# Simulation of the thermal interaction between a building integrated photovoltaic collector and an airsource heat pump

Bruno Filliard, Alain Guiavarch, Melda Jabbour

# SIMULATION OF THE THERMAL INTERACTION BETWEEN A BUILDING INTEGRATED PHOTOVOLTAIC COLLECTOR AND AN AIR-SOURCE HEAT PUMP

B. Filliard[1]; A. Guiavarch[1]; M. Jabbour[1].

*1: MINES ParisTech – CEP – Centre Energétique et Procédés – 60 Bd St Michel – 75272 Paris Cedex 06 - France*

**ABSTRACT**

The number of buildings simultaneously equipped with air-source heat pumps and photovoltaic collectors is constantly increasing. Nevertheless, both systems are installed independently, and their thermal interaction is not taken into account. In addition to electricity, the photovoltaic collector produces heat which can be used to increase the temperature of the source of the heat pump, thus improving its COP (Coefficient Of Performance). Inversely, the fluid cooled by the external unit of the heat pump can be used to lower the operating temperature of the photovoltaic collector, improving its electrical efficiency.

This paper presents the methodology employed to simulate this kind of system and gives some results. The two systems (heat pump and photovoltaic collector) have been modelled and implemented in a thermal simulation tool of buildings. The resulting software enables to take into account the thermal interaction between each physical object (heat pump, PV collector and building) in a dynamic way. Simulations are run for the whole year and with a time step of one hour.

The aim of this development is to evaluate the increase of efficiency of the combined system installed in a building compared to the case where both systems are installed independently. The simulation tool is applied on a case study : a single family house with a living area of 135 m² and recently renovated. The south oriented roof gives enough space to install a 30 m² photovoltaic collector. The external unit of the heat pump is installed in the attic just beneath the PV collector, which preheats the incoming air. The results illustrate how the thermal interaction between both systems can be taken into account.

## INTRODUCTION

The number of buildings simultaneously equipped with air heat pumps and photovoltaic collectors has been increasing. Nevertheless, both systems are installed independently, and their thermal interaction is not taken into account. In addition to electricity, the photovoltaic collector produces heat which can be used to increase the temperature of the source of the heat pump, thus improving its COP (Coefficient Of Performance). Inversely, the fluid cooled by the external unit of the heat pump can be used to lower the operating temperature of the photovoltaic collector, improving its electrical efficiency. This concept was investigated by [1] who designed systems in which the air heated by the PV collector is used as an air source for the heat pump. Other authors, as for instance [2], studied photovoltaic solar assisted heat pumps. The aforementioned researches gave interesting results, but didn't show the annual performance of the whole system integrated into the building.

The aim of the paper is to present how the thermal interaction between a Photovoltaic – Thermal (PV-T) collector and an air-source heat pump integrated into a building can be modelled and the annual performance of the whole system integrated into a building calculated. The model of the heat pump and the PV-T collector will be presented first. The coupling and integration into a building simulation tool is also explained. The resulting simulation tool is finally applied on a case study.

## MODELLING

### Heat Pump model

The heat pump model, whose heat balance is illustrated in figure 1-a, is based on a steady-state empirical model and considers full load and part load conditions [3]. A first set of equations is used to calculate the full load performance, for non rated conditions. The empirical model uses parameters which are deduced from manufacturer data.

