International High Performance Buildings Conference

School of Mechanical Engineering

2021

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Jorquera Ferrat, Pedro and Mondot, Michèle, "Technical and Economic Analysis of a Residential Heat Pump with Photovoltaic Solar Panels in Self-Consumption for Space Heating, Cooling and DHW Production" (2021). *International High Performance Buildings Conference.* Paper 344.
https://docs.lib.purdue.edu/ihpbc/344

Technical and Economic Analysis of a Residential Heat Pump with Photovoltaic Solar Panels in Self-Consumption for Space Heating, Cooling and DHW

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ABSTRACT

Two different thermodynamic systems for space heating, cooling, and domestic hot water production coupled to photovoltaic panels have been studied. The aim is to assess the PV electricity self-consumption variation with the heat storage volume and the applied control strategy. Each system has been studied using a 1D unsteady state modelisation software to simulate its performance in a house complying with the French building code (RT2012) having a DHW demand according to ErP's load profile M and with Paris weather data. The main parameters studied are the electricity consumption of the thermodynamic system, the seasonal performance factor (SPF), the self-consumption ratio, the self-production ratio, the coverage ratio and the Return on Investment. The results show that the seasonal efficiency can be doubled thanks to the optimization of the PV electricity self-consumption, which results in a return on investment lower than 15 years.

1. INTRODUCTION

The necessity to reduce both the energy consumption of residential heating appliances and the electrical network peak load (i.e. through aggregation scenarios) as well as the technical evolution of some heating or hot water production appliances (mainly thanks to new control strategies) allow us to consider possible the photovoltaic (PV) self-consumption in a detached house in order to feed a heat pump (HP) for space heating and domestic hot water (DHW) production.

Unsteady state, 1D simulations and calculations are widely used to study the PV self-consumption and the controls of the system. Pichler *et al.* (2016) showed that for a detached house with a HP+PV system for heating and DHW production, the use of a predictive control model (PCM) has the potential to increase the self-consumption ratio from 20% (base case scenario) to 50%. Haller *et al.* (2017) proved that the self-consumption ratio can be increased by 50% with a simple control strategy consisting of overheating the storage tank for the DHW production. However, Baeten (2017) indicated that large storage volumes may penalize the HP system performance. Thür *et al.* (2018) established that the implementation of a smart control strategy is far more efficient for the PV self-consumption than the increase of the thermal storage volume in a ground source HP+PV system for heating and DHW production. On the other hand, Jorquera (2018) showed that whilst thermal storage allows an increase of PV self-consumption of around 50% compared to a system without thermal storage, the use of electrical batteries increases the PV self-consumption up to 80%, but is not profitable as the costs of replacing the batteries are far too great.

Scientific publications show that studies generally focus on the controls of the system for one or two services at a time (heating + DHW production, cooling + heating, …). The objective of this study is to enlarge the knowledge of a thermodynamic system with PV panels. A techno-economic assessment has been carried out to optimize the utilization of PV electricity in order to minimize the electricity bill of a detached house.

The paper is divided in three parts:

- Description of the two systems studied
- Results for system #1
- Results for system #2

2. DESCRIPTION OF THE SYSTEMS

The thermodynamic systems have been studied for the two installation schemes represented in figures 1 and 2. The PV electricity produced by the photovoltaic panels installed on the roof of the house is either consumed by the house or exported to the electrical network, depending on the type of contract for the sale of PV electricity. In the first case, PV electricity not consumed by the thermodynamic system can be consumed by other usages in the house and the electricity not consumed by these is exported to the grid. In the second case, all produced PV is exported. Each component of the system and the associated simulation model are described in this chapter.

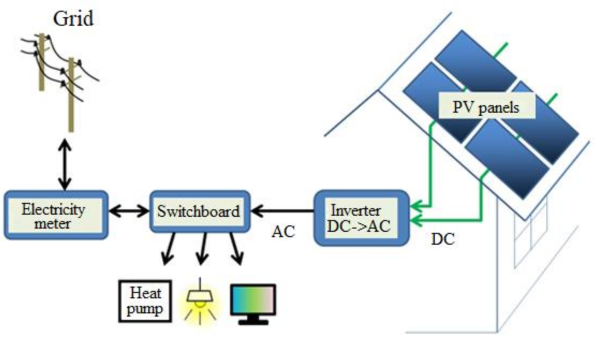

Figure 1: HP + PV system diagram with a contract of self-consumption of PV electricity

