PVT Wrap-Up:
Energy Systems with Photovoltaic-Thermal Solar Collectors
-
Technology, Market, Experiences

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Abstract

While the interest in Photovoltaic Thermal (PVT) solar collectors is growing, the related practical knowhow and experience are still rather sparse. In this context, a review study on PVT was carried out, focusing on three main aspects: 1) Technology : different types of collectors, different ways of integrating PVT into energy systems, energetic yields of different system configurations, 2) Market overview : PVT industry, available products, principle fields of application, 3) Experiences : experiences from 7 pilot plants with collector areas between 50 m^2 and 3500 m^2, additional PVT plants in operation, points of view of different actors involved in the planning, construction and operation of PVT systems. In this article, we present the key outcomes of the study.

Keywords: Photovoltaic-Thermal Collectors, PVT Collectors, PVT Review

1. Introduction

PVT collectors integrate photovoltaic and thermal solar energy conversion in a single device and thereby reach high yields per area. In situations where roof area is limited, and particularly in the light of new regulations requiring a part of the energy demand of buildings to be produced on site, PVT collectors provide an attractive option. In order to answer the growing interest in PVT, in particular from house builders and installation companies, the presented wrap-up study, mandated by the Swiss Federal Office of Energy, aims to give a concise overview of the PVT technology, the PVT market, and the experiences made with PVT in real system operation. Besides a thorough literature research, a survey as well as a number of interviews were carried out among the different actors related to PVT, such as manufacturers, distributors, planners and installers. The study further included several case studies, based on data acquired by different research groups. The full report of the study was published in german in Ref. (Zenhäusern, et al., 2017). The present article summarizes its key results.

2. Technology and Market

Different concepts of PVT collectors have been considered in applied research for about 40 years. Extensive reviews of the diverse developments, as well as entry points to the relevant literature are provided by Refs. (Zondag, 2008; Michael, et al., 2015). Numerous manufacturers have brought PVT products to the market. However, while new products regularly enter the market, other manufacturers withdraw from the PVT sector. Earlier market-related review studies were presented in Refs. (Adam, et al., 2014; Cremers, et al., 2015; UK Department for Business, Energy & Industrial Strategy, 2016). The PVT sector has gained interest in recent years. Among the reasons for this upsurge are the increased spread and the price drop of photovoltaic modules, as many PVT products are extensions of standard PV modules. In the case of Switzerland, the rise of interest in PVT collectors was particularly triggered by the increasing need of low-temperature heat for the regeneration of ground heat sources in heat pump systems.

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For the market survey in the present study, PVT collectors were grouped in three categories: collectors working with a liquid heat carrier medium divided into products with and without cover (transparent cover to reduce convective heat losses) and air-based collectors (typically without cover).[1] The survey with main focus on Switzerland and neighbouring countries revealed 53 PVT collector manufactures in 17 countries (Figure 1). The large majority of products (38) corresponds to liquid-cooled uncovered PVT collectors with or without heat insulation on their backside. 6 products are covered liquid-cooled collectors, and 9 products are uncovered air-cooled PVT collectors.

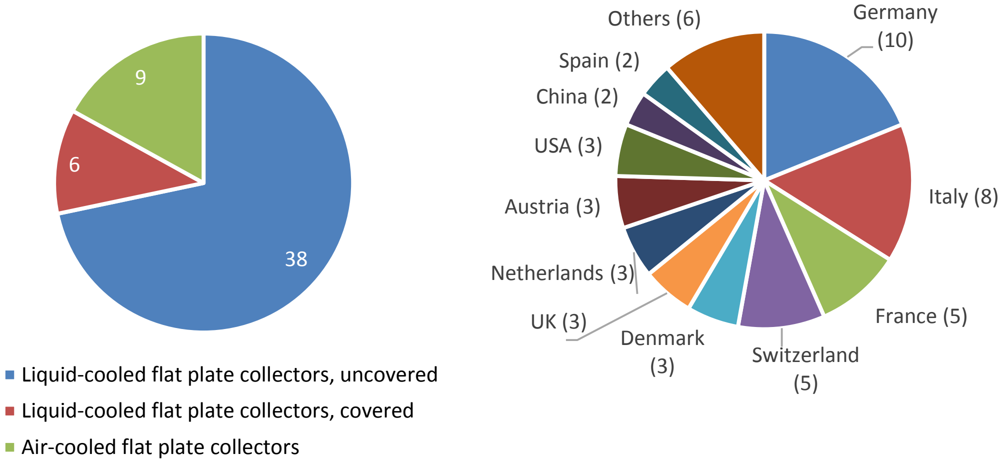

Figure 1: PVT products grouped in collector type categories (left) and number of manufacturers in the different countries (right).

3. System integration of PVT collectors

Like in the case of conventional solar thermal collectors, the thermal efficiency of the different types of PVT collectors strongly depends on their operating temperature. Thermal power curves for typical market-available products of the different categories are shown in Figure 2.

