Heat recovery and reversible heat pumping potentials in non-residential buildings

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1. INTRODUCTION

Environmental concern and recent increase of energy costs open the door to innovative techniques to provide heating and cooling in buildings. Among these techniques, heat pump systems represent an area of growing interest. Heat pumping is probably today one of the quickest and safest solutions to save energy and to reduce CO2 emissions.

The heat pump market was, till now, concentrated on residential buildings. Now, attention is given to (new and existing) non-residential buildings, where heating and cooling demands co-exist. In many non residential buildings, an attractive energy saving opportunity consists in using the chiller as a heat pump for heat production. Two of the most attractive applications consist in recovering the heat rejected by the condenser of a chiller in operation and in using it in heat pump mode.

Condenser heat recovery is possible whenever there is some simultaneity between heating and cooling demands. When there is no simultaneity, full reversibility has to be looked for. This is the matter considered in the frame of the International Energy Agency project: IEA-ECBCS Annex 48 “Heat pumping and reversible air conditioning” (Lebrun[1]).

In the first part of this paper, an overview of the project is presented, and the work of the different participants is briefly explained. In the second part of the paper, focus is given to the Belgian contribution.

2. PROJECT OVERVIEW

The Annex 48 project was proposed by Belgium and approved by the IEA-ECBCS executive committee in 2005. The working phase started in September 2006. More than 10 organizations and companies, coming from 4 countries (France, Germany, Italy and Belgium) are today involved in the project. The aim of the project is to promote the most efficient combinations of heating and cooling techniques in building air-conditioning, with heat recovery and/or reversible systems.

Five subtasks are being performed:

- Subtask 1: analysis of building heating and cooling demands and of equipment performances, characterization of existing HVAC systems, use of simulation models to identify the best heat pumping potentials;

- Subtask 2: elaboration of pre-design rules, design methodology and evaluation criteria;
- Subtask 3: global performance evaluation, selection of commissioning methods, development of evaluation methods, tests with synthetic and measured data;
- Subtask 4: documentation of reference case studies, use of these case studies to test the tools and the methods developed in the subtasks 1 to 3, conversion of most successful case studies into demonstration projects;
- Subtask 5: dissemination work (website[2], publications, workshops and seminars).

3. REVERSIBILITY AND RECOVERY POTENTIALS

3.1 Analysis of building heating and cooling demands

On the basis of the French building stock, a classification of office and health care buildings has been made according to their energy demands and to corresponding energy saving potentials. Five types of office buildings are distinguished, according to their floor area and their geometry (table 1). Two types of health care buildings are also distinguished. The so defined building types are supposed to be representative of the overall air-conditioned European building stock (Stabat[3]).

Table 1. Office buildings types.

Building type	Floor Area *[m²]*	Geometry
1a	15000	Broad open space offices
1b	15000	Broad portioned offices
1c	15000	Thin geometry – glazed rooms
2	5000	Medium glazed renewed buildings
3	1000	Small suburban office buildings

A typology is established for each building type (Fig.1). Standard ranges of values of envelope characteristics (U values, thermal inertia, glazing solar factors,…), internal gains (lighting, electrical appliances,…) and occupancy/operating profiles are defined for most of the European countries.

The heating and cooling building demands of those buildings are calculated for a large number of variants and for five European climate zones (South Europe, South-West Europe, Central Europe, North-West Europe and North-East Europe; Fig.1) by means of dynamic hourly multi-zone simulations.

On the basis of these results, reversibility and recovery potentials are evaluated and compared. The reversibility potential (Fig.2) is calculated, hour by hour, as the percentage of heating demand which could be provided by a chiller operating in heat pump mode. Of course, the chiller evaporator has then to be connected to some heat source (e.g. ground, outdoor air …). Generally a backup heating system is also needed to satisfy the heating demand when the heat pump capacity is too limited. A first estimation of the reversibility potential is obtained by assuming that priority is given to cooling (reversibility is only possible when no cooling is required) and that the heat pump is able to provide 80% of the nominal cooling power in heating mode. The supplementary demand is assumed to be covered by a backup system.

