Simulation based energy consumption calculation of an office building using solar-assisted air conditioning

S. Thomas[*] and P. André

Department of sciences and environmental management, University of Liège

185 Avenue de Longwy, 6700 ARLON, Belgium

[*] Corresponding Author, sebastien.thomas@ulg.ac.be

Abstract

To minimize environmental impact and CO2 production associated with air-conditioning system operation, it is reasonable to evaluate the prospects of a clean energy source. The targets of the study are to evaluate cooling energy consumption to maintain thermal comfort in an office building and to point out solar energy to satisfy these cooling needs. Simulations were carried out with three different cooling systems in the same operating conditions to determine as accurately as possible the potential use of solar energy. For comparison purpose, the base case is a classical air-conditioning system (heat pump for cooling, gas boiler for heating). Two other configurations were simulated: a classical vapour compression system fed by photovoltaic panels and electricity grid as back-up and, absorption chiller fed by solar thermal panel field and by gas boiler. In the three chosen locations (Paris, Lisbon and Stockholm), results shown that installing photovoltaic panels on the roof is really interesting from the primary energy consumption point of view.

Keywords: Solar cooling, absorption, photovoltaic, TRNSYS

1. Introduction

The present energy context is characterized by the imminent end of the era of fossil fuels and the environmental impact of their operation. Energy demand growth, local pollution, global climate change, … are problems that must be taken into account. It seems urgent to reconsider our way of life and design equipments as to minimise their energy consumption. Most air-conditioning equipments are currently electrically driven vapour compression systems. According to the International Institute of Refrigeration (IRR) [1] , 15% of the world's electricity is used for refrigeration and cooling. Moreover, the growth of cooling needs and consequently electricity consumption for cooling is an indisputable fact.

Using renewable energy such as solar energy is really feasible for air conditioning in building. Different technologies exist and can be compared based upon different characteristics: energy consumption, cost of the whole equipment, … The study is dedicated to office buildings which require especially high comfort levels and have often high heat gains due to glazed facades and electrical equipment. Small scale (round 5-10 kW) applications became recently market available. For large scale absorption and adsorption chillers the technology is more mature because of existing system driven by waste heat (coming generally from a cogeneration unit). In this work the emphasis is put on available technologies, key equipments are market available and data is taken directly from manufacturer.

The comparison exercise is realized on a theoretical office building. To point out use of solar energy in this building, three test cases have been defined. The first one is used as reference as it is a usual system implementation in real office building. For each case, three locations have been simulated using Meteonorm data files: Paris (Montsouris station), Stockholm (Arlanda station) and Lisbon.

Case	Heating		Cooling	
	Energy source	*Equipment*	*Energy source*	*Equipment*
1	Gas	Boiler	Electricity	Vapour compression system
2	Gas	Boiler	Sun, Electricity as back-up	Vapour compression system, PV panels
3	Gas, Sun	Boiler, solar thermal panels	Sun, Gas as back-up	Absorption chiller, solar thermal panels

Table 1. Three cases heating and cooling system

Especially for the last two cases, several aspects are to be addressed in order to provide a suitable solar air conditioning solution:

- Solar collectors
- Refrigeration equipment (chiller)
- Building
- Climate

Simulation of all these elements as well as links between them requires a very flexible simulation software. The dynamic simulation environment TRNSYS [2] is applied in this study. It makes possible the whole system simulation as well as the implementation of new models.

2. Building modelling

2.1. Main characteristics

The analysis will deal with a theoretical building (used in the IEA-ECBCS annex 48 project - Heating Pumping and Reversible Air Conditioning -) fully defined by P. Stabat [3] . It is a twelve identical floors, 15000 m² building with average 1000 persons occupancy. Representative existing European office building parameters are used [3] . Set points and ventilation rate are defined in table 2. . U value [W/(m² K)] for external walls is 0.8, 0.4 for roof and 2.95 for glazing.

Ventilation rate (maximum occupation)	25 m^3/h/person in offices (1 person/12 m²) 30 m^3/h/person in conference room (1 person/3.5 m²) 6h-20h during week – Stopped during weekend
Set point temperatures	21°C – 24°C inoccupation heating temperature : 15°C heating from 6h to 20h except Saturday and Sunday Air conditioning stopped during non occupation period

Table 2. Temperature set points and ventilation rate

In TRNSYS, only one floor with 5 thermal zones is simulated, there is no heat transfer considered between floors.

