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ENERGY AND ENVIRONMENTAL ANALYSIS OF A CCHP SYSTEM USED IN INDUSTRIAL FACILITY

The paper concentrates on problems of introducing a combined cooling, heating, and power (CCHP) system into an industrial facility with well-defined demand profiles of cooling, heating, and electricity. Environmental and energy evaluation covering the proposed CCHP system (Case 2) and the reference system (Case 1) has been carried out. The conventional system consists of three typical methods of energy supply: a) electricity from an external grid, b) heat from gas-fired boilers, and c) cooling from vapor compression chillers run by electricity from the grid. The CCHP system contains the combined heat and power (CHP) plant with a gas turbine–compressor arrangement and water/lithium bromide absorption chiller of a single-effect type. Those two cases were analyzed in terms of annual primary energy consumption as well as annual emissions of CO_2, NO_x, and SO_2. The results of the analysis show the primary energy savings of the CCHP system in comparison with the reference system. Furthermore, the environmental impact of the CCHP application, in the form of pollutant emission reductions, compares quite favorably with the reference conventional system.

1. INTRODUCTION

In a combined cooling, heating, and power (CCHP) system, electricity is produced on-site from the combustion of a fuel in an electricity generation unit (prime mover and generator). The main difference between the CCHP system and conventional ways of electricity generation is the utilization of waste heat rejected from the prime mower (e.g., gas turbine) to satisfy the thermal demand of a facility (cooling, heating, hot water or technology needs). The ultimate purpose of CCHP systems is to ensure savings in consumed primary energy and reduction of pollutant gas emissions. Conventional thermoelectric power plants convert only about 30% of primary energy into electricity. The rest of primary energy is usually released into the atmosphere as waste heat. One of the techniques of increasing the efficiency of electricity generation is combined heat and

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power (CHP) production known also as cogeneration. CHP plant transforms over 85% of primary energy to usable energy in the form of heat and power. Furthermore, that high conversion efficiency translates into improved environmental impact giving a considerable reduction in emissions of pollutants and greenhouse gases. The ideal situation is to run a CHP plant throughout the whole year with full utilization of produced heat and power. In the Polish climate while the heat from the CHP unit is being used in heating, ventilating, and air conditioning installations during wintertime, afterward, outside heating season there is always an excess of available heat that is a by-product of electricity generation. A method of using this excess heat is based on expanding the CHP plant to combined cooling, heating, and power generation process also known as a tri-generation. The tri-generation or the CCHP system is a CHP plant connected to an absorption chiller run by the heat produced in a CHP unit. In this way, the heat would not be wasted in the summer season due to the lack of heat demand but instead, it can be used effectively to make cooling energy, e.g., for air conditioning or technology purposes. The CCHP system considered for the particular application in the presented study can use the CHP plant with absorption cooling units. LiBr-water absorption cycle is chosen because the cooling effect is needed mostly in air conditioning installations with cooling water temperatures always above 5 °C. The choice of the most appropriate CCHP system arrangement depends on such factors as heat/power ratio, the temperature level of the required heat output, and variations of heating, cooling, and power demand. Numerous literature positions illustrate the specific benefits of using CCHP systems in comparison with conventional alternatives. Apart from a better conversion of primary energy and consequently reduction of greenhouse gas emission also economic benefits are evident for CCHP options [1–4]. The only energy cost involved in a CCHP system is the cost to supply the fuel necessary to run the prime mover, whereas in a conventional system the energy consumer has to pay monthly power demand and electrical energy usage charges. The energy supply from a CCHP plant is more reliable than the electricity from the grid. Additionally, the tri-generation units ensure some increase in the electricity grid stability. During hot summer, there would be a significant relief in the grid, since the cooling process changes from compression into absorption cycles. That further improves efficiency because summer demand peaks are often served by utilities through inefficient standby units and overloaded transmission lines.

