Conference Proceedings

EuroSun 2014
Aix-les-Bains (France), 16 - 19 September 2014

Market and simulation analysis of PVT applications for the determination of new PVT test procedures

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Abstract

PVT collectors produce simultaneously electricity and heat and combine the technologies of PV and solar heat in one product. Due to lack of testing and certification standards on energy yield and quality they are by now hardly established in the market. Thus, as part of a joint project the focus was to develop test methods for PVT collectors. First, a market research with subsequent typification of PVT products served to identify typical applications and system circuits of PVT collectors. As a result three typical PVT systems have been modeled in simulation models. Then, as basis of future tests on energy yield and quality of marketable products, both typical and extreme operating conditions of PVT collectors are determined by means of dynamic annual simulations of PVT systems in the simulation environment of TRNSYS. Following the module tests conducted by the project partners, exemplary annual simulations and yield forecasts were performed.

Key words: PVT collectors, PVT test procedures, TRNSYS simulation, market overview of PVT

1. Introduction

PV (photovoltaic) modules use only a part of the incident solar energy to generate electricity. The major part of the absorbed radiation is converted into unused heat. PVT collectors (combination of PV and solar heat) use the heat e.g. for producing hot water. In addition, the current efficiency can be increased by cooling of the solar cells and getting rid of ice or snow.

Certification and testing of PV modules are defined by the standards IEC 61215 (design qualification) and IEC 61730 (safety standards). The testing standards for solar heating collectors are specified in EN 12975. It is obvious that the existing standards for photovoltaic and solar thermal systems cannot be fully applied to the new combined product. Different security requirements, for example, are needed due to the interaction of electric and water-bearing parts in such a collector. In addition, reliable key indicators for electricity and heat production at different operating conditions of PVT collectors are not feasible due to lack of testing procedures. Without proper standardization and test methods they will not be competitive with the individual solutions of PV or solar heating modules.

Against this background, it was the aim of an one and a half year joint research project (Feb. 2013 - July 2014) to develop methods to determine the efficiency of PVT collectors and suggestions for appropriate safety and quality regulations.

2. Market Research and structuring of PVT applications

The development of a procedure for practical tests of PVT modules must consider the technical diversity of existing modules and their various ways of heat application (e.g. direct / indirect use of heat without / with heatpump). For this purpose, an extensive market research based on available manufacturer information was carried out.

2.1. Market overview of PVT collectors

The elaborated current overview of market participants (41 producers) of PVT collectors shows a significant concentration of PVT flat-plate collectors with liquid heat transfer medium (34 producers) (Mitina, 2014). Within this market segment in turn the uncovered variant is the most represented (30 producers). They look

doi:10.18086/eurosun.2014.16.09 Available at http://proceedings.ises.org

similar to photovoltaic modules. The thermal heat exchanger is placed on the back of the PV cells and ensures their cooling. Because of the missing front thermal insulation they are more suitable for low fluid temperatures, which increase the efficiency of the solar cells. Hence, they are especially suitable in connection with heat pumps which can be operated with low temperatures on heat source side.

Another less market-relevant design of PVT collectors is similar to solar thermal collectors. The PV cells are placed on the absorber or directly under the glass cover. They are known as covered PVT collectors. The improved thermal insulation leads to high operating temperatures as they are directly used for water and space heating.

Further, various designs of PVT air collectors and concentrated PVT parabolic trough collectors were found and classified. Here again, the number of manufacturers is low.

The developed market overview served first as a basis for the selection of the products to be examined by the project partners TÜV Rheinland and Fraunhofer ISE (Fritzsche, 2013, 2014). It is also the basis for an adequate description of market-relevant PVT systems to simulate their operating conditions with as few simulation models as possible.

In the course of categorization of PVT collectors it turned out that with respect to the design and function of PVT collectors a more precise language regime should be defined. That means that so far used terminology have to be replaced with new ones or revised. This recommendation applies to both the field of standardization as well as for funding guidelines.

The background for this recommendation is that the majority of PVT collectors generally have a glass cover, however, not in terms of thermal insulation of interim space filled with air, but to protect the photovoltaic cells. Such constructions are then despite glass cover referred to as uncovered (such as swimming pool absorbers). As a consequence of this language regime uncovered PVT collectors were in Germany previously declared within the market incentive program as principally not eligible. However, in the funding from 20.7.2012 of the German market incentive program (BMU, 2012) is literally stated under point 8.1: "Solar plants with panels without transparent cover on the front panel are not eligible (e.g. swimming pool absorbers)." Thus, as all available PVT collectors have a transparent cover, they actually would be eligible (if classified as a thermal collector).

The vast majority of PVT products can be found in uncovered collectors with (30 producers) and without (4 producers) rear thermal insulation. They are recommended by the manufacturers in various system configurations without and with heat pump. For these products the necessary testing procedures should be set up with the top priority to ensure a better introduction on the market. Some minimum specifications should be set up for the product information and included in the certification as accessible product information turned out to be in many cases insufficient. This concerns in particular the data sheet specifications and the design features. A data sheet of a PVT collector should at least include the following information:

- type (e.g. covered/uncovered with/without rear thermal insulation)
- dimensions
- all needed electrical characteristic values for performance characterization
- all needed thermal characteristic values for performance characterization
- mode of operation during the measurement
- materials used
- limit temperatures
- maximum operating pressure
- quality label

2.2. PVT system configurations

In the applications of PVT collectors a wide variety of systems is given. From market research and other studies (Ruschenburg, 2013a, 2013b) of the IEA - SHC Task 44 / HPP Annex 38: Solar and Heat Pump Systems (Jan. 2010 – Dec. 2013), however, three system circuits for PVT collectors have emerged as essential. These are the following systems:

- Generic parallel system (P) with conventional backup or heat pump
- Generic parallel/serial system (P/S) with heat pump

- Generic parallel/serial/regenerative system (P/S/R) with heat pump and geothermal regeneration

In all three systems a combined storage for water and space heating is integrated. Uncovered PVT collectors are used in all three systems. In comparison, covered collectors are primarily applied in parallel system circuits with conventional backup.

