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## Numerical model of solar assisted heat pump system: validation with long term monitoring data and sensitivity analysis

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### ABSTRACT

A system combining uncovered solar collectors (116 m<sup>2</sup>) and heat pump for space heating and domestic hot water production to a new multifamily building (927 heated m<sup>2</sup>) in Geneva, Switzerland was monitored for 2 years. This paper presents a simulation model that was developed to carry out a sensitivity analysis regarding different sizing and control strategies, as well as the adaptability of the concept on existing buildings (retrofitted or not). The validation of the model with the monitored data was accomplished with good accuracy for monthly and annual values. In particular, the  $SPF_{System}$  simulated of 3.1 is similar to the monitored value of 3.0. The sensitivity analysis shows that the replacement of a non-inverter by an inverter heat pump would decrease the electricity demand by a factor of 0.8 and increase the  $SPF_{System}$  to 3.8. As for the implementation of this concept in an existing retrofitted building (demand 1.5 times higher than the monitored building), without resizing the system, an increase of the annual electricity consumption by a factor of 1.6 is observed. If all system components are resized, the annual electricity consumption would increase by a factor of 1.5. When implementing this concept in existing non retrofitted buildings (demand 2.1 times higher than the monitored building) with all system components resized, an annual electricity consumption 2.2 times higher is observed. The system resizing may not be viable due to lack of space in the roof for the needed solar collector's area and the financial investment may not be affordable.

**KEYWORDS:** Solar driven heat pump; numerical simulation; system sensitivity analysis;

### 1 INTRODUCTION

In Switzerland, thermal energy – mainly devoted to space heating and domestic hot water production – accounts for 50% of the overall energy needs. Heat pumps could play an important role in the future energy scenarios, by the valorization of low temperature heat sources. Up to now, air, geothermal boreholes or aquifers were commonly used as heat sources, but for several years, alternative heat sources such as solar collectors or industrial waste heat are being investigated, aiming to improve the efficiency of the systems.

A specific IEA Task, namely IEA SHC Task 44 / HPP Annex 38 [1], is in charge of studying the coupling between heat pumps and solar collectors. Different authors [2-7] monitored such systems in individual housing with different configurations (with glazed or unglazed collectors, geothermal boreholes, ice storage, seasonal storage...). They reported SPF's varying widely, between 2.8 and 6. The potential of developing solar heat pumps systems for collective housing is important, but has not been investigated widely. Also, the performance of the system is expected to vary widely according to the type of building (new, retrofitted or non-retrofitted). The University of Geneva carried out a research project [8] that monitored the real performance of a solar driven heat pump system implemented in a new collective housing complex.

This paper presents the numerical model of the monitored system and the results of different simulations that were carried out.

### 2 SYSTEM DESCRIPTION

#### Research Project

The results presented here are part of a research project [8] which aims to assess the concept of coupling solar thermal collectors and heat pumps for domestic hot water (DHW) and space heating (SH) production in collective housing. The two main parts of the project are: 1. assess the actual operation and efficiency of an existing system implemented in a housing complex; 2. extrapolate the experimental results in different conditions (such as different sizing, different building – in particular retrofit – or different control strategy) by numerical simulation. The final goals are:

- Evaluate the relevance of this concept in a technical, energy and economical point of view, in order to identify its potential of standardization;
- Identify the opportunities and obstacles that may appear when applying this system in existing buildings with low quality envelope or in retrofit;
- Compare this system with other market possibilities, such as heat pumps coupled with geothermal boreholes.

This article presents the second part of the work, i.e. the extrapolation of the experimental results in different conditions via numerical simulation.

#### Case Study

A system coupling solar and heat pumps was implemented in a new housing complex, called SolarCity, located in Geneva (Switzerland) which was commissioned in autumn 2010. The complex is composed of 4 buildings, each divided into 2 or 3 blocks

of 8 flats (total of 10 blocks). The buildings present a high thermal performance envelope (Minergie standard<sup>1</sup>) and a total living surface of 9'552 m<sup>2</sup>. The monitored block has 927 m<sup>2</sup> and a total of 32 inhabitants.

The energy concept consists of a heat pump (HP) directly coupled to unglazed solar collectors as its heat source. The components of the system (Fig. 1) are: a 30 kW<sub>th</sub> heat pump; 116 m<sup>2</sup> of unglazed and non-insulated solar collectors; 2 x 3'000 L of water for centralized heat storage with an electric rod in the storage tank in case of heat pump failure. A specificity of the system consists in a single tube distribution circuit to the flats, so that SH (underfloor heating) and DHW are supplied alternatively. Each flat is equipped with a 300 L DHW tank. DHW distribution has priority over SH distribution.

The solar collectors can be used for direct solar heat production, via a heat exchanger, but are also the heat source of the heat pump (they are directly connected to the evaporator, without storage or geothermal boreholes). Hence, when there is no solar radiation, the collectors work as a heat absorber on ambient air. Whether by direct solar heat production or via the HP, the produced heat is used for SH (underfloor heating) or DHW (heat distribution to charge the individual 300 L tanks), and the surplus is stored in the centralized heat storage for future use.

