

Space Heating Load Estimation Procedure for CHP Systems sizing

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Abstract. Due to its environmental and energy benefits, the Combined Heat and Power (CHP) represents certainly an important measure to improve energy efficiency of buildings. Since the energy performance of the CHP systems strongly depends on the fraction of the useful cogenerated heat (i.e. the cogenerated heat that is actually used to meet building thermal demand), in building applications of CHP, it is necessary to know the space heating and cooling loads profile to optimise the system efficiency. When the heating load profile is unknown or difficult to calculate with a sufficient accuracy, as may occur for existing buildings, it can be estimated from the cumulated energy uses by adopting the loads estimation procedure (h-LEP). With the aim to evaluate the useful fraction of the cogenerated heat for different operating conditions in terms of buildings characteristics, weather data and system capacity, the h-LEP is here implemented with a single climate variable: the hourly average dry-bulb temperature. The proposed procedure have been validated resorting to the TRNSYS simulation tool. The results, obtained by considering a building for hospital use, reveal that the useful fraction of the cogenerated heat can be estimated with an average accuracy of $\pm 3\%$, within the range of operative conditions considered in the present study.

1. Introduction

Combined heat and power (CHP) is a highly efficient method of utilising the energy resources (fossil or renewable), therefore its use has become increasingly widespread in the construction sector in order to achieve primary energy savings and consequently reduce the greenhouse gas emissions. The increase in energy efficiency relating to the cogeneration with respect to separate fossil-fired generation of heat and electricity is mainly affected by the fraction of the cogenerated heat which is actually used to meet building thermal demand.

As a consequence, the matching between the cogenerated heat and the heat load demand plays a leading role in the CHP system optimization [1,2].

An attractive solution to improve the efficiency of the cogeneration systems is offered by the usage of thermal energy storage which allows to store the cogenerated heat when building heat demand is low thus making it available when load is high [3,4].

In absence of such devices, it is mandatory to perform a comparison between the cogenerated heat and the heat load demand to properly size the CHP systems.

Unlike what happens in industrial sector, where the time scheduling of heat load demand is generally known from the process characteristics, in building sector heating and cooling loads profile



depends on many factors, such as building characteristics, climatic conditions, building usage, ventilation and air conditioning equipment used and so on.

As highlighted by Pagliarini e Rainieri [5], when the CHP system is planned to meet buildings energy uses, the energy consumption on hourly basis have to be known. The hourly heating and cooling loads can be obtained by using monitored data or can be evaluated by resorting to a suitable simulation software.

For existing buildings it could be hard to perform hourly simulation of the space heating and cooling due to the possible lack of whole-building metering and detailed information about the building envelope.

On the other hand, for this kind of buildings average monitored data are usually available from utility bills, which can be used for buildings energy analysis.

By using a multivariate regression model, Pagliarini and Rainieri proposed an hourly Loads Estimation Procedure (h-LEP) which allows to restore the heating and cooling pattern of existing buildings on an hourly time scale from the monthly averaged energy consumption, the dry bulb air temperature and the global solar radiation on the horizontal plane [6].

More recently, the h-LEP based on a multivariate regression has been modified to dump the effect of the hourly solar radiation on the reconstruction of the hourly loads profile [7].

When the daily averaged energy consumption is regressed against the dry bulb air temperature only, the h-LEP does reduce to the single-variate two-parameter model [8].

In this paper the h-LEP is implemented with a single climate variable (i.e. the hourly average dry temperature) with the aim to evaluate the useful fraction of the cogenerated heat for different operating conditions in terms of buildings characteristics, weather data and system capacity.

Although the single variable regression analysis has been widely applied in building energy research and several inverse model have been proposed [8-10] (i.e. linear, change-point linear, variable-based degree-day and multivariate inverse models), it has to be pointed out that these inverse models have been developed and applied for establishing the baseline model which is used for identify energy savings in energy retrofiting projects.

To validate the proposed estimation procedure, a comparison between the restored heating loads profile and the hourly profile obtained by using TRNSYS software is performed. A building for hospital use has been considered as case study.

2. Problem statement

The overall energy efficiency of the CHP system, based on the first principle of thermodynamics, can be defined as the ratio of useful energy output to the energy input [11]:

$$\eta_{CHP} = \frac{W_{CHP} + Q_{CHP,u}}{E_{CHP,in}} \quad (1)$$

where W_{CHP} and $Q_{CHP,u}$ are the electricity and the useful thermal energy produced by the cogeneration unit, respectively, and $E_{CHP,in}$ is the energy supplied to the CHP system.

