LE GENERAZIONI DEL PENSIERO

# A Comparative Analysis of Simplified and Detailed Modelling Procedures for the Assessment of Chiller Efficiency in the European Context

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## Abstract

In the last years, several simplified methods for the assessment of the energy performance of technical building systems were developed. So far, these calculation methods have not been properly analysed, and the reliability of their results is still debatable; therefore, it is of crucial relevance to fully validate these procedures.

In this work, the simplified calculation procedures for chillers specified in European standards are investigated. A comparative validation analysis is performed, by comparing simplified and detailed procedures. Following a case study approach, some office building types − different by levels of insulation, geographical location, and chiller properties − are taken into account. The results show non-negligible variations in the energy consumption and highlight the need for standard procedures improvements in the perspective of widespread use.

## Highlights

- European simplified procedures for chiller performance are assessed
- A comparative validation is pursued
- A case study approach with twelve cases is presented
- The results show significant variation between the procedures

## Introduction

A phase of renovation and upgrading of standard methodologies for the assessment of the energy performance of buildings began with the mandate M/480 EN (European Commission, 2010) for the establishment of standards in accordance with the 2010/31/EU regulation (European Parliament, 2010). The new standards, as shown in Figure 1, provide a remarkable difference in the procedures compared to the withdrawn standards. Studies on some methodologies of the withdrawn standards were conducted in literature, such as the works of Mattarelli and Piva (2014) on boilers, and of Hantsch et al. (2016) on chillers.

Studies on the accuracy of new methods still need to be carried out since they were created and released very recently. The aforementioned updated standard procedures are part of a wider cluster of calculation models deployed to assess the energy performance of buildings that also includes the more complex calculation procedures frequently used in detailed energy simulation tools.

This paper is part of a wider study aimed at enhancing the simplified calculation procedures for the assessment of the energy performance of technical building systems. The work focuses on the chiller's simplified procedures and provides a validation approach finalised to check the accuracy and reliability of the methods.

The analysed simplified calculation procedures are the two methods described in the EN 16798-13 standard (CEN, 2017b), which are based respectively on extensive and non-extensive chiller properties. The analysed detailed calculation procedure was first deployed in DOE 2.1 (DOE, 1982), and in this paper was applied through EnergyPlus. This latter is applicable for electric chiller and is based on the condenser entering temperature available, deploying thorough input data and chiller performance curves.

Both the European standard for the assessment of cooling generators and the calculation procedure deployed in EnergyPlus are presented. The calculation procedures are detailed as well, to propose a comparison. Through a comparative validation approach, case studies were analysed to compare the standard methodologies procedures and the EnergyPlus ones. An office building was analysed in two different cities, with three different levels of insulation, and with chillers differing for nominal power and performances. The results in terms of energy consumption were then analysed and compared to exploit the main differences in the methodologies' results.

Similar approaches were also followed in the validation procedures of other chiller simplified procedures, such as in Kim and Kim (2007) and Wang et al. (2022).

This section presents the three calculation methods used to assess the energy efficiency of chillers along with the comparison procedure applied in the validation.


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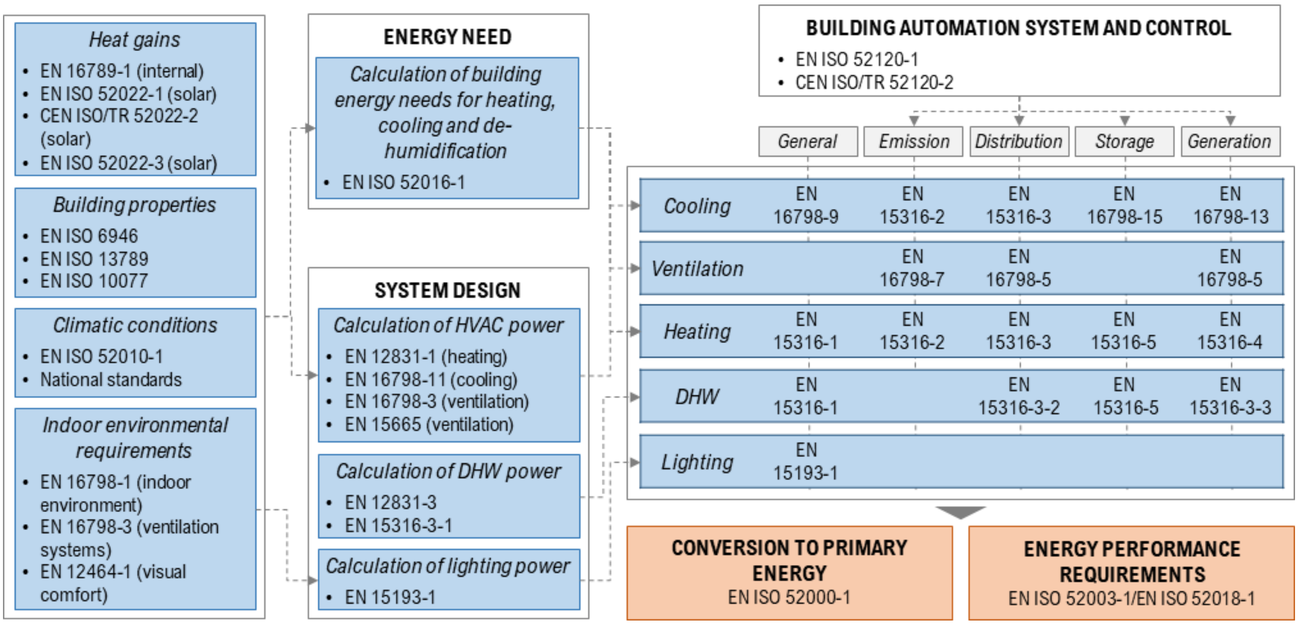


