Conference Proceedings

EuroSun 2014
Aix-les-Bains (France), 16 - 19 September 2014

Towards Intelligent Operation of Data Centres Integrating Renewables and Smart Energy Systems

Eduard Oró, Ioannis Dafnomilis, Albert Garcia and Jaume Salom

Catalonia Institute for Energy Research, IREC. Jardins de les Dones de Negre 1, 08930, Sant Adrià de Besòs - Barcelona (Spain)

Summary

The significant increase in the energy consumed by data centres has recently been driving the efforts for the implementation of energy efficiency measures and the use of renewable energy sources. Due to their unique nature, data centres are demanding enormous amounts of energy and therefore they are ideal candidates for implementing actions to reduce the energy consumption and thus improve their ecological footprint while at the same time reducing their operational costs. The aim of this work is to analyse the operational conditions of a medium size data centre using a developed TRNSYS model in order to identify potential for improving their energy performance and operational costs. This work also studies the potential of implementation of an on-site generation system, represented by a roof-mounted photovoltaic (PV) system. The results of this parametric analysis highlight the important features that need to be considered when optimizing the operation of air-cooled data centres, especially the trade-off between inlet air supply and chilled water temperature.

Keywords: Data centre, energy efficiency, energy modelling, CO_2 emissions, renewable energy.

1. Introduction

The depletion of the world reserves of fossil fuels, the global warming effect caused by their use and the increasing energy costs are driving the interest of firstly the utilization of energy efficiency strategies to decrease the overall energy demand and secondly the implementation of renewable energy technologies into many applications. Data centres which according to recent data account for almost 2% of the worldwide energy consumption and still growing (Koomey, 2011), are a prime target for implementing these measures. Moreover, due to the nature of their function, their need for performance, reliability and security of networking, computation and data storage, they are required to run continuously, 24 hours a day the 365 days a year, transforming them into a high energy demand infrastructures. Therefore, as servers' consumption (and the associated heat dissipation and cooling costs) continues to rise, there is greater interest by the industry to limit the consumption of this sector. The industry seems to have taken consciousness of the need of using energy efficiency techniques and incorporating renewable energy in data centres (Google Inc., 2014; Apple Inc., 2014), not only to show their environmental commitment, but also to reduce the weight of energy in their operational costs. Energy efficiency measures include all strategies which allow reducing the overall energy used to operate a data centre. In the last years several works either from the industry or from researchers have been published presenting best practices and techniques for energy savings (Vakiloroaya et al., 2014; Lee and Chen, 2013). These measures can be directed towards:

- Advanced technical concepts for efficient Information Technology (IT) management. The aim is to reduce the electricity demand from the IT equipment due to higher performance ratios such as the use of mechanisms to eliminate idle power waste in servers (Meisner et al., 2009) or their optimization using virtualization and consolidation (Goiri et al. 2012).
- Advanced technical concepts for efficient electric power distribution. The aim is to reduce the electric losses in power distribution such as the implementation of direct current distribution (Ton and Fortenbery, 2008) or the use of highly efficient power elements as Uninterrupted Power Systems (UPS) and Power Distribution Units (PDU).

Selection and/or peer review under responsibility of EuroSun2014 Scientific Committee
doi:10.18086/eurosun.2014.04.02 Available at http://proceedings.ises.org

- Advanced technical concepts for efficient cooling system. The aim is to enhance the efficiency of the cooling generation and distribution. Many strategies such as free cooling (Zhang et al., 2014), hot and cold aisle containment or increasing allowable IT temperatures are already being used by the industry (ASHRAE datacom series, 2009).

The goal of this paper is to study different cooling management strategies such as increasing IT room inlet air temperature, increasing chilled water temperature and variability of the temperature difference between IT room inlet air temperature and chilled water temperature. To do so, a dynamic energy model is developed using TRNSYS (Trnsys, 2014) which would estimate the consumed cooling and electrical power depending on the previous described operational conditions. Moreover, the potential use of on-site renewable energy generation represented by a photovoltaic (PV) system is also under study.

2. Methodology

a. *Thermal guidelines for data centres*

Data centres have traditionally had very controlled environments due to its singularity. In its thermal guidelines for data processing environments, the ASHRAE (ASHRAE whitepaper, 2011) provides suitable environmental conditions for electronic equipment. Figure 1a shows the temperatures and relative humidity (HR) recommended by the ASHRAE for all equipment classes. These values refer to the air inlet conditions in the IT equipment. A bad control of humidity ranges can put at risk the reliability of the computing equipment. Very high humidity can cause water vapour to condensate on the equipment, while very low humidity can cause electrostatic discharges. In the present work, the inlet air conditions are restricted to a dry bulb temperature between 18ºC and 27ºC and HR between 43.8% and 60%. Besides temperature and humidity, air pollution could also cause failures in IT equipment. It is well known that moisture is necessary for metals to corrode but pollution aggravates it. Therefore, when operating in polluted locations, data centre operators shall undertake contamination avoidance measures. In this sense, the ASHRAE (ASHRAE whitepaper, 2009) provides guidelines to control the gaseous and particle contaminations in these infrastructures.

