BBC PACS – SIMULATION OF DOMESTIC HOT WATER GENERATION FOR LOW ENERGY BUILDINGS

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ABSTRACT

In low energy residential buildings, the energy consumption for hot water generation becomes the main consumption item. In order to achieve the requirement of the new French thermal regulation [1], the consortium has developed a strategy to design a system of DHW generation on the basis of a thermodynamic system using heat sources available in and around the building. This plan is based on numerical simulation tools and field tests. This article shows that first field tests are in agreement with numerical simulations. Reaching the objectives require to minimize heat losses, high COP and possibly having recourse to renewable energies or energy recovery (grey water) or new sources of energy (hot air in attic or warm air in building basement).

INTRODUCTION

Since 2011, France has entered into a process of enforcing a new regulation for buildings energy performance. The new regulation, known as the RT2012 ("réglementation thermique 2012"), requires energy consumption of new buildings to be under an absolute performance value, set around 50 kWh of primary energy per square meter per year for 5 items: heating, cooling, hot water generation, lighting, ventilation and auxiliaries like pumps and fans associated with [1].

Domestic hot water generation becomes one of the most important part of these energy consumptions. In order to promote new solutions for domestic hot water generation, the French Energy Agency (ADEME) has launched a research program (called PACTE ECS) which main objective is to develop new systems matching the following requirements:

- achieve an energy consumption less than or equal to 15 $kWh_{ep}/m^2.yr$,
- have a factor two on the energy gain relatively to the reference technology,
- have a payback time less than half of the equipment lifespan,
- have an equipment life span over 15 years.

In addition, the consortium added a requirement on the CO_2 emissions (less than 350 g of $CO_2/m^2.year$).

The main goal of our project (BBC PACS: **B**âtiment **B**asse **C**onsommation- **P**ompe **A** Chaleur pour l'eau **C**haude **S**anitaire; Low energy building, Heat Pump for DHW generation) is to develop a system based on the thermodynamic cycle using heat sources available in and around the building (interior and ambient air, geothermal resource, grey water, etc.).

In order to design and select the most appropriate system, several simulation tools have been developed in the TRNSYS environment. The numerical simulations are based on the analysis of the thermal losses of the components, of hot water needs in relation with the number of occupants, of the energy available in each source around the building via an exergetic point of view. Each system is modelled and the results are compared in terms of energy efficiency, industrial and operating costs. Field tests in a collective building were carried out and the first results are in line with simulation tools.

SIMULATION AND EXPERIMENT

This part of the article presents, first, the objectives of the modelling tools developed during the project and second, the different preliminary studies made in order to be able to achieve these goals. These studies stretch from the hot water needs definition to the examination of the components of the generation system (distribution, storage, cold sources, heat pumps, fares).

Objectives

The simulation objectives can be grouped in two categories:

- The first is, of course, to be able to dispose of numerical elements (energetic consumption costs, CO_2 émissions) allowing to check that the consortium's objectives are reached.
- The second one is to realise sufficiently flexibles modeling tools in order to, at the same time, be able to carry out simulation/measures comparisons, but also make sensitivity studies on external (climate, hot water needs, ...) or internal (storage or distribution insulation, …) parameters possible for various generation systems.

The so considerered simulation has been conducted on the dynamic simulation software TRNSYS and has consisted in the modeling of seven domestic hot water generation systems.

Three for individual housing :

- MI1 : reference system (direct electric heated storage tank)
- MI2 : thermodynamic system, water heater with an air to water heat pump (outside air, exhaust air, indoor air)
- MI3 : Air to Water heat pump located in the underfloor space (use for different heat sources as exhaust air, attic air, …) coupled with grey water heat recovery.

Four systems in community housing :

- LC1 : reference system (semi-storage generation by central gaz boiler)
- LC2 : large community housing – grey water heat recovery through two separates storages. Therefore there is no need of synchronization between drawn and grey water.
- LC3 : small community housing – main generation by solar panels and additional generation by Air to Water heat pump during night
- LC4 : Geothermal Heat Pump generation

Simulation - Hot Water Needs

In order to develop a low consumption system of Domestic Hot Water generation, it is necessary to know well the occupant's domestic hot water needs. Therefore, the generation could be adapted to the needs of occupants, which represents one of the most important ways to reduce energy consumption.

Nevertheless, it appears that the DHW needs are widely variable from an occupant to another. The model of DHW needs has to deal with this specificity. That is the reason why we choose to develop a modular approach to calculate DHW needs in relation to some parameters.

