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The location as an energy efficiency and renewable energy supply measure for data centres in Europe

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HIGHLIGHTS

- A data centre energy model was developed using TRNSYS.
- The potential of direct air free cooling integration was evaluated around Europe.
- A set of energy indicators describing the operation of data centres were defined.
- The location of a data centre could significantly affect its operation and impact.
- Smart management of the IT load can reduce energy consumption and CO_2 emission.

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ABSTRACT

The massive data centre energy consumption has motivated significant efforts to use energy efficiency strategies and the implementation of renewable energy sources that reduce their operational costs and environmental impact. Considering that the potential of many of these measures is often closely linked to the climate conditions, the location of data centres can have a major impact on their energy demand. Moreover, from a holistic approach, differences among regions become even more important when accounting for the electricity attributes from the grid. To assess these differences this work compares by the use of energy indicators the behaviour of a data centre located at different representative emplacements in Europe. To do so, a dynamic energy model which incorporates free cooling strategy and photovoltaic energy is developed. The paper concludes by suggesting that future data centre developments could consider site selection as a new strategy to limit the environmental impact attributable to this sector.

1. Introduction

During the last decade, the information technologies (IT) sector has experienced a strong increase of cloud computing and high performance computing and a vast growth of the Internet use. To meet this demand, the number of data centres expanded rapidly. Considering the aforementioned phenomenon and the fact that they are working 24 h a day the 365 days of the year, the energy consumption of these facilities has increased considerably. Actually, world data centre electricity consumption doubled from 2000 to 2005. However, from 2005 to 2010, due to the increased prevalence of virtualization and the implementation of energy efficiency strategies, the growth rate was 56% accounting for about 1.3% of the world electricity consumption [1,2]. The data centre industry has taken consciousness of the need of the implementation of energy efficiency strategies and the use of renewable energy in data centres [3,4], not only to show their environmental commitment, but also to reduce the operational costs.

Energy efficiency measures include many strategies which allow reducing the energy used to operate a data centre. Several works have been published recently about best practices and techniques for energy savings in these facilities [5–7]. These measures can be directed towards reducing the consumption of the IT equipment itself by means of virtualization and consolidation [8], the power supply infrastructure through direct current distribution [9], efficient uninterrupted power systems [10], etc. and especially the cooling system. The industry and researchers have been focused in reducing the cooling demand using the well know techniques as hot and cold aisle containments [7], increase the allowable IT temperatures [11] and air–water side free cooling [12,13]. Currently, one of the most used energy efficiency strategies is so called direct air free cooling technology which uses the cold outside air directly to remove the heat generated inside these

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facilities. Lee and Chen [12] used a dynamic building energy simulation program to examine the potential energy saving of using direct air free cooling in data centres for 17 climate zones. The results showed a significant potential for data centre locations in mixed-humid and warm-marine climate zones. But in the zones with lower dew point temperatures such as very-cold and cold–dry climate zones, the power and water consumed by the humidification system can be important and they should be accounted. In a similar study, Siriwardana et al. [13] investigated the use of direct air free cooling in different Australian climate conditions. They highlighted that there is a potential use of this strategy in some states that could lead to significant energy saving and thus CO_2 mitigation. The use of district cooling systems [14] to provide more efficient cooling into data centres and the use of cooling roofs [15] to reduce the building energy consumption are other strategies to be investigated.

Once energy efficiency measures are applied, the electricity consumption should ideally come from renewable energy sources. In this sense, companies can follow different strategies to incorporate renewable energies into their overall energy portfolio. They can decide to generate their own renewable energy, either on-site or off-site, or to buy it to a third body through different legal instruments (electricity tracking certificates, power purchase agreements, etc.) as Fig. 1 shows [5]. Even though the use of on-site renewable energy into real data centres is still in the early stage, some companies have been implemented different green energy solutions in their portfolio. Emerson's data centre implemented a 100 kW solar panel in Missouri, Intel has installed a 10 kW of electricity in a data centre in New Mexico and Goiri et al. [16] developed Parasol, a prototype green data centre which comprises a small container, a set of solar panels, an electrical battery blank and a grid-tie. A small data centre in Illinois became the first 100% on-site wind power data centre in the US by switching its daily operations energy needs over to a 500 kW wind turbine [17]. Other on-site renewable energy data centre integration such as combined heat and power [18,19] and fuel cells [20] are under investigation.

The location of an operating data centre significantly affects its energy demand especially if free cooling technology is integrated and its renewable energy supply potential. Moreover, the attributes of the electricity grid by means of the energy mix would affect the CO_2 emissions, the primary energy consumption and the cost of the energy. This issue was studied by Shehabi et al. [21] who quantified how the electricity use and the CO_2 emissions varied for a data centre in several sites in the United States. In this paper, the potential integration of direct air free cooling and the implementation of on-site generation system represented by a roof-mounted photovoltaic (PV) system are evaluated at different European locations. London, Amsterdam and Frankfurt were selected as hotspots for data centre activity and Barcelona and Stockholm were added to incorporate Mediterranean and Nordic climates to the study (Fig. 2). To do so, a dynamic energy model was developed to evaluate the data centre behaviour in an hourly basis. The results of this analysis quantitatively demonstrate how data centre location and direct air free cooling use can influence energy demand and CO_2 emissions among other indicators.

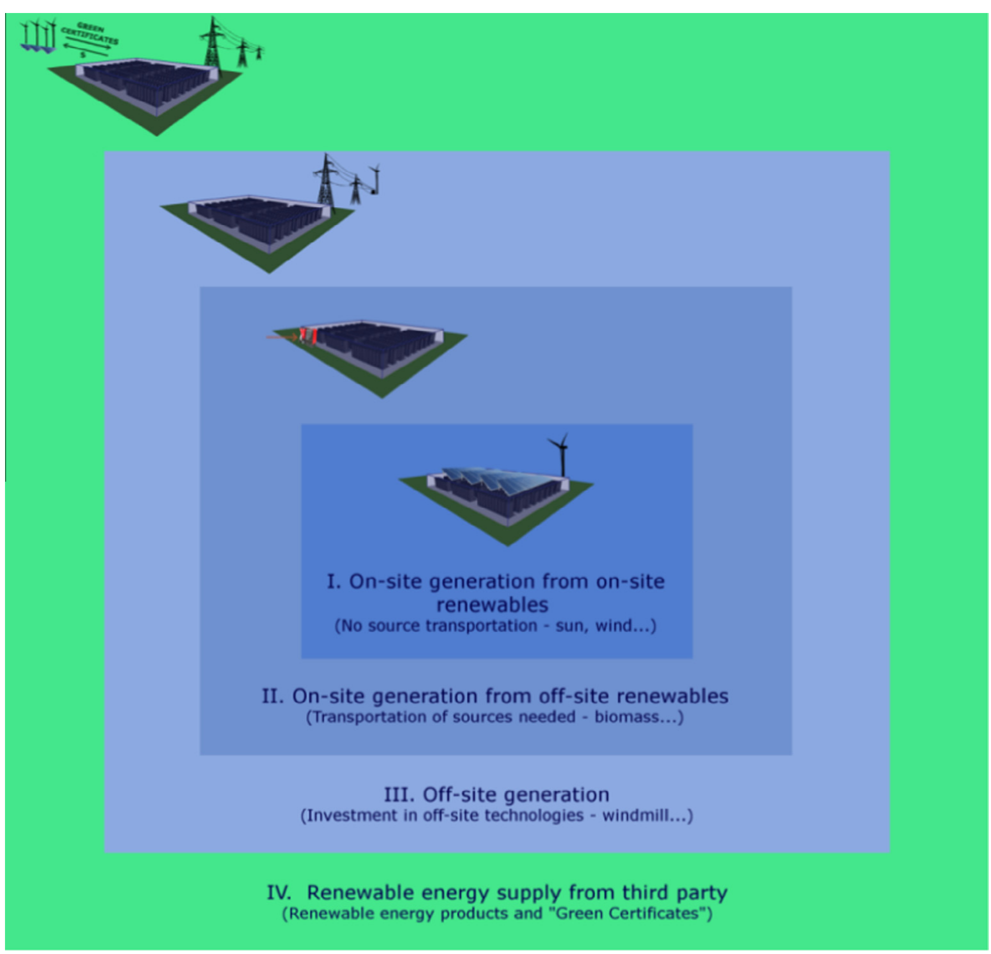

Fig. 1. Overview of possible renewable supply options for data centre industry [5].