Therefore by sizing the CHP for the thermal requirements of the facility, the highest CHP system efficiency can be reached.

Unfortunately, for existing buildings the hourly space heating profile is seldom known. However, it can be estimated from the cumulated energy consumption by adopting an inverse approach. Pagliarini and Rainieri [5] have suggested an interesting inverse model (h-LEP), based on a multivariate regression approach, which allows to restore the space heating pattern by regressing the monthly energy consumption against the dry-bulb temperature of the external air and the global solar radiation on the horizontal plane.

When considering the dry bulb temperature only, then h-LEP reduces to the single-variate two-parameter model [8], which expresses the daily net heat load of the building, as a linear function of the dry bulb temperature, averaged in the time period for which the cumulated energy use is known:

$$Q = K(T_{bal} - T_e) \quad (2)$$

being K (W/°C) the overall sensible heat transfer coefficient accounting for both transmission and ventilation, T_e (°C) the outdoor dry bulb temperature and T_{bal} (°C) the balance temperature, which accounts for both internal and solar heat gains [7].

In this condition, the estimation procedure becomes straightforward and it can be implementable on a spreadsheet.

It has to be highlighted as the assumptions made in the present analysis are consistent with the results of previous studies, which show that in the regression analysis the outdoor dry-bulb temperature is the most important weather variable, also when the hourly time scale is considered [12].

3. Case study

The inverse procedure here presented has been adopted to restore the hourly space heating load profile of a building for hospital use (Figure 1). This kind of building has been chosen because in hospitals a good simultaneity between the electric and thermal loads occurs, which is the best condition for consideration of cogeneration plant [13-15]. In particular, in winter the thermal energy can be used for space heating, water heating and for the process (sterilization, laboratory requirements, and so on). Since only the space heating is dependent on the climate data, in this work other contributions have been disregarded.

To evaluate the influence of climatic conditions, the building has been supposed located in two different climates, namely Berlin (Germany) and Stockholm (Sweden).

Since the inverse model here adopted considers only the influence of the external air temperature on the space heating demand, it is important to analyse different operating conditions in terms of heat gains and building thermal losses to better evaluate the accuracy of the proposed model.

For this purpose, the building behaviour has been studied by considering two values of internal heat generation per unit of floor surface area, namely $q_g = 0$ W/m² and $q_g = 5$ W/m² and three values of air change rate (i.e. $n = 0, 0.3$ and 1 h⁻¹). The internal temperature has been assumed equal to 20 °C.

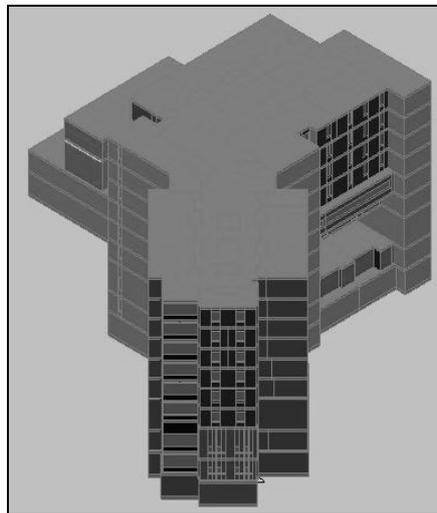


Figure 1. Case study building.

The thermal behaviour of the case study building has been analysed by using the *Multi-Zone Building* component within the TRNSYS environment.

Figure 2 shows the monthly daily averaged energy use as a function of the mean daily temperature in the period, as required by the application of the single-variate two-parameter model, together with the interpolating straight, for two different operating conditions and for all the months included in the heating season (i.e. from November to March).

