and risk it can be recommended to start ‘safe and simple’ and pursue first the development of Concept 1 (‘LT-Resist’), i.e. use standard PV modules and materials and add no significant thermal insulation as to stay below the virtual stagnation temperature limit used in PV tests. The main downside of this concept is the low thermal performance under challenging operating conditions i.e. at larger differences between mean fluid temperature and ambient temperature and low level of irradiation (winter season). For Concept 2 (‘HT-Protect/Switch’) the development of a ‘fail-safe’ stagnation protection mechanism is the main engineering challenge, which has implications for marketing, application and operation of the system. For example, the added stagnation protection adds complexity to the installation of the collector and possibly the system and its operation and maintenance as well. For Concept 3 (‘HT-Resist’) the development of a collector with high temperature resistant PV components and constructions is more a challenge in PV module development, in particular: to design a PV encapsulation which is resistant to elevated temperatures.

Another aspect worth highlighting from the table is a comparison of potential costs for each concept. For Concept 1 the costs per collector are roughly the sum of that of a PV module and a ST absorber, as the materials and production processes needed are roughly the sum of each, in other words no particular cost synergy in manufacturing is foreseen here. This option is considered the cheapest option on the short term because additional development costs are limited and the effects of economies of scale of the standard PV modules can be used. For Concept 2 the development, production and maintenance of the stagnation protection solution adds additional costs to the sum of PV module and ST collector manufacturing costs. For Concept 3 a potential synergy in a rationalized integrated design can be foreseen which could reduce costs below the sum of PV and ST. Any deviation from a standard PV module will, initially, significantly increase manufacturing costs per area, especially as development costs need to be added as well as the forfeiting of the benefits of economies of scale of standard modules.
Tab. 5: Table of basic classification of PVT concepts with direct distinguishing features.

<table>
<thead>
<tr>
<th>Thermal Insulation Level</th>
<th>Classification</th>
<th>Concept 1: LT-Resist</th>
<th>Concept 2: HT-Protect</th>
<th>Concept 3: HT-Resist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Construction/Materials</td>
<td>Standard PV/Module</td>
<td>Standard PV/Module +‘Fail-Safe’ stagnation protection</td>
<td>Inherently high-temperature resistant</td>
</tr>
<tr>
<td>Switchable</td>
<td>Thermal collector insulation</td>
<td>None</td>
<td>‘fail-safe’ switchable, ideally from ‘none’ to very good without affecting the optical performance</td>
<td>Good</td>
</tr>
<tr>
<td>High</td>
<td>Make/Buy</td>
<td>PV by PV-manufacturer ST by ST-manufacturer</td>
<td>PV (+ modification) by PV-manufacturer ST by ST-manufacturer</td>
<td>Purchase PV components only. Applied by ST-manufacturer in an Integrated Design</td>
</tr>
<tr>
<td>Classification</td>
<td>Production (modularity)</td>
<td>Standard PV module with HRC add-on with very good thermal contact</td>
<td>Standard/modified PV Module (depends on stagnation temperature) HRC + ‘fail-safe’ stagnation protection mechanism</td>
<td>Custom designed high-temperature resistant PV module + ST HRC or integrated design</td>
</tr>
<tr>
<td></td>
<td>Installation</td>
<td>Simple</td>
<td>Potentially complex (Stagnation Protection)</td>
<td>Simple</td>
</tr>
<tr>
<td></td>
<td>Operation</td>
<td>Similar to ST Systems</td>
<td>Complex</td>
<td>Similar to ST Systems but ideally with extra-large store or heat dump</td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td>None specific</td>
<td>High, specialist</td>
<td>None specific</td>
</tr>
<tr>
<td></td>
<td>PV Performance comparison</td>
<td>Similar to ’not building integrated’ PV Modules, with possible ‘Operating Synergy’</td>
<td>Affected by: cover optics, packing factor and operating and stagnation temperatures.</td>
<td>Similar to PV module during operation During Stagnation: Reduced.</td>
</tr>
<tr>
<td></td>
<td>ST performance comparison</td>
<td>Similar to non-covered ST collectors</td>
<td>Maximal close to covered ST collector (in OC-Mode)</td>
<td>Max. similar to covered ST collectors</td>
</tr>
<tr>
<td></td>
<td>Costs</td>
<td>Sum of PV + ST Initially the cheapest option</td>
<td>Sum of PV + ST + stagnation protection. Costly and requires inspection/maintenance</td>
<td>Potential for cost-reduction below the Sum (= synergy in a rationalized integrated design)</td>
</tr>
<tr>
<td></td>
<td>Tests (PV Standards)</td>
<td>Existing certified PV module</td>
<td>Retest modified (or possibly use an existing) certified PV Module</td>
<td>Extended high-temperature PV tests (tests do not exist yet!)</td>
</tr>
<tr>
<td></td>
<td>Building integration</td>
<td>Caution: Integrated back increases level of thermal insulation</td>
<td>Suitable, possibly preferred</td>
<td>Suitable, possibly preferred</td>
</tr>
<tr>
<td></td>
<td>Aesthetics</td>
<td>Similar to PV Module</td>
<td>Similar to PV module but with front cover, and possibly visible stagnation protection</td>
<td>Only similar to PV module when construction and PV lay-out is similar</td>
</tr>
<tr>
<td></td>
<td>Systems</td>
<td>Similar to non-covered ST Systems Potential: solar assisted heat pump</td>
<td>Similar to ST systems With stagnation controls</td>
<td>Possible recommendations: Extra-large heat store and/or heat dump</td>
</tr>
<tr>
<td></td>
<td>Applications</td>
<td>Low solar fractions, applications with relatively good matching supply-demand variations</td>
<td>Combi-systems</td>
<td>Applications with relatively good matching supply &amp; demand variations</td>
</tr>
<tr>
<td></td>
<td>Markets</td>
<td>Domestic Housing Market Single/multi-family homes</td>
<td>Domestic Housing Market Multi-Family Homes</td>
<td>Industrial markets and Cooperatives</td>
</tr>
</tbody>
</table>
4. Stagnation protection

