Systematic Classification of Combined Solar Thermal and Heat Pump Systems

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Abstract

In this paper several approaches are discussed for the analysis and comparison of combined solar thermal and heat pump systems. The discussion is based on a detailed literature review and investigations on market available systems. Based on this, an approach to describe and systematically classify combined solar thermal and heat pump systems is presented. The approach consists of three elements: A visualization scheme to systematically represent concepts of combined solar thermal and heat pump systems, a notation scheme providing the same information in letter combinations, and a simplified notation restricted to those parameters needed for classification. Such a classification is proposed with the kind of connection between the solar collector and the heat pump being the central aspect. For all three elements, examples are given.

1. Introduction

In the past years more and more systems combining solar thermal collectors with heat pumps have been developed and introduced to the market for both domestic hot water and space heating. Mostly, the manufacturer and/or distributors either have a solar thermal technology or a heat pump technology background. If they mainly have available detailed knowledge in only one of the technologies mentioned, they may have different approaches to develop a combined system concept: A) The heat pump replaces the burner of a "conventional" solar thermal combisystem, and B) the solar collector is solely used as an additional component of a heat pump system to avoid thermodynamic unfavourable operating conditions of the heat pump. Currently an increasing number of system concepts can be observed that are based on a combination of both approaches or even completely new arrangements, such as the integration of solar heat into the distribution system directly or via the heat pump, depending on the temperature level of the solar heat available. With regard to the specific system concept and boundary conditions, it has to be investigated whether a significant enhancement of the solar gain as well as a reduced primary energy demand of the heat supply system can be achieved compared to a "conventional" solution.

Many of the systems that have recently been introduced to the Central European markets are using several heat sources for the heat pump and/or more than one heat sink for the solar collector. There are various options to set up a combined system as well as categories for a system classification. Within the Task 44 “Solar and Heat Pump Systems” of IEA’s Solar Heating and Cooling Programme that has been started in the beginning of 2010, combined solar thermal and heat pump systems will be analyzed in detail and further developed. A systematic classification of such systems is needed from the very beginning in order to gain an overview of the various possible alternatives on the one hand and to provide a basis for the consideration of the respective pros and cons from a technical point of view on the other hand. In this paper, an approach for a systematic classification of combined solar thermal and heat pump systems is presented and discussed that is based on a review of previous publications and that should serve as a basis for developer, planner and installer as well as for evaluation and testing aspects.

2. Previous work

2.1. Classification approaches

Combined compression heat pumps and solar thermal heating systems have been reported for more than 50 years (see [1]). In some of the publications, different categories for such systems have been proposed. An overview is presented in [2]. The categories reach from rather simple approaches (dividing the systems into “parallel”, “serial” and “dual” systems, e.g. [3]) over application orientated categories (such as „solar boosted heat pump water heaters“, typically with direct evaporation of the heat pump working fluid in uncovered collectors, e.g. [4]) to phenomenological groupings or market orientated listings of existing systems (e.g. [5]). However, these system descriptions are difficult to be clearly defined and tend to present systems for different operating conditions.

2.2. Compilation of existing systems and its parameters

A comprehensive table can provide detailed information that may be needed for technical development and an overview of component interactions etc., such as the type of refrigerant of the heat pump, whether there is one (or several) storages on the cold side of the heat pump, which type of heat storage is being used, and so on. Furthermore, the applicability and reasonability of specific system concepts may depend on climatic conditions and the load characteristics. Therefore, a systematic presentation in tabular form has been derived from an extended literature review [2] containing aspects with detailed system information and aspects regarding boundary conditions (see Table 1).

All system concepts described in the selection displayed in Table 1 are designed for both DHW and space heating. However, the majority of the combined solar thermal and heat pump systems that have been investigated in the literature review only provide heat for one of the loads mentioned, mostly only for DHW. Furthermore, it is remarkable that in the studied literature usually a specification of the refrigerant is missing. If mentioned, in most cases R-22 has been used, so that the performance described in those papers can hardly be compared to recent products which do not make use of R-22 because of its ban due to harmfulness to the ozone layer (Montreal protocol).