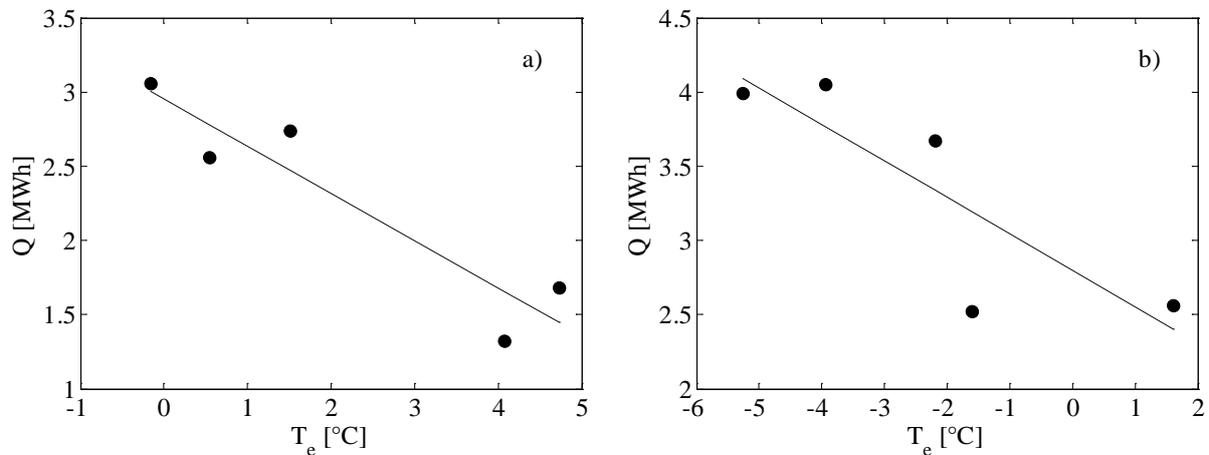


Figure 2. Daily average energy use as a function of the average temperature, for $q_g=5 \text{ W/m}^2$ and $n=0.3 \text{ h}^{-1}$: a) Berlin; b) Stockholm.

By regressing the daily average values of the energy use against the average temperature, the values of the overall heat transfer coefficient (K) and of the balance temperature (T_{bal}) can be estimated.

Once the unknown parameters are estimated, the hourly space heating profile can be restored, by means of Eq.(2).

The comparison between the heating profile obtained by using the TRNSYS tools and the restored hourly building load is shown in Figure 3, for two months of heating season. Since in the inverse procedure here adopted the effect of solar radiation is disregarded, the model leads to an overestimation of the peaks of the heating load, as it can be observed in Figure 3.

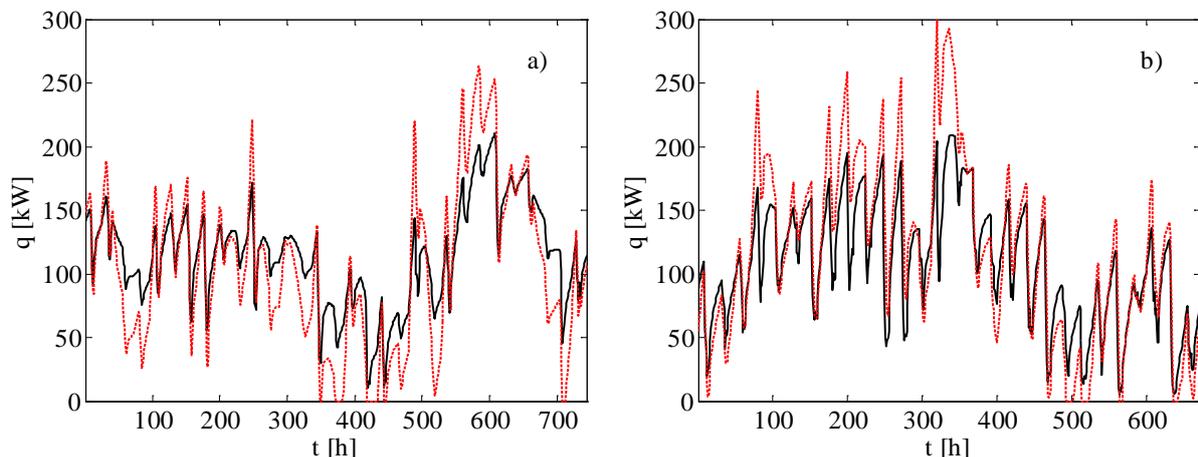


Figure 3. Comparison between the simulated heating load (continuous black line) and the restored one (dashed red line). Berlin, $q_g=5 \text{ W/m}^2$, $n=0.3 \text{ h}^{-1}$. a) December; b) February.

Therefore it is expected that the accuracy of the h-LEP with a single climate variable can be improved by considering only the months characterised by low values of both external air temperature and solar radiation. In fact if the unknown parameters (i.e. K and T_{bal}) for the case study building are evaluated by considering only four months of the heating season (i.e. from November to February), the estimated data fit the simulated ones much better.

Figure 4 shows a comparison between the simulated profiles (continuous black line) and the estimated ones obtained by regressing the monthly energy consumptions for the whole heating season (dashed red line), under the h-LEP with a single climate variable, and by excluding the consumption of March from the regression analysis (dashed blue line).