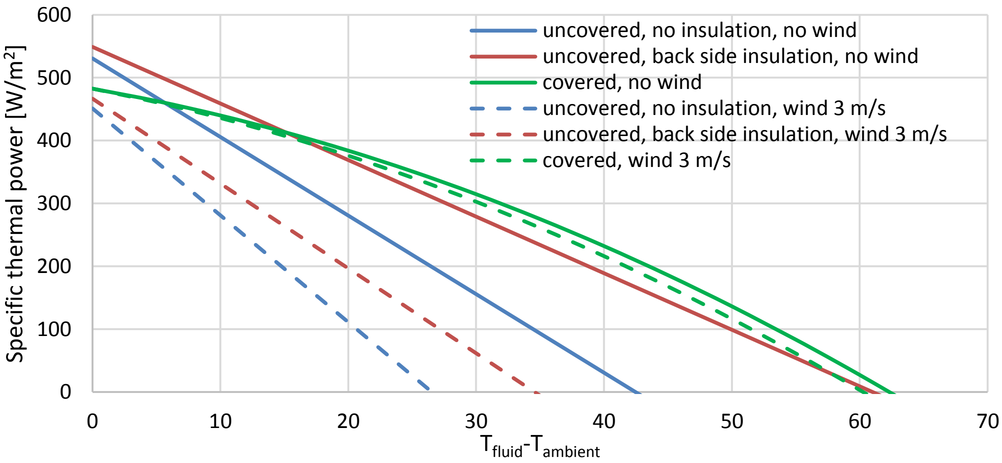

Figure 2: Thermal power of typical liquid-cooled PVT collectors at maximum electrical power point (MPP), related to the gross collector area and for a global solar irradiance of G=1000 W/m^2.

Expectable annual gross heat and electricity gains as well as differences in electricity gain compared to pure PV modules were calculated with the software Polysun, for different liquid-cooled PVT collectors and different operating temperatures. The gross heat and electricity gains correspond to the heat and electricity yields one would obtain, if the thermal circuit was turned on and operated at the specified temperature, whenever the thermal efficiency of the collector at this temperature is positive. Figure 3 shows the results for the climate of Zürich (CH) with a yearly solar irradiation on the horizontal plane of 1109 kWh/m^2 and a mean ambient temperature of 9.9 °C.

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[1] Concentrating PVT collectors were not considered in this survey.

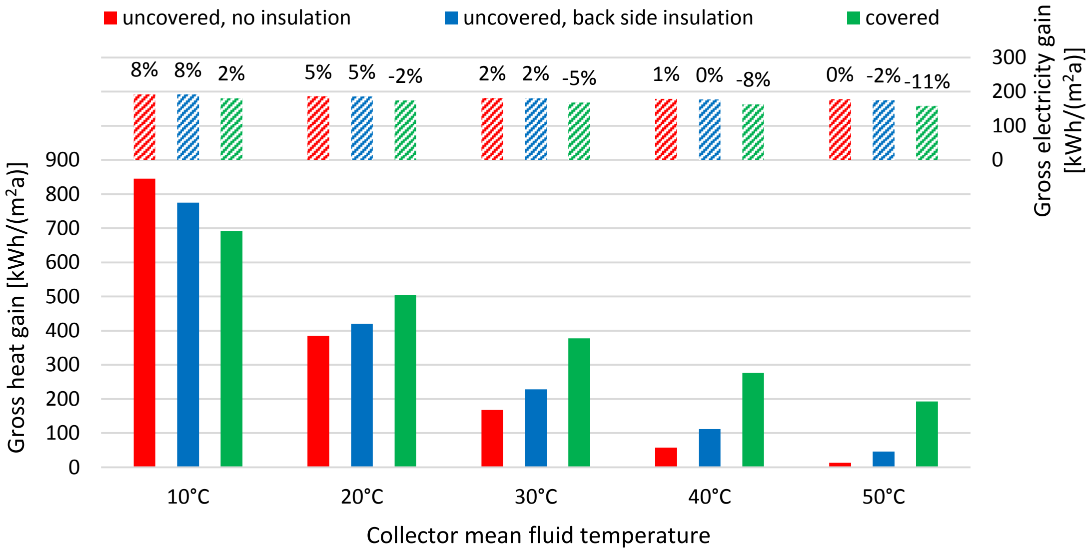

Figure 3: Gross heat and electricity gains for different liquid-cooled PVT collector types, climate of Zürich (CH), collector orientation south, inclination 45°. Percentages correspond to the difference in electrical yield compared to pure PV modules.

For low operating temperatures, the heat gains include converted solar irradiation as well as ambient heat collected in periods where the collector is operated below ambient temperature. Therefore, for low operating temperatures, uncovered collectors and collectors without back side heat insulation have an advantage. For higher operating temperatures, i.e. which over the year predominantly lie above ambient temperature, heat insulation and transparent covers are advantageous. In systems where the heat is always needed at temperatures above 50 °C, only covered collectors can contribute a notable amount of heat.