2.2. Geometrical description

Room's layout is presented in figure 1. Only South and North façade are glazed, height of room is 3 meters. Dimensions of each room are mentioned below. Toilets and circulation are not heated or cooled.

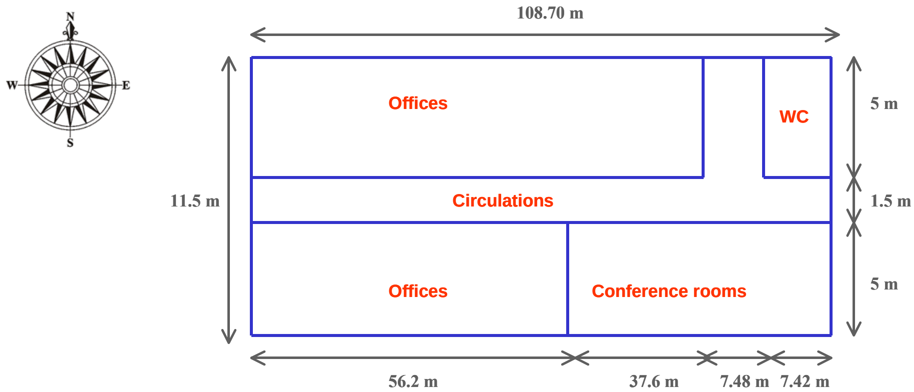

Fig 1. Typical floor of type 1C building [3]

2.3. Other features

Internal gains are computed based on occupancy (maximum value is given between brackets), they include the following list of features. Note that maximum occupancy is fixed as 80 % of value in table 2.

- people (8.75 W/m² in offices, 32.9 W/m² in conference room, 0 W in circulations and toilets)
- appliances (15 W/m² only in offices)
- lighting (18 W/m² in offices, 12 W/m² in circulations, 6 W/m² in toilets)
- fan coil unit ventilators (117 W/Fan coil unit)

Solar protections are also modelled, they are controlled by luminance passing through windows and by occupation. Artificial lighting depends on natural light available for workers [4] , and a correlation is implemented into TRNSYS. Occupancy profile is defined for offices and meeting room [3].

2.4. Emission and distribution heating and cooling system

Emission and distribution are the same for three cases. For distribution, it consists in cold water and hot water pipe network. Pipe losses are taken into account as well as pumps consumption (80% of pipe losses are recovered by building). Pump for hot network is only operating when there is a heating demand while cold network pump is always operating. Fan Coil Units (FCU) are installed for cooling and heating emission, fans are only in use in case of cooling or heating demand. The number of fan coil units is based on maximum cooling or heating load. There are 25 FCU for each floor (7 in meeting room and office South, 11 in office North).

3. Heating and cooling systems implementation

3.1. Introduction

Sizing of component is done for one floor. Extrapolation can be done to the whole building. For the different locations, the device power is equal to the maximum heating and cooling load computed before. Nevertheless the same performances are chosen whatever the nominal power. The three cases differ only by the heating and cooling production plant. Emission and distribution of heat/cold is kept as described above. In this way decoupling can be done about two parts of the simulation: building consumption; heating/cooling system consumption. For cases where solar energy is used, the collectors field is assumed to be located on the roof. This implies a limitation of collectors area. To go through this limitation, two versions are presented for case 2 and 3: one roof for 12 floors (case B.), one roof for 3 floors (case A).

3.2. Case 1: Gas boiler and vapour compression chiller

Heating and cooling production for this case has also been defined in the frame of the IEA Annex 48 report. Gas boiler performance is the same for each case: yield at 100 % load is 89.2 %; yield at 30% load is 88.2 %; losses at 0% load are 1.3 kW. Interpolation is done between these points. Heating curve has set point between 45°C and 90°C depending on external temperature.

The cold production is provided by an air-chiller with COP = 3.5. The set point of cold water is always 7°C whatever the case and external conditions. Due to lack of data, part load performance decrease is not taken into account.

