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LowEx solar building system: Integration of PV/T collectors into low exergy building systems

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Abstract

The integration of an unglazed solar photovoltaic/thermal (PV/T) collector to a ground source coupled heat pump system has the potential to increase the heat pump performance to a minimal SPF of 6 by providing higher average source temperature. Furthermore the integration of a PV/T collector increases the system stability and introduces new degrees of freedom in the design of renewable and zero emission energy supply for buildings.
This study shows the design of a low exergy (LowEx) solar building system and its potential for the total solar energy building supply in moderate climates as in the EU and northern China.
The collector array is dimensioned according to the building heat load. The area can be maximized to provide the entire yearly heat demand, without the problem of excess collector heat in summer, by employing solar ground regeneration. The low-temperature thermal collector supplies the heat needed by the heat pump to provide hot water and heating of the building, while the PV production exceeds the annual electricity demand of the heat pump and auxiliary pumps.
Different hydronic circuit layouts and controls have been evaluated by simulation according to reference buildings of SHC IEA task 44 with regard to the criteria of simplicity and reliability in order to realize LowEx solar buildings. An implementation of a system that maximizes the thermal system input considering minimal internal exergetic losses is presented. A PV/T collector has been realized as prototype, installed and tested in LowEx building systems.

Keywords: Unglazed solar PV/T; low exergy building systems; solar heat pump system combination; ground source heat exchanger

1. Introduction

The world is facing an increasing need of primary energy and rising greenhouse gas emissions, particularly CO_2, due to increasing global population and its enhanced electricity consumption. The building sector shares 38% of the world's primary energy consumption and causes around half of the

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global greenhouse gas emissions, 20% by operation [1] [2]. Various studies show the need of a drastic change from non-renewable to renewable and emission free energy supply of buildings, e.g. [3].

New building system concepts that minimize the primary energy demand for heating and hot water supply of buildings and can be implemented to a large extent in the existing building stock are needed. Local production of thermal and electrical energy becomes more important for supplying the desired thermal interior building comfort. At the same time, the adequate energy supply during the entire year must be guaranteed. Therefore concepts of buildings' heat and electricity supply cannot be evaluated separately, but must be discussed as an integrative system.

A highly efficient heat pump operation is crucial for a renewable and emission free heat supply of new and retrofit buildings. The concept of exergy is adopted in order to evaluate anergy sources of different temperatures and heat fluxes in building systems [4].

Nomenclature

PV/T	photovoltaic thermal
SPF	seasonal performance factor
COP	heat pump coefficient of performance
Q_h	output heat
W	input work
COP_{real}	real coefficient of performance
COP_{ideal}	theoretically possible coefficient of performance
T_{cold}	heat source temperature
T_{hot}	heat sink temperature
T_{coll}	collector fluid mean temperature
T_{amb}	ambient temperature
g	g-factor
GSHE	ground source heat exchanger
GSHP	ground source coupled heat pump
DHW	domestic hot water

2. Method

2.1. Concept of exergy in buildings

Considering heat pumps, the coefficient of performance (COP) is defined as the maximum amount of heat that is produced per unit input of work [4].

$$COP_{real} = \frac{Q_h}{W} = g * COP_{ideal} \tag{1}$$

$$COP_{ideal} = \frac{1}{\eta_{carnot}} = \frac{T_{hot}}{(T_{hot} - T_{cold})} \tag{2}$$

According to equations (1) and (2) a low temperature lift between the source and sink is crucial for high efficient heat pump operation. It can be achieved by:

- High g-factor
- Low sink temperature T_{hot}
- High source temperature T_{cold}

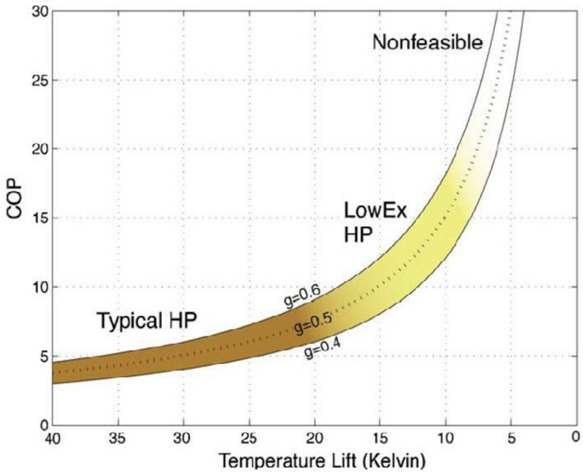

Fig. 1. COP_{real} dependency on temperature lift and g-factor [6]

