# The Influence of Weather Conditions on Energy Performance of HVAC System and Absorption Cooling System Coupling

Jerko Labus[1,*], Ivan Korolija[2], Ljiljana Marjanovic-Halburd[3], Alberto Coronas[1]

[1]CREVER-Group of Applied Thermal Energy, University Rovira i Virgili, Tarragona, Spain
[2]Institute of Energy and Sustainable Development, De Montfort University, Leicester, UK
[3]Department of Built Environment, Anglia Ruskin University, Chelmsford, UK

[*]*Corresponding email: jerko.labus1@urv.cat*

**ABSTRACT**
In this study, the attention is focused on the influence of climate conditions and absorption chiller configurations on the energy performance of heating, ventilating and air conditioning (HVAC) systems. We will analyze the correlation between HVAC system dynamic load profile and the performance of various absorption cooling system configurations for two typical European climates: Mediterranean (more specific Spain) and Mild Atlantic Climate (UK). Dynamic simulation software EnergyPlus is used to calculate HVAC system cooling demand of typical narrow plan office building, equipped with variable air volume (VAV) system and placed in chosen climate regions. This cooling demand has been coupled with different absorption cooling system configurations developed in MatLab in order to analyze absorption chiller heat energy consumption.

Preliminary results of this study shows that energy savings in terms of heat supply can be achieved when multiple absorption chillers are used. Spanish case study shows that up to 4.9% can be saved while in the UK savings go up to 6.17% when compared with basic scenario which is a single absorption chiller plant. The results also indicate that for the same building type, the combined influence of climate and national standards can produce up to four times higher cooling demand for building in Spain when compared with buildings in the UK. This directly affects the size of the absorption chiller plant which is 50% bigger and the number of hours when chillers are operating which is twice higher.

**KEYWORDS**
Absorption chiller, Cooling demand, VAV system, Office building simulation

## INTRODUCTION

Buildings in general are responsible for around 30% CO2 emission. A significant amount of energy in buildings is consumed by HVAC equipment. Over the last couple of decades, a significant increase of cooling energy demand, even in mild European climates, has been reported. That building cooling load is in direct correlation with chiller energy consumption. Improving the energy performance of the chiller plants is of particular interest because it usually presents the energy saving opportunity for air-conditioning systems in buildings. Therefore, design parameters such as number of chillers, chiller size, operating conditions and control strategy can be a key factor for improving overall building energy performance.

To achieve optimum plant performance, many central cooling systems are composed from multiple chillers which operate in parallel or in series with different control strategies. Sequencing control has been widely used in chiller plants as a method of achieving the operating chillers overall coefficient of performance (COP) as high as possible while delivering sufficient amount of energy to fulfill the building load demand. Chang at al (2005, 2008) demonstrated the applicability of advanced control methodologies to HVAC system management in order to improve its energy efficiency. They employed the genetic algorithm and evolution strategy, using Lagrangian method to determine the optimal chiller load. However, this is advanced method and it includes very difficult program code.

Lee and Lee (2006) developed a simplified model for evaluating chiller system configuration. The model was based on evaluation study of the energy performance of a multiple chiller system which is composed of 2-10 equally sized chillers. Study shows that larger chillers operated most of the time under full-load capacity do not necessarily lead to better energy performance. Moreover, the multiple chiller system energy efficiency improves with a larger number of chillers in use which can lead up to 9.5% saving. Although traditional practice recommends equally sized chillers, unequal capacity chillers may provide some advantages. Landman (1996) reported that the system with unequally capacity chillers would operate with higher percentage of full-load capacity and less running hours. Another research investigation on multiple chillers carried out by Yu and Chan (2006) showed that the chiller plant designed with unequally sized chillers can save by 10.1% of annual energy consumption in comparison with chiller plant designed with equally sized chillers.

Absorption chillers compared to conventional ones have much lower CO2 footprint. They have also been promoted by electrical utility companies as a measure of reducing utility demand peaks (Maidment and Tozer, 2002). Another advantage of absorption chillers is that working fluids are not harmful to the environment, unlike the CFC’s and HCFC’s refrigerants used in compression chillers. Nevertheless, absorption chillers are not as common as electrical chillers and there is almost no work reported on multiple absorption chiller plants configuration influence on its energy consumption. The usual approach is simply to adopt the analogy with conventional refrigeration systems.