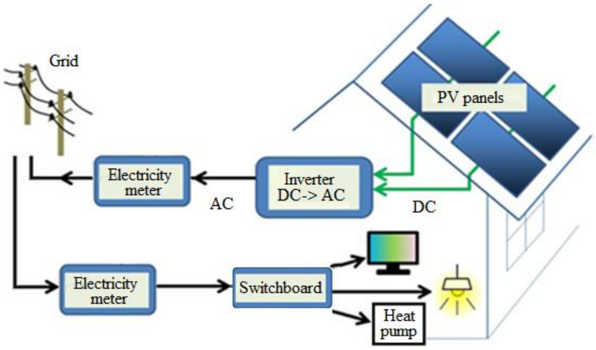

Figure 2: HP + PV system diagram with a contract of total PV electricity exportation

2.1 The Detached House

A detached house of medium inertia with a surface heat loss coefficient Ubat of 0.4 $W \cdot m^{-2} \cdot K^{-1}$ was considered. The heated surface area is 111.7 m², the ceiling height of 2.5 m and the glazed area facing South / East is 5 m². The ventilation air renewal is 140 m^3/h. The simulations were carried out over the period from January 1st to December 31st (365 days) with Paris weather data. The modelling of the building corresponds to a 5R/3C model inspired from NF EN ISO 13790:2013, as presented by Noël (2016). It takes into account the outdoor temperature, the solar gains and walls characteristics to calculate the thermal energy load as well as the air and walls temperature evolution over time. The 5R3C developed model has been compared to the BESTEST benchmark, a benchmark in the field of building thermal simulation presented by Judkoff and Neymark (1995). The comparison between model results and reference results is excellent. The electricity consumption profile is defined according to Bouvenot (2015) findings.

2.2Thermodynamic System

The thermodynamic system for heating, cooling and DHW production is described for the two following assemblies. In system #1 an air-to-water heat pump (HP) ensures the space heating and domestic hot water through a buffer tank and a DHW storage tank, respectively (see figure 3). It is associated with an air-to-air air conditioning (AC) unit for the cooling needs of the house (see figure 4). In system #2 an air-to-air reversible heat pump (RHP) provides both heating and cooling for the house (see figure 5). It is associated with a heat pump water heater (HPWH) for DHW production. Data used for the simulations is listed in table 1.

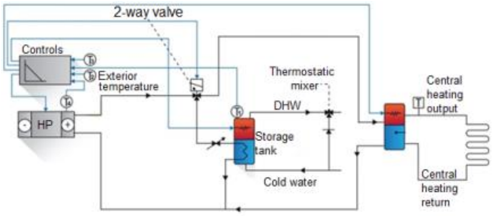

Figure 3: Hydraulic diagram of the HP for heating and DHW

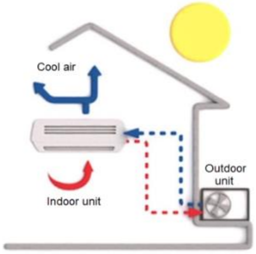

Figure 4: AC unit

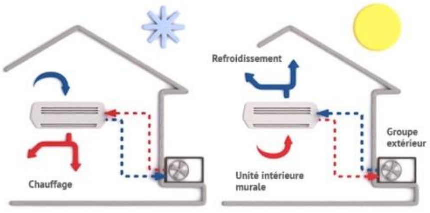

Figure 5: Representation of the reversible heat pump for heating and cooling

Table 1: Performances of the thermodynamic systems

Air-to-water heat pump (HP)	**Air-to-air reversible heat pump (RHP)**
Variable speed compressor	Variable speed compressor
Rated heating capacity @7/30-35 = 6 kW	Rated heating capacity @7/20 and cooling capacity @35/27 = 6 kW
COP @7/30-35 = 4,16	COP @7/20 = 4,16 & EER @35/27 = 4
heating capacity at LRContMin(1) = 2,4 kW	Heating (cooling) capacity at LRContMin = 2,4 kW
COP at LRContMin = 4,16	COP (EER) at LRContMin = 4,16 (4)

(1) LRContMin: switch point to On / Off operation mode of the heat pump or minimum heating capacity in continuous operation.