*Figure 1: Regulatory framework under Mandate M/480 EN of 2010 (Bianco Mauthe Degerfeld et al. 2022b).*

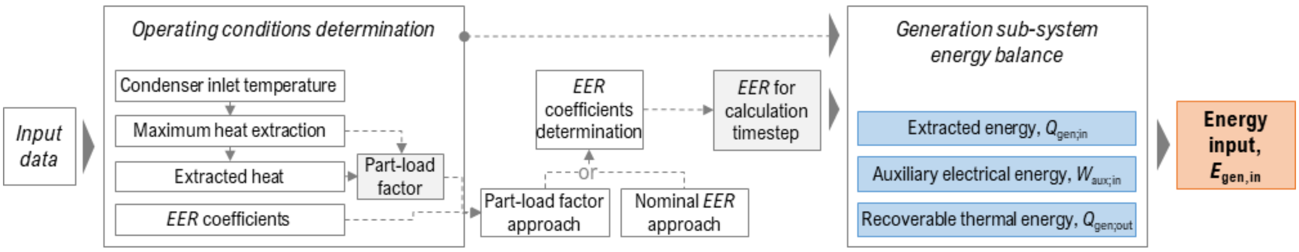


*Figure 2: Calculation procedure (Method 1 in EN 16798-13) for chiller generation sub-system (Bianco Mauthe Degerfeld et al. 2022b).*

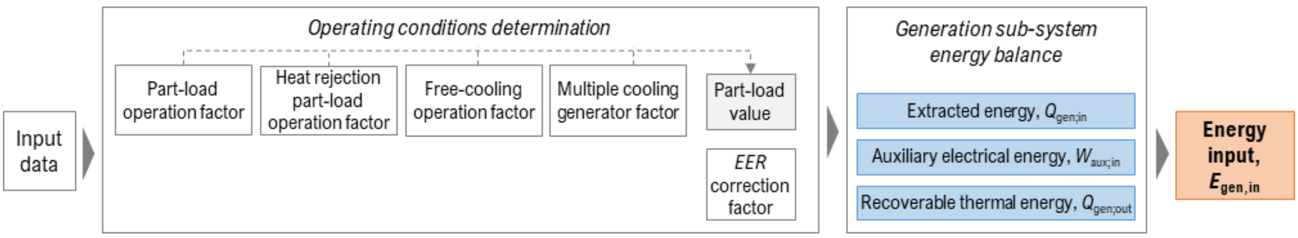


*Figure 3: Calculation procedure (Method 2 in EN 16798-13) for chiller generation sub-system (Bianco Mauthe Degerfeld et al. 2022b).*

## Simplified methods for chiller performance assessment

The EN 16798-13 technical standard (CEN, 2017b) specifies simplified calculation methods to assess the energy performance of refrigeration systems for space cooling. The standard, which can be used for compression or absorption units, aims to evaluate the electrical/thermal energy input, the thermal energy retrieved from the cold source, the recoverable thermal energy, and the auxiliary energy consumptions.

The standard offers two distinct calculation procedures; the first one (Method 1, Figure 2) applies to compression and absorption chillers, while the second one (Method 2, Figure 3) applies to refrigeration units, split and multi-splits, and variable refrigerant flow (VRF) systems.

The first method (Method 1, Figure 2) can be used with either hourly or per bin calculation time steps and is only advised if detailed input data regarding the machines are available. It is composed of three calculation phases, as follows:

1. Assessment of operating conditions,
2. Assessment of the chiller energy efficiency ratio (*EER*) coefficients, and
3. Evaluation of energy consumption through the energy balance of the generation sub-system.

