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Citation: BABICH, F. ...et al., 2017. The impact of ventilation cooling towers on plus energy houses in southern Europe. *International Journal of Ventilation*, 16(4), pp. 323-344.

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Metadata Record: <https://dspace.lboro.ac.uk/2134/24549>

Version: Published version

Publisher: © The Authors. Published by Taylor & Francis

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To cite this article: Francesco Babich, Malcolm Cook, Jan Cremers & George Papachristou (2017) The impact of ventilation cooling towers on plus energy houses in southern Europe, International Journal of Ventilation, 16:4, 323-344, DOI: [10.1080/14733315.2017.1305820](https://doi.org/10.1080/14733315.2017.1305820)

To link to this article: <http://dx.doi.org/10.1080/14733315.2017.1305820>



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Published online: 07 Apr 2017.



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The impact of ventilation cooling towers on plus energy houses in southern Europe

Francesco Babich^a, Malcolm Cook^a, Jan Cremers^b and George Papachristou^a

^aSchool of Civil and Building Engineering, Loughborough University, Loughborough, UK; ^bHochschule für Technik Stuttgart, Stuttgart, Germany

ABSTRACT

Cooling homes is often important to maintain acceptable internal comfort. This can be achieved by both active and passive solutions. This research focused on passive systems and has examined one hypothesis, that evaporative cooling towers are an important element of plus-energy houses in southern Europe. Refinements to the design of the existing ventilation tower of a Solar Decathlon House developed by the Hochschule für Technik Stuttgart are proposed and tested in eight locations in Greece, Italy, Portugal and Spain using dynamic thermal and computational fluid dynamics simulations in order to predict energy consumption, mean and peak CO₂ levels, temperatures, ventilation rates, cooling potential, fresh air distribution, indoor air quality and water consumption of the evaporative cooling system implemented within the tower. Results show that a 50% reduction of the annual energy demand for space cooling to be satisfied by other systems is achieved without compromising the internal comfort.

KEYWORDS

Passive cooling; plus-energy homes; PDEC; CFD; ventilation tower

1. Introduction

1.1. Background and context

In recent years, the reduction of the energy demand for building space conditioning has become an important issue and many studies have been conducted. In particular, statistical data shows that the residential sector represents more than 25% of the entire energy consumption in the EU and the trend is upwards (Eurostat, 2013).

Energy demand for space conditioning in the residential sector depends on several factors, namely the climatic conditions, the glazing ratio and quality of sun shading, the insulating standard, the air tightness of the building envelope, the thermal mass and the behaviour of occupants. Although the second and the third may have relevant effects, it is in general true that in northern Europe the main energy consumption is for space heating due to longer and colder winters and less intense solar gains. On the other hand, southern areas of Europe are characterised by a warmer and drier climate with longer summers, less rainfall and significantly higher solar gains. Therefore, in this case, the energy demand for space cooling has the most relevant role.

Furthermore, the situation is in continuous variation due to climate change. For instance, although diverse future scenarios are plausible for the UK, drier summers by up to 20% by the 2020s and up to 40% by the 2050s and warming up to 1.5 °C depending on region and scenario by the 2020s and up to 3.0 °C by the 2050s are forecast (West & Gawith, 2005). Longer term projections go in the same

direction (CIBSE, 2006). A warming climate and the increasing average level of home insulation, applied in order to save energy in winter, increase the risk of overheating in residential buildings, which sometimes is already a problem (Beizaee, Lomas, & Firth, 2013). A tendency towards higher glazing ratios and increasing comfort expectations will add to this development.

1.2. The research question

The aim of this research was to identify and test refinements to the design of the existing ventilation tower of a plus-energy house, called 'home+' (Cremers, Dalibard, & Binder, 2010). The performance of the tower integrated within the house has been estimated both in terms of energy savings and indoor air quality (IAQ) and thermal comfort using appropriate computer simulations.

The building is currently located in Stuttgart (Germany) and could not be physically rebuilt in other places. However, for the research reported here, it has been hypothetically located in eight different locations in southern Europe. Its original design environment was Madrid in Spain. Moreover, additional European locations have been considered for comparison purposes in the early stages of this study.

In particular, one main research question has been examined: are evaporative cooling towers an important element of plus-energy houses in southern Europe? This was plausible because in these areas of Europe, the demand for space conditioning energy is mainly space cooling energy and, therefore, efficient passive cooling systems are key to minimising the use of energy. In other words, the better they work, the less backup systems, such as heat-pumps, are required.

In this paper, the term 'plus-energy house' has been used because there are other aspects of the design and operation that embrace the ethos of a plus-energy home. However, these aspects are not discussed in the paper since they are not relevant to this study.

1.3. The structure of the paper

The paper is structured as follows. In section two, the findings of the previous work are discussed. This identifies the gap in knowledge this research filled and why certain methods were used. The third section introduces the case-study plus-energy home. Then, the main aspects of the methodology are described, including the different modelling approaches and assumptions and the performance evaluation criteria. Finally, results are presented and discussed and conclusions have been drawn.

2. Previous work

This section has been organised into two main parts. First, plus-energy homes and their cooling systems are briefly introduced, followed by the topic of draught cooling and ventilation towers, including a review of their theoretical aspects, the most relevant previous modelling and experimental works and the climatic applicability of these systems.

2.1. Plus-energy homes and concepts of their systems for space cooling

One of the most common terms for referring to low energy residential buildings is '*passive house*'. It may have a generic connotation or a specific well-defined meaning, when referred to the German Passivhaus standard (Feist, Peper, & Görg, 2001). In the latter case, by definition, the annual space heating and cooling requirements must not exceed 15 kWh/(m²year) and the total primary energy requirement for space heating and cooling, domestic hot water and household appliances must remain below 120 kWh/(m²year).

Zero Energy Buildings represent the next step. By definition, their annual energy balance is zero due to the implementation of a range of micro-generation technologies, such as solar PV, and the

integration and optimisation of passive solutions (Panagiotidou & Fuller, 2013; Sartori, Napolitano, & Voss, 2012).

A plus-energy house, as defined by Disch (2009), goes even further, being a residential building whose annual energy balance is positive. The reduction of the space conditioning loads with passive solutions is essential in order to reach this target. Solar Decathlon Houses demonstrate possible combinations of passive measures and renewable energy sources (Kazanci, Skrupskelis, Sevela, Pavlov, & Olesen, 2014).

Dealing with passive cooling, movable shadings, appropriate use of thermal mass, inertia effect and night ventilation are some of the key features of low energy buildings in southern Europe (Ford, Zhongcheng, & Schiano-phan, 2007). Other effective techniques include ground cooling, evaporative cooling, cool roofs and green roofs (Zinzi & Citterio, 2010).

Each of these techniques has different principles of operation, strengths and weaknesses (Santamouris, 2007). Some of them, such as phase changing materials (PCM), have a significant potential, but their costs may prove prohibitive. On the other hand, evaporative cooling is a potentially low cost solution and can be efficient in light-mass constructions, such as timber houses which are becoming more common in southern European countries.

2.2. *Downdraught cooling and ventilation towers*

Pioneering work by Bahadori (1985) aimed to improve ancient wind towers by developing solutions able to supply air to the building at higher flow rates, with less dust and at lower temperature, highlighting the great potential of this technique in hot-dry climates (Cunningham & Thompson, 1986).

Various systems have then been tested. Wetted columns performed better with strong wind conditions, while wetted surfaces, namely pads, proved more efficient with low wind conditions (Bahadori, 1994). In the former system, a wetted column is placed into the tower and its cross section and height can be defined to reach the desired air flow and temperature. The latter incorporates evaporative cooling pads at the tower entrance. Multi-directional evaporative cooling wind towers have also shown to lead to cost-effective solutions (Badran, 2003).

Multi-inlet passive downdraught evaporative cooling (PDEC) towers may allow a reduction in the water consumption within the system (Pearlmutter, Erell, & Etzion, 2008) and a significant increase of the air flow through the tower, while a deflector cone at the outlet of the tower may enhance its performance (Erell, Pearlmutter, & Etzion, 2008).