The lower the operating temperatures, the higher are the electrical yields. The percentage values in Figure 3 indicate the additional electrical yield compared to a standard PV module with average ventilation on the rear side. *Uncovered PVT modules without rear insulation* achieve the highest additional electricity yields. Their maximum (stagnation) temperatures correspond to the temperatures of pure PV modules. When no heat is extracted, they have the same electrical yield. *Uncovered PVT collectors with rear insulation* achieve similar additional electrical yields at low temperatures. As they can reach higher temperatures, their electrical yield at high temperatures is somewhat below the yield of PV modules. *Covered PVT collectors* generally reach lower electricity yields compared to uncovered ones. This is due to higher reflection losses at the transparent cover and due to longer periods of operation at higher temperatures. Compared to pure PV modules, a slight increase of electricity production can be achieved at low operating temperatures, in spite of the additional reflexion losses. At higher operating temperatures, however, their electrical yield can lie considerably below the one of PV modules. Therefore, in systems with covered PVT collectors, it is important to avoid long periods without heat consumption (stagnation).

Systems with uncovered liquid-cooled PVT collectors

From the above discussion, it is clear that uncovered PVT collectors are most suited for low-temperature applications. An important field of use is their integration in heat pump systems, where the low-temperature heat most commonly serves the following purposes: a) regeneration of a ground heat source, b) regeneration of a latent heat (ice) storage, c) regeneration of a cold sensible heat storage, d) pre-heating of a groundwater storage, and e) direct heat source of the heat pump (Figure 4). Variants a)-d) can all be combined with variant e). Further, all variants can be supplemented with the option to directly deliver solar heat to the secondary side of the heat pump, i.e. for example to a hot water or a space heating storage tank. This option is profitable to the energetic efficiency of the system. The quantitative benefit depends on storage temperatures and volumes. Further, one has to consider the additional complexity of the system.

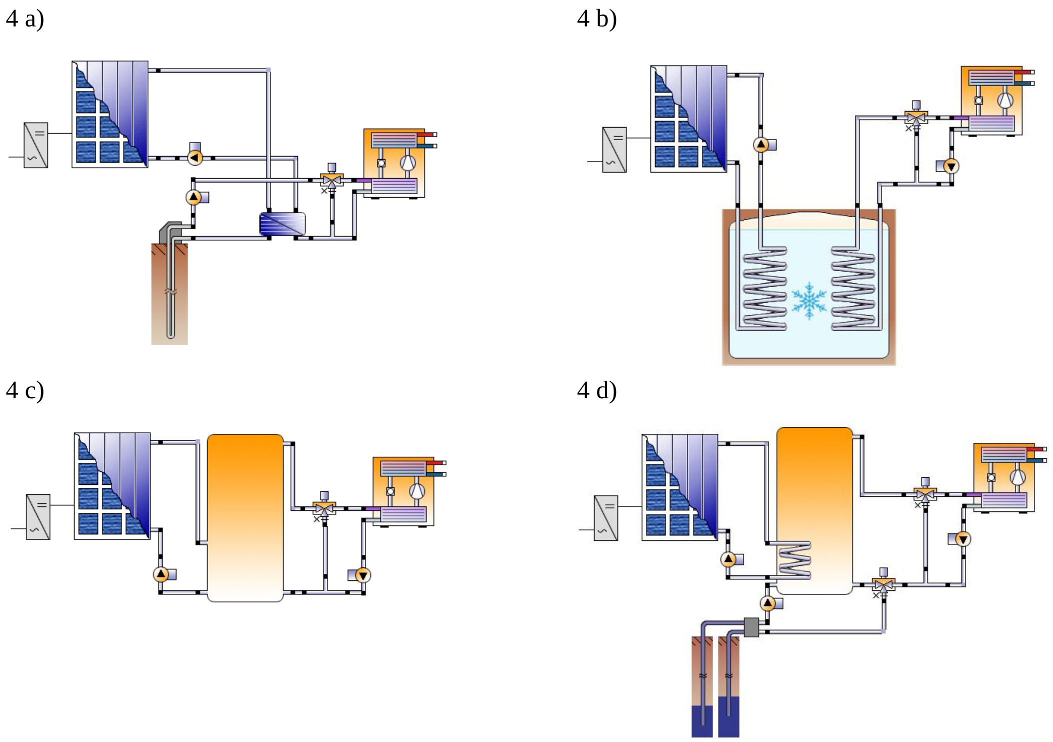

Figure 4: Schematics of different variants for integrating uncovered PVT collectors on the primary (source) side of a brine/water- or water/water-heat pump system. The heat sinks, which would be on the right side of the heat pump, are not depicted. (Schematics were made with the Software Polysun.)

