Chapter 22
Geo-Climatic Applicability of Direct Evaporative Cooling in Italy

Giacomo Chiesa, Fabio Acquiletti, and Mario Grosso

Abstract This chapter focuses on the climatic applicability of passive direct (downdraught) evaporative cooling (PDEC) techniques in the provincial capital cities of Italy. First, a PDEC potentiality map was produced using a previously developed method based on three variables: wet bulb depression, summer comfort air temperature threshold (25 °C) and cooling degree hours (CDHs). Second, an applicability map was produced by comparing the PDEC potentiality map to the local cooling energy demand. Third, a new method is presented including a calculation of the residual local cooling energy demand, i.e. residual CDH, related to air treatment by direct evaporative cooling. These residual CDH values were calculated considering different step-wise increasing outlet temperatures (WBT; WBT + 1 °C; . . .; WBT + 5 °C) as a function of the covered amount of wet bulb depression. Finally, three cities chosen as being representative of their respective Italian climatic macro-zones were selected in order to assess in greater detail the yearly variation of CDH aimed at supporting specific design strategies for ventilative passive cooling solutions.

Keywords Climatic applicability • Direct evaporative cooling • Passive cooling • GIS analysis

Nomenclature

WBT	Wet bulb temperature
DBT	Dry bulb temperature
dWBT	Wet bulb depression
CDH	Cooling degree hours
ext	External
int	Internal
T_{set}	Set-point temperature

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$T_{c,a}$	Temperature of comfort for adaptive model
$T_{ext,a}$	External running mean temperature
φ	Humidity rate [%]
X	Water vapour in mass unit of dry air [kg/kg]
PDEC	Passive direct (downdraught) evaporative cooling

1 Introduction

Energy consumption for air conditioning is a rising concern in the national energy balances of several countries, influencing the cost of electricity and the need for more power plants [1, 2]; in addition, it spurs increases in CO_2-equivalent emissions, a factor in global warming [3]. As stated by the European Union Directive EPBD 2010/31/EU for nearly zero-energy building and considering future perspectives on net-positive-energy buildings, it is essential to develop and diffuse alternative technologies for cooling based on passive and hybrid solutions. Recent studies report that passive direct evaporative cooling (PDEC) towers could be applied to the majority of European building stocks [4, 5] – more than 70 % – and cover from 25 to 85 % of the cooling energy load depending on local climatic conditions [4]. Hence, evaporative cooling seems to be a suitable solution for guaranteeing indoor thermal comfort, especially in southern Europe [6].

Recently, several studies have mapped the climatic applicability of PDEC techniques in Europe [6], Spain [4, 6] and China [7] and the suitability of evaporative air conditioning [8]. Following these examples, this chapter aims at analysing the suitability of PDEC techniques in Italy for achieving comfort conditions through the following steps. First, an already consolidated methodology used in [4, 6, 7] is applied to map the performance of PDEC systems as a function of new hourly typical meteorological year (TMY) data recently elaborated by the Italian Thermo-technical Committee (Comitato Termotecnico Italiano) (CTI) in Italian provincial capital cities [9]. This database considers recent climatic variations showing large differences with other climatic sources (AHSRAE and the data collection “Gianni De Giorgio”) [10]. Second, a new method is proposed for evaluating PDEC performance as a function of residual cooling energy demand, expressed by the parameter residual cooling degree hours (CDHs), dependent on varying a PDEC system’s outlet air temperature. This method seems to be more effective in assessing the performance of PDEC systems in temperate climate zones, which are often characterised by a medium-low applicability of PDEC systems. Third, cooling energy demand is estimated for the reference locations against a fixed comfort air temperature threshold value (25 °C). Finally, three cities chosen as being representative of respective different Italian climate macro-zones (Turin for the northern zone, Rome for the central one, and Palermo for the southern one) are analysed in greater detail by studying the yearly distribution of CDHs and the performance of a PDEC system as a function of wet-bulb-depression.

2 Geo-Climatic Potentiality of Passive Direct Evaporative Cooling in Italy

Italy, with a territory lying between 35° and 47° northern latitude, is characterised by a wide range of climatic conditions. These conditions are affected by the presence of the Mediterranean Sea surrounding Italy's boundaries along more than three-quarters of their length as well as by the country's orography: the Alps chain in the north ranging from east to west and the Apennine Mountains crossing Italy from north to south. According to Köppen's classification, Italian climate types include Mediterranean, mild Mediterranean, humid subtropical, suboceanic, humid continental, cold continental and tundra (alpine territories). For this reason, even if the Italian climate could be generally classified as temperate, the applicability of passive and natural cooling techniques presents different potentialities throughout Italy's territory. This chapter analyses the Italian climatic applicability of PDEC systems based on the division of its territory in the provinces; hence there is no direct link to Köppen's classification. Each province is represented by the climate characteristics of its capital city, for which it is possible to use the hourly TMYs produced by CTI (2012–2014) based on directly monitored data. The geo-climatic PDEC applicability in locations other than a provincial capital city can be assessed by interpolating climatic data of the two nearest capital cities, as described in [9].