At first, the boundary conditions for each time step are calculated or defined, including the external air


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temperature, the condenser inlet and outlet temperatures, and the part load factors (calculated as a function of the effective and maximum heat extraction).

The nominal energy efficiency ratio is corrected for each time step with the $f_{EER}$ factor. Two approaches can be deployed to derive this factor. For the first one, the part-load approach, two cases must be considered. If the effective part-load factor is higher than the minimum factor, Equation (1) should be used, otherwise, Equation (2) is applied. Alternatively, the second approach, the nominal *EER* one, whose procedures come from the EN 14825 standard (CEN, 2018), can be applied. At each time step the nominal *EER* is multiplied by four correction factors defined at five conditions that differ as a function of the partial load, the evaporator outlet temperature, and the condenser inlet temperature, and are calculated as presented in Equation (3).

Starting from the operative chiller *EER*, the extracted, recovered, and rejected heat are calculated for each time step, as well as the energy input and the auxiliary energy consumption.

$$f_{\mathrm{EER};j} = \frac{273{,}15 + \vartheta_{\mathrm{evap;out}}}{\vartheta_{\mathrm{cond;in}} - \vartheta_{\mathrm{evap;out}} + \left(\frac{LR_j}{100}\right)\cdot\Delta\vartheta_{\mathrm{corr};j}} \cdot \left[C_{1;j}\left(\frac{LR_j}{100}\right)^3 + C_{2;j}\left(\frac{LR_j}{100}\right)^2 + C_{3;j}\left(\frac{LR_j}{100}\right) + C_{4;j}\right] \quad (1)$$

$$f_{\mathrm{EER};j} = \frac{273{,}15 + \vartheta_{\mathrm{evap;out}}}{\vartheta_{\mathrm{cond;in}} - \vartheta_{\mathrm{evap;out}} + \left(\frac{LR_{j;\min}}{100}\right)\cdot\Delta\vartheta_{\mathrm{corr};j}} \cdot \left[C_{1;j}\left(\frac{LR_{j;\min}}{100}\right)^3 + C_{2;j}\left(\frac{LR_{j;\min}}{100}\right)^2 + C_{3;j}\left(\frac{LR_{j;\min}}{100}\right) + C_{4;j}\right] \quad (2)$$

$$f_{\mathrm{EER};j} = \frac{\dfrac{273{,}15 + \vartheta_{\mathrm{evap;out}}}{\vartheta_{\mathrm{cond;in}} - \vartheta_{\mathrm{evap;out}}}}{\dfrac{273{,}15 + \vartheta_{\mathrm{evap;out;n}}}{\vartheta_{\mathrm{cond;in;n}} - \vartheta_{\mathrm{evap;out;n}}}} \quad (3)$$

where, $f_{\mathrm{EER};j}$ [-] is the energy efficiency ratio correction factor, $\vartheta_{\mathrm{evap;out}}$ [°C] is the evaporator outlet temperature, $\vartheta_{\mathrm{cond;in}}$ [°C] is the condenser inlet temperature, $\vartheta_{\mathrm{cond;in;n}}$ is the condenser inlet temperature at nominal conditions, $\Delta\vartheta_{\mathrm{corr;j}}$ [°C] is the correction temperature difference of the chiller, $LR_j$ [-] is the effective part load ratio, $LR_{j;\min}$ [-] is the minimum part load ratio and $C_{1\text{-}4;j}$ [-] are the coefficients associated with the chiller characteristics.

While this procedure is mainly based on simple equations, both the energy efficiency ratio correction factor and the maximum heat extracted by the chiller are derived from the solution of a linear system of equations. This method can determine an increase in the computational time, despite presenting a low level of complexity in the application.

The second method (Method 2, Figure 3) can be used with hourly or monthly calculation time steps and is advised when detailed information regarding the machines is not available. It is composed of two calculation phases:

1. Assessment of the operating conditions, and
2. Resolution of the generation sub-system energy balance.

At first, the partial load value (*PLV*) is determined as a result of four factors, as presented in Equation (4). These are the part-load operation factor (Equation (6)), the heat rejection part-load operation factor (Equation (5)), the free-cooling operation factor, and the multiple cooling generator factor. The last two are derived from tabulated values.