3. Modelling of PVT systems

By means of the simulation environment of TRNSYS different types of modules and overall systems were modeled.

3.1. PVT modules

For the simulation of uncovered PVT collectors the TRNSYS Type 203 was chosen as it models the most important effects and can do without hardly available constructional details. It has been newly developed by the Institute for Solar Energy Research Hamelin (ISFH).

The required input parameters are based on laboratory measurements of two typical PVT collectors carried out at appropriate test facilities by the project partner TÜV Rheinland. Data of these collectors was chosen because they cover the whole range of thermal efficiency factors. The thermal efficiency characteristic of both collectors with a wind velocity of 2 m/s is shown in figure 1. In this report the designated "LTC" PVT collector is characterized with a 5 cm layer of rear thermal insulation (LTC = Low Thermal Conductivity to the environment) and the "HTC" PVT collector has no insulation (HTC = High Thermal Conductivity to the environment). For the simulation of these two collectors the three above-mentioned system circuits were modeled.

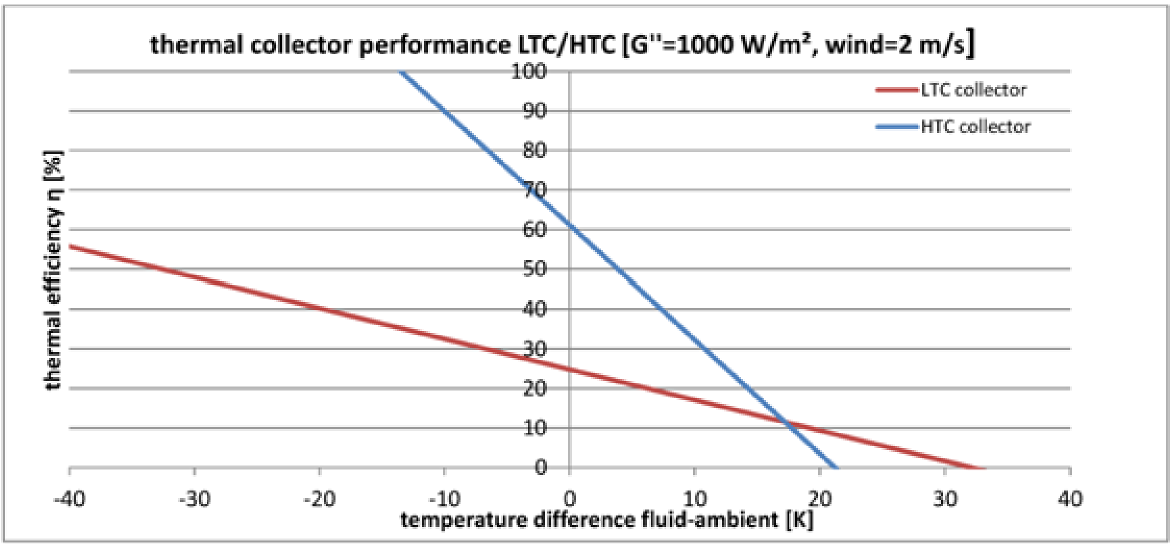

Fig. 1: thermal performance characteristics of HTC and LTC collectors from experimental tests at TÜV Rheinland

The appropriate modeling of covered PVT collectors proves to be more difficult. The eligible TRNSYS Type 50 as well as models of the other possible simulation tool of MATLAB®/Simulink® show inappropriate limitations. A major problem is that all known models assume that the PV cell temperature is equal to the absorber temperature. It was found that neither a model nor a theoretical approach considers that the cells are in or directly under the glass cover as it is the case for the majority of the few commercially marketed covered PVT collectors. Also, none of the few manufacturers of covered PVT collectors was willing to provide a test prototype in order to clarify outstanding issues concerning modeling and validation.

Against this background, the presented simulation results concentrate on the different system types with uncovered PVT collectors. Only for the simplest system PVT + boiler (or heat pump) in parallel connection, a plausibility check using default values of covered PVT collectors was simulated (with TRNSYS Type 203) and compared with the simulation results of an uncovered PVT collector.

3.2. Boundaries and remaining modules

Suitable TRNSYS models were selected and appropriately configured for other required components, such as the model of a heat pump (Type 401) and a single geothermal probe (Type 451). The parameterization of the heat pump type was based on real measured characteristic curves of a typical commercial heat pump. The design of the geothermal probe was performed according to VDI 4640 and the parameterization based on the Task 44 / HPP Annex 38 of the Solar Heating and Cooling Program of the International Energy Agency IEA.

Boundary conditions, such as weather data and load profiles are based on the standard DIN EN 12977-2:2012 “Test methods for solar water heaters and combisystems”. The standard specifies the weather records for the locations of Athens, Davos, Stockholm and Würzburg and the associated room heating and domestic hot water profiles of a characteristic new single-family house. The locations represent different European climate zones (Northern, Central and Southern Europe and mountain regions). When checking the weather records for Athens and Stockholm with the associated load profiles of room heating some unrealistic correlations have been detected. Thus, simulations refer for the most part to the locations of Davos and Würzburg.