As reported in [11], the evaporative cooling potential, when long-term local climatic conditions are known and required comfort temperatures from the evaporative system are established, can be estimated using one or more of the following indicators:

– Yearly availability of PDEC cooled air achieving the desired comfort conditions;
– Average monthly temperature of cooling [air for direct evaporative cooling (DEC) and water for indirect cooling];
– Analysis of periods during which PDEC is unavailable, such as periods with high humidity or too hot conditions.

Furthermore, the cooling potential of evaporative cooling systems, without using pretreatment (e.g. dehumidification), is a function of the outdoor wet bulb temperature (WBT), which is the theoretical temperature limit that could be reached with a DEC system, and of the wet bulb temperature depression [dWBT, calculated from the difference between the dry bulb temperature (DBT) and the WBT]. In [11, 12] it is estimated that the outlet temperature from a PDEC system could be approximately 3 °C above the WBT, while in [13] it is suggested that this value be calculated by increasing the ambient WBT by 20–30 % of the dWBT. However, it is possible to use these considerations for estimating outlet temperatures from a PDEC system. Paragraph 3 shows the reduction potential in cooling demand with PDEC.

In this section, the method described in [4, 6, 7] is used. This compares cooling demand, opportunity and potential for using evaporative cooling. This method could be summarised as follows:

- Mapping the potential of PDEC systems ($DBT_{ext}-WBT_{ext}$, which corresponds to the wet bulb depression), the WBT was calculated using [14];
- Mapping the applicability of PDEC for reducing the cooling demand ($DBT_{int}-WBT_{ext}$, where the internal DBT is the comfortable indoor summer temperature, considered to be 25 °C);
- Drawing up a potentiality map of PDEC application, calculated by overlapping the two previous maps;
- Calculating cooling needs using CDHs [7] or the average difference of DBT indoor comfort temperature [5];
- Integrating the previous points in a synthetic map to evaluate the potentiality of PDEC according to cooling needs.

2.1 Potentiality Map of PDEC Application

The geo-climatic, that is site-dependent, potential of PDEC systems for reducing cooling demand in summer (June–August) was represented by a PDEC potentiality map (Fig. 22.1), which illustrates a classification of the average hourly wet bulb depression in Italy by four zones with the boundaries defined in [6] and dividing zone 3 into two subclasses. Figure 22.2 shows a classification of the average hourly difference between the indoor comfort cooling temperature (25 °C) and external WBTs for each Italian provincial capital city (four classes divided as defined in [6]). The Italian dWBT is principally characterised by low and medium values, while the difference between comfort and wet bulb temperatures are medium-high.

Overlapping the PDEC potentiality maps of Figs. 22.1 and 22.2, a potential PDEC applicability map for each reference province is drawn as shown in Fig. 22.3, which represents a range of classes from very low to very high potentiality. The categories of PDEC potentiality are assumed from the literature [6], with some differences as summarised in Table 22.1.

The PDEC potentiality map of Fig. 22.3 shows a prevalence of very low values, especially in northern Italy and near the coast, while low and medium conditions are distributed in the centre and in the south. Both Sardinia and Sicily are characterised by medium-low levels of potentiality.

2.2 Cooling Degree Hours and PDEC Potential

Although the PDEC potentiality map shown in Fig. 22.3 is not related to local cooling energy demand, it is possible to draw an analogous map where the PDEC potential applicability is calculated as a function of CDH based on 25 °C as an