A bibliography was made to define the main influent values for the DHW needs evaluation, knowing that the most common available data are averaged values over a city, a county or even over France and averaged over a day.

The water needs averaged per day and per occupant is the main value. From this, a modulation is applied to take into account the type of dwellings, the number and age of occupants, the way of living, the price of water and the level of water-saving or energy-saving equipment. Each parameter could be set so that this modularity allows testing easily different configurations of occupancy from the single house occupied by one person to a block of flats of different sizes.

Once obtained the volume of water needed by the occupant during a day, we applied a repartition key depending on the month, the day of week and the hour of the day, to determine the water need and then the energy need at each time step of simulation (Figure 1).

The repartition key has been developed by the consortium or inspired by [7] for collective DHW needs.

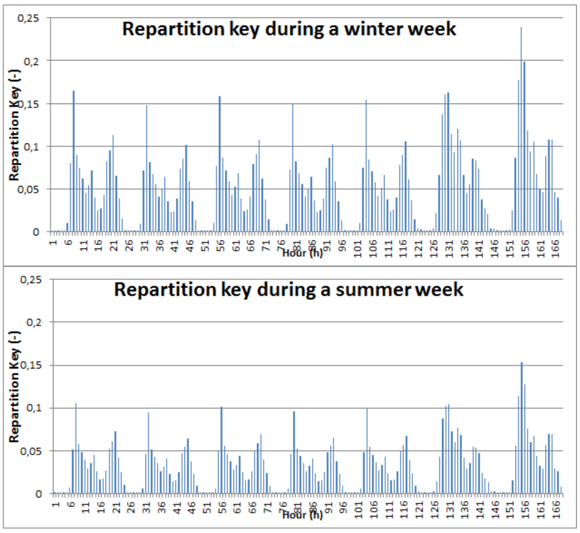

Figure 1 Examples of hourly draw off during a winter and a summer week for a collective building

The values of hourly cold water temperature are given in RT2012 [1].

All these elements lead to calculate the hourly DHW need of a building that has to be provided by the DHW system. However, if a shorter time step will be used later, for the moment the results are daily integrated in a monotonic function of daily DHW needs (the 365 daily DHW needs are ranked from highest to lowest – figure 2). Indeed, the future management of electricity tariff led to integrate the DHW needs on a day and not especially at a shorter time step.

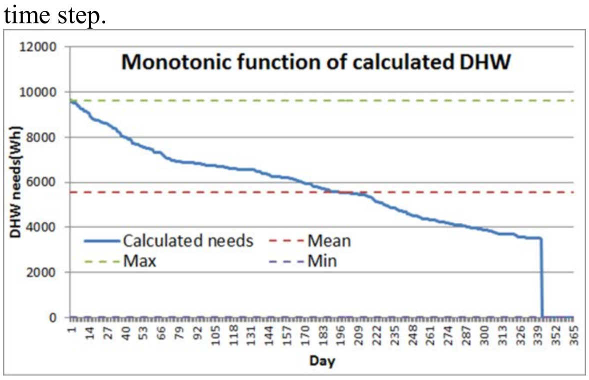

Figure 2 Monotonic function of calculated DHW need

To validate this model, it is compared to experimental ones. Because the type of person living in the apartment is unknown, the main goal is to find a set of parameters that achieves modelled monotonic needs close to the measured ones.

In blue and bold, the monotonic is measured in a two bedrooms apartment in Lozère, France. The other curves represent modelled monotonic DHW needs with different set of parameters (two adults are considered. Model #1 and #3 have variable draw off while #2 has regular one. The difference between #1 and #3 is due to the standard of living and the water equipment). It shows that the model achieves a good prediction of actual DHW needs.

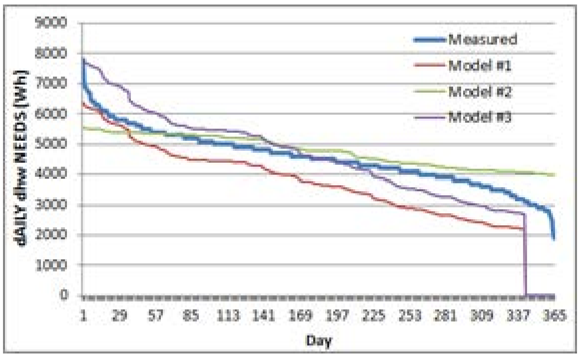

Figure 3 Comparison between calculated and measured monotonic

To conclude, a modular method was created to evaluate the DHW need of a building (individual or collective generation). This will allow to analyse the DHW need and to choose the DHW generation system that suits the best the building and their occupants. Beforehand, thermal losses from the DHW pipes (individual and/or collective) and storage tank losses have to be added to the DHW need to determine the characteristics of the system generation.