$$PLV = LR \cdot f_{\mathrm{hr;PL}} \cdot f_{\mathrm{hr;fc}} \cdot f_{\mathrm{C;mult}} \quad (4)$$

$$LR = Q_{\mathrm{C;gen;in;req}}/(t_{\mathrm{C}} \cdot \Phi_{\mathrm{C}}) \quad (5)$$

$$f_{\mathrm{hr;PL}} = a_0 + a_1\cdot\vartheta_{\mathrm{e}} + a_2\cdot\vartheta_{\mathrm{e}}^2 \quad (6)$$

where *PLV* [-] is the partial load value, *LR* [-] is the effective part load ratio, $f_{\mathrm{hr;PL}}$ [-] is the chiller part load factor of the heat rejection system, $f_{\mathrm{hr;fc}}$ [-] is the chiller free cooling factor, $f_{\mathrm{C;mult}}$ [-] is the factor for multiple refrigeration units, $Q_{\mathrm{C;gen;in;req}}$ [kWh] is the required thermal energy to be extracted by the refrigeration unit, $t_{\mathrm{C}}$ [h] is the cooling generation time step, $\Phi_{\mathrm{C}}$ [kW] is the chiller nominal thermal power, $\vartheta_{\mathrm{e}}$ [°C] is the external air temperature, and $a_0$ [-], $a_1$ [°C⁻¹], and $a_2$ [°C⁻²] are correction factors.

The *EER* is derived through a correction factor directly applied to the nominal value, which is the ratio between the Carnot *EER*s at operating and nominal conditions, according to Equation (7),

$$f_{\mathrm{EER;corr}} = \frac{\dfrac{T_{0;\mathrm{abs}} + \vartheta_{\mathrm{C;gen;req;out}} - \Delta\vartheta_{\mathrm{evap}}}{\left(T_{0;\mathrm{abs}} + \vartheta_{\mathrm{C;gen;hr;req;in;ref}} + \Delta\vartheta_{\mathrm{cond}}\right) - \left(T_{0;\mathrm{abs}} + \vartheta_{\mathrm{C;gen;req;out}} - \Delta\vartheta_{\mathrm{evap}}\right)}}{\dfrac{T_{0;abs} + \vartheta_{\mathrm{C;gen;req;out;n}} - \Delta\vartheta_{\mathrm{evap}}}{\left(T_{0;\mathrm{abs}} + \vartheta_{\mathrm{C;gen;hr;req;in;n}} + \Delta\vartheta_{\mathrm{cond}}\right) - \left(T_{0;\mathrm{abs}} + \vartheta_{\mathrm{C;gen;req;out;n}} - \Delta\vartheta_{\mathrm{evap}}\right)}} \quad (7)$$

where, $T_{0;\mathrm{abs}}$ [K] is the absolute reference temperature, $\vartheta_{\mathrm{C;gen;req;out}}$ [°C] and $\vartheta_{\mathrm{C;gen;req;out;n}}$ [°C] are the required cooling generation output temperatures, respectively at operating and nominal conditions, $\vartheta_{\mathrm{C;gen;hr;req;in;ref}}$ [°C] and $\vartheta_{\mathrm{C;gen;hr;req;in;n}}$ [°C] are the required heat rejection input temperatures, respectively at operating and nominal conditions, $\Delta\vartheta_{\mathrm{evap}}$ [K] is the temperature difference within the evaporator, and $\Delta\vartheta_{\mathrm{cond}}$ [K] is the temperature difference within the condenser.

Deploying the coefficients described above and through the energy balance, the extracted, recovered, and rejected heat are calculated, as well as the energy input and the auxiliary energy consumption.

## Detailed method for chiller performance assessment

The analysed detailed procedure for the electric chiller, which is applied in subroutine COMREF of DOE 2.1, deploys the adjustment curves in the equipment algorithms (DOE, 1982), and is used in EnergyPlus (DOE, 2022). It calculates the machine's thermal performance, and the compressor's and condenser fans' power consumptions, while the associated pumps are not considered. This model presents similar input data as in the EN 16798-13 technical standard (CEN, 2017b). Nevertheless, the procedure deploys a more accurate and complete set of data, including curves describing the chiller operative performance as a function of the partial


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load, entering condenser fluid temperature, and cold water inlet temperature.