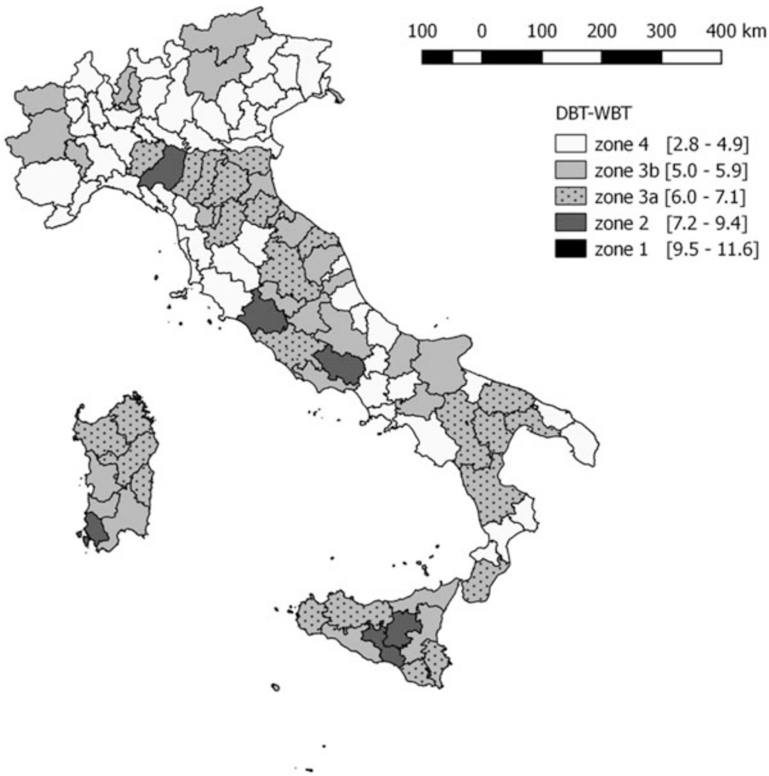

Fig. 22.1 Map of potential applicability zones of PDEC using as indicator the average hourly wet bulb depression

upper comfort limit for indoor air temperature. It is also possible to use the average difference in air temperature between local DBT and the set-point temperature for cooling, as reported in [6]. CDH data are calculated, for each reference location, using the following equation:

$$CDH = \sum (DBT - 25) \quad \text{for positive values.} \tag{22.1}$$

Results are shown in Fig. 22.4 and organised into five classes. Furthermore, Zone 1 (no need for cooling) is divided into two subclasses.

It is possible to assume 1000 CDHs as the minimum threshold for generating a demand for cooling [6]. As shown in Fig. 22.4, only three Italian provincial cities do not reach this limit, while the 33.6 and the 52.8 % show respectively a low and medium cooling energy demand.

The potential of PDEC systems could be estimated overlapping the potentiality map of Fig. 22.3 on the CDH map (Fig. 22.4). This resulting new map (Fig. 22.5) uses the classification presented in Table 22.2.

In particular, in the specific Italian conditions, Fig. 22.5 differs from Fig. 22.3 only in a few cases, showing good compatibility between PDEC potentiality and

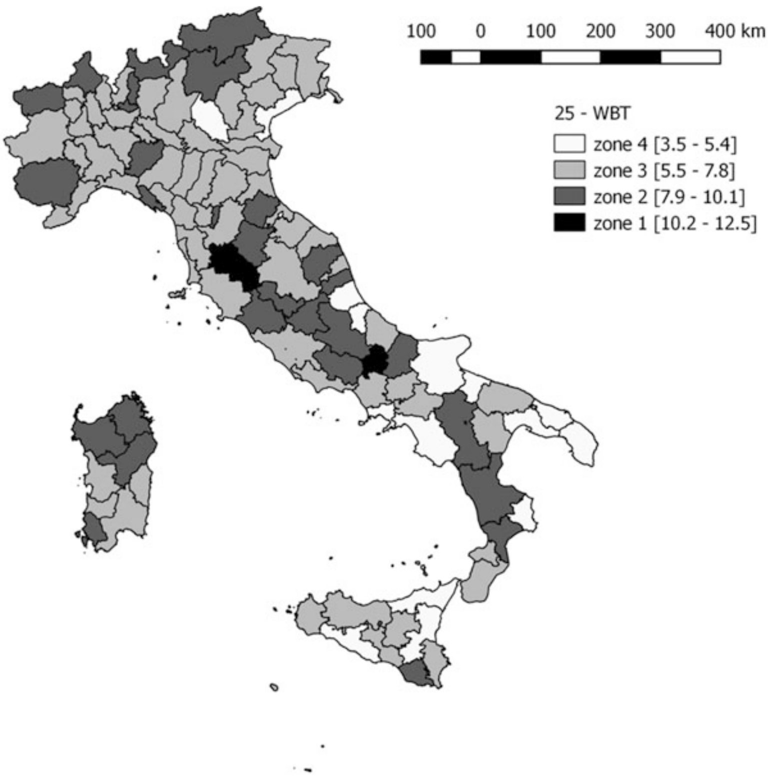

Fig. 22.2 Map of potential applicability zones of PDEC using as indicator the difference between indoor DBT set to 25 °C (as comfort reference) and outdoor WBT

cooling energy demand. To better analyse the geo-climatic applicability of PDEC systems, it is possible to use a new method based on the reduction in CDHs due to PDEC, as described in the following pages.