The main aim of this paper is to analyze different multiple absorption chiller configuration and their possible influence on reducing the primary energy consumption. This analysis includes the influence of different climates, in particular Mediterranean and mild Atlantic, on office building/HVAC system cooling demand and provides the comparison study on absorption cooling systems efficiency for two different climate conditions.

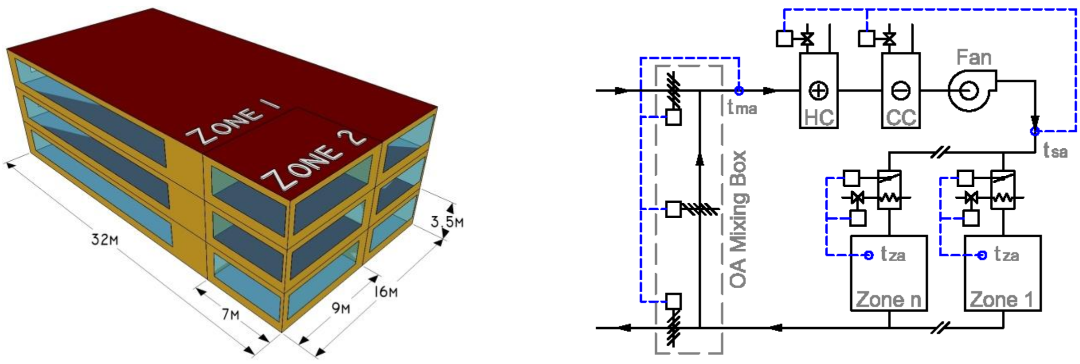
## METHODS

### Building model

The building model created for the purpose of this study is a three-story high narrow plan office building with a 32 by 16 meters footprint and floor-to-ceiling height of 3.5 meters (Figure 1a). Each floor is divided into two zones. First zone is a large open office area while second zone represents common spaces such as corridors, toilets, tea kitchen, etc. Each facade has the same quantity of glazing, 50% of external wall area, which is a typical value for medium glazed office buildings. The building fabrics are set to comply with the latest national standards; UK (Building Reg. App. Doc. L2, 2006) and Spanish (Documento Basico HE1, 2009). A parallel review of both building fabrics U-values is presented in Table 1.

Table 1. Building Fabrics U-Values

| Construction | UK [$W/m^2K$] | Spain [$W/m^2K$] |
|---|---|---|
| External wall | 0.35 | 0.73 |
| Flat roof / Ground floor | 0.25 / 0.25 | 0.41 / 0.50 |
| Glazing | 2.10 | 3.30 |




a) b)

Figure 1. a) Office building model, b) Variable air volume system

Office buildings belong to the building types with clearly defined occupancy pattern. Building is in use only during weekdays between 7am and 7pm and the indoor thermal condition and air quality has to be strictly controlled in that period. Due to aim of this paper to analyze cooling demand only, temperature setpoint is set to 24°C in offices and 26°C in common areas. During unoccupied period, to prevent overheating, the thermostat does not allow indoor air temperature to exceed 28°C in offices and 30°C in common spaces. These values are recommended by CIBSE (2006) and they are compatible with indoor air temperatures cited in the ASHRAE Handbook (2007).

Internal heat gains in office buildings can have a significant effect on their thermal behaviour and energy consumption. The occupant density is set to 9 $m^2$/person with a total heat gain of 108 W/person, while the equipment heat gain is limited to 15 $W/m^2$. Artificial lighting heat gains are selected to comply with the benchmark value of 12 $W/m^2$ (ECG019, 2003). To decrease a level of internal gains, we decided to implement daylight control in office zones. Artificial lighting is reduced whenever it is possible to benefit from daylighting while still achieving the desired illuminance target value which is set to 500 lux for the office type activity. In addition to internal gains, fresh air requirements and infiltration rates also have to be defined. A minimum of 10 l/s per person is needed to satisfy fresh air requirements while 0.3 air changes per hour is taken as the infiltration rate.