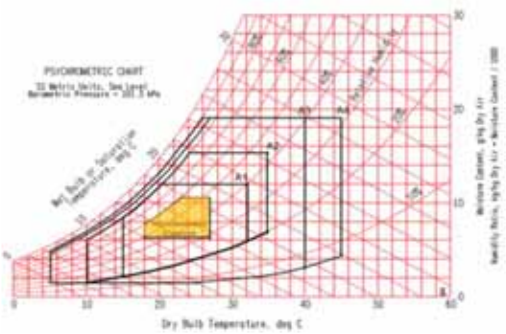

Fig. 1a: ASHRAE thermal guides for data centre operating environments.

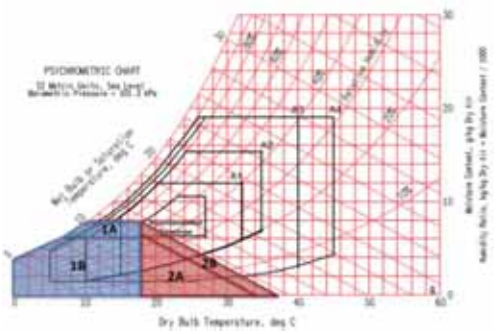

Fig. 1b: Conditions for outside air to be used for direct air free cooling.

b. *Geographical location of the data centre*

The location of the infrastructure can affect the energy demand of a data centre (Depoorter, 2015). Therefore, this study also evaluates different data centre location. Three sample cities (Barcelona, London and Stockholm) were chosen to represent different geographical and climate conditions (southern, central and northern Europe). Table 1 gives an overview on the reference locations. The Meteonorm weather files (Meteornom, 2014) were used for the potential evaluation in each city.

Location	Country	Latitude	Climate zone
Barcelona	Spain	41º 24’ N	Mediterranean climate
London	UK	51º 32’ N	Temperate oceanic climate
Stockholm	Sweden	59º 17’ N	Humid continental climate

Table 1. Geographical and climate characteristics of the selected cities.

c. Data centre characteristics

A fictional medium size data centre is used as the baseline for the present study. The total area of 1,375 m^2 with 500 m^2 of useful area of the IT room. The data centre consists of high density servers (20%), normal density and storage servers (50%), and networking (30%) resulting in an IT load of 1125 kW. Figure 2 shows schematically the main components from the main grid connexion to the IT equipment of the data centre.

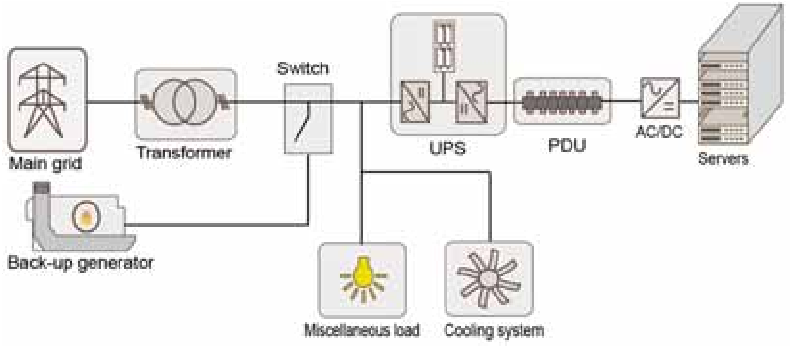

Fig. 2: Scheme of the main components of the data centre.

The IT room is distributed in a hot and cold aisles containment configuration and thus no mixing occurs. The cooling system responsible for removing the heat from the IT room consists of a vapour compression air cooled chiller with the support of a direct air free cooling system as it can be seen in Figure 3. The refrigeration system provides chilled water with a temperature gradient between 10 and 16 ºC to the computer room air handler (CRAH) units. The use of direct free cooling allows cooling the IT room when the outdoor air conditions are acceptable, avoiding part of the energy consumption of the conventional refrigeration system.

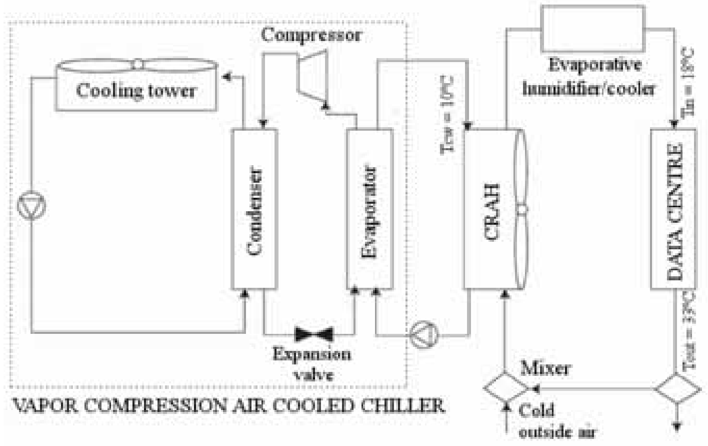

Fig. 3: Cooling system of the data centre in the free cooling scenario.