Simulation - Distribution and storage loss

In-between the hot water taps and the hot water generation, pipes and a possible storage are used (Figure 4). The thermal losses of pipes could reach 40% of the global DHW final energy consumption in a building (4% in a single house). The storage losses are around 25% of the global consumption of a single house (4% in a building) [6].

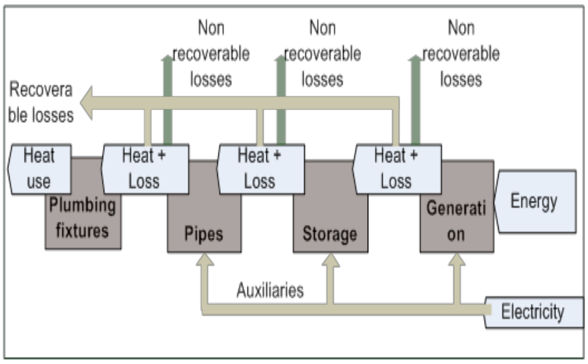

Figure 4 The DHW system

The thermal losses are energy consuming and have to be controlled. Then, after having modelled them (considering an ambient temperature of 18°C and a hot water temperature of 55°C), we found innovative and efficient materials to reduce them drastically.

Distribution pipes

The DHW pipes could be individual (short and commonly not insulated) or collective (longer and insulated). Type 604 of TRNSYS with only one fluid node (because of the time step) is used. The model calculates the radial heat flux lost in the environment based on the fluid properties, the pipe and insulation properties, convection and radiation from the outer surface to the environment [4].

Different types of pipes insulation (among common insulation, silica aerogel, Vacuum Insulated Panel, etc.) are tested in order to determine the best to reach the given objective of low energy consumption. We consider the thermal conductivity, the insulation thickness and the cost of each solution (Figure 5).

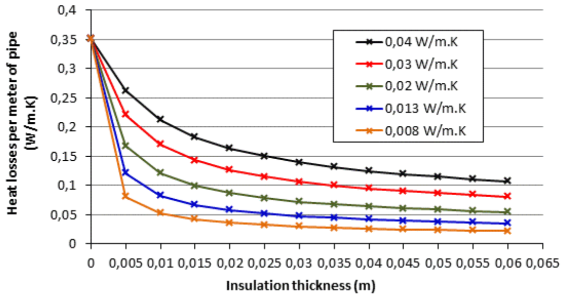

Figure 5 Heat losses depending on the thickness of insulation for different types of insulation

Thermal losses through DHW pipes could be easily reduced with some additional centimetres of insulation. Besides, using an efficient one, (thermal conductivity near 0,01 W/m.K) mainly for the long collective pipes, seems to be necessary in order to reach the BBCPACS objectives.

Storage

A similar work was made with storage insulation: static losses evaluation, suggestion of innovative solution to reduce them and study of the dynamic behaviour of the storage (for the energy consumption calculation).

We first used a finite elements method (Comsol) to model the tank and its insulation in a steady state. It allows determining the global heat losses, which was characterized with a *Cr* coefficient [Wh/l.K.day], for each type of insulation (PU, Aerogel, VIP and an innovative solution based vacuum insulation at different levels of pressure). (Table 1). These results have not been compared with experimental data but Cr values for the reference solution fits standards tank's values.

Table 1 - Energy performance evaluation of each vertical cylindrical storage tank (4 cm insulation solution for a 300 l storage)

Insulation type	C_r [Wh/l.K.day]	Daily losses [kWh]
PU 25 (ref)	0,128	2,37
PU 22	0,112	2,07
Blanket	0,074	1,37
VIP	0,045	0,83
VIP and PU 37	0,066	1,22
Silica 1hPa	0,029	0,54
Silica 10 hPa	0,034	0,63
Silica 100 hPa	0,048	0,89
Silica Patm	0,103	1,91

Once the static losses were evaluated, the whole DHW generation system has been modelled with TRNSYS. Thermal stratification in the storage, has been modelled by assuming that the tank consists of N fully mixed equal volumes (Figure 6).
Positions of inlets and outlets, presence of internal submersed heat exchangers and, of course, static thermal losses calculated below, can be set by the user.

