DYNAMIC SIMULATION OF A COMPLETE SOLAR ASSISTED CONDITIONING SYSTEM IN AN OFFICE BUILDING USING TRNSYS

Sébastien Thomas and Philippe André
Department of sciences and environmental management, University of Liège
185 Avenue de Longwy, 6700 ARLON, Belgium

ABSTRACT

To minimize environmental impact and CO_2 production associated with air-conditioning system operation, it is reasonable to evaluate the prospects of a clean energy source. Solar energy can drive an absorption chiller in order to satisfy the cooling needs of buildings. The objective of this work is to build a simulation environment that can evaluate accurately the energy consumption of an air conditioning system including a solar driven absorption chiller. This environment includes the absorption chiller itself, the rejection system, solar panels field, heater, storage devices, pumps, heating-cooling networks, emission system and building. TRNSYS software modular approach (Crawley, 2008).provides the possibility to model and simulate this complete system. Different strategies are proposed to minimize consumption for air-conditioning. Primary energy consumption for the whole building is presented by field (lighting, appliances, …)

INTRODUCTION

Solar air conditioning is a good way to use renewable energy instead of fossil fuels to meet heating and cooling needs of buildings. It implies a decrease in energy consumption and CO_2 rejection. Moreover, the absorption chiller modelled in this paper uses an environmentally friendly refrigerant. It is not the case for most of existing vapour compression chillers.

The development of solar air conditioning (SAC) technology is closely linked to its economical profitability. To check what are the real benefits of SAC installation, it is important to compute the energy savings as well as their essentials parameters (Casals 2005).

Previous works (Hensen 1991, Barbosa 2008) about analysis of heating and cooling consumption suggest considering an integral approach to evaluate energy savings. Moreover, in SAC systems, performance is greatly dependent of external conditions and on cooling load dynamics (Bujedo, 2008, Pollerberg 2008). Thus, it is important to think about the whole system (Mugnier 2002, Eicker 2008).

A complete simulation environment is presented in this paper. It includes specific aspects of each part of the system as well as interactions between them. Those sub-systems are named below:

- Building
- Hot and Cold distribution and emission
- Hot and cold production and storage
- Climate

The originality of this paper lies in the combined simulation of these sub-systems. Generally, cooling and heating are computed separately. It does not give the opportunity to analyse relations between the absorption chiller and the building.

The sub-systems modeling and simulation is described in this paper. The use of existing equipment and their key parameters is emphasized here, this is helpful for any further comparison.

In order to compare easily energy consumption, a reference case simulation is defined. It includes a classical vapour compression chiller for cold production and a boiler for heating but no solar panels nor storage devices. For a straightforward comparison, all consumptions are presented in kWh per squared meter per year. It can be expressed in net energy consumption or in primary energy consumption.

COMPLETE SYSTEM MODELLING

To have a clear view of the whole system, it has been divided into four parts. These parts are inter-connected as described in figure 1. This organisation highlights a key point of a solar air conditioning system: the link between four aspects named "layers" in the figure. The links are represented by grey arrows. In the following paragraphs, each layer is detailed.

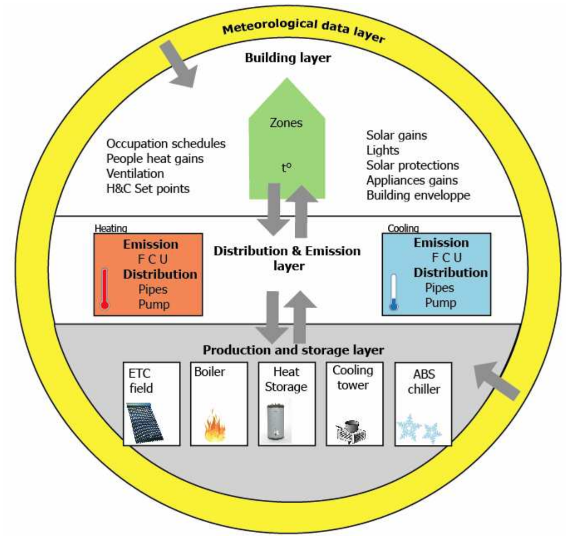

Figure 1 : Modelling layers

BUILDING MODELLING

Introduction

Here after are briefly presented the most important features of building modelling in TRNSYS. The multizone building (type 56a) is used.