4. Characteristic operating conditions and yield forecasts of PVT modules

The findings aim at pointing out, first, the range of operating conditions for PVT modules and secondly, exemplary yield and efficiency forecasts with respect on the modules specific type of system integration. Based on these results, important conclusions for new test procedures and possible impacts on future standardization of PVT collectors can be derived. Furthermore, further potential for development in integration and control of systems with PVT collectors can be revealed.

It was found that both operating conditions and thermal energy yields depend significantly on system configuration (without / with heat pump or geothermal probe), collector design (with / without rear insulation (HTC / LTC)) and boundary conditions with regard to location, design and control of the system. The presented results in this paper concentrate mainly on the system P/S (PVT + heat pump in parallel and serial connection) as it appeared to be the most efficient way to integrate uncovered PVT collectors in a system at a location like Würzburg (Central Europe).

4.1. Generic parallel system (P) with conventional backup or heat pump

The system P (PVT + boiler or heat pump in parallel connection, see Figure 2) was simulated for the location in Würzburg. For parallel connection of an uncovered PVT collector to a buffer, the solar radiation is the ultimate reference variable for the collector operation. Therefore, the operation is similar to a "classic solar thermal system" with covered collectors. However, the thermal yields of 5 to 30 m^2 uncovered PVT collectors range from 10 to 45 kWh/m²a and are far too low due to high heat losses. Under the climatic conditions of this location the uncovered PVT collector rarely achieves the required collector temperatures for the buffer charging. The annual electrical energy yields are almost independent of collector type and collector surface about 140 kWh/m²a.

The use of covered PVT collectors instead of uncovered ones is certainly more reasonable for this system configuration. The simulation results with a covered PVT collector show plausible values from 260 to 450 kWh/m^2a, even if the results should be handled with care as the used PVT model (TRNSYS Type 203) is not validated for covered PVT collectors.

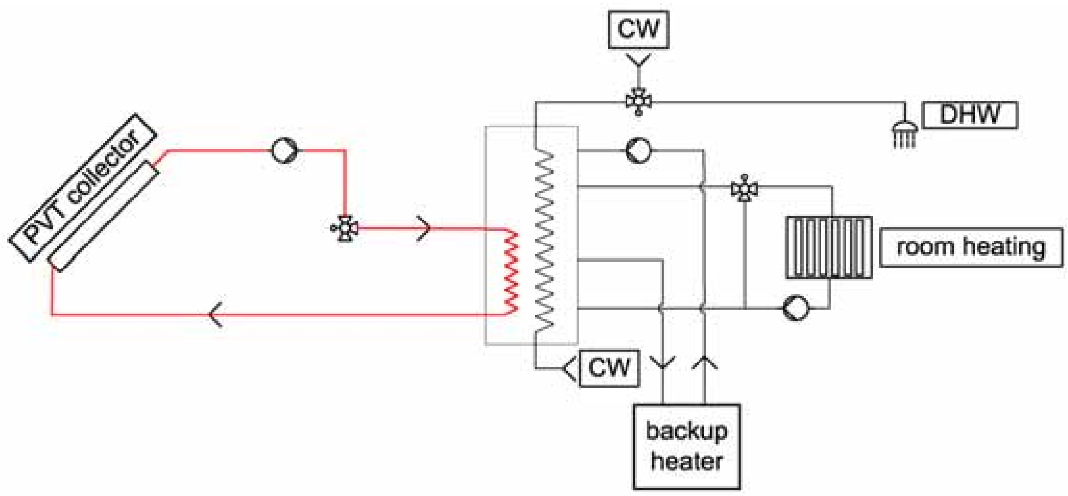

Fig. 2: hydraulic diagram of system P: PVT + boiler or heat pump in parallel connection (CW=cold water, DHW=domestic hot water)

4.2. Generic parallel/serial system (P/S) with heat pump

For the system P/S (PVT + heat pump in parallel and serial connection, see Figure 3) simulations were carried out for all four locations. The collector area (5-30 m^2) and the collector type were varied. In addition, some simulations were performed without using the thermal collector component to detect the influence on the electricity production.

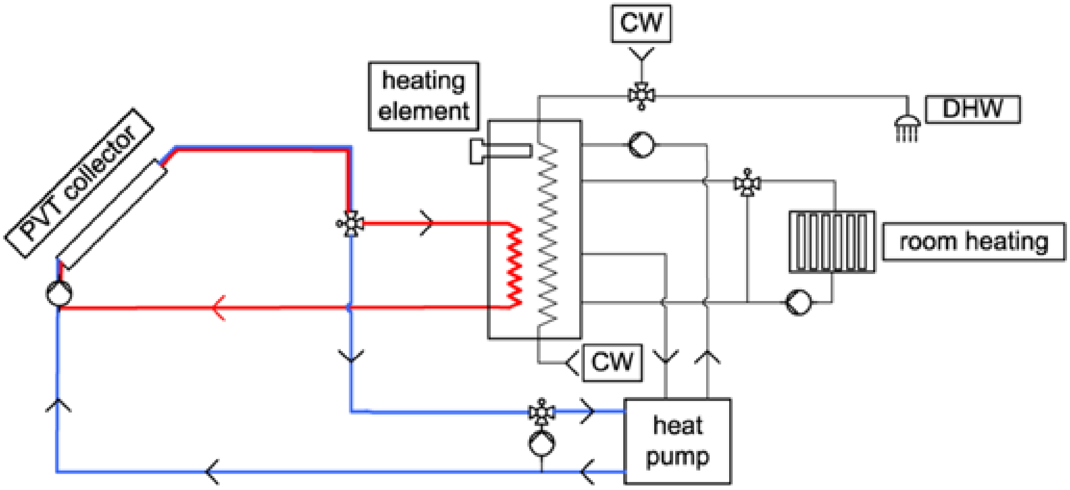

Fig. 3: hydraulic diagram of system P/S: PVT + heat pump in parallel and serial connection (CW=cold water, DHW=domestic hot water)