d. Operational requirements

When exterior conditions satisfy the environment control conditions of the data centre, the system introduces the outdoor cool air to remove the heat from the servers instead of running the cooling plant. In order to keep the inlet temperature at the desired set point during free cooling operation, the system uses a damper that mixes the hot return air and the outside air in the proper proportions. This system as uses outside air always needs filters to avoid pollution of the computing equipment by dust, particles or other gaseous contaminants. In addition, through a low energy humidification process, it is possible to use hot dry air from outdoor to cool the IT room. Figure 1b provides insight into the functioning of the cooling system according to the outdoor air conditions. When the outside air is neither in zone 1 nor zone 2, return air from the IT room is cooled directly by the chiller and the inlet temperature is controlled by regulating the chilled water flow rate passing throw the cooling coil of the CRAH. In that case, as no significant moisture sources are present in IT rooms, neither humidification nor dehumidification are required. Otherwise, when outdoor conditions are favourable, the cooling plant is stopped and the direct free cooling system is activated. It is important to note that, as an evaporative cooler is used, humidification process will always follow the equienthalpy lines of the psychometric diagram. Given this point and the fact that there is no dehumidification, outdoor favourable conditions for economizer cycle are represented by the zones 1A, 1B, 2A and 2B of the Figure 4. When the outdoor air is located within the zone 1A, inlet air conditions can be met only by mixing return air with outside air, without humidification. Instead, when mixing return air with outdoor air from zone 1B, air would be too dry, making humidification necessary after mixing. In the case of the zone 2A, as the enthalpy is too low, some mixing is also required before humidification. Finally, when air is within the zone 2B, only humidification is necessary.

e. Dynamic energy model description

An energy model using TRNSYS was developed to estimate the energy consumption and the PV power generation in the facility. The simulation is based on a component-by-component approach, in which the power use of each component of the infrastructure is related to its utilization. The structure of the model is represented in Figure 4. The rated capacity of the refrigeration units was sized according a redundancy of the equipment of N+1. N is here the number of equipment needed to cover the nominal capacity of the infrastructure. Moreover, the EER of the chiller (4 units) is assumed to correspond at 100% of load and varies according to the ambient temperature. The IT room was modelled with the Type 56 and the cooling system consists of main components including chillers (type 655), pumps (type 114), crahs (type 508c), buffers (type 531) and pipes (type 31) which are available in the TRNSYS library. Those components were connected according to the system configuration shown in Figure 5. The sizes and efficiencies of these mechanical system components were based on a combination of manufacturer design guidelines, fundamental HVAC sizing equations and the authors own experience. In order to follow a consistent pattern for the comparison between locations, the building envelope was considered to be highly insulated and thus thermal exchanges with the outside were neglected. The control sequence allowing switching between the different cooling modes described before according to the outdoor environmental conditions is shown in the flowchart of the Figure 6.

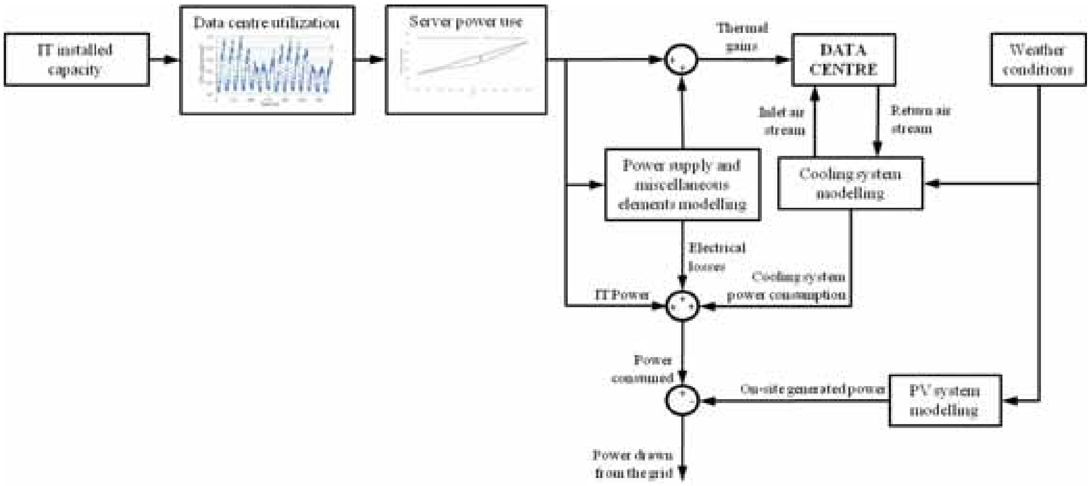

Fig. 4: Structure of the TRNSYS model developed.

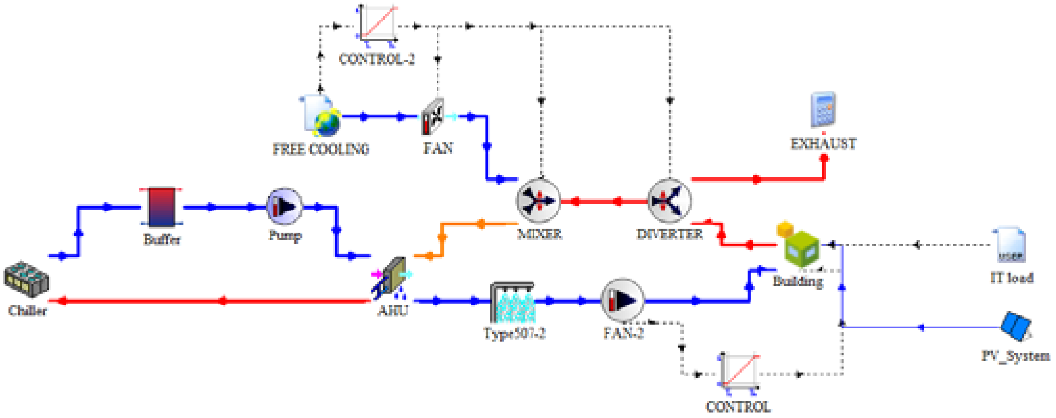

Fig. 5: Scheme diagram of the energy model for the data centre.