3 Cooling Energy Demand Reduction from PDEC Systems

3.1 PDEC Quantitative Potential in Reducing Cooling Demand

To assess in a quantitative way the PDEC potential in reducing the cooling energy demand in locations with low or medium applicability as shown in Fig. 22.5, the theoretical limit of the outlet air temperature from a PDEC system needs to be calculated. This is the WBT, even if, generally, the outlet value is some degrees above this limit [13, 15]. It is possible to estimate that, after a DEC treatment, the

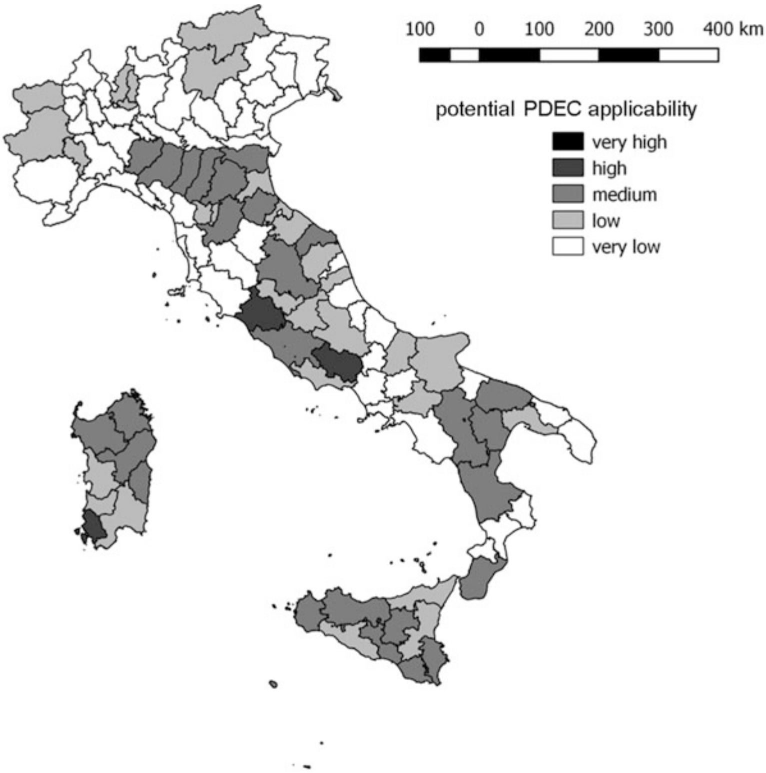

Fig. 22.3 Map of potential PDEC applicability by a classification based on method presented in [6]

Table 22.1 Categories of PDEC potentiality used for Fig. 22.3 (elaborated from [6])

		25-WBT			
		Zone 1 [10.2–12.5]	Zone 2 [7.9–10.1]	Zone 3 [5.5–7.8]	Zone 4 [3.1–5.4]
dWBT	Zone 1 [9.5–11.6]	Very high	Very high	Very high	High
	Zone 2 [7.2–9.4]	High	High	Medium	Medium
	Zone 3a [6.0–7.1]	High	Medium	Medium	Low
	Zone 3b [5.0–5.9]	Medium	Low	Low	Low
	Zone 4 [2.6–4.9]	Very low	Very low	Very low	Very low