The use of wetted curtains suspended inside the column implies smaller droplets, therefore the total evaporation surface is greater and this enhances the reduction of the air temperature through the tower (Saffari & Hosseinnia, 2009). Moreover, the exiting air temperature is more sensitive to the inlet air temperature, rather than to its relative humidity (Saffari & Hosseinnia, 2009). Also further studies highlight the effectiveness of wetted surfaces, such as cooling pads, which may lead to a temperature reduction of up to 15 °C (Hughes, Calautit, & Ghani, 2012).

Several other configurations have been tested and in all theoretical studies the fundamental role of computer simulations was highlighted, using both dynamic thermal modelling (DTM) and computational fluid dynamics (CFD). The use of both methods is specifically suggested as the optimal solution for testing PDEC buildings (Corney and Taniguchi, 2011), since they provide complementary information.

DTM can estimate temperatures, likely thermal comfort, energy saving generated by the PDEC system, exhaled CO₂ levels and also the consumption of water of the PDEC system. In particular, two approaches, namely '*post-processing*' and the '*coupled heat and mass flow*' method, may be adopted (Robinson, Lomas, Cook, & Eppel, 2004). The former is simpler and useful in order to test the applicability of the system across several locations and with different occupancy types in energy, CO₂ and water use terms. The latter is potentially more accurate, especially while comparing different PDEC design solutions, but also more complex and time consuming. Moreover, even if short time-steps are

chosen in DTM simulations, the models can produce unstable flow predictions, due to the fact that models are less refined than a real building energy management system. Therefore the '*coupled heat and mass flow*' does not ensure more accurate results. DTM also provides the boundary conditions for the CFD analyses.

The ventilation performance of a PDEC building can be accurately tested using CFD simulations, since these can predict air speed, temperature, humidity and fresh air distribution and the interaction between the two phases of the flow, namely air and water (Cook, Robinson, Lomas, Bowman, & Eppel, 2000).

2.3. Climatic applicability of PDEC

Whatever the mechanism used for inserting the water within the air stream is, the evaporation process follows the same thermodynamic principles: as water evaporates, the latent heat of vaporization is absorbed from the water by the surrounding air. Therefore, the dry bulb temperature (DBT) drops while its wet bulb temperature (WBT) remains constant (Lomas, Fiala, Cook, & Cropper, 2004). The higher the wet bulb depression (WBD), which is the difference between the DBT and the WBT, is, the better the performance of direct evaporative cooling becomes. Therefore this is the main climatic criterion for estimating its cooling potential (Givoni, 1991).

However, since even within a perfectly efficient system the DBT cannot be reduced below the WBT, this is actually the parameter to be analysed for the applicability of the system in a chosen location (Santamouris, 2007). Considering that the upper comfort limit for the temperature in developed countries is 26 °C, the outdoor WBT cannot be higher than 22 °C and the outdoor DBT higher than 42 °C (Givoni, 1992).

Then, it should be noted that comfort criteria vary in different countries, a wider range of conditions is accepted in naturally ventilated buildings and in warmer countries even higher temperatures may be considered within the comfort range (Givoni, 1992). As a result, the adaptive model of comfort is the most suitable in naturally ventilated buildings (Ford et al., 2007).

Having defined some comfort boundaries, building bioclimatic charts are an effective method for testing PDEC potential and comparing alternatives, such as other passive control strategies (Lomas et al., 2004).

A wide range of experimental and computer based work suggests these technologies have a huge potential (Bowman et al., 1997; Bowman et al., 1998; Ford, 2009; Lain & Hensen, 2006; Moura & Ford, 2003; Schiano-phan, 2010; Short, Cook, & Lomas, 2009). In most of these studies the importance of analysing both macro (Kottek et al. 2006) and micro (Hughes et al., 2012) climate is stated. However, little is known about the applicability of PDEC in plus-energy homes across southern Europe.

3. 'home⁺' and its ventilation tower

The Solar Decathlon competition is an international contest among universities in which self-sufficient grid-connected solar-powered plus-energy residential buildings are designed, built and monitored (Masseck & Tárrega, 2010).

The 'home⁺' (Figure 1) was designed by a multidisciplinary team at the Hochschule für Technik Stuttgart in Germany and it won the third prize in 2010 in Madrid, reaching also the first place in the Innovation Contest (Masseck & Tárrega, 2010) and another first place in 'construction and engineering'.

Its main passive features are thermal mass provided by PCM (regenerated by an innovative PVT-collector system), sun shading devices and an evaporative cooling system (Cremers et al., 2010). In particular, this last feature is integrated within the ventilation tower using pads for introducing water and wind is the main driving force. Its performance was estimated using both DTM (Team HFT Stuttgart, 2010) and experimental data (Schneider, 2010). DTM was used to predict the likely contribution of the tower to reducing cooling load over two different periods of time: one year and a short summer period. A full size experimental setup of the ventilation tower (Figure 2) was built at Stuttgart in



Figure 1. The 'home+' as it appears now in Stuttgart (photo by Elena Bagaeva, HFT Stuttgart).

order to study its cooling potential (Schneider, 2010). Several tests were conducted, and the key parameters of this system were determined, such as the heat transfer coefficient, equal to $7.0 \text{ W/m}^2\text{K}$, and the specific flow rate related to the pressure drop caused by the building. The maximum flow rate permitted was set to $900 \text{ m}^3/\text{h}$, approximately 6 air changes per hour (ACH), and this kind of control was realised in reality by controlling the lamellae aperture. Provided that the geometry of the tower is not modified, these key features do not change.

However, the tower did not operate as expected, providing a low contribution in terms of supplied space cooling energy. Based on the experience of the researchers who designed this building, the use of wind as a driving force has been identified as the element that mainly limits the effectiveness of this tower due to its unpredictable nature. Moreover, this idea is also supported by the literature review. First, the tower should extend above the roof by at least 6 m (Erell et al., 2008), which was not possible due to the height restriction included in the competition rules (5.5 m from the ground: in this case, including the open-lid-position of the tower and using the maximum foundation level adaptation, cp. Figure 3), in order to avoid wind turbulence problems. Second, wetted surfaces are preferable with low wind conditions (Bahadori, 1994), while in Madrid a strong wind from north was assumed (Team HFT Stuttgart, 2010). Here, the wind deflecting effect of the neighbouring building in this direction was not foreseen. Moreover, in a wind-driven system, the pressure coefficients of

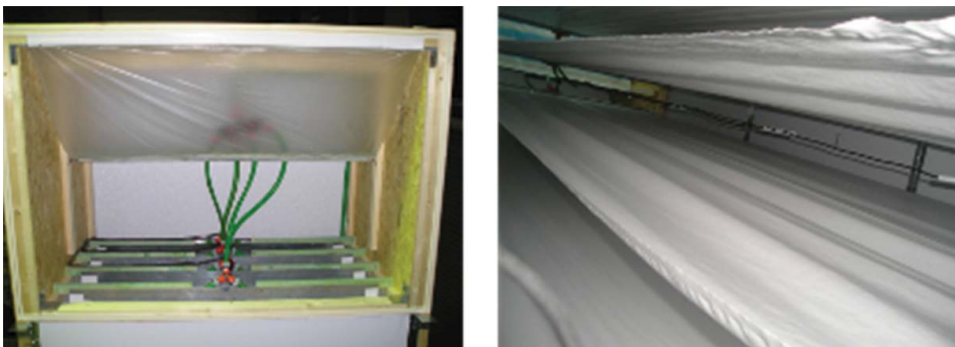


Figure 2. Experimental setup - top of the tower (left) and textiles used as moist surfaces (right) (Schneider, 2010)

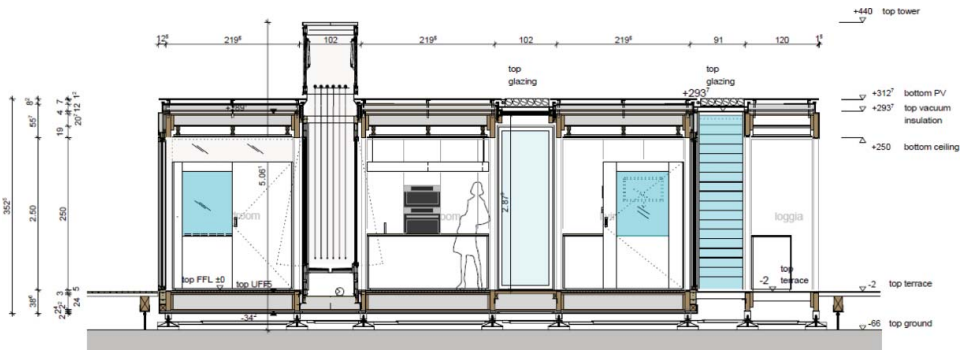


Figure 3. Section of the 'home+' (adapted from (Team HFT Stuttgart, 2010)).

the openings are erratic and the performance of the system less predictable (Calautit, Hughes, Chaudhry, & Ghani, 2013; Hughes et al., 2012). Hence, more analyses are required in order to enhance the effectiveness of this tower.