The recovery potential (Fig.2) is calculated, hour by hour, as the part of the heating demand which could be covered by condenser heat recovery. A backup heating system is needed to satisfy the heating demand when there is no cooling demand or when the heat demand overpasses the heat pump capacity. A first estimation of the recovery potential is obtained by assuming that condenser heat recovery is possible only when the chiller produces cold and that the maximal heating power is equal to (COP+1)/COP*(cooling demand).

In this first evaluation of both recovery and reversibility potentials, no consideration on the heat emitters temperature levels is made.

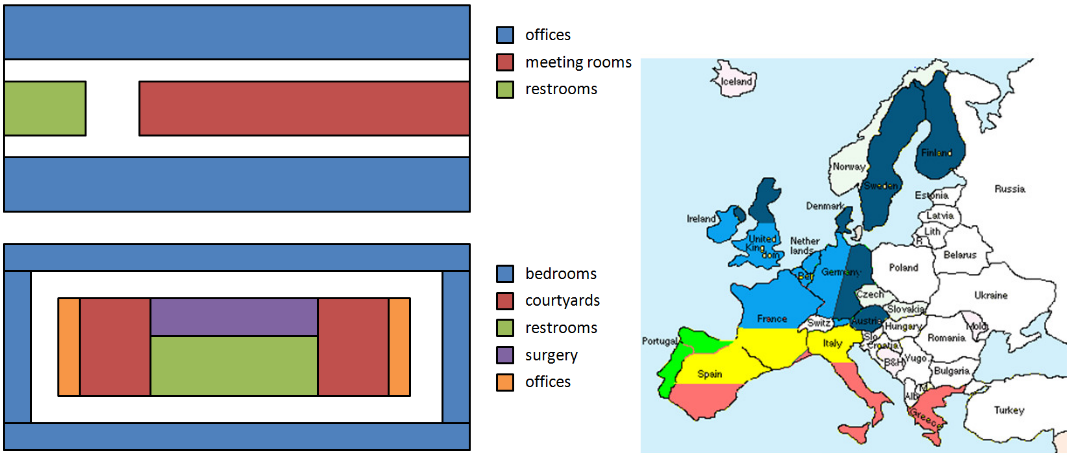


Fig.1: Type 2 office building (left-up) and Type 1 health care building (left-down) typologies and Five European climate zones (right)

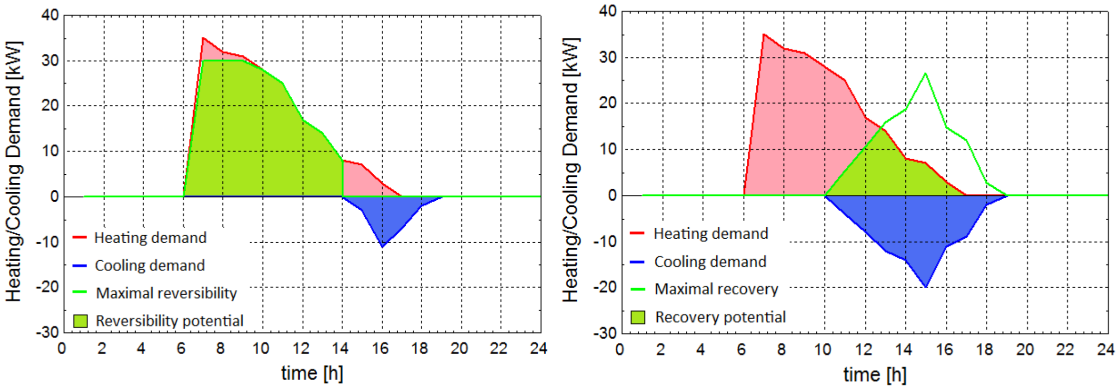


Fig.2: Reversibility (left) and Recovery (right) potentials for given days

It appears that office buildings offer a high potential of reversibility (till 99%) since the maximum cooling and heating powers are of the same order of magnitude (Stabat[3]). The reversibility is more interesting in temperate climates than in South Europe. In this region, heat recovery on chiller condenser appears as the most interesting solution (recovery potential reaching 45%).