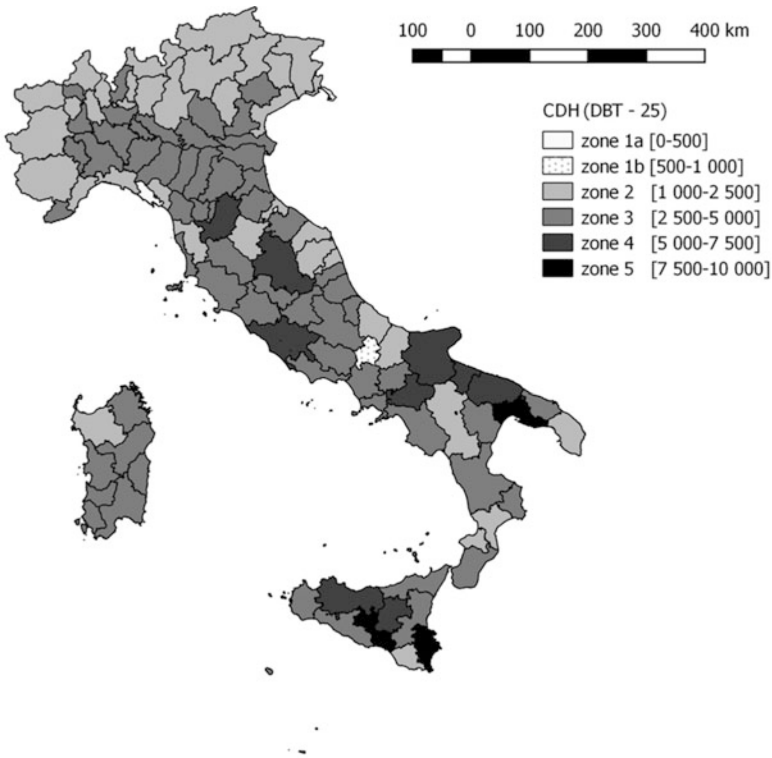

Fig. 22.4 CDH geographical classification for Italian provincial capital cities (TMY database elaborated by CTI) considering a comfort set-point temperature of 25 °C

outlet temperature will be WBT + n. In that sense, it is possible to define the residual cooling energy demand of a locality, for $T_{set} = 25$ °C, as the sum for positive values of the hourly difference WBT + $n - 25$, where dWBT is greater than n, and using Eq. (22.1) for other hours. This value could be used to identify the number of CDHs that could not be covered only by the PDEC system. Since this chapter focuses on climatic applicability, no specific building will be taken into account, only the change in residual cooling demand at different values of n. These values could be considered an inverse feasibility of PDEC in reducing cooling demand. In fact, where the residual CDH value for a given n is zero, theoretically no additional cooling is needed. Obviously, this value must be reconsidered when a specific building is taken into account. We defined the n domain as {0; 1; 2; 3; 4; 5}. For values $n = 3$ (Fig. 22.6) and $n = 5$ (Fig. 22.7) a map of residual CDH_25 was produced showing that evaporative cooling is a sufficient technology for meeting the cooling demand in many Italian provincial capital cities. In particular, in Fig. 22.6 only eight provinces show a residual cooling demand that outperforms 1000 CDH, and in any case these values never reach Zone 3. Of course, in those provinces where there is a residual demand in cooling, different techniques must be

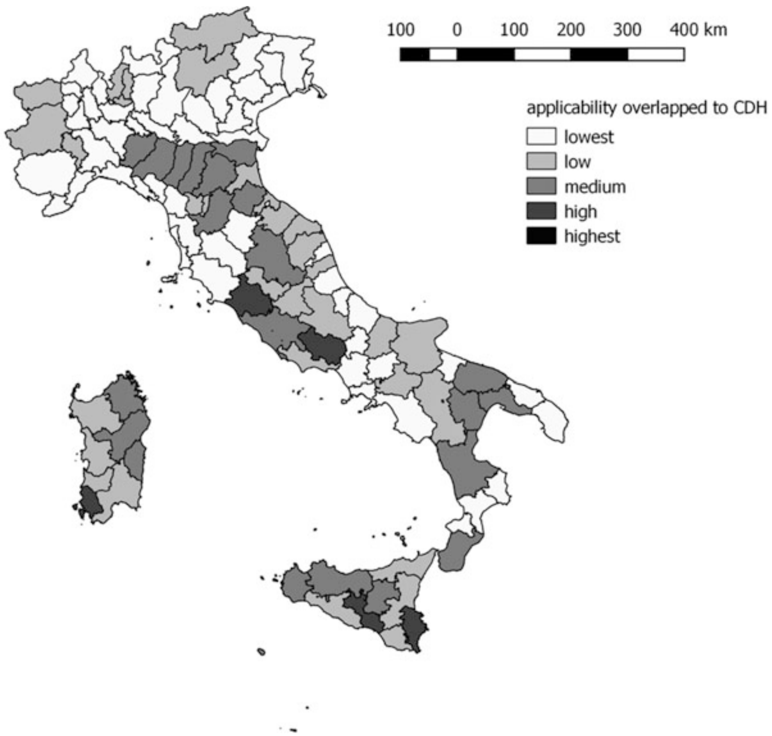

Fig. 22.5 Map of PDEC potentiality zones by overlapping Figs. 22.3 and 22.4

Table 22.2 Matrix of CDH and PDEC potentiality classification used in Fig. 22.5

		CDH				
		[0–1 k]	[1–2.5 k]	[2.5–5 k]	[5–7.5 k]	[7.5–10 k]
Potentiality of intervention	Very high	Lowest	High	Highest	Highest	Highest
	High	Lowest	Medium	High	High	Highest
	Medium	Lowest	Low	Medium	Medium	High
	Low	Lowest	Low	Low	Low	Medium
	Very low	Lowest	Lowest	Lowest	Lowest	Low

considered, even if this calculus is based on a fixed comfort temperature and not on an adaptive situation.