4. Methodology

4.1. Method for the selection of the locations

WBD and WBT have been used as the key parameters in order to predict whether a location is suitable for an evaporative cooling based system. Then, in this study, temperature between 20 °C and 27 °C and absolute humidity between 4 and 15 g/kg have been assumed as the ranges for the internal comfort conditions for the analysis of the locations (Givoni, 1992).

Climate Consultant (2014), a freely available computer program developed at UCLA, has been used to select the locations. Several parameters, such as WBT, WBD and wind speed and direction have been analysed. Moreover, the number of hours in which direct evaporative cooling can work has been estimated for each location, including Athens (Figure 4).

According to the availability of weather data (Energy Plus Weather Data, 2014), 34 locations spread across southern Europe have been tested, plus Phoenix (USA), whose climate is ideal for these

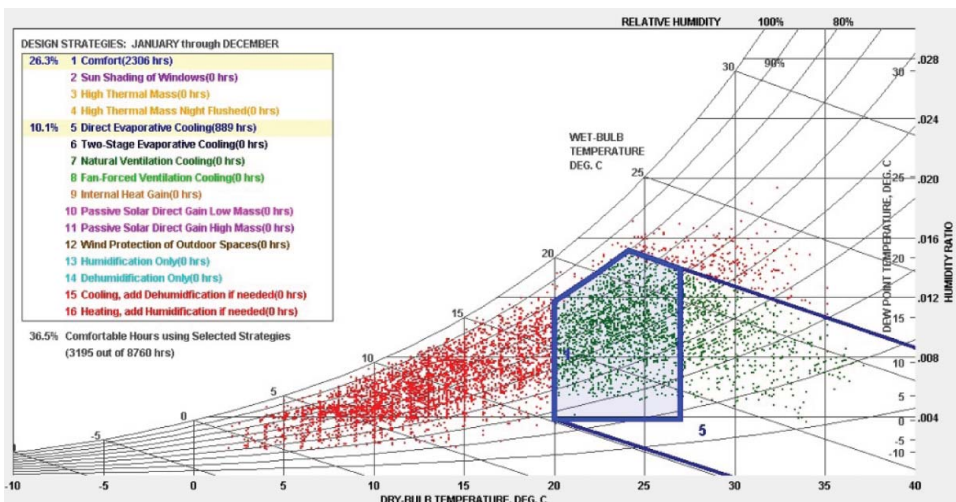


Figure 4. Psychrometric chart illustrating the climate of Athens (Greece) across one year, comfort boundaries and likely potential of evaporative cooling.

Table 1. Cities selected as the locations in this research.

Spain	Greece	Portugal	Italy
Cordoba	Athens	Evora	Catania (Sigonella)
Sevilla	Thessaloniki		Foggia
Zaragoza			

systems (Cunningham & Thompson, 1986). Based on preliminary analyses, eight European locations were finally chosen (Table 1), those that have a potential for evaporative cooling systems higher than 7.0% (percentage of hours of the year in which this type of cooling system is likely to be applicable according to Climate Consultant).

The weather data used in this research are in EPW¹ format and, when available, the source is IWEC². Otherwise they may be derived from IGDG³ (Italy), INETI⁴ (Portugal) or SWEC⁵ (Spain) (Weather Data Sources, 2014).

4.2. Design of refinements and their performance evaluation

The main modification is the change from a wind-driven system to a buoyancy-driven one, which relies essentially on temperature and moisture content. Since these are more consistent in one location than wind, the performance of the system is more predictable and the extension of the results to other locations is also easier. A possible disadvantage is a lower air flow rate, but this could happen also in a wind-driven system, for instance due to an unpredictable element such as a new adjacent construction. Moreover, a wind-driven system would require a tower at least 6m higher than the roof, while the existing tower is only 1.2 m higher. Since this is a small single storey residential building, such a taller tower may limit the wider applicability of this type of tower due to planning permission related problems. Indeed this is normally regulated by law. Furthermore, this will reduce the potential of using PV on the roof if the tower cannot be placed adequately.

Having changed the driving force, different building configurations have been tested, focusing especially on the performance of outlet openings. Both DTM and CFD have been used to establish whether the new solutions are viable or not and to predict their likely performance in terms of energy savings and thermal comfort.

4.3. Dynamic thermal modelling

DTM has been used to estimate mean and peak CO₂ and moisture content levels, energy consumption and likely water consumption of the system. For this research, IES-VE (IES-VE, 2014) was used as the DTM tool.

First, a base-case model of the house was built using the detailed information described within the German simulation report (Team HFT Stuttgart, 2010), and validated with results from the German TRNSYS (TRNSYS, 2014) model. Since this research focused on summer conditions, the main element of comparison has been the annual energy demand for space cooling in Madrid. The cooling demand for one year in Madrid estimated by TRNSYS was 2234 kWh, while IES-VE predicted 2262.4 kWh. Such a close agreement is thought to be due to the high quality of the data available to the authors (e.g. geometry, construction materials, occupancy profiles, heat gains and weather data). Thermal characteristics of the elements of the building are summarised in Table 2. A minimum hygienic air flow rate of 0.4 ACH or 60 m³/h for two people was assumed (Team HFT Stuttgart, 2010). A 26 °C set point temperature has been chosen for the cooling system.

In general, when an element, such as the occupancy schedule or the use of shading devices depends on time or on other parameters such as the temperature, the appropriate profile has been created within the model.

The PDEC system has been modelled within the DTM using the simplified approach known as the 'post-processing method' (Robinson et al., 2004), since this is suitable for testing the applicability of this system in many locations.

Table 2. U-value of the elements of the building.

Element	U-value (W/m ² K)
Wall façade	0.16
Ceiling	0.11
Floor	0.10
Wall groove	0.13
Wall tower	0.31
Wall north – south	0.13
Triple glazing (north)	0.40
Triple glazing (other)	0.52
Frame (tower)	1.80
Frame (other)	1.00

In particular, the temperature T_{air} of the air entering into the living space through the tower has been estimated using the following mathematical relationship (Robinson et al., 2004):

$$T_{\text{air}} = \text{DBT} - \alpha(\text{DBT} - \text{WBT})$$

where:

DBT = dry bulb temperature (°C)

WBT = wet bulb temperature (°C)

α = effectiveness of the evaporative cooler (-)

Using this relationship, a ventilation system has been implemented in IES-VE with its cooling temperature profile (Table 3) and control strategy (Table 4). TA indicates the ambient temperature inside the conditioned space and g is the moisture content of the ambient air. The 'Else' condition (Table 3) is defined only in order to satisfy software requirements. Indeed the system does not operate if DBT is lower than 26 °C (Table 4).

Based on the air change rate, the likely water volume usage V_w is:

$$V_w = \rho_a V_a (g' - g) \rho_w^{-1} \cdot 10^3 \text{ (m}^3\text{)}$$

where

ρ_a = air density (1.2 kg/m³)

V_a = air volume (m³)

g' = moisture content of the air exiting from the evaporative cooler (kg/kg)

g = moisture content of the air entering into the evaporative cooler (kg/kg)

ρ_w = water density (1000 kg/m³)

The initial value for the ventilation rates is 900 m³/h (Team HFT Stuttgart, 2010) and α has been assumed equal to 0.80, since this is the typical effectiveness of evaporative coolers (Salmerón, Álvarez, Sánchez, Ford, & Gillott, 2012).

Essentially, for each location, two simulations with the same set-point temperature for the active cooling system have been used, but one with the PDEC system and one without. The difference in

Table 3. Evaporative cooling temperature profile.

Condition	Temperature
DBT > 26 °C	$T_{\text{air}} = \text{DBT} - \alpha(\text{DBT} - \text{WBT})$
Else	$T_{\text{air}} = \text{DBT}$

Table 4. Evaporative cooling ventilation profile.