Last thing which has to be defined is HVAC system used to maintain desired indoor parameters. We selected one of the most popular systems in office buildings, VAV System. VAV System (Figure 1b) is an air system that varies its supply air volume rate, while keeping a supply air temperature constant, to match the reduction of space load during part-load, to maintain a predetermined space parameter, usually air temperature, and to conserve fan power at reduced volume flow. Main heating and cooling coils are controlled by supply air temperature (tsa) which is set to 16°C. Preconditioned air is distributed to the zones through the air reheating boxes where, if there is a need, is additionally heated. The outdoor air volume flow rate is controlled via the outdoor air mixing box equipped with economizer which increases the amount of outdoor air whenever is possible to benefit from free cooling.

**Absorption chiller model**

In this research, absorption cooling technology was selected to satisfy the HVAC System cooling demand. The main question is how to calculate the absorption chiller heat energy consumption for desired cooling demand. For that purpose, we created the Matlab model which is based on the EnergyPlus and the Building Loads and System Thermodynamics absorption chiller models (BLAST, 1999). The model uses performance curves of different hot water single-effect absorption chillers available on the market at the moment. In principle, it is built on multiple regression function for wide range of operating points found in manufacturers catalogues. This function is a cubic equation which determines the generator heat input ratio as a function of part-load ratio (PLR) only (Equation 1), where the part-load ratio is a ratio between cooling demand and chiller rated cooling capacity (Equation 2).

$$GenHIR = a + b \cdot (PLR) + c \cdot (PLR)^2 + d \cdot (PLR)^3 \tag{1}$$

$$PLR = {Q_{eva}}/{Q_{eva,rat}} \tag{2}$$

We also included cycling control in the model which means that the chiller will be on for a fraction of time step when operating part-load ratio is less than the minimum part-load ratio. This basically means that when HVAC system cooling demand is lower than available cooling energy generated by chiller at minimum power, chiller will operate at minimum power only for a fraction of time step. Actually, it will operate until it generates enough energy to cover cooling demand. Otherwise, the chiller will be on for entire time step if there is a need for cooling (Equation 3). Having defined CyclingFraction factor and previously described generator heat input ratio we can calculate generator heat input (Equation 4). The absorption chiller coefficient of performance (COP) is calculated as a ratio of cooling capacity and generator heat input (Equation 5).

$$CyclingFraction = MIN(1, {PLR}/{PLR_{\min}}) \tag{3}$$

$$Q_{gen} = GenHIR \cdot Q_{eva,rat} \cdot CyclingFraction \tag{4}$$

$$COP = {Q_{eva}}/{Q_{gen}} \tag{5}$$

To fulfill different scenarios requirements we selected five chillers available on the market and determined the multiple regression coefficients required for the model. Figure 2 shows the part load performance curves developed from the multiple regression chiller models. These data sets cover various operating conditions in terms of part load ratio from 0.2 to 1.1. The minimum adopted value for PLR in further analysis is 0.2 which gives the minimum obtained COP for the least efficient chiller slightly below 0.5. In terms of absorption chiller technology, 0.5 at 20% of full load can be considered as a very good performance. Among different units from different manufacturers, the best efficiency at part loads from 0.4 to 0.9 shows the chiller with nominal capacity of 70.3 kW with maximum reached COP between 0.6 and 0.7 while the worst COP has the smallest chiller of 35.2 kW. 105.6 kW unit has the

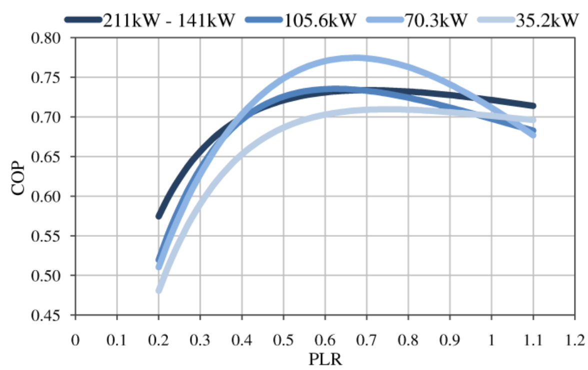



Figure 2. PLR vs. COP for different chiller units

maximum performance for PLR between 0.5 and 0.7 after which it drops significantly. Two largest units show almost constant COP when working with more than half capacity.