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 in literature (Stabat, 2007) and representative of European office buildings.

Initially it was made of 12 identical floors (see figure 2), 15000 m² with average 1000 persons occupancy. Previous work (Thomas et al., 2008) has showed that a three floor building is more adapted to solar air conditioning with panels only on the roof. In this paper, one floor (1250 m²) of a three floor building is simulated.

Heat and cold load (set point 21°C and 24°C) is supplied by fan coil units (FCU) only. Only Offices and conference room (called meeting room in the text below) are heated and cooled.

Miscellaneous features

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 (Alessandrini J.M. et al., 2006), and a correlation is implemented into TRNSYS. All other features such as occupation schedule, ventilation, solar protection management, internal gains and building envelope can be found in literature (Stabat, 2007 ; Thomas et al., 2008).

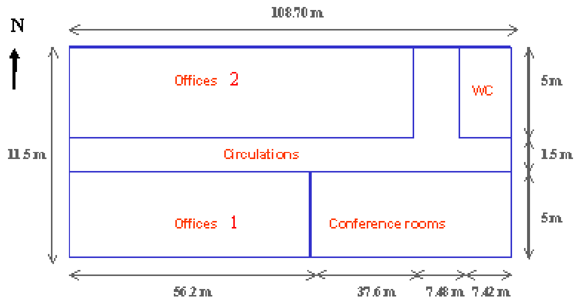

Figure 2 Building zones

H&C EMISSION AND DISTRIBUTION

Introduction

In such a building presented below, heating and cooling load are sometimes simultaneous. Heating and cooling have their own pipe network. In the figure 3, the layer is detailed, TRNSYS type numbers and links with other layers are mentioned.

Link with building layer consists in heating and cooling sensible energy given in each room by the FCU and pipe losses. The temperature of each room acts as an input for FCU control.

Links with production layer are temperature and mass flow for each network.

Pipes

As described in (Stabat, 2007), the pipes have a total length of 129.1 m (half for supply, half for return) and a U value of 0.28 W/(m K). 80% of energy losses are recovered by the building. The technical room temperature is set to 22°C all over the year.

Pumps

They have a constant mass flow, this one is set by the total number of FCUs. Pressure drop is 103 kPa, 40% yield and the whole power consumed by pump is transferred to the fluid.

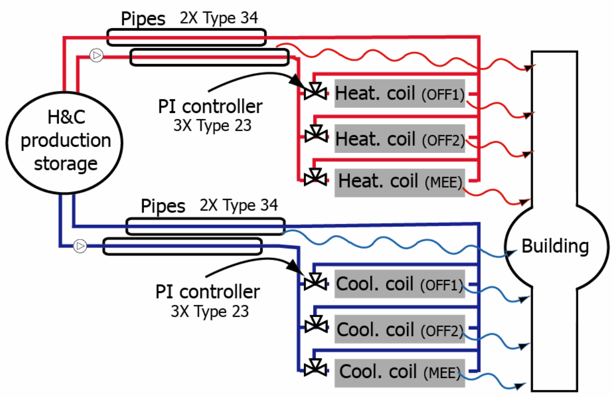

Figure 3. Emission and distribution layer

Fan coil units (FCU)

The number of fan coils has been chosen based on the highest cooling or heating loads and on FCU power at nominal capacity. This gives 25 FCU for the entire floor. They are distributed into the three zones : 7 for Offices 1 (OFF1), 11 for Offices 2 (OFF2), 7 for Meeting room (MEE).

In order to model as accurately as possible the heat-cold emission, the FCU power has to be modelled as function of entering water and room temperature. Some of the existing models of heating cooling coil in TRNSYS are tuned with only one parameter: heat exchanger efficiency or bypass air fraction (Klein, 2007). These models are not accurate for the whole range of FCU use. Another possibility is to read manufacturer data in an external file (e.g type 697b). This is a good way to have the real behaviour of fan coil. However, it requires classifying all the working points to a suitable file format (it can be source of numerous errors).