In serial connection with a heat pump, the PVT collectors work with a high proportion as flat-plate absorbers. The dominating variable for thermal use is the heat demand of the heat pump. The PVT collector serves essentially as a heat source for the heat pump. The direct input into the solar part of the buffer is comparatively low. In contrast to a classical solar thermal system and the aforementioned system P, the radiation plays only a minor role in times when the collector delivers useful heat. The radiation is only important when the buffer is directly charged by the PVT collector.

Based on real PVT systems, the mean absorber temperature of the collectors was limited in the simulation to 0°C (protection against ice formation). At the location of Würzburg a major proportion and at the locations Davos and Stockholm an even predominant proportion of the heating has to be provided by an electrical backup heating element. By operating below freezing (no limitation of absorber temperature) the operation time of the heating element is considerably reduced. Thus, the operation of a PVT collector below freezing has in this system configuration a significant impact on the thermal collector yield and offers potential for optimization of the entire system. However, the simulation results of this operation only have limited validity because the physical effects of ice formation on the collector are not modeled at all. For the southern European location Athens, the simulations show high thermal collector yields even without an operating of the collector below freezing. The proportion of the heating element is in this case very low.

During operation of the PVT collectors, the absorber temperatures cluster around two characteristic points of accumulation. These are both dependent on the location as well as on the operation mode (with or without limitation of absorber temperature). One point of accumulation arises due to operation with the heat pump and the other due to direct buffer charging by the PVT collectors. In figure 4 these characteristic points of accumulation are demonstrated for the locations Würzburg and Athens. For the location Würzburg with an operation limited above freezing (see red line) there is a peak from 0 to 2°C with exponential decreasing in direction of higher temperatures. The reason therefore is the thermal limitation. As soon as the limitation is reached the pump of the collector cycle is switched off. Then the collectors heat up again so that the pump switches on and the absorber temperature cools down again in the range of 0 to 2°C. This can be avoided by an operation below freezing. Then the minimum absorber temperature reaches -18°C in the case of Würzburg (see blue line). Thus, the operating time and the heat power absorbed by the collectors due to higher temperature differences towards the air are increasing. For the location Athens the maximum temperature is around 8°C and falls evenly on both sides off. The second maximum point is compared to Würzburg higher at around 40°C. The overall range of mean absorber temperatures vary from -24°C (location Davos, LTC collector, operation below freezing) to 64°C (location Würzburg, stagnation temperature).

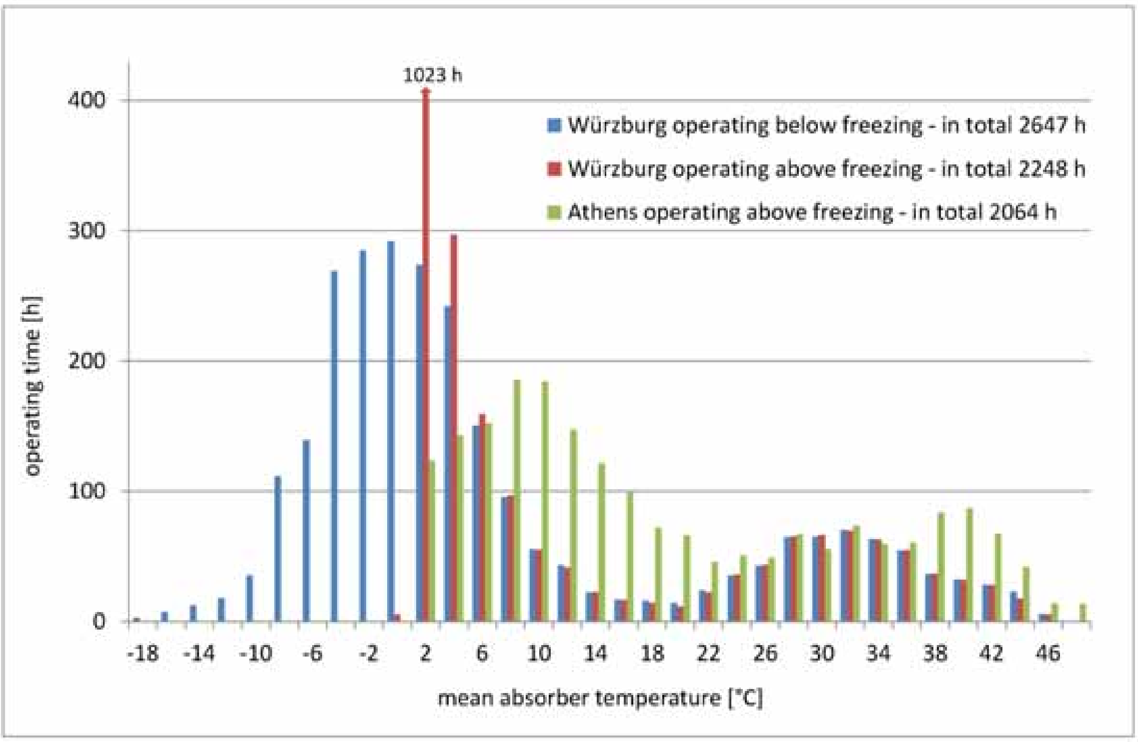

Fig. 4: time of simulated mean absorber temperature during operation of HTC collector for different locations and operation modes (collector area = 15m^2)

