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Domestic Hot Water - an Energy Approach

Application of heat pumps for residential apartment buildings

Master of Science Thesis in the Master's Programme Structural Engineering and Building Performance Design

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Department of Energy and Environment
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Cover:
Apricus for solar hot water - http://www.switchenergy.co.nz/index.cfm/1,300,0,0.html

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ABSTRACT

Heat pumps for production of Domestic Hot Water are getting more and more common in residential apartment buildings because of their interesting coefficient of performance. In order to increase energy savings, not only the heat pump but the whole system was considered - from the energy source to the production and distribution systems and finally the usage.

In the current project, three systems have been analyzed to produce hot water for residential apartment buildings. The goal was mainly to achieve a consumption of less than 15kWh of primary energy per square meter per year, while caring about the comfort and the cost for the user. The first system is a gas production with half accumulation storage defined like the reference technology used in most of the residential apartments in France. This system was used later to assess the performance of two other heat-pump-based systems based on outside air, solar preheating, and use of the grey water heat. The evaluation tool was the software package TRNSYS.

The analysis of the systems was based on a definition of Domestic Hot Water demands previously performed by CTSB where this Master's thesis was performed. Therefore, the systems could be assessed for different water draws and weather files.

The results showed that the insulation of both storage and distribution is an essential parameter in the process of energy savings, especially in the case of a water circulation. Fumed silica and polyurethane allow for a significant reduction of heat losses and are a good compromise between heat loss reduction and investment cost. Special attention is required in the case of a variable compressor power, since a better insulation of the storage increases the water temperature of the tank and then decreases the heat pump performance. In those systems, it seems more appropriate to insulate the distribution better. This technology is in any case particularly relevant in the process of reducing energy consumption, since adapting the compressor power to the load will avoid permanent relaunching of the compressor.

In summary, the goal of 15kWh/m² per year is quite ambitious, even more so when considering financial issues. The two systems studied here showed that they could achieve this performance with the main measures of insulation and compressor power adaptation. The use of free energy combined with an accumulation system enables both to reduce the energy consumptions and to delay the drawing time from the production time. However, this analysis has been done mainly from an energetic point of view; it would be of further interest to analyze the results from a manufacturer's perspective to examine the feasibility of the recommended measures, and against the opinion of the electricity producer in terms of electricity's peak demand erasing.

Key words: Domestic Hot Water, heat pump, energy savings, accumulation tank, TRNSYS simulations

Contents

Preface

The following Master’s thesis analyzes the design and efficiency of different heat-pump based systems to produce domestic hot water in residential apartment buildings. The work was carried out between January to July 2012 within the project BBC PACS at Scientific and Technical Centre for Building (*CSTB in French*) in Paris in France.

This enriching and worthwhile experience at the well-known research center CSTB was possible thanks to my supervisor, Mr Charles Pelé, who offered me to work with his team on this very interesting project and I would like to thank him warmly. Besides, I would not have been able to conduct this work without the guidance and involvement of my co-workers, Mr Jean-Baptiste Videau and Mr Laurent Reynier, who have been at my sides to help me to get familiar with the topic and the tools, and fed the discussions by their insightful comments and valuable knowledge.

I would like to thank everyone at the department Energy from CSTB because all of them have welcomed me warmly in their teams and supported me by their advice and sympathy.

Finally, sincere thanks go to my examinor at Chalmers University, Mr Jan Gustén, who followed my work during the whole period and encouraged me by his constant support and confidence.

Paris, August 2012

Caroline Rocheron

List of abbreviations

ADEME Agency for Environment and Energy Regulation (*Agence de l'Environnement et de la Maîtrise de l'Energie in French*)

BBC PACS Heat pumps for low-consumption buildings (*Pompes à Chaleur pour Bâtiments Basse Consommation*)

CFE Consumption of Final Energy

COP Coefficient of Performance

CPE Consumption of Primary Energy

CSTB French scientific and technical research center for buildings (*Centre Scientifique et Technique du Bâtiment in French*)

DHW Domestic Hot Water (*ECS in French*)

EDF French Electricity producer (Electricité de France)

GDF French gas producer (Gaz de France)

HHV High Heating Value (used for gas heater efficiency)

kWh Kilowatt per hour

LHV Low Heating Value (used for gas heater efficiency)

OHTC Overall Heat Transfer Coefficient

PEF Primary Energy Factor

RT Means Thermal Regulation (*Régulation Thermique in French*) and is used the two regulations RT2005 and RT2012 released in 2005 and 2012

RTE French company handling the electricity distribution grid (*Réseau de Transport d'Electricité in French*)

SFP Seasonal Performance Factor

1 Introduction

In a context where sustainability and energy savings become increasingly greater issues, building performance remains as an important area for potential advancement. In France, buildings are responsible for 40% of the final energy consumption and 20% of the emission of greenhouse gases. Due to these figures, the government has developed a program, called *Grenelle de l'environnement,* to support the effort in energy savings with particular interest in the building design.

The new French thermal regulation released at the beginning of 2012 implies that every new residential building has to meet a maximum energy consumption of 50kWh per square meter per year of primary energy for heating, ventilation, lightening, hot water, air conditioning and auxiliaries for these purposes. The insulation materials have seen recently a large period of improvement in order to reduce the heat losses through the facades and thereby decrease the energy consumed for heating. Therefore, the weight of the energy consumption dedicated to Domestic Hot Water production has increased significantly by comparison with the one for heating, representing up to 50% of the total energy consumption in the case of well insulated buildings.

The common solution today to achieve low consumptions is to have recourse to solar collectors and individual heat-pump-based heaters. However, those technologies have their limits: they strongly depend on geographical locations and economical conditions, and are typically only applied in individual houses. Thus, research had to be done to extend those solutions to every kind of household and particularly to apartment buildings. This is the aim of this work to design DHW systems based on heat pump for apartment buildings respecting the main following objectives:

- An energy consumption for producing DHW including auxiliaries not greater than 15kWh of primary energy per square meter per year,
- An energy gain of two by comparison with a reference technology,
- And CO_2 emission of less than 350g per square meter per year.

To perform this work, it was first required to choose a reference system defined to be the most common system in French apartment buildings. Then, based on a definition for modeling the DHW demands, two heat-pump-based systems have been developed using the energy of outside air, ambient air, grey water and solar preheating. Simulations have been carried out with the software TRNSYS which simulates the interaction between components in an iterative calculation method based on a ten-minute time step. The simulations have been carried out over a year period in order to assess the systems' performance per year in terms of: consumptions of primary and final energies, instantaneous Coefficients of Performance, Seasonal Performance Factors, costs and comfort for the user.

Due to time restrictions, the investigation has been limited primarily to an energy approach, although other factors could have been considered, such as: attractiveness to the customer, investment payback or insertion easiness inside the building.

The study will show how the goals can be achieved by increasing the insulation of storage and tank, using preheating with free energies like sun and grey water, and by adapting the power of compressor to the load.

2 Project background

2.1 Context and goal of the project

As part of the program *Grenelle de l'environnement*[1], the Agency for Environment and Energy Regulation (ADEME) has been created in 1991 in order to enable the application of the governmental decisions. Regarding the application of DHW production, the ADEME asked for project teams to carry out studies and investigate different ways on how to achieve a reduction of energy consumption in hot water production in the residential sector. In return, the ADEME is supporting financially the projects which aim to lead at the end to a development of the industrial offer in term of domestic hot water production. One of the five projects to be accepted is called ***BBC PACS***[2] headed by the consortium composed by CSTB (Technical and Scientific Center for Building), EDF (French electricity producer), Atlantic (leading French company in HVAC engineering) and Armines (research center of the engineering school Mines de Paris).

As already mentioned in Introduction, this study aims to perform systems which are suitable to produce collective domestic hot water and have lower energy consumptions than the actual systems on the market. The goals pursued by the consortium are listed below:

- An **energy need for DHW smaller than 15kWh** of primary energy per square meter per year,
- An **energy gain** of two by comparison with a reference technology,
- A **payback period** smaller than half of the life expectancy of the system with a life expectancy of 15 years at least,
- And a **CO_2 emission** of less than 350g per square meter per year.

The following Master's thesis has been a part of the project BBC PACS and was performed at **CSTB** which is a public industrial and commercial establishment under the joint of the Minister of Housing and the Minister of Ecology, Energy and Sustainable development. CSTB works to support innovation and act as a trustworthy third party in the building industry to develop and share scientific and technical knowledge so that buildings follow the sustainable development challenges.

2.2 Choice of a promising technology

2.2.1 A heat pump

Each partner influenced the choice of the systems to fulfill its own interest, except **CSTB** which, like explained previously, adopts a middle-of-the-road position. **Atlantic** would like to stimulate the heat pumps' market and aims to produce a heat pump system which would be conform to the RT2012 and attractive to the clients. The system proposed by Atlantic and studied here is a solar system with Inverter

[11] Political program decided by the former president Nicolas Sarkozy in 2007 in order to encourage the sustainable development and energy savings.
[2] Stands for Heat Pumps in Low Consumption Buildings (*Pompes à Chaleur en Bâtiments Basse Consommation*)

technology. In this project, **Armines** owns a patent of a heat pump system based on the grey water heat recovery and would like therefore to develop and commercialize it. Finally, **EDF** has a double goal of producing a system which would be efficient and would enable to decrease the peak of electricity consumptions at some critical hours of the day.

To meet the goals of BBC PACS project and the interests of the different partners, a choice had to be made regarding the heating technology. Among gas, electricity and renewable energies, the consortium chose to bet on the efficiency of heat pumps. The choice of the heat pumps becomes natural for several reasons. First, the heat pump technology is based on thermodynamics effects which allow producing more energy than the energy consumed by the compressor. This efficiency is expressed by the **Coefficient of Performance** which is greater than 1, in contrast with gas or electric systems that have efficiencies smaller than 1.

Moreover, heat pumps have already shown that they were resistant in the application of refrigerant systems. Their **life expectancy** is more than 15 years and the potential reduction for the equipment cost is not negligible when considering the price evolution of refrigerators.

In addition, regarding the CO_2 objective of the project, the electricity provided to the heat pump usually does not come from a fossil energy which would increase the greenhouse gas emissions, like a gas heater for instance. Although, a debate can be opened for discussing the relevance of a nuclear plant which produces nuclear waste which is as problematic for environment as CO_2. But this is not accounted in the current political context and therefore it has not been considered in the discussion of this thesis.

For those reasons, heat pumps are particularly relevant for a DHW application and this explains why the consortium decided to place their hopes in this technology.

2.2.2 Use of an accumulation tank

Like any other DHW heating device, the heat pump can have different heating modes: it can be chosen to have an instantaneous production or an accumulation solution.

One main issue when designing heating devices is to regulate the electrical consumption and be able to cope with the peaks of demands which appear usually during cold winters. RTE, the electricity distribution company of France, released Excel files corresponding to the daily consumptions profiles for each month of 2011 (except December which was not available). They have been gathered and represented on graphs presented in Figure 2.1:

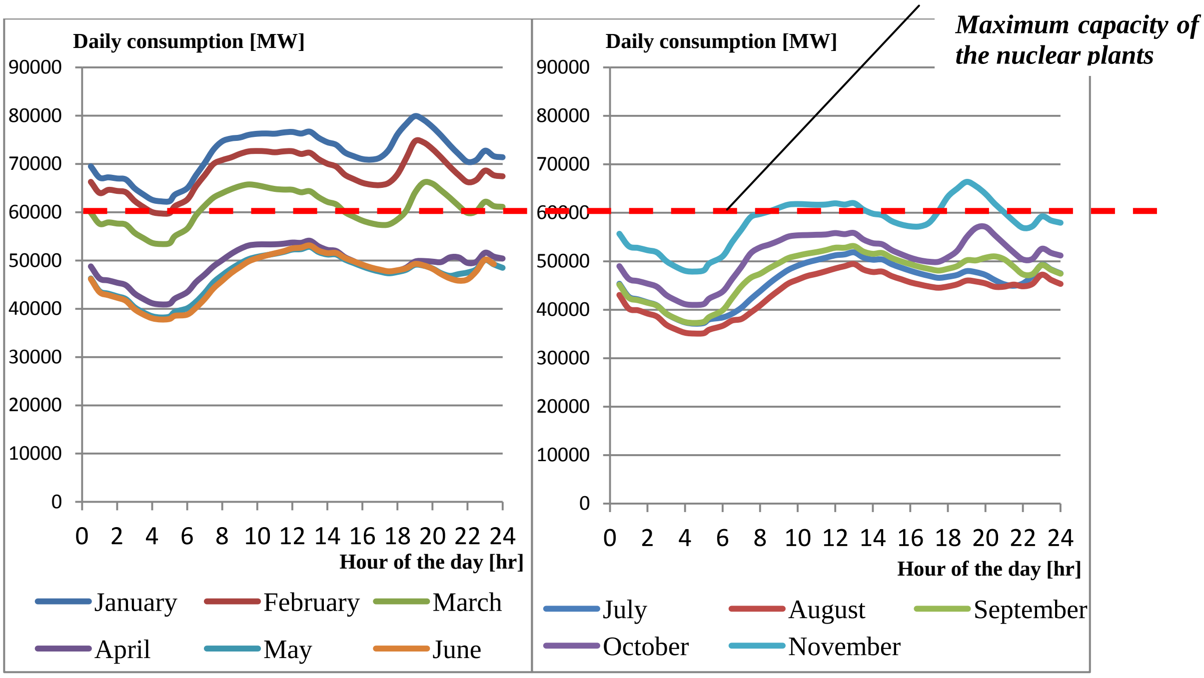


Figure 2.1 Daily consumption profiles for each month of 2011 in France [RTE-1 2012]

Those figures enable a better understanding of the problematic issue regarding the correlation between the production and the usage times. As a first reading, it can be observed that:

- From 0 to around 5am, the consumptions are rather low and decreasing to a minimum power (less than 40000MW). This low consumption is due to the nocturnal activity which is low, only the industries and some peak-off devices are in use at this time.

- Between 5 to 8am, the consumption curves are raising sharply to reach a quite stable consumption until 2pm. This corresponds to the beginning of the day when the users will require electricity for their personal hygiene in the morning, the re-run of heating and the use of electrical devices for cooking. The consumption of the day is then due to the professional activity.

- After 2pm, the consumptions decrease again, expressing progressive closing of the companies and reduction of professional usage.

- Between 6 to 8pm, another peak of consumption appears which corresponds to the second private usage of the day when people come back home.

- A last small peak appears at around 11pm, due to all the devices that are turned on during night to benefit from the preferential rate.

This has to be studied in parallel with the production capacity of the country. France can produce up to **60000MW with the nuclear plants**, as shown in Figure 2.2.

Beyond this, the thermal plants have to be called to fulfill the gap, which is not desired by EDF due to the heavy costs and the greenhouse gas emissions.

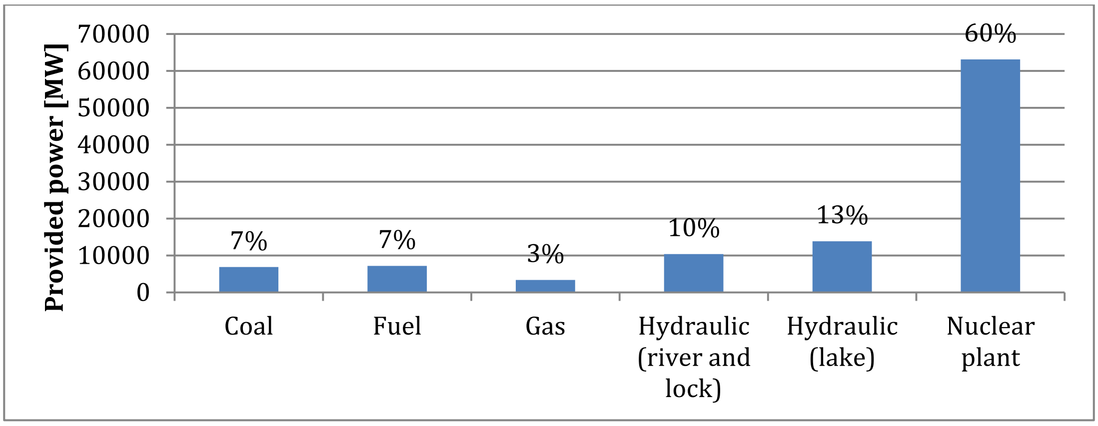


Figure 2.2 Individual reserve ratios of the French energy resource

Thus, coming back to Figure 2.1, it becomes obvious that due to the irregularities of the daily consumption, more electricity is needed from November to March which requires the recourse to the fossil fuels. An issue of this project will then be to study the possibility of asking for energy at off-peak times, to flatten the consumption demands and thus the energy production. This means promoting the energy consumption during night.

Regarding only the hot water demands, the peaks of consumption are usually observed in the morning and in the evening for personal needs when people are at home.

Consequently, trying to match the need of EDF to flatten the production curve and the comfort for DHW users at home, it becomes relevant to think of **an accumulation solution that will produce hot water during night at off-peaks hours** and guaranteeing comfort for the users when they are drawing water, since the water will be already hot and ready to be used.

The systems in this project will then focus on heat pumps related to an accumulation storage that will produce hot water independently from the usage time. To assess the capacity of the systems to face the demands, a definition of those hot water demands needs now to be given.

2.3 Definition of DHW demands

The starting point to be able to simulate and size the production systems of DHW consists in characterizing the consumption behavior of people, depending on several parameters such as the types of housing and inhabitants.

2.3.1 Principle and borders of the analysis

The definition of DHW demands can be very confusing due to the huge number of parameters which influences the consumption of the inhabitants. This is why a selection of the most relevant parameters has been done based on surveys of real consumptions. The work has been limited to the **residential area (individual houses and apartment buildings) in France**. This DHW demands model and the methodology have been performed by CSTB in agreement with the consortium [CSTB-1 2011]. The whole process carried out to give a DHW definition was not the aim of the Master's thesis here. Therefore, only the results of the models will be given here in order to continue with the heart of the work which was the simulation.

Besides, it must be noted that only the water consumed for **human hygiene, cleaning, kitchen and watering** have been considered, while the water used in the dishwasher and washing machine are disregarded, since those two devices have their own heating systems.

2.3.2 Hot water demand

Several documents coming from an important bibliography and giving results of surveys have been studied to be able to determine the total water volume consumed per person and per day in France, placed between 100 and 150l/(person,day). A global volume of **130l/(person,day)** has been chosen for both cold and warm water usages:

$$V_{total} = 130l \qquad (2.1)$$

The next step consists in evaluating the part of mixed water in this total volume. The results are based on a report made by CSTB [Zirngibl, François 2002]. A difference has to be made for a house, since water can be used outside for watering and cleaning.

Table 2.1 shows the repartition of this total water volume between the different usages for both a flat and a house.

Table 2.1 Partition of the water usages in a flat and in a house

Usage	**Part for each usage for a typical flat [%]**	**Part for each usage for a typical house [%]**	**Corresponding volume [m3]**
Bathroom	47	39	15
Toilets	32	27	10
Washing machine	9	8	3
Dish washing	6	5	2
Other internal usages (kitchen, cleaning, drinking)	6	5	2
External cleaning	-	4	1,5
External watering	-	12	4,5
Total	100	100	38 32 without the two last usages

Among all those usages, warm water will be used only for shower, bath, dishes and clothes. Depending on the type of housing and habits of people, the part of mixed water in the total volume varies from 45 to 60%. The part of mixed water is estimated at **45% in a house and at 55% in a flat**.

$$P_{mw} = \begin{cases} 0{,}45 \; if \; individual \; house \; (disregarded \; in \; this \; Master's \; thesis \\ 0{,}55 \; if \; apartment \; building \end{cases} \quad (2.2)$$

And finally, the last step will be to determine the part of hot water in the mixed water. Indeed, the mixed water is in average drawn at 40°C and the production temperature is usually higher. This last percentage depends therefore on the temperature of mixed water, of the temperature of hot water and the temperature of cold temperature. For the current project, the **temperature of usage has been fixed to 40°C.** Moreover, Figure 2.3 [Hilaire 2001] shows the evolution of the percentage of hot water in mixed water depending on the cold water temperature.

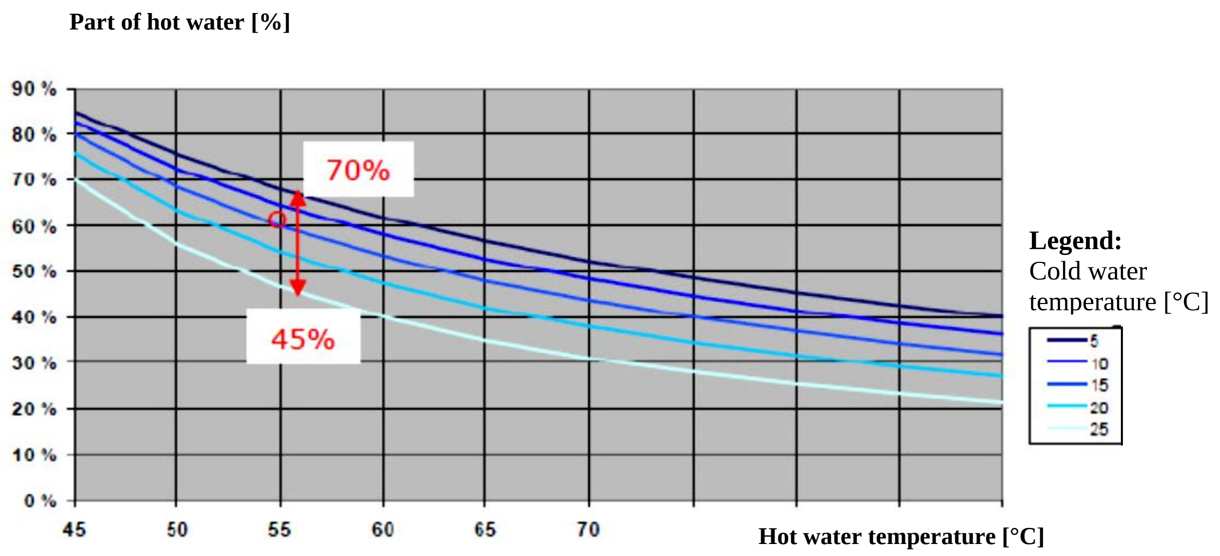


Figure 2.3 Hot water part in 40°C-mixed water depending on hot water and cold water temperatures

Based on this graph, a choice has again to be made: for a common stored **hot water temperature of 55°C**, the hot water part varies between 45 to 70%. An average cold water temperature of 15°C corresponds to a part of **60% of hot water in the mixed water**:

$$P_{hw} = 0{,}6 \quad (2.3)$$

The previous percentages enable to get the volume of hot water needed per person and per day, based on the total volume consumed per person. However, to be accurate, this total volume needs to be modulated depending on some parameters, such as the type of the housing which influence was shown in Table 2.1. This will be the topic of next paragraph.

