GENERATION OF THERMAL AND ELECTRIC LOAD PROFILES FOR THE OPTIMIZATION OF A COGENERATION SYSTEM

Marlon Huamaní Bellido
Mechanical Engineering Department – PUC-Rio, Rua Marquês de São Vicente 225, Gávea, Rio de Janeiro, Brazil
marlonmax@mec.puc-rio.br

Alcir de Faro Orlando
Mechanical Engineering Department – PUC-Rio, Rua Marquês de São Vicente 225, Gávea, Rio de Janeiro, Brazil
afo@mec.puc-rio.br

Abstract. *The design of a cogeneration system depends, case by case, on the thermal and electric load profiles. Cogeneration is a key concept for energy conversion in the future, since it proposes to optimize the use of the energy resources. The system specification goes necessarily through a technical economic analysis, where all the investments and operational costs are quantified for minimizing the cost of the produced energy. Nowadays, the majority of the cooling conventional facilities are intensive consumers of electric energy. When switching to the cogeneration mode, the power plant exhaust gas thermal energy can be used to fire an absorption chiller, thus displacing the electric energy that should be used otherwise. This work, develops a methodology for estimating the electric and thermal load profiles, month by month along the year, to be used in the design of cogeneration systems. It uses the electric energy consumption from the monthly available electric energy bill, together with a detailed energy profile, provided by the utility company for the last month of operation, every 15 minutes. This paper also discusses how the cooling load can be estimated from the available weather data. The electric energy consumption for the cooling facility can be estimated from the building cooling load, and deducted from the total electric energy consumption for estimating the need of electric energy in the cogeneration system. Electric energy consumption data, measured at PUC-Rio every 15 minutes over a one year period, was used to validate the methodology.*

Keywords*: Energy, Cogeneration, Electric and thermal profiles, Feasibility*

1. Introduction

Cogeneration is the simultaneous production of electrical or mechanical energy (power) and useful thermal energy from a single energy stream such as oil, coal, natural or liquefied gas, biomass or solar (ASHRAE, 2001), being its potential market made up of the industrial, residential and commercial sectors.

The decision of choosing an electric energy generating system (genset), or a cogeneration system, for supplying energy to building, in place of the energy presently supplied by the local utility company, is usually done on economic basis, and starts by the collection and analysis of end user energy requirements and costs (Orlando, 1996). At the initial stages of site evaluation, the objective is simply to determine whether a more detailed analysis of on-site alternatives is justified. Thus, both electrical and thermal energy requirements must be quantified.

The starting point for this analysis is the building electric load profile. Ideally, if the averaged power over every 15 minutes in the year is available, it is possible to calculate the cost of the electric energy purchased from de utility company. However, this information is seldom available. Rather, the utility company supplies, under request, the load profile for the last month of operation, only.

Therefore, the institution usually has a monthly record of the billing information for a one year period and the electric load profile for a one month period. A methodology was developed for estimating the electric profile month by month along one year, using the normally available electric energy consumption data. Electric energy consumption data, measured at PUC-Rio every 15 minutes over a one year period, was used to validate the methodology.

Air conditioning is a large electric energy consumer. Sometimes it is cheaper to switch to an absorption chiller that needs heat for its operation, either from burning fuel or waste heat, as in cogeneration systems. Sometimes direct fired chillers are specified. The absorption chiller itself is less efficient and more expensive than the electric ones. In order to quantify the contribution of the air conditioning load to the total electric energy consumption, a methodology was developed for estimating the thermal load profile month by month along the year.

2. Methodology

2.1. Electric load profile specification

The design of cogeneration systems requires a gradual evaluation of a great number of factors. The methodology requires the specification of the electric load profile of the institution, which can be obtained in different ways, **(i)** the electric utility log data for a one month period, every 15 minutes, **(ii)** from data collected by own means, etc.

Usually, the generator in a cogeneration system is not specified for attending full load, because it can be idle most of the time, thus increasing the generated energy cost. The simplest operating mode is a base loaded system, which consists of operation of the on site capacity at its prime power rating to the full extent of its availability.

For evaluating the power system, the load capacity curve was utilized; this curve is useful for estimating the energy supplied by a genset with a given capacity during the period. For a given power, the power profile (every 15 minutes) was integrated over the period, resulting in the energy consumed that has to be supplied by the genset. Simulating its operation, when the demand is larger than the given power, the genset operates at full load and this value has to be used in the integration scheme. Otherwise, the genset operates in partial load. One curve for each month of the year was developed using PUC-Rio data, and used as a reference to validate the methodology.