Condition	Status
(DBT > 26 °C) and (TA > DBT - α(DBT - WBT)) and (g ≤ 15 g/kg)	On
Else	Off

terms of kWh required for space cooling represents the contribution of the tower. Then, the acceptability of the IAQ has been evaluated comparing simulation results with best practice thresholds given by CIBSE (2006) and ASHRAE (2004). In this study, CO₂ levels have been used as a proxy for the IAQ evaluation.

4.4. CFD modelling

The 'post-processing' method for modelling a PDEC system requires that the hypothesised ventilation rates are actually realised in practice (Robinson et al., 2004). CFD analysis was used in this research mainly for this reason, but also to predict fresh air distribution, IAQ and cooling potential.

For this study, Phoenics CFD (Cham, 2015), a general-purpose commercial CFD code which uses a finite-volume solution algorithm, was chosen. For the construction of the model some simplifications were made, taking into account both accuracy and time required for a converged solution to be reached. External walls and windows had the same dimensions that they have in the DTM. The tower was implemented with openings at the top and at the bottom. Those at the top were supposed to operate as inlet. In other words, the outside air was supposed to enter through them into the tower. The openings at the bottom were expected to be the outlet, which means that through them the cooled air was supposed to pass from the tower to the living space.

The PDEC system has been modelled within the tower using five plates that are two-dimensional surfaces with infinitesimal volume as negative heat sources. The horizontal and vertical dimensions of each plate are 1.65 and 2.85 m, respectively. Each plate has two faces, therefore, in total there are 10 faces, and, at the point in time of the year chosen for the CFD simulation, the cooling load met by the tower is 2780 W (see Section 5.2.7). Thus, a negative heat flux equal to -278 W (2780 W divided by 10) was specified as the boundary condition on each face. This simplified approach does not affect the ACH calculation, which is the main reason for using CFD in this study, and the simulation of the temperature distribution within the building, but reduce the complexity of the model, and, therefore, the uncertainties and the required computational power. Two additional plates have been inserted within the conditioned space in order to simulate the internal gains. However, they have been placed in a position that does not increase the minimum number of mesh regions, which is defined by the CFD tool. For all openings, pressure loss through the opening is related to the flow through the opening via the orifice flow equation

$$\Delta P_{\text{loss}} = 0.5f\rho U_n^2$$

where

$f = 1/C_d^2$ loss coefficient (2.69)

C_d = discharge coefficient (0.61)

ρ = air density (1.2 kg/m³)

U_n = normal velocity to the opening (m/s)

The turbulence model used was the two differential equation k - ϵ Chen–Kim model (Chen & Kim, 1987). Previous studies have adopted two-equation k - ϵ models, such as the RNG k - ϵ model (Durrani, Cook, & McQuirk, 2015; Nguyen & Reiter, 2011). In this study, the Chen–Kim model was used because

it is a good compromise between accuracy and economy (Wu, 2010). In a standard k - ε turbulence model, the turbulent kinetic energy, k , and the turbulent dissipation, ε , are computed from two differential transport equations. The Chen–Kim model is an improved version of this type of model. In particular, the dynamic response of the ε equation is enhanced by introducing an additional time scale, k/P_k , where P_k is the volumetric production rate of k . This modification resulted in one extra term along with one extra modelling constant added to the standard k - ε model. Moreover, the standard-model coefficients are also adjusted. Thus, the coefficients used in this model are (Chen & Kim, 1987)

$$\sigma_k = 0.75 \quad \sigma_\varepsilon = 1.15 \quad C_1 = 1.15 \quad C_2 = 1.9 \quad C_3 = 0.25$$

Standard wall functions (Phoenix Wall Functions, 2017) are used to connect the wall conditions to the dependent variables at the near-wall grid node.

The density of the air is essentially assumed to be constant, except for the buoyancy term in the momentum equation where it is written as

$$\rho = \rho_0 [1 - \beta(T - T_0)]$$

where

ρ = fluid density at temperature T (kg/m³)

ρ_0 = fluid density at reference temperature T_0 (kg/m³)

β = coefficient of volume expansion (1/K)

The global convergence criterion was set equal to 1.00%. The user guide (Wu, 2010) does not suggest a particular value. In other studies, this parameter was also set equal to 1.00% (Nguyen & Reiter, 2011). For this study, a powerful i7-3630QM CPU was used.

In this study, an orthogonal mesh was used and a mesh sensitivity analysis completed (Table 5). Balancing quality and time required, the adopted mesh is the 006 case. The time required to complete the 006 mesh was 10 hours and 36 minutes.

Steady-state CFD simulations were run only for one specific point in time and for one location. The chosen location was Athens due its higher potential for PDEC application. Indeed climatic conditions are favourable and it also has a huge number of inhabitants and, therefore, potential applications. The point in time chosen was the 2 June at 17:30, because at this time the cooling tower was predicted to supply the entire required cooling. Therefore, the effect of the tower can be isolated and the potential sources of error minimised.

Boundary conditions for this point in time were exported from DTM to CFD. These include temperature of the internal surfaces, outside temperature, internal heat gains, and heat removed by the evaporative cooler within the tower.

ACH were used for comparison between DTM and CFD. An iterative process (Figure 5) was used to compare and improve the models until the difference between values used in DTM and predicted by CFD had become lower than 10%.

Inlets at the top of the tower have been assumed to be open in every simulation, while four outlet configurations have been tested (Table 6). According to the central position of the tower (Figure 6), a

Table 5. Mesh sensitivity analysis results, in red the adopted mesh.

Case	Cells	Iterations	Time required (s)	ACH (1/h)	Variation (%)
001	62,040	1500	877	6.99	4.76
005	65,042	1500	954	6.93	3.91
002	360,000	8000	25,980	6.91	3.67
006	420,750	10,000	38,160	6.66	0.00
004	570,000	12,000	58,260	6.60	-0.87

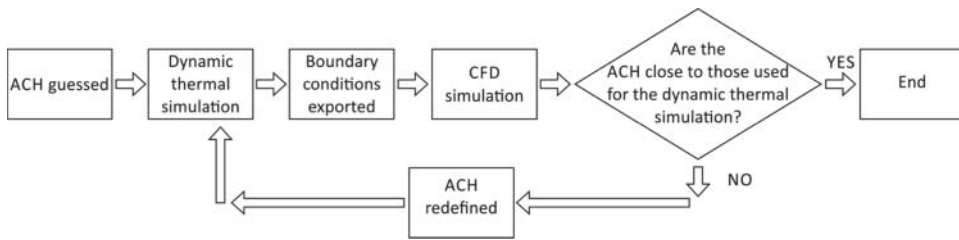


Figure 5. Iterative process used to compare and improve the models.

more homogeneous air distribution was expected with south and north facing windows opened. Moreover, the chosen configurations do not imply significant changes in the existing openings, avoiding high additional costs.

Using the ACH value automatically calculated by Phoenics for the entire building might lead to an overestimate of the ACH value since it is possible that a very small amount of air enters and exits from the top of the tower without actually passing through the cooling device. For this reason, the value of ACH for the comparison and use in IES-VE is calculated using the following formula:

$$\text{ACH} = \frac{\dot{V}_{\text{air}}}{\rho_a V_{\text{SDH}} \cdot 3600}$$

where

\dot{V}_{air} = net air flow rate entering from the inlets at the top of the tower (kg/s)

ρ_a = air density (1.2 kg/m³)

V_{SDH} = volume of the building (m³)

4.4.1. CFD model validation

The heat transfer coefficient is the key parameter used to compare the model with the real ventilation tower. This coefficient depends on the cooling load met by the tower at a certain point in time, the air temperature variation inside the tower at the same point in time, and the heat exchange area. Since the geometry of the tower has not been modified, this coefficient will not vary, and therefore the validation of the model is done comparing the value measured with the full size experimental setup and the value calculated based on the simulation results. The numerical comparison is given in Section 5.2.7.

4.5. Extension of the results to the other locations

Having completed a detailed CFD analysis in one location, results were extended to other using only DTM. The same ACH estimated at Athens for OC1 (Table 6) have been used and only the

Table 6. Outlet openings configurations (OC).