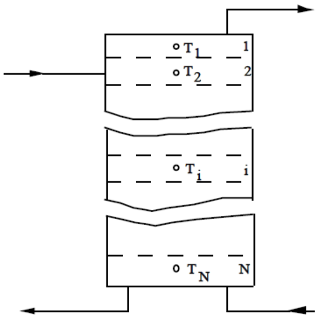

Figure 6 Model of storage [3]

The performance of insulation materials can reduce storage losses but their industrial use depends on cost and ease of implementation.

About 40% of the energy consumption for DHW generation is due to heat losses through pipes and storage. A way to reach the BBCPACS objectives is to improve the insulation. The generated energy savings compared to its cost make efforts interesting.

Simulation – Heat sources analysis

Domestic Heat sources
In this study, different heat sources located around a residential building have been identified. They are classified into two main axes: the first axis is the "Air" vector, and the second axis is the "Water" vector. These heat sources are cited in the following table:

Table 2 – Different sources of domestic housing

Source	***Vector***	
	Air	Water
Outdoor Air	X	
Energy recovered from occupied rooms		
Extracted Air	X	
Greywater		X
Energy stocked in non-occupied rooms of a house		
Eaves	X	
Crawl space	X	
Energy stocked in the ground		
At surface level		X
At 9 m of depth		X

In order to define the ability of these sources of being an energy performing heat source for a heat pump, energy and exergy analyses have been undertaken.

Energy and exergy analysis
Many authors have defined "Exergy" as the maximal work attainable in given reference state without generalized friction [2]. The Exergy analysis serves to classify the different sources according to their capability to deliver useful energy convertible to work in a Carnot thermodynamic cycle.

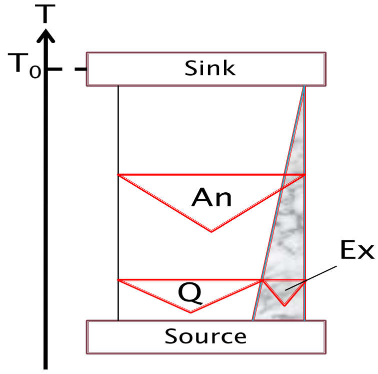

Figure 7 Energy transfer diagram

Therefore, the higher the source exergy is, the lower the heat pump compressors work will be.
In order to obtain the same sign of exergy and to compare the different sources, the sink temperature is chosen as the reference temperature (see figure 9).
The energy and the exergy analyses of the system are carried out by applying the first and the second principle of thermodynamic respectively:

$$\dot{W}_{comp} = \dot{m}_{sink} \cdot (h_{out,sink} - h_{in,sink}) - \dot{m}_{source} \cdot (h_{in,source} - h_{out,source}) \quad (1)$$

$$\dot{W}_{comp} + \dot{W}_{Aux} = \dot{m}_{sink} \cdot (e_{out,sink} - e_{in,sink}) - \dot{m}_{source} \cdot (e_{in,source} - e_{out,source}) + {}^{\cdot}T_0 \quad (2)$$

where $^{\cdot}T_0$ represents the exergetic losses in the system.

And:

$$e = h - T_0 \cdot s \quad (3)$$

For:

$$T_0 = \frac{h_{out,sink} - h_{in,sink}}{s_{out,sink} - s_{in,sink}} = ct. \quad (4)$$

The energy and the exergy equations are given respectively in the following equations:

$$\dot{Q}_{source} = \dot{m}_{source} \cdot (h_{in,source} - h_{out,source}) \quad (5)$$

$$Ex_{source} = \dot{m}_{source} \cdot (e_{in,source} - e_{out,source}) \quad (6)$$

According to these equations, energy and exergy are directly proportional to the mass flow rate and the heat capacity of the source vector. So, it is difficult to compare the "Air" vector sources and the "Water" vector sources. Therefore, energy and exergy are calculated and compared to the "outdoor Air" as presented in figure 8. The calculation assumptions are presented in table 3.

Table 3 – Calculation assumptions

Source	***Vector***	
	Air	Water
Outdoor Air	Annual temperature of La Rochelle in France	
Energy recovered from living space		
Extracted Air	19°C	
Greywater		31°C
Energy stocked in non-living space of a house		
Eaves	According temperature	
Crawl space	T_0 in La Rochelle, France	
Energy stocked in the ground		
At surface level	According temperature	
At 9 m of depth	T_0 in La Rochelle, France	