The annual thermal energy yields vary strongly. The biggest factors in this case are the controlling, the system configuration, the collector area (with respect to the heat load), the collector design and finally the climatic conditions. The range of specific real collector yields vary from 83 (30m²-LTC collector, location Stockholm) to 1244 kWh/m²a (5m²-HTC collector, location Athens). This demonstrates very clearly that the evaluation of the thermal performance of a PVT collector has to be linked to clearly defined standards.

The electrical energy yields depend mainly on climate conditions (outdoor temperature and radiation) and increase in proportion to the collector area. The cooling of PV cells leads only to a slight improvement. In case of the HTC collector operating without absorber, the annual electrical yield decreases at the two locations in Würzburg and Athens by 0.4%, in Davos by 0.3%. For the LTC collector the reductions in case of no cooling are larger: in Würzburg and Athens by 2.1% and in Davos by 1.7%. This is much less than often communicated. In brochures you can often find values of up to 30%.

In contrast to the PV yields, the annual PV efficiency is not depending on the collector area. The main factor is here the outdoor temperature. It ranges from 11.1 % (location Athens) to 12.0 % (Location Davos). Even if the variation of the heat demand was not subject of this study it is expected that especially the heat demand in summer is a further factor which affects the PV efficiency significantly. For higher heat demand in summer, for example due to higher hot water consumption (hotels, swimming pool, ...), the PVT collectors would particularly at high radiation be more chilled, along with an increase of the annual PV efficiency.

Figures 5 and 6 show exemplarily the previously mentioned results. In these figures, monthly values of energy and PV efficiencies are visualized for the locations Würzburg (see figure 5) and Athens (see figure 6) operating with the HTC collector type above freezing and using a collector area of 15m^2. The most conspicuous for this system configuration is the characteristic course of the useful heat gains of the collector. In both cases the useful collector heat (see dark brown bar) is higher in winter than in summer as the collectors serve essentially as a heat source for the heat pump. The buffer loading by PVT collectors just occurs rarely in summer (see light brown bar). As mentioned before the solar global radiation (see yellow bar) has only a minor role and is even sometimes below the useful heat gains of the collector. As the PV production mostly depends on radiation, the course of PV production (see green bar) throughout the year is more constant in Athens than in Würzburg. Finally, the figures show that there is no significant change of PV efficiency due to the cooling effect of the absorbers. In both cases the values of the blue line (without thermal use) are only slightly below the red line (with thermal use).

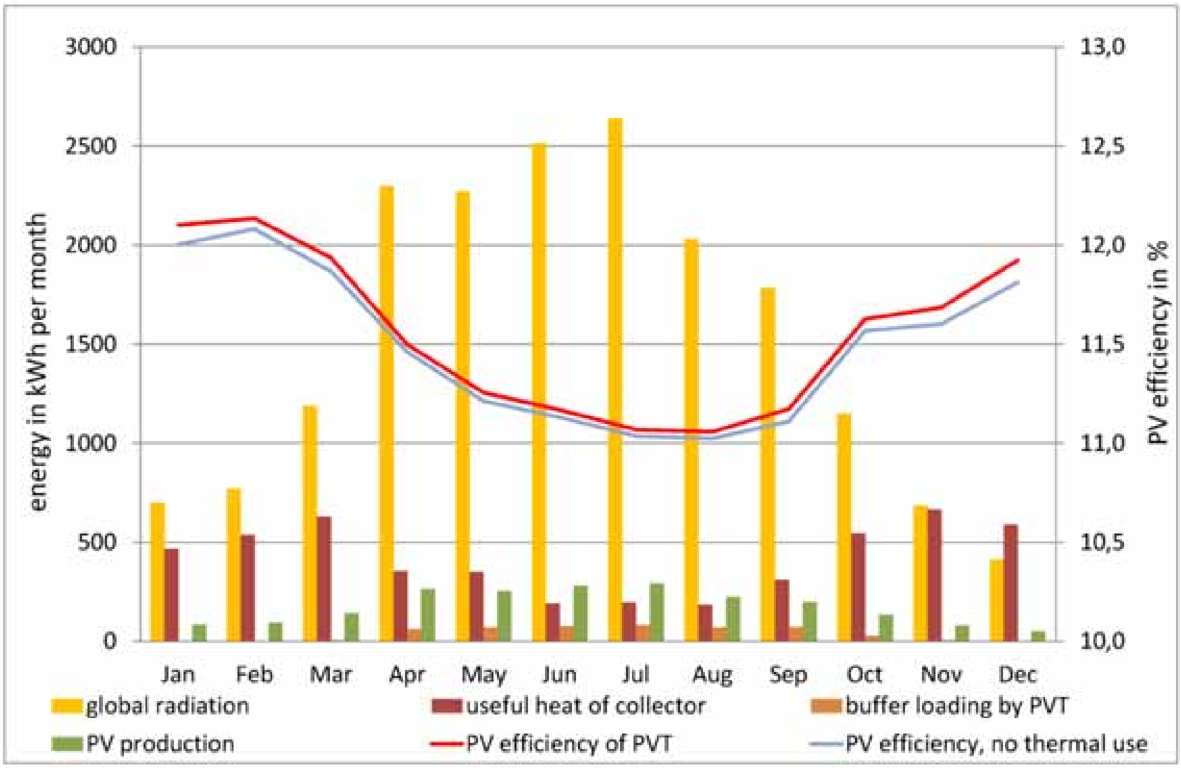

Fig. 5: monthly values for the location Würzburg with HTC collector (System P/S, operating above freezing, collector area = 15m²)