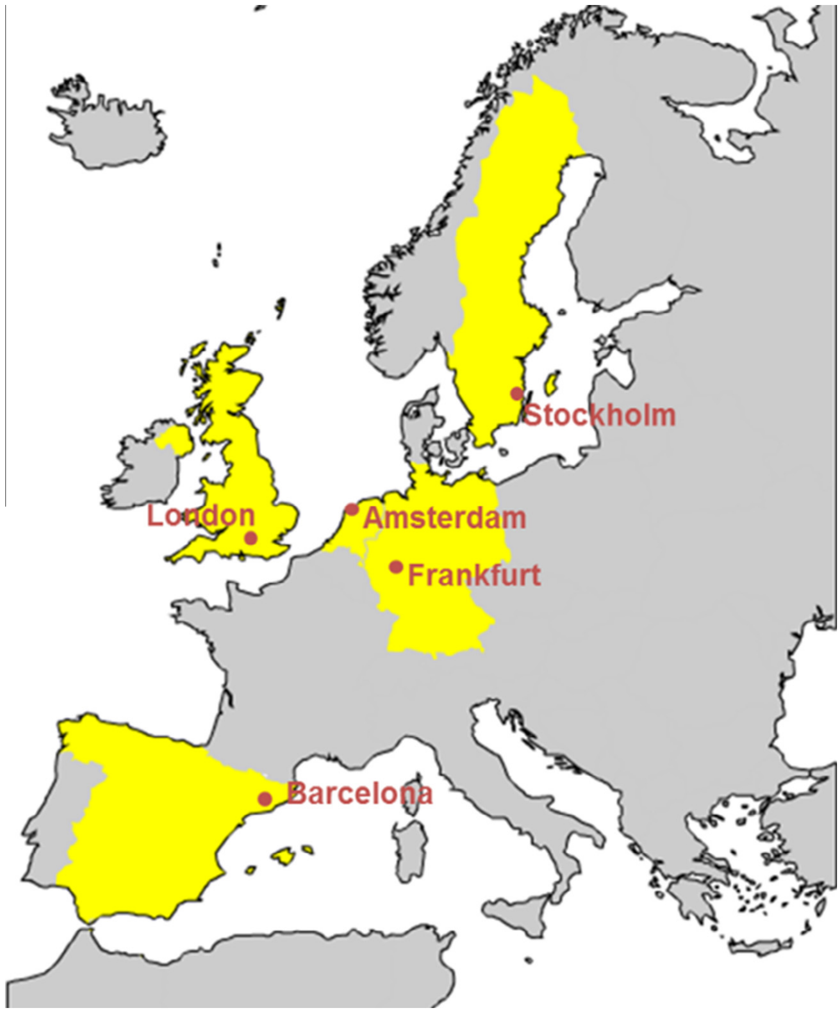

Fig. 2. Representative European cities for data centre activity included in this study.

2. Methodology

2.1. Operational requirements

The ASHRAE thermal guidelines [22] define recommended and allowable temperature and humidity ranges for four environmental classes, two of which are applicable to data centres. The recommended envelope (Table 1) defines the limits under which IT equipment would most reliably operate while still achieving reasonably energy efficient data centre operation. However, it is acceptable to operate outside the recommended envelope for short periods of time without risk of affecting the overall IT equipment reliability. In this study, the supply air temperature is set to 18 °C, which is the lowest inlet air temperature recommended. Additionally, the relative humidity must be between 43.8% and 60% as the Table 1 represents. Moreover, a server temperature rise of 15 °C is considered which is an acceptable value from the state of the art [23].

2.2. Data centre characteristics

A fictional medium size data centre is used as the baseline for the present study. The total area is 1375 m^2 with 500 m^2 as the useful area of the IT room. The data centre consists of high density

Table 1
ASHRAE environmental classes for data centres [22].

Class	Equipment environment specifications			
	Product operation		Product power off	
	Dry-bulb temp. range	Humidity range	Dry-bulb temp. range	Humidity range
Recommended				
A1–A4	18–27 °C	5.5 °C DP to 60% RH and 15 °C DP		
Allowable				
A1	15–32	20–80% RH	5–45	8–80% RH
A2	10–35	20–80% RH	5–45	8–80% RH
A3	5–40	−12 °C DP and 8% RH to 85% RH	5–45	8–80% RH
A4	5–45	−12 °C DP and 8% RH to 90% RH	5–45	8–80% RH

Table 2
Chiller energy efficiency ratio in function of the ambient temperature [24].

Temperature (°C)	0	5	10	15	20	25	30	35	41
EER (kW_c/kW_{el})	5.82	5.49	5.13	4.74	4.34	3.93	3.52	3.12	2.66

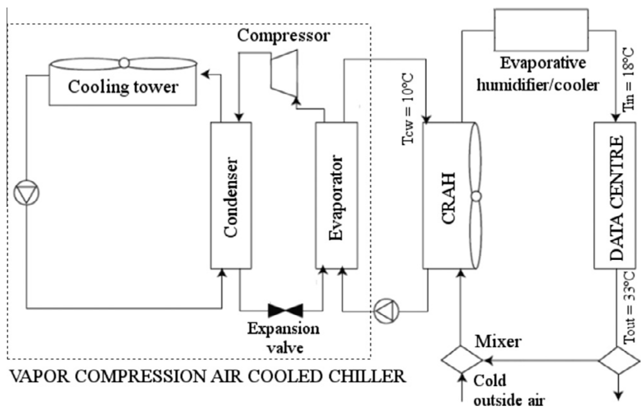

Fig. 3. Cooling system of the data centre in the Economizer scenario.

servers (20%), normal density and storage servers (50%), and networking (30%) resulting in an IT load of 1125 kW. The IT room is distributed in a hot and cold aisles containment configuration and thus no mixing occurs. For the calculation of the cooling load the electrical losses related to power distribution such as uninterrupted power systems, general switchgear, lighting and other miscellaneous loads are included. From an in depth study of the losses, the loads and the electrical and air circulation inefficiencies, the cooling load was estimated to be 1278 kW_{th} [24].

The Baseline scenario is represented by an air cooled vapour compression chiller that provides chilled water with a temperature gradient between 7 and 12 °C to the computer room air handler (CRAH) units. The rated capacity of the refrigeration units was sized according for a TIER III configuration which means 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 (Table 2). The 12 CRAH units placed in the IT room for refrigeration have an average EER of 12.

Fig. 3 shows the cooling system in the Economizer scenario. It consists in a vapour compression air cooled chiller coupled with a direct air free cooling system. Notice that this technology needs filters for the outside air to avoid pollution of the computing equipment by dust, particles or other gaseous contaminants. When exterior conditions satisfy the data centre supply air requirements, outdoor air is introduced into the IT room. In order to keep the inlet temperature at the 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. In addition, through alow energy humidification process, it is possible to use outdoor hot dry air. Fig. 3 provides insight into the cooling system operational mode 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 data centres, neither humidification nor dehumidification are required. Otherwise, when outdoor air conditions are favourable, the chilled water circulating pump is stopped and the free cooling strategy is activated. It is important to note that, as an evaporative cooler is used, humidification process will always follow the equienthalpy line of the psychometric diagram. Outdoor favourable conditions for direct air free cooling are represented by the zones 1A, 1B, 2A and 2B (Fig. 4). First, 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 to reach the inlet

