HEAT PUMPING AND REVERSIBLE AIR CONDITIONING: HOW TO MAKE THE BEST USE OF HVAC EQUIPMENT?

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Abstract: Substituting a heat pump to a boiler may save more than 50% of primary energy, if electricity is produced by a modern combined cycle power plant (and even more if a part of that electricity is produced using renewable sources). Two of the most attractive heat pumps applications consist in recovering the heat rejected by the condenser of an existing chiller and in using this chiller in reversible mode.
This is the topic of the IEA-ECBCS Annex 48 project ("Heat pumping and reversible air conditioning"). An overview of the project is presented and the work of the different participants is briefly explained. Case studies are also briefly presented and more details are given on one of them.

Key Words: ***chiller reversibility, condenser heat recovery, change over***

1 INTRODUCTION

Environmental concerns and the recent increase of energy costs open the door to innovative techniques to provide heating and cooling in buildings. Among these techniques, heat pumps represent an area of growing interest.

In many non-residential buildings, an attractive energy saving opportunity consists in using the refrigeration machine for heat production. This can be done by condenser heat recovery 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 et al., 2006).

A basic idea presented in the paper is trying to make all the time the best use of all components available in the existing HVAC system. This is true for the refrigeration system, but also for all heat exchangers, including the cooling coils located in air handling and in terminal units.

2 PROJECT OVERVIEW

IEA-ECBCS Annex 48 project was proposed by Belgium (J.Lebrun, P.André) and approved by the ECBCS executive committee in 2005. The working phase started in September 2006.

The aim of the project is to promote the most efficient combinations of heating and cooling techniques in air-conditioned buildings, thanks to heat recovery and reversible systems. The main goals are:

- To allow a quick identification of heat pumping potentials in existing buildings

- To help designers in preserving the future possibilities and in considering “heat pumping” solutions
- To document the technological possibilities and heat pumping solutions
- To improve commissioning and operation of buildings equipped with heat pump systems
- To make available a set of reference case studies

Five subtasks have been defined during the preparation phase of the project.

- **Subtask 1**: Analysis of building heating and cooling demands and of equipment performances
    - Classification among different building types
    - Characterization of existing HVAC systems
    - Use of simulation models to identify H/C demands and best heat pumping potentials

- **Subtask 2**: Design
    - Elaboration of pre-design rules
    - Definition of evaluation criteria
    - Project of sequential design methodology (including retrofit)

- **Subtask 3**: Global performance evaluation and commissioning methods
    - Development of evaluation methods devoted to heat pump solutions
    - Tests with synthetic data and with measured data
    - Development of computer-based tool for heat pump system operation

- **Subtask 4**: Case studies and demonstrations
    - Documentation of reference case studies
    - Use of case studies to test the methods and tools developed in the annex
    - Conversion of most successful case studies into demonstration projects.

- **Subtask 5**: Dissemination
    - Website (www.ecbcs-48.org)
    - Paper work (leaflet, handbooks)
    - Workshops, seminars and conferences.

2.1 Analysis of building demands and of equipment performances

Basing on the French building stock, the French partners have proposed a classification of buildings in view of the evaluation of their energy demands and energy saving potential (by applying heat pump strategies; Caciolo et al., 2008). Office buildings and health care buildings are considered in the project. The defined buildings are supposed to be representative of the overall air-conditioned European building stock.

The heating and cooling demands of those buildings were calculated for a number of variants which differ in function of (Stabat et al., 2007):

- The climate (five climate zones were defined basing on H&C degree-days, figure 1)
- The glazing solar heat gain coefficient
- The orientation
- The ventilation rate
- The heating and cooling set points
- The internal gains (lighting and appliances loads)

For all the other parameters, default values were fixed basing on the French building stock: U values, thermal inertia, occupancy profiles, infiltration rate, hot water production (in health care buildings).

