STUDY OF HEATING AND COOLING SYSTEMS TO DESIGN ZERO ENERGY BUILDINGS

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ABSTRACT

By 2020 all new buildings within the European Union should reach nearly zero energy levels. Their energy needs should be significantly covered by renewable energy sources. As a consequence, it is important to identify which combinations of technologies will be suitable in order to reach such objectives. Climate conditions, final energy and investment costs, technological maturity and stakeholders' services quality are key elements for the final choice. This paper presents the first results of a more general survey the purpose of which is to study different combinations of heating - cooling systems integrated in single-family dwellings under the Belgian climate conditions.

Eight representative dwellings and one heating system composed of solar collectors and an air-to-water heat pump were selected. The dwellings were chosen in such a way that different insulation levels may be studied: we considered houses with an insulation level that just respects the 2008 EPBD legislation (arête du gouvernement wallon, 2008) as well as very low energy houses.

The heat pump and solar collectors are connected to a heat storage water tank as well as to a DHW reservoir. A design procedure based on energy needs is proposed and applied to each dwelling-system. The design characteristics of the system are then integrated in a simulation software (TRNSYS 17) to perform a one-year energy performance calculation (Klein, S.A, et al.,2000).

The results show that the solar coverage ratio for DHW production ranges from 52% (very low energy buildings) to 76% (EPBD buildings). The solar coverage ratio for space heating ranges from 3% (very low energy buildings) to 9% (EPBD buildings). Whatever the kind of building, the seasonal performance factor of the heat pump is about 3.45. The total non renewable primary energy that is used is about 57% of the total heat demand.

INTRODUCTION

Improvement of the energy efficiency is the most cost-effective and fastest way both to increase security of energy supply and to reduce the greenhouse gases emissions responsible for climate change. In the EU, buildings represent about 40% of the final energy consumption. For residential houses, two thirds of this energy consumption is for space heating. Therefore, the reduction of energy consumption and the use of energy from renewable sources in the building sector are important measures for the European Union.

In May 2010, the EU recast the directive on the energy performance of buildings. In this directive (Directive 2010/31/EU, 2010), the European Commission proposes that Member States shall ensure that by 2020 all new buildings are Nearly Zero Energy Buildings (NZEB). NZEB means a building that requires a very low amount of energy so that it can be produced, to a very significant extent, by use of renewable sources (produced on-site or nearby the building). Member States shall transpose and precise these definitions in their own legislative system. Further information about the maximum allowable energy demand, the minimum coverage rate by renewable energy is indeed required. Considering the definition proposed by Torcellini, Pless and Deru (Torcelli et al., 2006), a ZEB (Zero Energy Building) produces on site at least as much energy as it uses in a year. There is no technological barrier to conceive a ZEB based on such a definition. However, economic considerations like investment and energy costs as well as climatic conditions and reliability of the stakeholders have to be taken into account at the national level. This is the reason why each Member State may adapt the concept of ZEB to NZEB to its own reality.

One of the main questions that arises when defining a NZEB is whether it is better to promote very low energy demand (passive houses) or high coverage by renewable energies in "just low energy buildings". Low energy demand should be encouraged before considering efficient and renewable energy production. However, it can be difficult to justify economically the use of complex energy production systems in passive houses due to low absolute energy gains they lead to. Furthermore, the maximum required heat power is often less than a few kW in such dwellings and the heat demand for DHW is often equal to the heat demand for space heating. These particularities require specific solutions (low power heat generators, high efficiency at both low and high production temperatures, new design procedures, adapted control strategy). Obviously, such solutions already exist: the PassivHaus Insitute reports that 33% of high performance buildings use integrated systems for heating and DHW production (Pfuger, 2008). These integrated systems use solar collectors and a water tank to cover the energy needs of the buildings.

Nevertheless, it is important that the public sector set clear rules and propose actions to accompagny both citizens and stakeholders in this technological transition. This is even more important in a country which mainly imports existing technologies rather than producing them. These rules and actions are:

- To define clear objectives in terms of maximum allowable energy demand and give advice as to the kind of technology to be used for energy production; these recommendations and rules will be based on scientific studies taking into account national specificities;
- To support measurement campaigns to validate new concepts of energy production;
- To develop and promote knowledge and education programmes for a suitable integration of energy production systems in low energy and passive buildings;
- To promote R&D activities in this domain.