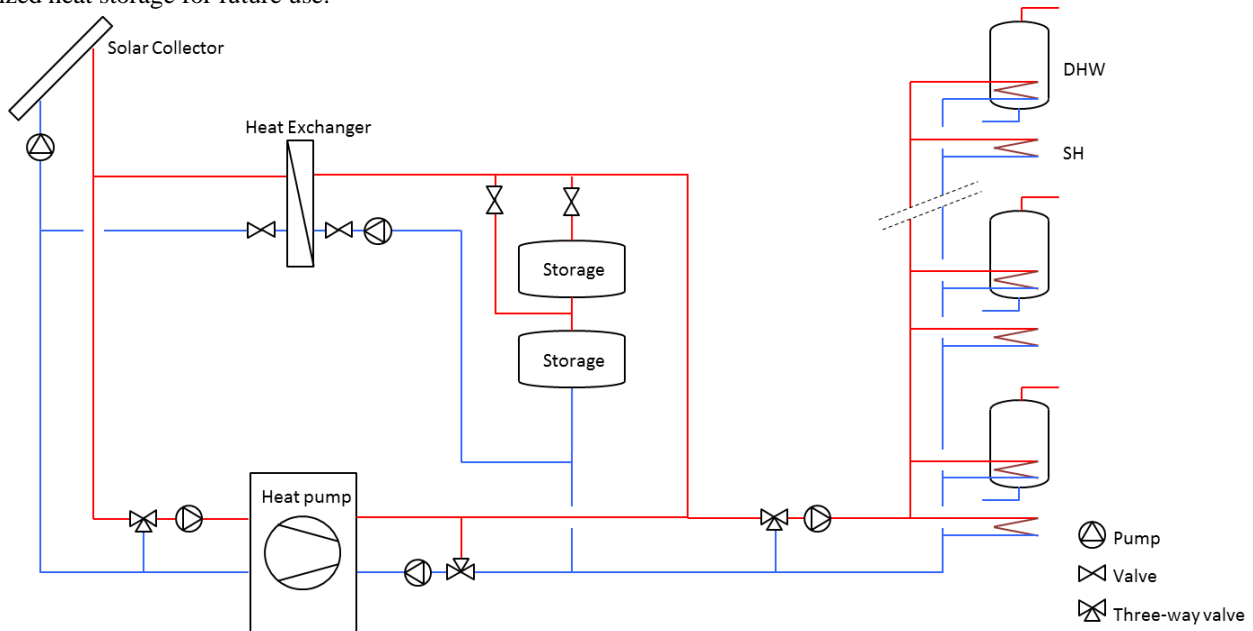


Fig. 1: Hydraulic diagram of the system.

The system has 4 main operating modes, with the following priorities: (i) Direct solar heat production for SH or DHW (bypassing the heat pump), the surplus being used to charge the heat storage; (ii) Storage discharge, which is activated when the solar production does not reach the required distribution temperature; (iii) Activation of the heat pump when the storage temperature is below the required distribution temperature, with surplus production used to charge the heat storage; (iv) Direct electric heating, which is activated in case of HP failure (in particular when the evaporator temperature drops below -15°C).

## Monitoring Results

The monitoring campaign covered 2 years of operation (November 2011-October 2013) and allowed to quantify the energy flows of the system: solar production (direct and to evaporator); heat pump production; heat storage (charge and discharge); electricity consumption (solar circuit, heat pump and backup); heat demand of the building (SH and DHW). The results obtained during winter 2012 are widely described in [9], the summer 2012 results in [10] and the 2012 annual results in [8]. The main results over the entire year 2012 are reminded below.

The SH demand is 19.1 kWh/m<sup>2</sup> and the DHW demand is 47.7 kWh/m<sup>2</sup>. Of the overall heat consumption (68.1 kWh/m<sup>2</sup>), 73% is supplied in winter (Oct-Apr) and 27% in summer (May-Sep).

Direct solar heat production (bypassing the HP) accounts for 19% of the total input energy (7% in winter and 49% in summer). This result is not surprising for winter but a better value was expected for DHW production in summer, due to the large solar collector area (3.6 m<sup>2</sup> and 190 L heat storage per person, as compared to standard design values of 0.5-1 m<sup>2</sup> and 40-50 L heat storage per person).

As a complement to direct solar heat production, the HP accounts for 80% of the total production. The annual SPF<sub>HP</sub> is 2.7, with only slight variations during the year (2.5 to 3), even in summer. Indeed, during this period, the HP only works for DHW production at around 60°C, i.e. in bad temperature conditions. Finally, electric heating in case of HP failure (if evaporator input temperature is too low) was mainly activated in February 2012, during the unusual cold period experienced in Europe. It represents 1% of the total energy input and less than 5% of the total electricity consumption.

As can be noticed, the thermal storage plays an important role, since 37% of the supplied heat goes through it. The associated heat losses amount to 14% of the storage input energy (6% of the total system energy input).

As an overall result, the renewable heat fraction corresponds to 68% of the total energy input. The complementary electricity consumption (32%) leads to an annual SPF<sub>System</sub> of 2.9 (with a wide variation over the year, from 2.2 during cold periods to 8.6 in

<sup>1</sup> <http://www.minergie.ch/> see "The MINERGIE-Standard for Buildings"

August, when an important share of direct solar heat production for DHW is possible). Due to the low total heat demand, the 23.8 kWh/m<sup>2</sup>/yr of electricity consumption represent a relatively low value.

### 3 DESCRIPTION OF THE NUMERICAL MODEL

#### Defenitions

The modeled energy flows are represented in Fig. 2.