## RESULTS

The simulation was performed for whole year although the cooling period has been set to be between 1st May and 31st October. HVAC system simulation outputs show the great diversity between Spanish and UK building cooling demands. If we have a look into the daily cooling demands, presented in Figure 3, we can see that the Spanish building requires significantly more cooling energy when compared with UK building. There are several reasons for this. First, Spanish current standard is less strict in comparison with the UK standard. Second one is that hot Mediterranean climate by itself involves higher cooling demand through the higher level of solar heat gains and higher outdoor temperature. Higher outdoor temperature also affects usage of a free cooling which is in the Spain much lower. Bars on the right side of the graph in Figure 3 show the maximum cooling load which is the starting point in sizing the cooling plant. It can be seen that the cooling plant in Spain has to be up to 50% higher compared with the cooling plant in the UK.

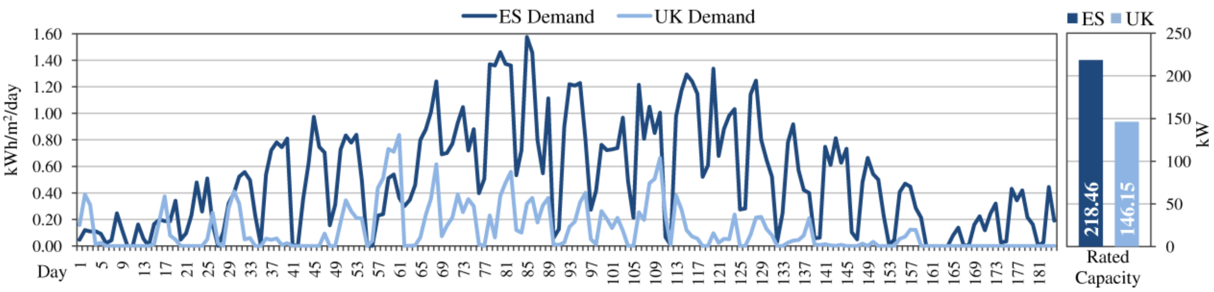



Figure 3. Daily cooling demands

The main objective of this paper is to discuss the advantages of different absorption chillers configurations for the two case studies. We defined four different scenarios which show how the cooling energy can be generated and delivered to the system. Scenario 1, which is the base case scenario, considers only one absorption chiller which can cover the whole system cooling demand. In the Scenario 2, two equally sized chillers operate in parallel. When the demand exceeds the capacity of the first, the both chillers start operating with equally divided cooling load. Scenario 3 uses two unequally sized chillers, one larger (approximately 2/3 of the cooling demand in the case of Spanish building, and 3/4 in the case of UK building) and one smaller (1/3 and 1/4 of the cooling demand, respectively for two case studies). When the demand exceeds the capacity of the first, second chiller starts to operate and cooling load is divided proportionally to the chillers size. Scenario 4 uses the same chillers from third scenario when they operate sequentially. If the demand is less than the small chiller capacity, only the small chiller runs. If it is higher, but less than the large chiller capacity, only the larger chiller runs. Otherwise, the both chillers are in operation with cooling load divided proportionally to their size. The analysis is only focused on the chillers heat energy demand. Therefore, energy consumption of auxiliary equipment is not included.

The simulation outputs for the base case scenario show that the heat energy consumption is 132.89 kWh/m$^2$/yr for Spanish building and 32.21 kWh/m$^2$/yr for UK building. Figure 4 shows the possibility of achieving energy savings if different scenarios are employed. Spanish case study gives the best results when Scenario 4 is employed. Two unequally sized chillers which work sequentially can save 4.9% of primary energy and also improve COP from 0.698 to 0.734 when compared with the base case. Opposite of Spanish, the UK case study gives the