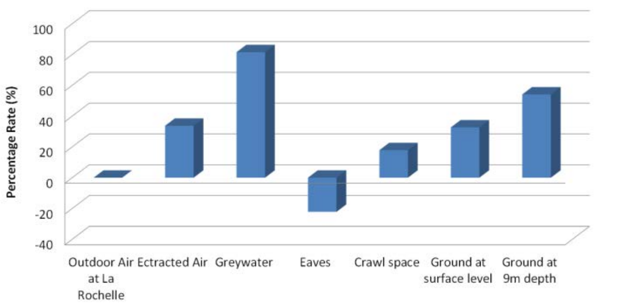

Figure 8 Energy and exergy comparison

The results show that the highest exergy is found in the grey water. The mass flow rate and the availability of the source vector affect the classification of the sources. For certain sources (as grey water), energy and exergy are high but the mass flow rate is limited. For other source as "eaves", energy and exergy are low due to the mass flow rate which is low and because the temperature is higher than outside air. Therefore, this study represents a first approach for selecting the most energy efficient sources. The detailed simulation, according to a specific application, is necessary to select the best heat source.

Simulation - Heat pumps

Modelled heat pumps can be divided in two types :

- On/off heat pump type, running at 0 or 100% of its capacity power.
- Inverter heat pump type (the speed and thus the power of the compressor is adapted to the load that has to be fulfilled at a certain time)

The first type has been taken into account by available models in TRNSYS library. In order to reduce dysfunctions using these models, we decided to reduce the simulation time step (dividing it by 6 to reach 10 minutes – going further would have been difficult, due to our lack of knowledge on dynamics of hot water needs).

For the second one, polynomials description has been chosen, using W programming language design for TRNSYS by CSTB in order to make TRNSYS components development easier.

This polynomial modelling allows to take into account the inverter heat pump partial load functioning. The principle of polynomials is presented in table 4.

Table 4 - Principles of polynomials representation

	Absorbed power			**Calorific power**		
	f1	**f2**	**f3**	**f4**	**f5**	**f6**
a3	X1	X5	X9	X13	X17	X21
a2	X2	X6	X10	X14	X18	X22
a1	X3	X7	X11	X15	X19	X23
a0	X4	X8	X12	X16	X20	X24

With

- f1, f4: a function of outside temperature
- f2, f5 : a function of fluid temperature leaving heat pump
- f3, f6 : heat pump load

Each function fi is a polynomial function of third degree where each *Xi* represents the numerical value of the corresponding coefficient *ai*. The example for f1 is given below:

$$f1(T_{out}) = X4 + X3.T_{out} + X2.T_{out}^2 + X1.T_{out}^3 \quad (7)$$

The absorbed power by the compressor and the calorific power as a product of polynomials are calculated by equations 8 and 9:

$$P_{absorbed} = f1(T_{out}) * f2(T_{fluid}) * f3(Load) \quad (8)$$

$$P_{calorific} = f4(T_{out}) * f5(T_{fluid}) * f6(Load) \quad (9)$$

Simulation – Energies rate modelling tool

In order to highlight potential changes in French electricity load curve peaks, some of the systems modelled can be driven according to different electric fares available for consumers. We are particularly thinking about peak (during day) and off-peak (during night) hours, key factors in the French electricity price plan. So, a tool has been included allowing, on one hand, to enter electricity fares at simulation time and, on the other hand, the calculation of annual energetic cost for the system on this basis.

Consortium use of these tools has given the opportunity to:

- realize parametric studies
- realize a simulation/measure comparison on one particular system (LC3).

Results are given in chapter (Discussion and Result analysis).

The following chapter presents the demonstrator for LC3 system set up in a residential building.

Experiment – Heat Pump and Solar Collectors System (LC3)

The solution called LC3 (collective housing in small buildings) is composed of DHW storage heated at night by a heat pump (HP) drawing calories from outdoor air. Distribution in flats uses a thermostatic mixer and a loop kept at its temperature by a second heat pump that draws calories from ambient air in the service room (loop reheater – Figure 9). The possibility of boosting by thermal solar collectors is considered.

The demonstrator used to validate the model is a set of 12 individual flats forming part of a collective building located in Soissons (northern part of France). The storage is composed of two 750-litres tanks fitted with a 10-kW electrical resistor for boosting if necessary. The nominal heating capacity of the main HP is 11 kW. The average DHW consumption is 91 litres at 50°C per flat and distribution losses are 15 kWh per day. Regulation controls heating of the tanks by night during off-peak electrical energy rates. The thermodynamic loop reheater may be used at any time to compensate for distribution losses. The thermal solar collector option has not been installed on this demonstrator.

The demonstrator is in service since March 2012, and measured results are compared with the LC3 simulation model over a period going from April to November.