3.3. Case 2: Gas boiler, vapour compression chiller, PV field

Gas boiler and chiller have similar behaviour as for case 1. The only difference is that Photovoltaic panels are placed on the roof to feed electrical grid (Panel chosen: SHARP NDL3E62). Given the roof surface, optimisation is done to produce maximum electricity on a yearly basis. A special TRNSYS shading model dedicated to PV is implemented (Type 551). A location has an optimal inclination angle [5] , the optimal number of rows is found (10 rows). Inverter efficiency is set to 0.78. It is assumed that PV panels work at their optimal point (current-voltage) each time. For case 2A building has 3 floors for case 2B, 12 floors. Roof panel field contains 700 elements and has a total net area of 610 m².

3.4. Case 3: Gas boiler, solar thermal field, absorption chiller

For this case, gas boiler power is designed to feed the absorption chiller when the load is maximum. It implies a higher power value than for previous cases. The heating/cooling system of case 3 requires additional equipment:

- Solar thermal panels : evacuated tube collector SCHOTT ETC 16
- Absorption chiller : YAZAKI WFC-SH 30 (Nominal point : 105 kWcold; thermal COP = 0.695)
- Storage tank
- Cooling tower : AEC Cooling Tower Systems FG 2004
- Heat exchanger

The central element of the simulation scheme is the storage tank (TRNSYS type 534); four circuits are linked to it: gas boiler, building heating network, absorption chiller hot water circuit and solar panel circuit. 20 cm width rockwool insulation has been modelled in order to decrease storage losses. Storage tank volume is optimized: this value ranges from 3 to 11 m³ depending on the simulation case and location.

Absorption chiller behaviour has been implemented in a new TRNSYS type 255 (nearly the same as existing type 107) based on manufacturer curves [6] . The model takes into account the energy balance, but not the chiller inertia nor other dynamic effects. Cooling tower fan speed is controlled by rejection circuit temperature. Solar energy passes trough a heat exchanger (95% efficiency) and heats the bottom of the storage tank. Its upper part is heated at 89°C by gas boiler in order to feed the absorption chiller at nominal point. No temperature control neither flow variation is provided on the hot water. Nominal power for absorption chiller is 105 kW for Paris and Stockholm, 150 kW for Lisbon.

The whole solar field has a net collector area of 427 m² and the slope is optimized for each location. There are four rows (less than case 2 due to size of panels). Mass flow of the fluid has been chosen to 30 litres/(m²_coll_net_area hour) [7] . New auxiliaries' consumptions have to be taken into account in this case. Common values are given by H.-M. Henning [8] : 0.02 kWh_{elec}/kWh_{th} for solar system, 0.03 kWh_{elec}/kWh_{th} for heat rejection, 0.01 kWh_{elec}/kWh_{th} for absorption chiller.

4. Results

4.1. Introduction

Hereafter are presented simulations results for each case and each location. They emphasize the energy consumption of building. Variable selection for presentation is based on reference book [9]; for example, primary energy savings are related to collector area. When converting net energy consumption in primary energy consumption, the selected coefficient is 2.5 for electricity and 1 for fossil fuels. These are legal values for Belgium. All values are given in kWh by building squared meter per year (building area is 15000 m² for twelve floor, internal zones area is used), or other units if necessary.

4.2. Building consumption without heating/cooling production

Results are including electricity consumption of different building devices including pumps for cooling and heating network (table 4). There is no huge variation between the three locations. These values are common for each case.

	Auxiliaries sum (primary)	Auxiliaries sum (elec. cons.)	Hot pump	Cold pump	FCU Fans	Vent Offices	Vent Meeting	Appliances	Light
Paris	180.03	72.01	1.09	13.21	8.08	0.96	2.76	25.56	20.36
Stockholm	186.90	74.76	1.28	13.21	8.60	0.96	2.76	25.56	22.40
Lisbon	176.90	70.76	0.70	13.21	6.96	0.96	2.76	25.56	20.61

Table 3. Auxiliaries consumption [kWh/(m² year)]

4.3. Heating and cooling load

These loads differ significantly between locations. Loads are not only including each thermal zone load but also losses due to heating and cooling network (fig. 3).