The HPWH and the DHW function of the air-to-water HP are characterized by a COP equal to 3.37 for a load profile L, corresponding to a total tapped energy of 11.655 kWh, i.e. 0.2 m^3 of hot water at 60°C per day. The performance of the thermodynamic system (HP, RHP, HPWH and AC unit) is calculated using a performance matrix established on the basis of the rated COP and the temperature ranges of the heat source (outdoor air) and the heat sink (recycled air or water). The model has a simple dynamic (small volume heated or cooled). The delivered capacity depends on a set point and the correlation laws in the form of a matrix. The modelling also takes into account the part load operation of the HP. The energy balance (energy requirement, energy supplied and energy consumed) is calculated by the model with a time step equal to 5 seconds and then integrated over the total simulated duration (in this case 1 year). The seasonal performance factor (SPF) is calculated using equation (1). The energies involved are calculated by the integration over time of the corresponding capacities and powers obtained by the simulation model.

$$SPF = \frac{E_{cooling} + E_{heating} + E_{DHW} + E_{backup}}{E_{consumed\ total} - E_{PV\ self-consumed}} \tag{1}$$

2.3 Control Strategies

A base case has been defined by means of a standard control strategy, without self-consumption improvement techniques. This base control strategy is defined as follows:

- In heating mode
    - Room set temperature (Ts_room) = 19°C (hysteresis ±0,5 K);
    - In system #1: heating buffer tank set temperature = 45°C (hysteresis – 5 K);
    - Heating season: between October 17th and April 1st;
- In DHW mode
    - Hot water storage tank set temperature = 45°C (hysteresis -5 K);
    - DHW set temperature = 39°C;
- In cooling mode
    - Room set temperature (Ts_room) = 24°C (hysteresis ±0,5 K);
    - Cooling season: between May 2nd and September 11th.

In order to increase PV electricity self-consumption several "enhanced" control strategies have been studied. This will allow us to determine their impact on system performance and overall economics. These control strategies are described below:

Control strategy 1:

- Heating mode:
    - If PV production over 500 W then room set temperature (Ts_room) and buffer set temperature (Ts_buffer) increased by +2 K and +10 K, respectively;
    - Heating reduction periods (00h-6h, 8h-10h and 22h-00h): Ts_room -3 K and Ts_buffer -5 K;
- DHW mode
    - If PV production over 500 W then storage set temperature (Ts_storage) increased to 55°C;
    - Ts_storage reduced by -10 K between 23h and 6h;
- Cooling mode
    - If PV production over 500 W then Ts_room = 21°C;

  - Between heating and cooling seasons, the AC unit is allowed to start if set temperature is not met when PV production > 500 W.

Control strategy 2: Control strategy 1 and:

- Heating / DHW / air cooling, if PV production > 500 W:
  - Heat pump capacity adjustment to PV power production.
    The modulation of the power input of the heat pump is obtained by calculating the output set temperature of the heat pump according to the available PV power and the operating conditions (water flow, return temperature) as well as the COP of the heat pump;
    In heating and DHW the set temperature is limited between 40°C and 70 ° C.

Control strategy 3: Control strategy 2 and:

- Heating / DHW / cooling, if PV production > 500 W:
  - For buffer and storage tanks: The hysteresis is reduced from 5 K to 1 K in order to restart the system quickly and to consume the photovoltaic production;
  - For the building: The air conditioning start hysteresis is reduced to 0 K and the stop hysteresis is increased to 2 K.

Control strategy 4: Control strategy 3 and:

- Heating: If PV production then heating of the buffer tank up to 60°C;
- DHW: If PV production then heating of the storage tank up to 60°C.

2.4 PV Panels

In this study, a power of 3.0 kWp was considered, i.e. 10 photovoltaic panels (~ 15 m²) of 300 Wp each. The model is based on TRNSYS 16, Type 180. Three parameters are calculated in order to characterize the use of photovoltaic electricity. The self-consumption rate indicates the share of photovoltaic production consumed directly by the house. The self-production rate indicates the share of total electricity consumption supplied by photovoltaic panels. The coverage rate makes it possible to establish an energy balance between annual production and annual electricity consumption. Two types of electricity contracts have been taken into account: Sale of the total PV production and Self-consumption with sale of PV production excess (Gabriele, 2019).

2.5 Water Storage Tanks

For system #1, three storage tank volumes for heating and DHW are simulated, as shown in Table 2 with their heat losses. For system #2, only DHW tank is simulated. A multi-layer model is taken into account with a defined number of layers (~ 100) of constant thickness. A convection / diffusion equation is completed by an algorithm for suppressing inverse gradients. The conductivity of the water and the metal of the wall are taken into account for the thermal diffusion in standby, as described by Noël *et al.* (2010).