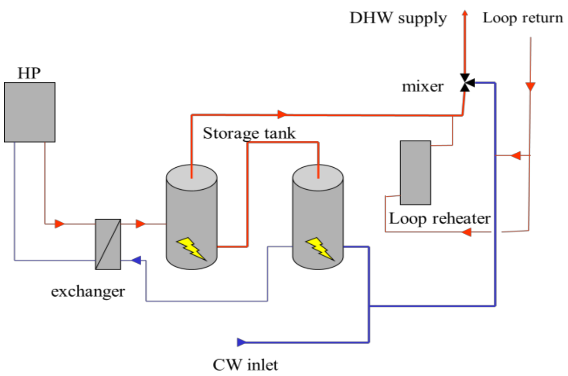

Figure 9 – schematic view of LC3 system

DISCUSSION AND RESULT ANALYSIS

Simulation – Results summary

Parametric study :

Below is presented a synthesis of results obtained by the parametric study. Given project progresses when the article was written, results are given only for multiple-housing building generation systems LC1 (as the reference), LC2 and LC3.

Parametric study has been operated with the following parameters (STEP 1) :

- system sensitivity to domestic hot water needs : thanks to the model presented above, three levels (low, standard and high going from around 30 to 60 litres per day per person of hot sanitary water at 55°C) have been defined. The system is designed for standard need, so its behaviour facing under or over request can be studied.
- Climate sensitivity simulations are run for two specific French locations: cold climate (near Paris) and hot climate (near Nice).

After these first simulations, and in order to evaluate which improvements can be made to reach the consortium objectives in terms of consumption and CO2 emissions, hot water storage insulation (with fumed silica) and distribution insulation (with 20 mm of Polyurethane) have been modified. This gives us STEP 2 results (presented in graphics below).

The first one presents comparison results between LC2 system (grey water recovery) and reference system in terms of primary energy consumption. Values are mean values from different climate zones.

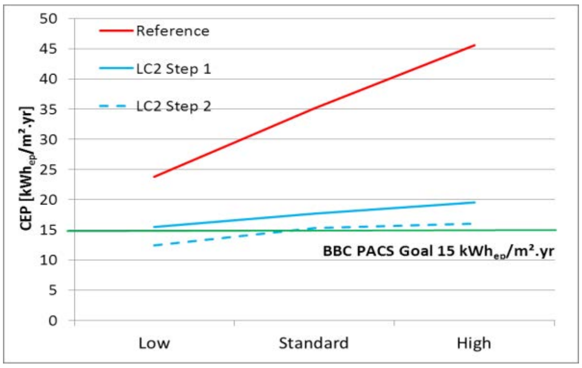

Figure 10 Consumptions ($kWh_{ep}/m^2.yr$) for LC2 system and reference

Regarding to the reference, significant gains are observed.

LC2 system shows his ability to absorb high hot sanitary water needs. This reinforces the interest for its use in large residential buildings, which also allow softening its quite high investment costs. The impact of the climatic zone (not visible here) is also less important for LC2 than for LC3 system, and is principally due to the cold water temperature.

Figure 11 presents the same results for LC3 system.

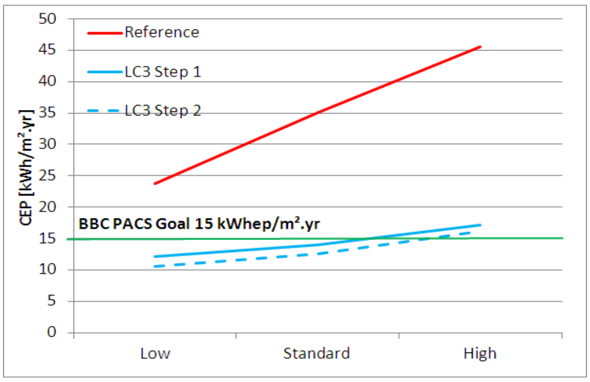

Figure 11 Consumptions ($kWh_{ep}/m^2.an$) for LC3 system and reference

This system proves to be more sensible to hot water needs evolution, due to the use of an outside air to water heat pump.

As a partial conclusion, for both systems, the low consumption objective can be reached with the insulation improvements made although it can be difficult for high needs.

Following figures 12 and 13 represent CO_2 emission results, respectively for LC2 and LC3 system. For clarity needs, a logarithmic scale for CO2 emissions has been used.