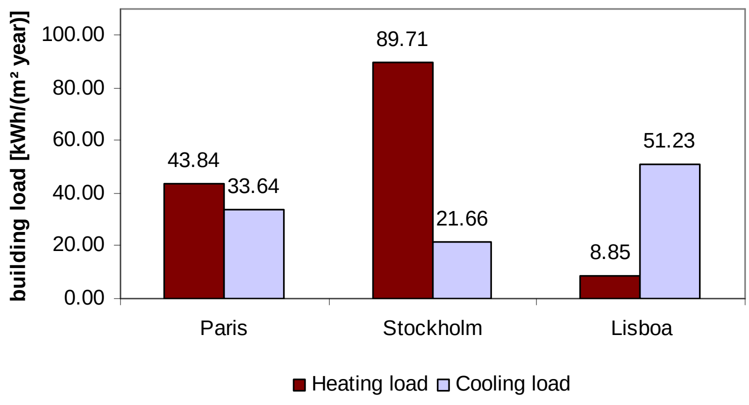

Fig 3. Building heating and cooling load [kWh/(m² year)]

4.4. Building consumption for each case

In this part, the auxiliaries consumption presented in paragraph 4.2 are not anymore taken into account. Net energy consumption and primary energy consumption are presented for different cases. Case 2A or 3A are related to a 3 floors building, case 2B or 3B to a 12 floors building. Figure 4 gives a diagram of heating and cooling energy consumption.

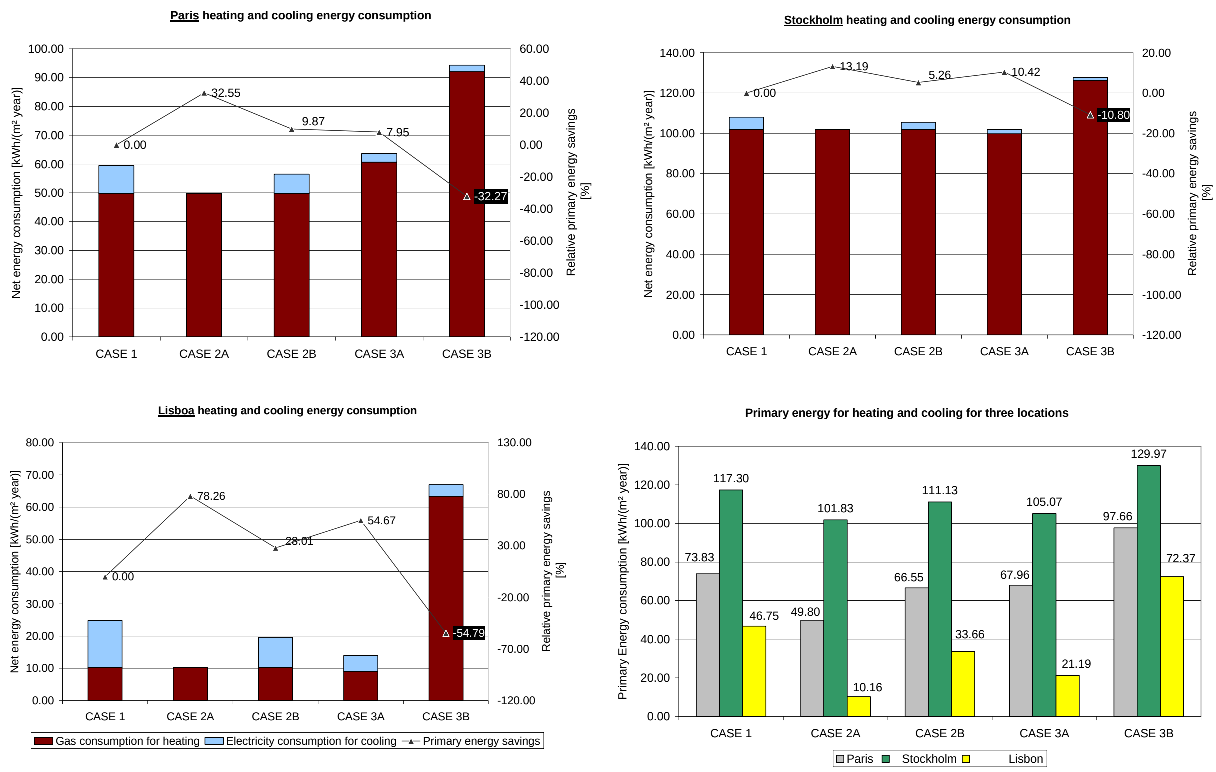

Fig. 4. Heating and cooling energy consumption

4.5. More results about case 2.

Cases 2A and 2B deal with photovoltaic panels, table 4 shows field production on the whole year. PV field feeds grid network, so electricity generation can be done when vapour compression chiller is not operating. Conservative shading assumptions is taken for all other results. For case 2A, PV field produces more than the whole vapour compression chiller electricity consumption, thus the auxiliaries consumption will be decreased respectively by 2.04, 3.68 and 6.31 kWh/(m² year) for Paris, Stockholm and Lisbon.