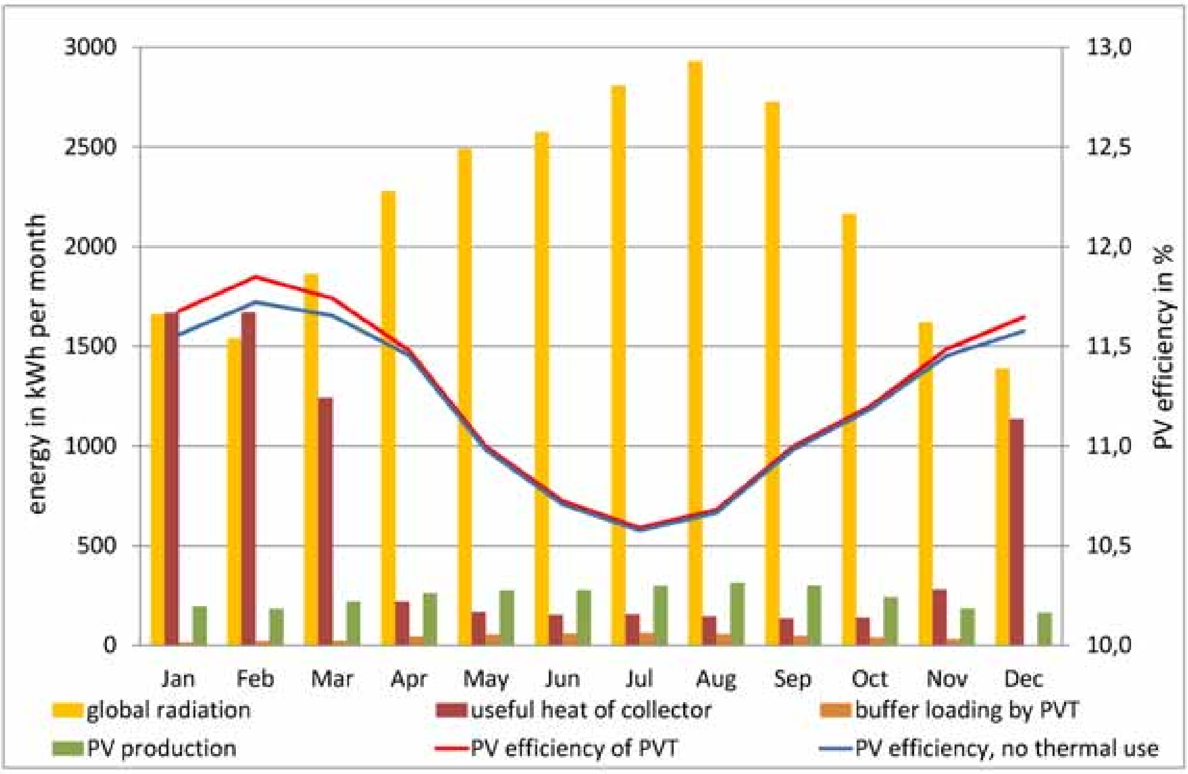

Fig. 6: monthly values for the location Athens with HTC collector (System P/S, operating above freezing, collector area = 15m²)

The Seasonal Performance Factor (SPF = heat delivery / (electricity consumption excluding pumps – electricity production)) of the entire system increases significantly as the absorber surface rises. The main reason for this is that the power generation rises and additionally the power consumption of heat pump and heating element is reduced with increasing surface. For the locations Davos and Stockholm and an operation with limitation of absorber temperature no SPF greater than 3 could be achieved within the largest simulated collector area of 30 m². For the location Würzburg SPFs greater than 3 were only achieved at a collector area of 20 m² (HTC) or 30 m² (LTC). For the location Athens a collector surface of 5m² (HTC) is already sufficient to achieve SPFs greater than 3. In this case a PVT collector surface of about 18 m² (HTC) is needed for a balanced annual overall energy balance: The electrical power generation is then equal to the consumption. Larger PVT surfaces generate excess electricity. SPF-values can be improved significantly without temperature limitation. In the example of the location Würzburg and a collector surface of 15 m^2 (HTC) the SPF is increased from 2.3 to 3.8.

Concerning this system configuration no advantage for the LTC collector type is recognizable. In winter, this system reaches its limits particularly with the LTC type due to the low air temperatures when operating above freezing (high proportion of electric backup heater). In figure 7 one can see that the useful heat of the collector throughout the year is far too low. The results speak rather in favor of using a PVT collector that is thermally well adapted to its environment (HTC type).