This paper presents the first results of a more general survey the purpose of which is to study different combinations of heating - cooling systems integrated in one-family dwellings. It is based on simulation rather than on experience. The dwellings were selected in such a way that different insulation levels may be studied: we considered houses with an high level of insulation as well as others that just respect the 2008 legislation (first EPBD rules in Belgium). Sample buildings are representative of what is being constructed now in Belgium on the one hand and in South of France on the other hand.

All buildings will be studied under Belgian and South of France climatic conditions so that experience in construction methods may be shared. All combinations of energy production technologies will also be tested in these two climatic conditions except that cooling technologies will not be considered for Belgium. The first technology combinations that are being considered are taken from Annex 38 – Task 44 of the HPP and SHC implementing agreements of IEA. Other technologies and their coupling will be considered in a second step of the research programme.

The final purpouse is to identify which heating-cooling system in which kind of building is the most appropriate solution to minimize the use of non renewable energy taking into account economic considerations. Conception and sizing rules as well as basic control strategies are also proposed.

In this paper we present results for the eight buildings under the Belgian climate conditions. The heating system that is considered is a coupling of a heat pump and solar colectors.

METHOD

This section presents the strategy for the whole project. It is divided in several steps:

- Sample buildings selection;
- Simulation of their thermal behaviour;
- Results analysis: annual heat demand, maximum required heat power;

For each combination of technologies for heating and cooling:

- Proposal of design rules for the main components of the heating-cooling system (production, storage and distribution/emission) and application to all buildings;
- Simulation of the thermal behaviour of the overall system (building + equipment);
- Results analysis (non renewable primary energy consumption; weight of the different technologies in the final energy production);
- Sensitivity study (based on design and control strategy parameters)
- Economic survey.

BUILDINGS MAIN CHARACTERISTICS

Single-family houses are the most common residential building type in Belgium. As stated in ESE 2001 study, 76% of the Belgian people live in a single-family dwelling. For the purpouse of this study, eight representative dwellings were selected. All of them have different energy performance, insulation concepts (outside, inside or distributed), structures (wood, brick or concrete) and thermal inertia. However, they all have similarities which allow for a better comparison: all houses have approximately 200m of living space, two floors, and are occupied by a four-person family. The characteristics of these reference buildings are presented in Table 1.

	Location	Structure	Insulation principle	Inertia	Area (m)
1	Strépy (Belgium)	Concrete	Outside	Medium	160
2	Epinois (Belgium)	Wood	Between-rafter	Light	194
3	Alès (France)	Concrete	Outside and inside	Medium	186
4	Lobbes (Belgium)	Wood	Outside	Low	138
5	Château Neuf (France)	Wood	Between-rafter	Light	200
6	Chiché (France)	Monomur blocks	Distributed	Low	183
7	Haine St Paul (Belgium)	Brick	Outside	Heavy	155
8	Strépy (Belgium)	Brick	Outside	Low	153

Table 1: Sample buildings information

The overall heat transfer coefficients (U value) for each building are given in table 2.

	U_value_wall (W/m .K)	U_value_roof (W/m .K)
1	0,084	0,049
2	0,100	0,090
3	0,154	0,025
4	0,335	0,383
5	0,21	0,167
6	0,292	0,139
7	0,265	0,164
8	0,312	0,216

Table 2: Overall heat transfer coefficient

HEATING SYSTEM DESCRIPTION

In the first combination of technologies that is studied, heat is produced by thermal collectors (TC) and by an air-to-water heat pump (HP). Both systems are used for space heating and DHW preparation. Figure 1 presents the complete system when working for space heating: a water tank (B1) is used as heat storage. The thermal solar collectors are connected to this heat storage by a heat exchanger (HX1) whereas the heat pump condenser is directly connected to it. The water tank is also linked to an air-to-water heat exchanger (HX2) which delivers warm air to the building. Whenever possible, thermal solar collectors are used to produce heat and to store it. The heat pump is used only if there is a heat demand from the building and if the temperature at the top of the water tank is below a set temperature.