The g-factor is a machine characteristic. Low-temperature lift heating systems need appropriate heat pumps with a g-factor of around 0.5 at low-temperature lifts of 10-20°C. Those already exist [5]. Current heating systems with large heat exchange surfaces as floor, wall or ceiling are supplied with low sink temperatures of 30 to 35°C. Constant high source temperature during the heating season can be found in the ground, which is defined as anergy source [4]. Given proportional increasing temperatures by increasing depth (3°C / 100 m), a deep borehole as heat pump source is favorable. For example, the ground in Zürich, Switzerland provides up to 27°C natural soil temperature at a depth of 500 m. The natural ground heat flow of around 0.5 W/m^2 is too low to regenerate the soil near the GSHE, it needs to be regenerated actively after the end of the heating period in order to provide the initial natural temperature level at the beginning of the next heating period. An active regeneration in summer time avoids decreasing source temperature during several heating periods.

A PV module based on crystalline silicon PV cell technology converts solar irradiance into 15% exergetically high valuable electricity and 85% lower valuable heat. This large and freely available source of low exergetically valuable heat is another anergy source of the building [4]. Around 70% of this heat can be removed from the PV module at useful temperatures for ground regeneration. Studies have shown the potential of increasing the average heat pump source temperature by ground regeneration in order to increase the heat pump efficiency, which eventually reduces the exergy use of buildings [7]. At the same time removing absorbed heat of a PV module cools the PV cells and increases its electrical yield [8].

Beside that, the exergetic efficiency of the LowEx solar system also depends on the electricity consumption of the auxiliary components such as pumps.

2.2. LowEx solar building system

Fig. 2 shows a principle scheme of the LowEx solar building system and its integration in the GSHP system's hydronic circuit.

The PV/T collector array is connected as direct source to the heat pump, to the GSHE for regenerating the ground and to the water tank to pre-warm the DHW. Other methods of heat storage are also possible, e.g. PCM or large water tanks. This study focuses on GSHE in single or borehole field array and its need of solar regeneration.

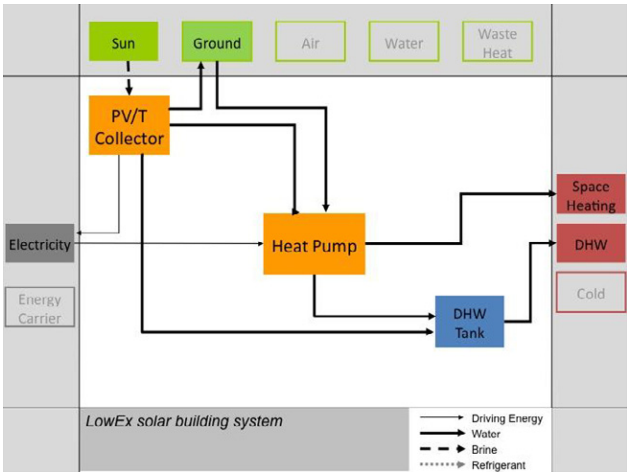

Fig. 2. LowEx solar building system according to [9]

2.3. Simulation

The described building system was implemented in TRNSYS simulation software and ran under the weather conditions of Zürich, Switzerland. A PV/T array of 74 m^2 at 10° installation angle is connected to a 400 m GSHE, which is thermally insulated and inactive at the first 150 m, and to a 16.5 kW heat pump, according to the layout shown in fig. 6. The heat pump was modeled with the type 668 and a performance file based on an actually installed low-temperature lift heat pump in a pilot installation. The GSHE was modeled with the type 557a. The building DHW profile and heating load was implemented according to the reference building SH100 of IEA task44 [10] but with a floor heating system and a net area of 300 m^2. The heat exchangers, valves and pumps were modeled as standard components: one 40 W pump for the solar circuit, one 300 W pump for GSHE and one pump for the transfer to the heating distribution system are ran at constant mass flow.

3. Results

3.1. PV/T collector

A new PV/T collector prototype was developed. It is classified, according to [11], as unglazed non-concentrated PV/T water round tube absorber collector. Fig. 3 shows the result of a performance test of the PV/T collector with an absorber area of 1.6m^2 at the SPF Rapperswil, Switzerland. One measurement was made without thermal backside insulation and one with additional insulation material on the collector backside.