Table 2: Characteristics of water storage tanks

Mode	Volume (l)	Thermal losses (W)
Heating	100	42.4
	200	52.6
	500	71.4
DHW	150	48.0
	300	60.1
	600	76.0

2.6 Return on Investment (ROI)

The data used to calculate the ROI for the two types of PV contract are shown in Table 3. A calculation of ROI based on the savings generated thanks to the PV, compared to the annual electricity bill without PV, was considered. The annual electricity bill without PV for year 1 is calculated according to equation (2). To calculate the electricity bill for the following years the price of the imported kWh and the cost of the subscription are updated. To simplify the calculations, it was considered that all costs (subscription, TURPE, kWh imported and exported) change at the same rate, obtaining equation (3). Finally, the electricity bill over n years is calculated using equation (4).

$$F_0 = C_{tot} * p_{imp} + A \tag{2}$$

$$F_i = C_{tot} * p_{imp} * (1+e)^i + A * (1+e)^i \tag{3}$$

$$F_n = \sum_{i=0}^{n} F_i = \sum_{i=0}^{n} (C_{tot} * p_{imp} + A) * (1+e)^i \tag{4}$$

Similarly, the electricity bill over n years for the system with PV panels for the excess PV production sale contract is calculated using equation (5). The electricity bill over n years for the system with PV panels for the total PV production sale contract is calculated with equation (6).

$$F_n^{PV} = \left(C_{imp} * p_{imp} + A + TURPE_{sp}\right) * \frac{(1+e)^n - 1}{e} - C_{ex} * p_{ex} * n \tag{5}$$

$$F_n^{PV} = \left(C_{tot} * p_{imp} + A + TURPE_{vs}\right) * \frac{(1+e)^n - 1}{e} - C_{ex} * p_{ex,100\%} * \frac{(1+g)^n - 1}{g} \tag{6}$$

The ROI corresponds to the number of years (n) in which the savings generated by the PV panels (F_n-F_{nPV}) equalize the initial investment and, if higher than 10 years, the replacement of the PV panels inverter.

Table 3: Economic data for the calculation of the ROI

Parameter	Value	
PV	7500 €	
Replacement of the PV panels inverter after 10 years	1000 €	
Thermal storage	Buffer tank 100 litres : 300 € Buffer tank 250 litres : 400 € Buffer tank 500 litres : 600 €	Storage tank 150 litres: 300 € Storage tank 300 litres: 400 € Storage tank 600 litres: 600 €
Electricity imported from the grid	15,6 c€/kWh +2,5%/year	
Electricity exported to the grid	Total PV production sale: 18,73 c€/kWh -2,5%/year capped at 10 c€/kWh Sell of excess: 10 c€/kWh + bonus of 1200 €	
Electricity meter Linky	Total PV production sale: 500 €	
Electricity subscription	150,93 €/year +2,5%/year	
TURPE	Total PV production sale: 41,6 €/year +2,5%/year Sell of excess: 10,8 €/year +2,5%/year	

3. RESULTS FOR SYSTEM #1: AIR-TO-AIR HEAT PUMP WITH AC UNIT

3.1 Electricity consumption and SPF

The annual electricity consumption shown in Figure 6 includes the electricity consumption of the HP, the electrical backup and the AC unit. The results are presented according to the storage volume (heating buffer volume – DHW storage tank volume) and the control strategy (1 to 4). These results show that a greater heat storage capacity implies a higher electricity consumption (Figure 6). With control strategies to increase PV self-consumption, system electricity consumption is increased in most cases from 2.5% to 10%. This increase is induced by greater thermal losses from the storage tanks heated up to a higher temperature. It is interesting to note that the difference in electricity consumption between the smallest volume and the largest volume increases with a strategy to optimize self-consumption of electricity. The results show a significant growth in SPF with the first control strategy compared to base case (Figure 7). This strategy allows to almost double the SPF of the system. The second control strategy (control strategy 1 with modulation of the heat pump capacity) brings little compared to the control strategy 1. The third control strategy (control strategy 2 with reduction of the hysteresis) is much more effective than the control strategy 2 and an optimum storage volume is found at 250-300 litres. The integration of the fourth strategy (control strategy 3 with +10 K water tank overheating) has a negative impact on the overall efficiency of the system and the SPF is reduced compared to control strategy 3 (water tank overheating at higher set temperature). This indicates that, for a thermodynamic system with heat storage for both heating and DHW, a compromise between self-consumption and performance must be found depending on the storage volume and the maximum heating temperature of the water storage tank. With any of the studied control strategies, the SPF of system #1 can therefore be more than doubled compared to the system with a basic control strategy.

