Performance analysis of a solar heating system coupled to a heat pump for building renovation purposes

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Abstract

The aim of this study is to analyse the energy and economic performances of different types of facilities coupling a ground/water heat pump with an air-heater equipped with solar thermal collectors. Different parameters such as the annual coefficient of performance or the power consumption were compared between various conditions. The optimization of the control and energy storage was investigated to reduce the triggering time of the air-heater.

This study was performed by dynamic simulation using TRNSYS. In the time allocated to this project, the icing of the air-heater as well as the defrost cycles could not be studied as no numerical model takes into account this phenomenon. At current energy prices, the most economical solution is the heat pump without solar thermal collectors. However, from the energy point of view, the overall annual coefficient of performance of the system could be improved by 15% to 36% depending on the climate.

Introduction

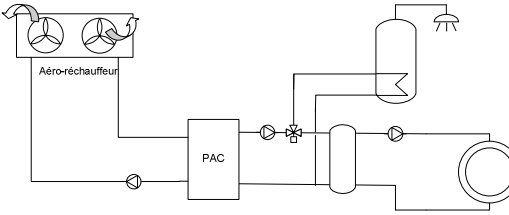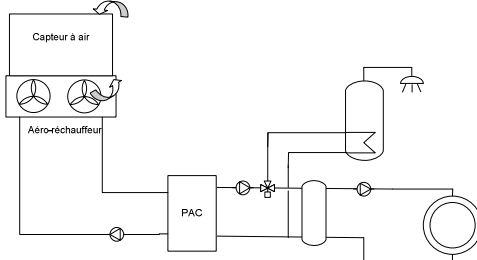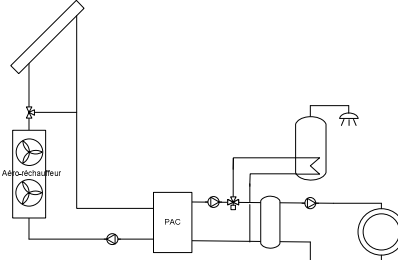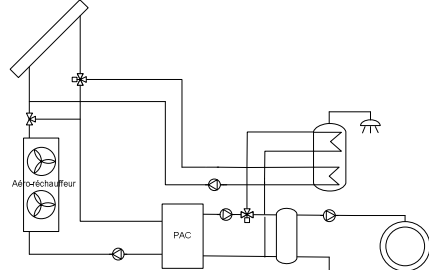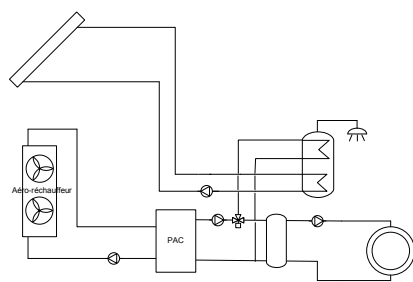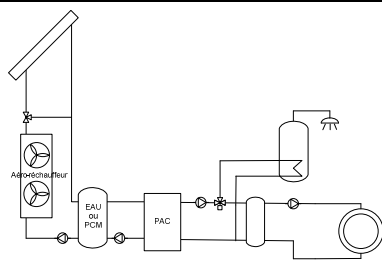Nowadays, solar installations are normally coupled with heat pumps (HP) through a hot water storage tank for space heating or domestic hot water (DHW) applications. The solar part of the installation occurs on the condenser side of the HP. Another possibility is to use solar energy on the evaporator side. While some studies present the solar collectors integrated into the evaporator circuit [1, 3], other studies have been performed with traditional thermal solar collectors connected in series with vertical borehole heat exchanger (VBHx) to recharge the heat [4]. On the other hand, it seems that the coupling of solar thermal collectors with an air-heater for a brine/water HP is not currently subject of any investigation. This type of facility could be used within the context of replacing a gas or oil boiler by a HP. Indeed, it is not always technically or financially possible to propose a ground source heat pump.

The purpose of this study is to explore the potential use of solar collectors coupled to a brine/water heat pump without geothermal probes but with an air-heater. The solar collectors are used to limit the defrost cycles and increase the evaporator inlet temperature, thereby improving the annual coefficient of performance (COPa).