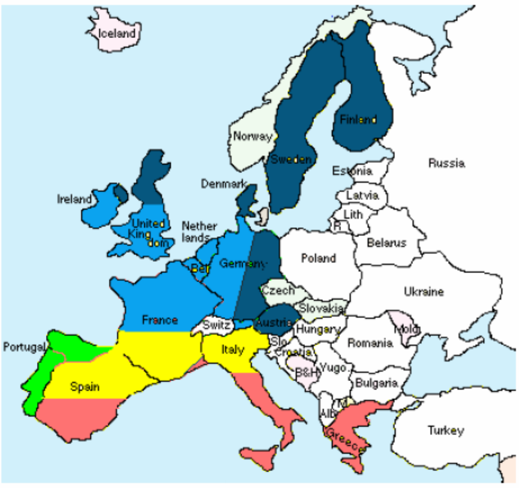

Figure 1: Five European Climate zones

On the basis of these results, reversibility and recovery potentials have been evaluated and compared. Reversibility potential are calculated hour by hour as the percentage of heating demand which could be provided by a chiller operating in heat pump. Recovery potential is calculated as the percentage of heating demand which could be provided by a chiller condenser. The remaining demand is assumed to be covered by an additional boiler.

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. 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 option (recovery potential reaching 45%).

For a typical day characterized by heating and cooling demands, the reversibility potential is shown in figure 2: the grey area corresponds to the maximum heating power coverable by the chiller working in heat pump mode. The heat recovery strategy is illustrated in figure 3. The heating and cooling demands are characterized by partially simultaneous demands between 10AM and 5PM. The maximum recoverable heat is a function of the chiller EER.

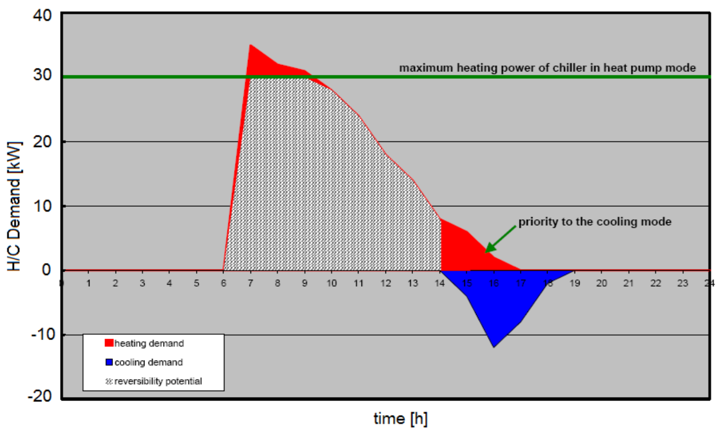

Figure 2: Visual interpretation of the reversibility potential for a given day

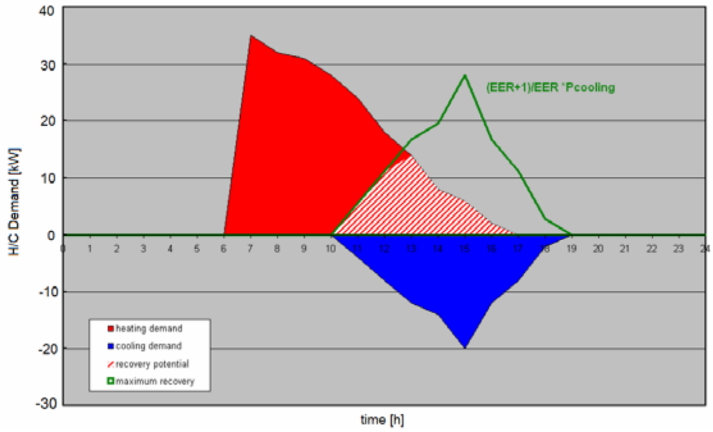

Figure 3: Visual interpretation of the recovery potential for a given day

The evaluation of reversibility and heat recovery potentials should be possible on the basis of a limited amount of information, for instance using very rough design data or measured consumptions. In this scope, a simple identification index and some simulation tools are being developed and adapted to the specific needs of the project.

2.2 Design

The work of the German group will lead to a computer based engineering guide. This innovative tool should support HVAC designers not only in design and evaluation of an optimal energy and climate concepts but also during the followed detailed planning and operation procedures of component sizing, description of commissioning procedures and control strategies.