2.3.3 Coefficients of modulation

As mentioned previously, the daily water demands depend on many parameters which are more or less independent. A selection of the most relevant ones has been made and the values given to them are based on the bibliography study made by CSTB [CSTB-1 2011]. The parameters that have been chosen are basically **the age of the person, the type of housing, the level of life, the price of water and the type of equipment**.

Thus, the volume of hot water at 55°C needed per person and per day can be expressed as below:

$$V_{55°C/day/person} = \left(V_{total} + \Delta V_{age} + \Delta V_{housing}\right) . P_{mw} . P_{hw} . C_{life\ mode} . C_{water\ price} . C_{equipment} \qquad (2.4)$$

Where:

$$V_{total} = 130l$$

$$\Delta V_{age} = \begin{cases} -60l \text{ if child} \\ +25l \text{ if adult} \\ -25l \text{ if old person} \end{cases}$$

$$\Delta V_{housing} = \begin{cases} +15l \text{ if individual house} \\ -20l \text{ if apartment building} \end{cases}$$

$$C_{life\ mode} = \begin{cases} 70\% \text{ if low level of life} \\ 100\% \text{ if normal level of life} \\ 130\% \text{ if high level of life} \end{cases}$$

$$C_{water\ price} = \begin{cases} 95\% \text{ if high or increasing price} \\ 100\% \text{ if stable price} \\ 105\% \text{ if low or decreasing price} \end{cases}$$

$$C_{equipment} = \begin{cases} 90\% \text{ if low} - \text{consumption technology} \\ 100\% \text{ if normal technology} \end{cases}$$

P_{mw} and P_{hw} are defined in the previous Equations (2.2) and (2.3)

Equation (2.4) allows a quite flexible variation of the water volume needed per day and can then be adapted to very different profiles of inhabitants. This first model will be useful to determine now the energy needed per day and required by the production system.

2.3.4 Energy demands for DHW

The previous paragraph translated the demands of hot water in term of a volume. It will now be expressed as a daily energy need to produce hot water at a temperature of 55°C.

This is basically the product of the water heat capacity times the volume times the temperature difference between the cold and hot water temperatures.

$$Needs_{Wh\ per\ day\ and\ person} = \rho . c . V_{55°C/day/person} . (T_{55} - T_{cold\ water}) \qquad (2.5)$$

Where:

$$\rho = 1kg/l \qquad (2.6)$$

$$c = 1{,}163Wh/(kg, K) \qquad (2.7)$$

$V_{55°C/day/person}$ is defined in the previous Equation(2.4)

$Needs_{DHW\ per\ day\ and\ person}$ is expressed in Wh per day and per person.

It is really important to notice here that this equation does not take into account the losses due to the storage and the distribution. Those losses will however increase the demands and will need to be considered later in the design.

Finally, a last modulation of this energy need can be done by looking at a need per hour and varying depending on the day of the week and on the month of the year.

2.3.5 Drawing profile per hour

Before assessing the systems with this new model, a last work needs to be performed regarding the repartition of this daily water volume on a smaller time step to be able to simulate later the performance of the technologies in an accurate way. In addition, a better accuracy would be achieved if the daily volume could be adjusted depending on the day of the week or the week of the year. This will be done by allocating a repartition key to the daily hot water needs calculated in Equation (2.5).

The study made by CSTB [CSTB-1 2011] proposed two profiles, one “variable” profile and one “less variable” profile corresponding to two different ways of water drawing. For each repartition, three coefficients were varying:

- One coefficient for the week in the year C_{week}: it enables to take into account the vacation weeks during which people are not home and the difference of needs between summer and winter (people usually consume less hot water in summer, preferring fresh showers for instance).
- One coefficient for the day in the week C_{day}: it has been noticed that water drawings are greater during weekend, since people spend more time at home.
- One coefficient for the hour of the day C_{hour}: peaks of consumption can be observed three times a day for meals and showers.

The final energy demand per hour is obtained by multiplying the daily demand in Equation (2.5) by those three coefficients:

$$C_{repartition\ per\ hour} = C_{week} . C_{day} . C_{hour} \qquad (2.8)$$

Consequently:

$$Needs_{Wh\ per\ hour\ and\ person} = Needs_{Wh\ per\ day\ and\ person} \cdot C_{repartion\ per\ hour} \quad (2.9)$$

Unlike individual houses, the probability of simultaneous drawings has been taken into account in those coefficients. A simultaneous coefficient reduces the peak value but increases the period of water drawing.

The **standard "less variable" profile** was chosen in the analysis carried out in this Master's thesis. Basically, the volume of drawn water is the same between the profiles but in the chosen drawing profile ("less variable" profile), the repartition is more stable and regular: each day of the week and each week of the year are the same, the coefficients being equal to one. The daily profile predicts three water drawings, in the morning, at lunch time and in the evening. For a reason of confidentiality, the tables of coefficients (see Appendix 8.2) cannot be all provided in this report.

The last step in preliminary work consists in listing and assessing the possible heat temperatures for the systems. This will be done in the next section.

2.4 Choice of the relevant heat sources

The performance of a heat pump system is strongly related to the choice of the energy sources that can be from different origins in different quantities and at different temperatures.

The different possibilities had already been studied in the project BBC PACS before the beginning of this Master's thesis. In the current section will be made a short summary of the main conclusions coming out from the study made by CSTB [CSTB-2 2011].

Each energy source has its own advantages and disadvantages, and is applied at different temperature ranges. The main conclusions are summarized in Table 2.2.

Table 2.2 Pros and cons of different energy sources

	Outside air [3°;40°C]	Solar collectors [0°;140°C]	Grey water [20°;55°C]	Ambient air [15°;35°C]	Air in attic and crawlspace [3°;35°C]	Close geothermal [3°;25°]	Deep geothermal [3°;20°C]
+	Infinite source Low investment	Very high temperature	High temperature Large quantity	Relatively high temperature Latent heat because of inside humidity	Relatively high temperature	High temperature in summer No risk of ground discharge	Relatively high and very stable temperature
-	Defrosting cycles necessary	Cannot be the same in every location Depends on the season: will be oversized in summer and undersized in winter	Requires a treatment of grey water before storing it Insulation needed on the grey water pipes Additional storage tank for grey water (cost, place)	Limited flow rate → the system has to be adjusted, so that the room does not get cold but has time to be re-heated	Higher heating demands depending on ceiling and floor insulations Requires special installation with unoccupied attic and crawlspace	Large space required for horizontal geothermal probes	Limited quantity → the soil can be completely discharged if the demand is too high High investment

The outside air should be used at more than 3°C to avoid frost inside the evaporator. The solar collectors can support a fluid temperature from 0° to 140°C. Regarding the use of grey water, some studies have been done[3] and show that the temperature of the water that can be reused after usage is in average at 30-35°C. The system studied here does not take water under 20°C; explanations of this system will be given later in Chapter 4. Ambient air usually is at around 15 to 20°C while air taken from attic or crawlspace can vary a lot during the year. Finally, geothermal probes will be subjected to a quite stable temperature of the ground at around 12°C. Disregarding the solar case, it can be observed that the grey water has a very high temperature and high potential heat for a heat pump.

Combining the advantages and disadvantages of the different cold sources and their temperature ranges, it seems to be promising in the case of apartment buildings to choose the following sources:

- Outside air (for its large availability)
- Solar collectors (for its free energy and easy preheating system)
- Grey water (for its high temperature in large volume)

[3] Principles and data of this system come from the results of the studies conducted by Armines.

- Geothermal (for its stable temperature)
- Ambient air (for its availability and relatively high temperature)

The systems studied in this Master's thesis are listed in Table 2.3, as well as the systems for the individual house for information which will be studied later by the consortium.

Table 2.3 Reference systems and heat pump systems for house and apartment buildings

Individual house	Apartment buildings
1. Reference system: electrical accumulation water tank 2. Normal heat pump on external air 3. *Heat pump placed in crawlspace, reuse of the air of the ventilation and sun-heated attic* 4. *Geothermal heat pump*	1. Reference system: gas production with semi-accumulation 2. Solar heat pump with reuse of exhaust air for the hot water circulating (developed by Atlantic) 3. Heat pump using the heat from waste water (developed by Armines) 4. Geothermal heat pump

Legend: Grey: Not presented in the current report ; *Italic → not simulated yet*

The following Master's thesis proceeded in two steps, first working on individual houses to get familiar to the design and simulation methods, and then working mainly for apartment buildings. A geothermal model was also developed but unfortunately did not show good performance. Difficulties were encountered regarding the component chosen on TRNSYS to simulate a geothermal borehole and which was not enough accurate or adapted to the model. Therefore, for reasons of consistency and concision, the report here will **focus only on the three first systems for apartment buildings, which means the reference gas system, the solar system and the grey water system.**

This last paragraph provided a justification of the choice made by the consortium regarding the systems to be studied. The simulations on TRNSYS are supposed to confirm this first assessment. But before, Chapter 3 will shortly present the software used, TRNSYS, as well as the assumptions made for the simulations.

***

The first chapter enabled the reader to understand the context and the area of development in which the current Master's thesis was inserted. Next chapter will present the simulation software TRNSYS, as well as the general assumptions made for design and calculations.

3 Simulation tool TRNSYS

Based on the previous analysis of the DHW demands and the available energies, the work consisted first in realizing some models of hot water production and performing dynamic simulations to evaluate their capacities to answer to the demands. TRNSYS was the software used to simulate the systems.

3.1 TRNSYS, a simulation software

TRNSYS is a software package for energy simulation that has been created and developed for around 35 years. It enables the user to simulate the behavior of transient systems and assess their performance. Mainly used for buildings, it can simulate very different kinds of systems, from the reduced scale of a pump to the large scale of a whole building.

To create a model, the user has to pick and connect graphically components that are already created and available in the TRNSYS library. Each type of component is described by a mathematical model in the TRNSYS simulation engine. The user needs to provide the parameters of each component and connect them by their inputs and outputs.

The engine will then run the input file following an iterative method. At each time step, the software solves the system and calculates the convergence rate. If the system does not converge, it will warn the user and stops the simulation. The outputs can be from different formats, Excel files, normal and online plots.

As said previously, the components are chosen from a library. The TRNSYS library includes around 150 standard components. However, other libraries have been developed to improve the standard components. TESS libraries have been used in this work to be able to simulate more accurately some systems. Besides, if one component is unique and cannot be found in the libraries, it is still possible to create a component and import it to TRNSYS through an application which is called ***W Editor***. This is done by writing the behavior of this component in the W language which is very basic to use. The variable compressor of the solar system of this study has been described by polynomials written in W Editor.

The TRNSYS package comes with a suite of tools. Once the model is created on TRNSYS, it is common to import it to **TRNEdit** to be able to run parametric simulations. If there is any need of change in the system, it is possible to access to the input file and re-write it if it is not too complex before running again the simulation.

And finally, once the system is reliable, a last application called **TRNSED** can be used to create a customized graphical interface to be able to diffuse it later to non-TRNSYS users. In this project, it has been useful to distribute the designed systems to the partners of the project, EDF, Atlantic and Armines.

CSTB chooses to use this software because of its flexibility and easy programming environment. The last library has been actually developed by CSTB to be able to produce W components and CSTB is now responsible for the distribution of TRNSYS in Europe.

3.2 Assumptions and background of the simulations

Before starting the simulations, some decisions had to be done regarding the general design, the climate data, the calculation assumptions and methods.

3.2.1 Design assumptions

- **Hot water needs**

The hot water demands have been described previously as a volume at 55°C drawn at each hour, depending on the type of inhabitants. However, it is rarely the case that the temperature of the tank is at exactly 55°C. Therefore, instead of talking in a term of a volume, this volume at 55°C has been converted into an energy need at each hour.

Thus, a special component in TRNSYS has been added to take the temperature at the top of the tank and calculate **the demands based on the temperature of the tank**. This temperature is held from the previous time step to avoid convergence problems. This trick does not have any impact on calculations, since the water does not change a lot within one time step (10 minutes here). Subsequently, the flow can vary but the amount of energy is the same: if the temperature of the tank is below 55°C, more hot water will be drawn in order to be able to dispose of a mixed water à 40°C for a fixed cold water temperature, and vice-versa. Therefore, this method enables to take into account the heat losses inside the tank.

More precisely, the flow rate required at each time step is equal to the energy calculated in the previous Equation (2.9) and divided by the real tank temperature:

$$\dot{Q}_{l/hour/person\_at\ tank\ temperature} = \frac{Needs_{Wh\ per\ hour\ and\ person}}{\rho.c.(T_{tank\ at\ previous\ time\ step} - T_{cold\ water})} \quad (3.1)$$

Moreover, heat losses also occur in the distribution pipes. The secondary heater of the water circulation will offset the heat losses occurring in the loop by heating again to reach 55°C. This extra energy will then be added automatically. However, the heat losses happening in the individual pipes of each flat will influence the demands of the users as well: indeed, if the water stored in the pipe has reached the ambient temperature, the user will draw more water until getting a hotter temperature.

To consider this phenomenon, it could have been chosen to calculate the needs at each time step based on the temperature of the pipe at the previous time step, developing the same method than explained in the previous paragraph. However, this has been tested and gave wrong results for two reasons:

- *The large calculation time step:* before each new drawing, the water temperature inside the individual pipe has reached the ambient temperature. The demand is re-calculated based on this temperature and the volume is increased to get the same energy during the whole time step of 10 minutes. This behavior of the model is not correct, since in the real case, the temperature of the pipe will rise much faster than 10 minutes and after some seconds, the water reaches the desired temperature, which reduces the volume of hot water drawn. The model is therefore calculating a discomfort for the first 10 minutes of each drawing.

- *The different behavior of the real user*: in real case, the user does not use the water at ambient temperature but waits for the water to reach the desired temperature. This means that extra water is needed each time and that the water stored inside the pipe is necessarily wasted heat. This has to be added to the primary demands.

Consequently, the method chosen here has consisted in taking a coefficient to increase the demands to take into account the losses that cannot be avoided inside the individual pipes. Based on a study in real apartments made by CSTB and presenting the impact of the different types of insulation on the heat losses occurring in the storage and distribution pipes [CSTB-3 2012], a coefficient could be determined as:

$$C_{heat\ losses\ in\ individual\ pipes} = 1{,}06 \quad (3.2)$$

This coefficient is then multiplied by the theoretical demands to **increase by 6%** the energy needs asked to the system. The final demand including the temperature of the tank and the heat losses in the individual pipe is then equal to:

$$\dot{Q}_{l/hour/person\_final} = \dot{Q}_{l/hour/person\_at\ tank\ temperature} \cdot C_{heat\ losses\ in\ individual\ pipes} \quad (3.3)$$

This last expression represents the energy that will be sent to the main heating system. Since the demand here is calculated for one hour, TRNSYS divides this need by 6 to get the demand for each time step of 10 minutes.

- **Storage**

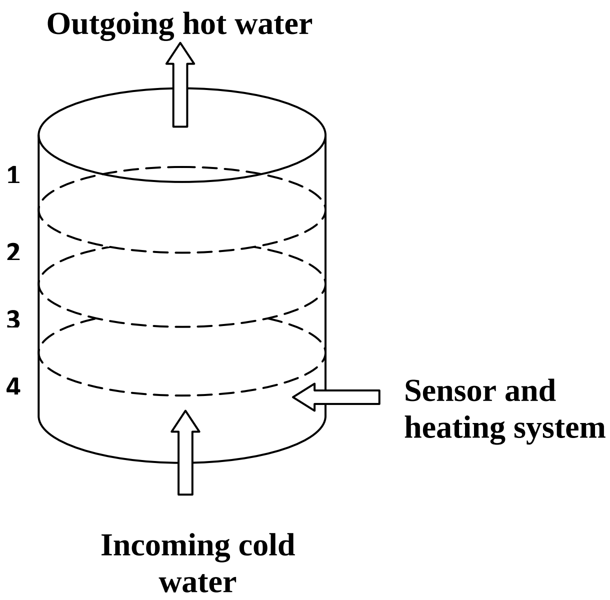


Figure 3.1 Model of a stratified tank

The tank storing DHW needs to be **stratified**. This means that there will be a gradient of temperature rising from the bottom to the top. This stratification enables a better comfort for the user who will draw water from the top that will have a higher temperature than at the bottom. Moreover, a low temperature will increase the coefficient of performance of the heat pump if this one is heating at the bottom of the tank. The TRNSYS component simulating the tank has been chosen to be divided in four nodes of temperatures, like shown in Figure 3.1.

The design has been chosen with the following characteristics:

- The height of the cold water inlet **at the bottom** of the tank to respect the stratification.

- The height of the outlet for water drawings **at the top** of the tank for the same reason of stratification.

- The height of the **heating system** (electric or gas heater, heat exchangers) that is **at the bottom** and will heat progressively the bottom to reach the same temperature up to the top.

- The height of the **temperature sensor at the bottom** of the tank. This is necessary especially in the case of a night-heating when the tank needs to be fully at the setpoint temperature at the end of the heating to be sure that this will cover the daily needs.

- **Uniform heat losses** all around the tank.

- An **ambient temperature of 20°C** assuming that the storage is located in a heated space in the building.

▪ Production system

The setpoint temperature for heating systems has been **set to 55°C** in every case. An hysteresis phenomenon can be then added to modulate the starting and stopping times of the heating device.

▪ Collective distribution

Two ways are possible to distribute water to apartments: a simple direct distribution or a water circulation. They are illustrated in Figure 3.2:

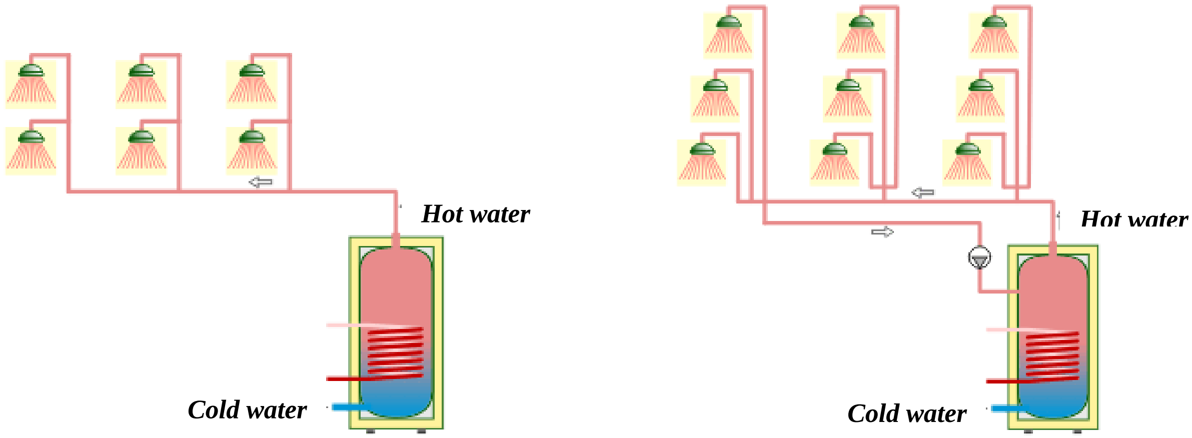


Figure 3.2 Direct water distribution (on left) and water circulation (on right) [Cellule Architecture et Climat 2012]

In apartment buildings, a **hot water circulation** is necessary to respect the waiting time at the usage and afford a better comfort to the user. Two main configurations of circulation are possible, horizontal or vertical distributions, like presented in Figure 3.3.

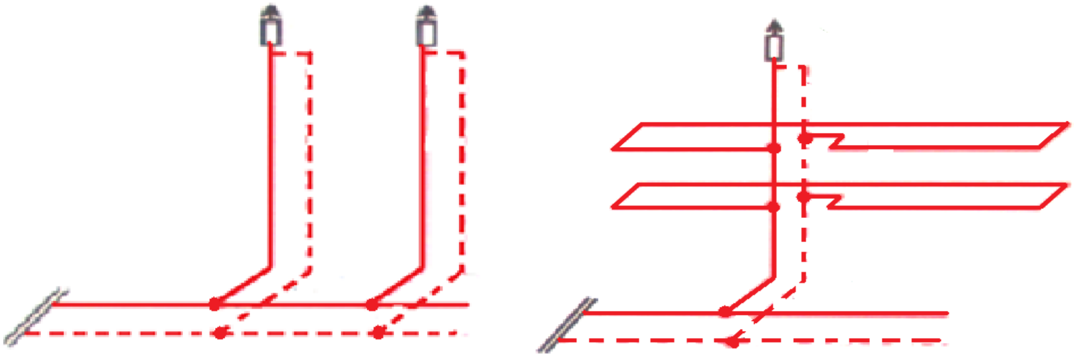


Figure 3.3 Vertical loops (left and horizontal loops (right)

The goal of simulating the distribution is to evaluate the comfort at drawing for the inhabitant. Since the simulation system should be used for different geometries of buildings, it is not possible to provide a model which performs the accurate design of the hot water circulation in each case. Instead, the choice has been made to design one **unique and basic loop with one pipe to the user, and another one back to the production system**.

The pipe material is chosen to be **cupper** because of its rigidity property which makes it easier to build a network in the whole building. Moreover it is meant to limit the bacteria development.

The French regulation (and more precisely the CCTG [Ministry of Ecology, Sustainable development and Energy 1991]) imposes some rules to design the diameter of the pipes. Depending on the flow rates of each distribution, the diameter will change to respect a minimum and a maximum speeds. This is given in Table 3.1.

Table 3.1 Dimensioning of the pipe diameters

	Inner/outer diameters	Minimum flow rate in m3/hr (left) for the minimum speed of 0,2m/s (right)		Maximum flow rate in m3/hr (left) for the maximum CCTG speeds (right)	
Cupper	14/16	0,1		0,3	0,55
	16/18	0,15		0,45	0,6
	20/22	0,25		0,8	0,7
	26/28	0,4		1,35	0,7**
	33/35	0,6		2,15	0,7**
	40/42	0,9	0,2	3,15	0,7**
PVC	DN15 - 15,4/20	0,15		0,4	0,6**
	DN20 - 19,4/25	0,2		0,75	0,7**
	DN25 - 24,8/32	0,35		1,2	0,7**
	DN32 - 31/40	0,55		1,9	0,7**
	DN40 - 38,8/50	0,85		3	0,7**

As said before, the accurate flow rate is not known in this project but will change from one application to another. The choice of the diameter had to be fixed however to be able to fit for most of the cases. It was decided to choose a rather large pipe, since it is representing the main circulation, which means the largest flow of the whole distribution system. Consequently, two pipes of **50 meters each** have been chosen with an inner/outer diameter of **33/35mm**.

The same regulation from the CCTG requires a minimum insulation for circulating water pipes. It can be deduced from Table 3.2 that it corresponds for a cupper 33/35 pipe to **25mm of foam rubber (λ = 0,042 W/(m.K))**.