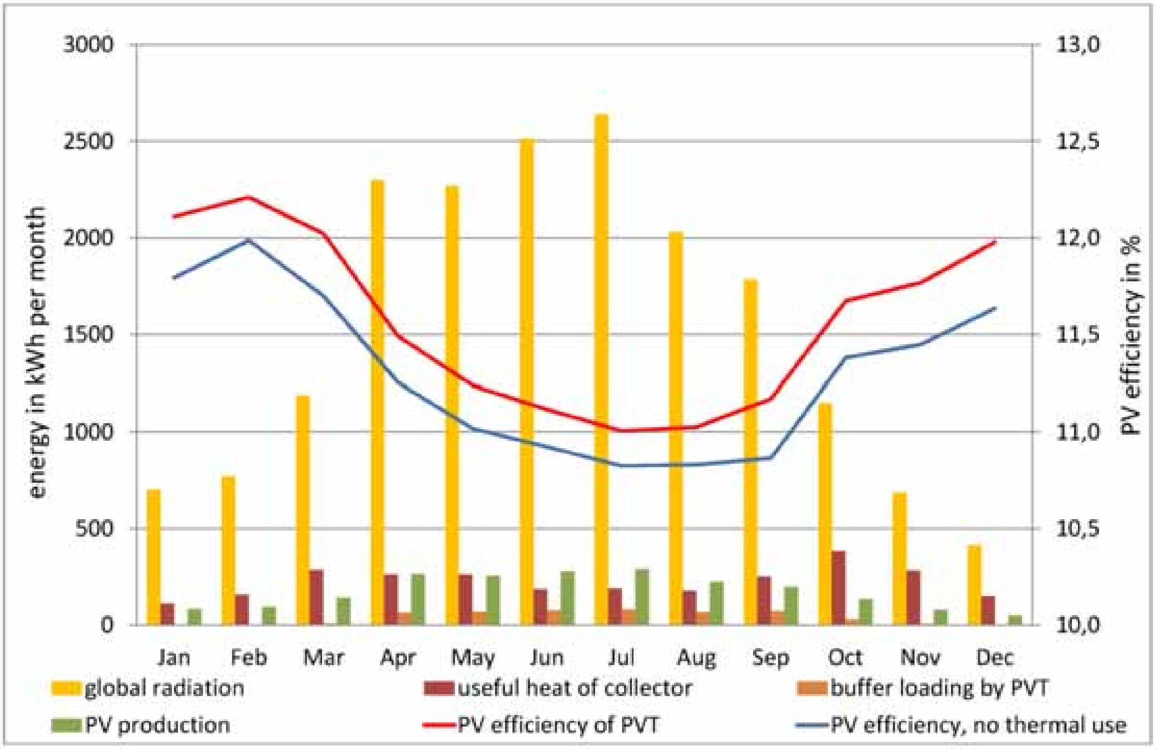

Fig. 7: monthly values for the location Würzburg with LTC collector (System P/S, operating above freezing, collector area = 15m^2)

4.3. Generic parallel/serial/regenerative system (P/S/R) with heat pump and geothermal regeneration

For the system P/S/R (PVT + heat pump + geothermal probe in parallel and serial connection, see figure 8) simulations were performed for the location Würzburg. The collector area (5-30m^2) and collector type were varied. The results show that the PVT collector operates mainly as heat source to regenerate the ground. For this reason relatively high specific collector yields from 316 to 800 kWh/m^2a were achieved with the HTC collector type. Even if there is a slight saving in electrical energy mainly because of an increased PV production, the regeneration mode causes additional power consumption because of the increased operation of the collector pump. As this can hardly be compensated by the gained savings, the geothermal regeneration can be viewed as unfavorable for this system configuration.

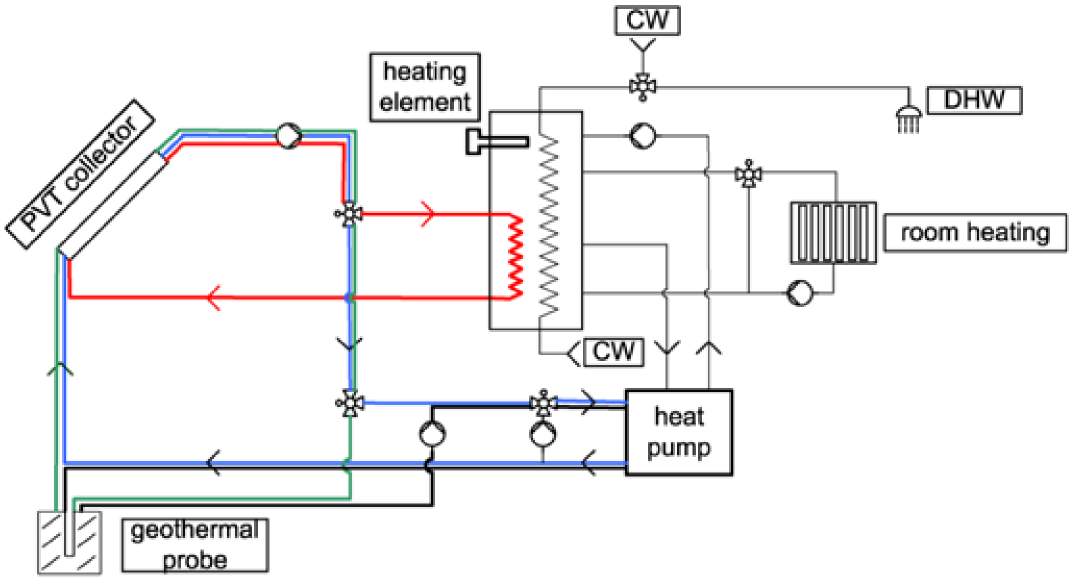

Fig. 8: hydraulic diagram of system P/S/R: PVT + heat pump + geothermal probe in parallel and serial connection (CW=cold water, DHW=domestic hot water)

This assessment is consistent with results from the Task 44 and other investigations. Thus, systems with uncovered collectors and regeneration of a single probe didn't lead to an increased SPF compared to systems without collectors and well dimensioned geothermal probe (Haller and Frank, 2014). In undersized probes and probe fields, however, the long-term cooling of the ground and the mutual interference of the probes can be avoided (Pärisch et al., 2014; Bertram et al., 2011). A slight improvement of system efficiency can also be achieved in the case of compact ground heat exchangers (Ochs et al., 2014).