The main deliverables of this part of the work will be a design guide handbook including the following items:

- Definition of boundary conditions
- Estimation of building and system energy demands
- Life-cycle and economical evaluation
- Selection and sizing of heat pump
- Selection and sizing of heat source (e.g. ground heat exchanger)
- Selection and sizing of secondary heat generators
- Control, fault detection and maintenance

As mentioned above, it appears that, in many installations, the nominal heating and cooling power demands are of the same order of magnitude. This means that a unique machine might be sufficient to cover both demands almost all along the year, providing that convenient heating and cooling sources are found.

The design guide will cover the design of new installations and the retrofit of existing ones.

Selection and sizing of the heat source is a critical issue in the design of a heat pump system. For cooling, outdoor air appears as a “good” heat sink, even very good if used with the help of a wet cooling tower. However, efficiency and capacity decrease with increasing outdoor temperature. In our climates, the same outdoor air appears as “less good” heat source, due to low temperature levels and defrosting requirements encountered in winter (ASHRAE, 2004). As shown hereafter, ventilation exhaust offers a high potential and heat pumping on this source has to be considered as complementary to “passive” heat recovery (Masoero et al., 2007).

The use of ground water and of ground (vertical or horizontal) heat exchangers as heat source will also be studied and described in the deliverable design guide.

2.3 Case studies

All the participant countries are encouraged to propose at least two case studies.
The first Italian case study is an administration office building dating from 18th century and rebuilt after WW2 (figure 4 left). The retrofitting consists in the installation of a VRF system and of a central HVAC system including recovery system and free cooling control.

French partners study an office building erected in the region of Lyon. The first retrofit opportunity was the external insulation of the building (figure 4 right). An air-water reversible heat pump has also been installed and provides heat and cool to the building. The boilers ensure the additional heating demand. To allow low-temperature heating, existing radiators were replaced by ceiling fan coil units.
After the retrofit, the heating primary energy consumption for heating should decrease from 140 kWh/m²/yr (measured consumption) to about 70 kWh/m²/yr (predicted consumption). The cooling energy consumption should not vary significantly.

Figure 4: Italian and French case study buildings

The German case studies consist in two commercial buildings equipped with geothermal heat pump systems (Dippel and Madjidi, 2006). The first case study is a medium office building (4000 m²) erected near Karlsruhe (figure 5) and equipped with a geothermal heat pump (heating capacity: 150 kW) used for heating and cooling. The heat pump evaporator is connected to a 120 concrete piles field (depth: 8m). The second German case study is a large office building (13500 m²) located in Münster and equipped with a set of geothermal heat pumps (total heating capacity : 500 kW) coupled to a large borefield (76 vertical boreholes, depth: 100m)

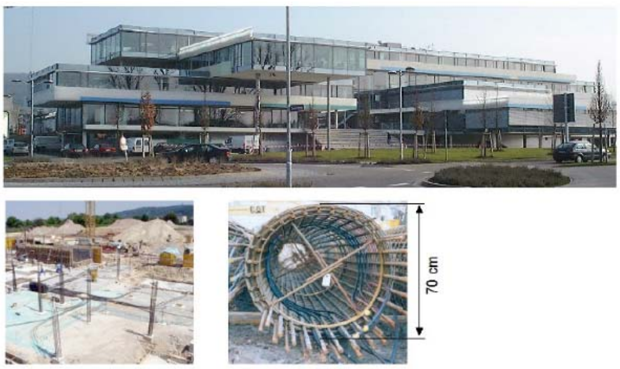

Figure 5: First German case study building

2.4 Modelling and evaluation tools

Evaluation of building and system loads brings additional challenges on models development and implementation. Different simulation softwares are used by the Annex 48 partners:

- Consoclim (Ecole des Mines de Paris),
- EES (University of Liege, University of Nuremberg, Ingenieurbüro Madjidi),
- TRNSYS (University of Nuremberg, University of Liege).