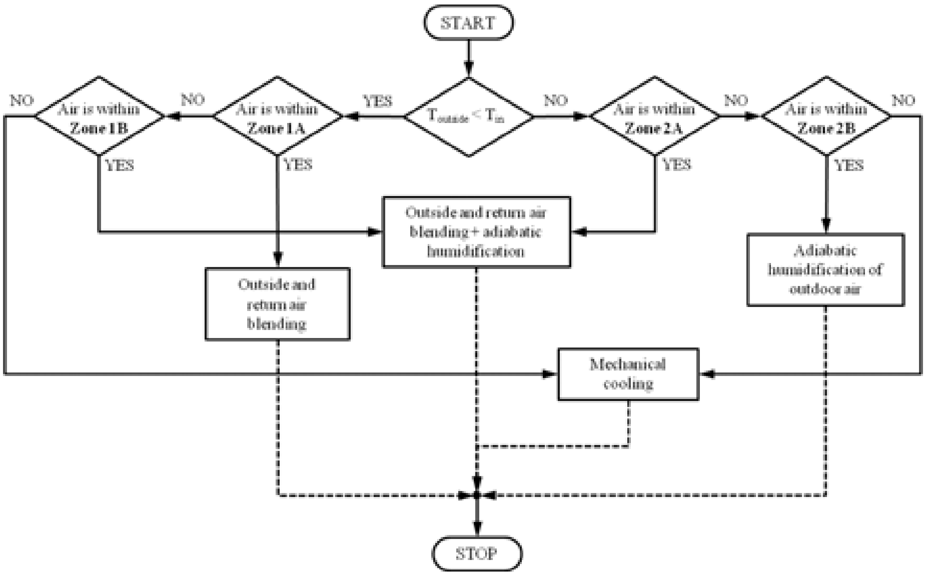

Fig. 6: Control flowchart for the direct air free cooling system proposed.

A homogeneous cluster and a perfect load balancing were assumed for this model. The model relates total data centre power draw to aggregate its utilization. Utilization varies from 0 to 1, with 1 representing the peak compute capacity of the infrastructure. Figure 7 shows the IT utilization profile for web workload applications which was used in this case and was presented by Macías and Guitart (2014). It can be observed that major differences exist between day and night workloads and between working days and weekends. Moreover, servers precise relationships between utilization and power draw varies significantly (near constant to quadratic), but they generally starts from a fixed idle power and power grows with utilization until peak load. For this study this relationship was assumed to be linear, similar to what is done in the European project RenewIT (Oró et al. 2014). The total power use of the data centre is the sum of the electrical power demand of the IT equipment, the power supply systems, the miscellaneous loads and the cooling system. The power use of the cooling system is simulated according to the thermal load and the outdoor air conditions. The thermal gains to be removed by the cooling system are the sum of the heats generated by the IT equipment and the power and cooling equipment within the data centre (UPS, PDU, artificial lighting, fans, etc.). The efficiency of many electrical components decreases significantly when used below equipment design rating. For this reason, losses in power conditioning and supply elements and miscellaneous loads were modelled taking into account the effect of partial load (Rasmussen, 2011).

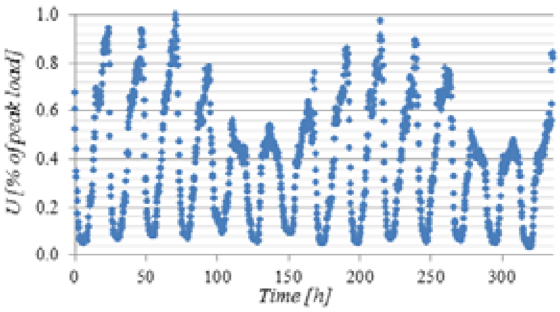

Fig. 7: Data centre utilization expressed as percentage of peak computing load.

3. Results

a. *On-site renewable energy integration*

A PV system was simulated using well known TRNSYS models to allow the estimation of the generated power over the year depending on the location. As the power consumption of the cooling system and the power generation of the PV system are affected by climate environments, differences between the selected locations could be assessed. Notice that for the study, 80% of the rooftop area is supposed to be available for mounting the solar panels which are optimally inclined to maximize their production throughout the year while the rest is for auxiliary systems. It can be observed from the results that the PV power generation has a small impact on the energy balance of the data centre, covering only less than 2% of its total consumption in the best case scenario, being this Barcelona. This is understandable considering that data centres require high energy demand, while the PV systems have low energy intensity. As expected, major differences are observed for the PV production depending on the selected location, what demonstrates that the place could severely affect the electricity balance for data centres with greater space availability. Because of this low potential application, the importance to undertake important energy efficiency measures in data centres and reduce their consumption are essential before implementing any renewable energy source (RES). This is demonstrated in Figure 8, where the percentage of RES and the cooling energy consumption for two different scenarios is represented. The baseline scenario is a typical data centre cooling configuration with mechanical cooling (chilled water and inlet air at 10 and 18 ºC, respectively) while the energy efficient scenario is considering air direct free cooling and modifying the chilled water and air working temperatures (16 and 27 ºC, respectively). Notice that only the cooling energy consumption is considered in order to clearly show the importance of applying energy efficiency strategies. The results show that when the energy consumption is reduced adopting energy efficiency measures, the implementation of RES takes importance in the overall cooling consumption reaching values above 30%.