Figure 22.7 illustrates that, even if PDEC systems do not attain a good efficiency (WBT + 5), the cooling demand is reduced in all Italian provincial capital cities. A residual cooling demand is evident in some provinces. A comparison with Fig. 22.2 shows that with low 25-WBT values, PDEC systems are effective only at high performance levels.

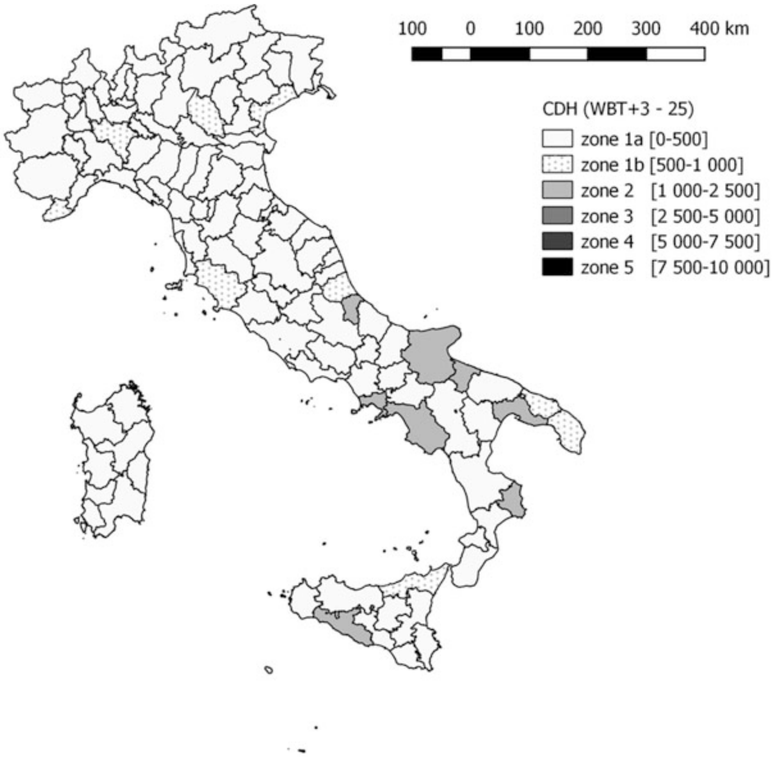

Fig. 22.6 Residual CDHs (comfort set to 25 °C) of Italian provincial capital cities when outlet temperatures from PDEC systems reach WBT + 3 (when dWBT ≤ 3 CDHs are calculated using DBT)

Looking at these figures, it is possible to state that downdraught PDEC systems could represent a very appealing solution for cooling in the Italian climate because of the difference between the CDH values based on DBT and on WBT + n. In any case, where the values reported in Fig. 22.2 are low (Zones 3 and 4), a possible residual cooling demand is expected. It is also possible to use a different approach that defines the residual cooling demand as a function of the covered percentage of the wet bulb depression. Nevertheless, this approach is more effective when specific PDEC systems are taken into account [15].

4 Climatic Analysis (Turin, Rome and Palermo)

To analyse in greater detail the Italian climate, three cities were selected (Turin, Rome and Palermo). Their localisations follow the Italian peninsula and represent three different typical climatic conditions. Analyses are based on four main