Type of facilities studied

Different types of installations have been investigated either by using the solar energy on the evaporator side or a combination with a conventional system using a DHW storage tank. Table 1 shows the system schematic of the different facilities considered.
For cases S1 to S3, three different types of collectors were used: unglazed (NV), glazed flat-plate (V) and evacuated tube (TSV).

Case: **S0** No solar collector: only the air-heater provides energy to the HP. • Serves as reference to estimate the benefits of using solar collectors.	
Case: **S1-air** Air solar collectors: directly connected to the inlet of the air-heater. • simple design • less investment • simple control	
Case: **S1** Solar collectors in series with the air-heater. • simple design • less investment • simple control	
Case: **S2** • Energy management - Solar collectors used either for the HP or for DHW: • optimal use of solar collectors • increased complex control	
Case: **S2bis** Energy management – direct use of solar collectors for DHW (in summer) without going through the HP: Equivalent to S0 case but with an added solar system for DHW.	
Case: **S3** Energy storage at low temperature (15-25 [° C]) for the primary circuit: • increased performance • higher costs	

Table 1: *Schematic diagram of the different cases studied*

Simulation Parameters

For this study, TRNSYS version 16 was used. This software is commonly used to simulate space heating and air conditioning installations in buildings.

Reference Climates

Three representative types of climates have been selected for Switzerland. They allow simulating the behaviour of facilities for the Swiss plateau, Ticino canton and mountains:

- Berne
- Lugano
- Château-d'Oex

Weather data comes from METEONORM.

Reference Building

Two types of buildings have been selected to simulate the performance of technical systems with different heating requirements. They are:

- Individual house
- Administrative building

Internal or external heat gains and heat losses are taken into account by the building model.

Simple family house

The architecture of the simple family house is identical to that used during Task 32 of IEA Solar Heating and Cooling program [6]. The energy reference area (A_E) is 140 m². The windows surface, represents 25% of the south side, 10% of the east and west façade and 6% of the northern front wall. Table 2 summarizes the main elements of the building envelope.

Element	U Value [W/m²·K]
Outer wall	0.49
Floor	0.56
Roof	0.38
Window with frame	2.70

Table 2: *Summary of the U coefficients for a simple family house*

The heating demand is 14'300, 10'900 and 18'900 [kWh] for Bern, Lugano and Château d'Oex, respectively.

Administrative building

The walls are made of rubble masonry with a thickness of 60 cm. The average U-value is 1.3 [W/m²K]. The windows have double glazing insulation (U value = 1.4 W/m²K). Internal heat gains are estimated at 20 [W/m²] [8]. Table 3 summarizes the main elements of the building envelope.

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Element	U Value [W/m^2.K]
Outer wall	1.3
Floor	1.1
Roof	1.1
Window with frame	1.4 to 3

*Table 1 : Summary of the U coefficients for an administrative building*

The A_E is 911 m^2 with a heating demand of 119'600, 162'300 and 87'700 [kWh] for Bern, Lugano and Chateau d'Oex, respectively.

Profile of domestic hot water needs

The time schedule of hot water drawoff and the amount of DHW during a day are taken from [9] for the simple family house, 200 litres per day. For the administrative building, the standard SIA 380 /1 defines a quantity of 355 litres per day. The flow rate is equal to 600 litres per hour at each drawoff. The inlet temperature of the cold water is 12 [°C] and the mixed temperature is 50 [°C]. Thus, the daily energy is 8.8 [kWh] and 15.7 [kWh] for the simple family house and the administrative building, respectively.