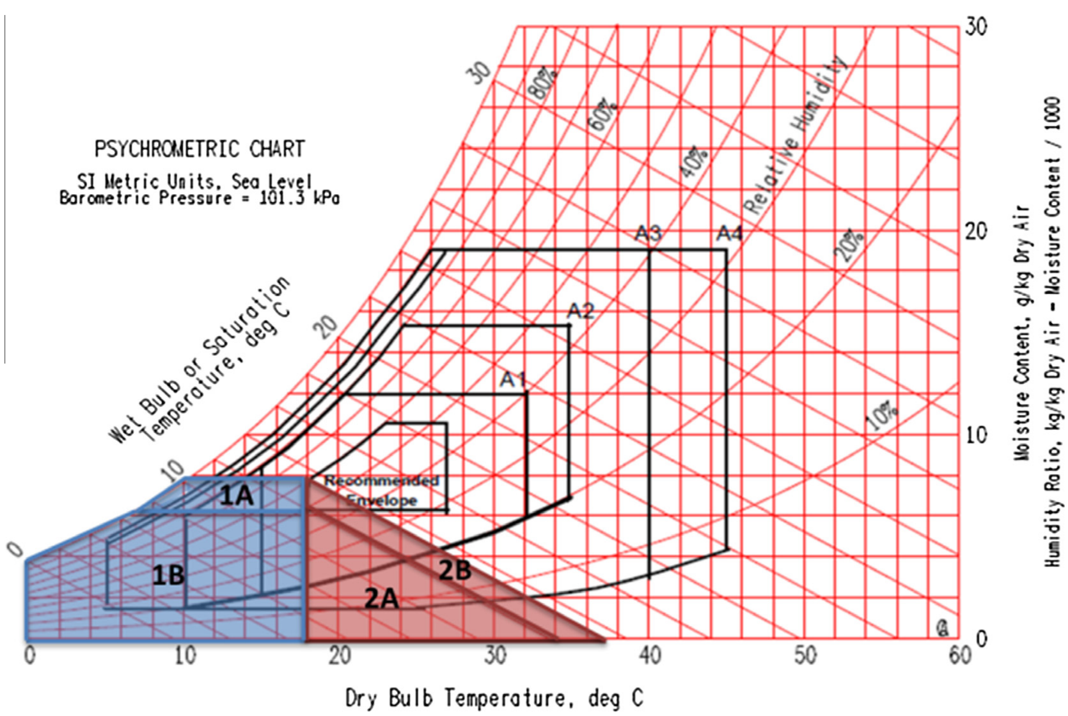

Fig. 4. Conditions for outside air to be used for direct free cooling or evaporative cooling.

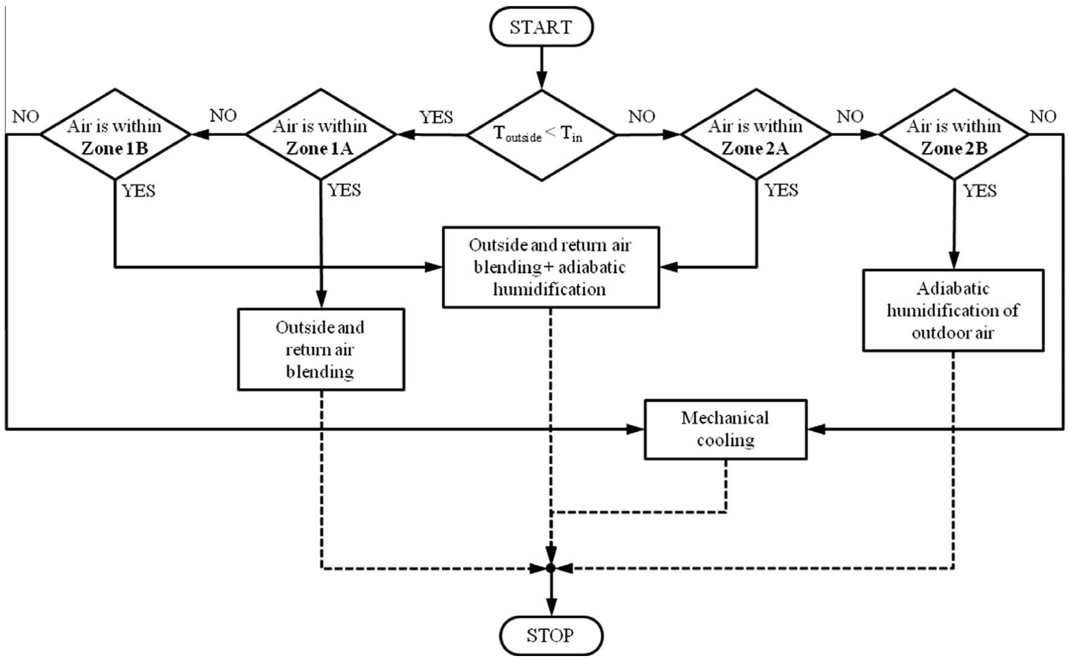

Fig. 5. Control flowchart for the air-side economiser with evaporative cooling.

Table 3
Effective PV area in function of the system location.

Location	Num. PV panels	PV area (m^2)	P_{gen} (MW h_e)	$P_{specific}$ (kW h_e/m^2)
Barcelona (ES)	243	401	104.7	261.1
Amsterdam (NL)	90	149	23.6	158.4
London (UK)	100	165	25.3	153.33
Frankfurt (DE)	118	195	32.3	165.6
Stockholm (SE)	35	58	9.8	168.9

requirements. 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 Fig. 5.

The on-site generation scenario additionally integrates a roof-mounted PV system. It is assumed that the rooftop is as high as there are no shadows on the solar field from the surrounding buildings. Moreover, only 80% of the rooftop area is supposed to be available for mounting the solar panels while the rest is for auxiliary systems, which are optimally inclined to maximize their production throughout the year. As the optimal inclination will vary according to the site, the effective PV array area (Table 3) is calculated to maximize power generation by PV square meter installed considering shadows between rows. The online PVGIS tool [25] has used to calculate optimal inclination for each location. The selected criterion maximizes the return of investment of the PV array in each location. The PV plant is composed of polycrystalline panels FV REC 245Wp [26] with the technical characteristics given in Table 4.

2.3. Energy model description

A dynamic energy model using TRNSYS was developed to estimate the consumed and the PV generated power in the data centre. The simulation is based on a component-by-component approach using well-known and already validated types, in which the power use of each data centre component is related to its utilization. The structure of the model is represented in Fig. 6. The IT room was modelled with the Type 56 and the cooling system with TRNSYS

Table 4
Technical characteristics of the PV panels [26].

Parameter	Value	Unit
Nominal power [P_{MPP}]	245	W
Nominal voltage [V_{MPP}]	30.1	V
Nominal intensity [I_{MPP}]	8.23	A
Open circuit voltage[V_{OC}]	37.1	V
Short circuit intensity [I_{SC}]	8.80	A
Efficiency [ε]	14.8	%
Dimensions	991 × 1665 × 38	mm

Types for HVAC elements. 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 isolated and thus thermal exchanges with the outside were neglected (all the heat gains in the data centre were removed by the cooling system) as usually happens in real data centres integrated into buildings. The PV system was implemented into the model to allow the estimation of the generated power over the year depending on the location.