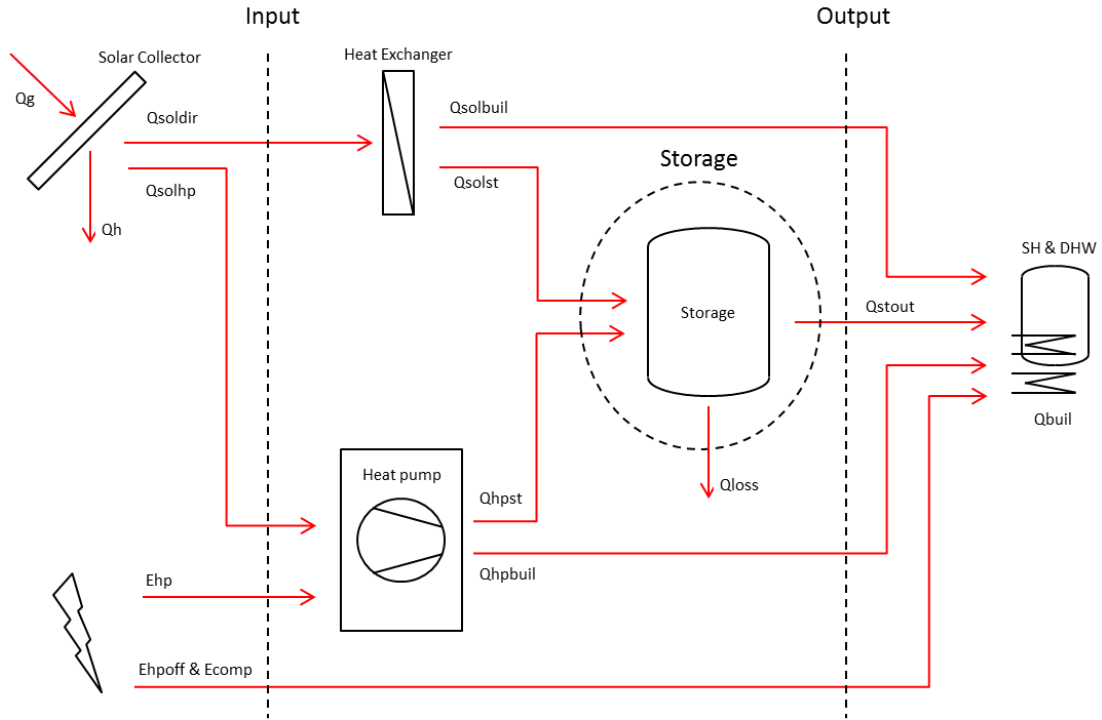


Fig. 2: Energy flows diagram of the modeled system.

The system input energy flows are: the energy absorbed by the solar collectors  $Q_g$ ; the solar collectors heat losses  $Q_h$ ; the solar collectors heat production  $Q_{sol}$  that is divided into 2 flows, the direct solar heat production  $Q_{sol\_dir}$  and the HP heat source energy flow  $Q_{sol\_hp}$ ; the HP electricity consumption  $E_{hp}$ ; the direct electric heating  $E_{dir}$  that can be due to periods of non-operation of the HP  $E_{hpoff}$  (because of low temperatures in the evaporator) or be a complement  $E_{comp}$  in case HP production does not cover the building heat demand.

Between input and output, the energy flows are: after the solar collectors heat exchanger  $Q_{sol\_dir}$  is divided into two flows, the heat that is directly delivered to the building  $Q_{sol\_buil}$  and heat that is stored for future use  $Q_{sol\_st}$ ; the HP production  $Q_{hp}$  is also divided in two, a flow that is delivered directly to the building  $Q_{hp\_buil}$  and another of surplus heat that is delivered to the storage  $Q_{hpst}$ . The system output energy flow is the building heat demand  $Q_{buil}$  that is covered by:  $Q_{sol\_buil}$ ; storage output  $Q_{stout}$ ;  $Q_{hp\_buil}$  and  $E_{dir}$ . As for the storage, the difference between input and output heat is defined as storage losses  $Q_{loss}$ .

The performance of the system is characterized as follows:

$$SPF_{HP} = \frac{Q_{hp}}{E_{hp}} \quad (\text{in annual values}) \quad (1)$$

$$SPF_{System} = \frac{Q_{buil}}{E_{hp} + E_{dir}} \quad (\text{in annual values}) \quad (2)$$

Where

$Q_{hp}$  : annual HP heat production [kWh/yr]

$E_{hp}$  : annual HP electricity consumption [kWh/yr]

$Q_{buil}$  : annual building heat demand [kWh/yr]

$E_{dir}$  : annual direct electric heating ( $E_{hpoff} + E_{comp}$ ) [kWh/yr]

NB: While  $SPF_{HP}$  only considers HP production the  $SPF_{System}$  considers HP production plus direct solar heat production.

#### Model of the System Components

##### Solar Collectors

The thermal balance of the solar collectors field, taking into account the wind effect, is as follows:

$$Q_{sol} = Q_g - Q_h \quad (3)$$

$$Q_g = \eta_0 \cdot G \cdot A_{sol} \quad (4)$$

$$Q_h = h_{sol} \cdot (T_{sol} - T_{ext}) \cdot A_{sol} \quad (5)$$

$$h_{sol} = (h_0 + h_v \cdot v) \quad (6)$$

Where

$Q_{sol}$  : global solar collectors heat production [W]

$Q_g$  : solar energy absorbed by the collectors [W]

$Q_h$  : solar collectors heat losses [W]

$A_{sol}$  : solar collector area [m<sup>2</sup>]

$\eta_0$  : optic efficiency

$G$  : solar irradiance in the collectors plane [W/m<sup>2</sup>]

$T_{sol}$  : solar collectors temperature [°C]

$T_{ext}$  : ambient temperature [°C]

$h_{sol}$  : solar collectors loss factor [W/K.m<sup>2</sup>]

$h_0$  : loss coefficient without wind [W/K.m<sup>2</sup>]

$h_v$  : loss coefficient proportional to the wind speed [W/K.m<sup>2</sup> per m/s]

$v$  : wind speed [m/s]

The solar collectors have the following characteristics (given by the monitoring results):

$A_{sol}$  : 116 m<sup>2</sup>

$\eta_0$  : 0.926

$h_0$  : 11.3 W/K.m<sup>2</sup>

$h_v$  : 2.47 W/K.m<sup>2</sup> per (m/s)

It has to be noted that the model does not take into account the following effects: ice or condensation on the solar collectors; heat capacity; infrared losses; connection of the solar collectors in a collector field.