Table 1. System Classification Table, divided into system information aspects and boundary conditions. Only a sample of the literature study described in [2] is presented. The table may be further extended.

		Freeman et al. 1979, parallel	Freeman et al. 1979, serial	Freeman et al. 1979, dual	Aderson et al. 1980	Hahne & Hornberger 1994	Schaap et al. 2000	Hafner 2004	Schmidt 2006	Kuang & Wang 2006	Trillat-Berdal et al. 2007	Citherlet et al. 2008, 1-air	Citherlet et al. 2008, 3	Tepe 2008	Kühl et al. 2008	Leibfried et al. 2008	Bauer et al. 2008: Eggenstein	Bauer et al. 2008: Rostock	Trinkl et al. 2009	etc.
	SYSTEM INFORMATION																			
1a	***Type of Solar Collector***																			
	Unspecified				X						X									
	Direct evaporation solar panel (uncovered)									X										
	Flat plate collector (uncovered)					X							X	X						
	Flat plate collector (covered)	X	X	X			X	X	X				X	X	X		X	X	X	
	Evacuated tube collector												X							
	Air collector											X								
	Other: …………………………………….															b)				
1b	***Heat Sinks for Solar Heat***																			
	Domestic Hot Water	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	
	Space Heating	X	X	X	X		X		X		X			X	X	X	X	X	X	
	Evaporator Heat Pump		X	X		X	X		X	X	X	X	X	X		X	X	X	X	
	Boreholes (BTES active regeneration)										X			X						
	Storage (cold side HP)	X	X	X		X	X				c)			c)		X	X	X	X	
2a	***Heat Source(s) for Heat Pump***																			
	Solar Collector (direct evaporation)		X							X										
	Solar Collector (heat exchanger)	X		X		X	X		X		X	X	X	X		X	X	X	X	
	Air	X		X	X			X		X		X	X			a)				
	Ground								X		X			X	X					
	Ground Water																	X		
	Waste Water						X													
2b	***Heat Pump Refrigerant***																			
	R-xxx (n.s. if not specified)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	R290	R22	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	
2c	***Heat Sinks for Heat Pump***																			
	Unspecified																			
	Domestic Hot Water						X	X	X	X		X	X	X	X	X	X	X	X	
	Space Heating	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
3a	***Storage Concept (cold side HP)***																			
	None				X			X		X	X	X			X					
	Sensible Heat (Water)	X	X	X		X	X		X				(X)							
	PCM (including ice)						X						(X)			X			X	
	Seasonal Storage					X	X				c)			c)		(X)	X	X	X	
	Other: …………………………………….					d)											d)	e)		
3b	***Storage Concept (load)***																			
	None	X	X	X																
	Water				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
4	***Additional Heating (backup)***																			
	Electricity (direct)	X	X	X	(X)		(X)	X			X			X	X	X				
	Oil				(X)															
	Gas				(X)												X	X		
	Other: …………………………………….					f)														
	BOUNDARY CONDITIONS																			
5	***Climate***																			
	Country	US	US	US	US	DE	NL	DE	DE	CN	FR	CH	CH	n.s.	DE	DE	DE	DE	DE	
6	***Application / Demand***																			
	Domestic Hot Water	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	Space heating via Water					X	X	X	X		X	X	X	X	X	X	X	X	X	
	Space heating via Air	X	X	X	X			X		X										
	Cooling	(X)	(X)	(X)						X	X									

a) *special solar collector with heat exchange air-absorber, no additional air heat exchanger*
b) *hybrid collector with ambient air entering the covered flat plate collector (open system)*
c) *aktive regeneration of ground not taken as seasonal storage due to limited storage efficiency*
d) *artificial aquifer: water flooded pebble bed*
e) *naturel aquifer (ATES)*
f) *CHP - combined heat and power (not described in detail)*

3. Analysis and Classification

As stated before, the possibilities to set up a combined system as well as categories for a system classification are various. The scope of classification requires analyses, i.e. searching and defining distinctive features in all examined systems. Examples for such parameters are:

- The sources of the heat pump,
- The sinks of the heat pump,
- The collector type,
- The storage concept and technology used in tanks,
- etc.