Two methodologies were tested, taking into account that the utility company only supplies detailed data for the last month of operation, together with the monthly energy consumption for billing purpose.

- Methodology 1: The load capacity curve, was calculated for the last month of operation and expressed percent wise, is supposed to be same for the remaining months of the year.
- Methodology 2: Similar profiles are respectively generated for each of the remaining months of the year, multiplying each average power in the reference load profile by the ratio between the consumed energy in a given month and the consumed energy in the reference month, as available to the building from the monthly electric energy billing records. The results are then expressed percent wise, as before, resulting in one load capacity curve for each month of the year.

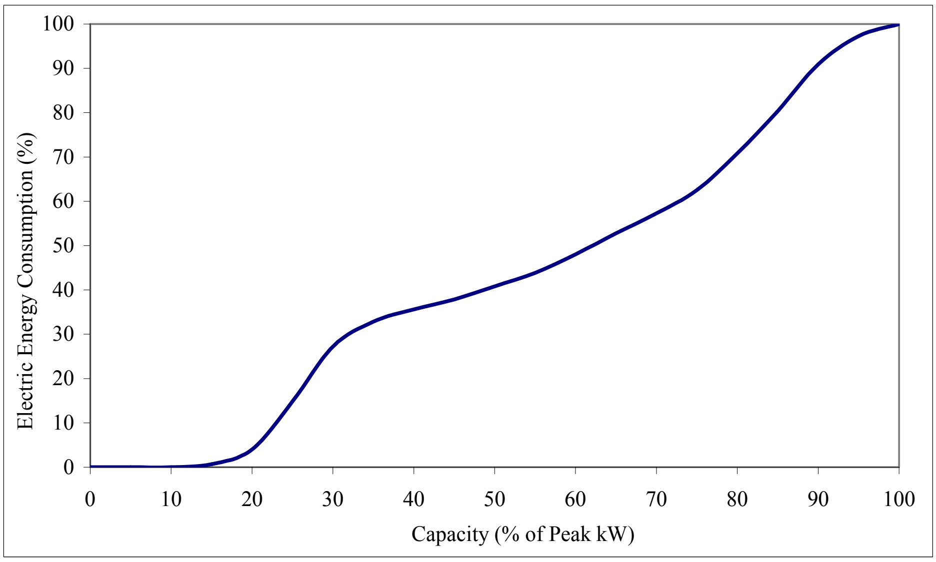

Figure 1. Load Capacity Curve.

2.2. Thermal load profile specification

2.2.1 Description

Thermal energy load can be obtained by **(i)** running available air conditioning computer programs, **(ii)** measuring over a one month period the electric load, **(iii)** using typical daily load profile from literature for similar business, etc. In some of these items it is necessary include hypotheses on the usage of the available air conditioning equipment. Knowing the thermal load profile and the efficiency of the electric equipments, the monthly electric energy consumption can be calculated, so that the electric energy consumption in the cogeneration mode can be estimated.

Estimating the energy consumption by a cooling equipment over a period requires the knowledge of the average conditions and building usage, whereas load calculations for equipment sizing purpose requires the knowledge of extreme conditions and usage for its estimation (Hui and Cheung, 1998).

The optimization of a cogeneration system can be done by utilizing average hourly values of the thermal load profile for each month of the year, which can be estimated through the detailed analysis of the heat transfer mechanisms.

The incident solar radiation on the walls, ceiling and windows of a building is one of the largest contribution to its thermal load profile. A methodology for estimating its average hourly values is described in this paper, following (Kusuda et al, 1977), complemented with expressions from (Duffie et al, 1980). The building thermal inertia usually influences the thermal load profile.

Heat is also transferred to the building due to the outside and inside air temperature difference. A methodology is also described for estimating average hourly values of the outside air temperature, following (Erbs et allii, 1983).

Some other components of thermal load profile are more predictable and do not depend on the atmospheric conditions. A methodology for estimating their contribution to the thermal load is described by (ASHRAE, 2001) for air contioning calculations, and includes people, lights, motors and other equipments.