Table 3.2 Dimensioning of the pipe insulation

	Diameter (mm)	Heat loss coefficient in W/mK								
		Safe limit	Reference	Foam rubber Thickness (mm)					Mineral wool Thickness	
				9	13	19	25	32	25	30
Stain less steel	DN15 - 16,7/21,3	0,29	0,26		0,27	**0,22**	0,20	0,18	**0,18**	0,17
	DN20 - 22,3/26,9	0,31	0,27			**0,26**	0,23	0,20	**0,21**	0,19
	DN25 - 27,9/33,7	0,33	0,29			0,3	**0,26**	0,23	**0,24**	0,21
	DN32 - 36,6/42,4	0,36	0,31			0,35	**0,30**	0,26	**0,27**	0,25
	DN40 - 42,5/48,3	0,38	0,33				0,33	**0,28**	**0,30**	0,27
	DN50 - 53,9/60,3	0,42	0,36				0,38	**0,33**	**0,35**	0,31
Cupper	14/16	0,27	0,24	0,27	**0,23**	0,19	0,17	0,15	**0,15**	0,14
	16/18	0,28	0,25		**0,24**	0,20	0,18	0,16	**0,16**	0,15
	20/22	0,29	0,26		0,28	**0,23**	0,20	0,18	**0,18**	0,17
	26/28	0,31	0,27			**0,27**	0,23	0,20	**0,21**	0,19
	33/35	0,34	0,29			0,31	**0,26**	0,23	**0,24**	0,22
	40/42	0,36	0,31			0,35	**0,30**	0,26	**0,27**	0,25
	52/54	0,40	0,34				0,35	**0,31**	**0,32**	0,29
PVC	DN15 - 15,4/20	0,29	0,25	0,28	**0,24**	0,20	0,18	0,16	**0,17**	0,15
	DN20 - 19,4/25	0,30	0,27		0,28	**0,23**	0,20	0,18	**0,19**	0,17
	DN25 - 24,8/32	0,33	0,28		0,32	**0,27**	0,23	0,21	**0,21**	0,20
	DN32 - 31/40	0,35	0,30			0,31	**0,27**	0,23	**0,24**	0,22
	DN40 - 38,8/50	0,39	0,33			0,35	**0,31**	0,27	**0,28**	0,25
	DN50 - 48,8/63	0,43	0,36			0,41	**0,35**	0,31	**0,33**	0,29

Finally, a **circulation pump** is added to the system. The nominal flow of the pump is calculated to obey to two rules. First, it has to be so that the heat losses do not generate more than **a five-degree decrease** during one loop, based on the standard level of insulation described previously. When there is no water drawing for more than the time for the water to make one loop, the temperature of the distribution will decrease below 50°C and a re-heating system has to be added. The ways to perform those systems will be given in Chapter 4.

The formula to get the pump flow rate can be written as in Equation (3.4):

$$\dot{Q}_{pump}\left[\frac{m3}{h}\right] = \frac{P[kW]}{1{,}163.\left(T_{departure} - T_{return}\right)} \qquad (3.4)$$

Where:

$\dot{Q}_{pump}$ is the flow rate of the pump in m3/h

$1{,}163.\left(T_{departure} - T_{return}\right).\dot{Q}_{pump}$ is the energy that we fix to be equivalent to a temperature loss $\left(T_{departure} - T_{return}\right)$ of 5°C

P represents the heat losses through the circulation and is calculated by:

$$P = L.k.(T_{DHW} - T_{ambiant}) = 610\ W \quad (3.5)$$

With $L = 2 \times 50\ m = 100\ m$, $k = \frac{0,042}{0,025}.2\pi.\frac{0,033}{2} = 0,174\ W/mK$ for 25mm of foam rubber on a 33mm-diameter pipe and $T_{DHW} - T_{ambiant} = 55 - 20 = 35°C$

The first condition for the flow rate is then: $\boldsymbol{\dot{Q}_{pump} > 105\ l/h}$ (3.6)

The second condition is related to the minimum and maximum speeds allowed in the pipes. The French rules indicate the limitations already presented in the previous Table 3.1.

Referring to this table, for a cupper pipe 33/35, the minimum velocity is 0,2 m/s in the starting distribution, while the maximum velocity is 0,7 m/s in the return distribution. This means that the pump has to keep a flow rate between 615 and 2150 l/h.

$$\boldsymbol{615\ l/h < \dot{Q}_{pump} < 2150\ l/h} \quad \textbf{(3.7)}$$

The resulting condition of (3.6) and (3.7) is that the flow rate will be **615 l/h**.

- **Individual distribution**

One horizontal three-meter long cupper pipe (14/16mm) is added at the end of the first collective distribution pipe. This diameter is indeed a standard diameter for individual distribution.

The insulation of individual distributions is very rarely done in real buildings because of the small part of the heat losses taking place at this part of the distribution by comparison with the whole system. It was then decided to **focus only on the insulation of the collective distributions** and not to test different levels of insulation in this study, even if the interfaces provided to the partners at the end of this project let them free to change it.

It is important to keep in mind that the coefficient presented in Equation (3.2) takes into account the heat losses. If any insulation was provided on the individual distribution, it would be necessary to reduce the heat demands by a coefficient between 0 and 6%.

3.2.2 Climates

In order to compare the impact of different geographical areas, two climatic areas have been chosen among the four available ones that were Trappes, Nancy, La Rochelle and Nice (see Figure 3.4). Only **Trappes (standard oceanic inner climate) and Nice (hot Mediterranean climate)** have been tested in this study due to time restriction.

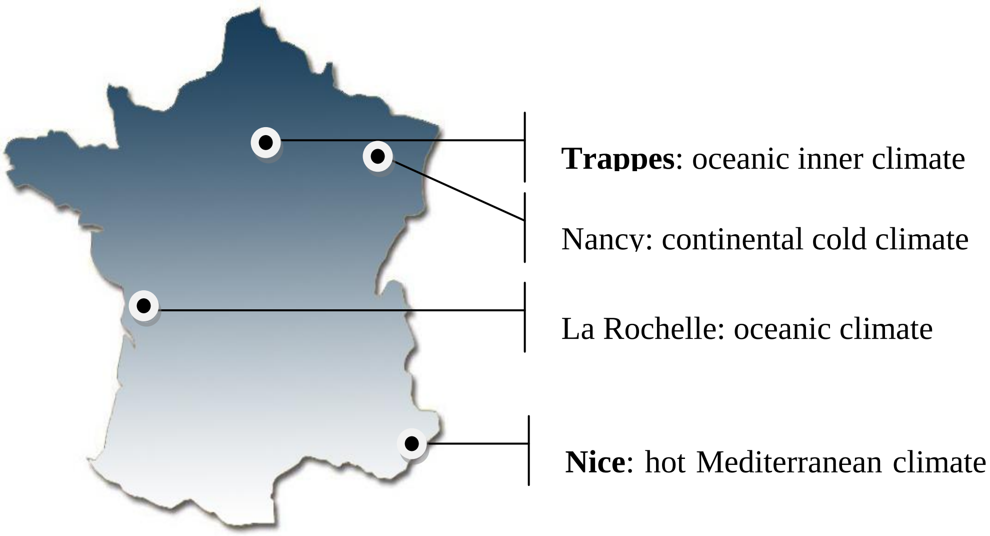


Figure 3.4 The four climate areas

Those weather files give the external temperature, the temperature of the ground at one meter deep and the sun radiations. The assumption has been made to consider the temperature of cold water equal to the ground temperature. Those files are provided by the national meteorological service MétéoFrance which updates them for each new thermal regulation.

3.2.3 Energy costs

The costs for electricity are the ones updated in January 2012 on the website of the French electricity producer [EDF 2012]. Depending on the usage of people, it is possible to choose between three main types of fee:

- The basic fee (called *Option Base*) provides a constant price of electricity per kWh plus the price of the subscription.
- The night-time fee (called Option *Heures pleines/heures creuses*) proposes to the users to pay less during the night which is generally defined as 8 hours per night, starting at 22, 23 or 24pm depending on the area.
- The last varying fee (called *Option Tempo*) makes not only the difference between night and day time but also between more or less loaded days which can be blue (the less expensive), white or red (the most expensive).

A special component in TRNSYS makes it possible to choose the type of fee, as well as the power required in kVA and the type of price: regulated (which means fixed by the government) or determined by the market.

For the gas reference system, the cost of gas has been picked out from the website of the French gas producer [GDF 2012] which proposes four fees depending on the usages again and two modulations, regulated or determined by the market again. In residential buildings with hot water produced by gas, only the fees B0 and B1 are of interest: B0 covers the DHW consumption while B1 covers both heating and DHW consumptions.

3.2.4 Calculation assumptions

The goals of the project are given as primary energy consumptions. The one that the user consumes and pays is directly the energy used by the local system at home and this form is called **final energy**. However, the whole system of energy production has losses in the production process and in transportation from the production place to the final house of the user. The total energy at the starting point in the extraction and production place is called **primary energy** and is usually greater, since it takes into account this conversion efficiency. The converting coefficient is called the **Primary Energy Factor**.

Besides, the different energy sources are responsible of different **amount of CO_2 released** in the atmosphere. The electricity produced in France is mainly based on nuclear plants, which will produce less CO_2 than gas.

To summarize in Table 3.3, the following coefficients are imposed by French regulation:

Table 3.3 Conversion coefficients

Energy form	Final energy	Primary energy	CO_2 emission
Electricity	1 kWh	2,58 kWh	40 g/kWh of final energy
Gas	1 kWh	1 kWh	205 g/kWh of final energy

An additional criterion has been assessed in the simulation, which is **the comfort at usage**. This is aimed to detect the times where the water is drawn at a temperature less than the comfort temperature. To perform this calculation, the bibliographic research made in the CSTB report [CSTB-1 2011] about the different temperatures of water demanded in different usages shows that the average temperature asked for hygiene, washing, cleaning and dishing is about 40°C. Thus, the comfort has been defined in this project as a **percentage of the total time in the year when the temperature after the individual distribution is less than 40°C**, divided by the total time of effective water drawings.

In TRNSYS, each time step where the temperature is below 40°C is integrated all over the year, so that the simulation returns the number of hours that did not satisfy the demand. And it is then divided by the number of hours of water drawings in the year, as presented in Equation (3.8):

$$Comfort = \frac{\int Time\ steps\ when\ t_{after\ individual\ pipe} < 40°C}{\int Time\ steps\ where\ water\ drawing\ \neq 0}\ [\%] \quad (3.8)$$

This indicator should be more considered like a way of comparing the system than to get a precise idea on the reliability of the system which can be defined in some other ways. It was one way to get a first rough estimation of the comfort but it could be of further interest to reduce the time step and measure a more accurate indicator. Besides, it also enables to assess the capacity of a system to answer to larger needs than the ones it is sized for.

3.2.5 Simulation assumptions

TRNSYS gives the choice of the time step of calculation. As seen in Chapter 2 and more specifically in Section 2.3, the DHW demands have a profile per hour, like it is the case in the Thermal Regulation RT2012. However, it is interesting here to reduce the time step to a smaller scale to be able to analyze the behavior and reactivity of systems when controlling the temperature level. To be able to measure this phenomenon, **a time step of 10 minutes** has been decided for the simulations. It is still a bit large by comparison with the real time of a water drawing but this is better than what is done in the regulation RT2012 and a compromise had to be done between the accuracy and the total time of simulation which can be long for one year, depending on the complexity of the system.

***

The background of the simulations has now been detailed with the main assumptions for the design of the systems in general. It is important to remember that an energy demand per hour will be sent to a heat pump which will be tested for apartment buildings only but for different cold sources. In the following chapter, the systems to be simulated will be introduced and described one by one.

4 The models

The idea of the simulations here consists in assessing the performance of the systems developed by Atlantic and Armines regarding the goals of the project compared to the reference gas system.

4.1 Reference gas system

4.1.1 General design

As already explained earlier, a reference system needs to be defined to compare the gain performed by the heat pump systems. In the context of the project BBC PACS, the reference system had already been decided. Based on statistics coming from the French institute of statistics INSEE[4] and on feedbacks from the actual buildings, it was determined that the most representative system for DHW production in apartment buildings was **a gas heater providing heat to a semi-accumulation storage tank**.

This system is an intermediate solution between a complete accumulation system which requires lots of space and an instantaneous system which does not need any storage but needs a high heating power. The semi-accumulation system has for main characteristic its capacity to cover the peak demand during 10 minutes without starting the power. For longer demand, the gas heater will start heating the water.

The living area has been fixed to be **1380m² divided in 20 flats**. The thermal regulation RT2012 gives a model relating the living area to the number of equivalent adults living in this space (see Appendix 8.2). Thus, the regulated calculation indicates that each apartment of **69m²** will be occupied by **1,9 equivalent adults**, which makes 38 adults for the whole surface.

A **500-liter-tank** provides hot water for this building with a loss coefficient of **0,196 Wh/(l.K.day).**

[4] Institut National de la Statistique et des Etudes Economiques in French. Stands for the National Institude of Statistics and Economical Studies.

The system designed on TRNSYS is shown in Figure 4.1:

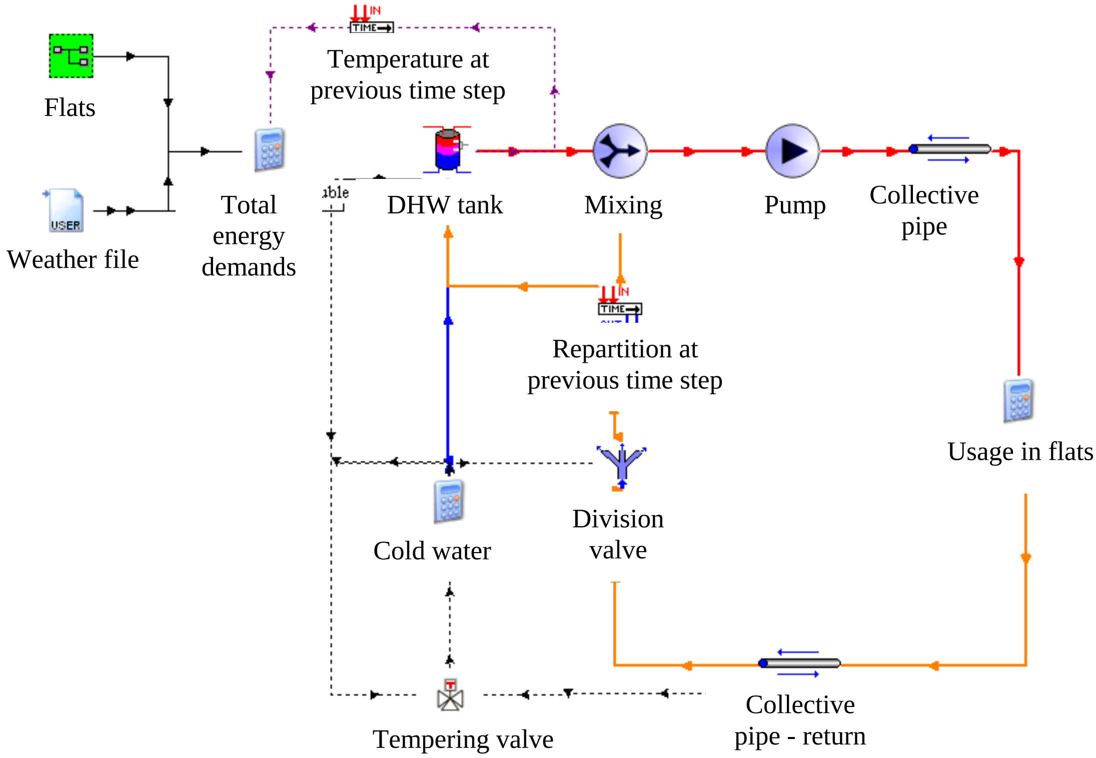


Figure 4.1 Reference system (TRNSYS assembly)

The energy demands are calculated based on the information given in the components Flats and Weather. This energy is sent to the tank which distributes the hot water inside the water circulation. The water circulating inside the loop is the mix of the water coming back from the loop and possibly some hot water coming out of the tank when any drawing occurs.

Besides, a system of repartition of the return water flow distributes the flow between the tank and the loop to ensure the stability of the temperature inside the circulation. This will be described in next section.

4.1.2 Detailed characteristics per component

- **Gas heater**

The guidelines report from the Association des Ingénieurs en Climatique, Ventilation et Froid [AICVF 2004] gives a dimensioning method to calculate the volume and the power required in the case of a semi accumulation system. This is the method followed below.

Using the model of DHW described in Section 2.3 (more precisely in Equation (2.4)), the daily standard volume per adult in apartment building is calculated as below:

$$V_{hot\ water\ at\ 55°/pers.day} = (130 + 25 - 20).0{,}55.0{,}6.1.1 = 44{,}55\ l \qquad (4.1)$$

For 20 flats of 1,9 adults each, it represents a volume of 1693 liters per day. In a half accumulated system, the volume of the tank has to be around **one fourth of this daily need**. A tank of **500 liters** is then well adapted. This justified the design made by the consortium for the reference volume.

As said previously, the power of the heater has to be sufficient to cover the needs when the peak demand exceeds 10 minutes. It is then needed to calculate the peak volume and the peak duration. Assuming a total volume of 150 liters of hot water needed per apartment and per day, the method indicates the peak volume to be 75% of this demand multiplied by the number of apartments:

$$V_{peak} = 0{,}75.150.N_{apartments} = 2250\ l\ for\ 20\ flats \quad (4.2)$$

The duration of the peak demand is described by an exponential equation based on a statistic study in typical apartment buildings performed by the AICVF and depends on the number of apartments.

$$t_{peak} = 5.N_{apartments}^{0,905}/(15 + N^{0,92}) = 2{,}45h\ for\ 20\ flats \quad (4.3)$$

The principle of the semi accumulated system ensures that the tank is enough to provide the first 10 minutes of the peak demand. The power of the gas heater has to be able to provide the remaining energy for all the duration of the peak period. Consequently, the heater power is calculated by:

$$P_{gas\ heater} = 1{,}16.\left(V_{peak} - V_{storage}\right).(55 - t_{cold\ water})/t_{peak} \quad (4.4)$$

For a tank of 500 liters and an average cold water temperature of 10°, the power required is of around **37 kW**.

The gas heater injects the heat directly inside the tank, controlled by a temperature sensor that keeps the water at 55°C with a hysteresis of 5°C. The heating power is reduced by the **heater efficiency** on Low Heating Value of **85%**. The **coefficient LHV/HHV** (low heating value on high heating value) is taken as **90%** to consider the part of energy used to vaporize the water vapor and that cannot be transferred into heat.

- **Collective distribution**

The water circulation is following the assumptions described in Section 3.2.4, which means mainly a water rate of 615 liters per hour in the circulation pipes.

To keep the temperature of the loop at the same range of temperature (between 50° and 55°C) when no water drawing occurs, the most commonly used way of doing is **to mix the return water with hot water from the top of the tank** to reach the setpoint temperature. It is a way to avoid an extra heater that will require energy and maintenance. Since both temperatures of return pipe and top tank are known, as well as the flow rate in the departure pipe, an energy balance gives the repartition of the return flow to put back to the tank and to the beginning of the loop.

This distribution valve to perform this mix will only be activated on those **two conditions**:

- The temperature of return water is below 50°C,
- And no water drawing occurs at this time.

The principle is illustrated on Figure 4.2:

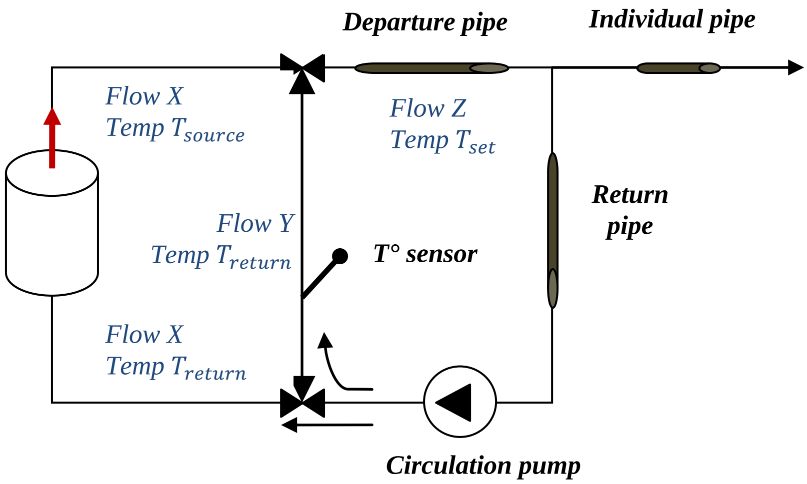


Figure 4.2 Re-heating system of the hot water circulation in the reference case

The balance equation can be written as:

$$\begin{cases} X + Y = Z \\ X.T_{source} + Y.T_{return} = Z.T_{set} \end{cases} \qquad (4.5)$$

Where:

- The source is the hot water coming out from the tank with a flow X and a temperature T_{source}. The same amount of water will be put back to the tank bottom from the return pipe.
- The return water has the temperature T_{return} and is divided between flows X and Y.
- The flow rate at the beginning of the circulation is the nominal flow rate of the system and is supposed to be at the setpoint temperature fixed at 55°C.

It gives the resulting flows:

$$\begin{cases} X = Z.\dfrac{T_{set} - T_{return}}{T_{source} - T_{return}} \\ Y = Z.\dfrac{T_{source} - T_{set}}{T_{source} - T_{return}} \end{cases} \qquad (4.6)$$

To be able to run the simulation without divergence, the flows are calculated to be applied at the next time step.

4.2 Inverter system with solar collectors - Atlantic

The heat pump-based system studied here is combining a heat pump and solar collectors. This system has been proposed by one of the partners, Atlantic, that aims to develop it so that it respects the new thermal regulation 2012 and has a reasonable cost for the customer. This system may be called later on as 'Atlantic system'.

4.2.1 General design

In Figure 4.3 is represented the general system:

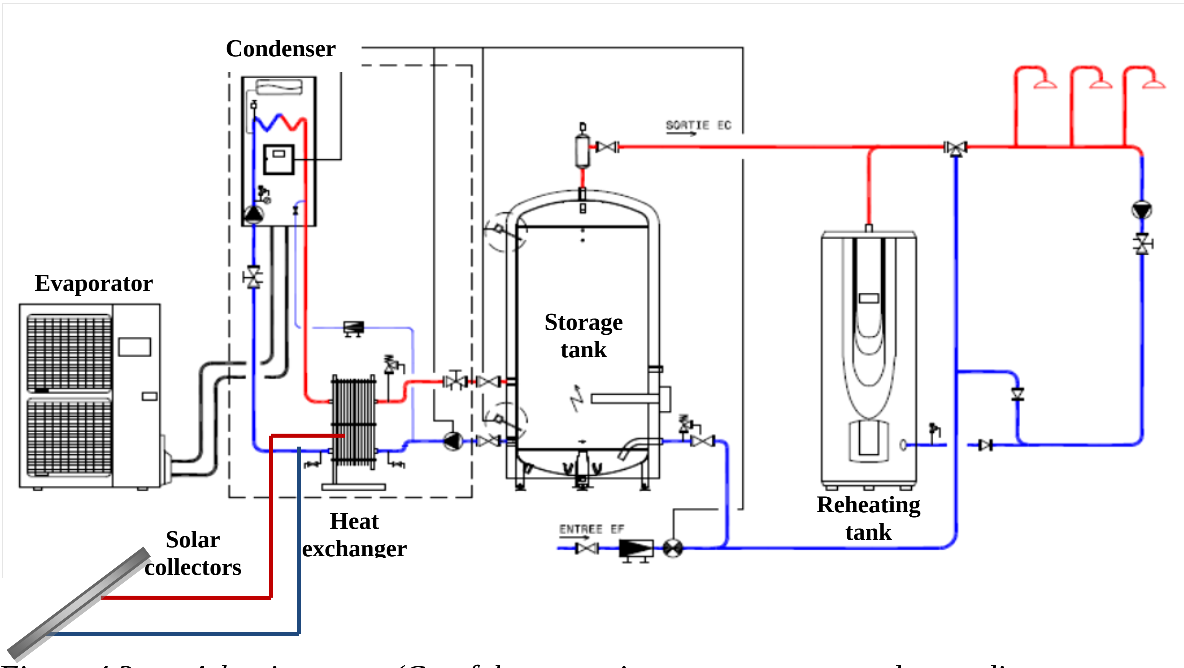


Figure 4.3 Atlantic system (<u>Careful</u>: proportions are not respected regarding tanks' sizes)

The storage tank is heated by a heat pump working on outside air and which is connected by an external plate heat exchanger. On the right of Figure 4.3, the water circulation is working with a second water tank heated itself by a smaller heat pump working on ambient air.