To have an accurate model as well as to translate the manufacturer data into TRNSYS, it is common to evaluate a polynomial estimation of the real behaviour (Barbosa 2008). It has been decided to prepare a multi dimension polynomial approximation of measured points using Matlab® (Matlab, 2007), which is entered into TRNSYS using a type equation. The inputs of the polynomial giving the heating power are: temperature difference between entering water and room air; mass flow entering the heating coil. For the sensible cooling power, inputs are: cooling coil entering temperature, temperature increase in the cooling coil, room temperature. It outputs the heating-cooling power, thus the return temperature of FCU in present situation.

Fan coil modelled has centrifugal fan. Manufacturer data (CARRIER, 2007) provides many working points. It has separated cooling and heating coils. Capacity is mentioned in table 1.

Control is done by proportional integral regulators (Type 23), in order to meet as quickly as possible the set points. There is one controller for each room and for each coil (heat-cool).

Table 1
*Fan coil characteristics**

	HEATING	COOLING
Water mass flow	0.025 kg/s	-
Dry bulb air temp	T	27°C
Supply water temp	T+60°C	7°C
Return temp	-	12°C
Sensible capacity	6725W	4880 W

* centrifugal fan at high speed.

H&C PRODUCTION AND STORAGE

Introduction

Previous section explains how to distribute H&C into the building, this one describes its production and storage. This layer contains elements of which the most important are displayed on figure 4. Links between this layer and distribution are temperature and water flow rates of hot and cold water.

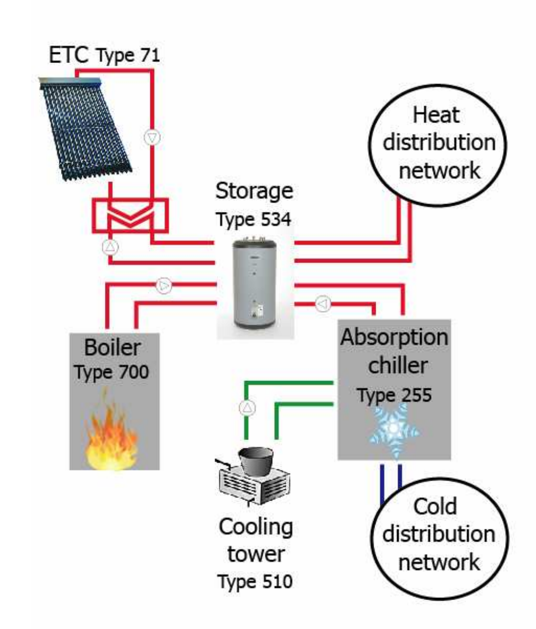

Figure 4. Production and storage layer CASE A

Absorption chiller

Among all kind of thermally driven chiller available on the market, a typical water bromide absorption chiller was chosen. This type of machine is mostly used in existing offices solar air conditioning installations (Preisler, 2008)

Absorption chiller behaviour has been implemented in a new TRNSYS type 255 (nearly the same as existing TRNSYS type 107) based on manufacturer curves (YAZAKI, 2008) related to absorption chiller YAZAKI WFC-SH 30. Rated power ($Q_{c,rated}$ = 105 kW), is adapted to modelled floor. Rated thermal COP (COP_{rated}) is 0.695.

The existing model is taking into account the energy balance, but not the chiller inertia nor other dynamic effects. It is based on energy balance equations and on external performance data supplying fraction of nominal capacity (f_{nc}) and fraction of design energy input (f_{dei}) for the chiller at current operating conditions. These conditions are :

- Chilled water set point
- Entering cooling water temperature
- Inlet hot water temperature
- Fraction of design load

Manufacturer gives curves of capacity and energy inputs for the three first conditions.