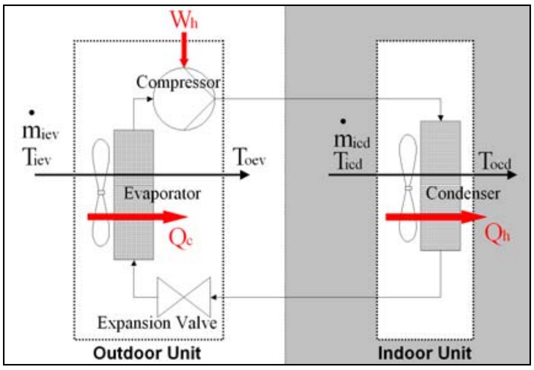


*Figure 1-a*
*Heat pump energy balance*

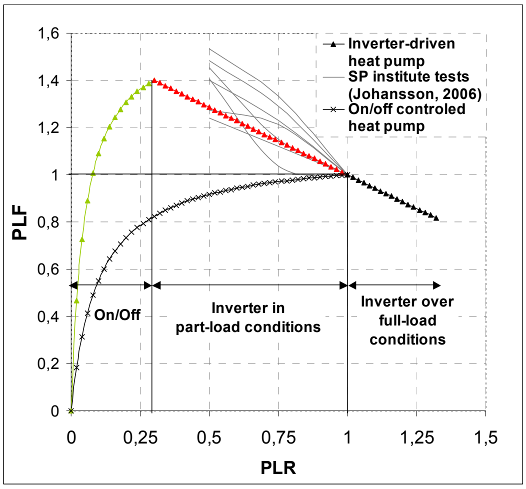


*Figure 1-b*
*PLF versus PLR*

The results calculated in full load conditions are then corrected to take into account the part load conditions, as illustrated in figure 1-b. The part load factor (PLF) is the ratio between the real COP (coefficient of performance) and the COP calculated for full load conditions. This PLF is function of the part load ratio (PLR), defined as the ratio between the heating load of the building and the heating capacity of the heat pump at full load conditions. The reader can find more details in [3], but we see in figure 1-b that, for part load conditions (PLR < 1), the PLF is higher for *inverter-driven* heat pumps than for *on-off* heat pumps. Moreover, for inverter-driven heat pumps, the fan speed varies according to the part load ratio. Performance degradation due to frost formation is also accounted for.

### Photovoltaic-thermal model

The production of electricity by photovoltaic modules is calculated with the 1-diode model, assuming the collector is grid-connected. The electrical efficiency is function of the junction temperature, which is equivalent to the operating temperature of the photovoltaic cells (and assumed to be uniform over the whole PV collector). This junction temperature depends on the type of integration of the PV collector, and is given by a PV-T model, developed by [4].

The PV-T model is able to represent many different types of integration of the PV collector in the building envelope : integration without thermal interaction with the building envelope (PV collector installed on a flat roof for instance) ; integration without air gap (PV collector directly integrated into the wall, and placed against an insulation for instance); and integration with a ventilated air gap (see figure 2).

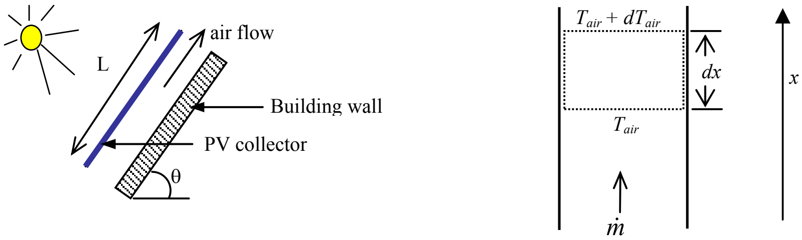


*Figure 2 – PV-T model illustration*

In the case with a ventilated air gap, a model has been developed to calculate the thermal efficiency of the PV-T collector. This model assumes steady-state conditions (the thermal mass of the PV collector is neglected) and a one-dimensional conduction heat transfer perpendicular to the collector surface. The bulk air temperature varies according to the direction parallel to the air flow, and the mean outlet air temperature $T_{air,out}$ is calculated according to the mean inlet air temperature $T_{air,in}$ . The heat transfer rate $q$ is deduced, $\dot{m}$ being the mass air flow rate and $Cp$ the specific heat of the air:

$$q=\dot{m}Cp\left(T_{air,out}-T_{air,in}\right)$$

In case of natural ventilation, several studies concerning the air flow in an air gap heated by a PV collector have been carried out (see [5] for instance). A rather simple method avoiding to use CFD (Computational Fluid Dynamics) type calculations allows to predict the air mass flow rate : a one-dimensional loop analysis in which the buoyancy forces are balanced by the pressure drops due to friction yields a third order polynomial equation. The calculation of the mass air flow rate $\dot{m}$ and q are inter-dependant and the solution is solved by using the Newton method.

#### COUPLING AND INTEGRATION INTO A BUILDING SIMULATION TOOL

The thermal simulation tool of multi-zone buildings named COMFIE allows heating and cooling loads as well as temperature profiles in different zones to be evaluated. It is based on a finite volume method, reduced after modal analysis [6]. The program has been developed using an object oriented approach, allowing modules to be linked to the core of the program. These modules can represent building integrated photovoltaic systems or heat pumps for instance.