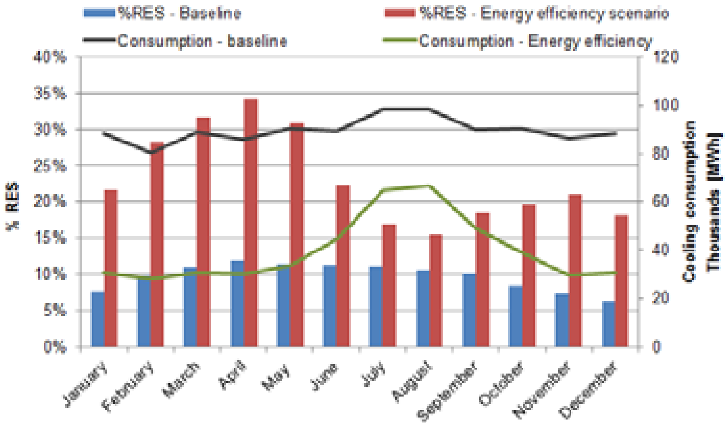

Fig. 8: Percentage of the renewable energy source used in cooling consumption (location: Barcelona).

b. Cooling management strategies

A parametric study using the energy model described before was performed. The energy modelling allowed the estimation of the energy use of the infrastructure in each location when certain operational parameters are modified. Based on simulation results, the effects of the different management strategies can be examined. Three different scenarios have been analysed:

- The IT room air inlet temperature is increased.
- The chilled water temperature from the chiller unit is increased.
- The optimal operational point.

Notice that all the scenario have been evaluated with and without direct air free cooling strategy to evaluate its effect on the mechanical cooling. The ASHRAE thermal guidelines (ASHRAE whitepaper, 2011) set the maximum server temperature rise to 20 ºC when operating with good air flow management, while a recent literature review (Ebrahimi et al. 2014) fixes this parameter at a range between 10 and 20 ºC. Thus, a temperature rise of 15 ºC is considered for the parametric study. The parametric study does not take into account the PV system in the portfolio of the data centre in order to compare solely the cooling system.

IT room air inlet temperature rise

Increasing the IT room supply temperature has been suggested as the easiest and most direct way to save energy in data centres. However, as Patterson (2010) noted, just implementing a higher inlet air temperature while still relying solely on mechanical cooling, may not improve the efficiency of the cooling system. That conclusion is confirmed from the results of the simulation, where an increase in the air inlet temperature has negligible results in the cooling energy savings of the infrastructure. Increasing the inlet air temperature from 18 ºC to 27 ºC and maintaining constant the chilled water temperature at 10ºC, a cooling energy reduction of only 3% was observed. Since the total heat that has to be removed from the IT room is the same and the temperature difference between air inlet and outlet is kept constant at 15 ºC then the volume flow is also constant, thus the fans does not experience less consumption. On the other hand, the chiller water pump operation is highly affected for this measure reducing its energy consumption drastically but it does not affect at the overall picture since its consumption is not significant. Alternatively, when direct air free cooling is implemented into the refrigeration system, the increase of the air inlet room temperature does have an important effect on the cooling energy reduction. Even though the use of direct air free cooling requires additional infrastructure (fan and humidification) and thus additional electricity consumption, the chiller is not running for many hours and therefore the overall energy consumption is being reduced. Indeed, as is shown in Figure 9, implementing a supply air temperature increase while operating under free cooling has a substantial effect on energy savings, leading to a 25-30% decrease in all locations, enabling the energy saving from 120 to 200 MWhe per year of operation. Breaking down the consumption in the different cooling components (chiller, fun, water pump and humidifier) as is depicted in Figure 10; it is clear that implementing this strategy allows the decrease of the chiller consumption; however at inlet temperatures above 24 ºC the energy reduction slope is drastically reduced. This phenomenon occurs because when increasing the inlet air temperature above 24 ºC the free cooling hours do not increase significantly in the locations analysed. Moreover, the EER of the chiller energy efficiency ratio decreases as the ambient temperature increases.

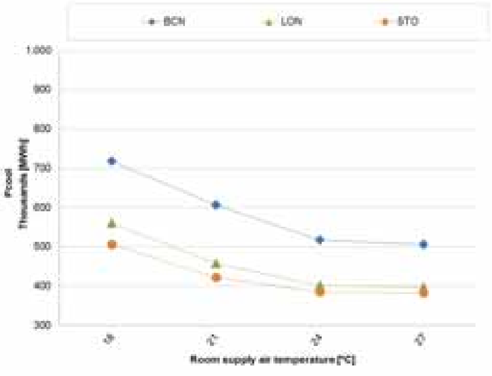

Fig. 9: IT room air inlet increase effect on cooling power when using air free cooling operation (chilled water temperature set at 10ºC).