The method employs data provided by the user about the chiller under reference conditions, and it adjusts them to fit with the operative conditions using the following factors:

- Temperature-dependant cooling capacity factor (*CC factor*) to be multiplied by the reference capacity to derive the available chiller capacity at operational temperatures. *CC factor* is calculated through the biquadratic function in Equation (8) as a function of the chilled water set-point temperature and the inlet condenser fluid temperature.

$$CC\ factor = a + b\cdot(\vartheta_{chw,set}) + c\cdot(\vartheta_{chw,set})^2 + d\cdot(\vartheta_{chw,in}) + e\cdot(\vartheta_{chw,in})^2 + f\cdot(\vartheta_{chw,set})\cdot(\vartheta_{chw,in}) \quad (8)$$

  where, $\vartheta_{chw,set}$ [°C] is the chilled water set-point temperature, $\vartheta_{chw,in}$ [°C] is the chilled water inlet temperature, and $a$ [-], $b$ [°C$^{-1}$], $c$ [°C$^{-2}$], $d$ [°C$^{-1}$], $e$ [°C$^{-2}$], and $f$ [°C$^{-2}$] are model built-in or user-defined factors,
- Energy input to output ratio function of temperature factor (*EIR-T factor*), from which the *EIR*, defined as $EER^{-1}$ [-], at operational temperatures, is derived by multiplying by the reference *EIR*. This factor is derived through a biquadratic equation based on the leaving chilled water temperature and the entering condenser fluid temperature,
- Energy input-to-output ratio function of partial load factor (*EIR-PLR factor*), from which the *EIR* at operational part load is derived by multiplying by both the *EIR* and the *EIR-T factor*. The quadratic equation that is deployed to derive this factor is based on the part-load ratio.

The procedure can be used either with hourly or sub-hourly calculation time steps. It is composed of five calculation phases, as follows:

1. Assessment of the operative maximum cooling capacity,
2. Assessment of the evaporator heat transfer rate needed to cool the inlet water to the outlet set-point temperature,
3. Assessment of the operative outlet water temperature in case the required cooling capacity associated with the results of point 2 does not meet the maximum cooling capacity obtained in point 1,
4. Assessment of the part-load ratio as the ratio between the evaporator heat transfer rate (point 2) and the available chiller capacity (point 1),
5. Assessment of the chiller condenser heat transfer energy, the chiller evaporator cooling energy, and the compressor and condenser fan electric energy through the solution of the generation energy balance.

# Methods

## Workflow

In this work, the findings of several calculation methodologies for evaluating the energy performance of chillers were compared and analysed. EnergyPlus was used to simulate the case study building, which is detailed in the next Section, to assess the thermal energy requirements for cooling in relation to the two climatic zones and three building typologies analysed.

These findings were then applied to three distinct calculation methodologies, namely the two methods published in the EN 16798-13 technical standard (CEN, 2017b) − also deploying tools published along the standard (EPBD Center, 2016) − and the calculation approach provided in EnergyPlus, as detailed in the previous sections, in order to evaluate the performance of the chiller.

Apart from the required energy to be extracted, the various chiller properties were defined as input data. Among them, the operational correction factors were described as curves and then, starting from that, the five reference points needed for the first simplified method and described in EN 14825 (CEN, 2018) were determined.

The findings were analysed in terms of monthly electrical energy input for cooling for the months between April and September. The results were analysed using the percentage deviation of the electrical energy input for cooling of each of the two simplified methods in comparison to the detailed method.

## Case study

The case study refers to an office building with five above-ground conditioned floors, representative of the Italian office building stock of the period 1977-1990 (Corrado et al. 2018). The building was analysed in two Italian cities representative of the colder northern and warmer southern climate, respectively Milan (Mi), and Palermo (Pa). For the purposes of this study, a single storey was taken into consideration (Figure 4). It is characterised by a 480 m$^2$ conditioned net floor area, a net volume of 1296 m$^3$, a window-to-wall ratio equal to 39 %, and a compactness ratio of 0,19 m$^{-1}$. It was assumed that the neighbor storeys have the same properties (geometry, building use, etc.).

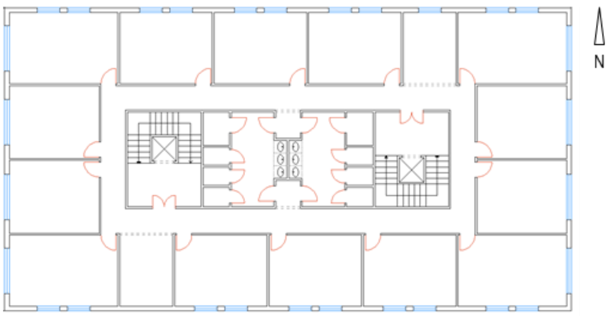


*Figure 4: Plan of the analysed storey.*

The external opaque vertical walls are composed of two layers of hollow brick masonry with a thermal insulation


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layer interposed. Three levels of thermal insulation (L_ins) were defined for the external walls with the consequent variation of the thermal conductance $\Lambda_{wall}$ (Table 1). Three levels of thermal insulation and total solar energy transmittance of glazing *g* are considered for the windows (Table 2). The horizontal internal partitions are hollow-core concrete slabs with a thermal transmittance $U_{hor}$=0,69 W·m$^{-2}$·K$^{-1}$. The thermal transmittances $U_{wall}$ and $U_{win}$ were determined using the surface heat transfer coefficients provided in EN ISO 6946 (CEN, 2017a).