The CCHP system consists of two parts, a CHP unit, and an absorption chiller. There is a variety of these two plants and thus one should choose the appropriate type of the plant for the particular application. Since it is assumed that, a continuous power demand prevails on the site and thermal energy can be utilized throughout the year a gas turbine type of CHP is chosen. As for the absorption chiller, it is decided to have the LiBr-water unit of two different effect types The first one is a single-effect appliance with a small coefficient of performance (*COP*) value of 0.65 and correspondingly low temperature of medium running the unit. The second one is a two-effect unit with a higher *COP* value of 1.2 and likewise a need for higher temperatures to run the chiller.

Most of the studies on CCHP system performance related to energy, environmental and economic evaluations [5–9]. The authors use primary energy savings ratio and CO_2 emission reduction ratio to assess the energy usage and environmental impact of the system, respectively. In general, it is well known that CCHP systems are rather difficult to design and operate in facilities with distinctively varying power, cooling and heating demands, as it is a case in residential and commercial buildings. However, some investigations were carried out for these types of buildings and reported in the technical literature [10–14]. There are some studies on the CCHP performance in cases with more uniform power and thermal loads, e.g., in data centers and hospitals. Comprehensive research on this type of site is described in [15, 16]. On the other hand, it is difficult to find evaluation studies on the CCHP application in the industrial facilities.

This paper evaluates the CCHP performance on the industrial site where power, heating, and cooling loads fluctuate in different modes than in separate buildings, due to power and thermal needs of the production processes. The evaluation covers the proposed CCHP system (Case 2) and the reference system (Case 1) that consists of three conventional methods of energy supply: a) electricity from an external grid, b) heat from gas-fired boilers and c) cooling from vapor compression chillers run by electricity from the grid. Those two cases are analyzed in terms of annual primary energy usage as well as annual emissions of CO_2, NO_x, and SO_2. The results of the analysis show the extent of primary energy savings of the CCHP system concerning the reference system. Furthermore, the environmental impact of the CCHP system, in the form of emission reductions, is compared with the reference conventional system.

2. CHARACTERISTICS OF THE CASE STUDY

The basic CCHP system contains two elements, a CHP unit, and an absorption chiller. The CHP unit can take different forms and thus one should choose the appropriate type of the plant for the particular application. Two types of the CHP unit concerning the prime mover have been considered, a gas turbine and an internal combustion reciprocating engine. Since it is assumed that a continuous power demand prevails on the site and thermal energy can be utilized throughout the whole year, a gas turbine type of CHP is chosen. The scheme of the basic CCHP system is illustrated in Fig. 1.

The case study presented in this paper focuses on issues regarding the problem of introducing the CCHP system to the industrial facility with well-defined demand for cooling, heating, and electricity. The industrial facility is a pharmaceutical factory producing adhesive dressings and plaster materials. The factory is currently being expanded by installing additional production lines. All new production lines should be housed in air-conditioned spaces. The production processes are assumed to be run of 16–20 hours per day with 5–6 days schedules depending on the product demand. Until now, air-conditioned spaces use heating energy provided by gas-fired boilers and cooling energy supplied from vapor compression type chillers. All electricity needs are covered by the external electrical grid. The outlined process of production expansion poses a question of whether it is a worthwhile attitude to increase the existing ways of energy supply, which means additional boilers, larger compression chillers, and bigger electricity demand from the grid. Alternatively, perhaps one should consider energy production on-site with the CCHP system. The most economic operation option is to run the CCHP plant throughout the year with almost full utilization of produced heat and power.