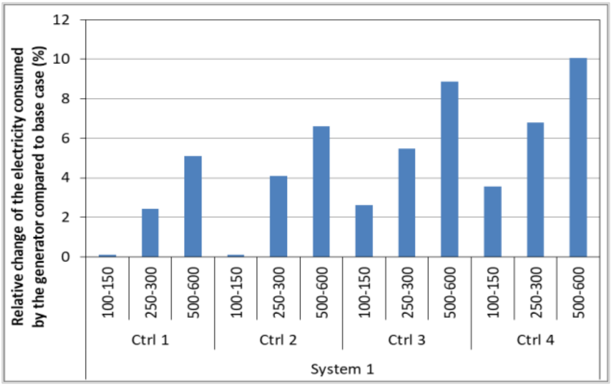

Figure 6: Electricity consumption of system #1

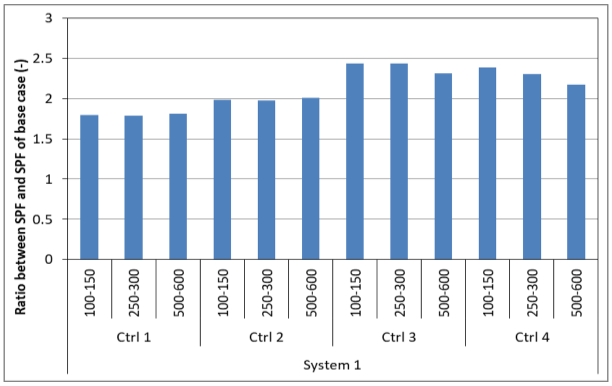

Figure 7: SPF of system #1 with photovoltaic panels in self-consumption

3.2 Self-consumption, self-production and coverage ratio

The results show that the implemented control strategies are very effective in increasing the self-consumption of the thermodynamic system. However, this increase leads to a decrease in the total self-consumption of the house (Figure 8). One can see that each additional control strategy to increase self-consumption is less and less effective, reaching a plateau at around 63% of self-consumption by the thermodynamic system alone (bottom bars) and 90% of the overall self-consumption for the house (bottom plus top bars). Going beyond this mark would require setting up a control strategy taking into account the consumption of other appliances in the house, the remaining 10% being to the other uses in the home (TV equipment, hi-fi, lighting, household appliances, etc.). The self-production rate results, in Figure 9, show that the control strategies are very effective, making it possible to triple the share of PV electricity consumed on site without any excessive increase of the electricty consumption. An optimum is found with an intermediate storage volume and the control strategy 3.