Components normally are operated below their rated capacity to provide a safety margin, to account for load diversity or they can be operating with other redundant components. This phenomenon can affect the efficiency of many power elements which decreases significantly when used below equipment design rating. While simple efficiency models use only a single efficiency value to model equipment, the present model evaluate the components efficiency in function of its load [27]. Finally the server utilization and the effects of task scheduling on the power and cooling systems were characterized. In real data centres, disparities in performance and power characteristics across servers and different scheduling, task migration or load balancing mechanisms, have effects on the cooling systems that can be difficult to predict. Thus, for simplicity a homogeneous cluster and a perfect load balancing were assumed for this model. The model relates total data centre power draw to aggregate data centre utilization. Utilization varies from 0 to 1, with 1 representing the peak compute capacity of the

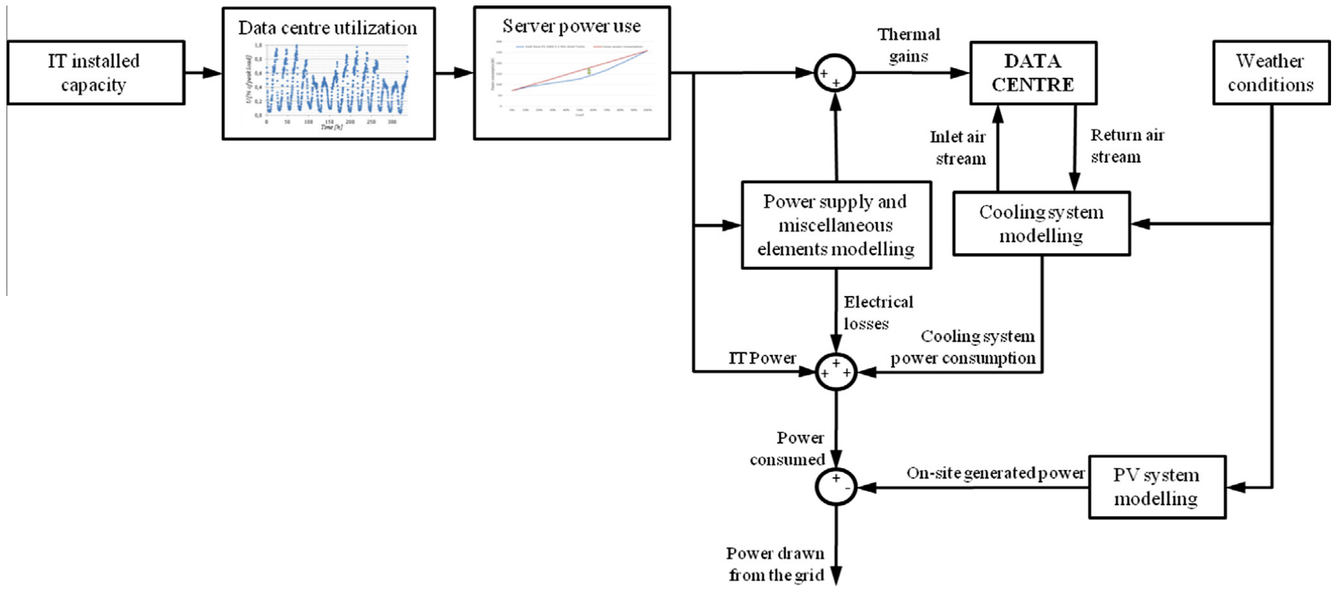

Fig. 6. Structure of the data centre energy model.

data centre. Fig. 7 shows the data centre utilization profile for web workload which was used for simulation corresponding to the web pattern of the access log of an ISP within the UPC [28]. It can be observed that major differences exist between day and night workloads and between working days and weekends. This workload profile was repeated leading to a constant pattern for all the year. 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 grows with utilization until the power peak load. As shown in Fig. 8, this relationship was assumed to be linear [29,30].

The main assumptions done in the model are summarized below:

- Homogenous server cluster and perfect load-balancing.
- Linear relationship between the computing load and the power consumed by the servers [29].
- All the power consumed by the IT equipment is converted into heat [31].
- Negligible heat exchanges through the building envelope compared to the internal gains due to the computing equipment.
- No air management inefficiencies.
- Heat transfer efficiency of 80% between the cooled air and the CRAH units.

2.4. Energy consumption and environmental indicators

To assess the impact of the data centre energy use in the selected European locations, different energy and environmental indicator shave been defined. The choice of these indicators aimed to be consistent with terminology used currently in Zero Energy Buildings [32,33] and data centre industry [34]:

- Electricity consumption (P_{DC}): This is the total power demand of the data centre, including the demand of the IT equipment, the cooling system, the power supply components and the miscellaneous load. The load may not coincide with the delivered energy from the grid due to self-consumption of energy generated on-site.
- Electricity generation (P_{gen}): This refers to the electricity generation of on-site power systems. The delivered power is the data centre electricity consumption minus the on-site generated power.

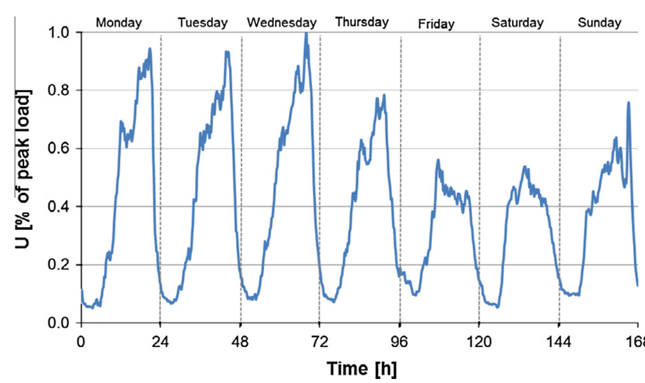

Fig. 7. Data centre utilization expressed as percentage of peak computing load.

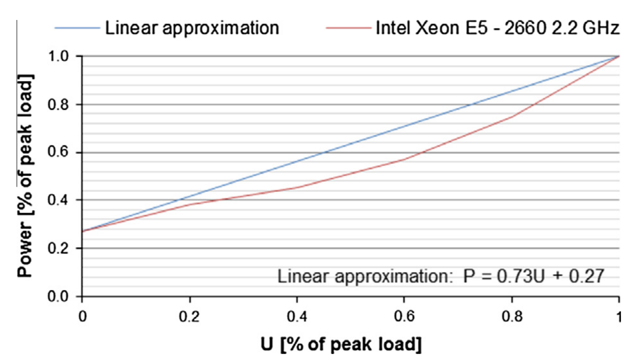

Fig. 8. Relationship between data centre utilization and servers power consumption.

- Renewable energy supply (RES_{DC}): This is the share of renewable energy that has been used for covering the data centre energy demand. It is calculated as shown in the Eq. (1), where REF_{grid} and REF_{gen} are the renewable energy fractions of the power imported from the grid and the power generated on-site.

$$RES_{DC} = \frac{(P_{DC} - P_{gen}) \cdot REF_{grid} + P_{gen} \cdot REF_{gen}}{P_{DC}} \quad (1)$$

- Primary energy consumption (PE_{DC}): This indicator takes into account that not all the electricity generation technologies have the same conversion efficiency and that transportation of electricity incurs power losses. Thus, this indicator assesses the actual amount of primary energy which was drawn from the nature to satisfy the data centre electricity demand. It is calculated in the Eq. (2), where PEF_{grid} and PEF_{gen} are the primary energy factors of the power imported from the grid and the power generated on-site, respectively.

$$PE_{DC} = (P_{DC} - P_{gen}) \cdot PEF_{grid} + P_{gen} \cdot PEF_{gen} \tag{2}$$

- Carbon emissions (EM_{DC}): these are the green-house gas emissions related to energy use. When a data centre consumes electricity which is produced in some extent from fossil fuels it automatically has associated emissions. To calculate these emissions, Eq. (3) is applied:

$$EM_{DC} = (P_{DC} - P_{gen}) \cdot EF_{grid} + P_{gen} \cdot EF_{gen} \tag{3}$$

where EF_{grid} is the emission factor, in $tCO_2/MW\,h_e$, of the electricity drawn from the grid and EF_{gen} is the emission factor of the electricity produced on-site.

- Energy cost (EC_{DC}): the energy cost can be calculated with Eq. (5), in which EP_{grid} is the electricity price of the power drawn from the grid and $LCOE_{gen}$ is the levelized cost of electricity produced from on-site. Eq. (4) only accounts for electricity but if other energy carriers are furnished to the data centre the same procedure has to be carried out and their associated costs added.

$$EC_{DC} = (P_{DC} - P_{gen}) \cdot EP_{grid} + P_{gen} \cdot LCOE_{gen} \tag{4}$$

- Power usage effectiveness (PUE): this is the most widely used metric to assess the power consumption of data centres. It is defined as the ratio between the power consumption of the data centre and the power consumed by the IT equipment (Eq. (5)). The closer the PUE is to 1 the more efficient the data centre is.

$$PUE = \frac{P_{DC}}{P_{IT}} \tag{5}$$

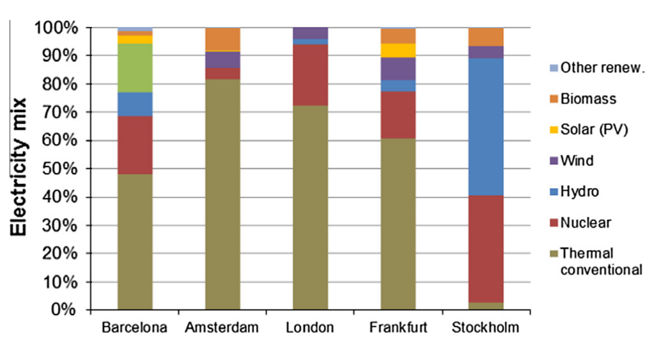

Fig. 9. Electricity mix of the selected regions in 2012 (data from ENTSO-E [35]).