Some of the approaches described in section 2.1. can give a quick but yet unspecific system overview that is not suitable for the definition of system classes. On the contrary, the table in section 2.2 contains more information than can be used for a classification. In a first step, the derivation of a tree structure to systematically define system categories was investigated. However, the search for an exclusive hierarchical nature that is needed for a tree structure was not successful, mainly because of a lack of exclusive categorization aspects. With a simplified graphical system description proposed in [2] many important system aspects can be displayed. In this paper, an enhanced visualization that is more systemized and a formula-like scheme are introduced for systematic analysis and comparison of solar thermal heat pump systems. These examinations are later used for the derivation of the classification shown in section 3.3. The approach comprises:

a) A visualization scheme systematically representing concepts of solar heat pump systems,
b) A notation scheme providing essentially the same information in letter combinations,
c) A simplified notation restricted to those parameters needed for classification.

3.1. Visualization

Basically, the visualisation presented in this paper is similar to energy flow charts that are frequently used in building energy engineering. Instead of a whole building, only the heating system is illustrated (see Fig. 1). Final energy flows (that have to be purchased, like electricity or natural gas) are shown at the system boundary to the left, useful energy flows like domestic hot water (DHW) to the right. Environmental energy sources such as ambient air are shown at the upper part (green fields). Consequently, any losses would be shown leaving the system downwards. However, losses are neglected during visualisation and classification because they are not needed for system characterisation, but can be introduced for visualisation of the energy quantities in performance investigations. A label for the manufacturer’s name and the system type is introduced in the lower left part.

As the next level of detail, the components of the heating systems are introduced. The analysis of many combined solar thermal and heat pump systems resulted in the finding of five recurring components: Solar collector, heat pump and backup heater (orange fields) complemented by a storage concept on the (usually cold) source side and one on the (usually hot) sink side of the heat pump (blue fields). For all these components, fixed positions are defined and can be highlighted when existing in the concept. Any components or energy sources/sinks that are not present or used in a system are also displayed via placeholders, but not highlighted. The different colours are used to distinguish between final (grey), environmental (green) and useful (red) energy as well as energy converters (orange) and storages (blue). However, the information provided by the colouring is not essential for understanding the presented concept.

The final step is the depiction of energy flows connecting certain components. In doing so, the figure is enhanced to become an energy flow chart. It should therefore be easy to understand, to analyse, and last but not least to compare systems. Each line style refers to the carrier medium, except the driving energies that are mostly without mass, e.g. solar irradiation. The line widths are indifferent, and thus not representing for example the quantity of transported energy. This is also valid for components in general. Therefore, it is not possible to distinguish for instance between a 100 ℓ and a 2000ℓ storage (in a later version more information may be displayed within the fields). Finally, it is of great importance to understand that any system is represented by exactly one flow chart. This means that no specific operating mode is shown but all operating modes that occur within the represented system are depicted simultaneously.

A simple example is given by Fig. 1.