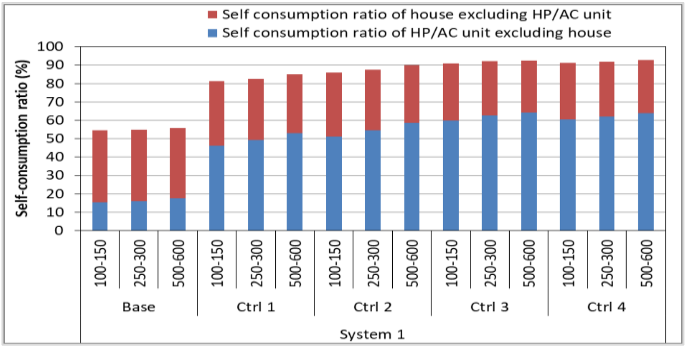

Figure 8: Self-consumption ratio with system #1

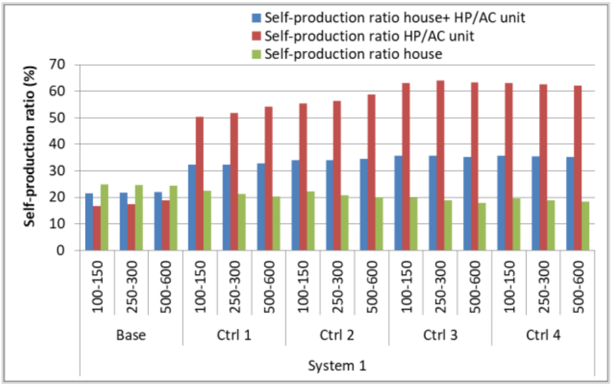

Figure 9: Self-production ratio with system #1

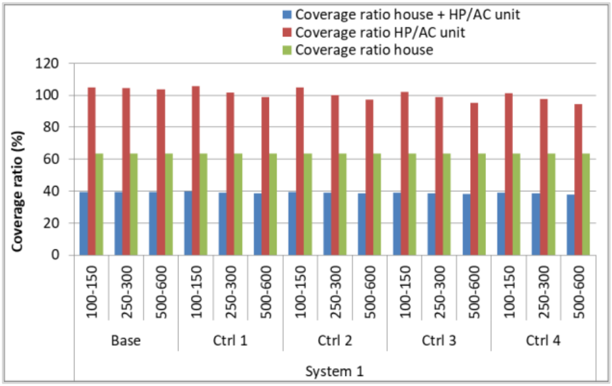

Figure 10: Coverage ratio with system #1

The coverage rate shown in Figure 10 is relatively constant. Indeed, it depends on the consumption of the thermodynamic system, the house and the photovoltaic production. However, the consumption of the system barely varies with the studied parameters (control strategy, storage volume) and both the photovoltaic production and the consumption of the house are kept constant.

3.3 Return on Investment

The initial investment costs include purchase and installation of the photovoltaic panels with the peripherals, and costs associated with thermal storage. The costs of the thermodynamic system are not included. The ROI then varies depending on the ratio of exported and self-consumed electricity as well as on the volume of storage tanks. The ROI with the total PV production sale contract does not depend on the self-consumption control strategy because with this contract all the PV production is exported and sold to the grid. As can be observed in Figure 11, the ROI with this contract increases with the storage volume, from 22 to almost 24 years. This is because larger storage volume requires a higher initial investment cost and induces higher thermal losses, whereas the PV production (then the PV exportation) is constant.

On the other hand, with an excess PV sales contract, the ROI varies according to the self-consumed and exported parts of PV production. Greater self-consumption reduces the import of electricity from the grid (at a price of around 15 c € / kWh) but also the sale of electricity exported to the network (at the price of 10 c € / kWh). With the considered costs, the ROI only becomes lower than 15 years when applying control strategies that lead to improving the self-consumption of the thermodynamic system. Thus, a system with control strategies to maximize self-consumption of PV electricity leads to a ROI of around 13 years, which is 2 to 3 years less than with a base control strategy. Regarding storage volumes, bests results are obtained with a medium to small storage volume.

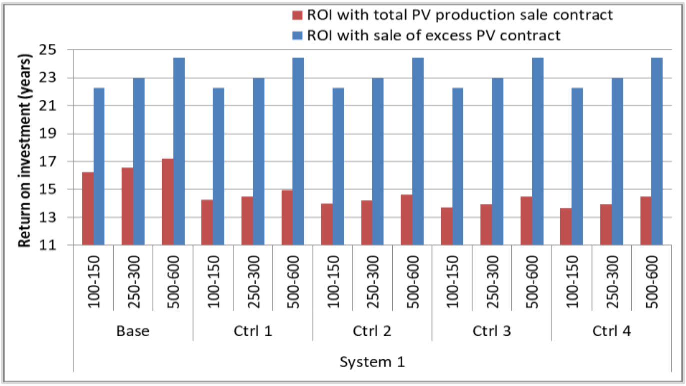

Figure 11: Return on investment with system #1 depending on PV production sale contract

4. RESULTS FOR SYSTEM #2: REVERSIBLE AIR-TO-AIR HEAT PUMP WITH HEAT PUMP WATER HEATER

4.1 Electricity consumption and SPF

The annual electricity consumption includes the electricity consumption of the reversible air-air heat pump, the heat pump water heater and an electrical back-up heater. The results in Figure 12 show that the electricity consumption of system #2 is weakly influenced by the control strategy implemented or by the storage volume. Control strategies aimed at increasing self-consumption of PV electricity have led to a reduction in the total consumption of the thermodynamic system by around 3.5%. This is because increase of non-heating and non-cooling periods in fact induced lower energy consumption (while maintaining comfort criteria). A small increase in SPF is observed with control strategies 1 to 4 (Figure 13), compared to base case. These results suggest that, compared to system #1, the lack of heat storage for heating (buffer tank) is greatly limiting the amount of PV electricity that can be self-consumed by the system. A control strategy for increasing self-consumption of PV electricity does not allow an increase in SPF of more than 26%.