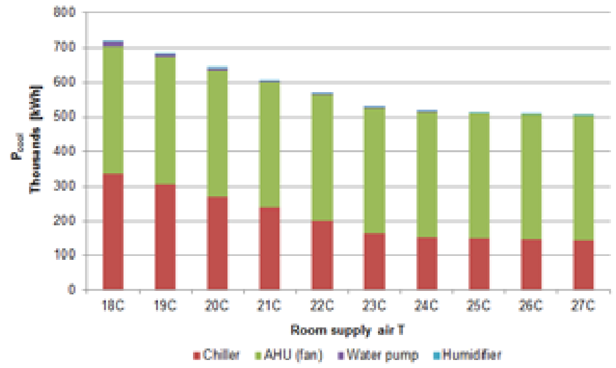

Fig. 10: Cooling power consumption when using air free cooling strategy (location: Barcelona).

- *Chilled water temperature rise*

In this scenario the authors wanted to study the effect on the energy consumption of the infrastructure when the chilled water temperature is raised from 10 to 16 ºC while the air supplied temperature is kept at 18ºC (the water temperature range is selected following ASHRAE and chiller manufacturer recommendations). Notice that in this case, the air inlet temperature is maintained constant while increasing the water temperature and therefore the heat transfer between the water and the air decreases and thus the water flow rate has to be increased in order to supply the same amount of cold to the IT room. As expected, the results show a significant increase in cooling power consumption across all locations (from 15 to 26 %) due to an increase of the water pumps consumption even under air free cooling operation (Figure 11).

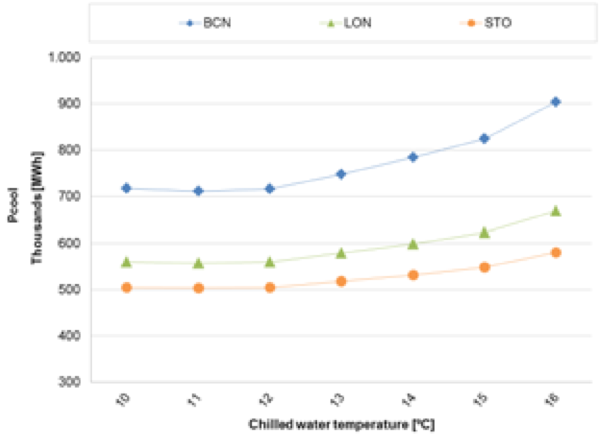

Fig. 11: Chilled water increase effect on cooling power when using air free cooling strategy (air inlet temperature set at 18 ºC).

- *Optimal operational point*

As highlighted before, the strategy of increasing the IT room air inlet or the chilled water temperature alone is not translated to energy savings when operating with solely mechanical cooling. This section aims to study the optimal operational point between both strategies. The air inlet temperature can be increased from 18 to 27 ºC while the chilled water temperature can be raised from 10 to 16 ºC. Both of them where increased with a temperature step of 1 ºC while the temperature difference between the inlet and outlet IT room air was kept constant. According to the recent data centre industry survey (Uptime Institute, 2014), nearly half (47%) of all data centres reported operating between 21 and 24 ºC. Then next largest temperature segment, from 18 to 21 ºC, was 37% of data centres. The most noticeable one is the percentage of infrastructures operating at temperatures higher than 24 ºC which accounted for 7%. The others 6% still are running below 18 ºC. Even the study has been done for an IT room temperature range between 18 and 27 ºC, the results are presented in a shorter range: 18 to 24 ºC, which are usually common set point temperatures in the real data centres.

The results, which contemplates direct air free cooling, are compared to a reference case without air free cooling strategy and with a chilled water and air inlet temperature of 10 and 18 ºC, respectively. Fig. 12, Fig. 13 and Fig. 14 show parametrically the cooling consumption in function of the management strategy adopted. It is important to highlight that a bad working mode represents an increasing of the energy consumption. On the other hand, if proper cooling management is proposed important energy savings are achieved. The optimal operational configuration is obtained when the chilled water temperature is between 7 and 8 ºC lower than the IT air inlet temperature. Notice that if this difference is smaller the cooling consumption starts to increase. As expected, higher total energy savings are achieved at higher air inlet temperatures either with mechanical cooling solely or air free cooling strategy. The energy saving in the cooling system comes from a reduction of the energy consumption of the main components (chiller, fans and water pumps circulation). The results show that the cooling energy demand can be reduced more than 50% when operating with free cooling strategy if proper cooling management is applied while just increasing the air inlet temperature this reduction was between 25 and 30% as is shown in Fig. 8. Therefore, it is demonstrated that with a correct operation cooling management, the energy savings can be increased. Moreover, it is observed that the reduction of the cooling consumption when solely mechanical cooling is higher if proper cooling management is applied in hot climates such as Barcelona. On the other hand, when air free cooling strategy is implemented this reduction is more significant in northern locations.