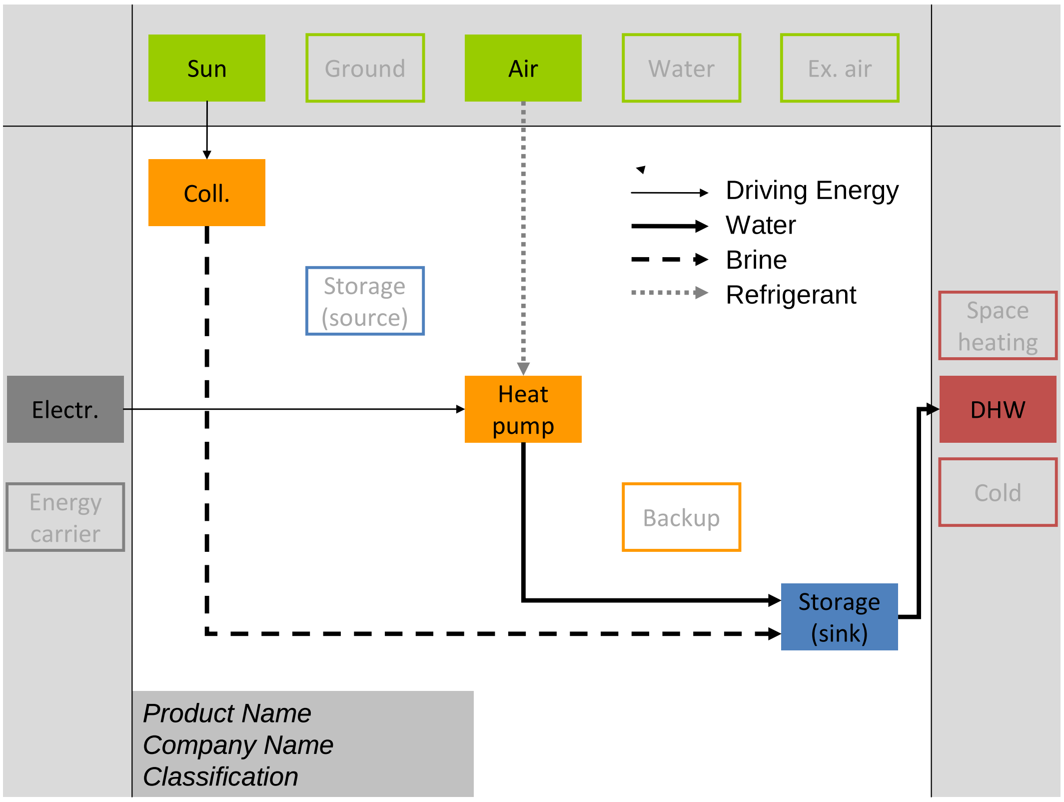

Fig. 1. Introductory example for the visualization scheme

In Fig. 2 and Fig. 3, the presented visualisation scheme is applied to different system concepts. The comparison between the figures gives an impression of the visualisation method’s capability. As an additional finding, it can be seen that the arrangement defined above results in energy flows mostly in left-to-right and up-down directions, though of course, the variety of combinations results in exceptions.

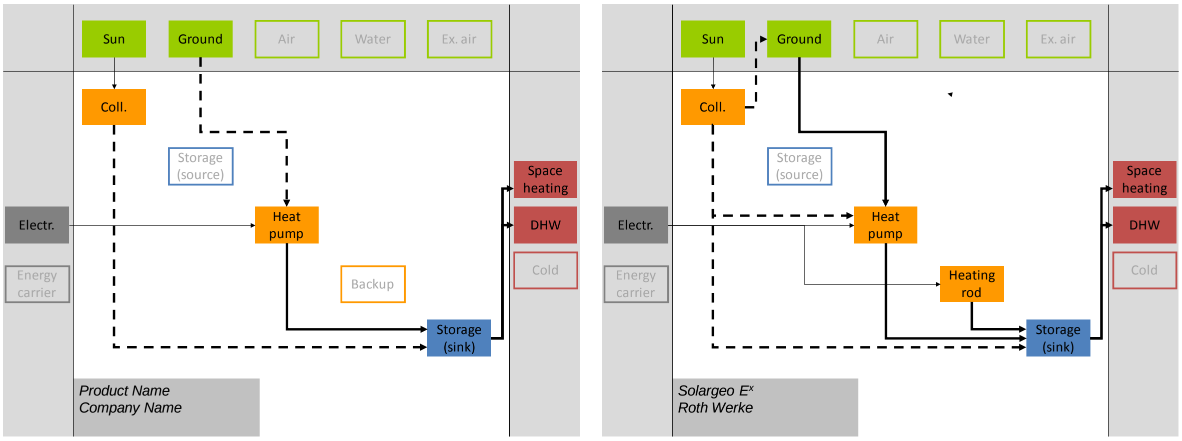

Fig. 2. Typical system with combistore (left) and “Solargeo E^{x}“ by Roth Werke (right)