During the simulation process, parameters are exchanged at each time step (typically 1 hour) between objects and/or the core of the program (see figure 3). For example, the outlet air temperature of the PV-T collector is injected as an input in the Heat Pump. As the fan speed of the external unit of the heat pump varies according to the heat load (for inverter driven heat pumps), the Heat Pump module gives as output the external unit air flow rate. In some cases, this output can be used by the PV-T collector module for the heat balance.

Moreover, both models (PV-T and Heat Pump) interact at each time step with the building model. For instance, the heat balance of the PV-T collector is function of the temperature of the adjacent building zones, and the heat balance of the building can depend on the air flow rate of the external unit of the heat pump (if for instance the external unit is placed in the attic of a house).

If more complex interactions are to be simulated, iterative algorithms are employed at each time step. This would be the case for instance if, in addition to inject the air heated by the PV -T collector into the external unit of the heat pump, the system inject the air cooled by the external unit into the PV-T collector.

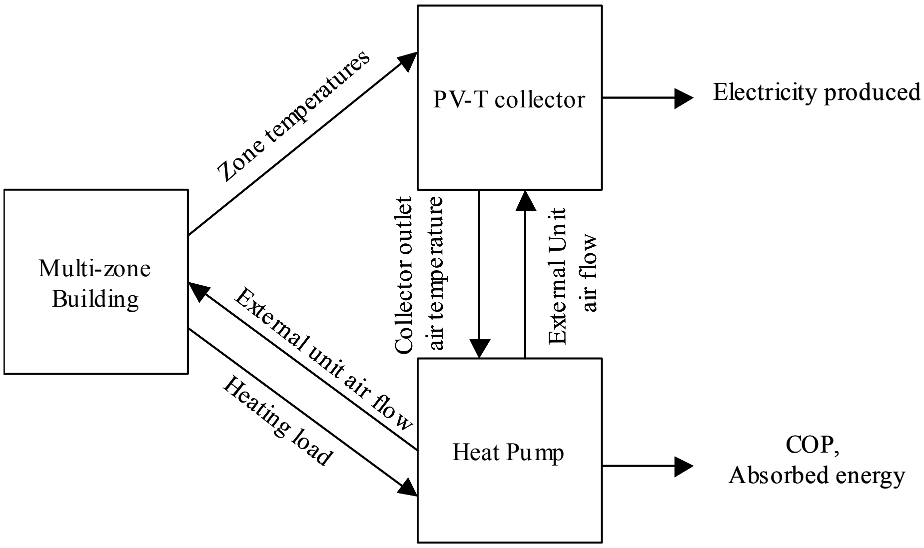


*Figure 3 – Coupling of the different modules*

The hourly output of the resulting simulation tool are the electricity produced by the PV collector, the absorbed energy and the COP of the heat pump. Theses results, once integrated over one year, will give the efficiency of the whole system. Other variables (hourly mean temperatures for instance) can also help to assess its performance.

**CASE STUDY**

## Description

The building is a single family house with a useful area of 135 m², and occupied by 4 inhabitants (see figure 4-a). This house was built in the seventies, and was recently fully retrofitted and well insulated. For instance, the pitched-roof wall is insulated with 18 cm of mineral wool. All windows are double glazed with low emissivity glass. A sunspace facing south has been added with low emissivity double-glazing. An efficient heat recovery system lowers the heat losses by ventilation. With this characteristics, the heating load is 40 kWh/m² if the house is located in Trappes (north of France)

The PV collector is made of 30 m² mc-Si (mono-cristalline silicon), with a total peak power of 4280 kWp. The collector is placed on the south oriented roof, with an inclination of 45°. An air gap of 10 cm is placed behind the PV collector to recover the heat produced. An inverter with a nominal power of 3850 kW is installed to convert direct current into alternative current.

The heat pump has a rated heating capacity of 4 kW, a rated COP of 3.46, and provides energy for heating only. The compressor is inverter driven and, and it is also assumed that the fan speed of the exterior unit varies according to the part load ratio of the heat pump (see above).

Two different configurations are studied. In the first case, the PV-T collector is naturally ventilated, and the external unit is placed outside the building. This is the reference case, without thermal interaction.