Cooling (Q_c) and heating (Q_h) are computed using equations 1 and 2.

$$Q_c = Q_{c,rated} \cdot f_{nc} \quad (1)$$

$$Q_h = \frac{Q_{e,rated}}{COP_{rated}} \cdot f_{dei} \qquad (2)$$

Two facts guided this implemenation of a new type :

1. In such chillers, the rated cooling power is generally not the highest cooling power. Nevertheless, in type 107, fraction of design load was computed based on rate capacity and was limited to 1. (Klein, 2007).
2. Fraction of design load (part load ratio) was independent of current conditions. This leads to a non convenient way to build external performance data.

A new Type 255 was created, rated power is maximum power of chiller. COP is also rated at those conditions. The second difference is about fraction of design load. It is now called "fraction of full load" and computed based on current conditions (based on rated power in type 107). It implies a second call to external data file. First call for discovering maximum capacity at current conditions, second call for fraction of full load evaluation.

For the selected chiller, no part load performance curve is available. Assumption is constant COP whatever the load.

Modelling of production and storage layer is designed to keep chiller operation into relevant conditions. This avoids unreliable results due to extrapolation outside of manufacturer data.

Heat storage

The central element of the simulation scheme is the storage tank (TRNSYS type 534); as shown on figure 4, four circuits are directly connected to it (no heat exchanger in the tank). A 20 cm thick rockwool insulation has been modelled in order to decrease storage losses. Storage tank volume is 7 m³, which is optimized to minimize boiler consumption.

Boiler circuit heats the upper part of the tank to maintain 89°C at the top. Tank model contains 10 nodes, each one is represented by one temperature. Higher node feed absorption chiller as well as heat distribution network.

Cooling tower

As mentioned below, heat rejection control is crucial to guarantee good performances of absorption chiller. Model used is Type 510. According to the authors (Zweifel at al., 1995) it is able to find accurately the power rejected based on only one design point. Control of outlet temperature is done by modifying the fan speed. Assumption done here is that fan speed varies continuously from zero to nominal speed.

Chosen cooling tower is AEC Cooling Tower Systems FG 2004. It has a nominal rejection power of 263 kW.

Solar panels

Evacuated tube collectors (ETC) are chosen because of the temperature to reach. Type 71 has been chosen to implement the panel SCHOTT ETC 16. Roof is the only available area for solar field. Optimisation has lead to four rows with 15° elevation. A total of 427 collector net area can be installed (it means 142,3 m² available for each building floor). Orientation has not been optimised, it is South due to building shape (figure 2).

Shading is considered between rows. Type 551 in TRNSYS is designed to do this computation.

Solar energy passes trough an heat exchanger with 95% constant efficiency.

Boiler

Heating production has also been defined by Stabat in the IEA Annex 48 report. Gas boiler performance is: 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. Boiler set point is 89°C all other the year. Rated power is 150 kW

Pumps and other auxiliaries

For pumps, no typical pression drops values are found for different circuits, pumps are not modelled as they were for distribution emission layer. Common consumption values are given (Henning, 2008): 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. These values include pumps consumptions and other auxiliaries such as cooling tower fans.

Reference case

As mentioned in the introduction, the reference case for comparison purpose contains a boiler and a vapour compression chiller. Boiler has same characteristics as previously defined but rated power is 130 kW. Heating curve has set point between 45°C and 90°C depending on external temperature (Stabat, 2007). Vapour compression chiller has 105 kW cold power, its seasonal COP is 3.5. No other devices are modelled. This reference case is a classical air-conditioing system.

CLIMATE

Meteorological data from Paris Montsouris station were taken to run simulations. These are data for the typical meteorological year (TMY) for the period 1961-1990. Type 15-6 is used in TRNSYS to read data and set them in the different layers (see figure 1).

Information provided to building layer is: external temperature, relative humidity, sky temperature, solar radiation (direct and diffuse) and incidence angle of sun. These data are influencing heating and cooling load in building.

For production and storage layer, type 15-6 is feeding data for solar collectors, shading type and cooling tower. The same data are provided as for building layer.

SIMULATION

Four layers presented in figure 1 are simulated in the same TRNSYS project file. Time step is 0.1 hour, simulation period is one year.

Solar-air conditioning control strategies

Energy consumption is closely linked to the control of storage (Kühn, 2008, Casals 2006). Three different strategies are described below.