Besides being integrated on the primary (source) side of heat pump systems, uncovered liquid-cooled collectors are also used in systems where they directly provide useful heat at the required temperature level. The applications basically correspond to the classical variants of solar thermal systems, such as: a) domestic hot water (pre-)heating, b) pool heating, and c) domestic hot water heating plus space heating (Figure 5).[1]

Systems with covered liquid-cooled PVT collectors

Regarding only the thermal part, covered PVT collectors can essentially be used like covered (glazed) solar thermal flat plate collectors. Most common is their application in systems for domestic hot water preparation with or without solar assisted space heating (Figure 5). A major difference to systems with pure thermal collectors lies in the handling of stagnation situations. In fact, several market-available covered PVT collectors must not be exposed to extended periods of stagnation at high temperatures, due to the low temperature resistance of the involved materials. Hence, the use of such products requires a fail save stagnation prevention on the system level, such as an additional heat dump (e.g. heat exchanger to ambient air) together with an appropriate system control.

Systems with air-cooled PVT collectors

Air-cooled PVT collectors are predominantly used in open systems. Ambient air is aspirated by a ventilator and guided behind the PV cells. The warmed-up air is often used for direct space heating or ventilation (Figure 6 a). The same configuration can serve be used for space cooling. An additional application is the use of the pre-heated air on the source side of an air/water-heat pump, for hot water preparation or space heating, permitting a rise of the performance factor of the heat pump (Figure 6 b). Further interesting applications of air-based PVT collectors include drying plants (e.g. for agricultural products or wood) and the ventilation of indoor swimming pools or enamelling plants.

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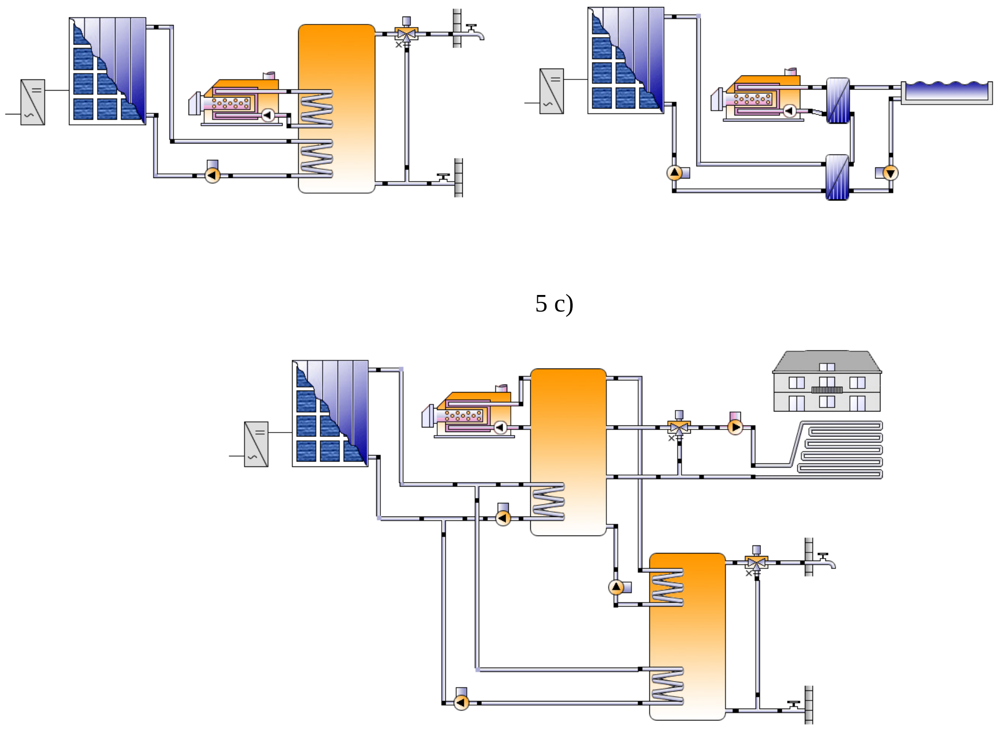
[1] For the case of domestic hot water (DHW) preparation, a “pre-heating” system is dimensioned such that it reaches a solar fraction around 20 %, while a standard solar DHW system reaches a solar fraction around 50 %.

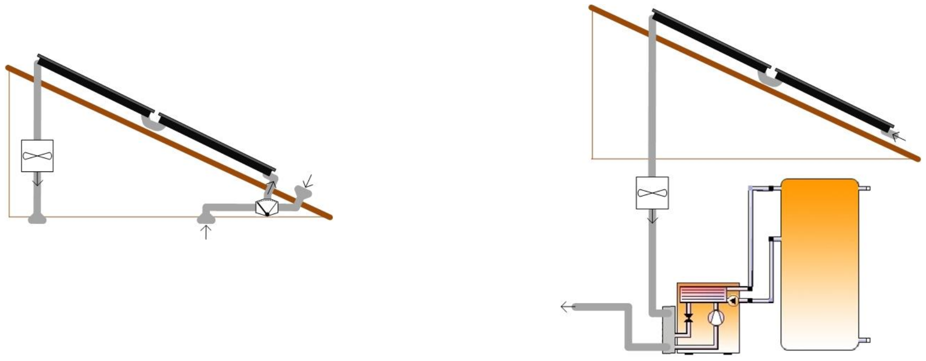


5 a)

5 b)

5 c)

Figure 5: Schematics of system variants with PVT collectors directly providing useful heat at required temperature level.