Simulation	Outlet openings configuration
OC1	Lower part of 4 and 9 open
OC2	Higher part of 4 and 9 open
OC3	5 and 10 fully open
OC4	All south and north facing are open

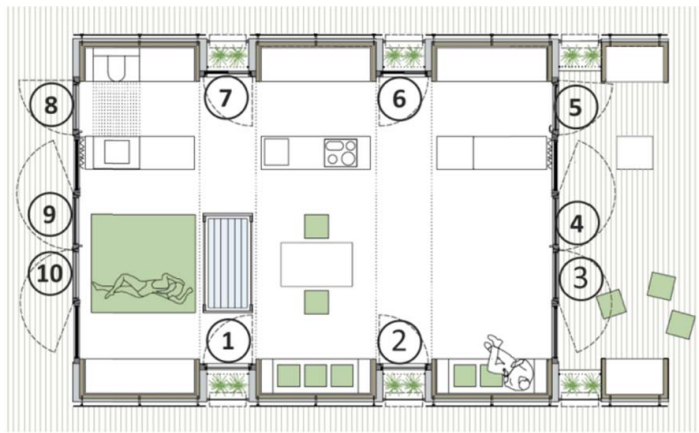


Figure 6. ‘Home+’ floor plan (Masseck & Tárrega 2010) with the possible outlet openings numbered and the tower highlighted in blue.

weather-data file has been changed. The features described above, such as energy consumption, have been then analysed for each location.

5. Results and discussion

5.1. Climate analysis

Results are expressed in percentage of hours of the year in which direct evaporative cooling could work. This does not mean that the developed and tested system operates this number of hours, but is an approximate method for comparing different macro climatic conditions. Only eight locations were chosen (Table 7), all of which have an annual potential for evaporative cooling higher than 7.0%.

Phoenix has by far the largest potential because, although it has about the same WBT values as the other locations (Figure 7), it has a significantly larger WBD (Figure 8). In European locations, the WBT exceeds 22 °C, which is the upper limit for the applicability of direct evaporative cooling in developed countries (Givoni, 1992), only in slightly more than 2% of the hours of the year in Athens and Sevilla, and even less in the other European locations.

5.2. Performance analysis for Athens

For convenience dynamic thermal and CFD outputs are presented together, but the iterative solving process described in the methodology section should be kept in mind.

Table 7. Selected locations, plus Phoenix, showing the potential for direct evaporative cooling.

Location	Potential January–December (%)	Potential May–September (%)
Cordoba	13.5	31.3
Sevilla	12.7	27.4
Zaragoza	7.4	17.8
Athens	10.1	24.1
Thessaloniki	7.7	18.3
Evora	7.5	17.4
Foggia	8.2	19.5
Catania	8.8	20.3
Phoenix	33.5	58.8

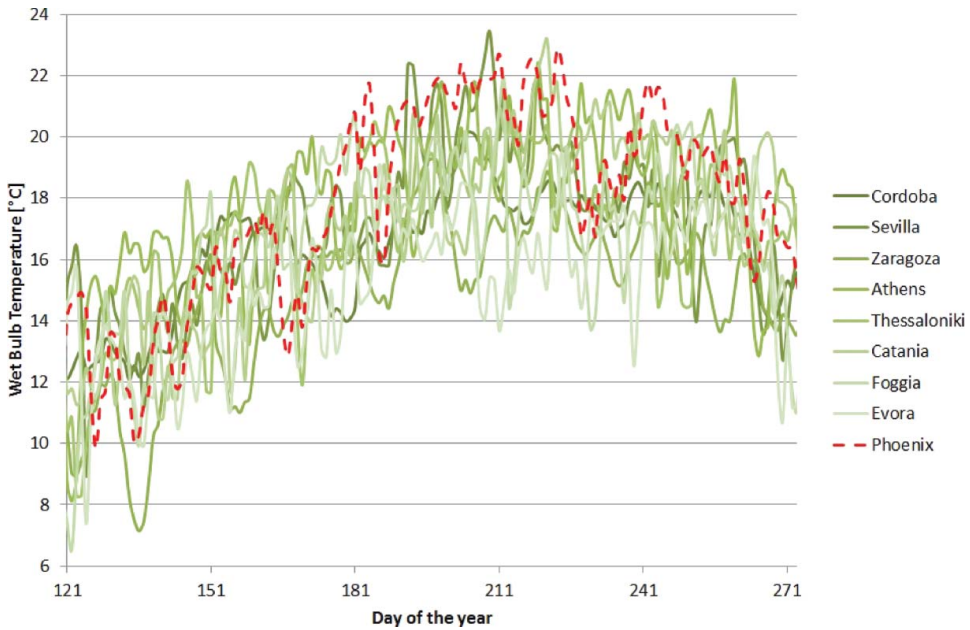


Figure 7. Wet bulb temperature (daily mean value) from May to September for the selected eight European locations plus Phoenix.

5.2.1. Energy demand for space cooling

Having set the maximum ACH in DTM, the annual energy demand for space cooling is 4430 kWh (79.1 kWh/m²). The contribution of the cooling tower is 1691 kWh (30.2 kWh/m²), while the remaining cooling load, 2740 kWh (48.9 kWh/m²) has to be satisfied using other systems. Thus, the tower satisfies 38% of the annual energy demand for space cooling. If the tower was the only cooling system used within this building, the temperature would significantly rise over 26 °C.

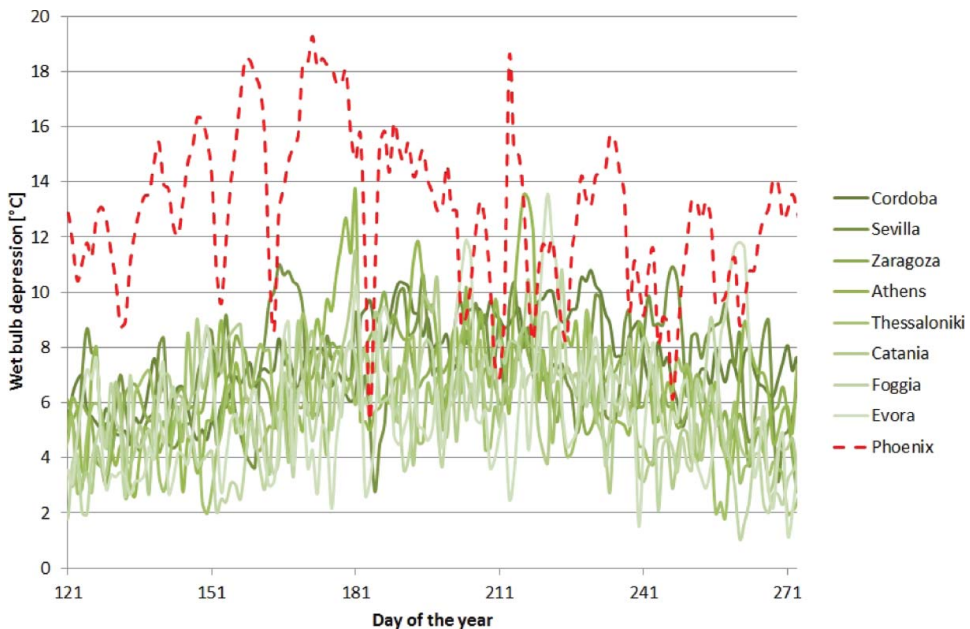


Figure 8. Wet bulb depression (daily mean value) from May to September for the selected eight European locations plus Phoenix.