#### Heat pump

The heat pump is modeled by an input/output table based on the heat pump working temperatures, as given by the manufacturer:

$$Q_{cond} = f(T_{EvapIn}; T_{CondOut}) : \text{data from manufacturer} \quad (7)$$

$$E_{hp} = f(T_{EvapIn}; T_{CondOut}) : \text{data from manufacturer} \quad (8)$$

$$Q_{evap} = Q_{cond} - E_{hp} \quad (9)$$

$$COP = \frac{Q_{cond}}{E_{hp}} \quad (10)$$

Where

$Q_{cond}$  : heat pump condenser output heat [W]

$Q_{evap}$  : heat pump evaporator input heat [W]

$E_{hp}$  : heat pump electricity consumption [W]

$T_{CondOut}$  : condenser output temperature [°C]

$T_{EvapIn}$  : evaporator input temperature [°C]

The working temperature of the evaporator is given by the solar collectors and the condenser working temperature by the building's heat demand. The three way valves in either side of the heat pump (see Fig. 1) were modeled by simple conditions. For the evaporator the valve limits the maximum temperature to 20°C (minimum value between the solar collectors temperature and 20°C). For the condenser the valve limits the minimum temperature to 30°C (maximum value between the building's demand temperature and 30 °C). The heat pump is non-operational when  $T_{EvapIn}$  is below -15°C (value given by the manufacturer).

#### Storage

The storage is composed by two tanks, one for high temperatures (mainly to store the HP surplus heat production) and the other for medium temperatures (mainly to store the solar collectors heat production). The two tanks have a parallel connection with the following control strategy: i) in case of excess heat storage from the HP or directly from the solar collectors, if the temperature is adequate the priority is given to the hot tank; ii) in case of storage output, if the temperature is adequate, the priority is given to the tepid tank. Both tanks are modeled by a one node model:

$$Q_{StIn} - Q_{StOut} - Q_{loss} = \frac{C_{St}}{dt} \cdot (T_{St} - T_{St-1}) \quad (11)$$

$$Q_{loss} = H_{St} \cdot (T_{St-1} - T_{TR}) \quad (12)$$

Where

$Q_{StIn}$  : input storage heat [W]

$Q_{StOut}$  : output storage heat [W]

$Q_{loss}$  : storage heat losses [W]

$C_{St}$  : effective heat capacity of the storage [Wh/K.m<sup>2</sup>]

$dt$  : time step [h]

$T_{St}$  : temperature of the storage [°C]

$T_{St-1}$  : temperature of the storage at the previous time step [°C]

$H_{St}$  : effective heat loss coefficient of the storage [W/K]

$T_{TR}$  : temperature of the technical room [°C]

The storage has the following characteristics (given by the monitoring results):

$C_{St}$  : 2.68 kWh/K per tank

$H_{St}$  : 11.33 W/K per tank

For the rest, the following simplifications were made: (i): backup electric heating ( $E_{comp}$ ) covers the instantaneous difference between demand and production (unlike in the real system, where the backup is integrated in the heat storage); (ii) in the case of direct solar production, the temperature drop due to the heat exchanger is disregarded; (iii) ancillary electricity for circulation pumps is not taken into account.

#### Weather Data and Heat Demand

Input to the model is given by nearby monitored meteorological data for 2012 (global horizontal solar irradiation, temperature and wind speed), in hourly values.

For the sake of sensitivity analysis concerning the building heat demand, latter is modelled in hourly time step, taking into account the alternate DHW and SH production. For DHW, the load profile is given by the monitored data, and is adjusted (multiplication factor) so that the integral of the load corresponds to the annual DHW demand. For SH (when DHW is off), the hourly heat load is given by a linear heat demand curve as a function of the outdoor temperature, with a set point of 15°C (above which SH is off) and a nominal heat load at 0°C. The latter is adjusted so that the integral of the load corresponds to the annual SH demand.

#### Overall System and Algorithm

At the level of the overall system, the model considers separately each of the operating modes (by order of priority: direct solar production, storage discharge, heat pump production, electrical backup).

For each of these modes, the energy balance of the system and of the involved components is resolved as a function of weather and building demand. This allows in particular to determine the temperature of the solar collector field. Conformingly to the order of priority, the appropriate operation mode is selected according to the temperature levels of the solar collector, the storage and the demand.

The algorithm is implemented in TRNSYS with use of Type42 as the input/output model of the heat pump and explicit equations for the modelling of all the other components. The simulation is done in hourly time step for a complete year.

#### 4 VALIDATION

In order to validate the model, simulation results were compared to the monitoring results for 2012. The energy flows from simulation and monitoring are compared at three different levels: system inputs; system outputs and storage (see Fig. 2). Both monthly and yearly results are presented in Fig. 3.