To put in evidence the difference between the multivariate regression models and the single variable ones, in Figure 4 the restored heating profiles obtained by applying the modified h-LEP [7] are presented as well.

It can be observed that if only four months are considered, both the h-LEP with a single climate variable and the modified h-LEP provide a satisfactory fit of the simulated load profiles.

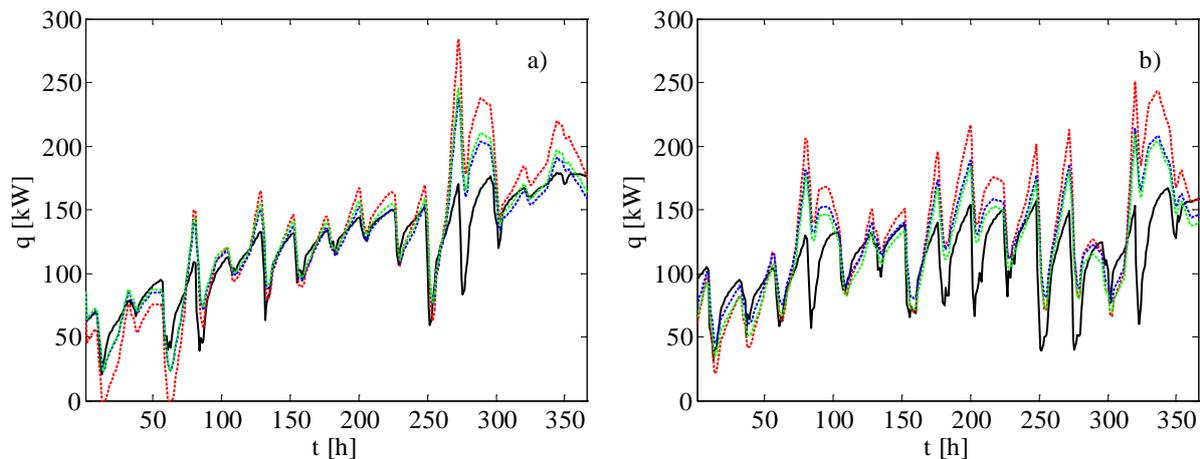


Figure 4. Comparison between the simulated heating load (continuous black line) and the restored ones (dashed red line for h-LEP with a single climate variable applied by considering 5 months, blue line for h-LEP with a single climate variable applied by considering 4 months and green line for the modified h-LEP). Berlin, $q_g = 0 \text{ W/m}^2$, $n = 0 \text{ h}^{-1}$. a) First and second week of January; b) first and second week of February.

As expected, the inverse model here adopted guarantees better accuracy if the thermal losses are relevant compared to the heat gains. This effect it is evident in Figure 5 where the influence of the air change rate (n) on the restored heat loads profile is presented.

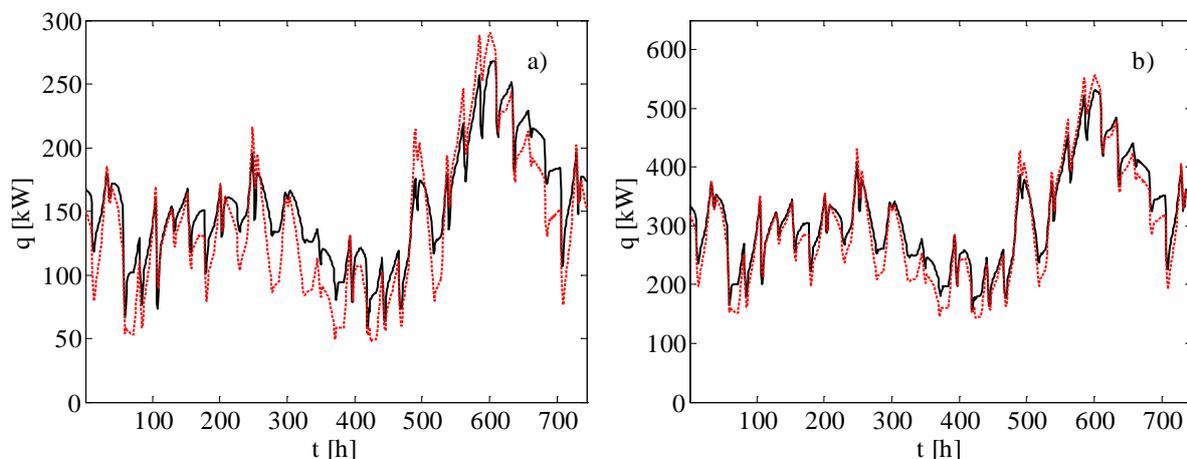


Figure 5. Comparison between the simulated heating load (continuous black line) and the restored one (dashed red line). Stockholm, $q_g = 5 \text{ W/m}^2$. a) $n = 0.3 \text{ h}^{-1}$; b) $n = 1 \text{ h}^{-1}$.