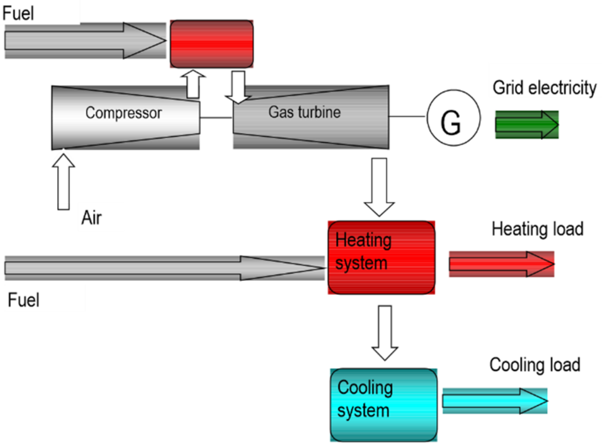

Fig. 1. Basic CCHP system

This type of operation will be possible if energy demand profiles are satisfactory. In this case, demand profiles are quite favorable. The basic power needs of production lines are nearly constant (with small variations) for 24 hours per day through almost the whole year (over 8000 hours). Thus, all electricity generated by the CHP plant can be utilized for main production purposes without a need of exporting it to the external electricity grid. The heat consumption from the CHP plant is a more complex process. The heat demand varies quite considerably because heating needs are changing during cold and warm seasons. All production areas must be air-conditioned 24 hours per day to attain constant indoor parameters all over the year. Additionally, there is always a steady demand for cooling in the production processes. Therefore, the excess heat from the CHP unit can be used to generate cooling energy in a quite stable way. Furthermore, the heat produced in the CHP plant has always priority over that delivered by gas-fired boilers. Similarly, the electricity from the plant has also priority over that drawn from the grid.

The CCHP system in this particular industrial facility should be evaluated by comparing it with a traditional option that is the reference scenario called Case 1. This reference scenario includes three standard ways of providing energy to the site: a) electricity from the external grid, b) heat from the gas-fired boilers, and c) cooling from vapor compression chillers, as is illustrated in Fig. 2. Electricity taken from the grid is used to cover a power load of production lines and to generate cooling energy in compression chillers. Conversely, natural gas is supplied to the boilers ensuring all heating needs.

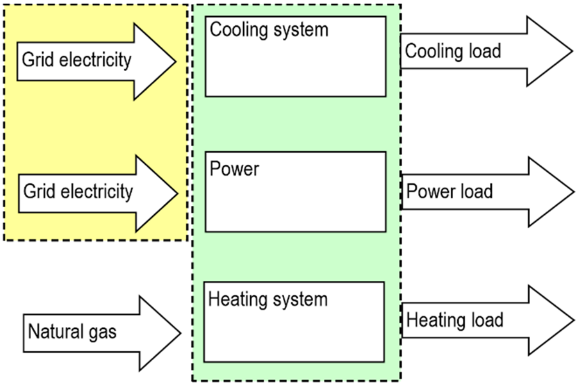

Fig. 2. Conventional system. Case 1

The CCHP scenario called Case 2 is based on the operation of the CHP plant producing all needed electricity while recovered heat is being used to generate cooling energy in an absorption chiller and to cover a heating load, as it is illustrated in Fig. 3.

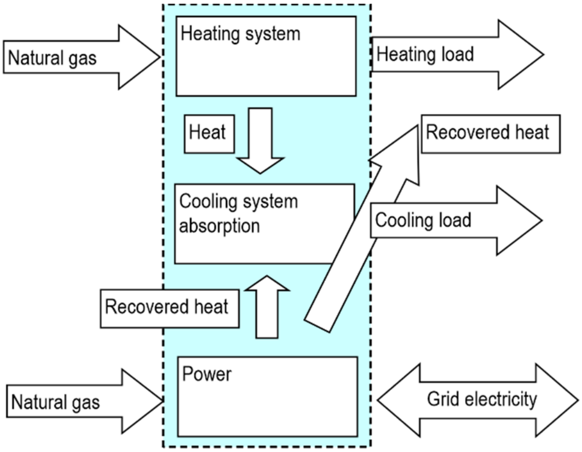

Fig. 3. CCHP system. Case 2

In the general practice of using CHP units, occasionally a certain amount of cooling energy could be also generated in vapor compression chillers supplied with electricity from the CHP unit. However, in the case discussed it is not a viable option because there always would be an excess of heat from the CHP unit in the summer season. That excess heat could be otherwise wasted and the overall efficiency of the system would decrease considerably. Additionally, the heating system is equipped with small gas boilers, which could be used as a backup.