	energy (linear shading)	energy (conservative shading)
Paris	*81.43*	71.76
Stockholm	*74.18*	60.72
Lisbon	*151.70*	128.93

Table 4. PV energy production [kWh/(net_panel_area year)]

4.6. More results about case 3.

Simulations run for case 3 have been optimised to minimise boiler gas consumption. For each location it results a panel slope, a storage tank volume. A summary of results dedicated to case 3 is presented in table 5. Figures given are only about heating and cooling production consumption.

	Gas cons	*Electricity cons*	*Solar fraction*	*Solar Energy*	*Solar energy*	*Electrical COP*	*m² coll by kWcold*	*Pannel slope*	*storage tank*
case 3A	*kWh/(m² year)*	*kWh/(m² year)*	*%*	*kWh/(m² year)*	*kWh/(coll_net_area year)*		*coll_net_area/ kWc nominal*	*degree*	*m³*
Paris	60.67	2.92	45	43.25	380.73	13.35	1.35	15.00	7.00
Stockholm	99.79	2.11	31	38.70	340.64	13.99	1.35	15.00	8.00
Lisbon	9.08	4.85	93	82.21	723.72	10.94	0.95	25.00	11.00
case 3B									
Paris	92.08	2.23	13	12.48	439.29	15.89	0.34	15.00	3.00
Stockholm	126.15	1.53	10	12.14	427.44	16.08	0.34	15.00	3.00
Lisbon	63.41	3.58	32	27.19	957.34	14.53	0.24	25.00	3.00

Table 5. Case 3 summary

Some details should be given on this table: solar energy is the heat collected by the solar field and feeding storage tank; solar fraction is computed following equation 1. Table 6 proposes primary energy savings by net collector area for case 3A. It can be put in relation with table 4 given for case 2 (table 4 values must be multiplied by 2.5 to have primary energy).

$$Solar\ \ fraction = \frac{Solar\ energy}{(Heating\ load + Chiller\ hot\ water\ consumption)} \qquad \text{(equ. 1)}$$

	Location	**CASE 3A**
Primary energy savings by area of collector [kWh/(net_coll_area year)]	Paris	51.67
	Stockholm	107.60
	Lisbon	225.02

Table 6. Primary energy savings by collector area

5. Conclusion

In this work, design and energy performance of different kinds of air conditioning system were analysed. A complete building simulation model was developed with parameters found in IEA ECBCS Annex 48 research project. Heating and cooling emission and distribution systems were also defined as well as heat/cold production devices. This simulation has been run in three different locations. The comparison between three cases gives the potential energy savings of two solar technologies in relation to classical air-conditioning. A first analysis of auxiliaries showed that they have a huge weight in the primary energy balance. For case 1, it varies from 60% in Stockholm to 80% in Lisbon. Therefore it shows an important energy savings potential. When using classical vapour compression chiller and no solar energy, cooling cost less primary energy than heating due to COP higher than 2.5 (converting net energy to primary energy for Belgium). If solar energy conversion technology is implemented, a key point is available area for installing panels. In each case (A or B), primary energy savings are higher using PV panels instead of thermally driven chiller (assisted by solar thermal panels). It is another important result of this study. PV panels are directly connected to grid, then solar energy is use even if the building has low needs (e.g. during the weekend). For case 3.B (12 floors), solar fraction is very low, operating this system consumes more energy than classical air-conditioning. A better control can reduce this trend but a much higher solar fraction is required to save primary energy.

Systems costs have not been approached in this study. If this analysis is performed, the comparison should be done between solar and classical air-conditioning. An important point for PV is that, nowadays, electrical energy can be sold by the producer at a very interesting price. Moreover in some countries, such Belgium, kWh photovoltaic are paid directly at the production, so money can be saved even if electricity is not used in the building. Solar thermal energy has no such high financial incentive.

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