General parameters of the simulated facilities

Figure 1 shows the main components of the facilities studied. Table 4 and Table 5 specify the parameter values used in the simulation for the simple family house and administrative building.
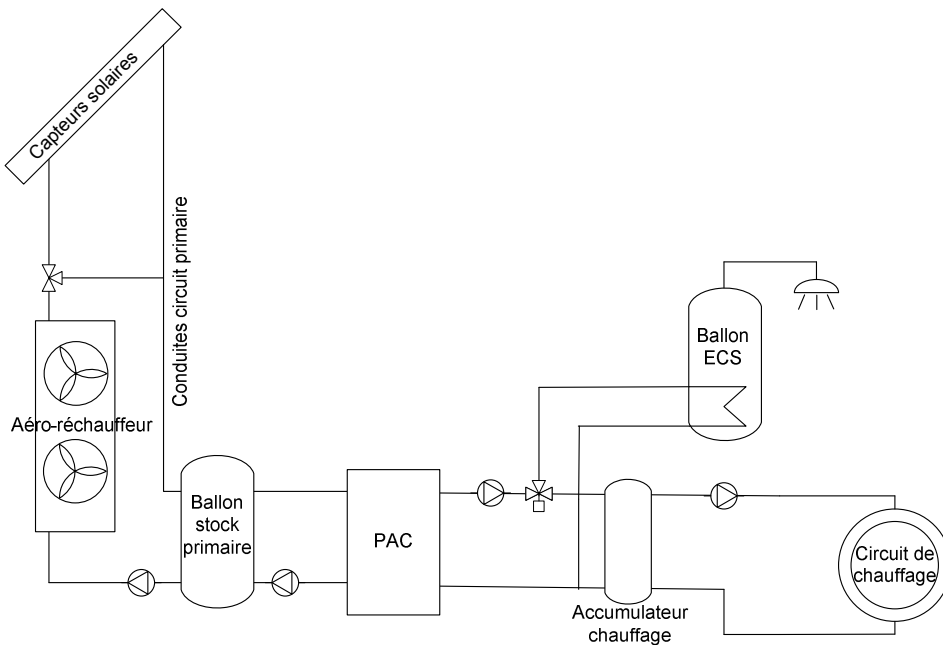
Figure 1 : Diagram of the simulated installation

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Case studies	Solar collectors	Solar piping system	Storage of the primary circuit	Storage of DHW	Heating storage [14]	Pumps
S1air	10 & 20 m^2	-	-	300 [litre]	200 [litre]	50 [W]
S1		L = 2 x 15 [m] Ø = 25 [mm] U = 2,7 [W/m^2.K]	-	300 [litre]		
S2			-	600 [litre]		
S2bis			-	600 [litre]		
S3			500 [litre]	300 [litre]		

***Table 2 :** Parameters used in the simulation of a simple family house*

Case studies	Solar collectors	Solar piping system	Storage of the primary circuit	Storage of DHW	Heating storage [14]	Pumps
S1air	50 & 100 m^2	-	-	300 [litre]	2'000 [litre]	500 [W]
S1		L = 2 x 40 [m] Ø = 52 [mm] U = 1,1 [W/m^2.K]	-	300 [litre]		
S2			-	1'200 [litre]		
S2bis			-	1'200 [litre]		
S3			5'000 [litre]	300 [litre]		

***Table 3 :** Parameters used in simulation for the administrative building*

For cases S2 and S2bis, the storage volume of DHW is more important than for the other cases. In fact, for all others there is a solar storage tank inside the DHW tank.

Heat Pump (HP)

The performance of heat pumps is provided by the WPZ (Wärmepumpen-Testzentrum) with operating temperatures ranging from -5 to 5 [°C] for the primary circuit (evaporator) and 35-50 [°C] for the condenser circuit [10] (secondary circuit). In reality, there is an important temperature range. To cover these values, a linear extrapolation of the COP was performed at temperatures ranging from -20 to 30 [°C] and +20 to +80 [°C] for the primary and the secondary circuits, respectively. This linear extrapolation is firstly performed for W35 and W50 temperatures from B-20 to B30. This is followed by another linear extrapolation for temperatures B-20 B-10, B0, B15, B30 W20 to W80. Figure 2 shows the different curves of the COP for a HP. The solid lines represent the measurements performed by WPZ. The dash lines represent the values extrapolated. It should be noticed that for temperature W80, the extrapolated COP was below 1. Being an unrealistic value, the COP was reset to 1. However, the goal of this project is to compare several systems with one type of HP and not to compare heat pumps between themselves.
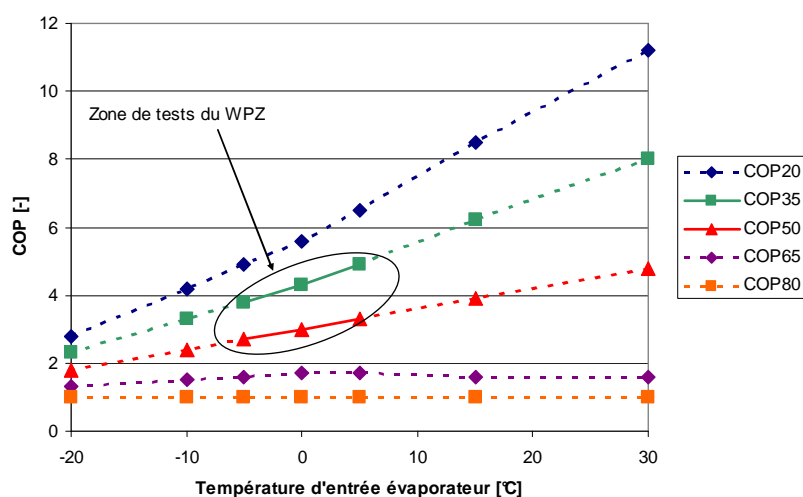
Figure 2 : *Interpolated COP for different operating temperatures for a HP*
COP20 = W20; CPO80 = W80