3.2 Identification methodology

In parallel with the parametric study realized by Stabat[3], a methodology is being developed to help practitioners and decision makers in quantifying recovery and reversibility potentials. It appears that the use of simulation tools cannot be avoided. Indeed, the reversibility and recovery potentials cannot be directly estimated on the basis of global data currently available (e.g. monthly energy consumptions). Moreover, even if the heating demand is usually easy to identify, this is not true for the cooling demand which can be totally hidden in the total electricity consumption.

The calculation of both heat recovery and reversibility potentials is based on the same assumptions as for the analysis of building heating and cooling demands. This quantification of the potentials requires having hourly values of the heating and cooling demands of the building. Calibrated simulation tools are used to generate these hourly values.

Simulation models are being developed and implemented in the equation solver EES (F-Chart Software, Klein[4]); they dynamic simulation model include two parts: a simplified dynamic building model and a steady-state HVAC system model (Bertagnolio[5]). Both models use a limited amount of inputs and parameters, defined on the basis of the information actually available.

Three steps are necessary to compute the demands and the heat pumping potentials:

1) Tuning of the parameters of the model with the information available (main dimensions and characteristics of the building and of the HVAC system, internal gains, operating schedules and electricity and fuel consumptions);
2) Simulating the building zones and the coupled HVAC system on a typical year with integration of the heating and cooling demands and corresponding consumptions;
3) Aggregating the demands computed for the different zones of the building, generating the global heating and cooling demands profile and computing the reversibility and recovery potentials

The development, the implementation, the parameterization and the application of these simulation models are discussed by André et al.[5]

4. ANALYSIS AND MODELING OF HEAT PUMP SYSTEMS PERFORMANCE

Some simulation tools are proposed to help practitioners and decision makers in making a rational choice among existing technologies and in establishing the most efficient combination between the heat and cold productions.

4.1 Review of heat pumping and heat recovery solutions

Heat pump systems typologies that can be used in office and heath care buildings for both heat and cold production are deeply studied in the frame of the project (Stabat and Bertagnolio[6]). Two examples of such systems are presented here.

4.1.1 Reversible air-water heat pump

The simplest system is based on the use of reversible air-water heat pump. Today, a large offer of reversible units is proposed, with investment costs comparable to these of non-reversible units. The system is reversed by means of a refrigerant side change-over (Fig.ure 3), which inverses the flow passage into the two exchangers. In cooling mode, the air exchanger works as condenser, rejecting heat, while the water-exchanger works as evaporator, transferring cooling power to the distribution system. In heating mode, the air exchanger works as evaporator, absorbing heat from external air, while the water exchanger works as condenser, transferring heat to the distribution system.

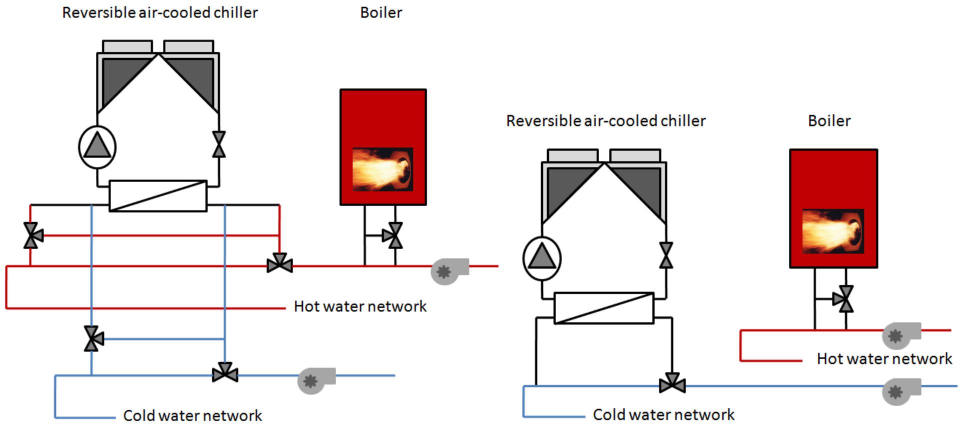


Fig. 3: Reversible air-to-water heat pump systems #1 (left) and #2 (right)

A reversible air-cooled unit has generally to be combined with a backup boiler, due to the following reasons:

- When the chiller works in cooling mode, it cannot provide any heating power;
- In heating mode, the air-water heat pump can generally not cover the maximal heating demand (the heating power at –5°C can be 30% lower than heating power in rating conditions);

- In extremely low outdoor temperature, boiler performances can become better than air-to-water unit performances.