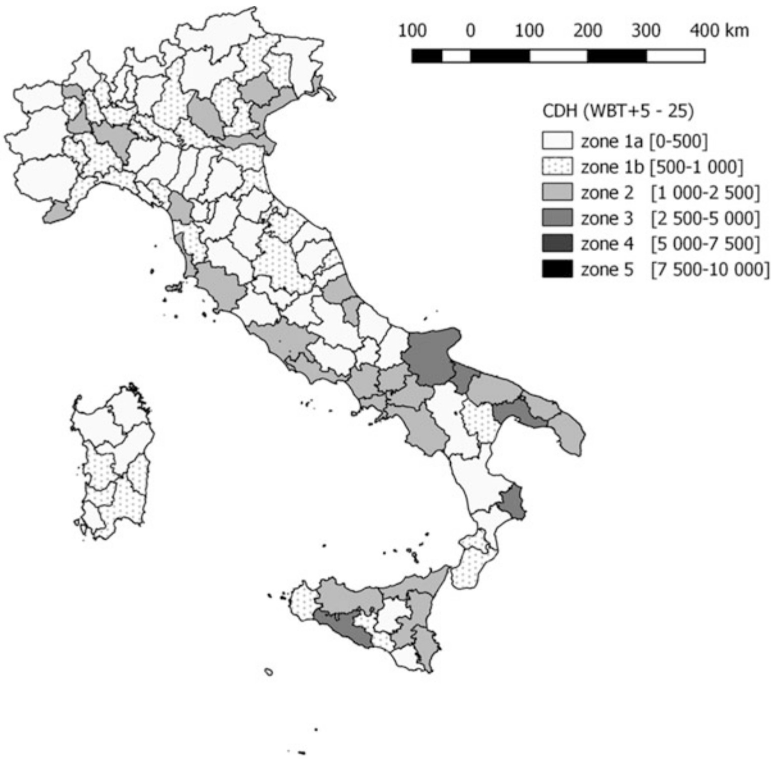

Fig. 22.7 Residual CDHs (comfort set to 25 °C) of Italian provincial capital cities when outlet temperatures from PDEC systems reach WBT + 5 (when dWBT ≤ 5 CDHs are calculated using DBT)

elaborations, described in what follows, which refer to a summer period (1 June–31 August).

Figure 22.8 was used to represent the hourly distribution of required air-temperature degrees for cooling (set point = 25 °C) in relation to the whole number of hours in the considered period. This division helps in analysing the CDH distribution and its hourly consistency. Figure 22.9 divides the percentage of hours in which cooling is and is not required if the comfort condition is set to 25 °C. In this figure different levels of WBT + *n* are compared (set of *n* equal to {0;1;2;3;4;5}). The last column is based on the DBT and for this reason corresponds to the benchmark.

Turin is the capital of the Piedmont region; it is classified in Zone 3b in Fig. 22.1 and in Zone 3 in Fig. 22.2. For these reasons it shows a low PDEC applicability in Fig. 22.3, confirmed by overlapping the CDHs (Fig. 22.5). Cooling demand is principally due to a low CDH hourly demand, which affects one third of the summer hours. By using PDEC the cooling requirements can be reduced to only 99 CDHs if the treated air reaches a WBT + 3 temperature. This contrasts with the

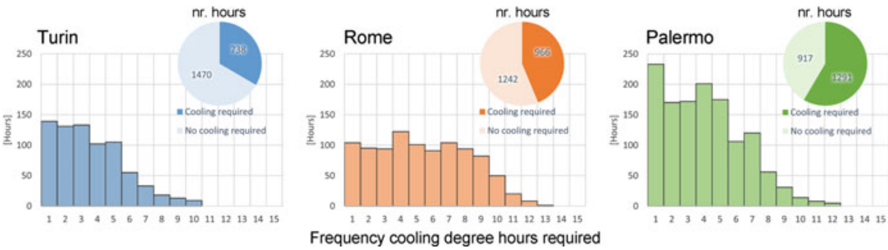

Fig. 22.8 Hourly distribution of required air-temperature degrees for cooling (set point equal to 25 °C) in Turin, Rome and Palermo (June–August)

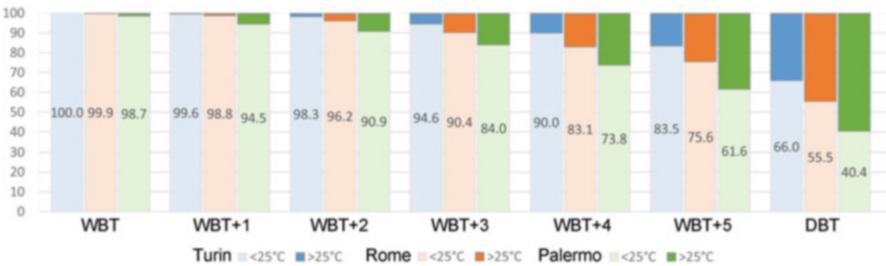

Fig. 22.9 Percentage of hours in which cooling is/is not required (June–August) in Turin, Rome and Palermo comparing the effect of different WBT + n outlet temperatures with benchmark based on DBT (comfort condition set to 25 °C)

traditional CDH at 25 °C that reaches 2433. For this reason, in similar climatic conditions, evaporative cooling can be a good cooling solution.

Rome is the Italian capital; it is classified in Zone 3a in Fig. 22.1 and in Zone 3 in Fig. 22.2. It is characterised by a high CDH value (Fig. 22.4) and a medium applicability of PDEC in both Figs. 22.3 and 22.5. Cooling demand is homogeneous from 1 to 9 °C/h (Fig. 22.8) with a low and medium CDH/h intensity that affects approximately 44 % of summer hours. Considering WBT + 3 temperatures, the residual cooling requirement is 243 CDHs (no cooling demand), but 1082 for WBT + 5. If a psychrometric analysis is considered, only a few hours are not included in the comfort DEC boundary. For these reasons in similar climatic conditions, evaporative cooling can be a good cooling solution, even if PDEC technologies must be correctly designed.