Air-heater

Modelling of the air-heater was made in TRNSYS using a heat exchanger with a heat exchange coefficient in W/K [11]. In this study, the defrost cycles of the air-heater have not been modelled. Indeed, there is no model in TRNSYS to simulate the complex phenomenon of icing which depends on the temperature and humidity of air. This simplification leads to a higher COP as compared to real values as the defrost cycles generates an additional consumption of energy.

Solar collectors

We took into account four different types of collectors:

- air   ($\eta_0 = 0,8$; $a_1 = 16,7$; $a_2 = 0$) [13]
- flat-plate glazed   (n° SPF C303)
- unglazed   (n° SPF C420)
- evacuated tubes   (n° SPF C815)

Definition of the annual coefficient of performance COPa

It is possible to define different annual coefficients of performance:

- $COP_{a,HP}$ (annual coefficient of performance of the HP). This coefficient is calculated only with the energy supplied by the condenser divided by the electrical energy required by the compressor.

$$COP_{a,HP} = \frac{Q_{condenser}}{W_{elect,compressor}} \qquad (1)$$

- $COP_{a,Global}$ (overall annual coefficient of performance). The calculation of this coefficient is achieved by dividing the heat required (QDHW + Qheating) by the total electricity consumption of the HP, the air-heater and individual circulators, except from the heating loop which is anyway necessary in a boiler installation.

$$COP_{a,Global} = \frac{Q_{DHW} + Q_{Heating}}{W_{elect,compressor} + W_{elect,air-heater} + W_{elect,pumps}} \qquad (2)$$
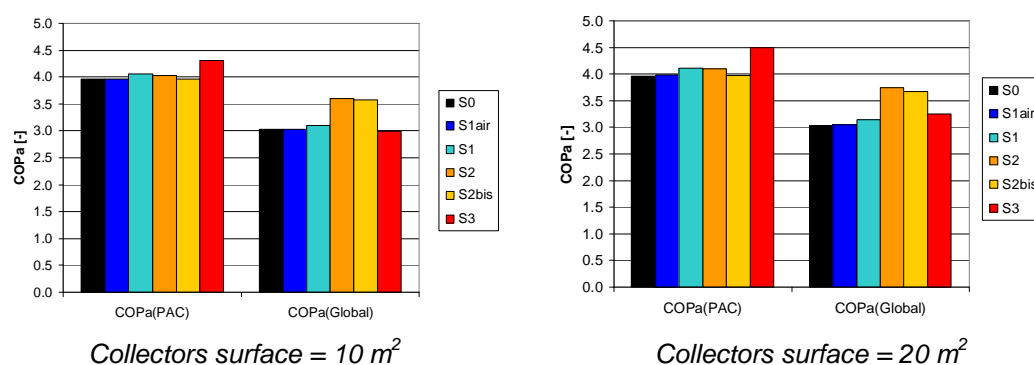
With:

$Q_{condenser}$	= thermal energy supplied by the HP for heating and DHW
$Q_{heating}$	= thermal energy for heating
Q_{DHW}	= Thermal energy for the DHW (tank losses included)
$W_{elect,\ compressor}$	= electrical energy supplied to the compressor by the HP
$W_{elect,\ air\text{-}heater}$	= electrical energy supplied to the air-heater
$W_{elect,\ pumps}$	= electrical energy supplied to pumps

Only the $COP_{a,Global}$ is representative of the performance of the facility as a whole. Its definition allows a comparison between different systems and it is directly related to the total consumption of electricity.