6 a)

6 b)

Figure 6: Schematics of system integrations of air-cooled PVT collectors: a) direct room heating or cooling, b) pre-heating of ambient air on the source side of an air/water heat pump.

Systems installed

In Switzerland, there are at present about 300 PVT systems in operation, with an estimated total area of 15’000 m^2. The vast majority of the plants uses liquid-cooled uncovered PVT collectors. According to the interviewed companies, in almost 50 % of the systems the PVT heat serves the (pre-)heating of domestic hot water (DHW), sometimes in a combination with space heating. In more than 40 % of the systems, the collectors are combined with heat pumps, where the solar heat is most commonly used for the regeneration of ground heat sources. A smaller share of the systems (< 10 %) uses PVT for pool heating. Given the generally large size of installations for ground source regeneration, this application makes for the largest part of the total installed collector area.

4. Survey results

A survey was conducted among two groups, manufacturers of PVT modules on one hand and planners/distributors/installers of PV, PVT and solar thermal systems on the other hand. Besides a number of other questions, participants of the survey were asked about the motivation of house builders for choosing PVT. The corresponding answers are shown in Figure 7.

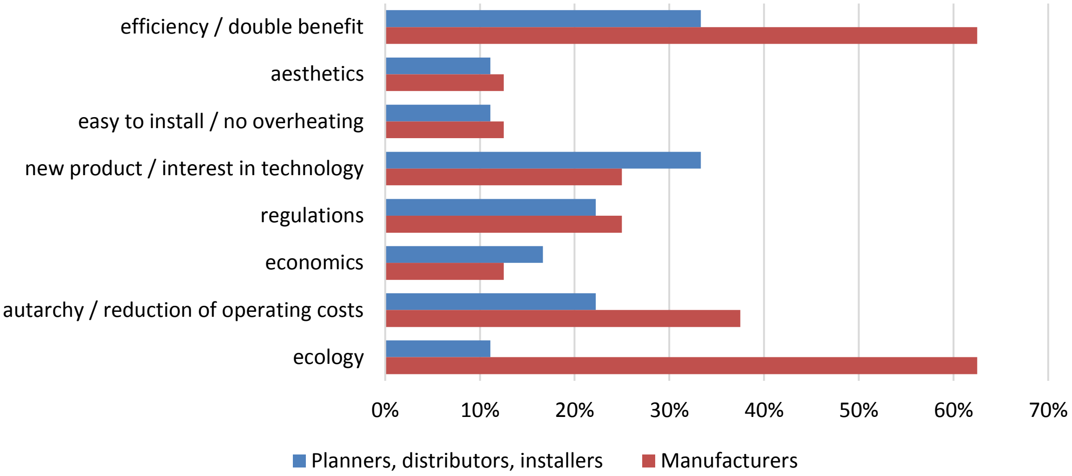


Figure 7: Motivations of house builders for choosing PVT collectors, as seen by manufactures and planners/distributors/installers respectively. The bars show the percentage of answering companies, which mentioned the corresponding argument.

Answers to the question about what should change in order to foster the deployment of PVT are shown in Figure 8. "high costs" and "sparse know-how" are raised as important aspects by both groups, manufacturers of PVT as well as distributors/planners/installers. It is interesting to notice that only the latter group mentions that product design and efficiency of PVT collectors should be improved.

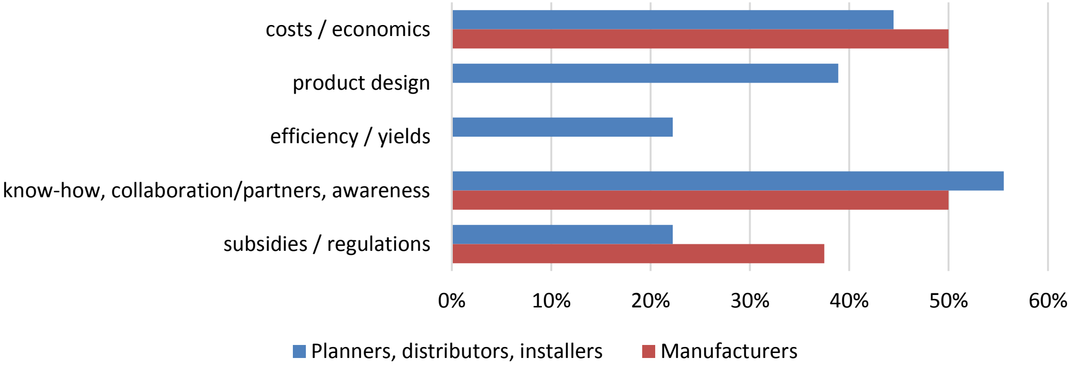


Figure 8: Survey results to the question about what should change, in order to foster the deployment of PVT.