CASE A.

Base case, storage tank is the only heat supply for heating and cooling. Gas and sun are the only energy sources. It is exatly what is displayed on figure 4.

Optimisation of parameters (storage tank, incidence angle) has been done on CASE A. Perhaps it is no optimized for other cases.

CASE B.

It is a combination of solar-air conditioning and reference case (so called classical air conditioning). For heating, the reference case configuration is taken. Boiler is directly plugged on the distribution emission layer. Storage is still there but is not heated by a boiler. For cooling, the reference case vapour compression chiller is used when storage is not hot enough (minus than 81°C) to feed absorption chiller. So the two chillers are plugged on the distribution emission layer.

CASE C.

Similar to case B for cooling. The storage is also fed by sun only. However, in this case building heating load can be supplied by storage tank. When building has heating needs, top tank temperature is compared to heating curve (see reference case paragraph). If the tank is hot enough, its water is provided to building otherwise auxiliary boiler heats water. So auxiliary boiler and storage tank are linked to distribution emission layer.

Problems encountered

Storage tank has a strange behaviour when submitted to high water flows. It implies non zero balances between inputs (sun energy, gas boiler) and outputs (heating load, tank losses, absorption chiller consumption). Integrated energy balance error on the whole year is round 370 kWh for case A while it is 290 kWh for case B 290 and 90 kWh for case C. In any cases it is less than 1% of energy supplied by tank.

DISCUSSION AND RESULTS ANALYSIS

The aim of the simulation is to compute the energy consumption of a European representative office building in Paris. Comparison is done between the different cases: Classical Air-Conditioning (reference case), Solar A-C cases A, B, C.

When converting net energy consumption into primary energy consumption, the selected coefficient is 2.5 for electricity and 1 for fossil fuels. These are legal values for Belgium. It does not differ a lot for other European countries.

The selection of variable for presentation is based on reference book (Hening, 2007); for example, primary energy savings are related to collector area.

Units of consumption given below are kWh per building squared meters per year (net or primary energy) or other units if mentioned.

Heating and cooling (H&C)

Consumptions vary greatly with the kind of strategy adopted. Whole year results are presented as well as monthly results.

On the figure 5 are presented heating and cooling load values which do not vary significantly between cases. This building has nearly the same heating and cooling maximal load. Heating load is present for each month. Loads are including distribution losses.

Different cases (reference case – clAC and solar air conditioning cases – SAC) consumptions are highlighted in figure 6 and table 4. Energy consumptions depend really on what kind of strategy is applied.

Case A is more energy-consuming than reference case, so it is important to adopt another strategy to have a better use of solar energy. Vapour compression chiller (VCC) is used as back up system for cases B and C while absorption chiller is the only cold production device for case A. Case C tells us it is more efficient to use solar energy for both heating and cooling, it represents a decrease of nearly 35% compared to reference case.

Other results such as solar fraction are presented in table 5. This simulated configuration contains 0.11 m² net collector area per building m². The solar fraction can raise up to 0.51. Monthly results show that solar fraction is not constant through year, in sunniest months solar fraction is around 80-90 %. The highest fractions are encountered from April to June when loads are not so high but the sun is nevertheless shining a lot.

Auxiliaries

Auxiliaries consumptions have been computed, different fields are mentioned in table 2. Total net energy and primary energy consumption are presented in table 3. In regard to heating and cooling, it represents a non negligible part of all building consumptions. In fact, it has the same order of magnitude as H&C energy consumption.

Table 2
Auxiliaries net electricity consumptions

Unit	[kWh/(m² year)]
Fan coil unit	9.5
Ventilation	3.7
Light	20.5
Appliances	25.6
Hot pump	3.3
Cold pump	10.4
Solar A-C auxilaries case A	2.8
Solar A-C auxilaries case B	1.9
Solar A-C auxilaries case C	2.1

Table 3
Total Auxiliaries consumption

	NET ENERGY	PRIMARY ENERGY
Units	[kWh/(m² year)]	[kWh/(m² year)]
Reference case	72.9	182.3
SAC case A	75.7	189.2
SAC case B	74.8	187.1
SAC case C	75.0	187.4