Energy analysis

Figures 3 shows the results of COPa for the simple family house and Bern's climate

Collectors surface = 10 m²   *Collectors surface = 20 m²*

Figure 3 : *COP for climate of Bern and the simple family house with 10 and 20 m2 of flat plate collectors (V)*

It can be seen that the gain for $COP_{a,HP}$ is small, except for case S3 which has a buffer storage tank on the primary circuit. Without the buffer storage, the solar collectors are less used because in case of sunny weather the heating demand is small. $COP_{a,Global}$ shows that the solar collectors facilities using solar directly for domestic hot water can reach a significant gain. For the other climates, similar results are obtained. For the administrative building, given the small energy demand for DHW in

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comparison with that for space heating, cases S2 and S2bis are less interesting to evaluate.

Comparison by collector type

The comparison was made for the three types of collectors considered earlier. This analysis was performed for cases S2 and S3, because the air collectors (S1air) and case S1 do not seem to have an attractive gain compared to the reference case S0. Figure 4 shows the COP for Bern and the simple family house. In the legend, "10 m^2 V" means 10 m^2 of flat plate collectors.

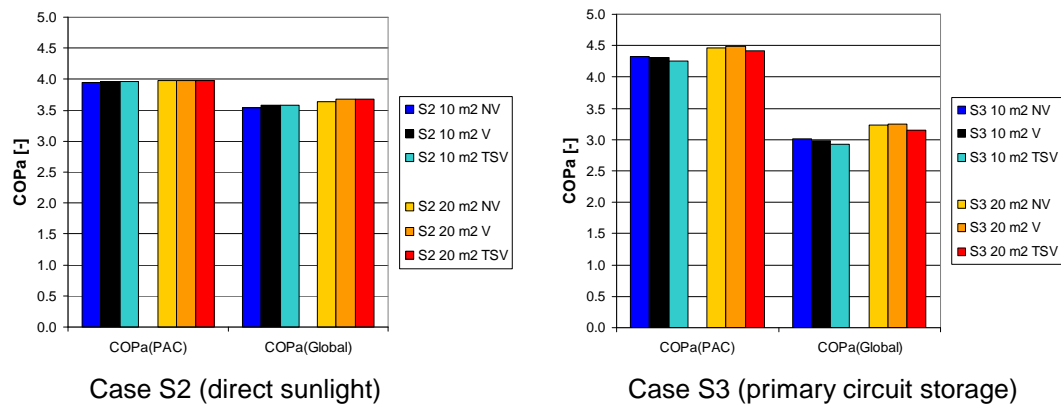Case S2 (direct sunlight)   Case S3 (primary circuit storage)

Figure 4 : COP for climate of Bern and the simple family house with 10 and 20 m^2 of flat plate collectors (V)

Despite three climates and two types of buildings, the differences between the types of collectors are similar and of the same order of magnitude. The evacuated tube collector is slightly less efficient than flat-plate collectors (glazed or unglazed). Indeed, flat-plate collectors perform well for low temperatures such as those encountered in this study.

Combining cases S2 et S3

Cases S2 + S3 allows operating directly with the solar collectors in the summer and in winter to have an energy storage on the primary circuit (Figure 5).
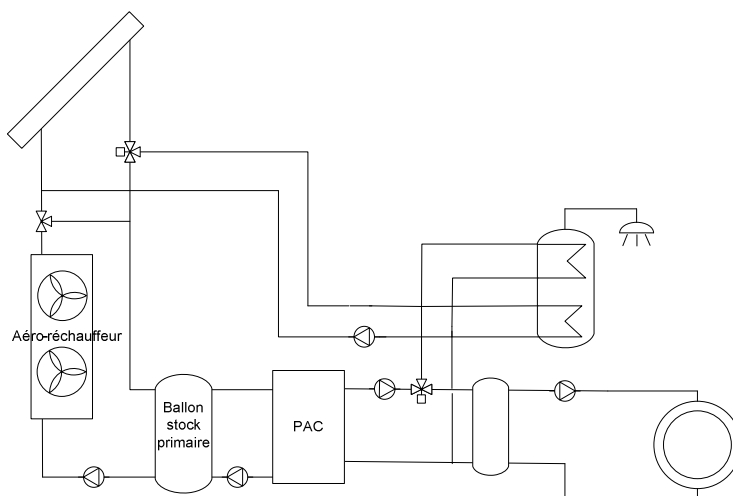