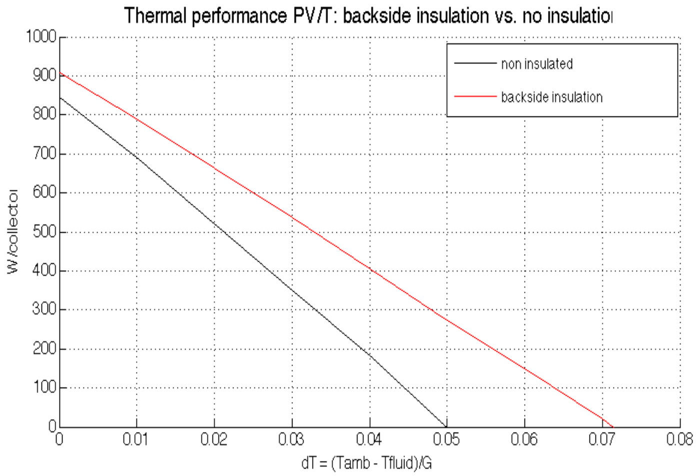

Fig. 3. Performance chart of PV/T at irradiance of 1000 W/m^2. The red line shows the performance of the collector with thermal backside insulation. The black line shows the performance without thermal insulation

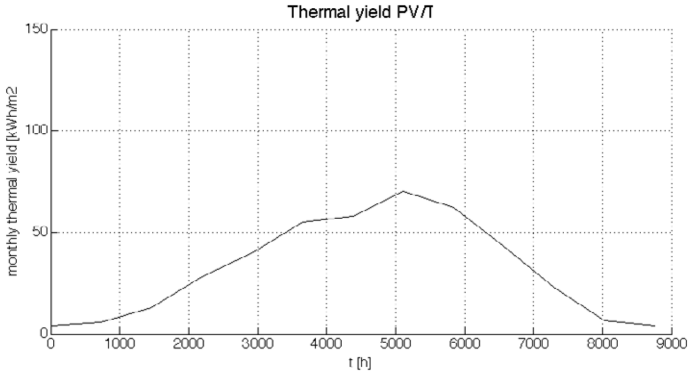

Fig. 4. Monthly thermal yield of the PV/T collector

Backside insulation increases the thermal efficiency by 7% at $\Delta T = T_{coll} - T_{amb} = 0°K$, respectively by 53% at $\Delta T = 30°K$. The bigger the temperature difference between the ambient and the fluid temperature, the higher the positive effect of backside insulation becomes.

Simulations with data of the insulated PV/T-collector in TRNSYS show an increase of the yearly thermal yield of 14% compared to the non-insulated collector. Since the increase of thermal yield with backside insulation is decent, it's disputable if the additional benefit of insulation justifies the additional insulation material in terms of cost and embedded energy. The collector used in this study was realized without backside insulation.

The performance chart in fig. 3 and the simulations in TRNSYS show an ideal operation at temperatures of 20-35°C and an average ΔT of fluid to ambient temperature in operation of 12°C. This temperature range coincides with the basic idea of cooling the PV cells. Therefore this uncovered thermal collector is not suited for producing direct domestic hot water.

Fig. 4 indicates that the PV/T collector generates 96% of its stochastic thermal yield from March to October in a simulated operation in Zürich, Switzerland. Most of the thermal yield is gained outside the heating season, which underlines the need of integrating the collector to a building system.

A further study of the thermal yield reveals a lower dependency on the collector installation angle and orientation than covered flat plate collectors, which enables more architectural freedom in the creation of building skin, in particular for building integration. An installation angle of 10° to 60° and orientation of -50° to 50° guarantees more than 91% of the maximal thermal yearly yield.

In two pilot installations a maximum collector's stagnancy temperature was measured at 74°C at full irradiation. Measurements in similar pilot installations, e.g. [12] confirm stagnancy temperature of less than 80°C. Overheating, which is one of the main difficulties of covered solar thermal collectors, is not possible in uncovered collectors.