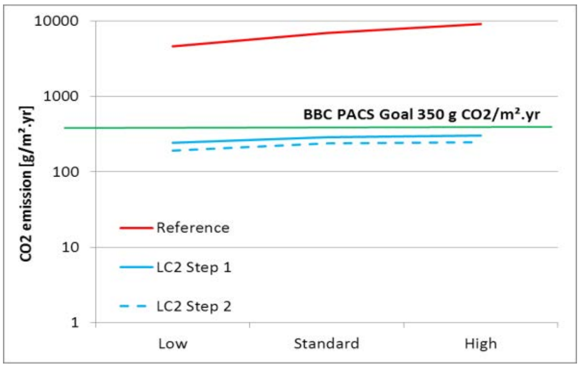

Figure 12 CO_2 emissions (g/m².yr) for LC2 system and reference

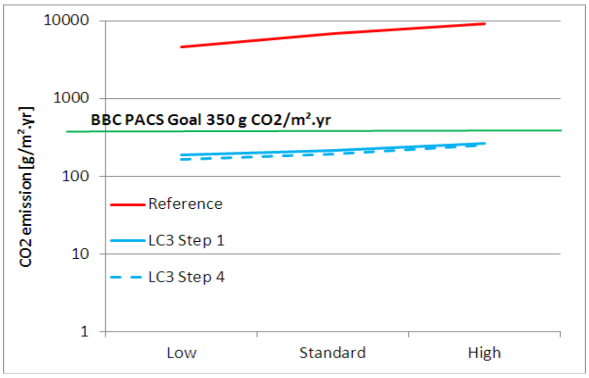

Figure 13 CO_2 emissions (g/m².yr) for LC3 system and reference

Here again, great improvement regarding to reference system are observed, reinforced by the fact that it is using gas for generation, which has a high level of CO_2 emission compared to the one used in France for electricity (234g/kWh to 40g/kWh, if electricity is used for DHW generation [5]).
The consortium low CO2 emission objective is reached, even with high hot water needs.

These first results are encouraging but have to be confirmed with additional simulations and confrontation to experimental results.
This is the goal of the next paragraph.

Experiment – Heat Pump and Solar Collectors System (LC3) - Results

The simulation tool was configured to make its usage conditions resemble the conditions of the demonstrator, considering the weather, draw-off profiles, and distribution losses. Technical systems were set into the simulation tool using manufacturer data, and in particular technical features of the main HP and the thermodynamic heater. The thermal solar collector option has been disabled. Storage consists of a single 1500-litre tank but with a coefficient of thermal losses applicable for two 750-litres tanks. The model storage does not include any boosting.
It can be seen in Figure 14 that the DHW need measured on site is fairly irregular with a significant increase in autumn. This parameter remains an uncontrollable variable. It reflects reality in a small group of flats, and affects all other results.

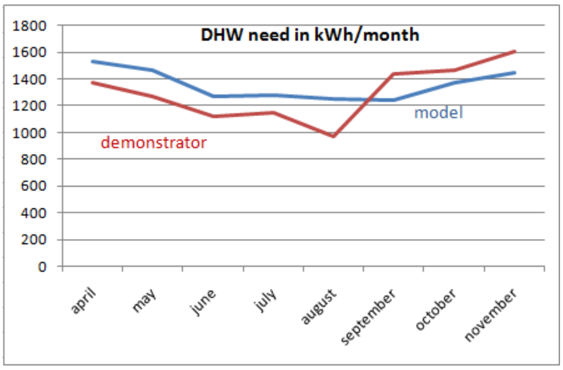

Figure 14 comparison between annual model and demonstrator

The final energy consumption (CW) on the demonstrator remained greater than the model but it is not very different in summer, which is partly due to the lesser use of electrical boosting resistances during this season. Remember that boosting was not taken into account in the model.

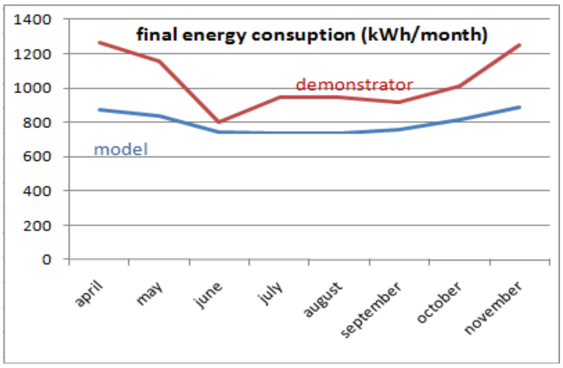

Figure 15 comparison between annual model and demonstrator

Later, the need was modelled month by month to fit the model scenario and the demonstrator scenario. It is called "model 2" on the following figure.