Figure 5 : Schematic diagram for S2 + S3 variant

For collector areas between 10 and 20 m^2, simulations have shown performances between those of S2 and S3 cases with a small gain for 10 m^2. In fact this surface area is not enough to provide power to the primary circuit storage and DHW tank. For small collector areas (10-20 m2), the overconsumption of the air-heater penalises S2 + S3 in comparison to S2. For larger collector areas, reducing the number of operational hours of the air-heater leads to a higher $COP_{a,Global}$ than for case S2.

Flat-plate collectors   *Unglazed collectors*
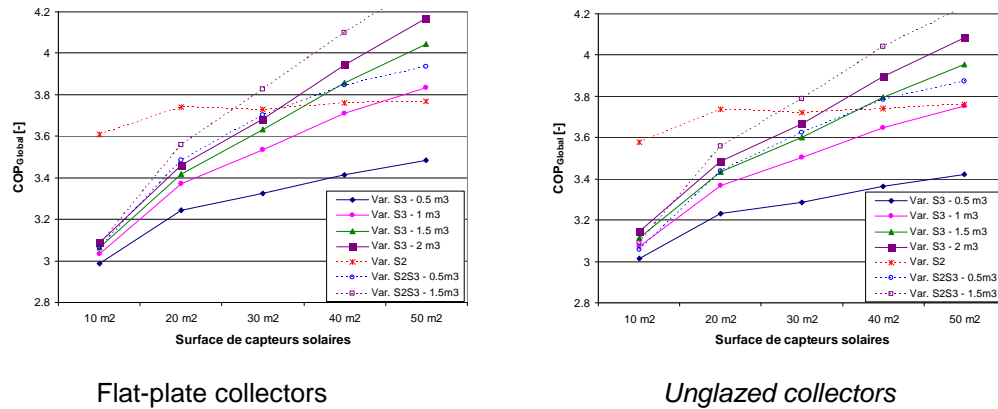
Figure 6 : *Overall evolution of the COP based on the collector's surface for different cases (climate: Bern)*

Economics

In this section, cases S1air and S1 were not taken into consideration as they appear to offer a small energy potential. Cases S0, S2, S3 and S2 + S3 were considered. For case S3, although not very efficient, it seems to offer some potential for optimization. These facilities are also compared with an oil furnace.

Costs are relative to the price lists of different suppliers [19, 22]. Since the purpose of this study is to compare different facilities for renovation purposes, it does not include capital gains due to manufacture of the chimney-flue, the fuel tank and the additional volume required for the tank and machine room. Moreover, we do not take into account the cost associated with the common parts of all facilities (e.g. heating circuit). In contrast, the operation costs (consumption and maintenance) and installation costs of solar collectors are accounted for.

It should be noted that the price of oil at the time of the study (122 CHF/100 litres - value in May 2008) had a strong influence on the annual cost, accounting for approximately two thirds of the total annual cost. So for the heat pump without solar collectors (case S0) the price related to the total power consumption is equivalent to one third. It was taken into consideration a lifespan of 15 years with a fixed interest rate of 4.87% (UBS in July 2008).

Figure 7 shows the evolution of the annual cost depending on the case used and the collector surface. The flat plate collectors are in full line while the unglazed are dashed. From the point of view of cost case S0 is the most advantageous. In this figure, the annual cost is calculated by adding the annual fees related to the initial investment, maintenance and energy consumption.