3. SYSTEM PERFORMANCE ANALYSIS

Three elements of the presented study: data patterns, the simulation model, and performance evaluation constitute a comprehensive procedure for the system operation and efficiency assessment. Besides, a sensitivity parameter analysis can be used to optimize the design of the system according to prevailing demand profiles. Data patterns describing the power and thermal demands serve as inputs to the simulation model. The model is based on the existing and validated procedures of the TRANSYS program considering equipment specifications, system configurations, and operational schedule. This paper focuses mostly on using the results of the simulation model in the process of energy and environmental evaluation of the CCHP system in a similar way as in the approach described in [9].

The primary energy consumption of the system is obtained by multiplying the entire amount of energy consumed on the site by the primary energy factor that considers all losses occurring throughout conversion, transmission, storage, and distribution. Hence, the primary energy consumption is used as the basis for energy performance evaluation. One should calculate primary energy consumption for both scenarios, the conventional system (Case 1) and CCHP system (Case 2). The principle difference between these two cases is the method of cooling energy production, in Case 1, a compression type chiller is operated, and Case 2 makes use of an absorption chiller. The energy needed for generating a cooling effect is calculated in the same way in two cases, by using the *COP* normalized over time. The annual consumption of primary energy in the conventional system, Case 1, PE_{conv}, is calculated as follows:

$$PE_{\mathrm{conv}} = \left(E_{\mathrm{el}} + \frac{E_{\mathrm{cool}}}{COP_{\mathrm{c}}} \right) F_{\mathrm{el}} + \frac{E_{\mathrm{hb}} F_{\mathrm{g}}}{\eta_{\mathrm{t}}} \qquad (1)$$

where E_{el} is the power load integrated over time, E_{cool} is the cooling energy generated by the compression chiller, COP_{c} is the coefficient of performance of the chiller, E_{hb} is the heating load taken as heating energy produced by gas boilers with a total efficiency of η_{t}. E_{hb} can also be interpreted as the amount of energy covering all central heating, ventilation, and technological needs. F_{g} and F_{el} are primary energy factors for gas heating and electricity, respectively. The following values of these factors were taken for the study: $F_{\mathrm{g}} = 1.1$ and $F_{\mathrm{el}} = 3.0$. Consequently, the primary energy consumption of the CCHP system in Case 2 is determined by:

$$PE_{\mathrm{CCHP}} = \left(E_{\mathrm{el}} + \frac{E_{\mathrm{cool}}}{COP_{\mathrm{abs}}} + E_{\mathrm{h}} \right) F_{\mathrm{g}} + \frac{E_{\mathrm{hbb}} F_{\mathrm{g}}}{\eta_{\mathrm{t}}} \tag{2}$$

where E_{cool} in this case is the cooling energy generated by the absorption chiller characterized by COP_{abs}, E_h is heating energy produced by the CCHP system and E_{hbb} denotes energy taken from the gas backup boilers.

In addition to the primary energy rating, an environmental evaluation taking into account CO_2, SO_2, and NO_x emissions of the analyzed systems is also performed. The combined environmental impact of all greenhouse gas compounds is commonly normalized to the specific effect of CO_2 and all emissions are expressed in CO_2 equivalents. For this study, the emissions are just expressed in the mass of CO_2. Emission factors for gas usage, EF_{g} and electricity production, EF_{e} representative in the local energy market were introduced to calculate actual emissions. The following values are currently used in Poland: $EF_{\mathrm{g}} = 0.202$ kg CO_2/kWh and $EF_{\mathrm{e}} = 0.812$ kg CO_2/kWh. The annual CO_2 emissions for the conventional system of Case 1 (AE_{conv}) are computed in the following way:

$$AE_{\mathrm{conv}} = \left(E_{\mathrm{el}} + \frac{E_{\mathrm{cool}}}{COP_{\mathrm{c}}} \right) EF_{\mathrm{e}} + \frac{E_{\mathrm{hb}} EF_{\mathrm{g}}}{\eta_{\mathrm{t}}} \tag{3}$$