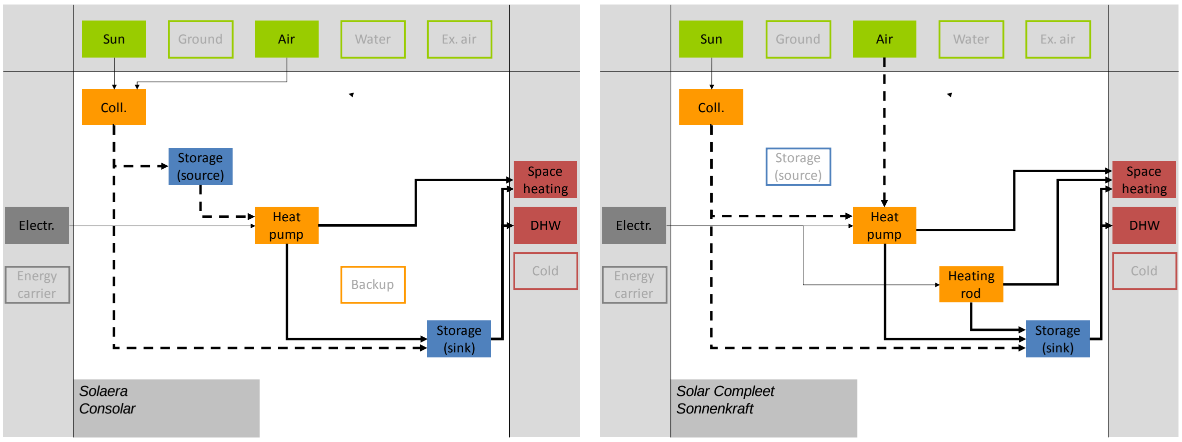

Fig. 3. “Solaera“ by Consolar (left) and “Solar Compleet“ by Sonnenkraft (right)

3.2. Notation Scheme

With the exception of backup heating, the information comprised in the schematics presented in Figs. 1 to 3 can also be denoted in letters with the abbreviation code shown in Table 2 and the convention that the sources and sinks of the solar collector (S) and the heat pump (HP) are indicated with superscripts (sources) and subscripts (sinks) around the abbreviation SHP which stands for solar heat pump:

$$ {}^{sources}_{sinks}SHP^{sources}_{sinks} $$

Table 2. Abbreviations used for transferring the system information into a letter code

S	solar collector	Air	air	srS	source storage (usually cold)
HP	heat pump	G	ground	skS	sink storage (usually hot)
Sol	solar irradiation	W	ground water	SH	space heat (directly)

With this way of notation, the systems shown in Figs 1 to 3 would be denoted as follows:

Fig. 1:	${}^{Sol}_{skS}SHP^{Air}_{skS}$		
Fig. 2 (left):	${}^{Sol}_{skS}SHP^{G}_{skS}$	Fig. 2 (right):	${}^{Sol}_{skS,G,HP}SHP^{G,S}_{skS}$
Fig. 3 (left):	${}^{Sol,Air}_{srS,skS}SHP^{srS}_{skS,SH}$	Fig. 3 (right):	${}^{Sol}_{skS,HP}SHP^{Air,S}_{skS,SH}$

Such a formalized notification system allows a further use as base for simplified performance calculation schemes for Solar Heat Pump Systems.

3.3. Simplified Notation and Classification

Within the previous sub-sections, three methods were used to describe solar heat pumps in different ways and by means of different parameters. Many systems were presented clearly and comparably. To categorize, however, means to simplify, to generalize and to group are needed. For this process, few characteristic parameters have to be defined, e.g. the sources of the heat pump or the type of solar collector. In relevant literature, a more abstract parameter is regarded as most influential, namely the interaction between collector and heat pump. It is typical described as “parallel” or “serial”, cf. for instance [6], [7] and [8] as well as further references in [2]. In this paper the interaction will also be used for defining categories. After analysing many systems combining solar collectors and heat pumps, it appears that interaction generally occurs in three distinctive ways:

- Parallel: Collector and heat pump independently supply useful energy (space heating and/or domestic hot water), sometimes via a storage,
- Serial: A collector acts as a heat source of a heat pump, either exclusively or as additional source, and either directly or via a storage,
- Regeneration: A collector is used for the regeneration of another source, usually ground.