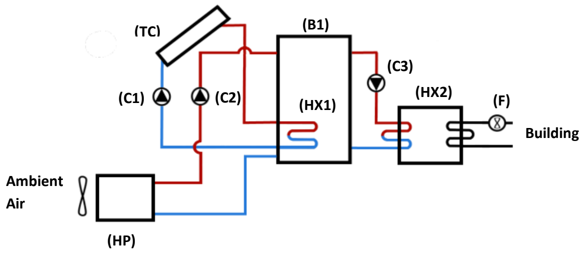

Figure 1: Heat production, storage and emission system (space heating)

As shown in Figure 2, a similar configuration is used for domestic hot water preparation: both the heat pump and the solar collectors are connected to another water tank (B2). Whenever possible, the water tank is heated using the solar collectors; the heat pump operates only in case of hot water demand if the required water temperature is not reached at the top of the tank.

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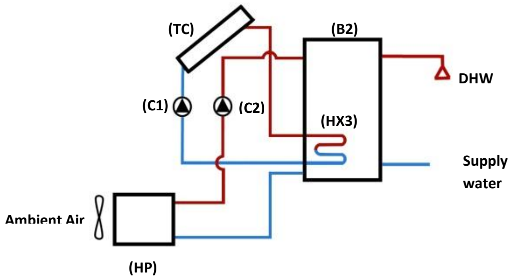

Figure 2: Heat production and hot water storage system (DHW preparation)

HEATING SYSTEM : DESIGN RULES AND MAIN CHARACTERISTICS FOR SIMULATION

Solar collectors

The following solar collectors' characteristics are taken for simulation:

- Orientation: South;
- Slope : 60°;
- No shade;
- Flat-plate solar collectors : efficiency curve parameters: η_0 = 0.8060, η_1 = 3.551 W/(m K) et η_2 = 0.013 W/(m K).

The total surface area is calculated in such a way that the estimated solar heat production during April, May, September and October may cover the space heating needs during the same period. Such a rule was developed in a first step of the study when only space heating was considered.

Heat pump

The air-to-water heat pump is selected in such a way that its heat capacity in standard conditions (A -5°C/W35°C) is equal to the building heat loss flow-rate calculated for an outside temperature of -5°C. The heat pump model consists in a performance map provided by the manufacturer and adapted to the simulation tool requirements (heat capacity and absorbed power as a function of outside temperature and inlet water temperature at the condenser). The same model is used for all buildings but a weighing factor is applied to the thermal heat capacity and absorbed power in order to fit the sizing rule for each building.

Water tanks

Water tanks are modelled as stratified vertical and cylindrical water tanks with two inlets and two outlets as well as connections to an internal heat exchanger. All stratification nodes of the tank have a uniform size. Low thermal losses (1.2 kJ/(m .K.h)) are considered. Volumes are taken equal to 1000 l for B1 and 200 l for B2.

Heat exchangers

The air-to-water heat exchanger that provides warm air to the building is modelled as a counter-flow fluid-to-fluid heat exchanger with a constant efficiency of 0.7.

The surface area of the solar heat exchanger is 0.9 m for DHW production and 1.12 m for space heating.

Pumps, fan and flow-rates

Mass flow-rates through the different elements are calculated using the following rules:

Heat exchanger HX2: the maximum required heat flow-rate must be transferred with air temperatures equal to 35°C (supplied air to the building) and 18°C (return air temperature). Water temperatures and mass flow-rate may be deduced from the heat flow-rate and heat exchanger efficiency.

HP condenser: the water mass flow-rate through the condenser is calculated considering a temperature difference equal to 5°C between inlet and outlet and the heat flow-rate value used for sizing procedure (A -5°C/W35°C).

Solar collectors, HX1 and HX3: the fluid mass flow-rate is calculated considering 40 l/(h m^2 of solar collectors).

Pressure drops are associated to each fluid loop so that energy requirement for pumps and fan (C1, C2, C3, F) may be calculated.

Control strategy

The solar collectors are considered as the prior heat generation system. The priority is given to domestic hot water production. If the difference between the temperature downstream the solar collectors and the water temperature inside the water tank (at the node located at HX3 outlet) is higher than 5°C, solar collectors are activated and heat is stored in B2. If such a condition is not respected, heat produced by the solar collectors is stored in the water tank for space heating (B1) provided this operation is possible (same criterion as for DHW production).
The heat pump does not take part to the storage process. It is activated only in case of heat demand from the building or in case of hot water demand provided that the set temperature is not reached at the inlet of HX2 for space heating (35°C) or at the top of B2 (45°C) for hot water supply.