Table 4
Net and primary energy consumption for H&C

Case	GAS BOILER NET CONSUMPTION	VCC NET CONSUMPTION	TOTAL NET ENERGY	TOTAL PRIMARY ENERGY	PRIMARY ENERGY VARIATION
Units	[kWh/(m² year)]	[kWh/(m² year)]	[kWh/(m² year)]	[kWh/(m² year)]	[%]
Classical air-cond.	52.6	10.6	63.2	79.1	0.0
Solar air-cond. A	81.1	-	81.1	81.1	2.6
Solar air-cond. B	52.0	3.6	55.5	60.9	-23.1
Solar air-cond. C	39.4	4.8	44.2	51.5	-34.9

Table 5
Other results about Solar air conditioning (SAC)

	SOLAR FRACTION	SOLAR FRACTION COOLING	SOLAR FRACTION HEATING	PRIMARY ENERGY SAVINGS PER COLLECTOR NET AREA
Units	[-]	[-]	[-]	[kWh/(m² coll. year)]
SAC case A	0.32	-	-	-17.8
SAC case B	0.38	0.63	0.00	160.2
SAC case C	0.51	0.53	0.32	242.5

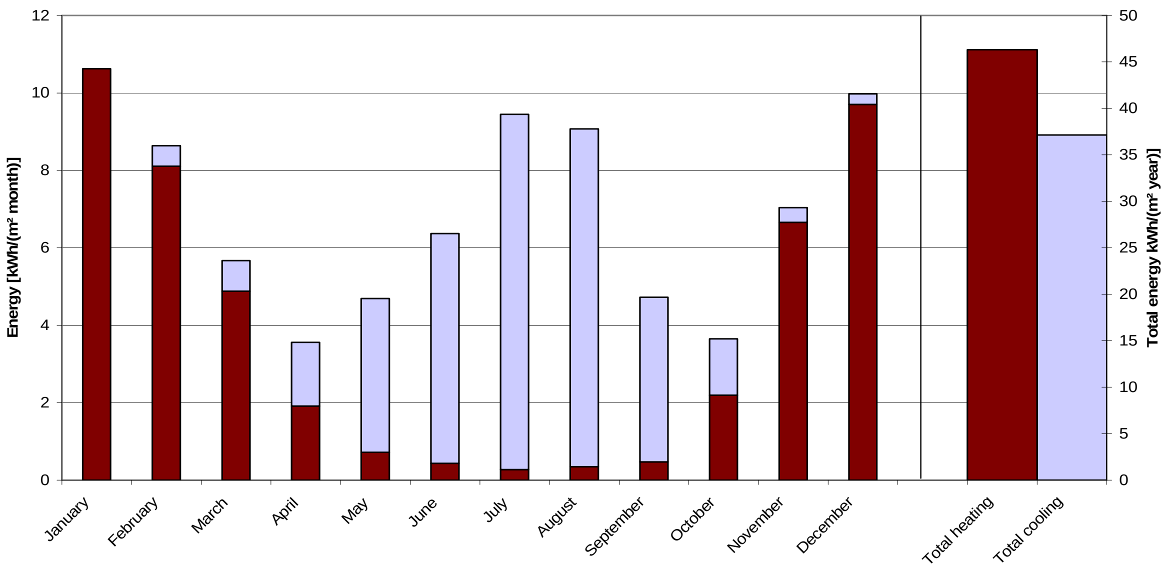

Figure 5. Heating and cooling load (dark- heating ; light –cooling)