- Water usage effectiveness (WUE): this is the water usage in data centres in function of the IT equipment power consumption (Eq. (6)).

$$WUE = \frac{\text{Annual water usage}}{P_{IT}} \tag{6}$$

Monthly values of the parameters REF_{grid}, PEF_{grid}, and EF_{grid} were used to calculate the defined indicators for the five selected emplacements. These values were estimated with the data provided by the European Network of Transmission System Operators for Electricity (ENTSO-E) [35] about the electricity mix of the different countries in 2012 (Fig. 9). To calculate the regional averages, a weighted average of the electricity produced by each technology was carried out considering their specific PEFs and EFs, published by the Spanish governmental energy agency IDEA [36]. Concerning the PEF, it is important to notice that the IDAE assumes the PEF for renewables to be 1, thus ideally the PEF converges to 1 as the penetration of renewables increases. It also assumes that 9% of the net electricity generation is lost in the transportation and distribution network. Moreover, biomass is considered to be carbon neutral. Since the distribution of energy sources in regional electricity mixes and the power consumption of the data centre vary throughout the year, calculating the indicators in monthly basis and then aggregating the total annuals permitted to obtain more accurate results.

Concerning the electricity cost, EP_{grid} depends on the type of contract accorded with the electricity retailer. In this case, a spot-pricetied contract was assumed when calculating the electricity cost for the data centre. These kinds of contracts are already widely used in Nordic countries (where between 70% and 75% of the electricity is traded through NordPool [37]) and are increasingly used by industrial consumers in Europe. Moreover, as it will be seen afterwards, these contracts can benefit data centres with certain flexibility in scheduling their load. Therefore, the values of EP_{grid} were first scaled using the end-user electricity prices published by the Eurostat for industrial end-consumer in the ID band (annual power consumption comprised between 2000 and 20,000 MW h) in 2012 [38]. As shown in the Table 5, the end-consumer prices include the cost of energy and supply, network charges and non-recoverable taxes and levies. Then the spot-price variations were incorporated in the energy and supply cost component using historical auction results in day-ahead electricity markets for the five countries: OMIE (Spain), APX (The Netherlands), N2Ex (United Kingdom), EPEX (Germany), and NordPool (Sweden). Table 5 also shows the assumed levelized costs of electricity for the PV system in the selected locations [39].

3. Results

The results are distributed in three subsections. First, a quantitative comparison of the different scenarios is done with annual values. Then, the second subsection investigates the monthly evolution of the indicators for the On-site generation scenario. Finally, the third subsection shows the daily profiles of the indicators for Barcelona (Spain).

Table 5
Electricity prices and levelized cost of PV generation [€/MW h] for industrial consumers in 2012.

Location	Energy and supply	Network costs	Taxes and levies[a]	Total grid electricity price	LCOE (PV system)
Barcelona (ES)	76.30	19.10	4.90	100.30	80.00
Amsterdam (NL)	59.40	17.30	9.40	86.10	110.00
London (UK)	79.60	25.10	4.30	109.00	130.00
Frankfurt (DE)	57.30	19.70	39.90	116.90	110.00
Stockholm (SE)	47.90	18.80	0.60	67.30	160.00

[a] Excluding VAT and other recoverable taxes.

3.1. Annual energy indicators results

This subsection aims to show how the energy demand and the efficiency of the data centre are affected by its location. Tables 6–8 show the energy demand and the indicators proposed in each location for the baseline, the economizer and the on-site generation scenario, respectively.

3.2. Monthly energy indicators results

Renewable energy availability and climate conditions and thus electricity prices vary over the year. Thus, this section aims to show how these variations affect the energy indicators proposed for the on-site generation scenario. From Figs. 10–17 all the energy indicators in monthly ratios are presented.

3.3. Hourly energy indicators results

Although seasonal variations of renewable energy availability and electricity prices can influence the energy indicators of data centres over the year, these facilities can hardly respond to these variations. However, many workloads in data centres are delay tolerant in short-time horizons, and can be scheduled to finish anytime before their deadlines. The maturity in cloud computing and virtualization technologies has also enabled data centres to dynamically migrate load to distributed data centres in response to changing grid supply. These features allow data centres to respond to hourly variations. Therefore, a great potential exists in load management for reducing the energy consumption, the carbon footprint and the energy costs of data centres.

In this sense, Figs. 18 and 19 show the hourly renewable energy supply and the energy cost for four typical days representing the four seasons (January, April, July and October) in Barcelona (Spain). Moreover, Figs. 20 and 21 show the hourly electricity consumption

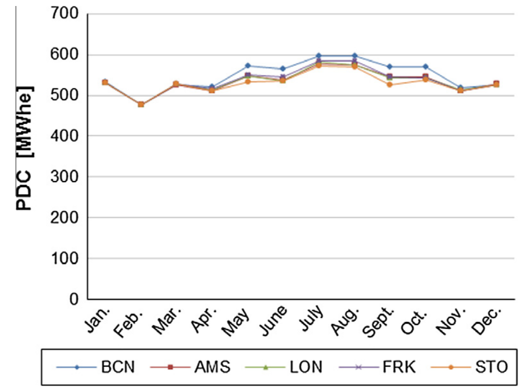

Fig. 10. Monthly electricity consumption for the different locations.

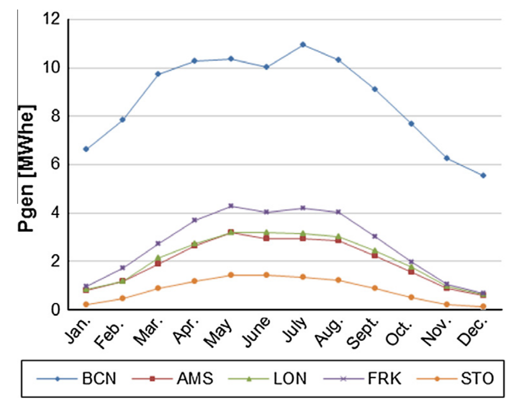

Fig. 11. Monthly electricity generation for the different locations.

Table 6
Energy indicators for the Baseline scenario.

Location	P_{DC} (MW h_e)	RES_{DC} (%)	PE_{DC} (MW h_p)	EM_{DC} (tCO_2)	EC_{DC} (€)	PUE (–)	WUE (m^3/kW)
Barcelona (ES)	6931	30.9	16,222	2410	694,873	1.44	0.0
Amsterdam (NL)	6905	11.9	17,060	3605	593,855	1.44	0.0
London (UK)	6906	5.7	18,907	4188	752,377	1.44	0.0
Frankfurt (DE)	6913	23.1	18,358	3959	807,186	1.44	0.0
Stockholm (SE)	6906	66.9	14,632	133	463,437	1.44	0.0

Table 7
Energy indicators for the Economizer scenario.

Location	P_{DC} (MW h_e)	REF (%)	PE_{DC} (MW h_p)	EM_{DC} (tCO_2)	EC_{DC} (€)	PUE (–)	WUE (m^3/kW)
Barcelona (ES)	6574	30.8	15,398	2288	659,664	1.37	0.26
Amsterdam (NL)	6415	11.9	15,849	3347	551,316	1.33	0.43
London (UK)	6417	5.7	17,568	3885	698,412	1.33	0.32
Frankfurt (DE)	6444	23.1	17,109	3686	752,360	1.34	0.48
Stockholm (SE)	6362	67.0	13,474	121	425,376	1.32	0.75

Table 8
Energy indicators for the On-site generation scenario.