The quality of the h-LEP with a single climate variable is presented in Tables 1 and 2 where the values of coefficient of determination R^2 [12] are indicated for each operating condition here analysed.

Table 1. Coefficient of determination R^2 . Berlin.

	Present model (5 months)	Present model (4 months)	Modified h-LEP [4]
$q_g = 0 \text{ W/m}^2, n = 0 \text{ h}^{-1}$	0.33	0.56	0.69
$q_g = 5 \text{ W/m}^2, n = 0.3 \text{ h}^{-1}$	0.63	0.77	0.80
$q_g = 5 \text{ W/m}^2, n = 1.0 \text{ h}^{-1}$	0.87	0.93	0.94

Table 2. Coefficient of determination R^2 . Stockholm.

	Present model (5 months)	Present model (4 months)	Modified h-LEP [4]
$q_g = 0 \text{ W/m}^2, n = 0 \text{ h}^{-1}$	0.58	0.70	0.71
$q_g = 5 \text{ W/m}^2, n = 0.3 \text{ h}^{-1}$	0.76	0.86	0.84
$q_g = 5 \text{ W/m}^2, n = 1.0 \text{ h}^{-1}$	0.91	0.96	0.94

To assess the effectiveness of the proposed approach in the evaluation of energy efficiency of the CHP systems, both the restored profiles and the simulated ones have been used to estimate the useful heat obtainable by the cogeneration unit.

With the aim of optimising the energy performance of the CHP systems, the analysis has been carried out by considering several values of the CHP unit capacity.

Figure 6 shows the useful fraction of the cogenerated heat α_u versus the normalized cogeneration unit capacity γ (i.e. the ratio between the CHP capacity and the average heating demand of the case study building) for both space heating profiles (i.e. the load pattern simulated with TRNSYS software and the profile restored by applying the h-LEP with a single climate variable).

It can be observed that the regression approach here adopted allows to evaluate the useful thermal energy with a good accuracy, especially for Stockholm which is characterized by values of the dry-bulb air temperature and solar radiation lower than those of Berlin.

The robustness of the h-LEP with a single climate variable has been quantified by calculating the relative error between the useful fraction of the cogenerated heat α_u estimated by considering the restored load profile and the corresponding one evaluated by means of the simulated load profile:

$$\mathcal{E}_r = \frac{\alpha_{u,est} - \alpha_{u,sim}}{\alpha_{u,sim}} \quad (3)$$

The restored profiles lead to an underestimation or overestimation of the useful cogenerated heat, depending on the operating conditions and on the CHP unit capacity. The maximum and minimum relative errors that occur by using the estimated load pattern are +2.51% and -6.87%, respectively, within the CHP capacity range considered in the present analysis. Nevertheless, the relative error, averaged over the operating conditions considered in the present study, ranges between -3% and +3%; therefore the h-LEP with a single climate variable performs quite satisfactorily.