In principle, a system designer can estimate the building average thermal load profile, if the internal loads are known, together with the heat transfer properties of the building structure. However, this methodology is not useful neither for sizing the air conditioning equipment, nor the energy consumption for cooling purposes. ASHRAE (2001) suggests a methodology for sizing the equipment, based on clear sky radiation profile and effective ambient temperature, which results in maximum thermal load within up to 95% confidence level.

Average energy consumption along the month can be estimated by integrating the thermal load profile over the time interval where cooling equipment is on, taking into account that there is no need of cooling the air inside the building when the ambient temperature drops bellow a certain level called balance point. This fact gives rise to the so called cooling degree day method for calculating the energy consumption, as described by ASHRAE (2001). There are several publications discussing how to determine the balance point. Because of the effects of internal heat gain on industrial and commercial buildings, the basic degree-day formula for a constant balance temperature has been discarded for all residential energy estimates (Guntermann, 1981), who also suggests that a system simulation would be perhaps the key to improving the accuracy of the degree-day method. Erbs et al. (1983) developed an expression for the cumulative probability distribution for ambient temperature as a function of the balance temperature, average ambient temperature and its standard deviation. As a consequence, an expression for the cooling-degree day was developed.

The methodology follows the one described by (ASHRAE, 2001) for cooling load calculations, using average hourly solar radiation and outside air temperature, instead of hourly clear sky radiation and effective outside air temperature, which are detailed in itens 2.2.2 and 2.2.3. The thermal load profile is calculated at every hour the cooling load equipment is on . If the building internal gain is negative (loosing heat to ambient) the cooling equipment must be turned off, and it is assumed to be zero for energy consumption estimates.

2.2.2 Average hourly solar radiation data

The procedure for calculating hourly solar radiation data for vertical and horizontal surfaces on average days are described by Kusuda and Ishii (1977), being a modification of Liu and Jordan (1963) procedure, and using expressions from (Duffie et al, 1980) to avoid entering a graph for obtaining empirical parameters . The following are the steps, with all angles in degrees

.

- Declination (δ)

$$\delta = 23{,}45\sin\left(360.\frac{284+n}{365}\right) \tag{1}$$

Where, n is the day of the year (n=1 for January 1, and n=365 for December 31).

- Extraterrestrial solar radiation intensity at normal incidence (I_{sc} , W/m^2)

$$I_{sc} = I_o.\left(1+0{,}033.\cos\left(\frac{360.n}{365}\right)\right) \tag{2}$$

$$I_o = 1353 \text{ W/m}^2 \tag{3}$$

- Extraterrestrial radiation on a horizontal surface (H_o , J/m^2)

$$H_o = \frac{24x3600}{\pi}.I_{sc}.\left[\cos(\varphi).\cos(\delta).\sin(\omega_s)+\frac{2.\pi\pi._s}{360}.\sin(\varphi).\sin(\delta)\right] \tag{4}$$

$$\cos(\omega_s) = -\tan(\phi).\tan(\delta) \tag{5}$$

Where, φ is latitude (negative for South).

ω_s is sunset hour angle.

- Monthly average daily total radiation on a horizontal surface, $\overline{H}$ (J/m^2)

- Monthly average clearness index, $\overline{K}_T$

$$\overline{K}_T = \frac{\overline{H}}{H_o} \tag{6}$$

- Monthly average diffuse index, $\overline{K}_d$

$$\overline{K}_d = \overline{K}_T.\{0{,}775 + 0{,}00653.(\omega_s - 90) - [0{,}505 + 0{,}00455.(\omega_s - 90)].\cos(115.\overline{K}_T - 103)\} \tag{7}$$

- Monthly average daily diffuse radiation on a horizontal surface, $\overline{D}$, (J/m^2)

$$\overline{D} = \overline{K}_d.H_o \tag{8}$$

- Average hourly diffuse radiation factor , r_d

$$r_d = \frac{\pi}{24}.\frac{\cos(\omega) - \cos(\omega_s)}{\sin(\omega_s) - (2.\pi.\omega_s / 360).\cos(\omega_s)} \tag{9}$$

Where ω is the hour angle corresponding to a given hour of the day.