*Table 1: External wall variants.*

| L_ins ID | $\Lambda_{wall}$ [W·m$^{-2}$·K$^{-1}$] | $U_{wall}$ [W·m$^{-2}$·K$^{-1}$] |
|---|---|---|
| 1 | 2,19 | 1,59 |
| 2 | 0,56 | 0,51 |
| 3 | 0,24 | 0,23 |

*Table 2: Window variants.*

| L_ins ID | *g* [-] | $U_{win}$ [W·m$^{-2}$·K$^{-1}$] |
|---|---|---|
| 1 | 0,85 | 5,70 |
| 2 | 0,75 | 2,80 |
| 3 | 0,67 | 1,40 |

For the purposes of this study, an air-to-water electric chiller with fan coil units was assumed as the only space cooling system of the storey. For each of the six case study variants, two sets of chillers were associated (S_ch) differing for *EER* and correction curves for the operative condition, as presented in Table 3. The declared values refer to an inlet air dry bulb temperature of 35 °C and outlet water temperature of 7 °C as reference conditions for the design.

*Table 3: Chiller sets variants.*

| S_ch ID | L_ins ID | City | *EER* [-] | $P_n$ [kW] |
|---|---|---|---|---|
| 1 | 1 | Mi | 2,67 | 34,5 |
| 1 | 2 | Mi | 2,71 | 29,0 |
| 1 | 3 | Mi | 2,71 | 29,0 |
| 2 | 1 | Mi | 3,07 | 36,2 |
| 2 | 2 | Mi | 3,01 | 26,0 |
| 2 | 3 | Mi | 3,01 | 26,0 |
| 1 | 1 | Pa | 2,67 | 34,5 |
| 1 | 2 | Pa | 2,71 | 29,0 |
| 1 | 3 | Pa | 2,71 | 29,0 |
| 2 | 1 | Pa | 3,07 | 36,2 |
| 2 | 2 | Pa | 3,09 | 29,7 |
| 2 | 3 | Pa | 3,09 | 29,7 |

The chillers were coupled with the twelve case study variants using the cooling design power and the chiller nominal cooling power $P_n$ with a tolerance of about 10%. The variants are associated with the results through the code “Aa_X.Y”, where Aa is the building location (Mi or Pa), X is the chiller set (S_ch ID in Table 3), and Y is the insulation level (L_ins ID in Tables 1 and 2). Due to similarities in the design power, five chillers were deployed as follows: chiller a for Mi_1.1 and Pa_1.1; chiller b for Mi_1.2, Mi_1.3, Pa_1.2, and Pa_1.3, chiller c for Mi_2.1 and Pa_2.1; chiller d for Mi_2.2 and Mi_2.3; chiller e for Pa_2.2 and Pa_2.3.

The performance curves for the *CC factor*, the *EIR-T factor*, and the *EIR-PLR factor* were derived by interpolating the chiller performance data from the technical sheets, and are presented respectively in Figure 5, Figure 6, and Figure 7. For the biquadratic curves, the reference temperature of 35 °C was assumed as the inlet fluid temperature.

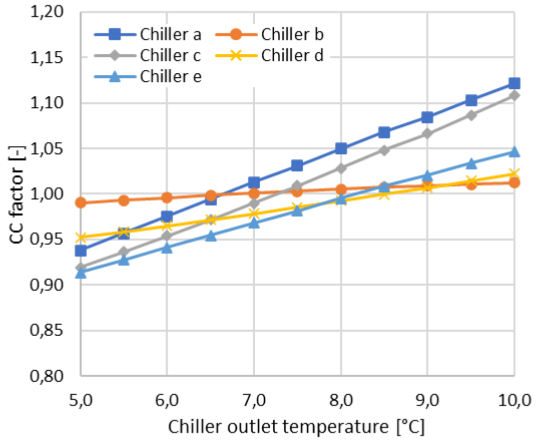


*Figure 5: Cooling capacity factor for the selected chillers.*

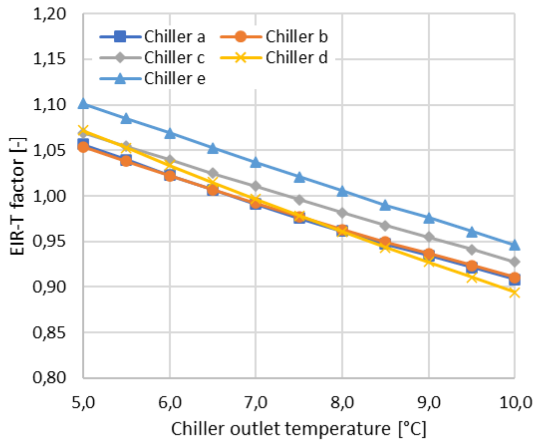


*Figure 6: Energy input to output ratio function of temperature factor for the selected chillers.*