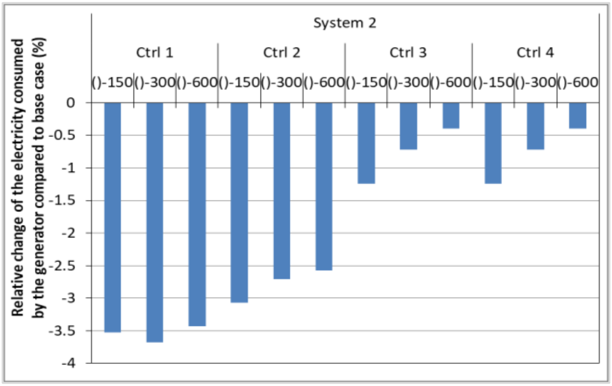

Figure 12: Electricity consumption of system #2

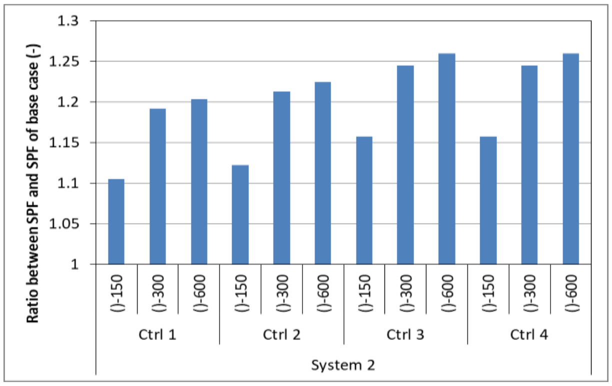

Figure 13: SPF of system #2

4.2 Self-consumption, self-production and coverage ratio

The control strategies introduced for system #2 lead to self-consumption rates of up to 70% (house + thermodynamic system), as shown in Figure 14. Compared to system #1, the base control strategy results in the same self-consumption rate of around 55%. However, with the optimized control strategies (1 to 4), the levels of self-consumption achieved with system #2 are much lower than with system #1. The self-production rate is around 23% with the base control strategy (Figure 15). With enhanced control strategies, the self-production rate only reaches 29%. Thermal storage for heating is therefore recommended in order to maximize self-consumption of PV electricity. The impact of the DHW water storage volume is noted with these enhanced control strategies, making it possible to gain around 2% of self-production with a larger storage volume. Other control strategies must be developed in order to maximize the consumption of this system during periods of PV production. The thermodynamic system coverage rate is greater than 100% (Figure 16) but the system's self-production rate is limited to 40%. This implies that the system consumption from PV is limited to 40% but could be completely covered as the system's coverage rate is over 100%. These results confirm a limited flexibility of system #2 to increase PV self-consumption due to studied control strategies or the lack of heat storage possibilities.

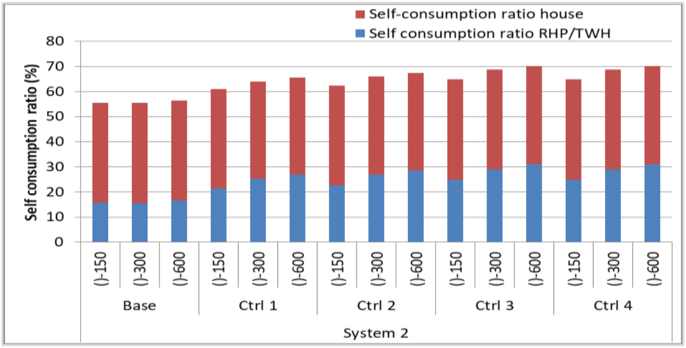

Figure 14: Self-consumption ratio with system # 2

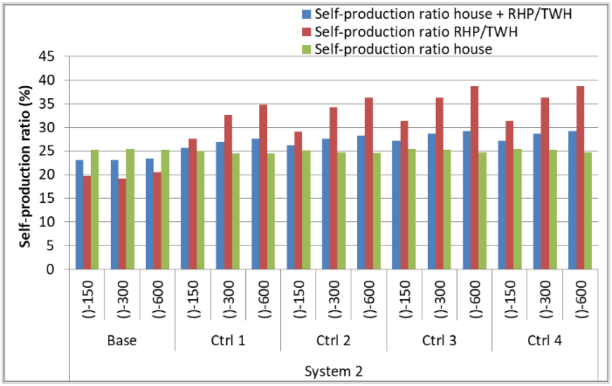

Figure 15: Self-production factor with system # 2

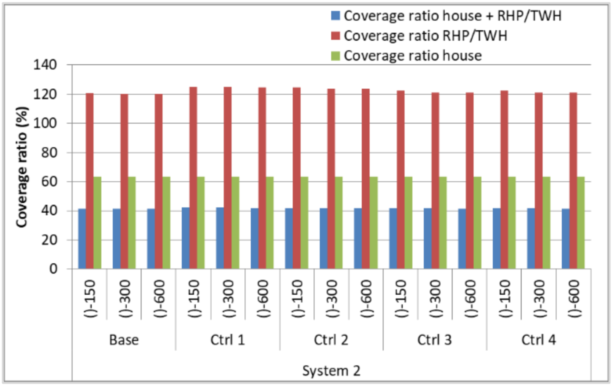

Figure 16: Coverage ratio with system # 2

4.3 Return on Investment

The payback time for system # 2 is shown in Figure 17. The ROI with the total PV sale contract is independent of the control strategy applied to the thermodynamic system, as explained in 3.3. This ROI is too high (around 22 years) and is negatively impacted by the increased cost of thermal storage. The ROI with an excess PV production sale contract is around 16 years with the base control strategy. It is reduced to around 15 years with the studied control strategies, thus having very little impact of ROI.