5. Case studies

In Switzerland, 7 large PVT plants with collector field areas between 50 m^2 and 3500 m^2 were built in connection with so-called Pilot and Demonstration (P&D) projects, which received public financial support. In these installations, PVT is used for ground source regeneration, pre-heating of ground water providing heat to a heat pump, and in connection with a low-temperature heat distribution network, respectively. All installations are equipped with detailed monitoring and data acquisition systems and their performance is analysed by different research groups. In the full report of the presented review study, all these projects are briefly presented together with the main results obtained by the respective groups and references to further information (Zenhäusern, et al., 2017). Two examples of pilot plants are shown in Figure 9 and Figure 10. Based on measurement data of various projects (P&D and other), one can state that standard uncovered liquid-cooled PVT collectors in a typical Swiss climate reach an electrical yield of ~ 170 kWh m^{-2} a^{-1} plus a thermal yield of ~ 150 kWh m^{-2} a^{-1} (DHW), ~ 250 kWh m^{-2} a^{-1} (DHW pre-heating), 300 – 400 kWh m^{-2} a^{-1} (regeneration of ground source), and > 400 kWh m^{-2} a^{-1} (pre-heating of ground water at the source of a heat pump), respectively.

Figure 9: P&D project Sotchà in Scuol (CH). Roof-integrated PVT plant for the regeneration of boreholes (Vassella & Baggenstos, 2015).

Figure 10: P&D project Lintharena in Näfels (CH). Uncovered PVT collectors for the pre-heating of groundwater providing heat to a heat pump (Rohrer, 2016).

Acknowledgements

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Paper formatting

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The paper size is A4 (210 mm x 297 mm). Margins are 19.0 mm top; 25.4 mm right and bottom and 30.0 mm left. Do not change the paper formatting and do not insert page numbers, headers or footers! Papers using incorrect formatting may be rejected for publication in the proceedings if the author does not make corrections. Insert the lead author name in header starting on the second page. References must be formatted exactly as shown in the examples given below. The sections and sub-sections must be numbered by the author(s); do not use automatic paragraph numbering.

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Tables, figures, equations, and lists

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All figures and tables must be cited in the text, numbered in order of appearance and followed by a centered title. Each table column should contain a brief explanatory heading.

Tab. 1: Table captions (8 pt) should be justified as block and placed above the table

Table Header	**Header**	**Header**
Tables	Text	Text

3.2. Figures

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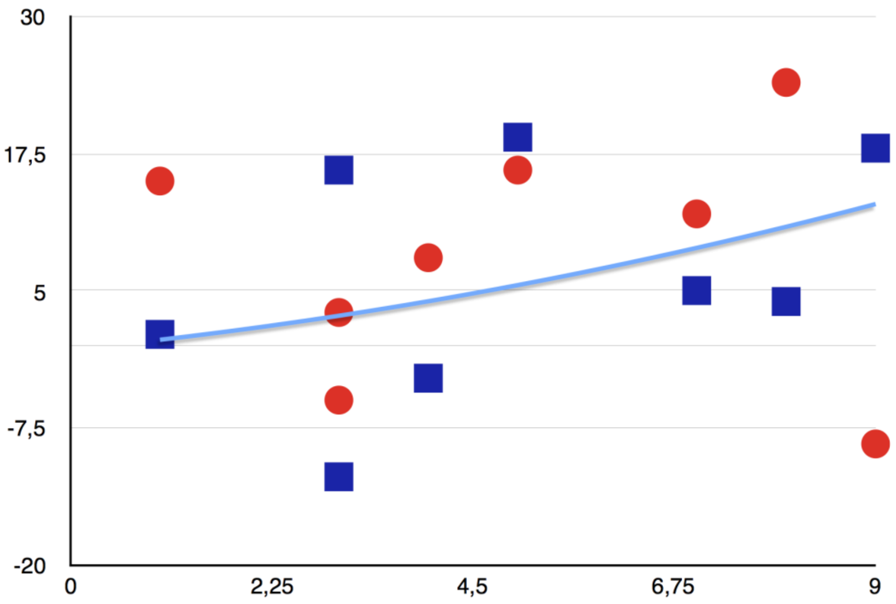

Fig. 1: Figure captions (8 pt) should be justified as block and placed below the figure

3.3 Equations

Equations should be arranged to the left, with characters similar to that of the body text and should be numbered.

$$\frac{1}{2\pi}\int_0^{2\pi}\frac{d\theta}{a+b\sin\theta}=\frac{1}{\sqrt{a^2-b^2}} \qquad \text{(eq. 1)}$$

$$\sin\alpha\pm\sin\beta=2\sin\tfrac{1}{2}(\alpha\pm\beta)\cos\tfrac{1}{2}(\alpha\mp\beta) \qquad \text{(eq. 2)}$$

3.4 Lists

- Bulleted lists can be used to arrange information more clearly in the text.