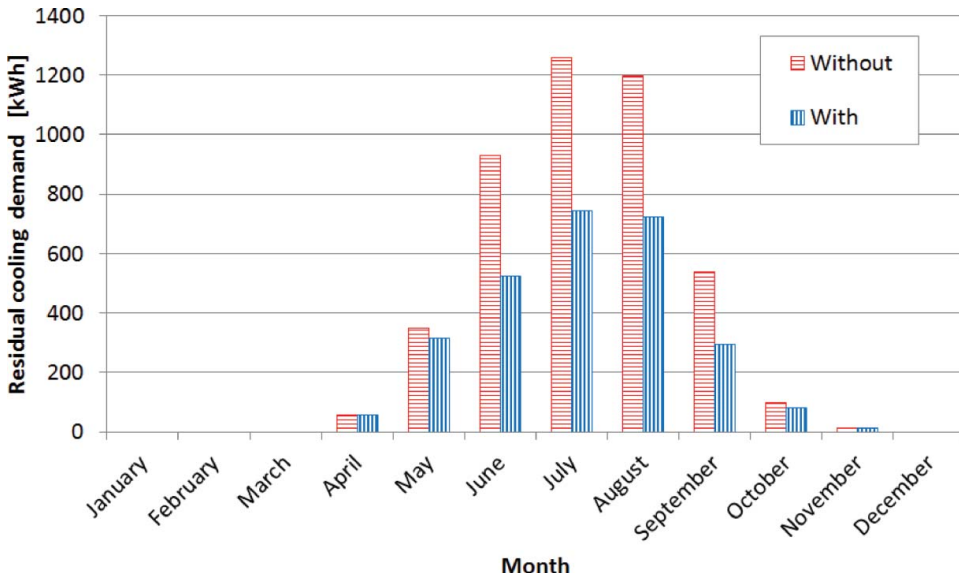


Figure 9. Monthly residual space cooling energy demand for Athens with and without the effect of the cooling tower.

The contribution of the tower is stable over the summer months, indeed between June and September it fluctuates between 40% and 43% of the energy required for space cooling (Figure 9). However, due to the variability of DBT, WBT and indoor moisture content, the effect slightly varies day by day.

Daily profiles for residual space cooling loads (Figure 10) show how these loads may be significantly reduced or even nullified by using the PDEC system. This is the condition that was used for choosing the point in time for the CFD analysis because no other negative heat source has to be implemented within the model and the possibility of modelling mistakes is lowered.

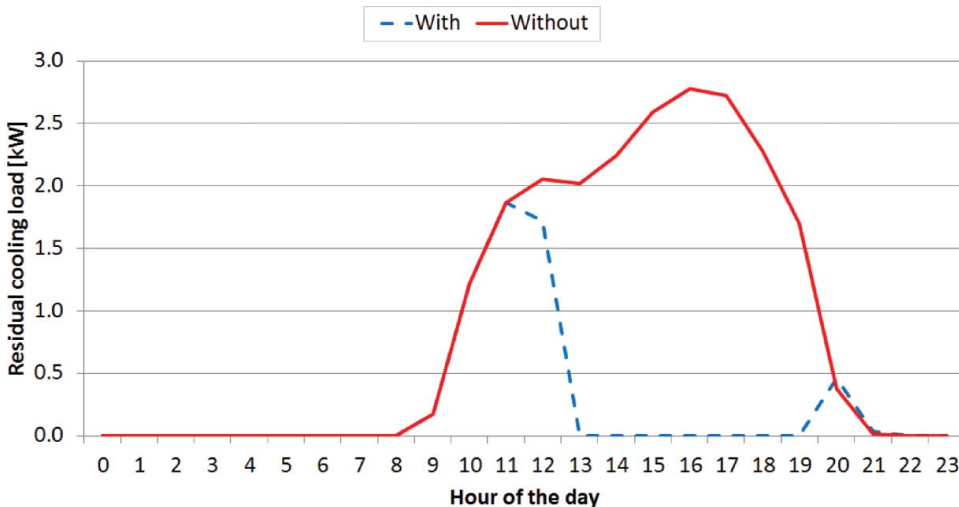


Figure 10. Hourly residual cooling load with and without the effect of the cooling tower on the 2 June.

5.2.2. PDEC system water consumption

The correct prediction of the water consumption is important at least for two reasons. First, PDEC has a huge potential in dry areas, in which an adequate water supply may be problematic. Therefore, the water consumption has to be estimated and guaranteed, otherwise the system cannot operate. Then, the better the prediction of the water consumption is, the more suitable the circulation pump may be. This leads to an optimised solution, with the minimum energy requirements.

Having defined this α value, the likely air change rates were estimated using CFD simulations, while the moisture content was evaluated with psychrometric relations (Jones, 1994). The real efficiency α would have been known only if a multi-phase CFD analysis had been completed and, possibly, real models had been built and tested.

In Athens, a mean water flow rate of 5.9 litres per hour is predicted for the PDEC system running for 1471 hours. These estimates are significantly affected by air volume flow rate and moisture content of the air entering from the evaporative cooling tower and entering into the conditioned space. These depend on the actual efficiency of the evaporative cooler system α , which was assumed to be 80%.

5.2.3. CO₂ and moisture content levels

Moisture content and CO₂ levels within the house were estimated by using DTM. Best practice CO₂ threshold given by CIBSE and ASHRAE are, respectively, 900 (CIBSE 2006) and 1000 ppm (ASHRAE 2004).

The moisture content has a mean value of 9.4 g/kg, while the CO₂ level never exceeds 833 ppm and its mean value is 770 ppm. These values show how the PDEC system allowed for a significant reduction of the residual energy demand for space cooling without jeopardising the IAQ.

5.2.4. Quality of the CFD simulations

The reliability of the CFD simulations was tested by monitoring values of the dependent variables and the equation residuals during the CFD iteration procedure. According to the chosen turbulence model, spot values and residuals are given for pressure (P1), velocities (three components: U1, V1, W1), kinetic energy (KE), potential energy (EP) and temperature (TEM1).

Convergence was reached in each of the four cases, namely OC1, OC2, OC3 and OC4 (Table 6). Indeed, in each simulation, the residuals became smaller than the chosen cut-off limit, 1.00%. Moreover, spot values of the dependent variables became steadier iteration after iteration.

5.2.5. Air change rates

Air change rate is the main parameter for comparison between CFD and DTM. Boundary conditions were exported from an IES-VE simulation in which the air change rate was set equal to 6.3 h⁻¹ and nearly the same values have been estimated in CFD. Indeed air change rates predicted by using CFD are 6.6 h⁻¹ for OC1, 5.6 h⁻¹ for OC2, 6.6 h⁻¹ for OC3 and 6.9 h⁻¹ for OC4.

These values exceed the minimum value recommended within design standards. CIBSE values for bedrooms and living rooms in dwellings are 0.4–1 ACH and 60 l/s for kitchens (CIBSE 2005). ASHRAE standard 62 (2013) indicates 2.5 l/s per person as the minimum ventilation rates in breathing zone (ASHRAE 2013). In the 'home+', 6.3 h⁻¹ is equal to 957 m³/h or 266 l/s. Thus, the minimum values were always guaranteed within the building, but, more important, when the tower was working, it provided with higher ventilation rates and, therefore, with better IAQ.

5.2.6. Temperature and air velocity profiles

Both velocities and temperatures are directly relevant for testing the research hypothesis. Indeed if the former had been too big or the latter too erratic, the applicability of this ventilation tower in plus-energy homes would have been reduced or nullified.

Velocities are always low (Figures 11 and 12), as expected in a buoyancy-driven system. Temperatures appear quite uniform inside the conditioned space when a horizontal section is considered, as

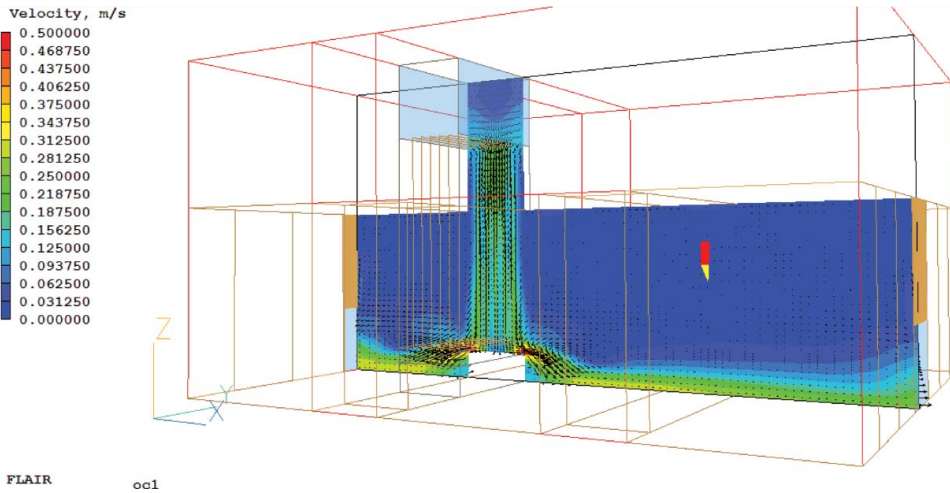


Figure 11. OC1 case: velocity distribution inside the conditioned space.

the one taken at 1.50 m above the floor in OC1 case (Figure 13). There is only a difference up to a 0.5 °C between south and north facing parts of the conditioned space. A vertical temperature profile highlights how temperatures gradually increase with the height within the living space, while they dramatically decrease going downwards inside the tower (Figure 13).