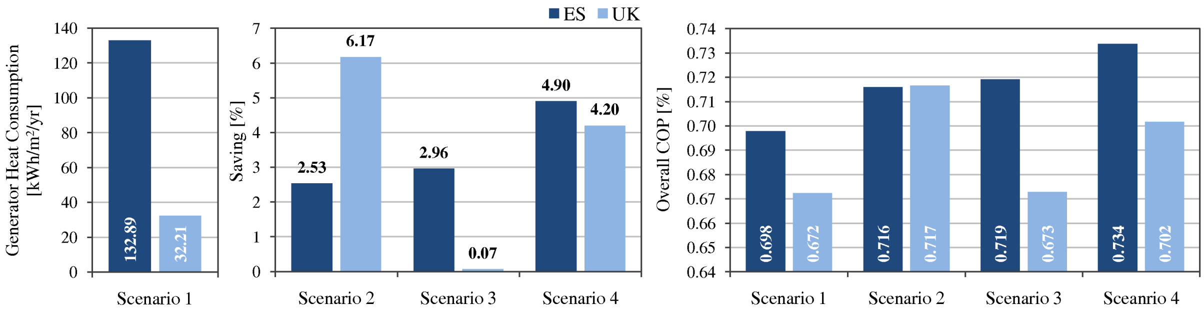



Figure 4. Generator heat consumption, potential savings and overall COP

best results when two equally sized chillers are used. 6.17% of primary energy can be saved while in the same time improves the COP from 0.672 to 0.717.

## DISCUSSIONS

Having identified the potential benefits of using different configurations, it is necessary to discuss different factors which might be very important when choosing the most suitable scenario for chiller plant design. Technical benefits were assessed by comparing the operating time of the chillers and part load ratio distribution with the basic scenario (Scenario 1). The PLR values in Figures 5 and 6 refer to individual chillers. Spanish base case presented in Figure 5 shows that majority of the time chillers operate with lower part loads. For most chillers, the chiller efficiency increases as the load ratio increases from 40% to 90%. When multiple chillers are used, it is clear that part load distribution of each chiller improves. The very high number of hours when chiller operates at low PLR in the Scenario 1 has been shifted to the zone with higher PLR in multiple chillers scenarios. That is particularly obvious in scenarios 2 and 4 where chillers operate most of the time with PLR more than 50%. On the other hand, operating time of the chillers varies. For Scenarios 2 and 3 it is higher than in the base case while Scenario 4 shows very balanced operating mode. Therefore, to optimize the system performance, chiller staging proved to be very efficient option.

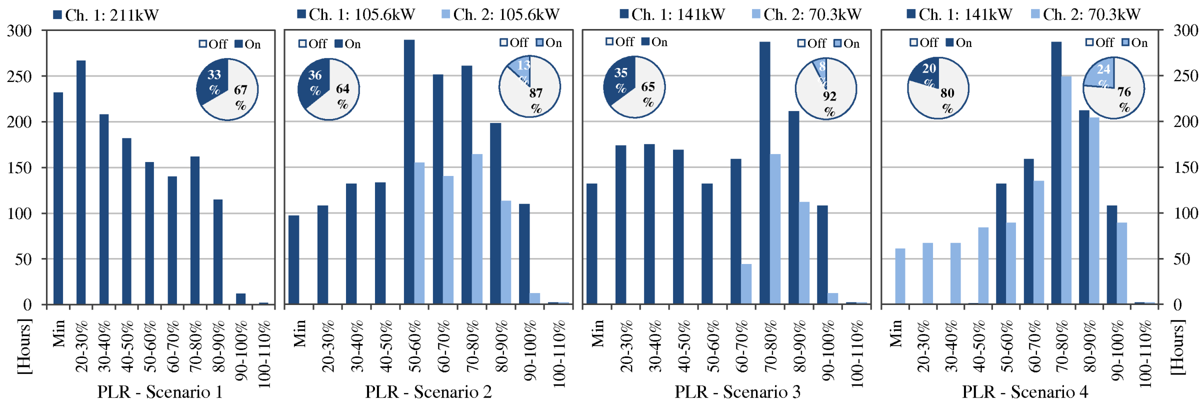



Figure 5. Operating time of the chillers: case study Spain

In moderate climate such as UK, multiple chillers also were confirmed as an advantageous solution. In the terms of energy savings, Scenario 2 gives the best results as mentioned before. The load distribution is better and total number of hours when chillers were in use shows the same trend as in Spain. But, as it can be seen from Figure 6, we still have a significant number of hours when chiller works at lower capacities. Another disadvantage is that auxiliary chiller in scenarios two and three works only 1% and 3% of full operating time. In those terms, Scenario 4 showed the best performance. This leads to a conclusion that the optimum