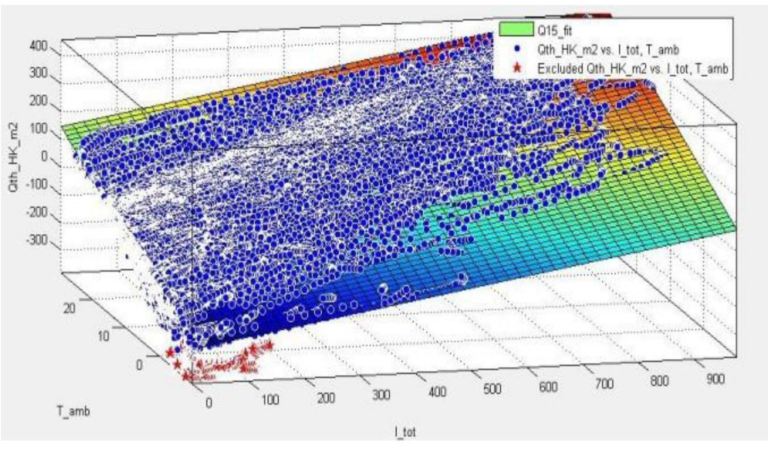

Fig. 5. Thermal collector performance dependency on irradiation, and ambient temperature

The collector operation starting point and its thermal performance are mainly dependent on the parameters solar irradiation, ambient temperature and wind speed as shown in fig. 5. The control parameters have a big influence on the system performance. E.g. a change from pump operation starting criteria of $Q_{coll} > 50$ W/m^2 to irradiation > 200 W/m^2 cause an earlier start of operation in colder months and higher collector yield, but later operation start in summer when T_{amb} can be > T_{coll} and heat gain through convection to air is possible. The collector's thermal performance is highly dependent on the collector array inlet temperature (17% higher thermal yield per 10° lower inlet temperature). The array inlet temperature depends on the heat amount that is absorbed in the building. The main difficulty in operation is to transfer a large amount of heat to the heat pump source circuit. Therefore a good control strategy and more than one heat sink in the building for enabling a high cooling performance of the PV are needed. The control criteria can be either optimized to a maximum exergetic or energetic collector yield, which is the competition between the exergetically more valuable higher temperature heat and more thermal yield at lower temperature. This system optimization can result in different operation modes in winter and summer season.

3.2. System layout

Different system layouts have been evaluated. The basic system layout is shown in fig.6. The PV/T collector acts as building system heat source in cases of solar irradiation. A heat exchanger enables the heat transfer to the heat pump source circuit, which fluid is water. The GSHE is run by water, too. Because of solar regeneration of the GSHE the temperature in the borehole never drops below 6°C, which makes brine unnecessary, see fig.7. The collector heat is used as direct heat pump source at high irradiation. In case of lower building heat demand than solar thermal yield, success heat is transferred to the GSHE to regenerate the soil. Three basic system operation modes are defined according to their priority:

1. PV/T as direct heat pump source
2. Solar ground regeneration
3. Ground as heat pump source

To optimize auxiliary energy consumption of pumps, the GSHE can be by-passed. A simple rule based control was implemented. The control runs the circulation pumps only if an exergetic profit of system input is possible.

The simulations show that the possibility of using PV/T as direct heating source without heat pump operation only exists during a few hours of a year. Therefore the additional hydraulic installations are not justified. The collector heat can be additionally used for pre-heating domestic hot water.

In January and February the collector generates useful heat amount only during a few hours at midday. In those periods the collector competes with the GSHE as exergetically more valuable heat pump source. In March and April the collector output reaches temperatures around 25° during 2-5 hours at midday so that conditions for short time ground regeneration are fulfilled. The same potential for short time regeneration exists in November. The shorter the time period between extraction and regeneration and the greater the heat extraction, the more efficient the system becomes.