In the second case, the external unit is placed in the attic (which is insulated with 4 cm mineral wool), as illustrated in figure 4-b. During the heating season, the air heated by the PV-T collector is injected in the attic. This air is blown by an additional fan (with a constant speed in our case, and assuming a consumption of 0.1 W/($m^3$/h)) if it is warmer than the air in the attic. If the air flow rate required by the external unit is higher than the air flow induced by the additional fan, the remaining air flow comes from outside (see figure 4-b). In other words, the air coming on the external unit is the air in the attic, which is a mix between the air coming from the PV-T collector and the outside air. During the summer, the PV-T collector is naturally ventilated as in case 1.

2

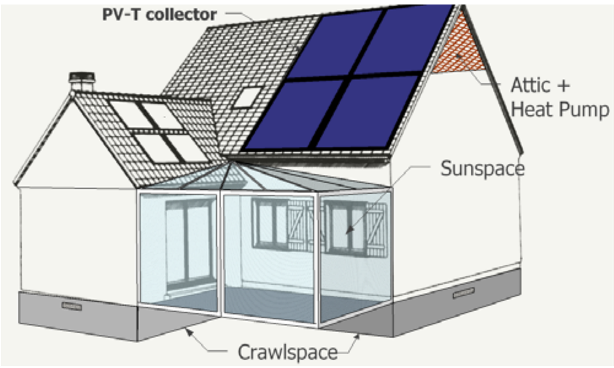


Figure 4-a – The studied house

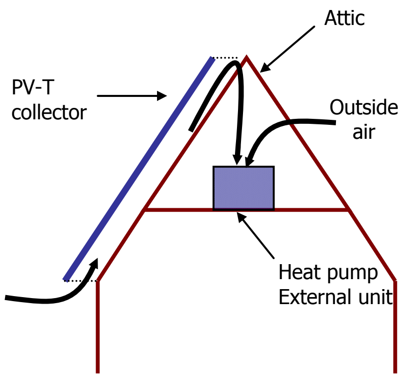


Figure 4-b –Heat pump in the attic (case2)

**Results**

The table 1 below gives the results for the two cases described above (with and without thermal coupling), and with Trappes for the meteorological location (north of France). In the second case, the air flow coming from the PV-T collector varies from 0 to 2000 $m^3$/ hour.

| **Heat pump air source** | **Outside air** | **Attic (PV-T collector + Outside air)** | | | |
|---|---|---|---|---|---|
| Air flow rate (m3 / h) | - | 0 | 500 | 1000 | 2000 |
| COP (Heat pump only) | 3.06 | 3.12 | 3.18 | 3.4 | 3.67 |
| COP (Heat pump + back up resistances) | 2.91 | 2.94 | 3 | 3.21 | 3.54 |
| COP (Heat pump + back up resistances + additional fan) | 2.91 | 2.94 | 2.77 | 2.71 | 2.51 |
| Building heating load (kWh) | 6420 | 6420 | 6394 | 6351 | 6327 |
| $E_{pv}$ (gross, collector output - kWh) | 4299 | 4113 | 4157 | 4170 | 4173 |

*Table 1: Annual results for the two cases described in the previous paragraph (reference case and heat pump in the attic with air preheated by the PV-T collector)*

We see that the annual COP of the heat pump slightly increases when the external unit is placed in the attic (3.12 against 3.06 for the reference case). Moreover, the COP increases according the air flow passing through the PV-T collector : the COP is 3.67 for a air flow rate of 2000 $m^3/h$, giving an increase of 20 % compared to the reference case. But the COP including also the back up resistance and the consumption of the additional fan decreases significantly (- 14 % compared to the reference case, the main part coming from the consumption of the additional fan).

The electricity produced by the PV collector (gross production, PV collector output) is lower in the second case than in the reference case. We have for instance 4113 kWh in the second case with no air circulation compared to 4299 kWh in the reference case, or approximately a 4 % loss. In the second case, during the heating season, the air flow is constant and fixed by the additional fan. The fan is off if the temperature of the air in the PV-T collector is lower than in the attic, and in this case the PV collector is not ventilated, compared to the reference case where the PV collector is always naturally ventilated. Nevertheless, we see that the electrical efficiency of the PV collector rises when the air flow rate increases.

## CONCLUSION AND PERSPECTIVE

This paper demonstrates how it is possible to model an air source heat pump coupled with a PV-T collector, and to simulate the global system integrated into the building envelope.

According to the case study, the COP of the heat pump increases if a PV-T collector injects warm air in the attic, where the external unit of the heat pump is placed. But the consumption of the additional fan required to blow the air in the attic lowers the COP of the system. Moreover, the electrical efficiency of the PV collector decreases slightly, but better control strategies are expected to be developed to increase the global efficiency of the system.