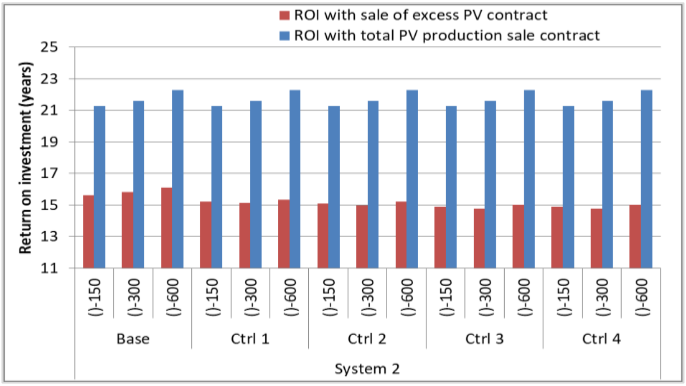

Figure 17: Return on investment with system # 2 depending on PV production sale contract

5. CONCLUSIONS

In this study, two types of thermodynamic systems for heating, cooling and DHW production associated with PV panels in self-consumption were simulated with different storage volumes and different control strategies:

- System # 1: air-to-water heat pump with heating storage and DHW storage, and air-to-air air conditioning unit;
- System # 2: reversible air-to-air heat pump and heat pump water heater.

The results showed that:

- The electricity consumption of system # 1 increases between +2.5 to +10% with the studied control strategies and the storage volumes;
- The electricity consumption of system # 2 can be reduced by 3.5% with control strategies;
- The SPF of system # 1 can be doubled thanks to optimized control strategies while, for system # 2, the SPF increases little (+ 26%);
- A self-consumption rate of 90% is achieved with system # 1. However, an increase in the system's self-consumption is obtained at the expense of the self-consumption of the house other uses. To further increase the total self-consumption rate, it would therefore be necessary to integrate a control strategy taking into account the consumption of the whole house as well as the state of charge of the storage;
- System # 2, because of no thermal storage for heating, leads to much lower self-consumption rates than system # 1. The control strategies studied are therefore less appropriate or effective for this system;
- System # 1 with an excess PV sale contract and enhanced control strategies lead to an ROI of less than 15 years;
- System # 1 shows a much greater ability than system # 2 for self-consumption and PV production management.

By comparing the results obtained with the two systems, it emerges that thermal storage for heating is recommended in order to maximize self-consumption of PV electricity, which makes it possible to achieve an SPF in the order of 7 to 9. The results also showed that, for a thermodynamic system with heat storage for heating and DHW, a compromise between self-consumption and performance must be found depending on the storage volume and its set temperature. From this study, it can be concluded that, to improve the performance and self-consumption of the HP + PV system, it is first necessary to prioritize the development effort over the control strategy put in place, which allows self-consumption to be achieved.

NOMENCLATURE

A	Electricity contract price per year	(€)
E	Energy	(kWh)
e	Annual increase in the price of electric kWh	(-)
F	Electrify bill	(€)
f	Annual increase in the cost of the electricity contract subscription	(-)
g	Evolution of PV price exported to grid per year with total PV production sale contract	(-)
n	Number of years	(-)
p	Price	(€)
T	Temperature	(°C)
Ubat	surface heat loss coefficient	($W \cdot m^{-2} \cdot K^{-1}$)

Abbreviations	
AC	Air conditioning
COP	Coefficient of performance
DHW	Domestic hot water
ErP	Energy related products
HP	Heat pump
HPWH	Heat pump water heater
PCM	Predictive control model
PV	Photovoltaic
RHP	Reversible heat pump
ROI	Return on Investment
SPF	Seasonal performance factor
TURPE	Tariff of Use of Public Electricity Networks

Subscript	
100%	Total PV production sale contract
ex	Exported
imp	Imported
p	Peak
s	Set
sp	Excess PV sale contract
tot	Total

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