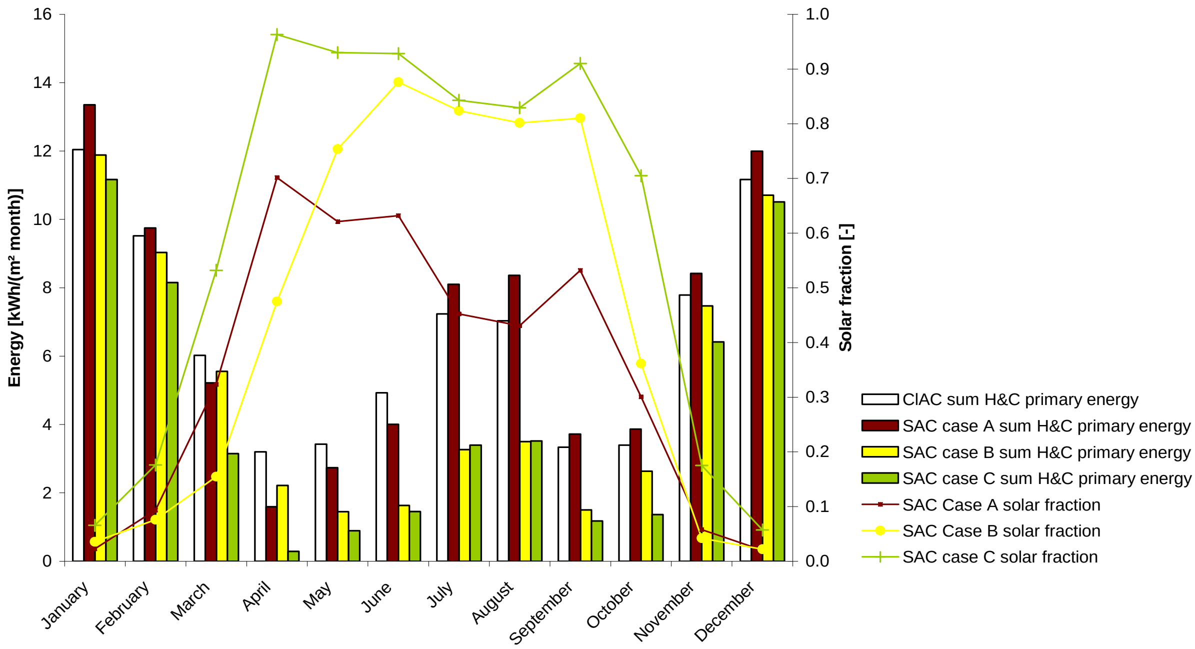

Figure 6. Monthly primary energy consumption for heating and cooling and solar fraction

CONCLUSIONS

A complete office building solar air conditioning application was presented, and provided energy consumption results. Simulation features were defined closely to real life operation : Typical European office building was defined, almost all air-conditioning devices have their parameters taken in manufaturers data sheets.

This complex simulation becomes easier to understand by dividing the problem into three parts. They are the three layers defined in this paper. For further work these layers can be replaced to simulate an other building or other emission devices for example.

Results underline the fact that solar-air conditioning is able to reduce energy consumption… but not in all cases ! Three kinds of control strategies have lead to find a case were energy use is decreased by 34.9 % compared to a classical air conditioning system. When sun does not give enough power to feed absorption chiller, it is reasonable to use a vapour compression chiller instead of a boiler preparing hot water. Solar energy through collectors should also contribute to heat the building.

The auxiliaries have also be computed regarding a common building use. Implementation of solar-air conditioning increases a little bit this energy amount. One of the most important fact is that auxiliaries consumption in terms of primary energy is allways higher than energy for heating and cooling. Moreover, these auxiliaries add cooling load in the room. Dicreasing their consumption by using energy efficient electrical devices is a key point. The more you pay attention to decrease cooling load the more you have interests to do solar air-conditioning.

Limitations and further work :

Optimisation of parameters has been done for case A. Doing it on other cases would certainly decrease consumption again.

Convergence problems were encountered with hot water storage. These have to be solved to be accurate when evaluating different flows temperatures.

Absorption chiller model is at the moment not including dynamic effets. It should be interesting to add them and it will probably decrease effiency given in steady state conditions by manufacturer.

Control strategy has a huge impact on results, new scenarios can be implemented. For example, absorption chiller feeding temperature can be adjusted in relation to cooling load.

The simulation environement includes a complete model, it is now able to assess many parameters impact on consumption.

By including the building into this environment is an open invitation to a new kind of analysis : impact of air-conditioning on people comfort in building. For example, it could be possible to determine if offices temperatures are acceptable when using only sun energy for cooling.

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