In system #1 (Fig. 3), the reversible air-to-water heat pump can be coupled to both hot and cold water networks, using only a refrigerant change-over to switch between heat and cold production. In this configuration, the cold and hot water networks are respectively only used for cooling and heating respectively. In configuration #2 (fig 3), a water-circuit change-over is used to satisfy the heating demand. The heat pump is only connected to the cold water network and uses this circuit to satisfy alternatively the cooling and heating demands of the building. Of course, this configuration cannot be used when heating and cooling demands co-exist. The main advantage of this solution is that the large heat transfer areas of the cooling HVAC equipment are used for low-temperature heating.

4.1.2 Exhaust ventilation air heat pumps

Extracted air represents a very interesting heat source because of its good availability, its good coincidence with needs and its very constant temperature. Condensing the water contained in extracted air allows also recovering a part of the latent energy and increases the capacity of the extracted air as heat source. In cooling mode, condenser heat can also be easily rejected in the exhaust ventilation air flow, which is often at lower temperature than outdoor air. However, the exhaust ventilation source capacity is limited and an additional heat source or sink is very often required.

At least two configurations are possible when using extracted air as heat source. The first configuration is based on the use of air-air dual duct reversible heat pump. The other configuration is based on the use of a water-to-water or a dual condenser heat pump.

With water-to-water heat pump, the extracted air is used as heat source in heating mode and as heat sink in cooling mode. The heat pump is not reversible but a change-over is made on the water circuit to allow heat pumping or heat rejection in the exhaust air. With dual-condenser heat pumps, the extracted air can be used only as heat source for heating and the air condenser can be used to reject heat in cooling mode (Fig.4). Such a system has been installed in a Belgian case study building located in the region of Liege (Bertagnolio[7]).

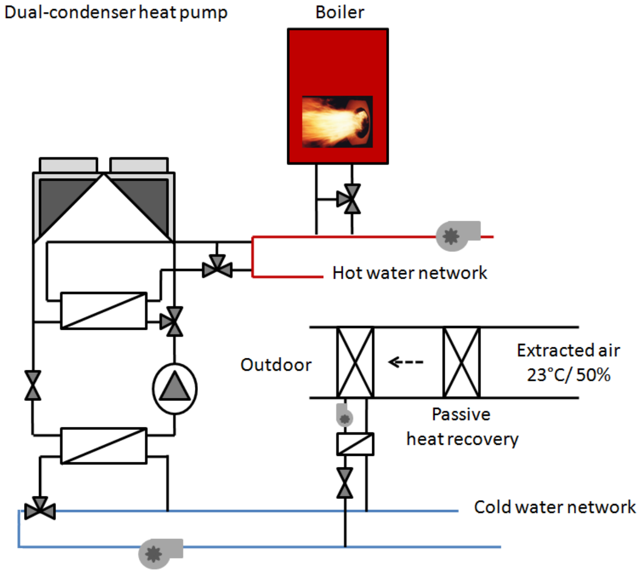


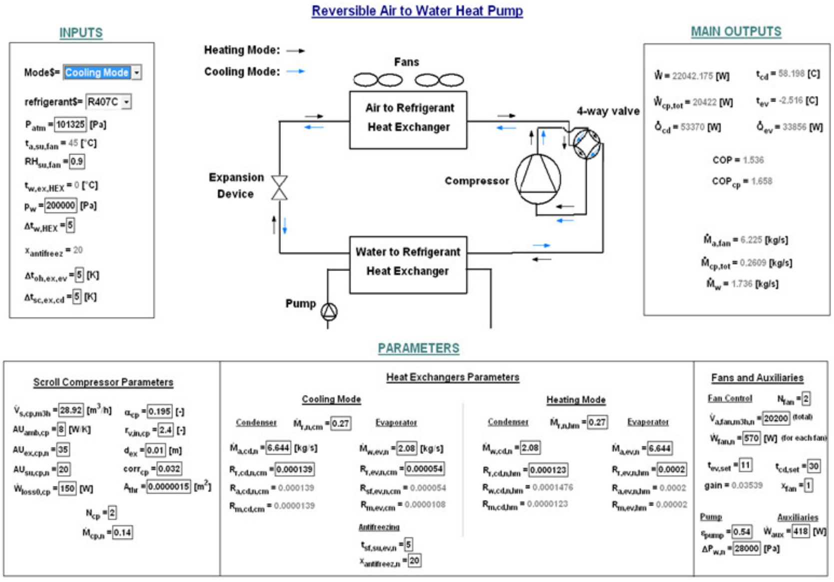
Fig 4: Exhaust ventilation air source heat pump system