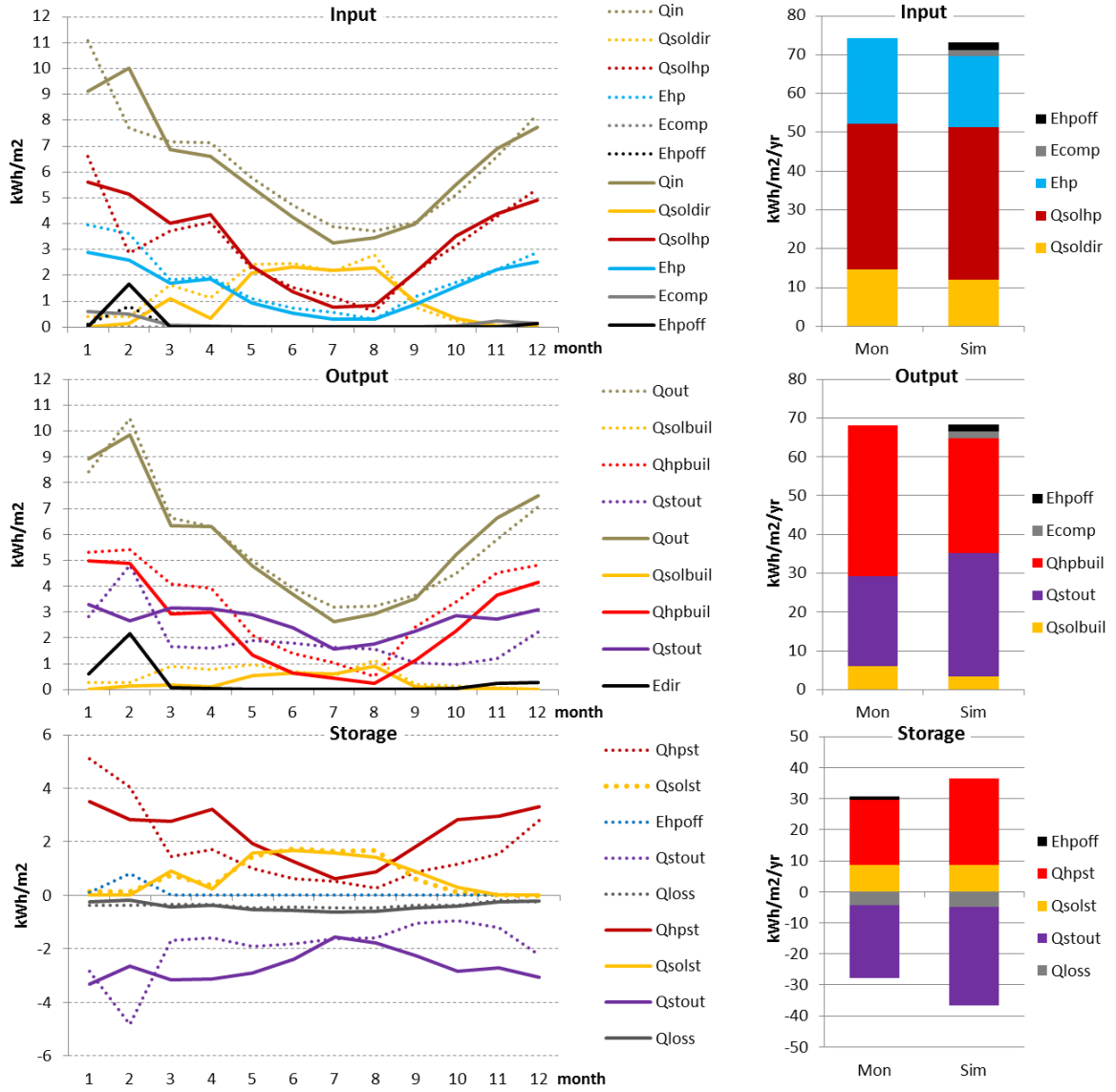


Fig. 3: Left - monthly evolution of the system energy flows: monitored data (dotted line) and simulated (solid line). Right - yearly system energy flows: monitored data (Mon) and simulated (Sim).

As it can be seen in Fig. 3, the simulation reproduces appropriately the monitored energy flows at an annual and monthly level. For the input energy flows we have:  $Q_{solldir}$  simulated is slightly below the monitored value as well as  $Q_{solhp}$  and  $E_{hp}$ , especially in winter months. February is an exception because of a failure in the heat flow meter while the monitoring took place.  $E_{hpoff}$ , only used in February, was well reproduced. However,  $Q_{hp}$  is not always enough to cover the building demand in winter therefore  $E_{comp}$  is used to overcome that difference. In the monitored values this gap also exists but is overcome by storage output (as explained at the end of section “Model of the System Components”). Finally the total input energy flows  $Q_{in}$  simulated are very close to the monitored value, with a difference of less than 3%.

For the output energy flows we have:  $Q_{solbuil}$  simulated is close to the monitored value in summer months. From Mars to May it is not the same because of the difference in the building demand (simulation demand that was modeled has a different day/night dynamics). This results in a higher use of the storage;  $Q_{hpbuil}$  simulated is constantly inferior to the monitored value. This difference results in a higher share of  $Q_{hpst}$  which means that along the year  $Q_{stout}$  simulated is higher than the monitored. Finally, the total output energy  $Q_{out}$  is an exact match because of how the heat demand is defined (see section “weather data and heat demand”). For the storage, apart from the higher share of  $Q_{hpst}$  that leads to a higher  $Q_{stout}$  (mentioned above),  $Q_{solst}$  and  $Q_{loss}$  are both well reproduced.