Warm air circulation through HX2 is allowed when inside ambient temperature is lower than 18°C and is stopped when it is higher than 21°C.

Domestic hot water tapping program is inspired from French regulations (Figure 3). It depends on the heated area.

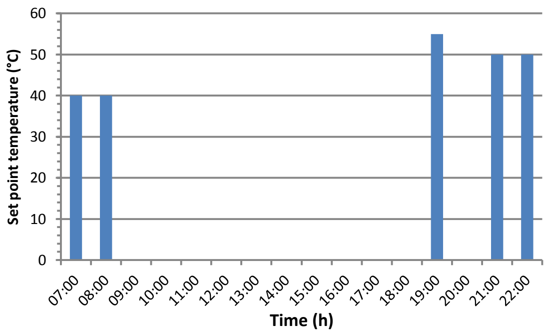

Figure 3: Tapping program

SIMULATION RESULTS

All buildings and equipment are simulated using TRNSYS 17 with a time step of 10 minutes. Components models come from two sources: the TRSNSYS standard models library and the TESS library.

The dwellings are modelled using TRNSYS's TYPE 56 with three or four distinct thermal zones. The weather-processing model uses standard TRNSYS TYPE 15 with the climate data file from Uccle (Belgium).

First simulation runs are achieved considering only the building. Results are then used to size the different elements of the heating system. Table 3 presents the annual heat demand, the installed thermal power of the heat pump as well as the solar collectors surface area for each dwelling.

Figure 4 present the month heat demand for space heating for buildings 1 and 4.

N°	Solar collectors surface area (m)	Heat pump thermal power in design conditions (kW)	Annual heat demand (space heating) kWh/(y m^2)
1	5	4.1	30.3
2	6	2.5	31.6
3	6	3.2	30.1
4	21	9.3	120.4
5	13	5.3	63.3
6	16	5.3	73.4
7	21	6.5	98.0
8	21	4.6	66.6

Table 3: Installed surface area of solar collectors, heat pump thermal power and annual heat demand for space heating

Buildings 1, 2 and 3 may be considered as very low energy buildings in terms of heat demand. Buildings 4 and 7 have characteristics close to the minimum EPBD requirements in Belgium. Building 8 is representative of what is commonly built in Belgium in 2012. Buildings 5 and 6 are close to building 8 whereas they are located in the South of France.

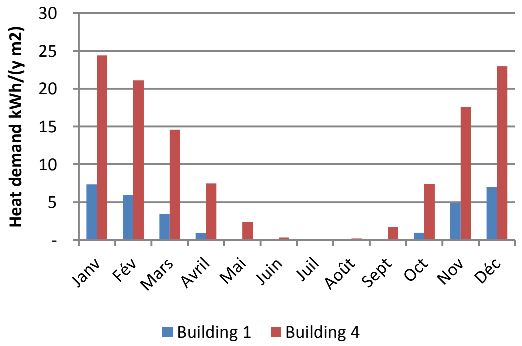

Figure 4: Heat demand (space heating) for two buildings

Heating system + building behaviour are then simulated. Table 4 shows the main results on an annual base. Energy data are all given per square meter of heated area.

Q_{SH} is the annual heat quantity released to the building for space heating. These values are close to the annual heat demand given in Table 3. Slight discrepancies (up to 10 kWh/(y m^2)) may be observed due to the offset of the control strategy of the heating system.

Q_{DHW} is the annual energy quantity in the domestic hot water that is consumed in one year.

Q_{SC} and Q_{HP} are respectively the heat quantities produced by the solar collectors on the one hand and by the heat pump on the other hand. Q_{loss} and Q_{bu} are the annual heat losses in the water tanks and the annual heat produced by a back-up system when set temperatures (inside ambient temperature and DHW) may not be reached. It appears that the heat pump is the supply technology with the highest heating contribution for all cases. The proposed design procedure seems to be satisfactory in terms of comfort as the back-up system contribution remains low. OSC, SCSH and SCDHW are respectively the overall solar coverage ratio, the solar coverage ratio for space heating and the solar coverage ratio for DHW production.