5. Conclusions and their impact on test procedures and standards

From market research and simulation results important conclusions for new test procedures and possible impacts on future standardization of PVT collectors could be provided. It could also be shown that there is further potential for development in integration and control of systems with PVT collectors. At this point, basic tests on real systems are still necessary.

The vast majority of PVT products can be found in uncovered collectors with and without rear thermal insulation. For these products the necessary testing procedures should be set up with the top priority to ensure a better introduction on the market. Some minimum specifications mainly concerning data sheet specifications and the design features should be set up for the product information and included in the certification. Moreover, it turned out that with respect to the design and function of PVT collectors a more precise language regime should be defined for both, the field of standardization as well as for funding guidelines.

By means of simulations operation conditions and yields of uncovered collectors could be identified in the course of the year with respect on their specific type of system integration. It was found that both operating conditions and thermal energy yields depend significantly on system configuration (without / with heat pump or geothermal probe), collector design (with / without rear insulation (HTC / LTC)) and boundary conditions with regard to location, design and control of the system.

The system P/S (PVT + heat pump in parallel and serial connection) in combination with a HTC collector type turned out to be the most efficient and promising way to integrate uncovered PVT collectors in a system at a location like Würzburg. As the PVT collector serves essentially as a heat source for the heat pump (and is thus independent of solar radiation), the useful heat gains of the collectors occurs at the same time as heat is needed in winter. The rear insulation of the PVT collector is in terms of best possible heat absorption from ambient air rather obstructive for such a system configuration.

By operating below freezing the thermal collector yield can be considerably increased and offers potential for optimization of the entire system. The lower temperature range with sub-zero temperatures during the thermal operation (= heat extraction from the collector) is for solar thermal collectors atypical. It has therefore to be checked to what extent an additional material stress is for example caused by condensation and ice formation. As such a continuous operation below freezing is quite realistic, it should be considered in new PVT test procedures.

The points of accumulation of mean absorber temperatures depend mainly on system configuration, location and system control. From these points of accumulation typical absorber temperatures can be derived and taken into account in new test procedures.

Electrical yields depend mainly on climate conditions and only marginally on system configuration. The cooling of PV cells leads only to a slight improvement.

In contrast, the thermal yields vary very strongly and depend on many factors. It is therefore important that the evaluation of the thermal performance of a PVT collector has to be linked to clearly defined standards. These requirements must be defined in the standardization. The same applies also for future funding conditions. In the end, arises due to the spectrum of possible applications and the high range of resulting yields of useful collector heat the question, whether the specific thermal yields of a collector may be a suitable evaluation criterion for the overall objective of energy conservation. It would be more appropriate to consider the entire system under the respective boundary conditions and to use the Seasonal Performance Factor as an additional quality criterion.

6. References

Bertram, E., et al., 2011. Abschlussbericht zum Vorhaben Solarthermie2000plus: Kurzbezeichnung: BiSolar-WP. Hameln/Emmerthal.

BMU, 2012. Richtlinien zur Fördermaßnahmen zur Nutzung erneuerbarer Energien im Wärmemarkt. Berlin.

Fritzsche, U., 2013. Evaluating Performance, Qualification and Durability of PVT Hybrid Collectors: Toward a Dedicated Industry Standard. in: conference proceedings of 2nd International Conference on Solar Heating and Cooling for Buildings and Industry, Elsevier’s Energy Procedia, Freiburg.

Fritzsche, U., et al., 2014. Qualifizierung von PVT Kollektoren - ein Statusbericht –. in: Tagungsband 24. Symposium thermische Solarenergie, OTTI e.V, Bad Staffelstein.

Haller, M.Y., Frank, E., 2014. Solarwärme Wärmepumpen - Interpretationen der Simulationen des IEA SHC Task 44 / HPP Annex 38. in: Tagungsband 24. Symposium thermische Solarenergie, OTTI e.V, Bad Staffelstein.

Mitina, I., 2014. Technology survey: pros and cons of different PVT collectors. in: conference proceedings SMEThermal 2014, Solarpraxis AG, Berlin.

Ochs, F., et al., 2014. Thermodynamische Analyse von erdgekoppelten Wärmepumpen mit solarer Regeneration. in: Tagungsband 24. Symposium thermische Solarenergie, OTTI e.V, Bad Staffelstein.

Pärisch P., et al., 2014. 5 Regelungskonzepte für die parallel/serielle Einbindung von Solarkollektoren in erdgekoppelte Wärmepumpensysteme. in: Tagungsband 24. Symposium thermische Solarenergie, OTTI e.V, Bad Staffelstein.

Ruschenburg J., et al., 2013a. A Review of Market-Available Solar Thermal Heat Pump Systems - A technical report of subtask A of IEA SHC Task 44 / HPP Annex 38, Freiburg (Germany).

Ruschenburg J., et al., 2013b. A statistical analysis on market-available solar thermal heat pump systems. Solar Energy 95, 79–8