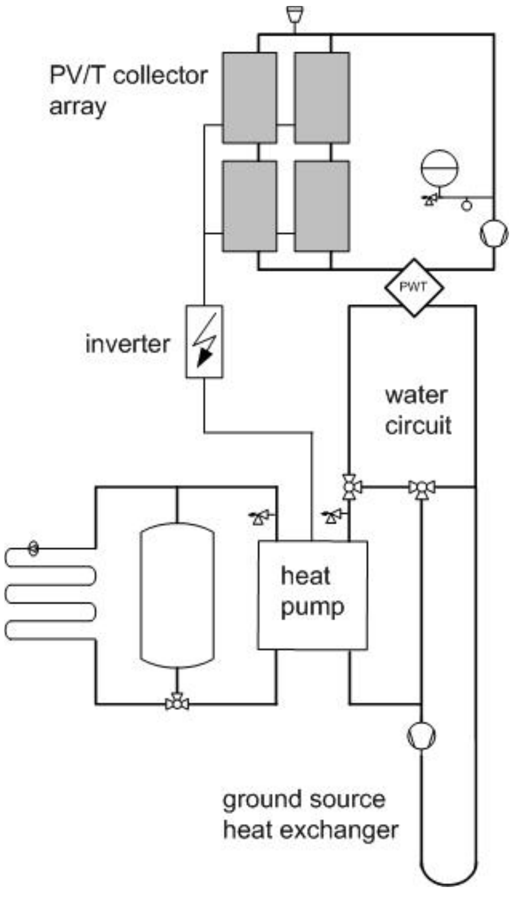

Fig. 6. Hydronic circuit layout without DHW pre-heating

3.3. System design

The stagnancy temperature below 80°C allows another system design since there's the possibility to stop the running system without causing damages to the collector or the whole installation and also no risk of evaporation of the fluid. The system can be suited to days in spring and fall and not necessarily to the most extreme day in summer. In case of stagnancy the PV/T collector reaches the same temperatures as a regular PV installation.

3.4. System results

In a first step, a heating season was simulated and resulted in a SPF_{HPv} of 7.3 and considering all auxiliary energy a SPF_{sys} of 6.0. The auxiliary energy consumption was 21% of the heat pump electricity consumption. The average GSHE temperature is 16.5°C. Fig.7 shows the GSHE outlet temperature. The heat pump source inlet temperature lies between 10.5 and 15°C, the PV/T array outlet temperature between 22 and 33°C. The electricity production of the PV/T array exceeds the total electricity use of heat pump and pumps by 32 %.

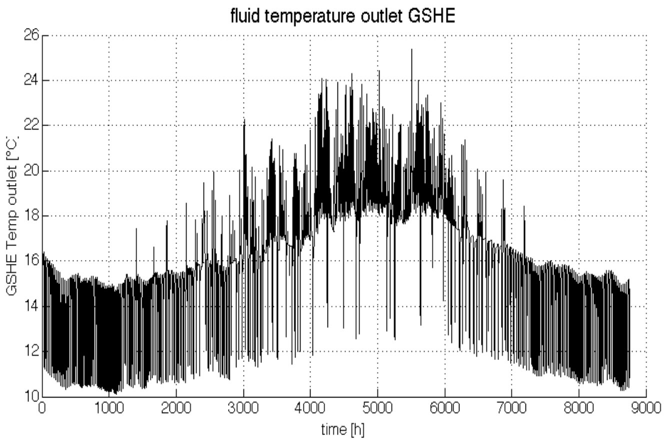

Fig. 7. GSHE outlet temperature never drop below 10°C

4. Conclusion and discussion

The concept of exergy is introduced and leads to a new system concept, which focuses on the implementation of active energy generating elements. The integration of a PV/T collector to a ground source coupled heat pump system enables low-temperature lift heat pump operating at a high efficiency. Various degrees of freedom in the design of such a system allow the realization of not only new but also retrofitting existing buildings into zero emission operation. This concept has been implemented in new and retrofitted buildings. The combination of solar low-temperature collector to GSHP leads to a new system stability, which helps to overcome following problems of designing building systems, what enables lower security factors in the dimensioning process, which finally ends in lower total investment costs:

- Ground heat transfer coefficient lambda is unknown, range between 1.5 and 3
- User behavior changes over the years and therefore the building heat demand
- Reciprocal interference of nearby GSHEs, particularly in living areas of high density
- Existing low-dimensioned GSHE, which soil temperature is decreasing and so the COP
- Lifetime of a GSHE is by factors higher than that of the heat pump

A prototype PV/T collector has been installed and tested in the LowEx building system B35 and was coupled to a novel dual-zone GSHE. The PV/T was connected to a 400 m coaxial GSHE in another recent installation. Performance test results of the PV/T collector are presented. Beside that, its implementation in simulation and resulted system characteristics are presented. The PV/T array size is designed according to the building heat demand in order to recover the entire extracted heat amount of the ground by the GSHP. Hydronic circuit layouts for the integration of PV/T collector to GSHP are discussed by the criteria of simplicity and reliability and optimized to a system operation with low total exergy input. Direct heating is not realized, since it is only possible during few hours per year in Switzerland. In other geographical regions, where high solar irradiance during heating period exists, e.g. northern China, this design option should be considered.

Following further future research and development on components contain potential and increase the effectiveness of the presented system:

1. Progress in industrialization of low-temperature lift heat pumps, which are already tested in laboratories [5]
2. Realization of seasonal thermal storage in borehole fields [5]
3. New constructions of GSHE tubes and progress in drilling technology
4. Research on short time regeneration and storage of GSHE
5. Research on new simulation models in the field of solar operated deep GSHE
6. Building integration of PV/T: function unification of building insulation, skin and energy generation

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