Location	P_{DC} (MW h_e)	P_{gen} (MW h_e)	REF (%)	PE_{DC} (MW h_p)	EM_{DC} (tCO_2)	EC_{DC} (€)	PUE (–)	WUE (m^3/kW)
Barcelona (ES)	6574	104.7	31.9	15,257	2252	657,504	1.37	0.26
Amsterdam (NL)	6415	23.6	12.2	15,815	3335	551,912	1.33	0.43
London (UK)	6417	25.3	6.1	17,524	3870	698,977	1.33	0.32
Frankfurt (DE)	6444	32.3	23.3	17,056	3668	752,146	1.34	0.48
Stockholm (SE)	6362	9.8	66.2	13,463	121	426,726	1.32	0.75

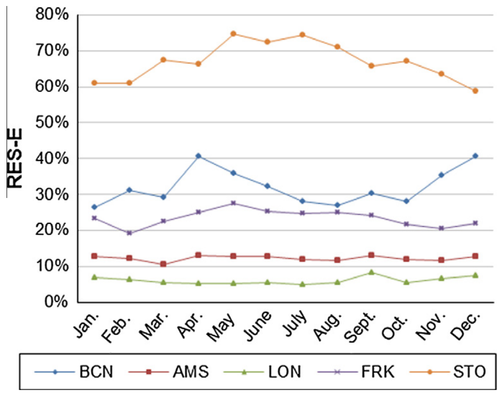

Fig. 12. Monthly renewable energy supply for the different locations.

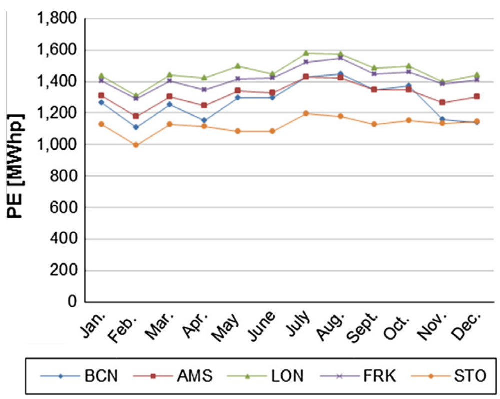

Fig. 13. Monthly primary energy consumption for the different locations.

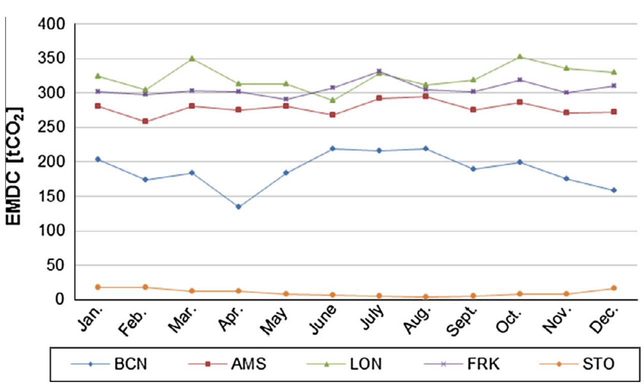

Fig. 14. Monthly carbon emission for the different locations.

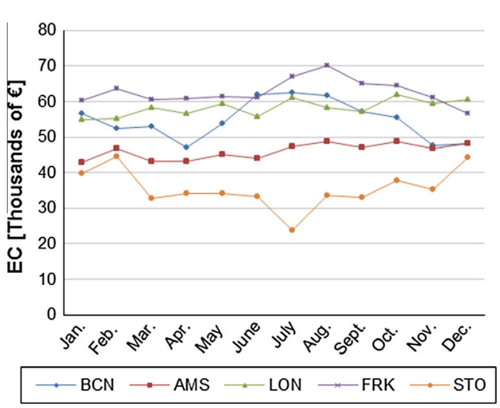

Fig. 15. Monthly energy cost for the different locations.

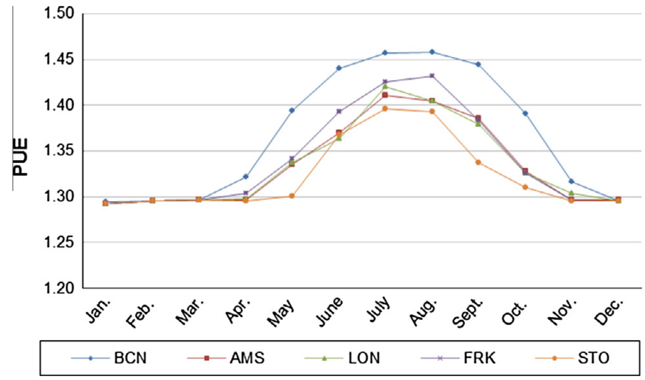

Fig. 16. Monthly PUE for the different locations.

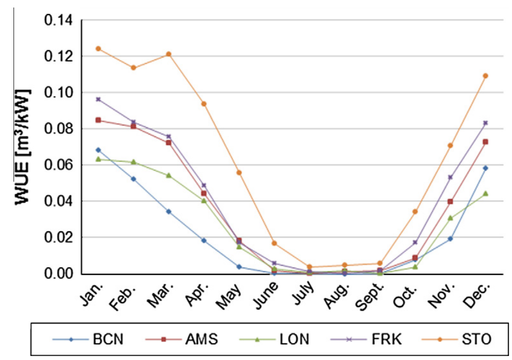

Fig. 17. Monthly WUE for the different locations.

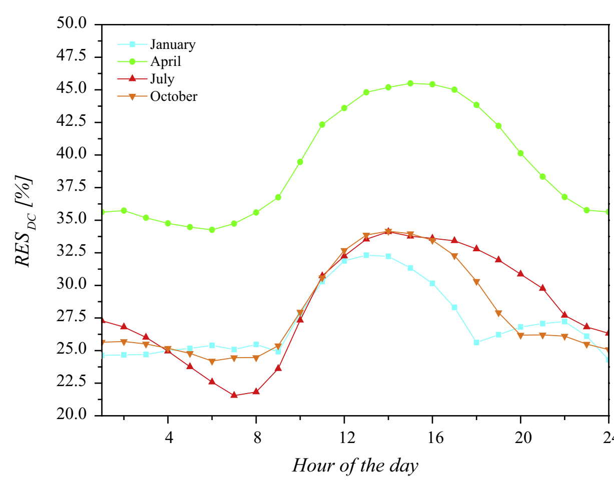

Fig. 18. Hourly renewable energy supply for the grid in Barcelona (Spain).

and the PUE ratio for the on-site generation data centre located in Barcelona.

4. Discussion

4.1. Annual energy indicators discussion

In the data centre reference case (baseline scenario) no appreciable differences take place in the energy use or the PUE across the different locations due to the interaction with outdoor conditions is minimal. The minor differences in the electricity consumption of the data centre are mainly due to the chiller EER

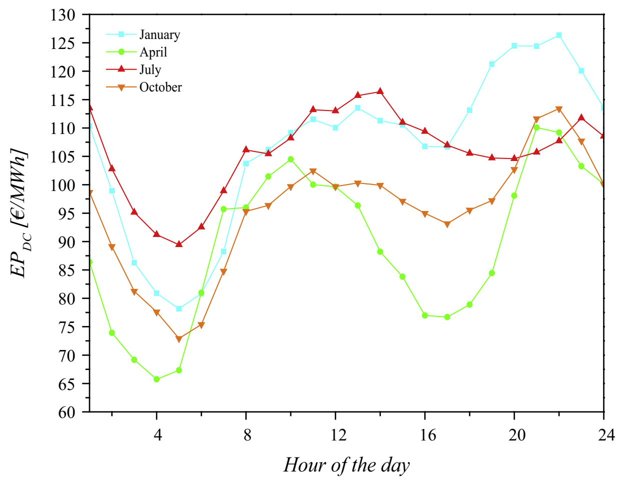

Fig. 19. Hourly energy cost in Barcelona (Spain).