Consequently, for the CCHP system in Case 2, the annual CO_2 emissions are found from the following formula:

$$AE_{\mathrm{CCHP}} = \left(E_{\mathrm{el}} + \frac{E_{\mathrm{cool}}}{COP_{\mathrm{abs}}} + E_{\mathrm{h}} \right) EF_{\mathrm{g}} + \frac{E_{\mathrm{hbb}} EF_{\mathrm{g}}}{\eta_{\mathrm{t}}} \tag{4}$$

Annual emissions of SO_2 and NO_x in both cases are computed in a similar way as for the CO_2 annual emission, with the only difference being emission factors of these pollutants.

4. RESULTS AND DISCUSSION

The principle goal in optimizing the CCHP system performance is to coordinate its operation with existing heating, cooling, and power load profiles. Figure 4 shows the monthly power demands as well as heating and cooling loads occurring on the site.

Maximum heating needs occur during winter months, but heating is also required during the summer, mostly due to the production lines demand. The cooling energy is not only required in the summer for air conditioning installations but there is also quite a considerable demand of cooling for manufacturing purposes. Overall, all energy load profiles on the site look rather suitable for the usage of the CCHP system.

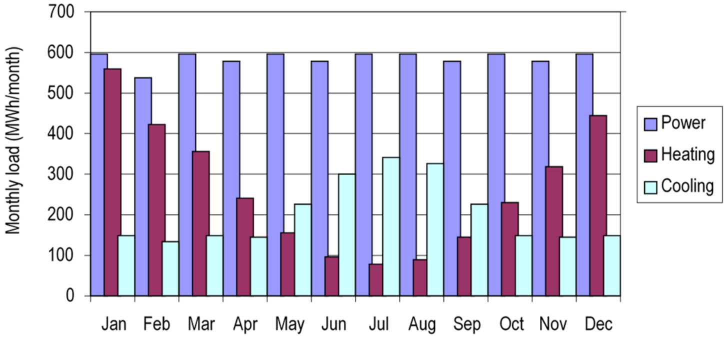

Fig. 4. Power, cooling and heating monthly loads

Nevertheless, the problem with the instantaneous capacity demands can take place when both production and HVAC needs (expressed in kW) attain their maximum values at the same time, resulting in either peak load heating or peak load cooling as shown in Fig. 5.

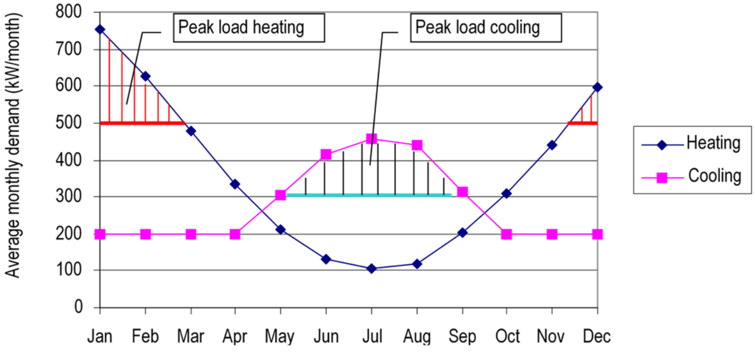

Fig. 5. Average monthly demand for heating and cooling

Figure 6 shows how the CCHP system can adapt to the monthly power, heating, and cooling loads of the facility. The total heating load in the form of heat recovered from the CCHP system is increased to the value covering the heating and cooling needs. The cooling energy is then generated by heat in the absorption chiller.