The heat pump solutions analyzed in this project involve the following specific developments:

- New components: heat exchanger, heat recovery devices, reversible heat pumps…
- New system architectures: recovery loop, reversible distribution systems, water circuit change over…
- New control and management strategies; including recovery, reversibility, and change over …

The evaluation of reversibility and heat recovery potentials should also be possible on the basis of a limited amount of information (depending upon the status of the building project; for instance: design data and simulation results for new buildings and as-built file or measured consumptions for existing buildings). In this scope, an evaluation index is developed. This index can be calculated using monthly, daily or hourly consumptions and demands and could provide useful information to identify the most attractive retrofit opportunity: reversible heat pumping or chiller heat recovery. In the case of an existing building, data to be used could be monthly measured consumptions. In the case of a new building, the index could be calculated on the basis of hourly demands and consumptions generated by simulations.

3 CASE STUDY: LABORATORY BUILDING

The first Belgian case study is a laboratory building, erected in 2003 near Liege. The building has a total floor area of about 6200 m² distributed between offices (1600 m²), laboratories (1300 m²), technical room (1800 m²), sanitaries and small meeting rooms (figure 6). Only the two first zones, responsible of the largest part of the demands of the building, were taken into account in the calculations (Bertagnolio et al., 2007a, 2007b).

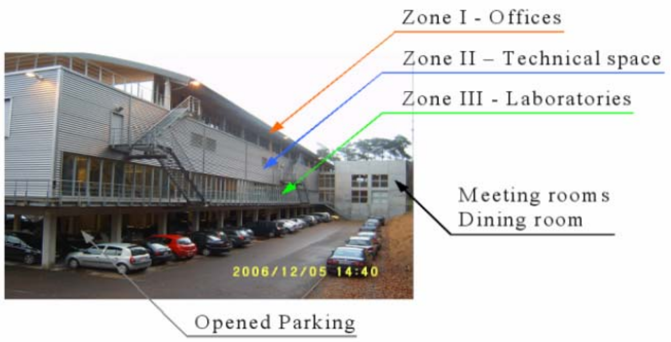

Figure 6: First Belgian case study building

3.1. Existing Installation

The ventilation of the offices is ensured by a CAV Air Handling Unit blowing about 5000 m³/h of fresh air (no recirculation). Thermal comfort is ensured in this zone by fifty heating/cooling fan coil units distributed in the zone. 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, cooling the extracted air ~~till~~ to a minimum temperature of about 12°C in extreme conditions (outdoor temperature: -12°C).

The hot water supplying AHU's coils and terminal units' coils is produced by two gas boilers of 300kW each. An R134a air-cooled chiller of 400kW (cooling capacity) ensures the chilled water production at 7°C.

3.2. Humidification system

The audit of the installation and the dynamic simulations have shown that the chiller consumption was hidden behind the electrical steam humidification system consumption. Indeed, humidification is responsible of about 34% of the total electricity consumption. Fans and pumps are responsible of about 24% of the electricity consumption whereas the chiller consumption represents less than 1%.

Several options are currently under study as the installation of clean water adiabatic humidification. However, in the case of laboratories steam humidification is generally preferred for hygiene considerations. A more rational way would consist in producing steam by an "evaporating unit", consisting of an expansion device, a low temperature evaporator and a dry compressor (figure 7). Some experimental tests will be made in the Thermodynamics Laboratory of University of Liege with a dry twin-screw compressor.

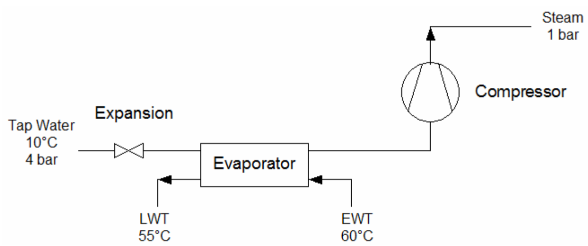

Figure 7: Steam generator – Evaporating unit

3.3. Passive heat recovery system

The study of the actual installation has shown that existing recovery loops are not well-controlled and switched off most of the time. The studied zones have been simulated over a typical meteorological year by using a building-HVAC system simulation tool developed in University of Liege and implemented in an Engineering Equation Solver (EES). The measured consumptions (2005) and the computed consumptions (typical meteorological year) with and without passive heat recovery are given in table 1.