Annual cost = annual fee + maintenance + energy consumption

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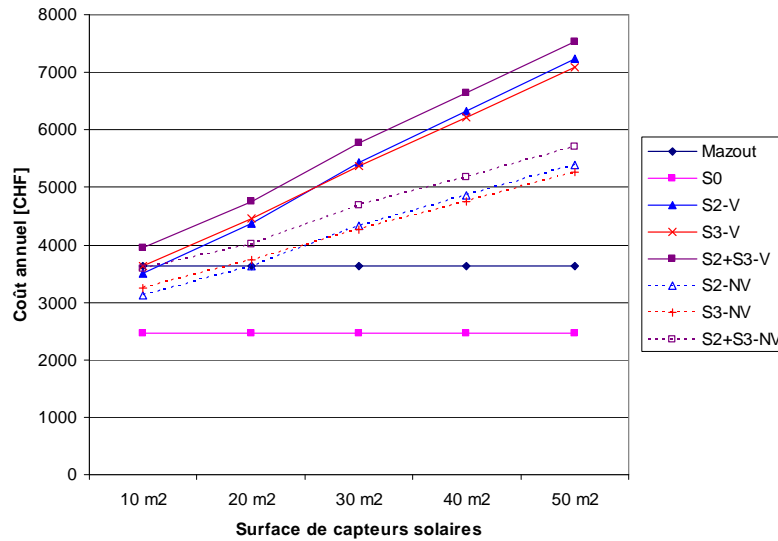
Figure 7: *Evolution of the annual cost as a function of the collector's area for different cases for the simple family house, climate: Bern. V = flat plate; NV = unglazed*

In this figure, incentive funds were not taken into account, whether related to solar or HP (Geneva). In fact, these vary from one canton to another, so it is difficult to establish a comparison for each case. Energy wise, flat plate collectors are slightly more efficient than unglazed ones. On the other hand, the lower cost of the latter leads to a more interesting annual cost than the flat-plate collectors and the vacuum tubes.

It is possible to financially analyse the price per kWh "useful" to compare the different case studies. The kWh "useful" is defined as the heating demand added to that for DHW. Tables 6 and 7 show an example of the price per kWh "useful" for case S0 (HP without solar system) and case S2 (economically more efficient with a collector area of 10 m^2) for different climates.

	Demande		Coût	Prix du
	Chauffage	ECS	annuel	kWh "utile"
	[kWh]	[kWh]	[CHF]	[CHF]
Berne - Maison individuelle	14'300	3'250	2'390	0.136
Lugano - Maison individuelle	10'900	3'250	2'200	0.155
Château-d'Oex - Maison individuelle	18'900	3'250	2'680	0.121

Table 4 : *Cost per kWh "useful" for the SO case (single family house)*

	Demande		Coût	Prix du
	Chauffage	ECS	annuel	kWh "utile"
	[kWh]	[kWh]	[CHF]	[CHF]
Berne - Maison individuelle	14'300	3'250	3'130	0.178
Lugano - Maison individuelle	10'900	3'250	2'940	0.208
Château-d'Oex - Maison individuelle	18'900	3'250	3'400	0.153

Table 5 : *Cost per kWh "useful" for case S2 with 10m2 of unglazed solar collectors (single family house)*

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Conclusion

In this study, the performances of a standard heat pump were compared with those of a HP coupled with different types of solar thermal collectors

It appears from this study that the coupling of an installation type S2 with 20 m^2 of solar thermal collectors improves overall performance compared to traditional HP (S0) by 15% for Château d'Oex's climate and 36% for Lugano's climate (COPa global).

However, these results must be used with caution, if the investment cost of the solar system is to be taken into account. Indeed, the HP without solar thermal system (S0) is financially the most profitable as the cost per kWh is the smallest. For example, with a HP (S0) for a simple family house in Bern, the kWh capacity is less than 7 cents / kWh compared to case S2 with 10 m^2 of solar thermal unglazed collectors (Tables 6 and 7).

It should also be remembered that in this study, the effect of the frosting/defrosting cycles was not included in the simulation because there is currently no model available. Therefore, it is difficult to provide an adequate comparison between all cases. However, the additional consumption of electricity by the defrost cycle represents about 10 % of the total consumption of the HP.

Finally, it must be remembered that these results are only the outcome of simulations without any experimental measurements.

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Annex

Trnsys deck diagram about S3 case