System concepts may feature more than one of these options as the options do not exclude each other. This non-hierarchical or exclusive structure is the main reason why a tree structure is regarded unsuitable for classification. The counting of all possible combinations of the three options of interaction mentioned – while ignoring permutations, redundancies and the trivial case of “none” – results in seven categories.

Using “P” (parallel), “S” (serial or source) and “R” (regeneration) as abbreviations for the options and introducing the abbreviation SHP for “Solar Heat Pump” to indicate the subject of classification and to add recognition value, we end up with these categories:

- SHP/P (the most common system, cf. to Fig. 2 (left))
- SHP/P,S (cf. to Fig. 3)
- SHP/P,S,R (cf. to Fig. 2 (right))
- SHP/P,R, SHP/S, SHP/R, SHP/S,R (no examples shown in this paper)

4. Conclusion

With the approach presented in this paper to describe and classify combined solar thermal and heat pump systems it is possible to visualize such systems systematically and clearly simplified. Furthermore, a distinct system description can be carried out with notation described in section 3.2. With a simplification, a classification of the various system concepts can be achieved. With the simplification of introducing the kind of connection between the solar collector and the heat pump as central aspect, seven classes can be derived. The whole approach consisting of the three steps described has been tested successfully on a number of existing system concepts. If (e.g. for system development) more system details are needed, the table described in section 2.2 can be used.

With this approach, a basis is provided for the systematic description and comparison of combined solar thermal and heat pump systems, e.g. in the framework of IEA-SHC Task 44. The approach should be suitable to replace antecedent description concepts and should be able to comprise both existing and newly developed system concepts. Based on this, the classification proposed should be consolidated. Possibly, some system concepts or developments can be identified as less or even not expedient.

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References

[1] Sporn, P. & Ambrose, E., 1955. The Heat Pump and Solar Energy. In: Proc. of the World Symposium on Applied Solar Energy. Phoenix, US.

[2] Haller, M., Frank, E., Trinkl, C., Zoerner, W.: Systematische Gliederung der Systemkombination von solarthermischen Anlagen und Wärmepumpen. Proceeding of 20th Symposium Thermische Solarenergie, Bad Staffelstein/Germany, May 2010.

[3] Freeman, T.L., Mitchell, J.W. & Audit, T.E.: Performance of combined solar-heat pump systems. Solar Energy, 22(2) 1979, pp. 125-135.

[4] Hepbasli, A. & Kalinci, Y.: A review of heat pump water heating systems. Renewable and Sustainable Energy Reviews, 13(6-7) 2009, pp. 1211-1229.

[5] Trojek, S. & Augsten, E.: Solartechnik und Wärmepumpe - Sie finden zusammen. Sonne Wind & Wärme, 6/2009, pp. 62-71.

[6] Rieger, I. & Hube, W.: Wärmepumpe und Solarthermie. Erfolgversprechendes Doppel. TGA Fachplaner 3/2010, pp. 30-35.

[7] Citherlet, S., Bony, J., Nguyen, B. 2008: SOL-PAC. Analyse des performances du couplage d'une pompe à chaleur avec une installation solaire thermique pour la rénovation.

[8] Trinkl, C., Zörner, W. & Hanby, V., 2004. A Review on Solar-Assisted Heat Pump Systems for Domestic Heating. In: Proc. of EuroSun Conference, Freiburg / Germany.

[9] Henning, H.-M.; Miara, M. Solarthermie und Wärmepumpen – getrennt oder zusammen? in Erneuerbare Energien 3/2009, pp. 4-7.