CFD analysis has also highlighted that when most of the outlet openings are opened (OC4) there is a local effect close to the south and north facing openings inside the living space. Indeed a relevant amount of warm air was coming in and going out through them (Figure 12), while with the other opening configurations (Figure 11) there was no warm air coming in through them. This does not jeopardise the effectiveness of the tower, but it generates local discomfort effects because air becomes warmer and therefore occupants that are next to these openings experience a less comfortable environment.

5.2.7. CFD model validation

Given the assumptions stated in the methodology, in Athens on the 2 June at 17:30 the cooling load met by the tower is 2780 W, the air temperature variation inside the tower is 10.06 K, and the heat

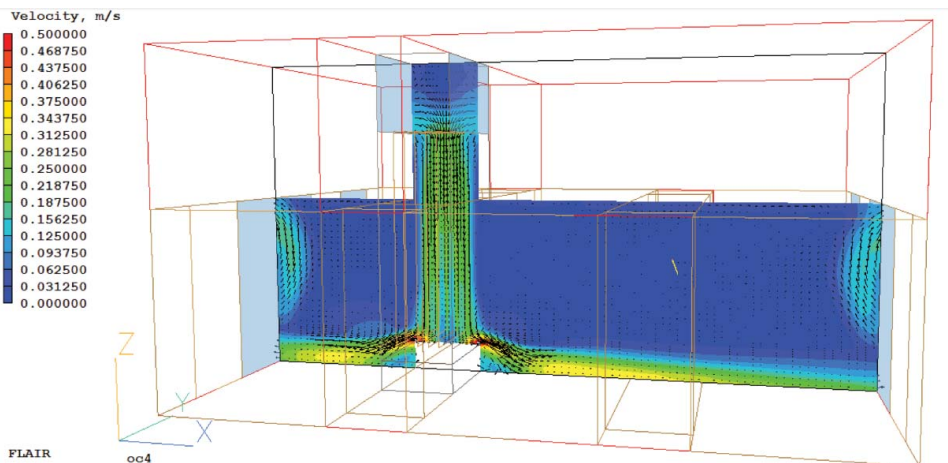


Figure 12. OC4 case: velocity distribution inside the conditioned space.

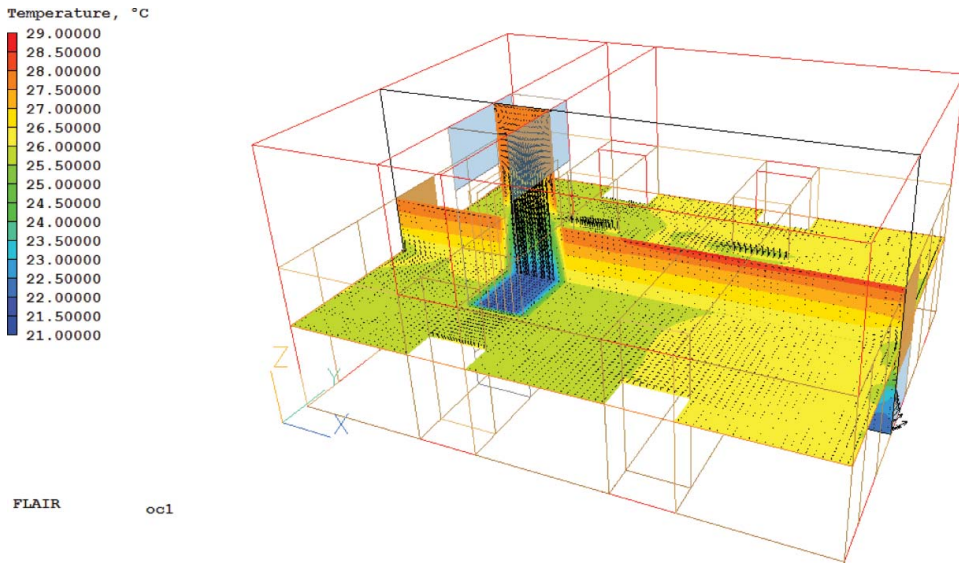


Figure 13. Temperature distribution inside the conditioned space.

exchange area is 47.025 m^2 . Thus, the 'simulated' heat transfer coefficient is equal to $2780/(47.025 \times 10.06) = 6.90 \text{ W/m}^2\text{K}$, which is close to the experimental value of $7.0 \text{ W/m}^2\text{K}$ (Schneider, 2010). Therefore, the simplifications made based on previous research and the chosen modelling technique were considered to be accurate.

5.3. Performance analysis for other southern European locations

5.3.1. Energy demand for space cooling

Different locations and points in time would have various optimal opening configurations, but there is no reason to expect that the performance of the cooling tower would be significantly lower.

The maximum energy demand for space cooling is in Sevilla (Table 8), both with and without the tower, closely followed by Cordoba. However, the maximum effect in absolute terms takes place in Cordoba, with a reduction of around 2000 kWh, 47% of the total annual cooling load.

DTM results confirm most of the Climate Consultant predictions. For instance, around the same potential was predicted in Evora, Zaragoza and Thessaloniki and indeed the contribution of the tower is, respectively, 1335, 1324 and 1275 kWh in these locations. However, due to different climates and, therefore, different annual energy demand for space cooling, the need for back-up systems varies and the lowest back-up requirement in percentage value, 48%, is reached in Zaragoza (Table 8).

Monthly energy demand for space cooling has nearly the same pattern in all locations: the peak is reached in July and the tower does not affect this pattern (Figure 14). Moreover, a noticeable amount of cooling from other sources is required in July and August, especially in the warmest locations. For instance, the contribution of the tower expressed in kWh has nearly the same value from June to

Table 8. Residual annual energy demand for space cooling with and without the cooling tower.

	Cordoba	Sevilla	Zaragoza	Thessaloniki	Evora	Catania	Foggia
Without (kWh)	4257	4903	2563	3347	2818	3139	2700
(kWh/m ²)	76.0	87.5	45.8	59.8	50.3	56.1	48.2
With (kWh)	2253	3196	1239	2072	1483	1728	1467
(kWh/m ²)	40.2	57.2	22.1	37.0	26.5	30.9	26.2
Difference (kWh)	2004	1707	1324	1275	1335	1411	1233
(%)	47	35	52	38	47	45	46

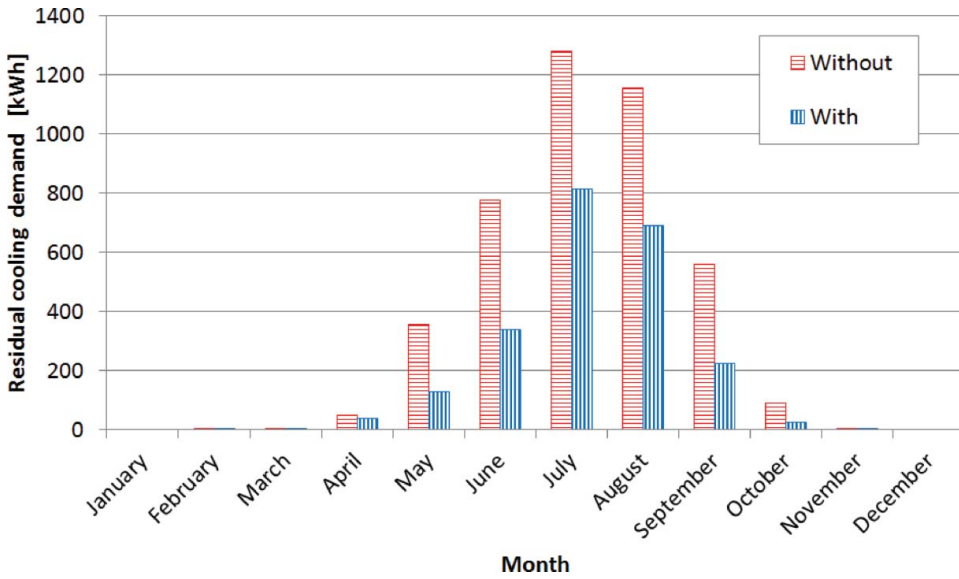


Figure 14. Monthly residual space cooling energy demand for Cordoba with and without the effect of the tower.