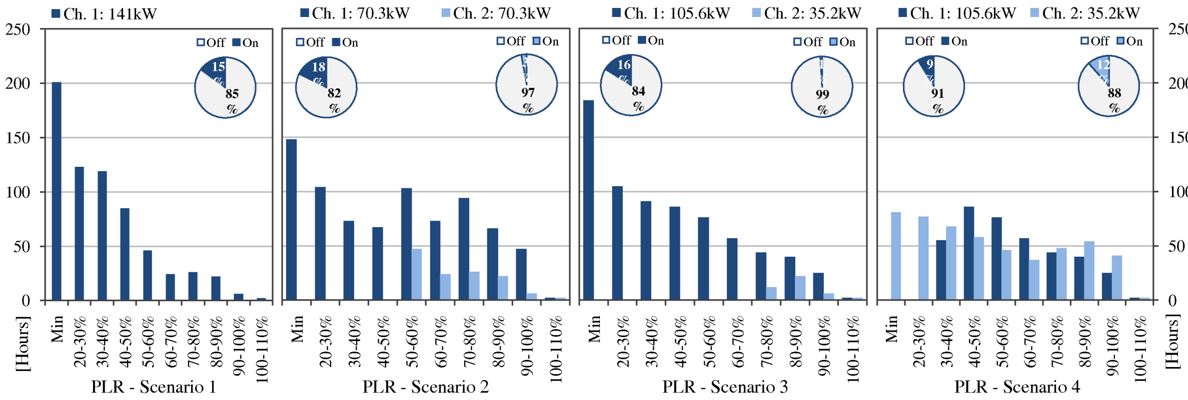



Figure 6. Operating time of the chillers: case study UK

performance can be achieved by choosing smaller capacity units as well as determining the optimal chiller sequencing control.

The overall seasonal performance for each of four scenarios is shown in Figure 7. Shaded areas emphasize overlapping between third and fourth scenarios. For the Spanish case study, Scenario 4 provides the best performance showing balanced behaviour most of the time and having the highest COP at lower PLRs in comparison with other scenarios. For the UK case study Scenario 2 shows the best performance but most of the time second chiller is out of use. In this case, more recommendable would be to employ Scenario 4 which occupies both chillers equally. Although there is no doubt that multiple chillers improve system's performance, it should be noted that chillers still operate a significant amount of time with minimum part loads, including cycling fraction. The on/off regime reduces the chiller efficiency and can make damage to the system. This indicates that chiller sequencing control plays one of the key roles in optimizing the system efficiency together with appropriate chiller plant design. However, these issues exceed the aims of this paper and it has been left for future studies to analyze them.