The heat recovery on ventilation exhaust air requires the use of classical coils. These coils are supplied by glycol water to prevent freezing when the ventilation is switched off. A classical plate heat exchanger can be used to couple the closed glycol loop to the water network(s). The coil must be designed to allow condensation and to work at very different temperature regimes if used as heat source and heat sink.

The coupling between an “active” and a “passive” heat recovery system has to be optimized.

4.2 Development of simulation models for heat pump systems assessment

A reference thermodynamic model of the reversible air-to-water heat pump (Fig. 5) has been developed and tuned on manufacturer data (Gennen[8]). This model predicts the heating/cooling capacity and the compressor power consumption with an accuracy of less than 10%.



Reversible Air to Water Heat Pump

INPUTS

Mode$= Cooling Mode
refrigerant$= R407C
P_{atm} = 101325 [Pa]
$t_{a,su,fan}$ = 45 [°C]
$RH_{su,fan}$ = 0.9
$t_{w,ex,HEX}$ = 0 [°C]
P_w = 200000 [Pa]
$\Delta t_{w,HEX}$ = 5
$x_{antifreez}$ = 20
$\Delta t_{oh,ex,ev}$ = 5 [K]
$\Delta t_{sc,ex,cd}$ = 5 [K]

MAIN OUTPUTS

$\dot{W}$ = 22042.175 [W]
t_{cd} = 58.198 [C]
$\dot{W}_{cp,tot}$ = 20422 [W]
t_{ev} = -2.516 [C]
$\dot{Q}_{cd}$ = 53370 [W]
$\dot{Q}_{ev}$ = 33856 [W]
COP = 1.536
COP_{cp} = 1.658
$\dot{M}_{a,fan}$ = 6.225 [kg/s]
$\dot{M}_{cp,tot}$ = 0.2609 [kg/s]
$\dot{M}_w$ = 1.736 [kg/s]

PARAMETERS

Scroll Compressor Parameters

$\dot{V}_{s,cp,m3h}$ = 28.92 [m³/h]
α_{cp} = 0.195 [-]
$AU_{amb,cp}$ = 8 [W/K]
$r_{v,in,cp}$ = 2.4 [-]
$AU_{ex,cp,n}$ = 35
d_{ex} = 0.01 [m]
$AU_{su,cp,n}$ = 20
$corr_{cp}$ = 0.032
$\dot{W}_{loss0,cp}$ = 150 [W]
A_{thr} = 0.0000015 [m²]
N_{cp} = 2
$\dot{M}_{cp,n}$ = 0.14

Heat Exchangers Parameters

Cooling Mode

Condenser
$\dot{M}_{r,n,cm}$ = 0.27
Evaporator
$\dot{M}_{a,cd,n}$ = 6.644 [kg/s]
$\dot{M}_{w,ev,n}$ = 2.08 [kg/s]
$R_{r,cd,n,cm}$ = 0.000139
$R_{r,ev,n,cm}$ = 0.000054
$R_{a,cd,n,cm}$ = 0.000139
$R_{sf,ev,n,cm}$ = 0.000054
$R_{m,cd,cm}$ = 0.0000139
$R_{m,ev,cm}$ = 0.0000108
Antifreezing
$t_{sf,su,ev,n}$ = 5
$x_{antifreez,n}$ = 20

Heating Mode

Condenser
$\dot{M}_{r,n,hm}$ = 0.27
Evaporator
$\dot{M}_{w,cd,n}$ = 2.08
$\dot{M}_{a,ev,n}$ = 6.644
$R_{r,cd,n,hm}$ = 0.000123
$R_{r,ev,n,hm}$ = 0.0002
$R_{w,cd,n,hm}$ = 0.0001476
$R_{a,ev,n,hm}$ = 0.0002
$R_{m,cd,hm}$ = 0.0000123
$R_{m,ev,hm}$ = 0.00002