The solar collectors come as a preheating device. They are also connected to the tank by the external heat exchanger which transfers the heat from the calorific fluid of the collectors to the water of the tank.

Figure 4.4 shows the model designed on TRNSYS.

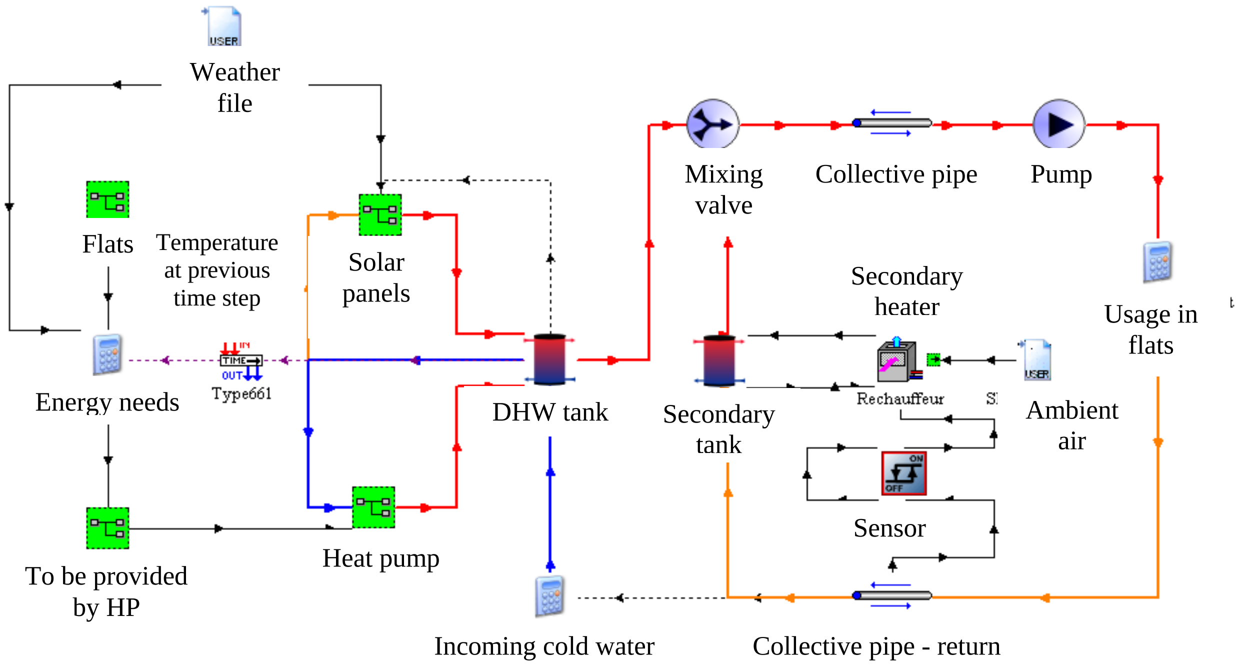


Figure 4.4 TRNSYS assembly of Atlantic system

The TRNSYS assembly is very similar to Figure 4.3. The main difference may be that the TRNSYS model simulates two different heat exchangers for the two loops of the heat pump and the solar panels. This has been done to allow a larger flexibility later on but the design of the heat exchanger is the same in both cases.

4.2.2 Detailed characteristics per component

- **Storage tank**

As presented in

Figure 4.5, the system is designed for a tank of 2500 liters and two-meter high. The departure pipe to the heat exchanger is placed at the bottom of the tank, at the fourth node of the tank, while the arrival pipe coming from the heat exchanger is placed at the third node, to respect the temperature gradient of temperature inside the tank.

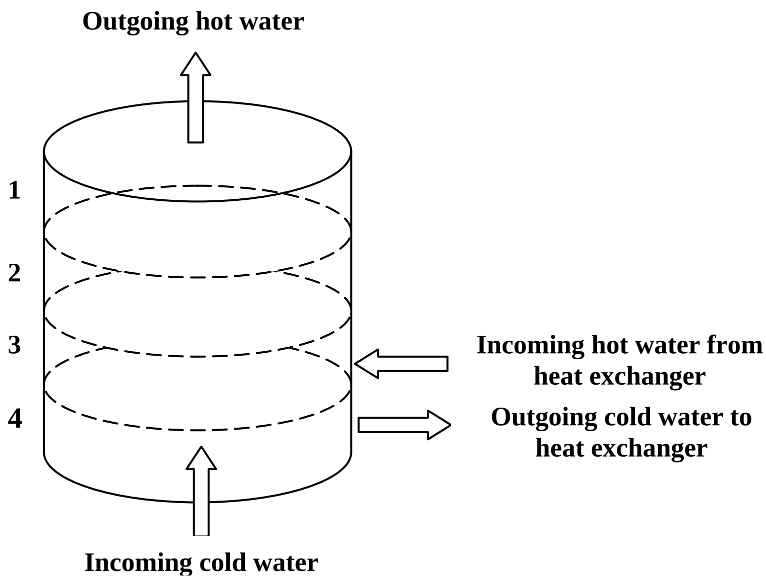


Figure 4.5 Inlets and outlets of Atlantic tank

The insulation recommended by Atlantic is 50mm thick, giving a heat loss coefficient of **0,090 Wh/(24h,l,K)**. The parametric study will determine if those measures are sufficient to reach the objectives.

- **Main heat pump**

Unlike the traditional heat pumps which are working in an all-or-nothing way, the heat pump chosen in this system has an **Inverter compressor** and will work only eight hours every night to benefit from the low electricity fee during night. This technology is made to adapt the speed and thus the power of the compressor to the load that has to be fulfilled at a certain time. While the conventional heat pump will work at full rate until reaching the set temperature, stop and start again, the Inverter heat pump will modulate its power to work continuously during the decided period at a smaller rate. The Coefficient of Performance will be better at the beginning because of the low temperature of the water in the tank. The heat pump will start working with a partial load up to a 100% load at the end of the working time.

The advantages of this Inverter technology are mainly the **energy savings** that are done by regulating the power at a reduced rate. It will **damp the variations** of temperature inside the tank as well. Finally, this system has a **better life expectancy** of the heat pump which avoids sudden startups and stops like the all-or-nothing devices do.

The performance of a heat pump is usually expressed in a matrix of COP given for different couples of temperatures (Tsource-Tload). For the Inverter heat pump, the **polynomials description** has been chosen. It enables to take into account the load that is a percentage translating the energy that the heat pump has to provide, so that the temperature of the fluid leaving the heat pump is five degrees higher than when entering the heat pump. The absorbed energy will be modulated by the actual load and make the compressor work at a reduced rate. The heat source here is outside air.

The principle of polynomials is presented in Table 4.1:

Table 4.1 Principle of polynomial description of a heat pump[5]

	Absorbed power			**Calorific power**		
	f1(Outside temperature)	**f2(Fluid temperature leaving heat pump)**	**f3(Load)**	**f4(Outside temperature)**	**f5(Fluid temperature leaving heat pump)**	**f6(Load)**
a3	X1	X5	X9	X13	X17	X21=0
a2	X2	X6	X10	X14	X18	X22=0
a1	X3	X7	X11	X15	X19	X23
a0	X4	X8	X12	X16	X20	X24=0

[5] For confidentiality issues required by Atlantic, the real coefficients are not provided in this report.

On Table 4.1, each Xi represents the numerical value of the corresponding coefficient ai and it enables to calculate the absorbed and the calorific power as a product of polynomials:

$$P_{absorbed} = f1(T_{out}) * f2(T_{fluid}) * f3(Load) \quad (4.7)$$

$$P_{calorific} = f4(T_{out}) * f5(T_{fluid}) * f6(Load) \quad (4.8)$$

Where T_{out} is the air temperature given by the climate file and T_{fluid} is calculated as the temperature of the tank plus five degrees.

Each function *fi* is a polynomial function from third degree. The example for f1 is given below:

$$f1(T_{out}) = X4 + X3.T_{out} + X2.T_{out}^2 + X1.T_{out}^3 \quad (4.9)$$

The calculation method is **based on the demands of the day before**: the total energy used during the day is integrated all over the day and is sent to the heat pump at the beginning of the heating period to deduce the energy that needs to be provided to the tank to reach again 55°C. This gives the calorific power of the heat pump on an eight-hour basis. When the solar collectors are activated, the solar gains are deducted from the needs to reduce the power asked to the heat pump.

$$P_{total\ heating} = \frac{Energy\ needs\ of\ the\ day\ before}{8\ hours} = Constant \quad (4.10)$$

This value is then used to calculate the load. Indeed, the last column with coefficients equal to zero shows that the calorific power is directly proportional to the load.

$$P_{calorific} = f4(T_{out}) * f5(T_{fluid}) * X23 * Load = P_{total\ heating} \quad (4.11)$$

At each time step, the load is re-calculated depending on the outside temperature and the temperature of the fluid leaving the heat pump to the tank. Thus, the calorific power is constant all over the eight hours, while the power absorbed by the heat pump varies depending on the load.

As said before, the heat pump works eight hours per night. More accurately, it has been designed to work exactly from 22pm to 6am, independently from the off-peak time in electricity costs. Indeed, the idea was here first to limit the possible water drawings during the heating period of the tank. It has been then evaluated by Atlantic that this range from 22pm to 6am suits the best this condition.

Typically, the TRNSYS simulations given in Figure 4.6 and Figure 4.7 show the evolution of the Inverter heat pump during five days (four nights):

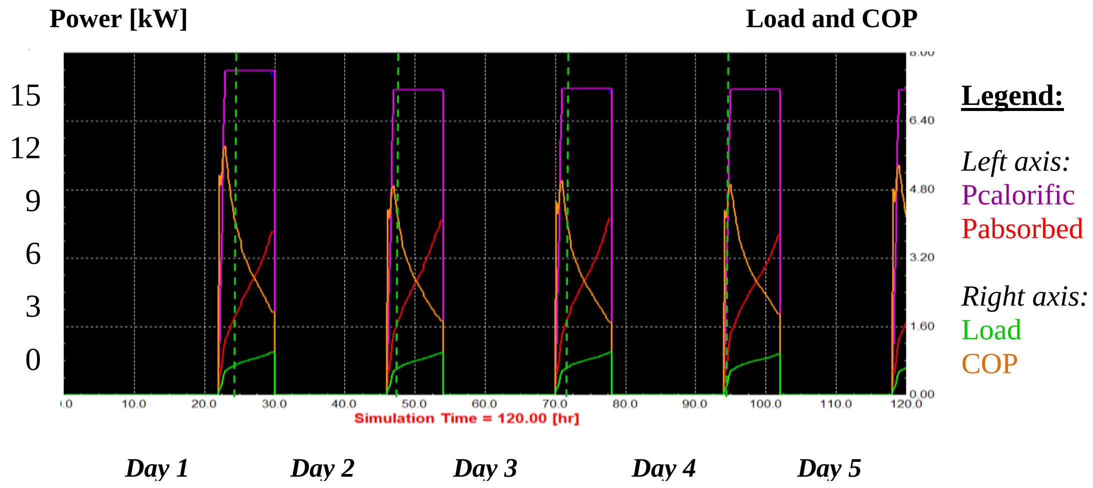


Figure 4.6 Evolution of the absorbed power depending on the load over 4 nights

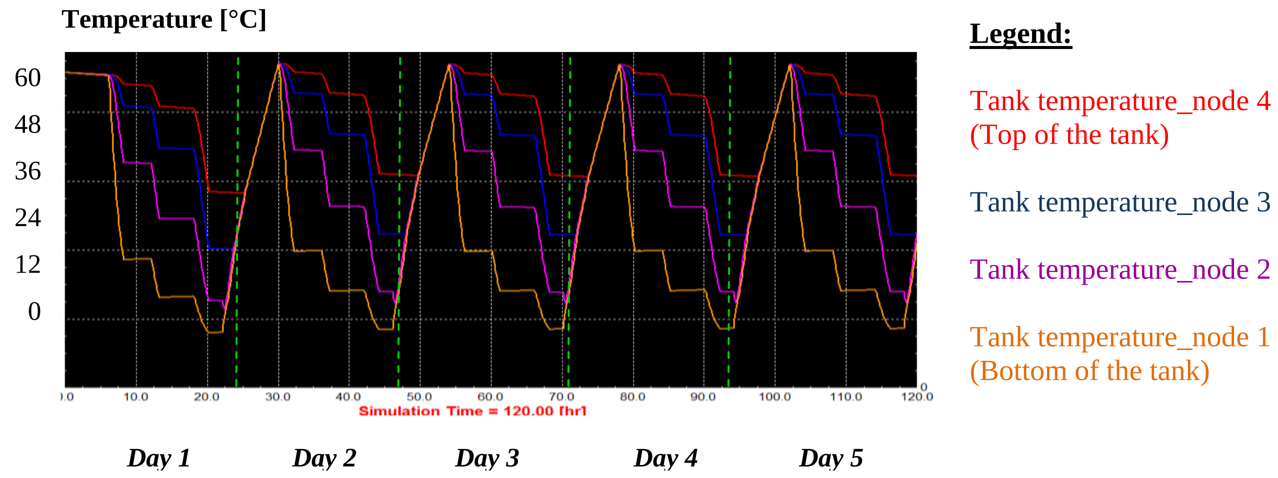


Figure 4.7 Typical evolution of the tank temperatures over 4 nights

Figure 4.6 and Figure 4.7 show clearly the evolution of the compressor power depending on the time. While the demand is constant over the eight hours of each heating period (constant calorific power), the load is increasing progressively up to 100% because of the temperature of the tank which gets higher. This leads to a higher absorbed power and a diminishing coefficient of performance.

Figure 4.7 shows the stratification of the tank with four different zones of temperature. During the heating cycles, the first zone (node 1) at the bottom is first heated and the whole tank is progressively heated up to the top at 55°C. After eight hours, the four zones of the tank are at 55°C. The first water drawing occurs at 6am, just after the end of the heating period, which reduces the bottom temperature because of the entrance of cold water. The top temperature will decrease due to stratification as seen before. Finally, heat losses of the tank can be observed from the slightly inclined temperature curves between the daily water drawings.

Secondary heat pump

A secondary heat pump is used to re-heat the water in the circulation. The technology here is a standard all-or-nothing heat pump which works on ambient air in this application. The **performance matrix** has been provided by Atlantic but the values are kept confidential.

Only the principle of a matrix description will be given in Table 4.2. It consists of giving for some couples of critical temperatures (T_source, T_load) the values of the absorbed and calorific powers. TRNSYS will then interpolate between those values.

Table 4.2 Performance of the secondary Odyssée heat pump

$T_{load} = T_{water}$ [°C]	$T_{source} = T_{\text{ambient air}}$ [°C]	Pabsorbed	Pcalorific
55/60	5	X	X
	…	X	X
	35	X	X

One couple of temperatures is said to be nominal and correspond to a conventional source temperature of 22,5°C. The matrix which is given to TRNSYS is then a table of modulating coefficients that will be multiplied by the nominal couple of powers ($P_{calorific}; P_{absorbed}$) to get the powers at the specific temperature couple.

As said previously, the heat source used is ambient air of a non heated space in contact with the heated volume. It is typically in the basement of a building. The temperature varies during the year but with small amplitude. As a first approach in this project, no accurate calculation has been performed, since the building is not especially defined, and an external text file has been created to be read by TRNSYS with a constant temperature of 15° throughout the year.

Finally, this secondary heat pump is heating a small water tank of **270 liters** placed on the return pipe of the circulation. The heat pump is started if the temperature of the returning water is below **50°C**.

Heat exchanger

External heat exchangers give the advantage to have a better **Overall Heat Transfer Coefficient (OHTC)** than a conventional heat exchanger, because of their configuration that increases the contact surfaces. Moreover, in this system, water is circulating from both sides of the exchanger, from heat pump and from the tank. This enables the plates to be made only from one simple skin instead of two, which increases even more the OHTC.

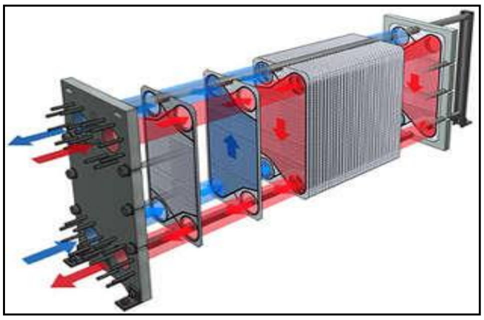


Figure 4.8 Principle of a plate heat exchanger [Whaley Products 2012]

Unfortunately, TRNSYS does not propose any component to simulate a plate heat exchanger but only a normal heat transferring device based on the Overall Heat Transfer Coefficient in W/K. Atlantic provided the technical specifications of the heat exchanger that is larger depending on the power of the heat pump. One more time, for confidentiality reason, the details will not be given in this report but the exchange coefficient was obtained by choosing the exchanger adapted to the heat pump power and multiplying the OHTC in W/(m²,K) by the surface of the plate. This constant coefficient was given to the exchanger component of TRNSYS and the transfer was then calculated depending on the temperature difference between source and load water. The flow rates were specified as well by Atlantic and are constant over time.

- **Solar collectors**

The efficiency of a solar collector can be described by a quadratic equation like in Equation (4.12):

$$\eta = a_0 + a_1 \frac{\Delta T}{I} + a_2 \frac{\Delta T^2}{I} \qquad (4.12)$$

Where:

a_0 is the intercept efficiency [-]

a_1 is the efficiency slope [W/(m²,K)]

a_2 is the efficiency curvature [W/(m²,K²)]

ΔT is the difference temperature between ambient air and the fluid temperature entering the collector

I is the sun irradiation coming to the collector surface [W/(m²,K)]

The TRNSYS component asks for those coefficients and is related to the climate file to get the sun radiation on the surface of the collector. Moreover, it is needed to give the inclination, the surface the latitude of collectors. The flow rate of fluid to heat exchanger is recommended by the technical specification given by Atlantic.

The sun collectors will start working depending on the difference of temperature between the collector and the water tank. A hysteresis has been created to start the collectors when the temperature difference is 6°C and stop it when it is below 4°C, as presented in Figure 4.9.

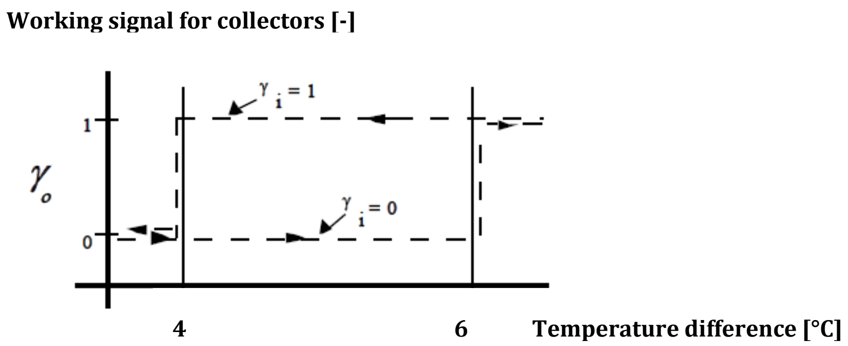


Figure 4.9 Start and stop conditions of the solar collectors

For safety reason, two temperatures need to be controlled: the solar collectors will stop working if the temperature of the collectors reaches 140°C, which could damage them, or if the temperature of the tank reaches 90°C to avoid over-heating of the stored water and risk of scalding.

The area of collectors has been chosen to cover at least 60% of the needs and not to exceed 95% in summer, so that the collectors are not damaged. The website from the *Design office in solar energy* [TECSOL 2012] enables to size the collectors using the SOLO method developed by CSTB. The areas needed for Nice and Trappes were determined with *Tecsol* and are summarized in Table 4.3.