Concept 2, ‘HT-Protect/Switch’, requires a stagnation protection mechanism. The requirements for a stagnation protection solution include:

- A sufficient switching range: between high insulation for good thermal performance and low insulation for ‘safe’ stagnation temperatures.
- The need to be ‘fail-safe’: it works always when needed, repeatedly and ideally with little to no maintenance and additional energy consumption, while being exposed to various climatic and environmental conditions.
- It has, ideally, little effect on optical and thermal performances i.e. have little impact on gross/aperture area ratio, optical efficiency and packing factor.

The combination of these three requirements provides the research and development challenge for Concept 2.

In principle, options for stagnation protection in solar thermal collectors consist of:

- Reducing insolation and/or
- Increasing thermal losses when needed.

Because it is assumed that PV electricity can always be usefully removed and applied, reducing irradiation is not an option for PVT, because this would also reduce the PV yield. A stagnation protection solution for PVT collectors thus consists of changing the level of effective thermal insulation.

In any case the ‘switch’ needs to be ‘fail-safe’ executed, i.e. be inherently safe, redundant, backed up or executed as a combination of these.

In addition, switching thermal insulation may not only be used as a ‘fail-safe’ stagnation protection solution, indispensable for Concept 2, but may also offer an additional, manual (seasonal) performance enhancement for Concept 1 and Concept 3. The thought behind this is that the thermal insulation of the collector can be low in periods when supply of thermal energy is in excess (e.g. in summer) and increased when high stagnation temperatures can be ruled out (e.g. in winter).

5. Performance results from prototypes built

Over the past few years, several PVT prototypes were developed and built as part of different projects; some of which with industry partners. Performance results from measurements carried out at Fraunhofer ISE on these prototypes are shown in Fig. 6. The black line shows the performance of a good solar thermal collector with selectively coated absorber. The orange line shows the thermal performance (in MPP mode: i.e. dotted lines) of a covered PVT collector commercially available a few years ago. The purple dotted line shows the performance of a prototype (PVT ISE 2010 Prototype) developed by Dupeyrat [7] during his PhD at Fraunhofer ISE. This collector was optimized optically ((τα)_{eff}) and has a much improved aluminum roll-bond HRC with FracTherm® channel structure instead of a standard sheet-and-tube HRC, resulting in a relatively high η_{0}. The green line shows the performance of a collector (PVT Low-e Prototype) with a prototypal, optimized low-e coating specifically for PVT applications developed by Fraunhofer ISE (using a standard sheet-and-tube HRC). It shows much improved thermal performance at higher temperature differences, but it also has a slightly lesser optical performance. The dotted blue line shows the performance of a prototype collector developed together with an industry partner, again with the optimized low-e coating, but now with additional switchable thermal insulation. This shows further reduced thermal losses because its thermal insulation is switched on here. The blue dots show its performance with the insulation turned off, resulting in a strongly reduced stagnation temperature at 1000 W/m² insolation. The continuous blue line shows its thermal performance in ‘open circuit mode’ and shows that the thermal performance of a PVT collector in OC-mode can be almost as good as that of a good solar thermal collector.

From many stagnation protection options investigated, the option mentioned above (blue lines) is particularly promising because it is, from our investigations carried out so far, the only stagnation protection solution which not
only is potentially ‘fail-safe’ but which also significantly improves thermal performance. Details of the underlying switching concept cannot be disclosed yet for confidentiality reasons.

![Graph](image.png)

Fig. 6: Performance test results from prototypes compared to a ST collector (MPP: Maximum Power Point mode, i.e. PV and ST operating; OC: Open Current mode, i.e. PV electricity is not removed from the collector.

6. Remaining research and development needs and outlook

Although we were able to almost match the PVT thermal performance of a prototype collector with that of a good ST collector, several material and construction issues still remain. Current research needs, with varying importance depending on the concept applied, include further investigation of:

- Temperature resistance of standard and new PV materials and constructions for elevated and high stagnation and operating temperatures.
- Reliability of electrical isolation of high-voltage and current-carrying parts from the heat removal construction whilst achieving good thermal contact between them.
- New solutions with excellent heat transfer between PV and heat removal medium, in particular for Concept 1: ‘LT-Resist’.
- Dependence of the electrical performance and yield on operating temperature, collector and system configuration, control strategies, solar thermal supply/heat demand ratio and environmental factors for all concepts.
- Options for and reliability of switchable thermal insulation solutions.

The performance results obtained from our prototypes indicate that it is worthwhile to further pursue and assess the paths of all three concepts. Our recommendation for solving the challenges is to align research and development needs for each individual concept, which should speed up PVT collector development towards reliable and commercially viable and successful products.

References

[1] Bundesverband Solarwirtschaft e.V. (BSW-Solar). Statistische Zahlen der deutschen Solarwärmebranche (Solarthermie); February 2013