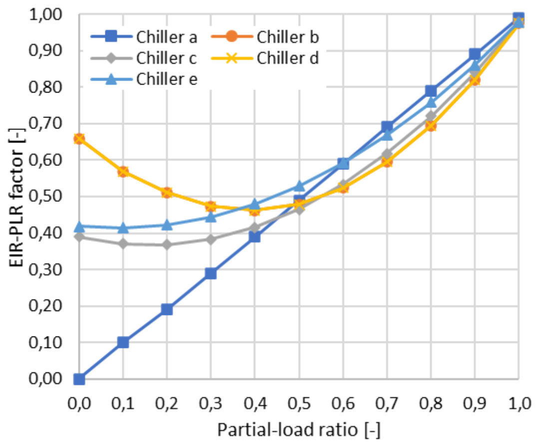


*Figure 7: Energy input to output ratio function of partial load factor for the selected chillers.*


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## Results and discussion

The results of the case study variants are presented in Figure 8 on a monthly basis. The comparison between the cases shows a common trend in the outcomes.

The application of EN 16798-13 (CEN, 2017b) Method 1 turns out to be the most reliable procedure between the two standard methods. The monthly percentage deviation of the electrical energy input for cooling ranges from a minimum of -1,5% to a maximum of about 50% between Method 1 and EnergyPlus for the twelve considered combinations.

The variation of the climatic data determines non-negligible changes in the results. In most of the cases, the absolute deviation of monthly electrical energy input for cooling between Method 1 and EnergyPlus decreases in Palermo (Pa) from the corresponding values in Milano (Mi).

The modification of the chiller set (S_ch) turns out to be quite influential with a decrease in the deviations between Method 1 and EnergyPlus from 5% to 20% in the case studies associated with the second set (S_ch = 2).

The results show quite negligible changes related to the modification of the insulation level (L_ins). The difference in the deviation of the results of Method 1 and EnergyPlus comparing two adjacent L_ins is included between 5% and 15%. The variation in the results associated with the external wall insulation is negligible in the cases with the same chiller.

The application of EN 16798-13 (CEN, 2017b) Method 2 on the other hand, turns out to be completely unreliable, with a monthly value of the chiller electrical energy input for cooling that are double the EnergyPlus ones for the twelve considered cases. The results related to the three variants applied to the cases, i.e., the climatic data, the level of insulation, and the set of chillers, show the same variations in Method 1 and Method 2.