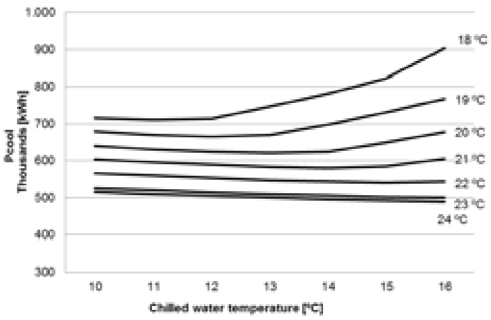

Fig. 12: Power cooling consumption in function of chilled water and air inlet temperatures (location: Barcelona).

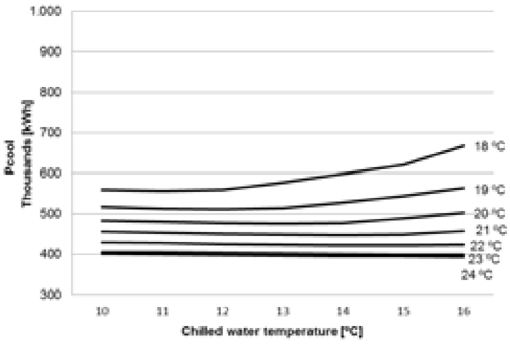

Fig. 13: Power cooling consumption in function of chilled water and air inlet temperatures (location: London).

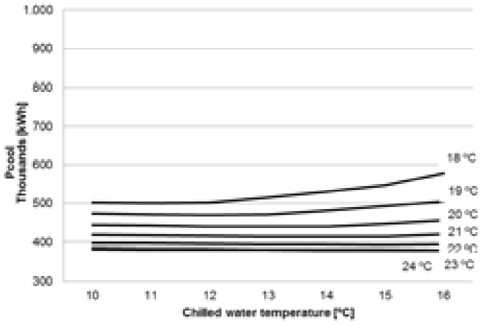

Fig. 14: Power cooling consumption in function of chilled water and air inlet temperatures (location: Stockholm).

These energy savings impact obviously in the PUE value and in the CO_2 emissions which are shown in Fig. 15 and Fig. 16, respectively. Both figures compare for each location the most promising case, obtained with an air inlet temperature of 24ºC and a chilled water temperature of 16ºC when operates with air free cooling, with the baseline. It can be observed that using solely mechanical system the PUE value is similar throughout the year. On the other hand, results indicate that when using air free cooling strategy, the PUE value increase notably in warm/hot locations during summer because of the more hours of chiller operation. The total CO2 emission is greatly influenced by the conversion technologies used to produce the electricity not only seasonal (renewable energy available such as solar, wind or hydro) but daily (when cogeneration and thermal power stations are working to meet the power increase). These results indicate that major differences between regions could be found related to the attributes of the electricity imported from the grid. Actually, a data centre operating only with mechanical cooling could have very similar energy consumption in Stockholm or in London, but it would have associated emissions of 20 tCO_2 instead of 350 tCO_2. This indicates that with only locating the data centre on one site rather than another significant environmental enhancement could be achieved, RenewIT has also been proved this phenomenon (Gavaldà et al. 2014).

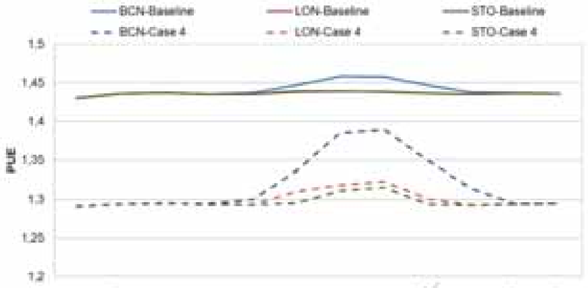

Fig. 15: Monthly PUE values for the 3 selected locations

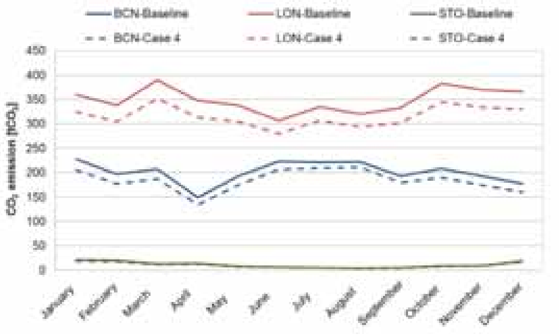

Fig. 16: Monthly CO_2 emission values for the 3 selected locations

4. Conclusions

Due to the high growth on Information Technology (IT) and Internet over the last years, the electricity and cooling demand of data centres has increased dramatically. To reduce the impact of the energy demand of these unique infrastructures, energy efficiency strategies first and the implementation of renewable energy afterwards are policies to be considered. Thus, energy efficiency implementation can not only reduce the electricity used to run IT equipment but also can reduce the energy required to fulfil the cooling demand. The work presented in this paper describes a TRNSYS dynamic model that can be used for exploring optimization possibilities in air cooled data centres which use direct air free cooling. Different cooling management strategies have been analysed at 3 different locations around Europe (Barcelona, London and Stockholm). This study also investigated the potential of implementation of on-site renewable energy generation represented with a photovoltaic (PV) system. Solely PV systems resulted not to be an effective measure to lower neither the imported power from grid neither their associated energy costs. This is mainly due to the fact that data centres are energy intensive facilities and roof mounted PV systems are only able to cover a very little part of their energy consumption (less than 2% in Barcelona, which is the more favourable location for PV generation). Because of this low potential application, the importance to undertake important energy efficiency measures in data centres and reduce their consumption are essential before implementing any renewable energy source.