The simulation total electric consumption of 21.8 kWh/m<sup>2</sup>/yr is close to the 23.0 kWh/m<sup>2</sup>/yr measured in situ. Likewise the  $SPF_{System}$  simulated of 3.1 is close to the measured value of 3.0.

From this comparison the model is considered to be validated. This specific simulation, called from now on SolarCity, will be used as the base simulation in the following analysis.

## 5 SENSITIVITY ANALYSIS

### Sensitivity to Technical Parameters

For this sensitivity analysis, two technical parameters were chosen through the analysis of the monitored data.

The monitoring results show an unusual low share of direct solar heat production in summer (49%). Even if the solar collectors in SolarCity are unglazed and non-insulated, a higher share was expected because in a previous study [11], with the same sizing, the same collectors reached 90%. The main difference between these two solar collectors field is the insulation on the rear face of the collectors. Therefore a simulation of the SolarCity system was carried out with the solar collectors characteristics given by the study [11], that are:  $\eta_0 = 0.9$ ,  $h_0 = 9.7 \text{ W/K.m}^2$ ,  $h_v = 1.8 \text{ W/K.m}^2 \text{ per m/s}$ .

The monitored data also showed a regular overproduction of the HP at DHW mode (high temperature cycles), that was therefore stored. This high temperature surplus heat is then used for SH (low temperature). This leads to a possible degradation of both SPF<sub>s</sub> because the HP mostly works in high temperature cycles. Therefore a simulation of SolarCity with an inverter HP was carried out, to analyze how a HP that produces the exact match of the heat demand would affect the system. The inverter HP model is  $Q_{cond} = Q_{buil}$ , with the same COP given by the manufacturer for the required  $T_{evap}$  and  $T_{cond}$ . Note that no degradation of the COP was taken into account.

Results of both these simulations are presented in Fig. 4.

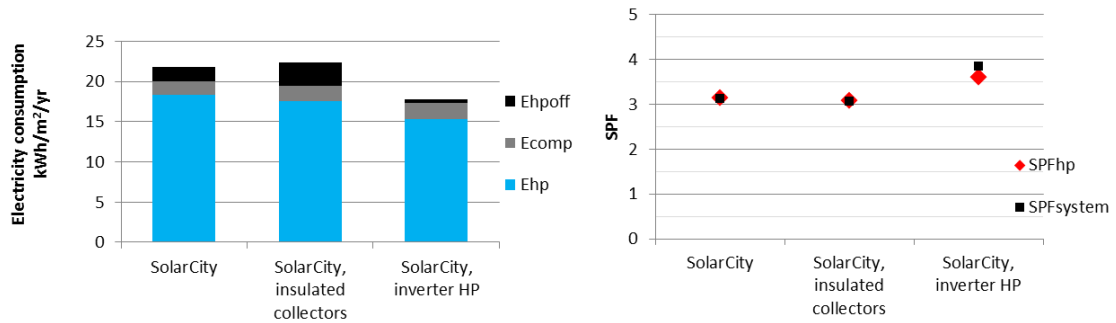


Fig. 4: System sensitivity to technical parameters. Left – annual electricity consumption. Right – SPF<sub>HP</sub> and SPF<sub>System</sub>.

As seen in Fig. 4, the insulation of the solar collectors rear face does not improve the system. In fact, the reduction of the solar collectors loss coefficients due to the insulation leads to higher temperatures in the solar collectors in summer but lower temperatures in winter. Therefore, the higher share of direct solar heat production obtained in summer is counterbalanced, in winter, by an increase of non-operation HP periods (low evaporator temperatures) that increase the direct electricity consumption  $E_{hpoff}$ . As for the inverter HP, the variable capacity leads to a decrease in the overall electricity consumption (17.7 kWh/m²/yr) because the HP heat production at 60°C for DHW demand is without surplus heat, which leads to a HP heat production at ~30°C for SH demand (better SPF<sub>HP</sub>). Also, due to less storage of high temperature heat (no surplus heat production from the HP) the storage remains at temperature levels that allow direct solar heat storage which than is used to cover the building demand. This explains the difference between the SPF<sub>HP</sub> of 3.6 and the SPF<sub>System</sub> of 3.8.

### Sensitivity to Heat Demand

The concept has been tested with other heat demands from existing buildings. The heat demand used for the simulation comes from the analysis of two buildings from the 60's [12]. One is retrofitted according to Minergie Standards while the other has suffered no major refurbishments. A climatic correction was applied to fit the demands with 2012 weather conditions.

The heat demand of the retrofitted building is 1.5 times the demand of SolarCity and the non-retrofitted 2.1. Since these buildings are from the 60's (heat distribution by radiators) the heat demand temperature for SH was modeled according to their heating curve. Both temperature and heat demands are given in Tab. 1.