Table 4.3 Surfaces of solar collectors for both cases Nice and Trappes

	Nice	**Trappes**
Surface [m²]	30	35
Solar energy by collectors [kWh/year]	23253	19751
Part of the total demand [%]	79	62

The TRNSYS simulations show the significant effect of the collectors heating of the water tank. In

Figure ***4.10*** below is presented the difference of temperature evolution with and without collectors over 5 days:

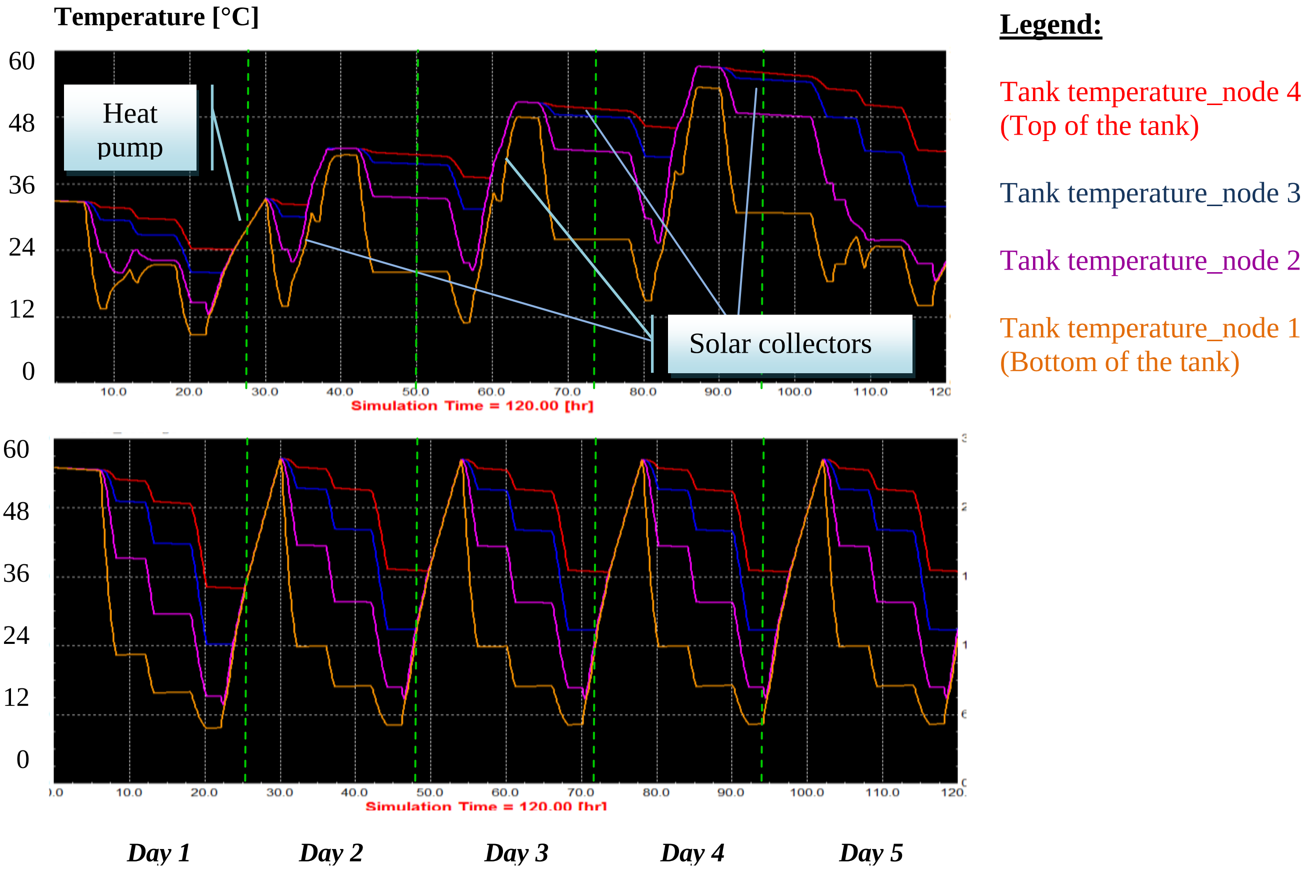


Figure 4.10 Tank heating with (first graph) and without solar collectors (second graph)

On the first graph, the temperature is raising up during day due to the activation of the solar collectors. The first day, it is not enough to offset the water drawings and the heat pump needs to work during the first night. However, the following days show a very high effect of the solar collectors that enable not to start the heat pump during the night.

4.3 Heat pump system with grey water heat recovery - Armines

The second system is based on the heat recovery of grey water. This system has been proposed by another partner, Armines, which obtained a patent for this very innovative system. This system may be called later on as 'Armines system'.

4.3.1 General design

This system is based on the **combination of a heat pump and a heat exchanger** using both the heat from grey water. Figure 4.11 is showing the main components of the system.

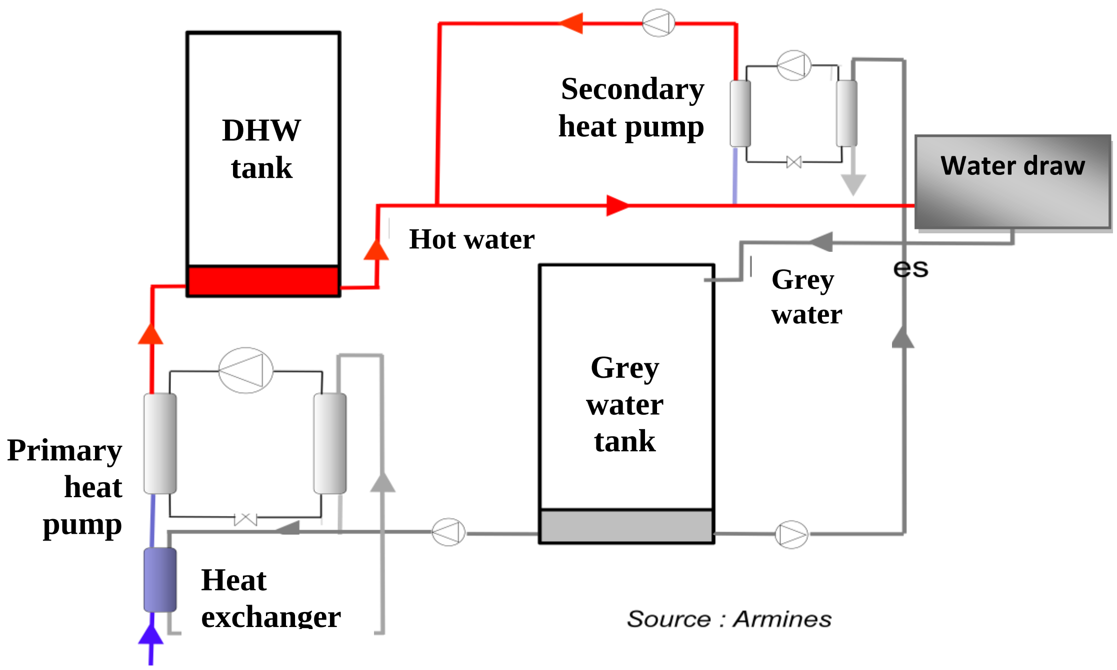


Figure 4.11 Principle figure of Armines system

Cold water is first pre-heated up to 28°C in a heat exchanger with the grey water. Then, it comes to the main heat pump which is using again the same grey water for its evaporator and raises the final temperature to 55°C. A secondary heat pump is placed on the circulation distribution to re-heat the water when the temperature is below 50°C. This extra heat pump also works on grey water.

One essential characteristic of the system is based on the **variable volumes** of water in the tanks. Ordinary water tanks are always fully filled, since cold water is replacing instantaneously the hot water that is drawn. However, this system is somehow inspired from the principle of connected vessels:

- At the end of the night, the DHW tank is full, the grey water tank is inversely empty at the beginning of the day.
- During the day, the DHW is drawn, which makes the DHW tank empty while filling the grey water tank.
- At the beginning of the night, the heat pump starts working by taking the calories from the grey water tank that gets empty.

This system is designed mainly for large buildings to guarantee significant daily water drawings of the DHW tank. In smaller buildings, the hot water could remain more than one day in the tank and since there is no extra heater in the tank, the water could get cold.

The TRNSYS assembly is shown in Figure 4.12:

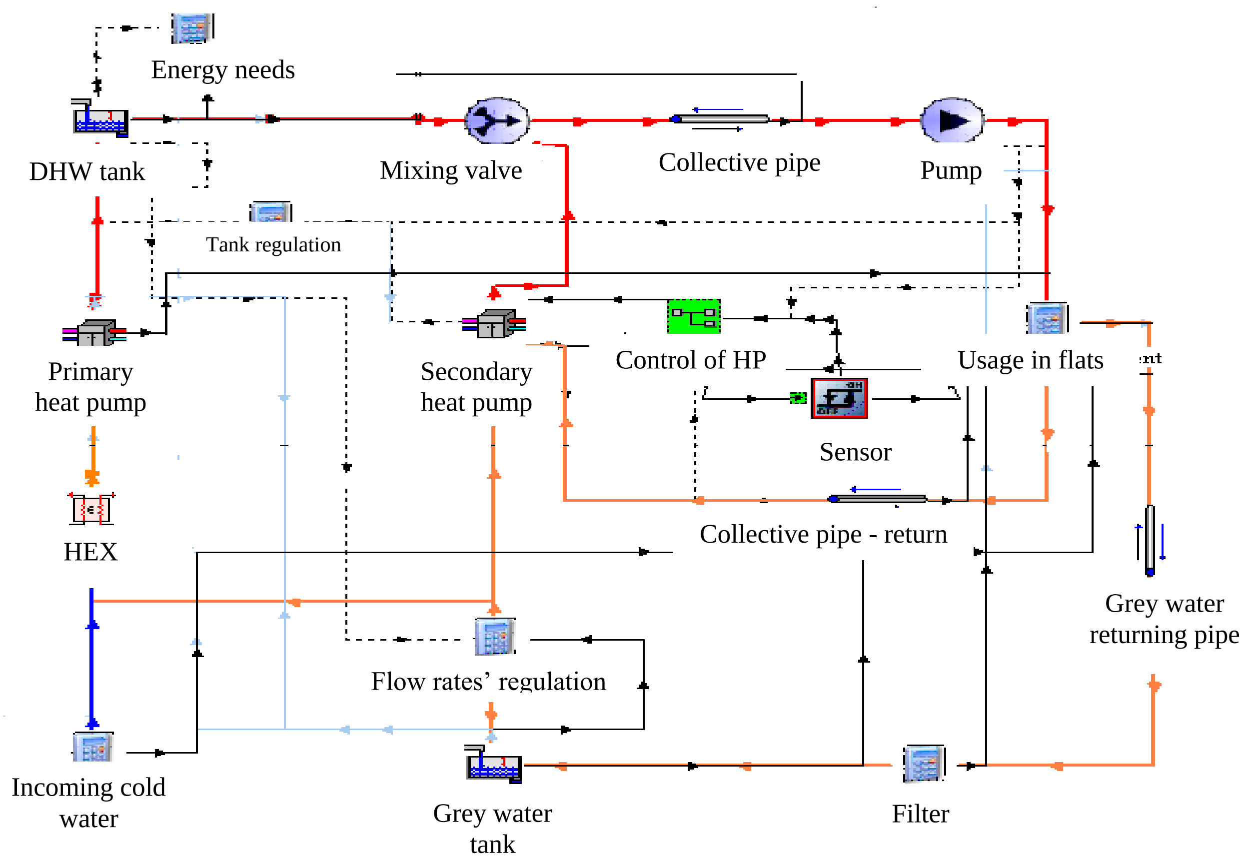


Figure 4.12 TRNSYS assembly of Armines system

This assembly contains more connections because the system requires a lot of controls on different parameters and each component works depending on the behaviors of the others.

4.3.2 Detailed characteristics per component

- **Heat exchanger**

The heat exchanger used in this system is a plate heat exchanger with a given **efficiency of 90%**. It would be more accurate to simulate a variable efficiency to take into account the annual clogging of the plates but the version of TRNSYS used during this Master's thesis did not allow this possibility.

- **DHW tank**

Dimensioning for 20 flats, the needs are calculated following the method of Chapter 2 and in the same way as done in Equation (4.1) for the reference gas system:

$$V_{hot\ water\ at\ 55°/pers.day} = (130 + 25 - 20).0{,}55.0{,}6.1.1 = 44{,}55\ l \quad (4.13)$$

For 38 adults, this represents **1693 liters per day**. The water tank used will be here of **2000 liters** to be on the safe side. The insulation recommended by Armines is **100mm of polyurethane** (λ=0,028W/(m,K)), which is already a very high level of insulation.

As said previously, the water volume is variable and air will be injected inside the tank when water is drawn during the day. The heat losses due to the fresh air are considered negligible and there is no stratification in this tank, since the water entering during night comes already heated from the heat pump.

The tank has sensors assessing **two level indicators**:

- A low level at 5% of the total capacity of the tank
- A high level at 95% of the total capacity of the tank

Those levels are used to regulate the start and stop of the main heat pump. This will be described in the following paragraph.

- **Main heat pumps**

Pre-heated water coming from the heat exchanger is then heated to 55°C by two heat pumps in parallel. This is a safety configuration that ensures that one heat pump will always be in use if the other needs a maintenance operation. The power of the heat pump is adjusted to the building needs and so that it will work only **eight hours per night**.

The nominal flow rate entering the DHW tank each night is equal to the need calculated previously divided by the working time:

$$Nominal\ flow\ rate_{on\ 8\ hours} = 1693\ \text{l}/8\ =\ 212\ \text{l/hr} \quad (4.14)$$

This means that the heat pump has to have the sufficient power to heat 212 liters to 55°C in one hour:

$$P_{calorific} = \frac{212}{3600}.4185.\left(55 - T_{pre-heated\ water}\right) = 8{,}6\ kW$$

$$for\ T_{pre-heated\ water} = 20°$$

(4.15)

The system has to be composed of **two heat pumps of each 4,3 kW**.

Armines provided a matrix description giving the coefficient of performance for couples of temperatures. In the same manner that was used to simulate the secondary air heat pump of the previous solar system, the matrix of modulating coefficients around the nominal couple (P_calorific, Pabsorbed) was created but will be kept confidential in this report.

The **regulation of the heat pumps** and actually of the pump injecting cold water into the system is **depending both on the off-peak hours and on the volumetric levels** of the DHW tank. The heating system will start for two conditions:

- If this is off peak time and the high level of the tank is not reached and has not already been reached during the night,
- Or if during the peak hours, the tank is at its low level.

The incoming cold water will stop when:

- During off peak hours, the tank has reached its high level,
- Or when during peak hours, the tank has reached 25% of its capacity.

Indicators checking all those parameters independently first and then combined together enabled to simulate the right regulation on TRNSYS. The off-peak hours were set to be 22pm to 6am, as it is the standard case in the French electrical structure.

Finally, the **cold water flow rate** is calculated at each time step to ensure two conditions:

- That the DHW tank will be full at the end of the night,
- And that the temperature of the tank will be 55°C.

More precisely, to be able to perform those conditions, the temperature of the water coming outside the heat exchanger and the calorific power of the heat pump are held for one time step to be able to calculate the adjusted flow rate to get 55°C at the next time step. Besides this flow rate should not be smaller than the volume to be filled at 22pm divided by eight hours to be sure to get a full tank.

$$\dot{m}_{cold\ water} = \max\left(\frac{P_{calorific}}{4{,}918.\left(55 - T_{after\ heat\ exchanger}\right)}; \frac{V_{DHW\ tank}}{8hours}\right) \times Regulation\ signal$$

(4.16)

The regulation signal controls the incoming water like described previously on the levels indicators of the tank.

Regarding the grey water flow rate at the evaporator, the value is calculated so that the totality of the grey water tank is made empty at the end of the off peak hours, while allowing the secondary heat pump to work during those eight hours as well. Since the volume of grey water at the beginning of the night and the flow rate of grey water for the secondary heat pump are known, the grey water flow rate to the main heat pumps can be deduced as:

$$\dot{m}_{grey\ water} = \frac{V_{grey\ water\ at\ 22pm} - V_{dedicated\ to\ secondary\ heat\ pump}}{8\ hours}$$

(4.17)

It will be variable from one night to another.

- **Grey water tank**

The grey water tank is designed to be around 1,6 times larger than the DHW tank. This coefficient comes from the mixing of hot and cold water to reach the usage temperature of 40°C. Indeed, it is assumed that the average temperature of water drawn at the faucet is 40°C. For a hot water of 55°C and a cold water of 15°C, the balance equation can be written as in Equation (4.18):

$$V_{mixed\ water}.40 = V_{hot\ water}.55 + V_{cold\ water}.15 \qquad (4.18)$$

$$\text{And } V_{mixed\ water} = V_{hot\ water} + V_{cold\ water} \qquad (4.19)$$

Combining (4.18) and (4.19):

$$V_{mixed\ water} = \left(1 + \frac{55-40}{40-15}\right).V_{hot\ water} = 1{,}6V_{hot\ water} \qquad (4.20)$$

The grey water tank should therefore be of 1,6.2000 = 3200 liters. For the study and to respect a safety margin, the grey water tank volume will be **3500 liters**.

Another assumption is done regarding the temperature of the grey water after usage. Armines performed a statistic analysis to assess the temperature of the grey water returning to the pipes. It seems that **the average temperature loss at usage is from 5°C**. This means that for the simulation, the temperature of the water is directly set at (40-5) = 35°C at the entrance of the returning grey water pipe.

Another important assumption needs to be noted: **the whole volume of DHW drawn is assumed to be used by the heat recovery unit**. In the real system, a filter is used to store only the grey water at more than 25°C. However, Armines considers that for large buildings, the abundance of water drawings at the same time will give lead to a temperature of grey water always at more than 25°C. Thus, the TRNSYS model is driving back to the grey water tank all the water coming out after the usage. The temperature is 35°C minus the heat losses in the distribution.

One **pipe of 50 meters** with the same geometrical and insulation properties as the circulation pipes is used to make the distribution leading the grey water back to the grey water tank.

- **Secondary heat pump**

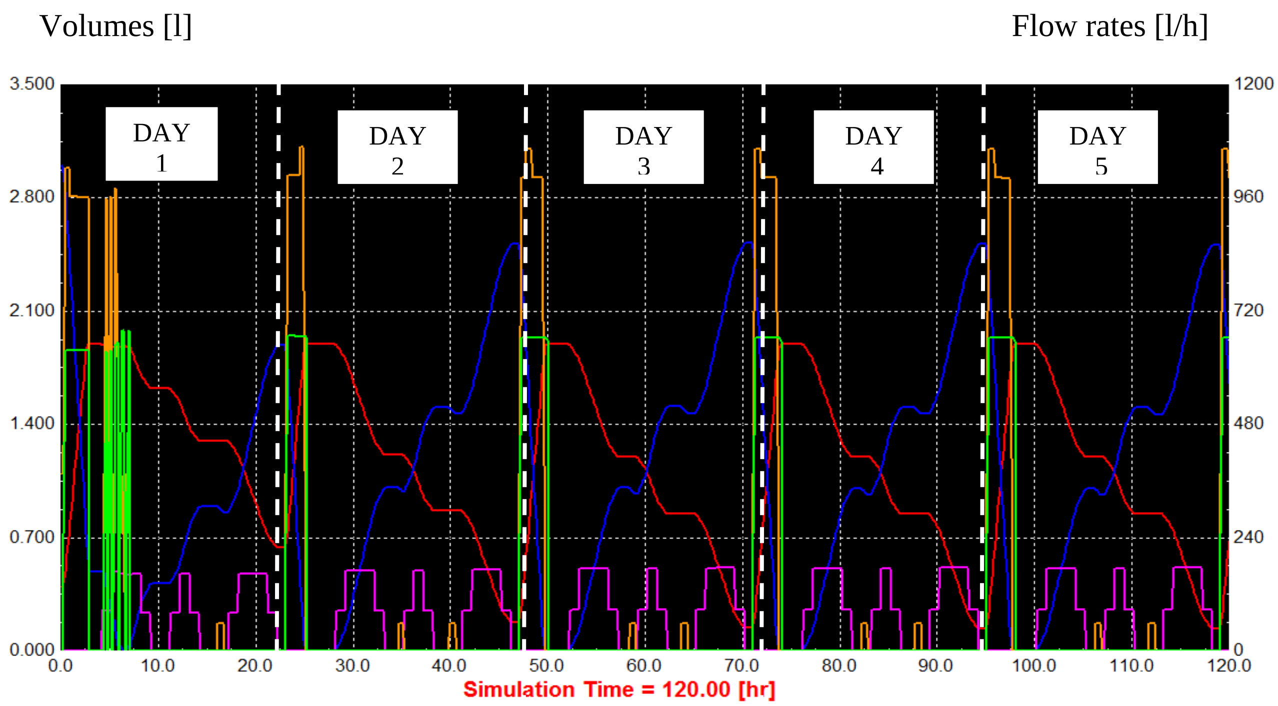
The water circulation is re-heated if necessary by this secondary heat pump when the temperature of the loop is decreasing below 50°C. This is a smaller heat pump with a calorific power of **4 kW with a coefficient of performance of around 2**. The matrix of performance has been provided by Armines as for the main one and is kept confidential.

The heat pump is working for the combination of those three conditions:

- The temperature of the returning water in the circulation is below 50°C,
- The output grey water at the evaporator is above 3°C,
- No water drawing occurs at the same time.

The heat pump is working on the grey water source as well. The grey water flow rate at the evaporator is fixed at **1 l/min**.

The whole system is simulated on the graph of Figure 4.13:



Legend:

Left axis:
Volume of the DHW tank
Volume of the grey water tank

Right axis:
DHW draw for the user
Grey water flow coming out of the grey water tank
Cold water flow entering the heating system

Figure 4.13 Grey water system: tank volumes and flow rates

In Figure 4.13 , the first day should be disregarded, because the regulation of the system is done by integration over one day and the indicators are consequently not respected at the beginning of the first day. However, the system starts working efficiently from the second day. The graph shows well the principle of communicating vessels with the red DHW tank that gets empty during the day while the blue grey water tank is filled. The green cold water flow is entering the system during night and fills the DHW tank, while the orange grey water flow works at the same time to transfer heat at the evaporator of the main heat pumps. An irregularity of this grey water flow appears a short time each night; this is due to the secondary heat pump that is working around one hour each night to re-heat the water circulation. This small grey water also appears twice during the day for the same reason.

***

This chapter enabled a better understanding of the reference system and the two heat-pump based systems. The first one will work permanently using a gas heater, while the two others start heating water only during night with the heat pump technology. Next chapter will assess which design is the most relevant to reach the objectives of the project by use of the software TRNSYS.

5 Results of simulations and deepening

The systems described in Chapter 4 have been implemented with the software TRNSYS to be studied more accurately by performing a parametric analysis. Subsequently, the TRNSYS input files were transformed with TRNEdit and finally TRNSED to create interfaces which enable to run parametric tables, as explained in Section 3.1. An example of interface is provided in Appendix 8.3. In this chapter, the method of the analysis will first be described before giving the results and conclusions on the systems.

5.1 Method of the parametric analysis

The idea of the parametric analysis consists in assessing the systems described in previous chapter, compare them to the reference gas system and conclude about their capacity to reach the goals of the project BBC PACS while ensuring the comfort of the users.

The parametric analysis will be done in two steps: first, the system will be evaluated for different consumption profiles and demands, and in a second time, the parameters will be improved if necessary to reach the objectives of the project.

5.1.1 1st step: Definition of the types of consumption demands to test

The DHW consumption of the users can vary a lot from one family to another. The system has still to be able to cover the needs in every case. This means that a minimal comfort should be ensured in both cases of high or low DHW demands. In order to be able to assess this capacity of the systems, three types of DHW needs will be tested:

- **Low DHW needs** which are defined by combining a low level of life, a high price for water and a low-consumption heating system. Those three coefficients are defined in Chapter 2 and will have the effect of reducing the standard DHW consumption.
- **Standard DHW needs** defined by a normal level of life, a stable price for water and standard technology.
- **High DHW needs** defined by a high level of life, a low price for water and standard technology.

Those three types of needs can be evaluated in term of energy by following the method of Chapter 2 and using the climate file giving the temperature of cold water at each hour of the year. Two climate files have been chosen to perform the analysis**, Trappes and Nice**. As a remainder, the referent building is consisting of 20 flats of 1,9 equivalent adults each, which means 38 adults in total.

The energy demands for those six demands types are giving in Table 5.1 to be compared later with the systems' energy consumptions.