Fans and Auxiliaries

Fan Control
N_{fan} = 2
$\dot{V}_{a,fan,m3h,n}$ = 20200 (total)
$\dot{W}_{fan,n}$ = 570 [W] (for each fan)
$t_{ev,set}$ = 11
$t_{cd,set}$ = 30
gain = 0.03539
x_{fan} = 1
Pump
Auxiliaries
ϵ_{pump} = 0.54
$\dot{W}_{aux}$ = 418 [W]
$\Delta P_{w,n}$ = 28000 [Pa]

Fig.5: Reversible air-to-water heat pump model control panel

By coupling this model to a boiler model (Bourdouxhe et al.[9]) and by using the pre-computed heating and cooling demands of a given building as inputs, the configurations shown in Fig.3 can be simulated et assessed in economical and environmental views. Similar models are being developed for other systems.

5. CASE STUDY

Case studies are performed by all the participants. The Belgian case studies are an office building located in Charleroi and a laboratory building located in the region of Liege. This second building has a total floor area of about 6200 m², distributed between offices (1600 m²), laboratories (1300 m²), technical room (1800 m²), sanitaries and a few small meeting rooms (Fig.6).

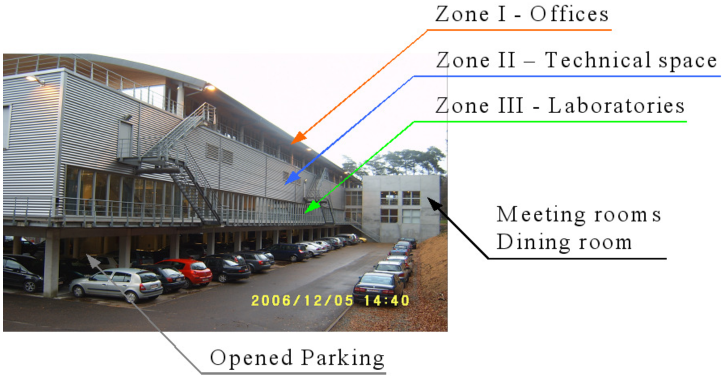


Fig.6: First Belgian case study building

The ventilation of the offices is ensured by a CAV Air Handling Unit, blowing about 5000 m³/h of fresh air, without recirculation. Thermal comfort is ensured in this zone by fifty heating/cooling fan coil units. The laboratories are supplied with 33000 m³/h of fresh air and are fully conditioned trough three CAV AHU's, equipped with electrical steam humidifiers. The ventilation flow rate and the temperature and humidity setpoints (23°C/50%) of this second zone are maintained 24h/day and 7d/week due to hygienic considerations. The four AHU's are equipped with glycol heat recovery loops. Heat and cold productions are ensured, respectively, by two gas boilers of 300kW each and an R134a air-cooled chiller of 400kW (rating cooling capacity).

The building is characterized by comparable heating and cooling peak demands. In winter time, the building cooling demand is almost or completely null. In summer time, the building heating and cooling demands are alternated, according to the day/night periods. However, cooling and heating demands are sometimes simultaneous in different building zones. The reversibility and recovery potentials are respectively equal to 98% and 1%.

The existing air-cooled chiller has been replaced by a dual-condenser chiller equipped with air and water condensers connected in parallel (Fig. 4). The water condenser delivers hot water at maximum 55°C.

It has been decided to use the extracted air as heat source. Indeed, about 33000 m³/h of (hot and humid) air are extracted from the laboratories. Downstream of the passive recovery loops, the air temperature does not go below 12°C (RH90%). Additional air/water coils will be designed to recover the largest part of the available energy to supply the heat pump evaporator. In case of too limited capacity of the heat pump, the boilers will intervene, as backup heat source, to satisfy the supplemental heating demand. The existing boilers stay installed also to provide heat to other building zones.