Solar contribution for space heating remains low for all cases (from 3% to 9%). The lowest values are for very low energy buildings (1, 2 and 3). Their heating demand is already nearly zero during the mid-season which is less the case for the other buildings for which a solar contribution is possible mainly in April, May, September and October. The solar contribution for DHW production ranges from 52% to 76%. Once again, very low energy buildings are characterized by low solar coverage ratios compared to other ones. This is due to the fact that the sizing of the solar collectors surface area is based on the heat demand for space heating. For low energy buildings, the resulting surface area is low, comparable to what is commonly used in Belgium for solar preparation of DHW, leading to typical values of solar coverage ratio of 50 to 60%. For the other buildings, the solar collectors surface area is oversized and higher coverage ratio may be reached.

E_{aux}, E_{HP} and SPF are respectively the annual electricity consumption of pumps and fan, the annual electricity consumption of the heat pump and its seasonal performance factor.

It can be concluded that the very low energy buildings can be turned into zero energy buildings (when considering only energy requirements for heating and DHW preparation) as the electricity needs to run the heat pump and auxilaries can be produced by PV panels. This will be practically impossible or quite difficult for the other buildings if only the roof surface is considered for PV panels installation.

The design procedure and the control strategy allow for low temperature heat production and high values of heat pump seasonal performance factor (around 3.5 for most cases). The renewable contribution of the heat pump is estimated to 29% of its heat production. Solar contribution and heat pumping lead to a ratio $E_{prim}/(Q_{sh}+Q_{DHW}+Q_{loss})$ of about 57% (E_{prim} is the non renewable primary energy consumed for space heating and DHW production).

	Unit	1	2	3	4	5	6	7	8
Q_{sh}	kWh/(y m^2)	36,4	29,9	36,3	130,2	72,0	63,8	94,5	75,9
Q_{DHW}	kWh/(y m^2)	14,6	15,8	15,9	22,3	15,2	16,7	19,8	21,1
Q_{SC}	kWh/(y m^2)	9,1	11,3	11,3	31,8	14,2	20,5	28,1	29,3
Q_{HP}	kWh/(y m^2)	43,9	37,1	43,6	131,2	77,1	66,3	95,6	77,9
Q_{loss}	kWh/(y m^2)	2,9	3,8	3,7	13,0	4,9	8,1	11,7	12,7
Q_{bu}	kWh/(y m^2)	0,1	0,8	0,1	1,9	0,8	1,6	1,1	0,9
OSC		17,0%	23,0%	21,0%	19,0%	15,0%	23,0%	23,0%	27,0%
SCSH		3,0%	6,0%	4,0%	7,0%	3,0%	8,0%	8,0%	9,0%
SCDHW		52,0%	54,0%	55,0%	75,0%	65,0%	72,0%	76,0%	76,0%
E_{aux}	kWh/(y m^2)	0,2	0,2	0,2	0,3	0,2	0,2	0,3	0,3
E_{HP}	kWh/(y m^2)	11,0	10,7	12,6	39,0	22,0	19,0	27,4	22,3
SPF		4,0	3,5	3,5	3,4	3,5	3,5	3,5	3,5
E_{prim}	kWh/(y m^2)	27,7	28,9	31,9	102,1	56,9	51,4	71,3	58,0

Table 4: Energy balance

CONCLUSIONS

A heating system composed of a heat pump and solar collectors connected to two water tanks (one for heat storage and one for DHW preparation) was tested by simulation in eight single-family dwellings under Belgian climate conditions. Such systems are well known but still not too much used in Belgium. Problems in the design choices and during operation (control strategy) were identified in real such systems installed in Belgium. These problems generally result from a lack of knowledge due to unaivalable information on best practices. The use of a heat pump for space heating and of solar collectors for DHW production (the heat pump is sometimes used as the back-up system) is a more widespread and well handled solution. Our study aimed at testing an integrated system (both technologies are used both for space heating and for DHW preparation) and at proposing design rules for stakeholders.

Whatever the building characteristics the integrated system allows for a drastic reduction (43%) of non renewable primary energy use when compared to an hypothetic system with a 100% yield (heat produced/non renewable primary energy). Nevertheless, the sizing procedure and/or the control strategy leads to quite low solar coverage ratio for space heating so that the benefit of using a completely integrated system instead of the most common solution (no heat storage and no solar contribution for space heating) can not be clearly established. This is particularly true for very low energy buildings. For such buildings the low electricity requirement to run the heat pump makes possible the net zero energy target if PV panels are used.

Further developments, namely on the sizing procedure (heat storage, solar collectors) are needed as well as an economic survey. These works are undergoing.

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