August (Figure 15) at Cordoba, around 450 kWh. However, when this is analysed in percentage terms, the curve on the graph assumes a sort of M shape due to a combination of less dry air, greater solar gains and higher DBT.

In relationship to the research hypothesis, cooling tower can therefore halve the energy demand for space cooling in southern European plus-energy homes and they can be effective even with a shorter tower than those that previous studies proposed for non-residential building.

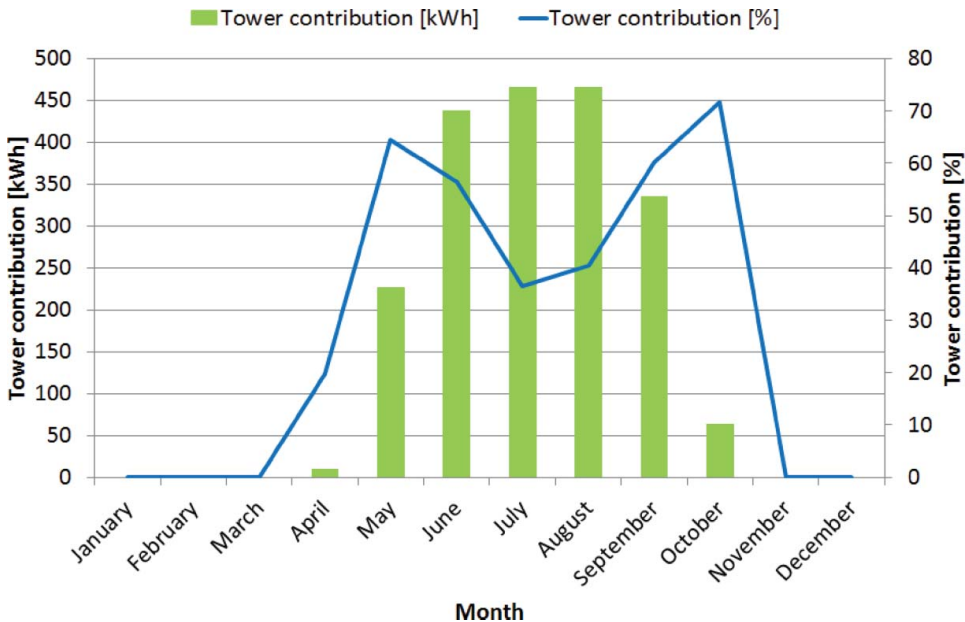


Figure 15. Monthly space cooling energy contribution of the tower in absolute and percentage terms for Cordoba.

Table 9. Water consumption of the direct evaporative cooling system and number of hours in which the tower works.

	Cordoba	Sevilla	Zaragoza	Thessaloniki	Evora	Catania	Foggia
Mean water consumption (l/h)	7.7	7.2	6.2	5.8	6.4	6.6	6.3
Peak water consumption (l/h)	14.4	13.9	10.9	10.9	8.5	14.3	12.8
Time of operation (h)	1499	1437	898	1010	897	1155	975

Table 10. Mean CO₂ levels inside the conditioned space.

	Cordoba	Sevilla	Zaragoza	Thessaloniki	Evora	Catania	Foggia
Mean CO ₂ level (ppm)	746	749	779	774	781	762	775

Further studies may investigate how the residual energy demand could be satisfied. An optimised overall design should integrate passive technologies that allow to keep loads satisfied by active systems not too erratic, avoiding the need for big and expensive back-up active systems.

5.3.2. PDEC system water consumption

The estimation of the water required in order to cool down the expected air flow rate (Table 9) shows that the driest locations, namely Cordoba and Sevilla, have the highest mean values. These two places are also characterised by the biggest number of hours in which the system can operate (Table 9).

5.3.3. CO₂ and moisture content levels

Results of this research demonstrate how best practice CO₂ thresholds are never reached in any of the locations considered, 833 ppm being the highest predicted value with significantly lower mean values (Table 10). These estimates are based on two occupants. According to the chosen control strategy, the PDEC system does not operate when the moisture content within the house exceeds 15 g/kg. Mean levels are between 8.41 g/kg, at Zaragoza, and 10.13 g/kg, at Catania, significantly below this threshold.

Thus, also in these seven southern European locations the cooling tower can significantly reduce the residual energy demand for space cooling without jeopardising the IAQ.

6. Conclusions

The research reported in this paper aimed to address one research question: are evaporative cooling towers an important element of plus-energy houses in southern Europe? In order to achieve this aim, the performance of a PDEC system implemented within the ventilation tower of an existing plus-energy house was predicted in eight locations using dynamic thermal simulations and CFD. The models were validated comparing the simulation results with either results of models that had been previously validated with experimental data, or directly with parameters determined from experiments.

The key findings of this research are as follows.

- Dynamic thermal simulations carried out for eight different locations demonstrated that a ventilation cooling tower integrated within a plus-energy home can halve its annual energy demand for space cooling. For example, in Zaragoza, it drops from 45.8 to 22.1 kWh/m².
- Avoiding the exploitation of the wind effect made the performance of the tower more predictable.
- CFD simulations were used to integrate the dynamic thermal model results. Acceptable ventilation rates are achieved, fresh air is almost uniformly distributed across the conditioned space, and air velocities never exceed 0.5 m/s, avoiding the risk of an unpleasant elevated air movement. However, possible local discomfort is noted when large numbers of outlets are opened.
- Predicted mean and peak CO₂ and moisture content levels also indicate an acceptable IAQ.

However, this does not mean that every plus-energy home in these regions must have a ventilation cooling tower. Findings simply indicate that it may be an efficient solution and methods for testing its performance in other buildings and locations are suggested within this study.

6.1. Limitation of this research and further studies

The limitations of this research provide a basis for further work as follows.

- The availability of more field data from experimental facilities would have two important consequences: the models would be better validated by comparing data over time, and also new ideas and solutions might be suggested by the field data itself.
- The present research analysed in detail one component: the tower. The complete implementation of all technological systems of the plus-energy home into the same model would lead to a more complete solution, in which their operation is optimised.
- A more complex climatic analysis could have been used to investigate the role of the ventilation tower under future climatic conditions.
- Occupants' thermal comfort is a combination of physical and psychological aspects. Different models have been developed, but little is known about thermal comfort in low energy residences, such as passive and plus-energy houses. Thus, more research is needed to investigate what conditions, such as temperature and relative humidity, are expected by occupants in these types of houses, since this is the main driver for their energy consumption.
- A detailed economic analysis would provide a comparison of both initial and running costs of different energy efficient solutions, such as the ventilation cooling tower presented in this paper.

Notes

1. EnergyPlus weather file format.
2. International Weather for Energy Calculations format from ASHRAE.
3. Italian Climatic data collection 'Gianni De Giorgio'.
4. Synthetic data for Portugal - Instituto Nacional de Engenharia, Tecnologia e Inovação.
5. Spanish Weather for Energy Calculations.

Acknowledgments

This research was financially supported by the Engineering and Physical Sciences Research Council (EPSRC) via the London-Loughborough Centre for Doctoral Research in Energy Demand (LoLo). The authors are grateful to Professor Markus Binder, Antoine Dalibard, Xavier Jobard and Jasmin Janiak from Hochschule für Technik – Stuttgart whose research provided the basis of the idea for this study.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was financially supported by the Engineering and Physical Sciences Research Council (EPSRC) via the London-Loughborough Centre for Doctoral Research in Energy Demand (LoLo) [grant number EP/H009612/1].

Notes on contributors

Francesco Babich is a PhD researcher and university teacher at Loughborough University (UK). He is part of the London-Loughborough (LoLo) EPSRC Centre for Doctoral Training in energy demand.

Malcolm Cook is professor of building performance analysis and associate dean (research) at Loughborough University (UK).

Jan Cremers is professor for building technology and integrated architecture at the Faculty of Architecture and Design at Hochschule für Technik/University of Applied Sciences, Stuttgart (Germany).

George Papachristou is a PhD researcher at Loughborough University (UK). He is part of the London-Loughborough (LoLo) EPSRC Centre for Doctoral Training in energy demand.

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