Table 1: Measured and computed energy consumptions

	Gas Consumption	Electricity Consumption
	[MWh]	*[MWh]*
Actual Installation	1239	1504
Simulation results w. heat recovery	766	1260
Simulation results w/o heat recovery	1307	1260

It appears that electricity consumption is quite well explained. The discrepancy is certainly due to the zones which are not taken into account in the calculations.

As expected, the heating demand is better explained when supposing that there is almost no passive recovery. A first and cheap retrofit opportunity would be to identify the dysfunction in the heat recovery system. This first retrofit might decrease the gas consumption of about 40%. Of course, the two cases considered here, w. or w/o passive heat recovery, are, respectively, optimistic and pessimistic.

3.4. Reversible heat pump,

As mentioned above, two heat pumping modes are considered:

- Condenser heat recovery (simultaneous heating and cooling demands)
- Reversible heat pumping (non-simultaneous heating and cooling demands)

The studied building is characterized by comparable heating and cooling peak demands. During winter, the building cooling demand is almost or completely null. During summer, the building heating and cooling demands are alternated, according to the day/night cycle. However, cooling and heating demands could be sometimes simultaneous in different building zones.

So, in the present case, according to the period of the year and the simultaneity of the demands, both reversible heat pumping and condenser heat recovery strategies can be used to satisfy the building demands.

To make it possible, the existing air-cooled chiller has been replaced by a dual-condenser chiller equipped with air and water condensers connected in parallel (figure 8). A three-way valve ensures the control of the machine and the supplying of one or both condensers. The water condenser delivers hot water at maximum 55°C.

To allow reversible heat pumping during winter, an additional heat source is required. It has been decided to use the hot and humid 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/90%. Additional air/water coils will be designed to recover the largest part of the available energy to supply the heat pump evaporator. Of course, practical considerations, as available space in ducts, fans and pumps consumptions, and glycol protection of the heat source have to be taken into account.

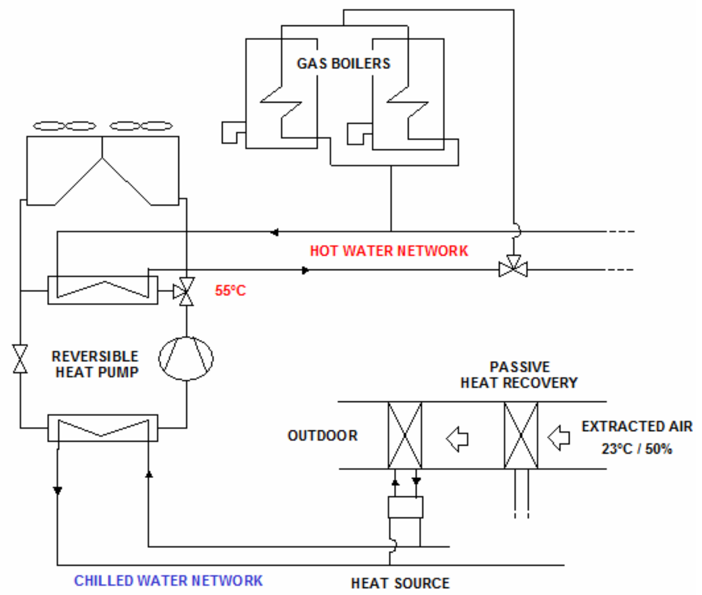

Figure 8: Modified Installation Scheme

In case of a too limited capacity of the heat pump (because of technical constrains or of heat source capacity limit), the boilers will intervene, as back-boosting devices, to provide the additional heating ~~demand~~needed. The existing boilers stay installed to provide heat to other building zones.

3.5. Water circuit change over

Heating the building with hot water at 55°C could be problematic if the installation has been designed for an 80/60°C temperature regime. Lowering the water supply temperature from 80 to 55°C could reduce too much the heating capacity of the heating devices (AHU and TU heating coils). It appears that already installed terminal units 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 (figure 9).

Instead of replacing the heating coils by larger coils offering a larger heat transfer surface, it has been decided to use the cooling coils as secondary heating coils. Indeed, in the present case, cooling and heating coils are never used simultaneously (no dehumidification control). So, during heating periods, the cooling coils constitute large un-used heat exchangers. The change over technique consists in using also these heat exchangers to heat the air (in addition to the heating coils already available).