- Average hourly diffuse radiation on a horizontal surface, $\bar{I}_{dh}$, (J/m^2)

$$\bar{I}_{dh} = r_d.\overline{D} \tag{10}$$

- Average hourly total radiation factor , r_t

$$r_t = \frac{\pi.[a + b.\cos(\omega)]}{24}.\frac{\cos(\omega) - \cos(\omega_s)}{\sin(\omega_s) - (2.\pi.\omega_s / 360).\cos(\omega_s)} \tag{11}$$

$$a = 0{,}409 + 0{,}5016.\sin(\omega_s - 60) \tag{12}$$

$$b = 0{,}6609 - 0{,}4767.\sin(\omega_s - 60) \tag{13}$$

- Average hourly total radiation on a horizontal surface, $\bar{I}_{Th}$, (J/m^2)

$$\bar{I}_{Th} = r_t.\overline{H} \tag{14}$$

- Average hourly direct radiation on a horizontal surface, $\bar{I}_{Dh}$, (J/m^2)

$$\bar{I}_{Dh} = \bar{I}_{Th} - \bar{I}_{dh} \tag{15}$$

- Angle of incidence between the sun's direct beam and the horizontal surface, θ_H

$$\cos(\theta_H) = \cos(\phi).\cos(\delta).\cos(\omega) + \sin(\phi).\sin(\delta) \tag{16}$$

- Angle of incidence between the sun's direct beam and a vertical surface, θ_v

$$\cos(\theta_v) = -\sin(\delta).\cos(\phi).\cos(\gamma) + \cos(\delta).\sin(\phi).\cos(\gamma).\cos(\omega) + \cos(\delta).\sin(\gamma).\sin(\omega) \tag{17}$$

Where γ is the wall azimuth angle, with zero due south, east negative, west positive, $-180^o \le \gamma \le 180^o$

- Average hourly direct radiation on a given vertical surface, $\bar{I}_{Dv}$, (J/m^2)

$$\bar{I}_{Dv} = \frac{\bar{I}_{Dh}}{\cos(\theta_H)}.\cos(\theta_v) \tag{18}$$

- Average hourly diffuse radiation on a given vertical surface, $\bar{I}_{dv}$, (J/m^2)

$$\bar{I}_{dv} = \frac{\bar{I}_{dh}}{2} \tag{19}$$

- Average hourly reflected radiation from the ground on a given vertical surface, $\bar{I}_{gv}$, (J/m^2)

$$\bar{I}_{gv} = \frac{\rho_g.\bar{I}_{Th}}{2} \tag{20}$$

Where ρ_g is the ground reflectance, being equal to 0,2 for no snow, and 0,7 for fresh snow.

- Average hourly total radiation on a given vertical surface, $\bar{I}_{Tv}$, (J/m^2)

$$\bar{I}_{Tv} = \bar{I}_{Dv} + \bar{I}_{dv} + \bar{I}_{gv} \tag{21}$$

2.2.3 Hourly monthly average ambient temperature, $\bar{T}_{a,h}$ from monthly average ambient temperature, $\bar{T}_a$

Eq. 25 was developed by (Erbs et alli,1983) and relates hourly monthly average temperature to monthly average temperature and clearness index.

This equations show how calculate the hourly ambient temperature with the monthly average ambient temperature and the difference between the indoor temperature and the outdoor temperature, this work was developed by Erbs et al. (1983).

$$\frac{\bar{T}_{a,h} - \bar{T}_a}{A} = 0{,}4632.\cos\left(t^* - 3{,}805\right) + 0{,}0984.\cos\left(2.t^* - 0{,}360\right) + \tag{22}$$

$$+ 0{,}0168.\cos(3.t^* - 0{,}822) + 0{,}0138.\cos\left(4.t^* - 3{,}513\right)$$

$$t^* = \frac{2.\pi.(t-1)}{24} \tag{23}$$

Where t is in hours, t=1 at 1 a.m., and t=24 at midnight.

$$A = 25{,}8\bar{K}_T - 5{,}21 \tag{24}$$

3. Results

3.1 Electric load profile

The available data from PUC-Rio, every 15 minutes, over a 1 year period, was used as a reference for validating de methodology, and is called BASE.

Table 1 shows the computed values for the yearly electric energy produced and comparisons with the Reference, for each genset power.

JMA : Load capacity curve for January. Used for the remaining months.
AMA : Load capacity curve for April. Used for the remaining months.
JRM : January is the BASE month for generating the load capacity curve for the remaining months.
ARM : April is the BASE month for generating the load capacity curve for the remaining months.