For both heat demands a simulation was made in the following conditions (see also Tab. 1):

- Same configuration and sizing as SolarCity;
- HP resized according to the total annual demand (factor 1.5 for retrofitted and 2.1 for non- retrofitted building);
- HP and solar collector field resized according to the total annual demand (factor 1.5 for retrofitted and 2.1 for non- retrofitted building);
- HP, solar collector field and storage resized according to the total annual demand (factor 1.5 for retrofitted and 2.1 for non- retrofitted building);

Tab. 1: Simulations hypothesis for heat demand and system components sizing

	Demand								System		
	$Q_{buil}$ kWh/m²	$Q_{DHW}$	$P_{max,DHW}$ W/m²	$P_{max,SH}$ W/m²	$P_{SH,0}$ W/m²	$T_{nSH}$ °C	$T_{SH,0°C}$ °C	$T_{SH,15°C}$ °C	$P_{HP}$ W/m²	$A_{sol}$ m²/m²	$V_{storage}$ Wh/m²
SolarCity	68.3	70%	46.4	14.0	8.5	15	30	28	37.6	0.13	5.78
Retrofitted	102.1	28%	30.2	45.3	27.6	17	50	30	37.6	0.13	5.78
Retrofitted / Resize HP	102.1	28%	30.2	45.3	27.6	17	50	30	56.5	0.13	5.78
Retrofitted / Resize HP & Asol	102.1	28%	30.2	45.3	27.6	17	50	30	56.5	0.19	5.78
Retrofitted / Resize HP, Asol & storage	102.1	28%	30.2	45.3	27.6	17	50	30	56.5	0.19	8.67
Non-retrofitted / Resize HP, Asol & storage	145.9	19%	30.2	70.1	44.0	17	50	30	79.1	0.26	12.1



Where:

$Q_{\text{buil}}$  : Building total heat demand (DHW+SH) [kWh/m<sup>2</sup>]

$Q_{\text{DHW}}$  : DHW heat demand

$P_{\text{max,DHW}}$  : maximum DHW load [W/m<sup>2</sup>]

$P_{\text{max,SH}}$  : maximum SH load [W/m<sup>2</sup>]

$P_{\text{SH},0}$  : SH load at 0°C outdoor temperature [W/m<sup>2</sup>]

$T_{\text{nSH}}$  : Non SH outdoor temperature [°C]

$T_{\text{SH},0^\circ\text{C}}$  : SH distribution temperature at 0°C outdoor temperature [°C]

$T_{\text{SH},15^\circ\text{C}}$  : SH distribution temperature at 15°C outdoor temperature [°C]

$P_{\text{HP}}$  : HP power (at 0/35°C working temperatures) [W/m<sup>2</sup>]

$A_{\text{sol}}$  : solar area [solar m<sup>2</sup>/ heated m<sup>2</sup>]

$V_{\text{storage}}$  : Storage volume [Wh/m<sup>2</sup>]

The retrofitted building results are shown in Fig. 5.

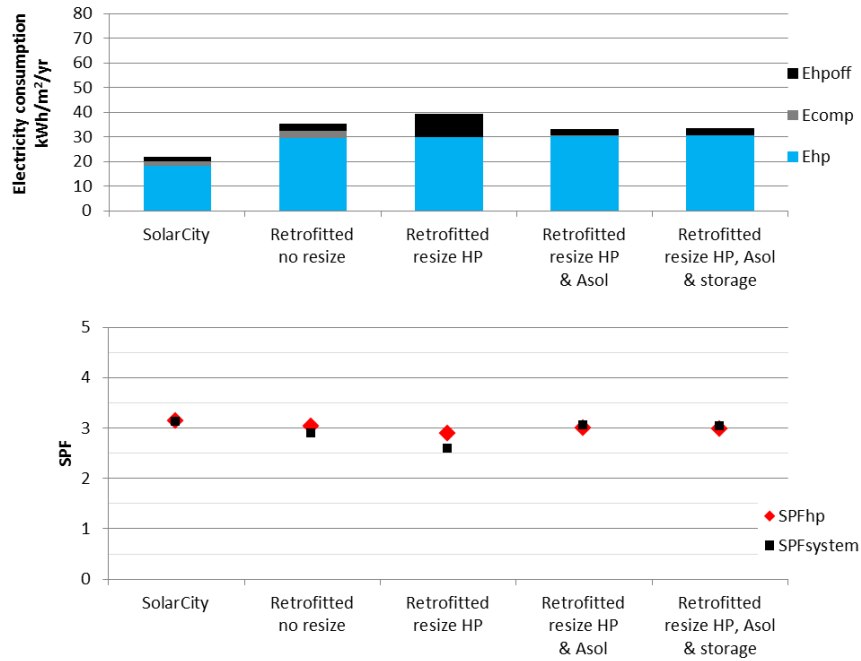


Fig. 5: System sensitivity to heat demand (new and retrofitted building) and resizing of system components. Top – Electricity consumption; Bottom –  $\text{SPF}_{\text{HP}}$  and  $\text{SPF}_{\text{System}}$ .

Fig. 5 shows that without resizing the heating system, the electricity demand increases by the same factor as the total heat demand (1.5) and the  $\text{SPF}_{\text{System}}$  remains the same. When resizing only the HP, since the solar collectors surface is not adjusted, the evaporator temperature reaches non operation conditions more often, which leads to an increase in the electricity consumption by a factor of 1.8 and the  $\text{SPF}_{\text{System}}$  drops to 2.6. With HP and solar collectors resizing the electricity consumption stabilizes at 33.4 kWh/m<sup>2</sup>/yr with a  $\text{SPF}_{\text{System}}$  of 3.1. The resizing of the storage has no effect in the overall electricity consumption nor in the  $\text{SPF}_{\text{System}}$ . Finally, even with a heat demand 1.5 times higher than SolarCity, there is a low sensitivity to the system component resizing. This is explained by the peak loads. While in SolarCity the peak load is during DHW production (SH load is lower), in the retrofitted building the peak load is during SH production. However,  $P_{\text{max,SH}}$  of the retrofitted building is similar to  $P_{\text{max,DHW}}$  of SolarCity, therefore resizing the system is not necessary.