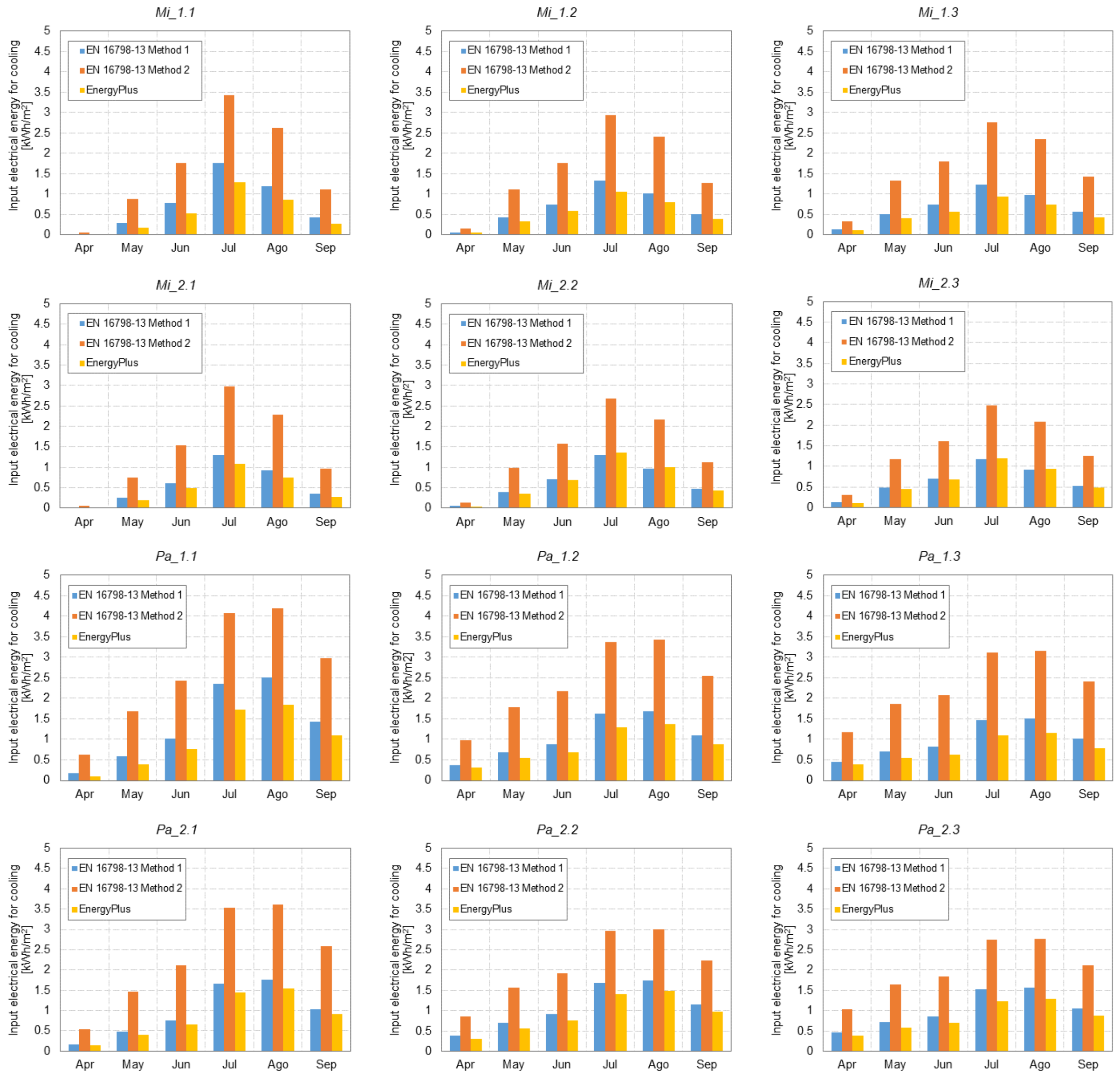


*Figure 8: Chiller electrical energy input for cooling in the analysed case studies.*


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These results, compared to the outcomes of a previous study (Bianco Mauthe Degerfeld et al., 2022a) carried out on a single building located in two cities, show a similar trend and lead to similar conclusions regarding the two Methods reliability. A general overestimation of the standardised approaches from the detailed method results was highlighted. Whereas Method 1 represents a more precise approach, even if with non-negligible deviations, Method 2, instead, shows unrealistic results. The choice of the deployed chiller showed a great influence on the accuracy of the method. Further studies will need to assess which chiller properties influence the accuracy and how they are doing it.

## Conclusion

The performance of the chiller was determined in the present work by analysing three distinct calculation methods. To emphasise the main calculation differences in terms of logical process and simplifications, the two methods specified by the EN 16798-13 (CEN, 2017b) technical standard and the model applied in EnergyPlus were discussed.

The two approaches described in EN 16798-13 (CEN, 2017b) were then examined and compared with the calculating procedure based on the condenser entering temperature, using EnergyPlus, through a case study approach.

A typical office building was chosen and evaluated in two cities (Milan and Palermo), considering three envelope levels with different insulation and windows properties, and two sets of chillers for a total number of twelve cases.

The findings were examined in terms of monthly electrical energy input for cooling and the results were compared in terms of the deviation of each of the standard methods from the detailed one.

The simplified calculation procedure of EN 16798-13 (CEN, 2017b) Method 1, which is based on specific chiller performance parameters, showed the best coherence on both a monthly and hourly basis with the detailed procedure. The results are influenced in different ways by the three considered variants. The monthly deviation ranges from -1,5% to +50%, depending on the case.

On the other hand, Method 2 of the standard, which is based on condensed chiller performance characteristics and corrective performance factors, showed substantial results variation and can be considered unreliable. This is directly tied to the accuracy of the applied *EER* correction factors, that in the case of Method 2 were significantly different from the one derived with the detailed method.

The results show that the input data employed, particularly with regard to the chiller properties and the formulation of the performance curves, is closely related to and has a strong impact on the accuracy of the standard calculation technique.

Future work will need to deploy a wide number of detailed procedures to be used in the comparison testing, as well as testing the effect of sequential and parallel cooling generators arrangement and the effect of the variation of the chilled water temperature. The results highlighted also the importance of an analysis based on the input data; in particular, a sensitivity analysis should be performed on the chiller main properties to determine the influence of the single input information on the results. Together with the comparative analysis, an empirical validation should be also applied to confirm the quality of the analysed procedures with in field measurements.

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