Table 5.1 Definition of the three types of DHW demands

	For an apartment building of 20 flats, 38 adults
Low DHW needs	26.7 l at 55°C /day/person 503 kWh/year/person in Trappes 458 kWh/year/ person in Nice x 38 adults = **19114 kWh/year in Trappes** **= 17404 kWh/year in Nice**
Standards DHW needs	44.6 l at 55°C /day/person 841 kWh/year/person in Trappes 765 kWh/year/ person in Nice x 38 adults **= 31958 kWh/year in Trappes** **= 29070 kWh/year in Nice**
High DHW needs	60.8 l à 55°C /day/person 1148 kWh/year/person in Trappes 1045 kWh/year/ person in Nice x 38 adults = **43624 kWh/year in Trappes** **= 39710 kWh/year in Nice**

This gives consequently **six DHW profiles to be tested for each system**. Table 5.1 shows that the demands can turn out to be twice as high when varying from the low to the high demands.

5.1.2 2nd step: Definition of the parameters to test

In order to achieve the performance required by the project BBC PACS, the different parameters are likely to be changed but the improvements of their values have to be reasonable, so that the systems can be still financially attractive to buyers. It was chosen to study mainly the **impact of insulation for both the storage and the distribution pipes.**

Therefore, the parameters will first be set either to the recommendations of Armines and Atlantic, or to the regulation recommendations. In a second time, the impact of a better insulation of the storage and of the distribution pipes will be studied to see if the objective of 15 kWh per square meter per year can be achieved without jeopardizing the comfort of the users.

The choice of the insulation level has been made using the report written by CSTB and presenting the impact of different types of insulation on the heat losses occurring in the storage and distribution pipes [CSTB-3 2012].

First, regarding the storage insulation, four kinds of materials were compared in this report: polyurethane, aerogel, Vacuum Insulated Panels and fumed silica at different pressures. Performance and prices of those materials are presented in Table 5.2:

Table 5.2 Properties of four insulating materials for DHW storage tank

	Aerogel	VIP	Fumed silica	Polyurethane
Thermal conductivity [mW/m.K]	14 to 16 depending on temperature	7 to 10	5 to 20 depending on the pressure within the material	22
Cost [€/m3]	3800	2100	500	300

This table indicates a large difference of price between the materials. Fumed silica and polyurethane seem to be more affordable financially and may be more durable than aerogel and VIP which are new materials. The choice was made to improve the storage insulation by **fumed silica at a pressure of 0,1kPa**, which gives a thermal conductivity of 0,009W/(m,K) and a heat loss coefficient of **0,048Wh/(l,K,day) for a 2000-liter tank**. The cost is reasonable by comparison with aerogel and VIP and the thermal conductivity is much better than polyurethane. If PUR was chosen, an important thickness would be needed to achieve the same performance. Yet, one criterion to be considered is the place occupied by the tank whih should not be increased too much by the insulation. This explains the choice of fumed silica.

Then, the insulation materials for the distribution pipes have also been studied and four of them were compared: EPS, polyurethane, VIP and aerogel. For the same reasons as for the storage, VIP and aerogel have been eliminated. **Polyurethane** was selected for its better thermal conductivity than EPS (0,02W/(m,K) instead of 42). A thickness of **20mm** was chosen.

5.1.3 Simulations and outputs

To summarize, four main sets of simulations have to be performed for each system and for each of those set, the six types of DHW needs have to be simulated. The numbering of the simulations will be done as explained in Table 5.3:

Table 5.3 Simulations for each system

For one system:	**Weather file**	**STEP 1 : Initial conditions**	**STEP 2 : Storage tank insulated with silica**	**STEP 3 : Distribution pipes insulated with PUR**	**STEP 4 : Combination of silica for tank and PUR for pipes**
Low DHW needs	Trappes	1.1	2.1	3.1	4.1
	Nice	1.2	2.2	3.2	4.2
Standard DHW needs	Trappes	1.3	2.3	3.3	4.3
	Nice	1.4	2.4	3.4	4.4
High DHW needs	Trappes	1.5	2.5	3.5	4.5
	Nice	1.6	2.6	3.6	4.6

<u>To be noted:</u> only the six DHW needs with the initial conditions (simulations 1.1 to 1.6) will be tested for the reference system.

The simulations are running **for one year**. For each simulation, the expected results are the consumptions of primary and final energy, the CO_2 gas emission, the cost of the energy used, the comfort and the performance of the system which will be assessed by three coefficients. A short description is given for each output:

- **CFE:** Consumption of Final Energy → stands for the final energy consumed by the whole system in one year in kWh/year

- **CPE:** Consumption of Primary Energy → stands for the primary energy consumed by the whole system in one year in kWh/year

- **Energy running cost** which is calculated by multiplying the final energy used at each time step by the cost at this time of the day (the price of the subscription has not been taken into account here, since the DHW production is often combined with other usages, like heating and lightening, which increases the price of the subscription)

- **Discomfort** which is, as defined in Section 3.2.4, the number of hours during which the water drawn is below 40°C divided by the number of hours of water drawing

- $\mathbf{CO_2}$ **emissions** calculated on the basis of the assumptions in Section 3.2.4

- $\boldsymbol{SPF_{HP}}$ equal to the calorific power provided divided by the power absorbed by the heat pump – this is by definition the coefficient of performance of the heat pump only with an annual calculation

- $\boldsymbol{SPF_{useful}}$ equal to the real DHW needs divided by the whole final energy consumption. In this case, the DHW needs correspond to the energies that have been calculated in Table 5.1 corresponding to the energy needed to heat the required volume to 55°C.

Those last two definitions for the coefficient of performance will give a different understanding of the systems and will enable to distinguish the performance of the heat pump itself from the one from the whole system.

- **CFE/m²:** Consumption of Final Energy divided by the building surface 1380m² giving the consumption per year and per square meter

- **CPEmax:** this is to remind the objective of the project which is 15 kWh/m²/year

- **CPEref:** it corresponds to the consumption of the reference gas system

- **Gain** by comparison to the referent system and equal to the consumption of the referent system divided by the one of the system studied

5.2 Results of parametric analysis

5.2.1 Reference gas system

As explained before, the reference system is simulated for the six types of DHW needs. The results are presented in Table 5.4:

Table 5.4 Performance of the reference gas system of 20 flats

	Gas CFE	Gas CPE	Annual cost for gas	Electricity CFE	Electricity CPE	Annual cost for electricity
N°	[x10^3 kWh /year]	[x10^3 kWh /year]	[€]	[x10^3 kWh /year]	[x10^3 kWh /year]	[€]
1.1	31,96	31,96	2163	0,88	2,26	106
1.2	29,22	29,22	1974	0,88	2,26	106
1.3	48,58	48,58	2958	0,88	2,26	106
1.4	43,89	43,89	2971	0,88	2,26	106
1.5	63,83	63,83	4322	0,88	2,26	106
1.6	57,48	57,48	3892	0,88	2,26	106

	Total CFE	Total CPE	Total cost	Discomfort	CO_2 released	CPE per unit area	Maximum CEP per unit area
N°	[x10^3 kWh /year]	[x10^3 kWh /year]	[€]	[%]	[g/(m²,an)]	[kWh/(m² ,year)]	[kWh/(m² ,year)]
1.1	32,84	34,22	2269	0	**4773**	**24,79**	15
1.2	30,10	31,48	2080	0	**4366**	**22,81**	15
1.3	49,46	50,84	3064	0	**7242**	**36,84**	15
1.4	44,77	46,15	3077	0	**6545**	**33,44**	15
1.5	64,71	66,09	4428	0	**9508**	**47,89**	15
1.6	58,36	59,74	3998	0	**8564**	**43,29**	15

The consumptions of energy are divided into the electric and the gas consumptions. The CFE and CPE for the gas are identical, since the coefficient used in France to convert final energy to primary energy is 1.

The costs are expressed as the addition of the cost of the kWh consumed plus the cost of the yearly subscription. Referring to Section 3.2.3, it was assumed in this case that the gas subscription corresponds to a B0 subscription to the gas producer GDF with the level of price n°2, while the electrical subscription corresponds to 9kVA with regulated prices. The costs are first calculated separately for gas and electricity and finally added. It should be noted that the subscription prices may be different if the building heating consumption is considered and added to the energy demand. This price could then be different in this perspective.

Even if the comfort is ensured for the user – no discomfort occurs due to a permanent working system facing all the demands – it can be noted that **the cost of the system is quite high**, of around 3000€, which makes **2,17€/(m²,year)**.

As expected, the "low DHW needs" profile show reduced CFE and CPE by comparison with the "high DHW needs" profile. The values almost double from low to high demands. Only the gas consumption is different from one type of need to another, while the electricity demand remains the same. Indeed, this electrical consumption is due to the pump of the water circulation which is working continuously at the same rate, whatever the demand.

The consumption of primary energy per unit area is **more than twice the objective of the project**, at around 35kWh/(m²,year). The heat pump systems have to show that they can divide this consumption by more than two. Besides, the CO_2 emissions are much larger than the objective of 350g/(m²,year). A large progress has to be done for both the CPE and the CO_2 releases.

5.2.2 Heat pump system with grey water heat recovery - Armines

- **STEP 1 : The 6 demand types**

The first step of the simulations in Table 5.5 consists in testing the system for the six types of DHW demands.

Table 5.5 Results of step 1 for the grey water heat recovery system

	CFE	CPE	Cost	Discom fort	CO_2	SPF HP	SPF useful	CPE /m²	CPE max	CPE ref	Gain
N°	**[x10³ kWh /year]**	**[x10³ kWh /year]**	**[€/ year]**	**[%]**	**[g/(m² ,year)]**	**[-]**	**[-]**	**[kWh/(m²,year)]**	**[kWh/(m²,year)]**	**[kWh/(m²,year)]**	**[-]**
1.1	7,4	19,1	784	0	**215**	3,2	2,6	**13,9**	15	24,8	**1,6**
1.2	7,3	18,9	774	0	**212**	3,2	2,4	**13,8**	15	22,8	**1,5**
1.3	9,4	24,3	993	0	**272**	3,2	3,4	**17,6**	15	36,8	**2,1**
1.4	9,3	23,9	949	0	**269**	3,2	3,1	**17,3**	15	33,4	**1,9**
1.5	9,7	25,1	986	0	**282**	3,2	4,5	**18,2**	15	47,9	**2,4**
1.6	9,6	24,7	973	0	**278**	3,2	4,1	**17,9**	15	43,3	**2,2**

The colored columns represent the three objectives of the project BBC PACS. It can be noted that the system is already quite optimized, with a standard consumption of **17kWh of primary energy per square meter per year**. However, it is not enough to fulfill the BBC PACS goal of 15kWh/(m²,year).

The gain by comparison with the reference system is at around 2, while the CO_2 emissions are well below the target of 350g/(m²,year).

Regarding the running cost, it seems that the heat pump system is much more interesting, around 1000€ per year (**0,70€/(m²,year)**), which is three times smaller than the gas system, due to the heat pump COP of 3,2. However, this has to be put in balance with the initial investment cost for equipment (number of tanks, high insulation, extra heat exchanger) which is probably higher here.

When comparing the two cities Trappes and Nice for the same type of need, it can be observed that the difference is very little. This can be explained by the fact that the only parameter which will differ is the temperature of the incoming cold water which will be a bit higher in Nice and thus reduce a little the energy consumption. In the case of a heat pump based on external air, it will be shown that the difference is much greater.

The comfort is ensured for any need, which proves the reliability of the system, even when facing more or less demands. A last comment can be made about the performance coefficients: the SPF_{HP} is the same for any of the six simulations, which is coherent, since it is just assessing the performance of the heat pump independently from the demands. The heat pump will provide more or less energy but will consume in the same proportions.

However, the SPF_{useful} is bigger when having larger demands. **The larger are the demands, the more efficient the system can be.** This can be explained by the heat losses both in storage and circulation which are relatively more important for smaller needs. Indeed, less water will be drawn in the storage, which implies higher losses, a reduced temperature and larger demands to the heat pump. Moreover, the water in the circulation will also be subjected to higher heat losses for the same reason and will increase the calorific power asked to the second heat pump.

- **STEP 2 : Insulation of the storage reinforced**

Armines already recommended highly insulated tanks for both DHW and grey water. Insulated by 100mm of polyurethane, the comparison of the coefficients for a water tank of 2000 liters between polyurethane and fumed silica shows that the solution of Armines is better in this case than the recommendation of step 2.

$$U_{recommended\ by\ Armines} = 0.28W/(m^2, K) = 1.01kJ/(h, m^2, K) \quad (5.1)$$

$$U_{Step\ 2} = \frac{0,048.2000.3,6}{24.(2.1 + 2.3,5)} = 1.6kJ/(h, m^2, K) \ > 1.01kJ/(h, m^2, K) \quad (5.2)$$

Therefore, step 2 will not be tested in this case because it would on the contrary increase the energy consumptions. Step 3 will then directly be studied.

- **STEP 3-4 : Insulation of the water circulation reinforced**

The replacement of foam rubber by 20mm of polyurethane around the collective distribution pipes gives the results of Table 5.6:

Table 5.6 Results of step 3-4 for the grey water heat recovery system

	CFE	CPE	Cost	Dis co m fort	CO_2	SPF HP	SPF useful	CPE /m²	CPE max	CPE ref	Gain
N°	**[x10^3 kWh /year]**	**[x10^3 kWh /year]**	**[€/ year]**	**[%]**	**[g/(m², yea r)]**	**[-]**	**[-]**	**[kWh/(m²,year)]**	**[kWh/(m²,year)]**	**[kWh/(m²,year)]**	**[-]**
3.1	6,7	17,3	662	0	**194**	3,2	2,9	**12,5**	15	24,8	**1,8**
3.2	6,6	17,1	656	0	**192**	3,2	2,6	**12,4**	15	22,8	**1,7**
3.3	8,4	21,5	805	0	**242**	3,2	3,8	**15,6**	15	36,8	**2,2**
3.4	8,2	21,1	790	0	**237**	3,2	3,6	**15,3**	15	33,4	**2,0**
3.5	8,7	22,4	835	0	**251**	3,2	5,0	**16,2**	15	47,9	**2,7**
3.6	8,6	22,1	823	0	**248**	3,2	4,6	**16,0**	15	43,3	**2,5**

It can be noted that between steps 1 and 3-4, the SPF of the heat pump has not changed, which is logical since it represents the intrinsic performance of the heat pump, but the useful SFP has a bit increased due to the smaller energy consumptions of the whole system.

The energy consumptions compared to step 1 have been decreased by around 12% with a final standard CPE of **15,6 kWh/(m²,year)**. This is thus very close to the final objective of 15kWh/(m²,year).

However, to be on the safe side and be distinctly below 15, two areas of research could be explored. First, the heat pump itself was announced by Armines with a higher coefficient of performance, up to 5, which was not the case in the simulation. Some additional work has to be done to improve the simulated COP to get closer to the one predicted by the manufacturer.

Besides, the system recommended here is working with a heater for the water circulation but the configuration of the reference gas system could be tested by deleting the secondary heat pump of the water circulation and sending the water back to the main heat pumps and to the DHW tank. This would increase the working time of the main heat pumps but it may be more efficient because of the better performance of the main heat pumps by comparison with the secondary heat pump. It would also reduce the maintenance and the investment cost.

- **Global comparison**

In order to be able to compare the performance of this system in steps 1 and 3-4 to the gas referent system, the consumption of primary energy per unit area is presented in Figure 5.1 for the six types of DHW needs.

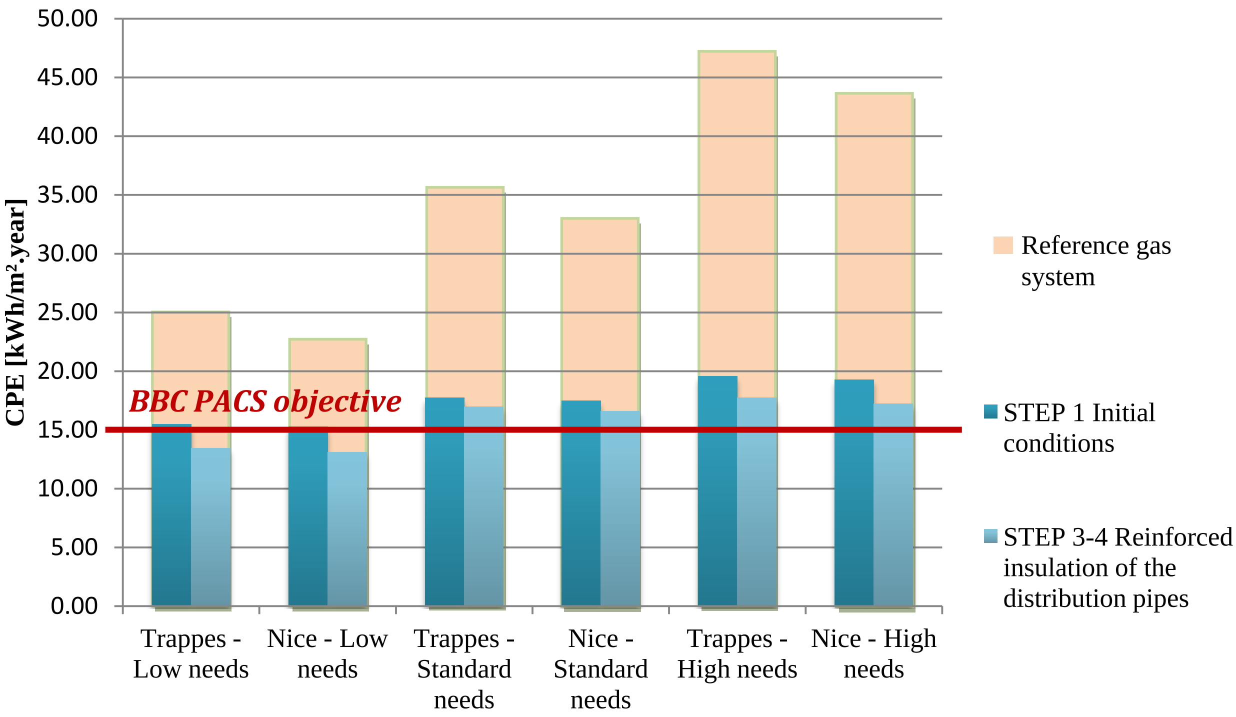


Figure 5.1 Comparison of step 1 and step3-4 for the grey water heat recovery system

The gain between gas and thermodynamic systems is obvious on the previous figure, and especially for higher demands. Rather small difference is noted between the low, standard and high needs. Indeed, the system seems to be more efficient when subjected to higher water drawings. This can be explained by the fact that the more water is drawn, the less DHW will remain in the tank at the end of the day and the less heat losses will occur.

This system is already tested in a hotel of 130 rooms and the performance is evaluated. However this technical solution is rather expensive and needs to be tested and run in apartment buildings on the long-range to get feedback from experience. Some critical points have to be checked:

- The clogging process of the pipes because the human sebum coming with the grey water
- The initial investment of the equipment
- The cost of maintenance of two water tanks and three heat pumps

Next system developed by Atlantic can come as an alternative for smaller buildings.

5.2.3 Inverter system with solar collectors - Atlantic

This system has been analyzed in order to see the effect of each element of the system. First, the COPs of the main and secondary heat pumps were replaced by 1 to simulate an electrical system. Then, the secondary heat pump was added with the normal performance matrix. The third step is with normal performance of the main heat pumps as well. Finally, the fourth step is the real system recommended by Atlantic with the solar collectors coming for pre-heating. The optimization process with better insulation can be done on this last system.

To clarify the methodology, the different steps of simulation are summarized in Table 5.7. The numbering of the four steps of the parametric analysis has been respected.

Table 5.7 Summarizing of the simulations to perform for the inverter system with solar collectors

N° of step	N° of simulation	Description
0.1	**0.1.1 to 0.1.6**	Simulation of an electric system (COP = 1 for all the heat pumps)
0.2	**0.2.1 to 0.2.6**	Simulation of an electric device for the main heating (COP = 1 for the main heat pump) and a heat pump for the water circulation
0.3	**0.3.1 to 0.3.6**	Simulation of the Atlantic system with heat pumps without the solar preheating
1	**1.1 to 1.6**	STEP 1 of the parametric analysis: Total system developed by Atlantic with solar preheating
2	**2.1 to 2.6**	STEP2 of the parametric analysis: Insulation of the water tank with fumed silica
3	**3.1 to 3.6**	STEP 3 of the parametric analysis: Insulation of the water pipes with PUR
4	**4.1 to 4.6**	STEP 4 of the parametric analysis: Combination of steps 3 and 4

- **STEP 0.1 : COP = 1**

At this step, the COPs of the heat pumps have been replaced by 1 to simulate an electrical working system which would consume as much as it would provide to the water tank. The results are presented in Table 5.8.

Table 5.8 Results of step 0.1 for the inverter system with solar collectors

	CFE	CPE	Cost	Discomfort	CO_2	SPF HP	SPF useful	CPE /m²	CPE max	CPE ref	Gain
N°	**[x10³ kWh /year]**	**[x10³ kWh /year]**	**[€/ year]**	**[%]**	**[g/(m²,year)]**	**[-]**	**[-]**	**[kWh/(m²,year)]**	**[kWh/(m²,year)]**	**[kWh/(m²,year)]**	**[-]**
0.1.1	34,0	87,6	3405	0	**984**	1	0,6	**63,5**	15	24,8	**0,4**
0.1.2	31,8	81,9	3203	0	**920**	1	0,5	**59,3**	15	22,8	**0,4**
0.1.3	48,1	124,0	4661	0	**1393**	1	0,7	**89,8**	15	36,8	**0,4**
0.1.4	44,0	113,5	4291	0	**1274**	1	0,7	**82,2**	15	33,4	**0,4**
0.1.5	57,1	147,4	5375	9	**1656**	1	0,8	**106,8**	15	47,9	**0,4**
0.1.6	51,7	133,3	4890	9	**1498**	1	0,8	**96,6**	15	43,3	**0,4**

The energy consumptions of the system are excessively high and twice as less efficient than the gas system because of the coefficient of primary energy which is 2,58 for electricity here. The parameter SPF_{useful} inferior to 1 indicates that the system needs more energy than the real needs. The difference between SPF_{useful} and SPF_{HP} is due to the losses occuring in the distributions and which are taken into account only in SPF_{useful}.

Besides, the comfort is completely ensured for high demands.

- **STEP 0.2 : COP = 1 for the main heat pumps, real matrix for the secondary heat pump**

In Table 5.9, the real performance matrix for the secondary heat pump in the water circulation is simulated, while the main heat pumps still have a COP equal to 1:

Table 5.9 Results of step 0.2 for the inverter system with solar collectors

	CFE	CPE	Cost	Discomfort	CO_2	SPF HP	SPF useful	CPE /m²	CPE max	CPE ref	Gain
N°	**[x10³ kWh /year]**	**[x10³ kWh /year]**	**[€/ year]**	**[%]**	**[g/(m²,year)]**	**[-]**	**[-]**	**[kWh/(m²,year)]**	**[kWh/(m²,year)]**	**[kWh/(m²,year)]**	**[-]**
0.2.1	27,2	70,1	2583	0	**788**	**1**	0,7	**50,8**	15	24,8	**0,5**
0.2.2	25,2	64,9	2403	0	**730**	**1**	0,7	**47,1**	15	22,8	**0,5**
0.2.3	40,2	103,7	3748	3	**1166**	**1**	0,8	**75,2**	15	36,8	**0,5**
0.2.4	36,8	94,8	3439	1	**1066**	**1**	0,8	**68,7**	15	33,4	**0,5**

0.2.5	51,3	132,4	4712	10	**1487**	**1**	0,9	**95,9**	15	47,9	**0,5**
0.2.6	46,5	119,9	4274	9	**1347**	**1**	0,9	**86,9**	15	43,3	**0,5**

The different indicators show diminished values of consumptions. However, they remain really high and the gas system remains more relevant to be used.