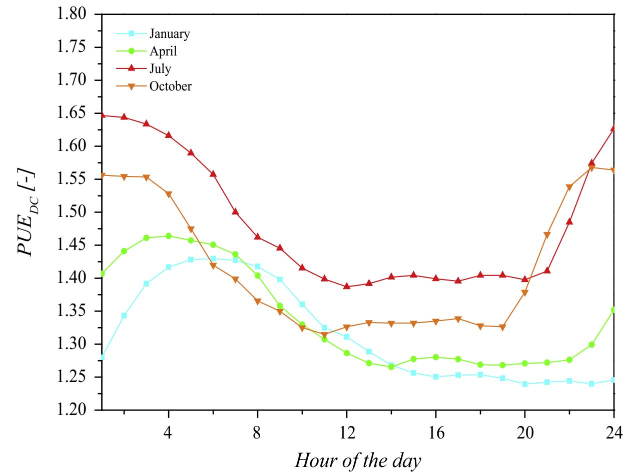

Fig. 21. Hourly PUE ratio for a data centre located in Barcelona (Spain).

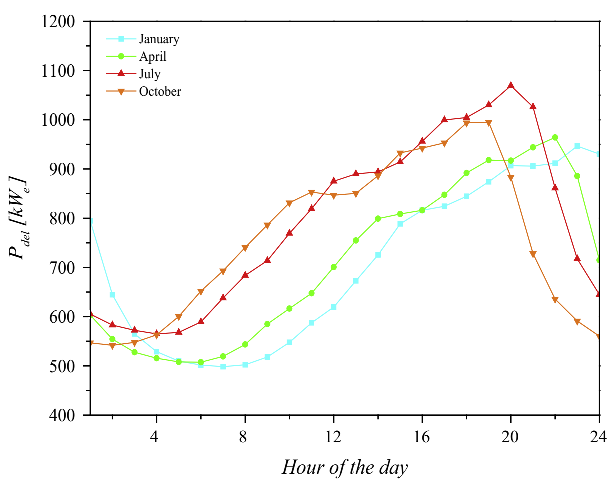

Fig. 20. Hourly electricity consumption for a data centre located in Barcelona (Spain).

dependence on external temperature, resulting to higher energy demand in warmer climates like Barcelona. The energy model developed assumes a homogeneous interior space, with ideal hot and cold aisles containment, and correctly implemented control sequences. Thus, it does not capture improperly functioning equipment or improperly programmed systems that may occur in the operation of real data centres. It is for this reason that the PUE value of 1.44 is lower than the average PUE value reported in the literature [40]. Instead the results showed major differences in its energy supply, its carbon footprint and its energy costs. For instance, the electricity consumed by a data centre located in Stockholm (Sweden) is 11 times greener than if located in London (UK). Thus, the data centre reference case emits 4188 tCO_2 in London while it would only emit 133 tCO_2 in Stockholm. This phenomenon is mainly due to the electricity attributes from the grid which may vary at each region. While the emissions factor in the United Kingdom goes up to 0.61 tCO_2/MW h_e due to the extensive use of coal to produce electricity, the emissions factor in Sweden is 0.02 tCO_2/MW h_e as they produce their electricity mainly from hydro and nuclear energy. The same phenomenon occurs for electricity prices. Sweden is the location where electricity prices for industrial consumers are lower. Therefore, data centre operators could reduce their energy bills by 42.5% locating the facility in Stockholm instead of Frankfurt.

The results of the direct air free cooling system implementation indicate that the data centre energy consumption could be reduced between 5.4% and 7.9% depending on the location. This turns into a PUE reduction from the reference case of 1.44 to a value comprised between 1.37 (Barcelona) and 1.32 (Stockholm). These could seem modest reductions, but it must be taken into account that the initial PUE in the Baseline scenario was already quite low meaning that the cooling system weight was small in the total power consumption. However, the Economizer scenario requires additional costs respect to the water consumption. Although energy is often the biggest concern in data centre operation, water consumption cannot be ignored as it is a critical component for some cooling systems and overstated consumption could have an impact on local resources and utilities. The results have shown that the higher WUE occur in Stockholm, while the smaller occur in Barcelona. This is explained by the cold and dry climates of the Nordic countries. As cold outside air is very dry, it makes necessary to add high amounts of moisture to achieve the minimum inlet humidity. This distribution is appropriate considering that the Nordic countries enjoy of abundant water resource while in Mediterranean areas the presence of water is scarcer.

From the on-site generation scenario results can be observed that the generation of the PV system has a small impact on the energy balance of the data centre, covering only 1.6% of its total consumption in the best case (Barcelona). This is understandable considering that data centres are energetically very demanding, while the PV systems have low energy intensity. However, major differences are observed for the PV production depending on the selected spot, what demonstrates that the location could severely affect the electricity balance for data centres with greater space availability. It is also worthy to note that, as the levelized cost of energy for PV systems varies according to the incident irradiation, the impact of on-site generation on the reference case energy costs also vary with the location, being profitable only in Barcelona and Frankfurt.

4.2. Monthly energy indicators discussion

Results indicate that the power consumption increases in summer season since the use of direct air free cooling is not available. This directly affects the PUE ratio, especially in warmer climates like Barcelona where its value increases by 13.1% during that period. The renewable energy supply is greatly influenced by the conversion technologies used to produce the electricity and the primary energy source availability. Thus, the RES_{DC} profile in

Fig. 12 shows that greater shares of renewables occur during spring and summer months coinciding with improved availabilities of renewable resources such as hydro, wind or solar energies. Nevertheless, an exception to this trend is noticed in Spain, for which hydro and wind power had a great upturn at the end of the year. It is also worthy to note that the greater the share of renewables is the more variable the indicator became. This phenomenon is attributable to the fluctuating nature of renewable energy sources. It is difficult to identify a systematic trend in the evolution of electricity prices across the analysed locations (Fig. 13). While prices rise during summer in Spain and Germany, they go down in Sweden. In any case, since maximum consumptions take place in summer periods, it is more advantageous prices decreasing in summer than in winter periods. Finally, concerning the water utilization it can be observed that major consumptions occur during winter because outside air used by the free cooling has a lower HR and needs to be humidified after blending with return air. In contrast, as summer periods are characterized by warmer air conditions with higher HR, only mechanical cooling is used and thus no humidification is needed.

4.3. Hourly energy indicators discussion

The results from Spain show that peak renewables availability occurs at midday, advising to shift the IT load to the middle hours of the day. The electricity prices seem to be strongly related to the global electricity demand in the country, which show the higher increments during the morning and the evening. Therefore, these results demonstrate that a great potential for reducing the primary energy consumption, the carbon emissions and the electrical costs exist for data centre operators through the smart management of their loads by shifting their load to non-peak periods or moments with a higher presence of green energy on the grid. Additional strategies introducing short term flexibility through energy storage integrated in the electrical and/or mechanical systems supplying power and cooling, respectively could take advantage of the daily variability of electricity prices and primary energy factors from the grid.

As expected, the power consumption follows the IT load. It is fair to mention that the data centre has been simulated considering a web workload. Therefore, this workload lead to a fluctuating data centre utilization, in which peak load occurs during the afternoon and the evening and non-peak hours overnight. The PUE is also clearly affected by the IT load and indicates that partial loads during nigh period lead to major inefficiencies of the infrastructure. This plays in favour of shaving peak loads and adjusting sizing parameters of the data centres.

5. Conclusion

During the last decade, the increasing energy demand of the data centres industry has put the sector under pressure to limit its environmental impact. Companies have taken consciousness of the issue and several energy efficiency measures have already been investigated and implemented. This paper aimed to demonstrate that the location of a data centre could significantly affect its operation and its associated impact on the environment. To accomplish this goal an energy model of a reference data centre was developed in TRNSYS. Direct air free cooling strategy and PV system integration were analysed using many energy indicators at different European locations.