Table 2 shows the standard deviation and average values for both methodologies, where:

X.M.A. : Load capacity curve for “X” month. Used for the remaining months.
X.R.M. : “X”is the BASE month for generating the load capacity curve for the remaining months.

Table 1. Comparison of yearly electric energy produced between proposed methodologies and BASE.

P_G (kW)	BASE (kWh/year)		JMA (kWh/year)	AMA (kWh/year)	JMA (%)	AMA (%)		JRM (kWh/year)	ARM (kWh/year)	JRM (%)	ARM (%)
3000	8971509	**METHOD. 1**	8977205	8978056	0.06	0.07	**METHOD. 2**	8979197	8987834	0.09	0.18
2500	8038020		7929499	7880522	1.35	1.96		8005100	7879743	0.41	1.97
2000	6724392		6276906	5969483	6.65	11.23		6285201	5967987	6.53	11.25
1500	4698961		4686001	4429809	0.28	5.73		4682861	4372342	0.34	6.95
1000	3199276		3248991	2913903	1.55	8.92		3192562	2911146	0.21	9.01
500	734167		606510	780876	17.3	6.36		596953	780732	18.69	6.34

3.2 Thermal load profile

Fig. 2 shows the hourly values of monthly average ambient temperature computed by the Eq. (22) and Table 3 shows the value of average hourly solar radiation according to subtitle 2.2.1, for each wall, in Albuquerque (USA).

Table 2. Standard Deviation and Average Value for both methodologies proposed for electric load profile (MWh).

X.M.A.	**METHODOLOGY 1**		**X.R.M.**	**METHODOLOGY 2**	
	Average Value	Standard Deviation		Average Value	Standard Deviation
Jan	5288	3098	Jan	5290	3123
Feb	5900	3002	Feb	5898	3021
Mar	5315	2922	Mar	5314	2922
Apr	5159	3079	Apr	5150	3084
Mai	5635	3062	Mai	5648	3061
Jun	5601	3096	Jun	5775	3095
Jul	5877	3347	Jul	5901	3385
Ago	4628	3077	Ago	4618	3085
Set	4643	2993	Set	4621	3013
Oct	5633	3190	Oct	5638	3194
Nov	5735	2990	Nov	5721	2992
Dec	5343	3137	Dec	5344	3150
BASE	5394		BASE	5394	

Table 3. Average hourly incident solar radiation (W/m^2) on vertical and horizontal surfaces

Orient.	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
S	0	0	32	72	113	217	315	378	400	378	315	217	113	72	32	0	0
SW	0	0	32	72	113	148	173	189	340	460	536	555	507	394	195	0	0
W	0	0	32	72	113	148	173	189	195	385	542	649	684	611	366	0	0
NW	0	0	32	72	113	148	173	189	195	195	334	451	523	517	340	0	0
NW	0	0	132	161	123	148	173	189	195	189	173	148	123	161	132	0	0
NE	0	0	340	517	523	451	334	195	195	189	173	148	113	72	32	0	0
E	0	0	366	611	684	649	542	385	195	189	173	148	113	72	32	0	0
SE	0	0	195	394	507	555	536	460	340	189	173	148	113	72	32	0	0
Horiz	0	0	113	318	530	716	857	949	980	949	857	716	530	318	113	0	0