- ### STEP 0.3 : Atlantic system without the solar collectors

The performance of the system without the solar preheating is described in Table 5.10:

Table 5.10 Results of step 0.3 for the inverter system with solar collectors

	CFE	**CPE**	**Cost**	**Discomfort**	CO_2	**SPF HP**	**SPF useful**	**CPE /m²**	**CPE max**	**CPE ref**	**Gain**
N°	**[x10³ kWh /year]**	**[x10³ kWh /year]**	**[€/ year]**	**[%]**	**[g/(m², year)]**	**[-]**	**[-]**	**[kWh/(m²,year)]**	**[kWh/(m²,year)]**	**[kWh/(m²,year)]**	**[-]**
0.3.1	15,2	39,2	1511	0	**440**	2,3	1,3	**28,4**	15	24,8	**0,9**
0.3.2	14,3	36,9	1431	0	**414**	2,3	1,2	**26,7**	15	22,8	**0,9**
0.3.3	19,1	49,3	1861	0	**554**	2,6	1,7	**35,7**	15	36,8	**1,0**
0.3.4	17,8	45,8	1741	0	**515**	2,6	1,6	**33,2**	15	33,4	**1,0**
0.3.5	23,2	59,9	2216	2	**673**	2,6	1,9	**43,4**	15	47,9	**1,1**
0.3.6	21,3	55,0	2056	1	**618**	2,7	1,9	**39,8**	15	43,3	**1,1**

The system with only heat pumps reduced a lot the consumptions of energy by comparison with the previous step. In term of final energy, this system consumes less than the reference gas system, which can be observed by the coefficient SPF_{useful} which is larger than 1. Moreover, the heat pumps enable to reduce the discomfort appearing for large needs and observed in the two last systems.

However, when translating to primary energy, the final CPE/m² is more than 15 and gives a gain equivalent to the gas system. This is why the solar collectors need to be added.

- ### STEP 1 : The 6 demand types

The performance of the whole system with the solar preheating is described in Table 5.11:

Table 5.11 Results of step 1 for the inverter system with solar collectors

	CFE	CPE	Cost	Dis co m fort	CO_2	SPF HP	SPF useful	CPE /m²	CPE max	CPE ref	Gain
N°	**[x10³ kWh /year]**	**[x10³ kWh /year]**	**[€/ year]**	**[%]**	**[g/(m², yea r)]**	**[-]**	**[-]**	**[kWh/(m²,year)]**	**[kWh/(m²,year)]**	**[kWh/(m²,year)]**	**[-]**
0.3 .1	5,9	15,2	603	0	**171**	1,7	3,2	**11,0**	15	24,8	**2,3**
0.3 .2	7,1	18,4	707	0	**207**	1,7	2,4	**13,4**	15	22,8	**1,7**
0.3 .3	7,8	20,0	795	1	**225**	2,3	4,1	**14,5**	15	36,8	**2,5**
0.3 .4	7,2	18,5	719	0	**208**	2,2	4,0	**13,4**	15	33,4	**2,5**
0.3 .5	10,4	26,9	1040	3	**302**	2,4	4,2	**19,5**	15	47,9	**2,5**
0.3 .6	7,9	20,5	794	2	**593**	2,4	5,0	**14,8**	15	43,3	**2,9**

The **addition of the solar collectors enables to respect immediately the limitations** of the project. For standard demands, the CPE/m² is below 15kWh per square meter per year, the gain is around 2,5 by comparison with the gas system and finally the CO_2 released is about 220g/(m²,year), which validates all the objectives. The final energy cost is of around **0,60€/(m²,year),** which makes it the most economical solution between gas and grey water.

The performance of the heat pump is rather moderate, with a SPF_{HP} of 2,3 and actually smaller than the system without solar collectors of previous step. This is due to the temperature of the DHW tank which is higher with solar collectors. It will increase the load and reduce the coefficient of performance of the heat pump which is on the contrary getting larger for a low temperature of the incoming cold water from the tank.

However, the SPF_{useful} is quite large thanks to the calorific intake of the solar collectors which have a very good ratio Provided energy/Absorbed energy. Only the pump of the solar loop is requiring electricity, which is rather small by comparison with the solar energy received by the collector.

It can then be interesting to see the impact of insulation to possibly reduce the solar collectors' area.

- **STEP 2 : Insulation of the storage reinforced**

The impact of the silica insulation on the storage is simulated in Table 5.12:

Table 5.12 Results of step 2 for the inverter system with solar collectors

	CFE	CPE	Cost	Discomfort	CO_2	SPF HP	SPF useful	CPE /m²	CPE max	CPE ref	Gain
N°	[x10³ kWh /year]	[x10³ kWh /year]	[€/ year]	[%]	[g/(m²,year)]	[-]	[-]	[kWh/(m²,year)]	[kWh/(m²,year)]	[kWh/(m²,year)]	[-]
0.3.1	5,7	14,8	582	0	**166**	1,7	3,3	**10,7**	15	24,8	**2,3**
0.3.2	7,2	18,7	710	0	**210**	1,7	2,4	**13,5**	15	22,8	**1,7**
0.3.3	7,4	19,0	756	0	**214**	2,3	4,3	**13,8**	15	36,8	**2,7**
0.3.4	7,1	18,3	708	0	**206**	2,1	4,1	**13,3**	15	33,4	**2,5**
0.3.5	10,1	26,1	1006	3	**293**	2,4	4,3	**18,9**	15	47,9	**2,5**
0.3.6	8,1	20,9	806	1	**235**	2,4	4,9	**15,1**	15	43,3	**2,9**

The difference is not as large as the effect of the addition of solar panels. However, this enables **to reduce the consumption of 1kWh/(m²,year) of primary energy**, which may be interesting if we want to design the system to cover also the high demands and respect the objectives.

- **STEP 3 : Insulation of the water circulation reinforced**

The impact of the polyurethane insulation on the pipes is simulated in Table 5.13:

Table 5.13 Results of step 3 for the inverter system with solar collectors

	CFE	CPE	Cost	Discomfort	CO_2	SPF HP	SPF useful	CPE /m²	CPE max	CPE ref	Gain
N°	[x10³ kWh /year]	[x10³ kWh /year]	[€/ year]	[%]	[g/(m²,year)]	[-]	[-]	[kWh/(m²,year)]	[kWh/(m²,year)]	[kWh/(m²,year)]	[-]
0.3.1	5,1	13,1	517	0	**147**	1,7	3,8	**9,5**	15	24,8	**2,6**
0.3.2	6,2	15,9	605	0	**179**	1,7	2,8	**11,5**	15	22,8	**2,0**
0.3.3	7,2	18,6	730	0	**209**	2,3	4,4	**13,5**	15	36,8	**2,7**
0.3.4	6,8	17,4	669	0	**196**	2,2	4,3	**12,6**	15	33,4	**2,7**
0.3.5	9,9	25,5	976	3	**286**	2,4	4,4	**18,5**	15	47,9	**2,6**
0.3.6	7,4	19,2	737	1	**216**	2,4	5,3	**13,9**	15	43,3	**3,1**

The effect is **similar to the insulation of the storage**, with a reduction of around 1kWh/(m²,year) of primary energy on the final result.

- **STEP 4 : Combination of steps 3 and 4**

Finally, both effects of high insulated tank and high insulated pipes are combined in Table 5.14:

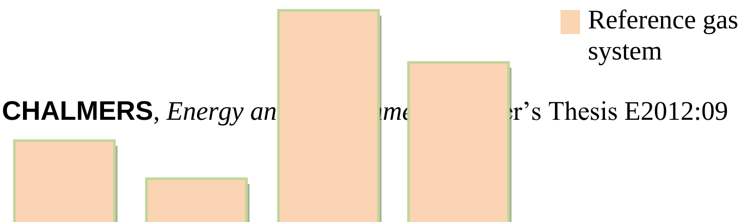
Table 5.14 Results of step 4 for the inverter system with solar collectors

	CFE	CPE	Cost	Discomfort	CO_2	SPF HP	SPF useful	CPE /m²	CPE max	CPE ref	Gain
N°	[x10³ kWh /year]	[x10³ kWh /year]	[€/ year]	[%]	[g/(m², year)]	[-]	[-]	[kWh/(m²,year)]	[kWh/(m²,year)]	[kWh/(m²,year)]	[-]
0.3.1	5,0	12,9	504	0	**145**	1,7	3,8	**9,3**	15	24,8	**2,7**
0.3.2	6,3	16,2	611	0	**182**	1,7	2,8	**11,8**	15	22,8	**1,9**
0.3.3	6,8	17,6	693	0	**198**	2,3	4,7	**12,8**	15	36,8	**2,9**
0.3.4	6,7	17,2	658	0	**193**	2,1	4,4	**12,5**	15	33,4	**2,7**
0.3.5	9,6	24,8	947	3	**279**	2,4	4,5	**18,0**	15	47,9	**2,7**
0.3.6	7,6	19,7	749	1	**221**	2,4	5,2	**14,2**	15	43,3	**3,0**

The goal of 15kWh/(m²,year) is achieved here with a safety margin, except for the large demands in Trappes.

- **Global comparison**

A comparison graphic of primary energy consumptions is presented in Figure 5.2:



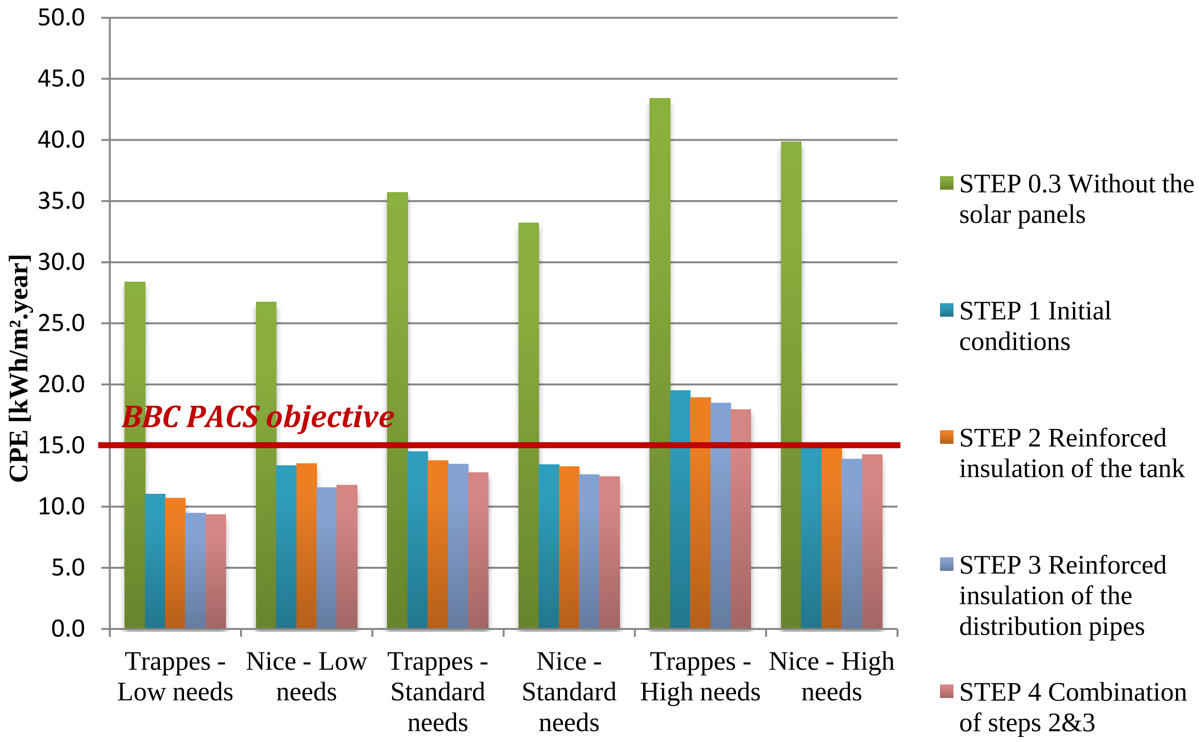


Figure 5.2 Comparison of the different steps for the inverter system with solar collectors

Unlike the grey water system, the difference between Trappes and Nice can be well observed on the figure. This gap is mainly explained by the difference of temperature of outside air which gives better performance in Nice where it is hotter. Last reason of this part is explained by the difference of temperatures of cold water between the two cities, like it was already the case of the grey water heat recovery system.

As said previously, the consumption respects the objective of the project only thanks to the contribution of the solar energy. The system Atlantic with the only heat pumps cannot be as efficient, since it is an accumulation system and will have more heat losses.

However, the total system is quite expensive when adding the solar collectors. Reducing the solar collectors' area and increasing the insulation may be more interesting but it has to be checked with the costs of investment and maintenance, which was not the topic of this work.

5.3 Discussion

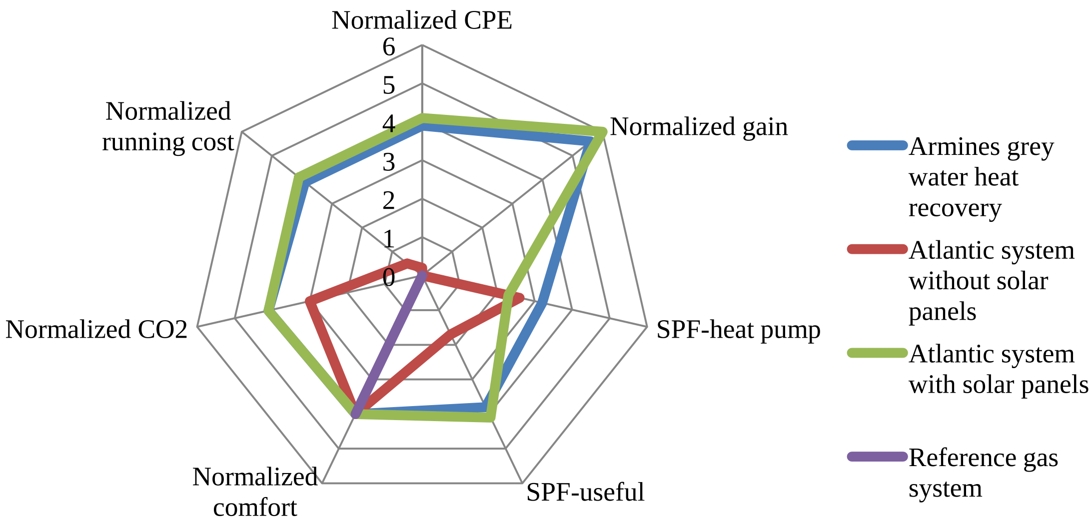
The results which have been obtained can lead to some questions and discussions. First, it can be interesting to assess the systems between themselves.

5.3.1 Comparison between systems

The previous systems can be analyzed for some criteria relevant for the project BBC PACS:

- The consumption of primary energy
- The CO_2 emissions
- The gain by comparison with the referent system
- The running cost
- The comfort for the user
- The seasonal performance factor for the heat pump SPF_{HP}
- The useful seasonal performance factor SPF_{useful}

In Figure 5.3, the SPF factors are equal to their own value. However, the other criteria have been normalized, so that the different systems can be compared. The grading scale has been provided in the table below the figure: for instance, grade 4 means that the goal fixed by the project is achieved.



Grade	0	1	3	3	4	5
Meaning	Level of reference system				Level of the project's objectives	Beyond the project's objectives

Figure 5.3 Performance of the different thermodynamic systems

As it already appeared in the previous tables, Atlantic system with solar collectors and Armines system respect the different objectives of the project. Armines seems to have developed a heat pump with a **better coefficient of performance**, which may be explained by the high temperature of its cold source (grey water).

Those two systems seem to have an equivalent area of performance of the graph of Figure 5.3, except the Inverter system without solar collectors of course. But it is of great importance to remember that **the system using the grey water heat needs to be implemented in large buildings** to ensure a high quantity of grey water to provide to the heating system. It is therefore not equivalent to the Inverter system with solar collectors which can be adapted for smaller buildings as well.

The reference system is only satisfying the comfort; all the other criteria are equal to zero.

It should be noted that the performance of a system strongly depends on the definition of the parameters: the coefficient of performance (or SFP here) can be defined in different ways and will be more or less favorable. Depending on if the SFP takes into account the energy provided by the system or the real needs, if the SFP considers the solar energy in the same way as the energy coming from the heat pump, if the energy absorbed takes into account the losses, the SFP can vary a lot and give different interpretations.

This was the reason why it was chosen to evaluate both SPF_{useful} and SPF_{HP}. But it could have been chosen to calculate the total energy provided by the system (including solar energy and secondary heat pumps) divided by the total energy absorbed. This would have given another assessment of the system as well, probably giving advantage to the solar system since it would consider all the energy brought by the solar panels but that would not have corresponded to the real needs.

5.3.2 Cost analysis

The promising systems are therefore the Armines system and the Atlantic system with solar collectors. Since both systems are running during night, the price per kWh is the same and the running cost follows the tendency of the consumption of the final energy absorbed: as shown in Figure 5.4, the system will be more expensive for Armines configuration.

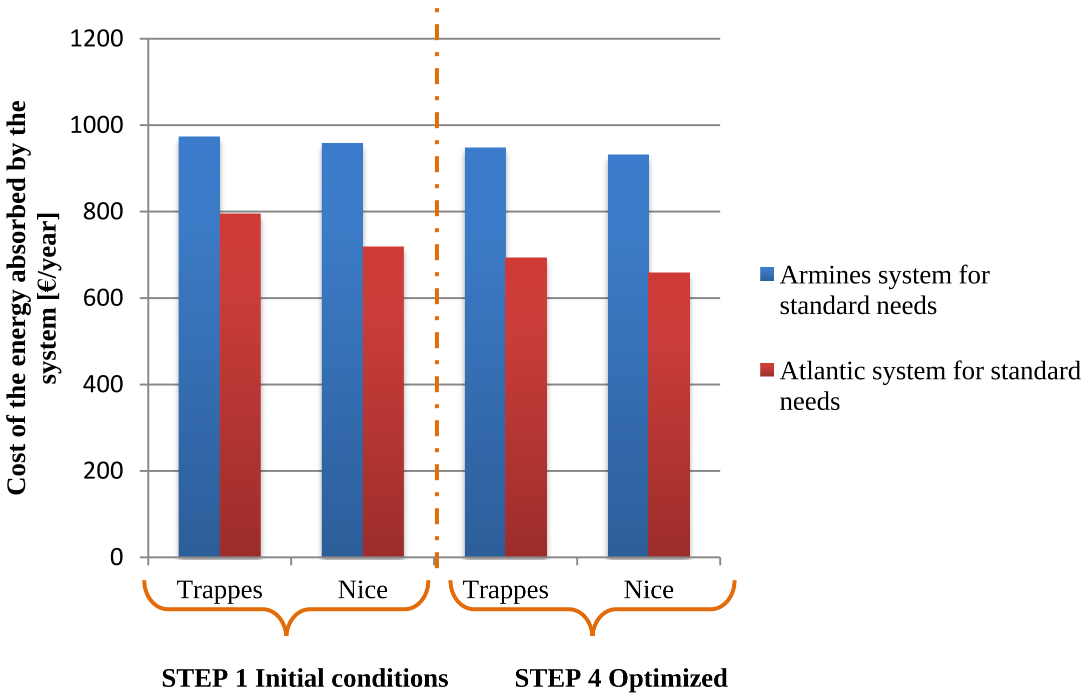


Figure 5.4 Cost of the energy absorbed by Atlantic and Armines system per year

The difference is not large between the initial and the optimized conditions for the Armines system, since only the insulation was changed. The difference becomes more visible for the Atlantic system whose cost is reduced by 13% of its initial price.

But the financial analysis should include the initial **investment for the equipment**, as well as the **cost of the maintenance**. Indeed, grey water recovery requires two high-insulated tanks, as well as an insulated pipe system for both DHW and grey water. The pipes clogging asks for maintenance with filter replacements which can occur quite regularly. This high cost is an additional reason to install preferably this system in larger buildings, so that the cost can be divided between a higher number of inhabitants.

Regarding the second system, solar collectors are not only expensive at the beginning but will also require some maintenance. Moreover, high class insulation like fumed silica remains more expensive than normal insulation, which will probably be considered by the inhabitant.

Subsequently, some work has to be done later on to determine the impact of those parameters on the relevance of those systems. This will be the object of the future investigations to be performed by the partners of the project.

***

Thus, the analysis performed in this Master's thesis provided preliminary results of the systems which need now to be more investigated to have a modeling even closer to real systems and to have a complete view of the real systems by their costs. However, this first work enabled to show that the use of grey water and solar energy combined to a heat pump reduce the consumption by comparison with the reference gas system. Comfort is ensured in any case, the next step will be the economical analysis.

6 Conclusion

This analysis highlighted the possibility of achieving good performance of domestic hot water heat pump based systems by the use of renewable or “free” energy like the sun or the grey water. The French regulation already stated about a maximum consumption level of energy for residential buildings and the calculation based on the RT2012 regulation gives a consumption of around 25kWh/(m²,year) of primary energy for the Domestic Hot Water production. The goal of the project BBC PACS was to improve even more this limit to 15kWh/(m²,year) and the Master’s thesis objective was to perform simulations on the software TRNSYS and assess the feasibility of reaching such a goal with the technologies available today.

The TRNSYS results show that the project’s objectives are realistic from an energetic point of view. The combination of efficient heat pumps with good insulation and renewable energies enables the systems to fit into the limit. The system developed by Armines is clearly more adapted to large apartment buildings to increase the volume of grey water accumulated and the efficiency of the system, while the Atlantic system suits well to smaller areas.

It is legitimate then to discuss the validity of the method adopted and the results obtained in this study. For instance, the reference technology chosen by the consortium shows larger energy demands than the objective of the new regulation RT2012. Therefore, the gain compared to the reference system is achieved more easily. The reference was chosen at the beginning of the project in 2010, which explains why it has lower performance. But it is important to keep in mind that the reference has a very low level of performance and the calculated gain has a meaning in this reference context.

Besides, the analysis could be improved by reducing the time step to one minute to get drawing profiles more realistic and analyze the reactivity of the systems. A last comment could be done regarding the simulation model of heat pump which is based on the performance matrix for Armines and the polynomials for Atlantic. The second method based on polynomials is more accurate and can give an advantage to Atlantic in this case.

In addition, the recommendations deduced from the energy simulations have not been considered from the point of view of the manufacturer or the electricity producer. This will be the next steps of the project to analyze the systems with financial considerations from both the industrial and the client’s sides.