Palermo, the capital of the Sicily region, is classified in Zone 3a in Fig. 22.1 and in Zone 3 in Fig. 22.2. It is in Zone 3 in Fig. 22.4 and is characterised by a medium PDEC applicability (Figs. 22.3 and 22.5). The climate of Palermo seems to be similar to that of Rome, but its cooling demand consistency is characterised by a very high frequency between 1 and 5 °C/h (Fig. 22.8). Cooling is required in 58.5 % of summer hours. DEC results in a good applicability with WBT + 3, but it is not sufficient for WBT + 5. From a psychrometric point of view, several values are not included in the general comfort DEC boundary, although PDEC solutions could drastically reduce the need for cooling, as illustrated in Fig. 22.9.

5 Discussion and Conclusions

This chapter presented two different methodologies for evaluating the applicability of PDEC techniques. The Italian climate is characterised by medium CDH values, with a high potentiality for passive cooling solutions. Air could represent a good natural heat sink in many situations, as illustrated in [16]. In addition, evaporative cooling represents a good solution for several Italian provinces. Figures 22.6 and 22.7 demonstrate that PDEC solutions are able to meet the climatic cooling demand in the majority of Italian climatic conditions. Direct evaporative cooling can be used to attain a climatic comfort condition at 25 °C, even in those areas where the PDEC applicability is medium (Figs. 22.3 and 22.5). In some climatic conditions, there is a residual cooling demand, as illustrated in Figs. 22.6 and 22.7. In addition, the applicability of PDEC solutions in the three cities analysed in Sect. 4 is effective.

However, the presented analysis is geo-climatic and does not consider actual building conditions. These techniques are effective, both energetically and economically, but there is a lack of legislation, incentives and design tools to promote the use of the techniques.

References

1. Santamouris M (2007) Preface: why passive cooling? In: Santamouris M (ed) Advances in passive cooling. Earthscan, London, pp xix–xxxii
2. Unità centrale Studi e strategie dell'ENEA (2013) Verso un'Italia low carbon: sistema energetico, occupazione e investimenti, Rapporto Energia e Ambiente. Scenari e strategie, ENEA, Roma
3. European Commission (2010) How to develop a sustainable energy action plan (SEAP)—guidebook. Publications Office of the European Union, Luxembourg, p 63
4. Ford B, Schiano-Phan R, Francis E (eds) (2010) The architecture & engineering of downdraught cooling. A design sourcebook. PHDC Press, London
5. Moura R, Ford B (2003) ALTENER FINAL REPORT. Part 1: market assessment of passive downdraught evaporative cooling in non-domestic buildings in southern Europe, final report. ALTENER II project on solar passive heating and cooling. European Commission—DG Research
6. Salmeron JM, Sànchez FJ, Sànchez J, Alvarez S, Molina LJ, Salmeron R (2012) Climatic applicability of downdraught cooling in Europe. Arch Sci Rev 55(4):259–272
7. Xuan H, Ford B (2012) Climatic applicability of downdraught cooling in China. Arch Sci Rev 55(4):273–286. doi:10.1080/00038628.2012.717687
8. Bom GJ, Foster R, Dijkstra E, Tummers M (1999) Evaporative air-conditioning: applications for environmental friendly cooling. Word Bank Technical Paper No. 421. Energy Series, Washington

9. Comitato Termotecnico Italiano (CTI) (2014) Hourly typical meteorological data for Italian Provincial Capital cities, in accordance with ENEA and Italian Ministry of economic development. http://shop.cti2000.it/
10. Chiesa G, Grosso M (2015) The influence of different hourly typical meteorological years on dynamic simulation of buildings. Energy Procedia 78:2560–2565
11. Costelloe B, Finn D (2003) Indirect evaporative cooling potential in air-water systems in temperate climates. Energy Build 35:573–591
12. Erell E (2007) Evaporative cooling. In: Santamouris M (ed) Advances in passive cooling. Earthscan, London, pp 228–261
13. Givoni B (1994) Passive and low energy cooling of buildings. Van Nostrand Reinhold, New York
14. Stull R (2011) Wet-bulb temperature from relative humidity and air temperature. J Appl Meteorol Climatol 50:2267–2269
15. Chiesa G, Grosso M (2015) Direct evaporative passive cooling of building. A comparison amid simplified simulation models based on experimental data. Build Environ 94:263–272. doi:10.1016/j.buildenv.2015.08.014
16. Chiesa G, Grosso M (2015) Geo-climatic applicability of natural ventilative cooling in the Mediterranean area. Energy Build 107:376–391. doi:10.1016/j.enbuild.2015.08.043i