## ACKNOWLEDGEMENTS

This work has been supported by the French Research National Agency (ANR) through the Habitat Intelligent et Solaire Photovoltaïque program (project PACAirPV n°ANR-08-HABISOL-005).

## REFERENCES

1. Zondag H. A.: “Combined pv-air collector as heat pump preheater” ; 9th International Conference on Solar Energy in High Latitudes. Northsun 2001, Leiden, The Netherlands, 6-8 May, 2001.
2. Jie Ji, Hanfeng He, Tintai Chow, Gang Pei, Wei He, Keliang Liu: “Distributed dynamic modelling and experimental study of PV evaporator in a PV-T solar-assisted heat pump” ; International Journal of Heat and Mass Transfer, vol. 52, 2009.
3. Filliard B., Guiavarch A. and Peuportier B.: “Performance evaluation of an air-to-air pump coupled with temperate air-sources integrated into a dwelling”, IBPSA, Glasgow, 2009.
4. Guiavarch A. and Peuportier B. : "Photovoltaic collectors efficiency according to their integration in buildings", Solar Energy ; 80, 65-77, 2006.
5. Brinkworth, B. J., Marshall, R. H., and Ibarahim, Z., 2000: “A validated model of naturally ventilated PV cladding”; Solar Energy. 69, 67-81.
6. Peuportier, B., and Blanc Sommereux, I.: “Simulation tool with its expert interface for the thermal design of multizone buildings”. International Journal of Solar Energy. 8, 1990.

# INTEGRATION OF RENEWABLES TO COVER COOLING LOAD OF BUILDING. FEASIBILITY AND APPLICATION

D. Jaunzems[1]; I. Veidenbergs[2];

*1: Institute of Energy Systems and Environment, Riga Technical University, Kronvalda boulv. 1, LV-1010, Riga, Latvia.*

*2: Institute of Energy Systems and Environment, Riga Technical University, Kronvalda boulv. 1, LV-1010, Riga, Latvia.*

## ABSTRACT

The paper reports on the calculation of hourly cooling loads of a building in the climate conditions of Latvia with the aim to estimate and survey existing solar cooling technologies and their limitations, and also to consider possible application in Latvia. The hourly cooling load of a building is used to evaluate the reasonable fraction of the needed primary energy to be replaced by solar energy and to assess the collector area required to achieve the fixed primary energy savings. Analyses of research and results of simulation of solar thermal systems in climate conditions of Latvia allowed using this data for solar cooling applications. For energy calculation, a solar fraction 50% was assumed for solar absorption and adsorption cooling technologies. Analyses showed that solar cooling could be an attractive solution to increase the use of renewable energy and diminish the use of electricity for cooling applications.

## INTRODUCTION

Buildings are responsible for about 40% of the global primary energy consumption. Despite the fact that for much of Europe's increases in cooling energy demand due to global warming will be outweighed by reductions in the need for heating energy [1] there is still a need for investigation. In most European areas both cooling and heating are needed, as well as in Latvia. Therefore, the capacity of solar-assisted air-conditioning systems which fulfil both requirements is a key element for techno-economic feasibility [2]. Solar cooling has a strong potential for significant primary energy savings [3]. Other assessments claim that around 120-150 systems are operational in Europe with a capacity over 12 $MW_{th}$ and collector area of 36 000 $m^2$ giving 3 $m^2/kW$ of cooling capacity mainly used in buildings but some by industry such as for wine cooling [4]. Nowadays solar energy is one of the promising resources not only for heating of buildings, but also for cooling. Solar fractions therefore need to be higher than about 50% to start saving primary energy [8]. A typical solar cooling system includes three main sub-systems: (1) Cooling load of building, characterized by the required cold energy, temperature and power, e.g. the cooling system. (2) The thermally driven cooling system (thermally driven water chiller or refrigeration cycle, open sorptive cooling cycle etc.). (3) Heat source: the solar collector system as the essential driving heat source and additional heat source, for example, pellet or woodchip boiler, to cover the necessary heat load when solar energy is not enough. All these three sub-systems are coupled to each other by heat fluxes at different temperature levels and other thermal engineering parameters and solutions.

For each MWh of cooling energy demand, between 1.6 and 6.2 $m^2$ collector aperture area are required for the cooling installation. The total system costs for commercially available solar