In conclusion, the simulations here already provided relevant and logical results which show the potential interest of using heat pumps. Although heat pumps theoretically exhibit idealistic characteristics to achieve low energy consumptions, the TRNSYS simulations showed results which were not always up to the expectations, which suggests that additional research is needed prior to any conclusion on the systems. The project will be continued based on this first analysis which emphasized both the strengths and the weaknesses of the models which deserved to be explored more deeply.

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8 Appendices

8.1 Repartition key for the “less variable” water drawing

The key coefficient is obtained by multiplying the three coefficients coming from the Table 8.1, Table 8.2 and Table 8.3.

Table 8.1 Coefficients for the week of the year

Week	Jan.	Feb.	Mar.	Apr	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1	1	1
5			1		1			1			1	

Table 8.2 Coefficients for the day of the week

Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Coeff.	1	1	1	1	1	1	1

Table 8.3 Coefficients for the hour of the day (hidden for confidentiality reasons)

Hour	Any day of the week
1	X
2	X
3	X
4	X
5	X
6	X
7	X
8	X
9	X
10	X
11	X
12	X
13	X
14	X
15	X
16	X
17	X
18	X
19	X
20	X
21	X
22	X
23	X
24	X

8.2 Model Inhabitants – Living area (RT2012)

The French regulation RT2012 enables to calculate the number of inhabitants from the living area.

In individual house, the model is:

$$N_{inhab} = \begin{cases} 1 \; if \; A < 30m^2 \\ 1.75 - 0.01875 * (70 - A) if \; 30m^2 \leq A < 70m^2 \\ 0.025 * A \; if \; A \geq 70m^2 \end{cases} \quad (8.1)$$

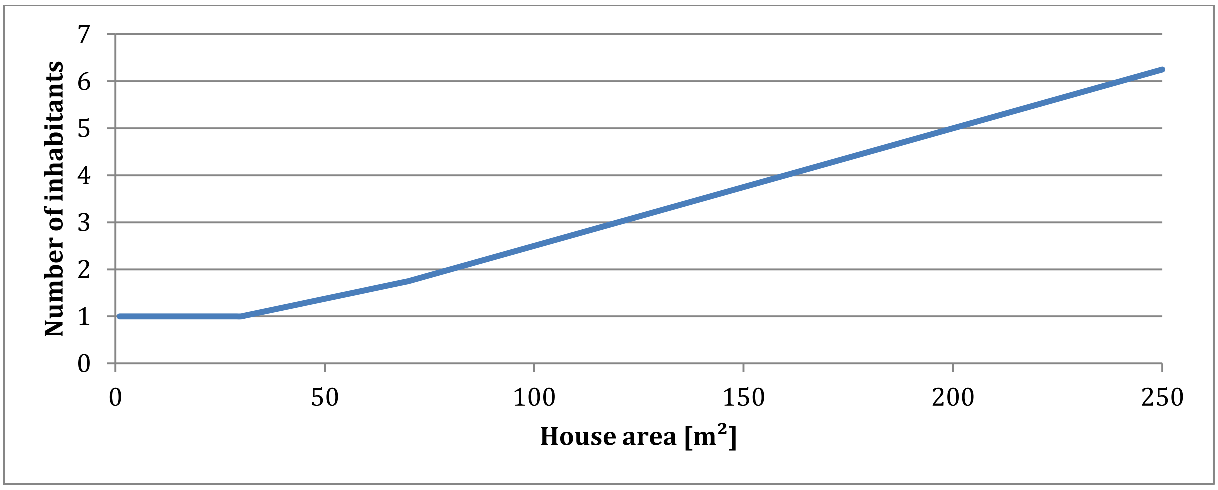


Figure 8.1 Number of inhabitants calculated by the model of the RT2012 in a house

In apartment buildings (model used in this report), the model is:

$$N_{inhab} = \begin{cases} 1 \; if A < 10m^2 \\ 1.75 - 0.01875 * (50 - A) \; if \; 10m^2 \leq A < 50m^2 \\ 0.035 * A \; if \; A \geq 50m^2 \end{cases} \quad (8.2)$$

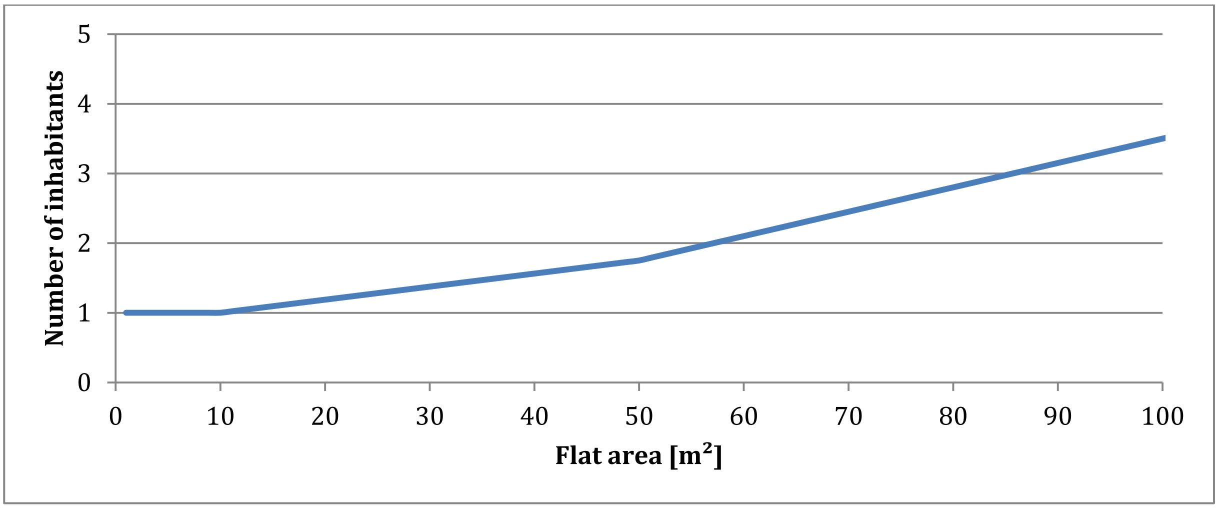


Figure 8.2 Number of inhabitants calculated by the model of the RT2012 in a flat

8.3 Graphic user interfaces

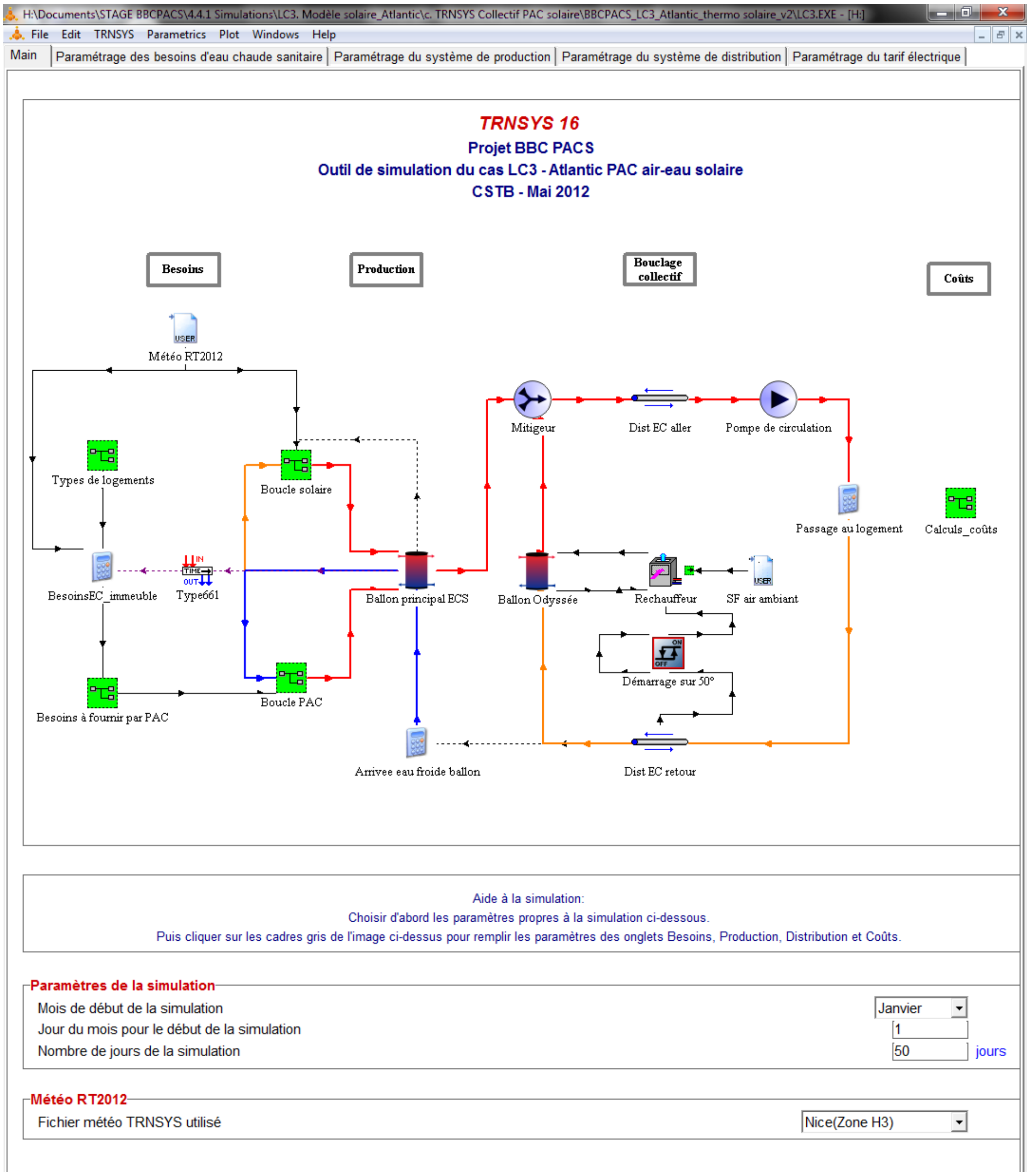
To make a convenient way of working with the parametric analysis, a graphic user interface has been designed for each system based on the TRNSYS input files.

Each interface was divided in 5 sections:

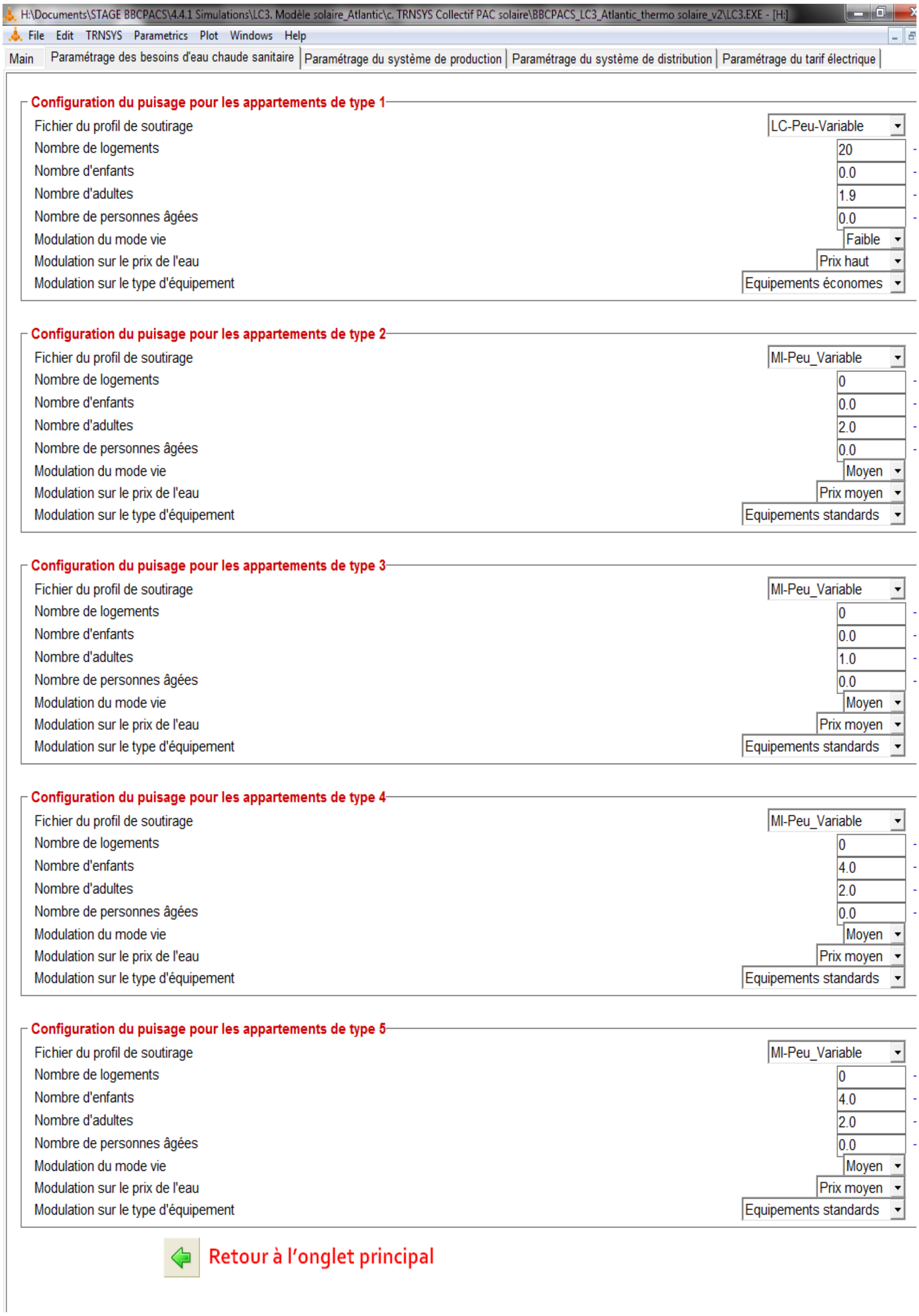
- **Section 1:** called 'Main' with a figure of the TRNSYS assembly and the parameters of simulation (time of simulation and location). Links on the picture to the other sections were provided
- **Section 2:** called 'Paramétrage des besoins d'eau chaude sanitaire' (Definition of the DHW demands in English) and which gives the choice to select different kinds of households with different usages
- **Section 3:** called 'Paramétrage du système de production' (Definition of the production system in English) to provide the technical characteristics of the heating system
- **Section 4:** called 'Paramétrage du système de distribution'(Definition of the distribution system in English) to provide the technical characteristics of the distribution system
- **Section 5:** called 'Paramétrage du tarif électrique et gaz' (Definition of the electricity and gas fees in English) to choose the types of energy fees for electricity and gas

An example of this interface is provided here, corresponding to the interface performed for the inverter system with solar collectors (Atlantic system).

- ## Section 1 of the interface of Atlantic system: Main section



- ## Section 2 of the interface of Atlantic system: Definition of the demands

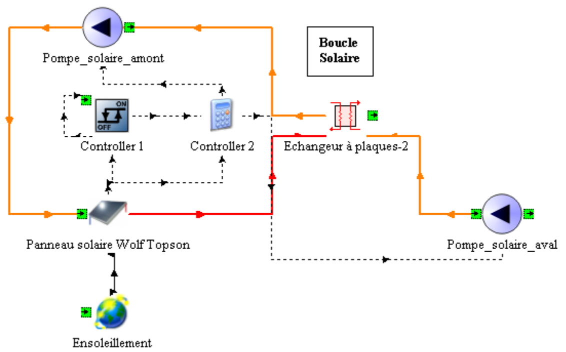


▪ Section 3 of the interface of Atlantic system: Definition of the production

Main | Paramétrage des besoins d'eau chaude sanitaire | Paramétrage du système de production | Paramétrage du système de distribution | Paramétrage du tarif électrique

Boucle solaire

Les capteurs sont reliés au ballon par un échangeur à plaques externe. Leur ajout au système de production est optionnel.
L'arrêt est automatique si la température du capteur atteint 140°.



AJOUT OPTIONNEL DU SYSTEME SOLAIRE

Mise en marche des capteurs (0 arrêt, 1 marche)	1	-

CAPTEURS SOLAIRES

Nombre de panneaux en série	1	-
Surface totale de panneaux solaires	30	m²
Chaleur spécifique du fluide dans les capteurs	3.700	kJ/kg.K
Débit test lors de la mesure des caractéristiques techniques du capteur	78.00	kg/h.m2
Rendement optique	0.804	-
Coefficient de pertes du premier ordre	3.235	-
Coefficient de pertes du second ordre	0.0117	-
Latitude	48.46	°

Aide à la saisie :
La Rochelle (46°09) ; Nancy (48°41) ; Nice (43°41) ; Trappes (48°46)

Inclinaison des capteurs	35	°

POMPE CONDUISANT LE FLUIDE SOLAIRE DES CAPTEURS VERS L'ECHANGEUR

Débit du fluide provenant des capteurs	792	kg/hr
Puissance de la pompe	540	kJ/hr

POMPE CONDUISANT L'EAU DU BALLON VERS L'ECHANGEUR SOLAIRE

Débit de l'eau provenant du ballon	790	kg/hr
Puissance de la pompe	720	kJ/hr

ECHANGEUR A PLAQUES ENTRE LES CAPTEURS ET LE BALLON
Ce coefficient correspond au coefficient d'échange thermique surfacique O.H.T.C présent sur l'avis technique multiplié par la surface de capteur.

Coefficient de transfert de l'échangeur	18000	kJ/hr.K

Ballon principal ECS

CARACTERISTIQUES DE L'ENVELOPPE DU BALLON

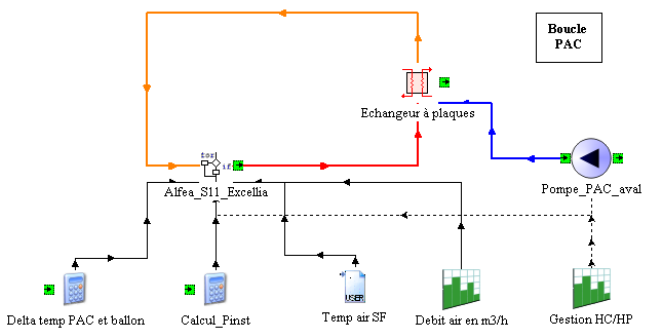
Volume du ballon	2.50	m^3
Hauteur du ballon	2.00	m
Coefficient de pertes thermiques surfaciques du stockage	3.240	kJ/hr.m^2.K

POSITION DES ECHANGEURS
La stratification du ballon a été modélisée par 4 couches.
Les 4 paramètres suivants demandent la position de l'entrée ou de la sortie des échangeurs sur le ballon.
Donner un numéro de 1 à 4, le haut du ballon correspondant à la couche 1, le bas à la couche 4.

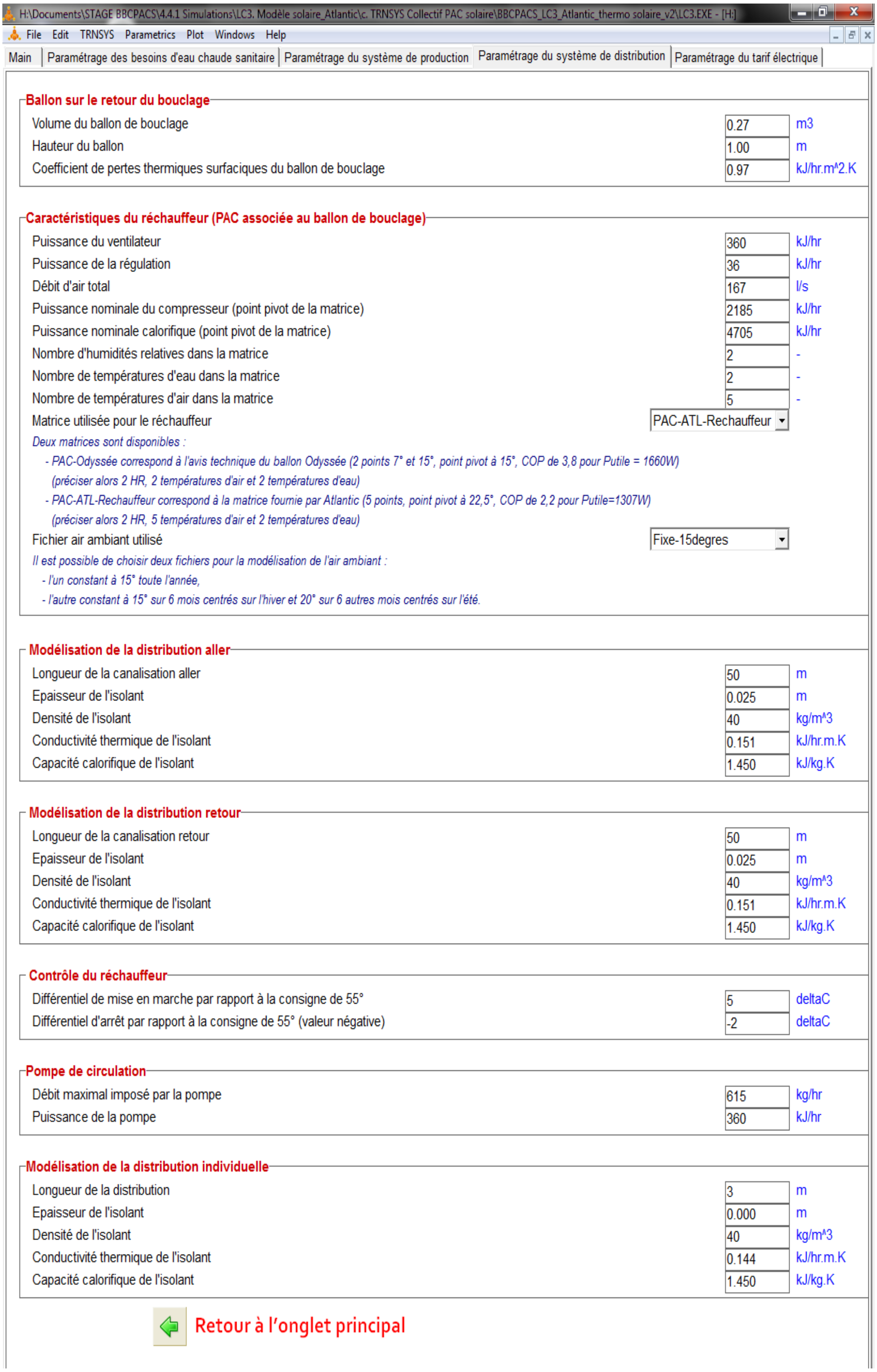
Position du retour de l'échangeur PAC	3	-
Position de sortie vers l'échangeur PAC	4	-
Position du retour de l'échangeur solaire	3	-
Position de sortie vers l'échangeur solaire	4	-

Boucle PAC

La génération est assurée par une PAC Atlantic modélisée par polynômes et reliée au ballon par un échangeur à plaques externe.
Le fonctionnement est imposé de 22h à 6h chaque nuit.



▪ Section 4 of the interface of Atlantic system: Definition of the distribution



▪ Section 5 of the interface of Atlantic system: Definition of the energy fees