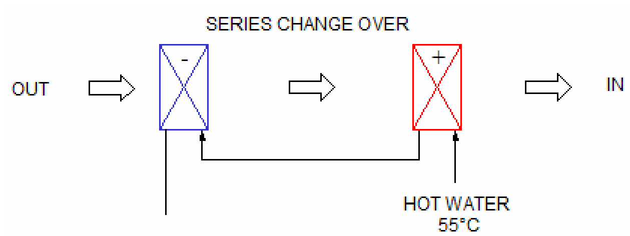

Figure 9: Series change over on water circuit

In addition to allowing the heating of the building with lower temperature hot water, the use of a larger heat transfer area allows to decrease the hot water temperature and to improve the performances of the heat pump.

3.6. Results

After the installation of the heat pump system, the gas consumption should almost be cancelled~~ed~~. The interventions of the boiler stay very limited for the two zones considered and the gas consumption will decrease ~~of~~ about 98%. The over-consumption of electricity will stay limited to about 190 MWh.

The money saving per year will be of about 15000€ and will correspond to a payback time of about 7 years. About 110 tons of CO_2 will be spared each year, corresponding to about 18% of the actual emissions. The yearly mean COP of the heat pump will reach about 3.9.

In the present case, using a chiller in heat pump mode appears as very valuable retrofit. This retrofit is even more efficient and interesting when coupled to a change over process on AHU coils.

4 CONCLUSION

The use of heat pumping for space heating in office buildings is probably today one of the quickest and most cost-effective solutions to save energy and to reduce CO2 emission.

Most~~of~~ air-conditioned buildings offer attractive opportunities, because:

1) When a chiller is used, the condenser heat can cover (at least a part of) the heating demand;
2) When a chiller is not used for cooling, it can be used in heat pump mode.

The retrofit of an existing building and, even more, *the design of a new one* should take all possibilities of heat pumping into consideration, in such a way to make air conditioning as “reversible” as possible.

The work made by the different participants in the frame of the IEA-ECBCS Annex 48 project has been briefly presented. Focus has been made on the first Belgian case study. In the frame of this case study, several technical solutions are presented to make the best use of available HVAC equipment. The heat pump solution seems to be a very interesting choice in the present case, even more when this solution is coupled to a change over processed on water network.

5 REFERENCES

ASHRAE 2004. “ASHRAE Handbook-HVAC Systems and Equipment” American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta.

Bertagnolio S. 2007a. “Study, Modelling and Analysis of heat pumping solutions in a commercial building”. Electromechanical Engineering Thesis. University of Liège.

Bertagnolio S., Lebrun J., Hannay J., Aparecida Silva C. 2007b. “Heat pumping and reversible air conditioning: Retrofit opportunities in a laboratory building”. 5th International Symposium on Heating, Ventilating and Air Conditioning, Beijing, China.

Caciolo M., Stabat P., Marchio D. 2008. , “Reversible air conditioning potential in office buildings in Europe”. IEECB 08 Conference, Frankfurt, Germany.

Dippel T., Madjidi M. 2006. “Two Case Studies on Heat Pump Systems with Ground Heat Exchanger and Thermal Concrete Core Activation for Heating and Cooling of Commercial Buildings”. 4th European Conference on Energy Performance and Indoor Climate in buildings, EPIC Conference, Lyon, France.

Lebrun J., Bertagnolio S. 2007. “Heat pumping and reversible air conditioning: First case study results”. Heat Transfer in Components and Systems for Sustainable Energy Technologies, Heat SET 2007 Conference, Chambery, France.

Lebrun J., André P., Madjidi M., Thonon B. 2006. “Heat pumping and reversible air conditioning; A new project of the International Energy Agency”. IEECB 06 Conference, Frankfurt, Germany.

Masoero M., Serraino M., Grisot M., Ranzato G. 2007. “Energy recovery from exhausted air: potentially in the Mediterranean climate”. Climamed 2007 conference, Genoa, Italy.

Stabat P. 2007. “Subtask 1: Analysis of building heating and cooling demands”. IEA-ECBCS Annex 48, Subtask 1 report.