References

All references should be made according to the guidelines, as shown below.

Please ensure that each reference cited in the text is also present in the reference list (and vice versa). Any references cited in the abstract must be indicated completely. Unpublished results and personal communications are not recommended in the reference list, but may be mentioned in the text.

For web references, at least the full URL should be given and the date when the reference was last accessed. Any further information, if known (DOI, author names, dates, reference to a source publication, etc.), must also be given. Web references can be listed separately (e.g., after the reference list) under a different heading if desired, or can be included in the reference list. DOI must be included if available.

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All citations in the text should refer to:

1. *Single author*: the author's name (without initials, unless there is ambiguity) and the year of publication;

2. *Two authors*: both authors' names and the year of publication;

3. *Three or more authors*: first author's name followed by "et al." and the year of publication. Citations may be made directly (or parenthetically). Groups of references should be listed first alphabetically, then chronologically.

Example: "as demonstrated (Allan, 1996a, 1996b, 1999; Allan and Jones, 1995). Kramer et al. (2000) have recently shown ...."

List:

References should be arranged first alphabetically and then further sorted chronologically if necessary. More than one reference from the same author(s) in the same year must be identified by the letters "a", "b", "c", etc., placed after the year of publication.

Examples for references:

Reference to a journal publication:

Van der Geer, J., Hanraads, J.A.J., Lupton, R.A., 2000. The art of writing a scientific article. J. Sci. Commun. 163, 51-59.

Reference to a book: Strunk Jr., W., White, E.B., 1979. The Elements of Style, third ed. Macmillan, New York.

Reference to a chapter in an edited book: Mettam, G.R., Adams, L.B., 1999. How to prepare an electronic version of your article, in: Jones, B.S., Smith, R.Z. (Eds.), Introduction to the Electronic Age. E-Publishing Inc., New York, pp. 281-304.

Use of units and symbols:

For the use of units and symbols, please see the appendix below.

Appendix: Unites and Symbols

1. Units

The use of S.I. (Système International d'unités) in papers is mandatory. The following is a discussion of the various S.I. units relevant to solar energy applications.

Energy

The S.I. unit is the joule (J ≡ kg m^2 s^{-2}). The calorie and derivatives, such as the langley (cal cm^{-2}), are not acceptable. No distinction is made between different forms of energy in the S.I. system so that mechanical, electrical and heat energy are all measured in joules. Because the watt-hour is used in many countries for commercial metering of electrical energy, its use is tolerated here as well.

Power

The S.I. unit is the watt (W ≡ kg m^2 s^{-3} ≡ J s^{-1}). The watt will be used to measure power or energy rate for all forms of energy and should be used wherever instantaneous values of energy flow rate are involved. Thus, energy flux density will be expressed as W m^{-2} and heat transfer coefficient as W m^{-2} K^{-1}. Energy rate should not be expressed as J h^{-1}.

When power is integrated for a time period, the result is energy that should be expressed in joules, e.g. an energy rate of 1.2 kW would produce 1.2 kW x 3600 s = 4.3 MJ if maintained for 1 h. It is preferable to say that

Hourly energy = 4.3 MJ

rather than

Energy=4.3 MJ h^{-l}.

Force

The S.I. unit is the Newton (N ≡ kg m s^{-2}). The kilogram weight is not acceptable.

Pressure

The S.I. unit is the Pascal (Pa ≡ N m^{-2} ≡ k^2 m^{-1} s^{-2}). The unit kg cm^{-2} should not be used. It is sometimes practical to use 10^5 Pa = 1 bar = 0.1 MPa. The atmosphere (1 atm = 101.325 kPa) and the bar, if used, should be in parenthesis, after the unit has been first expressed in Pascals. e.g. 1.23 x 10^6 Pa (12.3 atm). Manometric pressures in meters or millimeters are acceptable if one is reporting raw experimental results. Otherwise they should be convened to Pa.

Velocity

Velocity is measured in m s^{-1}. Popular units such as km h^{-1} may be in parentheses afterward.

Volume

Volumes are measured in m^3 or litres (1 litre = 10^{-3} m^3). Abbreviations should not be used for the litre.

2. Flow

In S.I. units, flow should be expressed in kg s^{-1}, m^3 s^{-1}, litre s^{-1}. If non-standard units such as litre min^{-1} or kg h^{-1} must be used, they should be in parentheses afterward.

Temperature

The S.I. unit is the degree Kelvin (K). However, it is also permissible to express temperatures in the degree Celsius (°C). Temperature differences are best expressed in Kelvin (K).