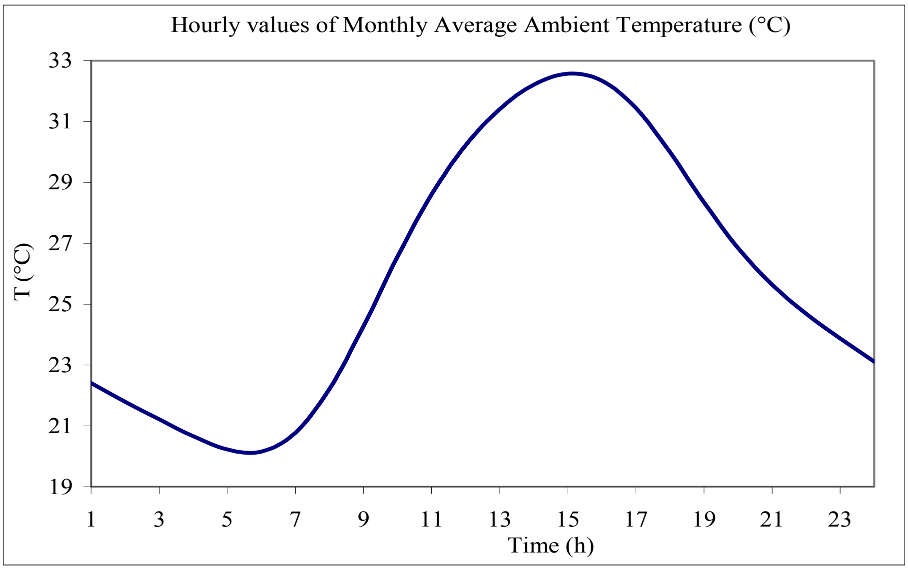

Figure 2. Hourly values of Monthly Average Ambient Temperature (July).

4. Conclusions

Using, as a reference, available data for PUC-Rio every 15 minutes, over a one year period, it was shown that the predictions made with two methodologies are of good acceptance; but due to its simplicity and, basically, because their standard deviation is smaller if are compared with the second one, methodology 1 should be used for estimating the electric energy load for each month of the year. Thus, a load capacity curve should be generated for the reference month, and used for the remaining months of the year. It was also shown that this methodology can be used when operating the genset at partial load. Small values of genset power, however, produces a larger error.

Using a methodology developed by Kusuda et al (1977), and expressions from Duffie et al (1980) to avoid entering a graph for obtaining empirical parameters, the average hourly incident solar radiation on vertical and horizontal surfaces was calculated. Also, using an expression developed by Erbs et alli (1983), the average hourly ambient temperature was calculated for each month of the year. Using these two parameters, instead of the clear sky solar radiation and the effective ambient temperature, (ASHRAE, 2001)´methodology can be used for estimating the thermal load profile of a building

5. Acknowledgements

The authors are indebted to PUC-Rio by making available the electric energy profile used for the development of this work.

6. References

ASHRAE, 2001, "Air Conditioning Systems Design Manual", American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Georgia, United States, Chapter 7.

Do Val, L.G., 2001, "Análise Crítica de Desempenho de Plantas de Cogeração", MSc thesis, PUC-Rio, Rio de Janreiro, Brazil, 196 p.

Duffie,J.A. & Beckman, W.A.,1980, "Solar Engineering of thermal Processes", John Wiley and Sons, New York,

Erbs, D.G., 1983, "Estimation of Degree-Days and Ambient Temperature Bin Data From Monthly-Average Temperatures", ASHRAE Journal, pp. 60-65.

Guntermann, P.E., 1981, "A Simplified Degree-Day Method for Commercial and Industrial Buildings", ASHRAE Journal, pp. 461-472.

Hui, S.C. and Cheung, K.P., 1998, "Application of Building Energy Simulation to Air-Conditioning Design", Mainland-Hong Kong HVAC Seminar March '98, pp. 12-20.

Khan, K.H., Rasul, M.G. and Khan, M.M.K., 2004, "Energy Conservation in Buildings: Cogeneration and Cogeneration Coupled with Thermal-Energy", Applied Energy, Vol.77, pp. 15-34.

Kusuda, T. and Ishii, K., 1977, "Hourly Solar Radiation Data for Vertical and Horizontal Surfaces on Average Days in the United States and Canada", U.S. Department of Commerce / National Bureau of Standards, 405 p.

Orlando, A.DF. and Do Val, L.G., 2003, "Analysis of the criteria for Designing, Installing and Operating a Cogeneration System", COBEM 2003
Orlando, J.A., 1996, "Cogeneration Design Guide", Ed. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Georgia, United States, 346 p.
Roy-Aikins, J.E.A., 1995, "An Investigation of the Factors that Determine the Attractiveness of Cogeneration", Heat Recovery Systems & CHP, Vol.15, No 5, pp. 473-480.
Tolmasquim, M.T., Szklo, A.S. and Soares, J.B., 2002, "Economic Potential of Natural Gas Fired Cogeneration Plants at Malls in Rio de Janeiro", Energy Conversion & Management, Vol. 42, pp. 663-674.
TRANE, "Air Conditioning Manual", Ed. McGill Graphic Arts, Wisconsin, United States, 456 p.

7. Responsibility notice

The authors are the only responsible for the printed material included in this paper.