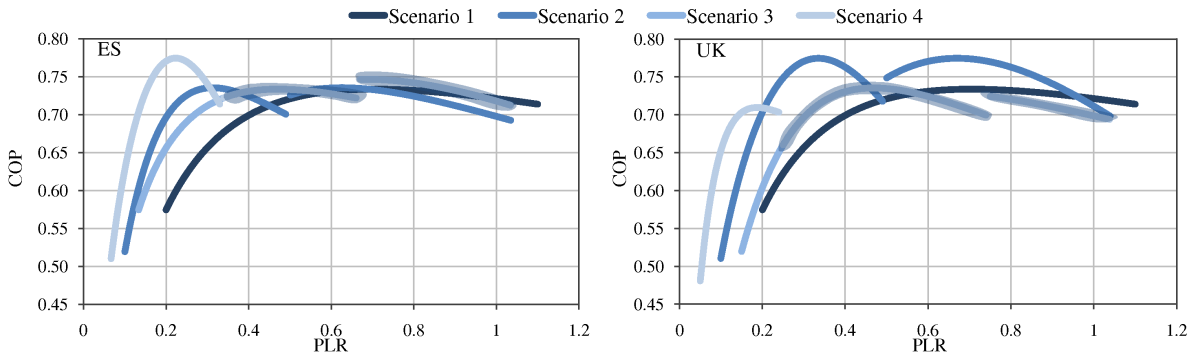



Figure 7. Overall COP vs. system PLR

## CONCLUSIONS

In this paper, some initial findings of the current research about optimal absorption chiller plant configuration are presented. For typical narrow plan office building in two different European climate regions (Spanish and UK case studies) and corresponding building standards, four different scenarios are defined. The base case scenario 1 is single chiller plant which can cover the whole system cooling demand. Scenario 2 uses two equally sized chillers operating in parallel, where one is the lead chiller and the second one is supporting. Third scenario uses two unequally sized chillers, one larger and one smaller where the larger chiller is the lead one. Last scenario has the same chillers from third scenario when they operate sequentially. For all of the 4 scenarios, the absorption chiller energy performance have been simulated in purposely developed MatLab model based on EnergyPlus and BLAST absorption chiller models.

By performing simulations for different scenarios, we have verified that multiple absorption chillers can provide important savings in terms of heat supply to the chillers. It is also important to mention that, due to different cooling demands, the chiller plant in Spain operates more than double time than the chiller plant in the UK. Cooling demand of the Spanish building is more than 4 times higher, but the size of the chiller plant is only 50% bigger. From technical point of view, it is very reasonable to install two chillers in a chiller plant instead of one to provide better efficiency. This is because the operating conditions are more stable at higher part load ratios leading to higher COPs. However, in the case of the UK climate, this can lead to the second chiller operating only 3% of total time, which is quite low. However, this can be overridden by implementing advance control strategies. The appropriate control strategies, plant design as well as techno-economical aspects of different solutions will be the topics of future research. The final aim is a complete performance and economical map which could help engineers to design high efficient absorption chiller plants.

**ACKNOWLEDGEMENT**
The authors would like to acknowledge financial support of this work which forms part of the CITYNET project funded via the Marie Curie Research Training Network.

**REFERENCES**

ASHRAE 2007. Handbook-HVAC Applications (SI), American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.

BLAST 3.0 Users Manual. 1999. Building Systems Laboratory. Urbana-Champaign: Building Systems Laboratory, Department of Mechanical and Industrial Engineering, University of Illinois.

CIBSE 2006. Guide A: Environmental design, Chartered Institution of Building Services Engineers, London, UK.

Chang Y.C., Lin J.K. and Chuang M.H. 2005. Optimal chiller loading by genetic algorithm for reducing energy consumption. Energy and Buildings, 37(2), pp. 47–155.

Chang Y.C., Lee C.Y., Chen C.R., Chou C.J. and Chen W.H. 2008. Evolution strategy based optimal chiller loading for saving energy. Energy Conversion and Management, 50(1), pp. 132–139.

Documento Basico 2009. HE1: Limitacion de demanda energetica, Código Técnico de la Edificación aprobados por el Real Decreto 314/2006 y el Real Decreto 1371/2007, (BOE 23-abril-2009), Ministerio de vivienda, Spain.

ECG019 2003. Energy Efficiency-Best Practice Programme – Energy Consumption Guide 019: Energy Use in Offices, Carbon Trust.

Landman W. 1996. Off-design chiller performance. Trane Eng. Newslett, 25.

Lee W.L. and Lee S.H. 2007. Developing a simplified model for evaluating chiller-system configurations. Applied Energy, 84(3), pp. 290-306.

Maidment G.G. and Tozer R.M. 2002. Combined cooling heat and power in supermarkets. Applied Thermal Engineering, 22(6), pp. 653–665

The Building Regulations 2006. Approved document L2: Conservation of fuel and power, Office of the Deputy Prime Minister, UK.

Yu F.W. and Chan K.T. 2007. Strategy for designing more energy efficient chiller plants serving air-conditioned buildings. Building and Environment, 42(10), pp. 3737-3746.