The non-retrofitted building results are shown in Fig. 6.

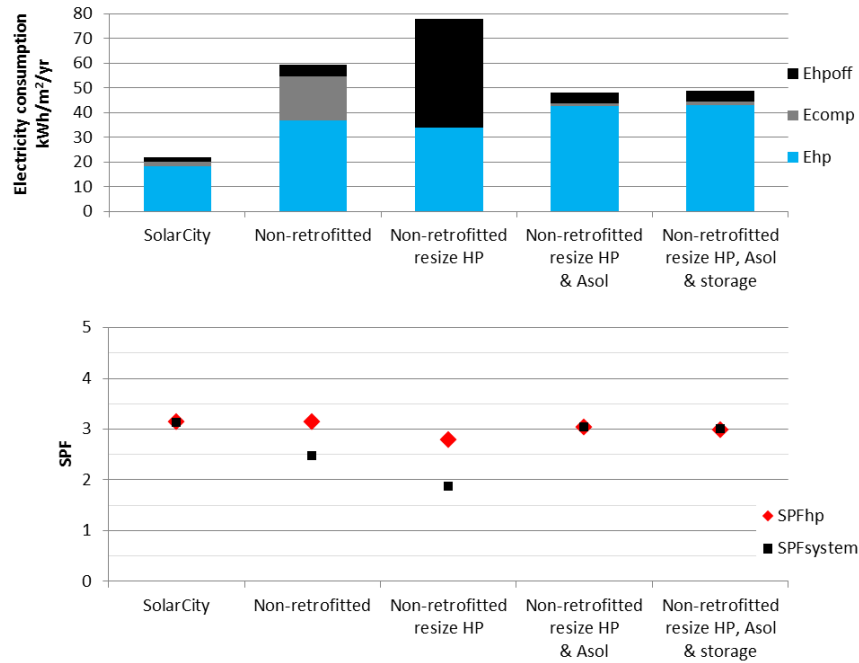


Fig. 6: System sensitivity to heat demand (new and non-retrofitted building) and resizing of system components. Top – Electricity consumption; Bottom –  $SPF_{HP}$  and  $SPF_{System}$ .

Fig. 6 shows that without resizing the heating system, the electricity demand increases by a factor of 2.7 even if the demand only increased by a factor of 2.1. The  $SPF_{System}$  decreases to 2.5. When resizing only the HP, since the solar collectors surface is not adjusted, the evaporator reaches non operation temperature conditions more frequently which leads to an important increase of the total electricity consumption (78.1 kWh/m²/yr) due to direct electric heating. The  $SPF_{System}$  drops below 2. With HP and solar collectors resizing the electricity consumption stabilizes at 48.2 kWh/m²/yr with a  $SPF_{System}$  of 3.0. Again, the resizing of the storage as no effect in the overall electricity consumption nor in the  $SPF_{System}$ . Contrary to what was observed in the retrofitted building, in this case the resizing of the system components is necessary. This is due to the fact that  $P_{max,SH}$  of the non-retrofitted building is higher than  $P_{max,DHW}$  of SolarCity. The use of this concept in a non-retrofitted building may not be viable due to: i) restricted roof surface (with the solar collectors resizing, the system needs 25m² of solar collectors per 100m² of building heated surface); ii) the financial investments are likely to be 2 times higher (with the system resize by a factor of 2.1); iii) the total electricity consumption remains high.

## 6 CONCLUSIONS

A model of a system combining uncovered, non-insulated solar collectors and heat pump for space heating and domestic hot water production to a new multifamily building was validated with long term monitoring data.

The validation was accomplished with good accuracy for monthly and annual values. In particular, the total input energy flows simulated are very close to the monitored value, with a difference of less than 3% and the  $SPF_{System}$  simulated of 3.1 is similar to the monitored value of 3.0.

A sensitivity analysis was carried out for two technical parameters: the insulation of the rear face of the solar collectors and the use of an inverter heat pump. With the insulation of the solar collectors a higher share of direct solar heat production is achieved in summer, but in winter the collectors reach non-operation heat pump temperatures more frequently which leads to more direct electric heating consumption. These effects counterbalance themselves making the insulation of the collectors ineffective in the overall analysis of the system. The simulation with an inverter heat pump allowed to avoid all surplus heat production at high temperature that was stored and afterwards used to cover demand at lower temperature (observed in the case of a non-inverter heat pump). This leads to a decrease of the overall electricity consumption of the system to 17.7 kWh/m²/yr and a  $SPF_{System}$  of 3.8 as opposed to the non-inverter heat pump case where the overall electricity consumption of the system is 21.8 kWh/m²/yr and the  $SPF_{System}$  is 3.1.

The concept has been tested considering the heat demand of a retrofitted building with Minergie standard and the results show that it should reach an  $SPF_{System}$  of 3, similar to the monitored case (new building). However, an increase of total electricity consumption, proportional to the increase of the heat demand, is expected.

The implementation of this concept in a non-retrofitted building seems unviable because of the large solar collector area required (proportional to the increase of the heat demand) that can be larger than the rooftop surface available. Large financial investments are also expected considering that the investment is already substantial in the base case.

Finally, we highlight the negative role of the “single tube” heat distribution system (alternate DHW and SH production), which does not allow for solar preheating of DHW, since the individual storage tanks are situated in the flats. In this regard it is foreseen to further develop the numerical model, in order to assess the benefit of a classical centralized DHW tank with solar preheating.

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