When compound units involving temperature are used, they should be expressed in terms of Kelvin, e.g. specific heat J kg^{-1} K^{-1}.

3. Nomenclature and Symbols

Tables 1-5 list recommended symbols for physical quantities. Obviously, historical usage is of considerable importance in the choice of names and symbols and attempts have been made to reflect this fact in the tables. But conflicts do arise between lists that are derived from different disciplines. Generally, a firm recommendation has been made for each quantity, except for radiation where two options are given in Table 5.

In the recommendations for *material properties* (see Table 1), the emission, absorption, reflection, and transmission of radiation by materials have been described in terms of quantities with suffixes 'ance' rather than 'ivity', which is also sometimes used, depending on the discipline. It is recommended that the suffix 'ance' be used for the following four quantities:

$$\text{emittance } \varepsilon = \frac{E}{E_b}\left(or\ \frac{M_s}{M_{sb}} \right)$$

$$\text{absorptance } \alpha = \frac{\Phi}{\Phi_i}$$

$$\text{reflectance } \rho = \frac{\Phi}{\Phi_i}$$

$$\text{transmittance } \tau = \frac{\Phi}{\Phi_i}$$

where E and ϕ is the radiant flux density that is involved in the particular process. The double use of α for both absorptance and thermal diffusivity is usual, as is the double use of ρ for both reflectance and density. Neither double use should give much concern in practice.

Table 1: Recommended symbols for materials properties

Quantity	Symbol	Unit
Specific heat	c	J kg^{-1} K^{-1}
Thermal conductivity	k	W m^{-1} K^{-1}
Extinction coefficient^{+}	K	m^{-1}
Index of refraction	n	
Absorptance	α	
Thermal diffusivity	α	m^{2} s^{-1}
Specific heat ratio	γ	
Emittance	ε	
Reflectance	ρ	
Density	ρ	kg m^{-3}
Transmittance	τ	

$^{+}$ In meteorology, the *extinction coefficient* is the product of K and the path length and is thus dimensionless.

Table 2: Recommended symbols and sign convention for sun and related angles

Quantity	Symbol	Range and sign convention
Altitude	α	0 to ± 90°
Surface tilt	β	0 to ± 90°; toward the equator is +ive
Azimuth (of surface)	γ	0 to 360°; clockwise from North is +ive
Declination	δ	0 to ± 23.45°
Incidence (on surface)	Θ, i	0 to + 90°
Zenith angle	Θ_z	0 to + 90°
Latitude	Φ	0 to ± 90°; North is +ive
Hour angle	ω	-180° to +180°; solar noon is 0°, afternoon is +ive
Reflection (from surface)	r	0 to + 90°

Table 3: Recommended symbols for miscellaneous quantities

Quantity	Symbol	Unit
Area	A	m^{2}
Heat transfer coefficient	h	W m^{-2} K^{-1}
System mass	m	kg
Air mass (or air mass factor)	M	
Mass flow rate	$\dot{m}$	kg s^{-1}
Heat	Q	J
Heat flow rate	$\dot{Q}$	W
Heat flux	q	W m^{-2}
Temperature	T	K
Overall heat transfer coefficient	U	W m^{-2} K^{-1}
Efficiency	η	
Wavelength	λ	m
Frequency	ν	s^{-1}
Stefan-Boltzmann constant	σ	W m^{-2} K^{-4}
Time	t, τ, Θ	s

Table 4: Recommended subscripts

Quantity	Symbol
Ambient	a
Black-body	b
Beam (direct)	b
Diffuse (scattered)	d
Horizontal	h
Incident	i
Normal	n
Outside atmosphere	o
Reflected	r
Solar	s
Solar constant	sc
Sunrise (sunset)	sr, (ss)
Total of global	t
Thermal	t, th
Useful	u
Spectral	λ

Table 5: Recommended symbols for radiation quantities

	Preferred name	Symbol	Unit
a)	Nonsolar radiation		
	Radiant energy	Q	J
	Radiant flux	Φ	W
	Radiant flux density	Φ	W m^{-2}
	Irradiance	E, H	W m^{-2}
	Radiosity or Radiant exitance	M, J	W m^{-2}
	Radiant emissive power (radiant self-exitance)	Ms, E	W m^{-2}
	Radiant intensity (radiance)	L	W m^{-2} sr^{-1}
	Irradiation or radiant exposure	H	J m^{-2}
b)	Solar radiation		
	Global irradiance or solar flux density	G	W m^{-2}
	Beam irradiance	G_b	W m^{-2}
	Diffuse irradiance	G_d	W m^{-2}
	Global irradiation	H	J m^{-2}
	Beam irradiation	H_b	J m^{-2}
	Diffuse irradiation	H_d	J m^{-2}
c)	Atmospheric radiation		
	Irradiation	$\Phi\downarrow$	W m^{-2}
	Radiosity	$\Phi\uparrow$	W m^{-2}
	Exchange	Φ_N	W m^{-2}