The results confirm that the only increase of the IT room supply temperature when operating with mechanical cooling has no significant decrease in the energy savings. However when direct air free cooling strategy is operative, the increase in the air inlet temperature leads to a reduction between 25 and 30%, depending on the location of the infrastructure. It is worth to notice that the solely strategy of increasing the chilled water temperature is not recommended because an increase of the overall energy consumption is observed due to much higher water pump consumptions. Alternatively, when both strategies are implemented together important savings can be achieved. The parametric study shows that the appropriated temperature difference between the air inlet and the chilled water temperature is between 7 and 8 ºC. When proper cooling management policies are applied, notable (up to 14% in mechanical cooling systems) and excellent (up to 54% if air free cooling is used) energy savings are obtained. Notice that the implementation of direct air free cooling strategy yields to positive results since it is the major contributor to the differences in cooling power consumption in all the cases, as data centres, especially in London and Stockholm are able to operate with no chiller for far more hours in the year than the ones situated in warmer locations such as Barcelona. Moreover, replacing the fans of the CRAH units with more efficient ones can bring about even greater rates for cooling performance since its consumption accounts for roughly 50% of the total cooling power consumption in most cases in the present work. Finally, the results indicate that the data centre location is an energy efficiency strategy since significant environmental enhancement could be achieved depending on the place.

5. References

Apple Inc., 2014. Apple and the environment. [Online]. Available: https://www.apple.com/environment/renewable-energy/. [Accessed April 2014]

ASHRAE, 2009. Best practices for datacom facility energy efficiency. Second Edition, Atlanta USA.

ASHRAE whitepaper, 2009. Gaseous and particulate contamination guidelines for data centers, Technical Committee (TC) 9.9, ASHRAE.

ASHRAE whitepaper, 2011. Thermal guidelines for data processing environments – expanded data center classes and usage guidance, Technical Committee (TC) 9.9, ASHRAE.

Depoorter, V., Oró, E., Salom, J., 2015. The location as an energy efficiency and renewable energy supply measure for data centres in Europe. Appl Energ. 140, 338-349.

Ebrahimi, K., Jones, G.F., Fleischer, A.S., 2014. A review of state center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. Renew Sust Energ Rev. 31, 622-638.

Flucker, S., Tozer, R., 2011. Data Center Cooling Air Performance Metrics. CIBSE Technical Symposium, DeMontfort University, Leicester.

Gavaldà, O., Depoorter, V., Oppelt, T., van Ginderdeuren, K., 2014. Report of different options for renewable energy supply in Data Centres in Europe. Available: http://www.renewit-project.eu/documents/deliverable/

Goiri, I., Berral, J.L., Fitó, J.O., Juli, F., Nou, R., Guitart, J., Gavaldà, R., Torres, J, 2012. Energy-efficient and multifaceted resource management for profit-driven virtualized data centers. Future Gener Comp Sy. 28, 718-731.

Google Inc., 2014. Renewable energy. [Online]. Available: http://www.google.com/green/energy/. [Accessed April 2014]

Koomey, J., 2011. Growth in data center electricity use 2005 to 2010. Analytics Press, Oakland, CA

Lee, K.P., Chen, H. L., 2013. Analysis of energy saving potential of air-side free cooling for data centers in worldwide climate zones. Energ Building. 64, 103-112.

Macías, M., Guitart, J., 2014. SLA negotiation and enforcement policies for Revenue Maximization and Client Classification in Cloud providers. Future Gener Comp Sy, doi:http://dx.doi.org/10.1016/j.future.2014.03.004.

Meiser, D., Gold, B.T., Wenisch, T.F., 2009. Powernap: eliminating server idle power. In Porceeding of the 14th International conference on architectural support for programming languages and operating systems.

Meteornorm Software version 7.1.1, August 2014. [Online]. Available: http://www.meteonorm.com/. [Accessed August 2014].

Oró, E., Pflugradt, N., Macías, M., Nardi, D., 2014. Energy requirements for IT equipment. Technical report of RenewIT. Available: http://www.renewit-project.eu/documents/deliverable/

Patterson, M., 2010. The Effect of Data Center Temperature on Energy Efficiency. Intel Corporation, USA.

Rasmussen, N., 2011. Electrical efficiency modelling for data centers. Schneider electric, white paper 113.

Ton, F., Fortenbery, B., 2008. DC power for improved data center efficiency. Lawrence Berkley National Laboratory.

Thermal Energy System Specialists, LLC, “Transient System Simulation Tool - TRNSYS,” TESS, August 2014. [Online]. Available: http://www.trnsys.com/. [Accessed August 2014].

Uptime Institute, 2014. 2013 Uptime Institute annual data center industry survey report and full results.

Vakiloroaya, V., Samali, B., Fakhar, A., Pishghadam, K., 2014. A review of different strategies for HVAC energy saving. Energ Con Manage. 77, 738–754.

Zhang, H., Shao, S., Xu, H., Zou, H., Tian, C., 2014. Free cooling of data centers: A review. Renew Sust Energ Rev. 35, 171-182.