Heating the building with hot water at 55°C would be problematic if the installation had been designed for an 80/60°C temperature regime. But it appears that terminal units already installed are sufficiently oversized to function with low temperature hot water most of the time. For AHU coils, a series change over (to maximize the counter-flow effect) will be made on the water circuit. Instead of replacing the heating coils by coils with larger heat transfer areas: it has been decided to use the cooling coils as secondary heating coils (Fig.7). In the present case, cooling and heating coils are never used simultaneously, because there is no dehumidification control. The use of a larger heat transfer area allows to decrease the hot water temperature and to improve the performances of the heat pump.

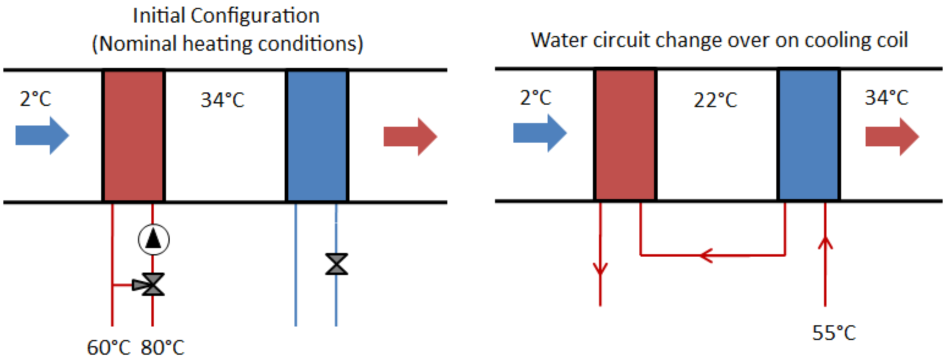


Fig.7: Water circuit change over on AHU coils

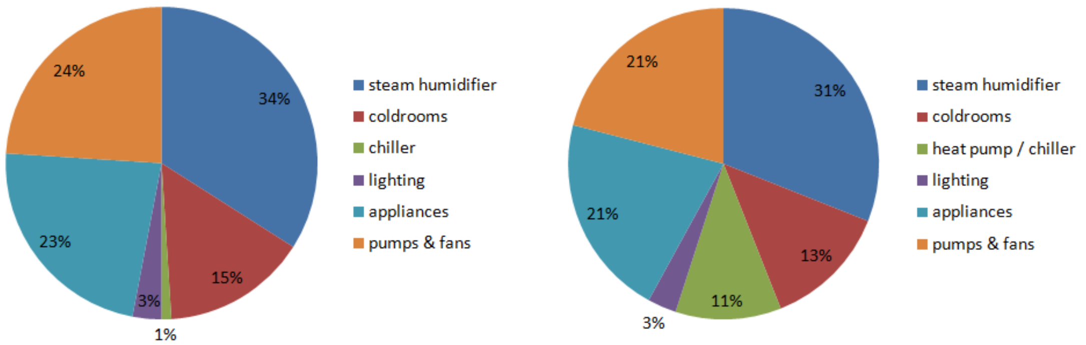


Fig. 8: Computed electrical consumption before (left) and after (right) retrofit

Heat pumping coupled with a change over technique is sufficient to satisfy almost all the heating demand of the building. Only a limited intervention of the existing natural gas boilers, as backup devices, is necessary during winter. The economical and environmental studies reveal a quite short payback time (about 8 years) and a significant reduction (-95%) of natural gas consumption. This gas consumption decreasing is consistent with the reversibility potential previously identified (98%). Considering also the increasing of the electricity consumption (+15%), the reduction of total CO2 emissions is about 18% of the current emissions (Bertagnolio[7]). As shown in Fig.8, the main part of the electricity consumption remains caused by auxiliaries (pumps and fans; about 20%), electrical appliances (about 20%) and electrical steam humidifiers (about 30%). The contribution of the chiller/heat pump stays quite marginal and does not overpass 11%.

6. FUTURE WORK

Future work will consist, among other, in continuing the development of the presented simulation tools. Additional tools will be developed to assess other heat pumping solutions. Design guidelines and some calculation tools will also be developed to help the practitioners in sizing, commissioning and operating heat pump systems. These commissioning guidelines will be established in close cooperation with the IEA-ECBCS Annex 47 project[10] ("Cost-effective commissioning").

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