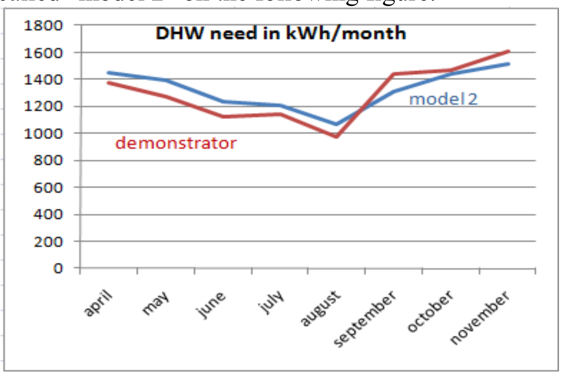

Figure 16 comparison between monthly model and demonstrator

With some slight modifications on the field test measurements, we can reach a better reproducibility between the model and the demonstrator (optimised curve on figure 17):

- As the model did not include the electrical boosting, we applied to field measurement the COP of the HP to these consumptions (if we do not use booster, all the energy is provided by the HP).

- For loop losses, we applied the nominal COP of the reheater to field measurement (to correct some malfunction of loop reheater during the period).

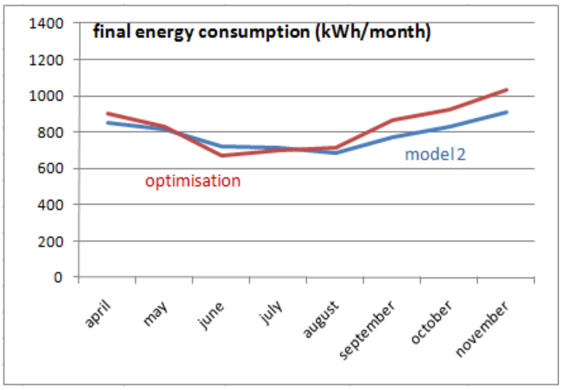

Figure 17 comparison between monthly model and optimised demonstrator

CONCLUSION

Given the fact that our project is still in progress, results presented in this article are mainly linked to some of the objectives listed earlier (energetic performance and CO2 emissions). Some other aspects need to be dealt with (economic aspect for example).

Nevertheless, it has been possible to obtain these results thanks to preliminary studies, which have highlighted some important conclusions.

A DHW need model has been developed and its monotonic compared to measures, achieving a good prediction.

A work has been done on the possibility to evaluate energetic gains linked with better insulation of storage and pipes. This study showed that these losses can be significantly reduced with an appropriate insulation.

An analysis of heat sources available around residential building has been conducted. It showed that the higher exergy potential is found in grey water, source which we put in application and modelled in LC2 system.

First simulations / measures comparisons have been made on LC3 system. Results obtained are encouraging. Indeed, they showed that, when DHW need can be set in our simulation tools at values close from field tests measures, then the measured consumptions could be well predicted.

This implies, first, to be able to have an accurate knowledge of real DHW need. The fact that the measurement or estimation of these needs is now compulsory for new buildings will help us for this objective.

Second, for our project, even if some others comparisons are going to be made on others DHW generations, it allows us to consider serenely to use our simulations results for making a multi criteria analysis of DHW systems.

One of the objective for the rest of the project is to be able to select the solution(s) fitting to one particular building and its occupants, incorporating in the reflection, next to energetic and CO_2 emission goals, the equipment cost (both investment and during life span), the comfort obtained for the occupants, the environmental impact, the electricity consumption peaks. These elements will allow us to identify the most relevant solution(s) from various points of view (user, manufacturer, and electricity supplier).

NOMENCLATURE

kWh_{ep} = kiloWatthours of primary energy
Silica xx hPa stands for vaccum insulation with a vaccum pressure of xx hPa
PUxx stands for Polyuréthane with a thermal conductivity value of xx
V.I.P stands for Vacuum Insulated Panel
Cr = thermal losses per water content and difference of temperature inside-outside par day
An = Anergy (kJ/kg)
$\dot{W}$ = Work (kW)
Q = Energy (kW)
$\dot{m}$ = Mass flow rate (kg/s)
h = Enthalpy (kJ/kg)
e = Exergy (kJ/kg)
T = Temperature (°C) or (K)
s = Entropy (kJ/kg.K)
$\dot{\sigma}$ = Entropy generation rate (kW/K)
f1 = polynomial function of outside temperature
Xi = coefficent factor for polynomials function
T_{out} = Outside temperature (°C)
$P_{absorbed}$ = Absorbed power by heat pump (kW)
$P_{calorific}$ = Calorific power of heat pump (kW)
T_{fluid} = Temperature of fluid leaving heat pump (°C)
Load = Heat pump Load (%)

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