In the reference case where a state of the art vapour compression system is used as the cooling system, the overall energy consumption is not affected by the location. However major differences between regions were found out related to the electricity attributes from the grid. Actually, a reference data centre located in Stockholm would emit 30 times less CO_2 than the same infrastructure located in London. Similarly, energy costs savings could be achieved by appropriately select the location of the data centre. Therefore, the location of the facility does not only reduce drastically the energy bill but the environmental footprint. The use of direct air free cooling strategy is proved to be beneficial in any location reducing the energy consumption of the entire data centre between 5.4% and 7.9%, depending on the location. Consequently, the location of the infrastructure will have a greater effect on their overall energy demand if free cooling is installed. In contrast, on-site generation with PV systems resulted not to be an effective measure to lower neither the imported power from grid nor their associated energy costs. This is mainly due to the fact that data centres are energy-intensive facilities and PV systems are only able to cover a very little part of their energy.

The monthly analysis showed an increase of the total energy consumption during summer due to the reduction of available free cooling hours and the lower efficiency of the chiller. In Mediterranean location like Barcelona this increase could be more than 10%. Important variations of other indicators such as renewable energy supply and electricity prices were also observed throughout the year. Finally, when analysing the hourly Spanish energy mix, it is observed that the peak renewables availability occur at midday while the electricity prices follows the global electricity demand which experiences higher increments at morning and evening. These results demonstrate that a great potential for reducing the primary energy consumption, the carbon emissions and the electrical costs exist for data centre operators through the smart management of the IT load by shifting it to non-peak periods or moments with a higher presence of green energy on the grid.

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References

[1] Koomey J. Growth in data center electricity use 2005 to 2010. Oakland (CA): Analytics Press; 2011.
[2] Datacenter Works. Growth in electricity consumption flattens. February 2014. <http://datacenterworks.nl/2014/02/07/groei-in-elektriciteitsverbruik-vlakt-af/>; 2014 [accessed august 2014].
[3] Google Inc. Renewable energy. February 2014. <http://www.google.com/green/energy/>; 2014 [accessed august 2014].
[4] Apple Inc. Apple and the environment. February 2014. <https://www.apple.com/environment/renewable-energy/>; 2014 [accessed august 2014].
[5] Oró E, Depoorter V, Salom J. Energy efficiency and renewable energy integration in Data Centres. Strategies and modelling review. Renew Sust Energy Rev 2014;42:429–45.
[6] Data center operational efficiency best practices. IBM Corporation; 2012.
[7] Linter W, Tschudi B, VanGeet O. Best practices guide for energy-efficient data center design. U.S. Department of Energy. Renew. Energy 2011.
[8] Goiri I, Berral JL, Fitó JO, Julià F, Nou R, Guitart J, et al. Energy-efficient and multifaceted resource management for profit-driven virtualized data centres. Future Gener Comp Syst 2012;28:718–31.
[9] Ton F, Fortenbery B. DC power for improved data center efficiency. Lawrence Berkley National Laboratory; 2008.
[10] Urgaonkar R, Urgaonkar B, Neely M, Sivasubramaniam A. Optimal power cost management using stored energy in data centres. In: Proceedings of the ACM sigmetrics; 2011.
[11] Patterson MK. The effect of data centre temperature on energy efficiency. In: Proceedings of thermal and thermomechanical phenomena in electronic systems; 2008.
[12] Lee KP, Chen HL. Analysis of energy saving potential of air-side free cooling for data centers in worldwide climate zones. Energy Build 2013;64:103–12.
[13] Siriwardana J, Jayasekara S, Halgamuge SK. Potential of air-side economizers for data center cooling: a case study for key Australian cities. Appl Energy 2013;104:207–19.
[14] Rezaie B, Rosen MA. District heating and cooling: review of technology and potential enhancements. Appl Energy 2012;93:2–10.

[15] Pisello AL, Rossi F, Cotana F. Summer and winter effect of innovative cool roof tiles on the dynamic thermal behaviour of buildings. Energies 2014;7:2343–61.

[16] Goiri I, Katsan W, Le K, Nguyen TD, Bianchini R. Parasol and GreenSwitch: managing data centres powered by renewable energy. In: Proceedings of the 18th international conference on architectural support for programming languages and operating systems; 2013.

[17] Special Report: Data Centers & Renewable Energy. <http://www.datacenterknowledge.com/special-report-data-centers-renewable-energy/> [accessed august 2014].

[18] Guizzi GL, Manno M. Fuel cell-based cogeneration system covering data centres' energy needs. Energy 2012;41:56–64.

[19] Xu D, Qu M. Energy, environmental and economic evaluation of a CCHP system for a data centre based on operational data. Energy Build 2013;67:176–86.

[20] http://tech.ebay.com/ [Accessed August 2014].

[21] Shehabi A, Masanet E, Price H, Horvath A, Nazaroff WW. Data center design and location: consequences for electricity use and greenhouse-gas emissions. Build Environ 2011;46:990–8.

[22] ASHRAE TC 9.9. Thermal guidelines for data processing environments. third ed. Atlanta: ASHRAE; 2012.

[23] Ebrahimi K, Jones GF, Fleischer AS. A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities. Renew Sust Energy Rev 2014;31:622–38.

[24] Salom J, Sisó L, Sansigre M. Cost-effective renewable cooling on Green Data Centres. Technical report IREC-TR-00004 <http://www.irec.cat/publicacions/technical-reports-energia-termica-i-edificacio.html>; 2014 [accessed november 2014].

[25] Photovoltaic geographic information system (PVGIS). Geographical assessment of solar resource and performance of photovoltaic technology. <http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php> [accessed november 2014].

[26] PV panels characteristics. <http://www.recgroup.com/Documents/Downloadcenter/Solar%20product%20downloads/Solar%20Product%20Datasheets/REC%20PE%20Series%20Rev%20R.3%20ESP.pdf?epslanguage=en> [accessed november 2014].

[27] Rasmussen N. Electrical efficiency modeling for data centres. Schneider Electric. 2011.

[28] Macías M, Guitart J. SLA negotiation and enforcement policies for revenue maximization and client classification in cloud providers. Futur Gen Comp Syst 2014. http://dx.doi.org/10.1016/j.future.2014.03.004.

[29] Oró E, Pflugradt N, Macías M, Nardi D. Deliverable D4.2. Energy requirements for IT equipment. RenewIT project; 2014.

[30] Pelley S, Meisner D, Wenisch TF, VanGilder JW. Understanding and abstracting total data center power. In: Workshop on Energy Efficient Design (WEED), Austin, Texas; 2009.

[31] Rasmussen N. Calculating total cooling requirements for data centers. Schneider Electric 2011.

[32] IEA. SHC Task 40/EBC Annex 52, "Net Zero Energy Solar Buildings. <http://task40.iea-shc.org/> [accessed august 2014].

[33] Sartori I, Napolitano A, Voss K. Net zero energy buildings: a consistent definition framework. Energy Build 2012. http://dx.doi.org/10.1016/j.enbuild.2012.01.032.

[34] The Green Grid. PUE™: A comprehensive examination of the metric. The Green Grid, Beaverton; 2012.

[35] European Network of Transmission System Operators for Electricity. Statistical Database. <https://www.entsoe.eu/data/data-portal/>; 2013. [accessed august 2014].

[36] Instituto para la Diversificación y Ahorro de la Energía (IDAE). Factores de conversión a energía primaria y factores de emisión de CO2. <http://www.idae.es/index.php/mod.documentos/mem.descarga?file=/documentos_Factores_Conversion_Energia_y_CO2_2011_0a9cb734.pdf>; 2011 [accessed august 2014].

[37] VaasaETT. European Residential Energy Price Report 2013. VaasaETT; 2013.

[38] Eurostat. Statistics database. European Commission, <http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database>; 2014. [accessed august 2014].

[39] Kost C, Mayer JN, Thomsen J, Hartmann N, Senkpiel C, Phillipps S, et al. Levelized cost of electricity renewable energy technologies. Fraunhofer Institute for Solar Energy Systems ISE, Freiburg; 2013.

[40] Uptime Institute. Data Center Industry Survey. New York; 2013.