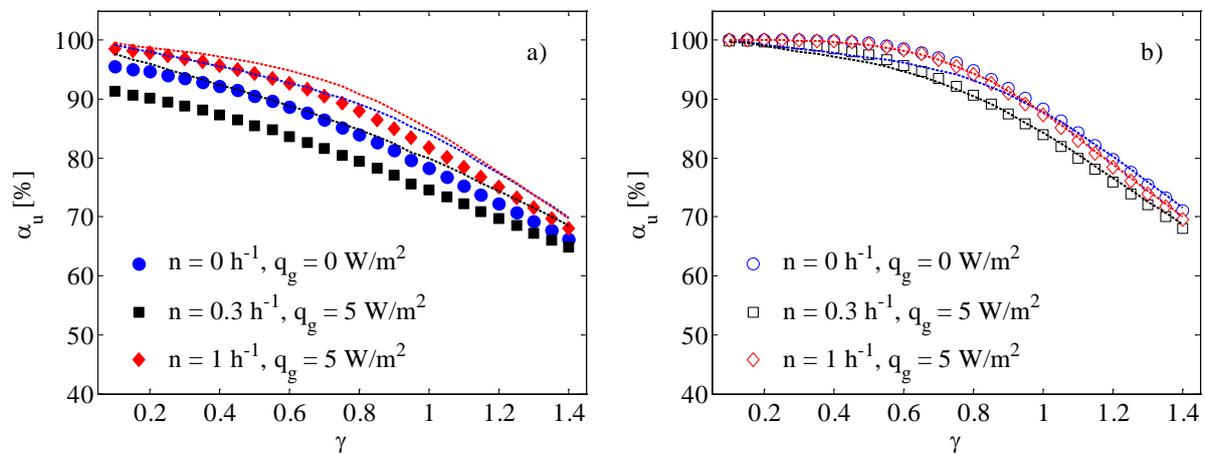


Figure 6. Comparison between the useful fraction of the cogenerated heat obtained by the simulated load profile (dashed lines) and the corresponding values evaluated by means of the space heating pattern restored by considering the whole heating season (markers): a) Berlin climate data; b) Stockholm climate data.

As discussed below, if the h-LEP with a single climate variable is applied by considering only the months characterized by low values of external air temperature and solar irradiation (i.e. the period from November to February for the here considered case study), the estimated profiles fit better the simulated ones and consequently the fraction of useful heat achievable by the CHP system can be estimated with better accuracy, as it can be observed in Figure 7.

The maximum and minimum relative errors on the useful fraction of the cogenerated heat, within the here considered operating conditions, are +0.46% and -4.38%, respectively.

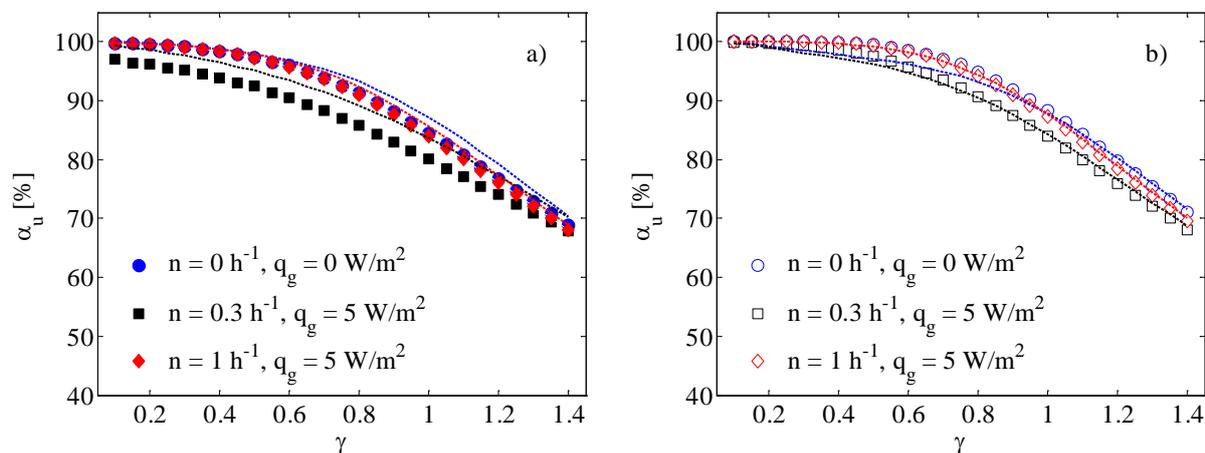


Figure 7. Comparison between the useful fraction of the cogenerated heat obtained by the simulated load profile (dashed lines) and the corresponding values evaluated by means of the space heating pattern restored by considering four months of the heating season (markers): a) Berlin; b) Stockholm.

4. Conclusions

With the aim to restore the hourly load profiles of existing buildings from the monthly energy consumption, the hourly loads estimation procedure (h-LEP) has been implemented by using as input variable only the dry-bulb air temperature.

The validity of the here adopted model has been assessed by comparing the estimated space heating load of a case study building (i.e. a building for hospital use) with the heating demand obtained by using the TRNSYS tool.

To evaluate the influence of the building characteristics and weather data on the accuracy of the h-LEP with a single climate variable, several operating conditions have been analysed by changing the value of the internal heat generation, the air change rate and the building location.

The results of the simulations point out that the h-LEP with a single climate variable works quite satisfactorily; however it has to be highlighted that the here adopted procedure works better for buildings characterized by constant internal heat gains and air ventilation rates and for locations characterized by low solar radiation.

By using the restored heating load, the useful fraction of the cogenerated heat can be estimated with an average relative error ranging between -3% and +3%, for the operative conditions here considered.

5. References

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