Figure 7 depicts the entire annual primary energy consumption for the conventional system of Case 1 and the CCHP system of Case 2. This total primary energy is additionally allocated to specific installations such as power, heating, and cooling systems. The usage of the total primary in the CCHP system is 24% smaller than that in the conventional system. In power utilization, the reduction in Case 2 versus Case 1 range up to 32%. Alternatively, in heating production, Case 2 gives an increase of 55% in comparison with Case 1. In contrast, cooling generation in Case 2 offers a primary energy reduction of 67% as opposed to Case 1.

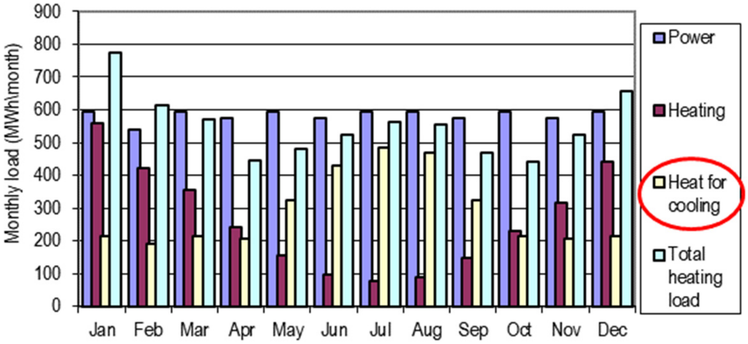

Fig. 6. Monthly loads of power, heating, and cooling – modified for the CCHP

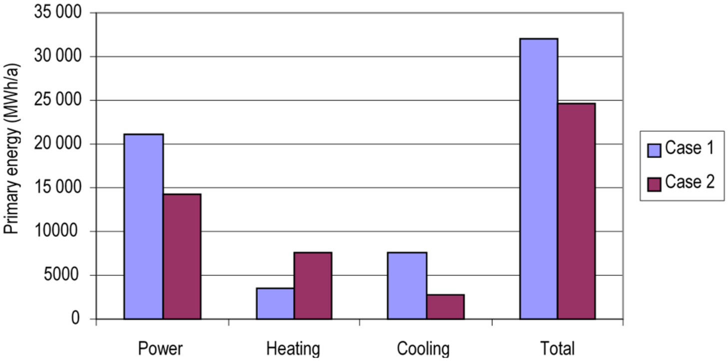

Fig. 7. Primary energy consumption – Cases 1 and 2

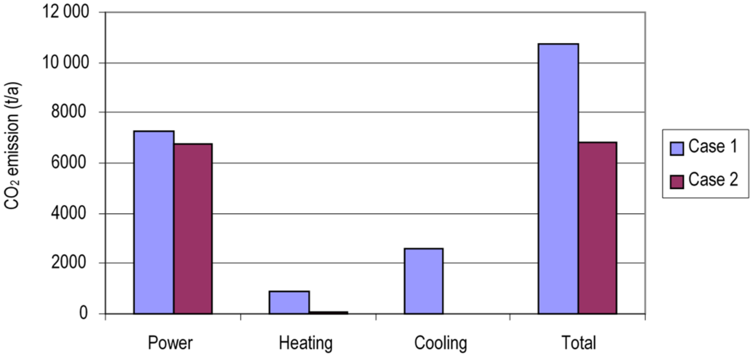

Fig. 8. Annual CO_2 emissions. Cases 1 and 2

Figure 8 illustrates annual CO_2 emissions for Case 1 of the conventional system and Case 2 of the CCHP system. The total CO_2 emissions are similarly assigned to power, heating, and cooling installations. The total annual emissions in the CCHP system is around 36% lower than that in the conventional system. The emission reduction in power utilization in Case 2 is just 7% lower than in Case 1. Alternatively, in heating energy production the emission reduction in Case 2 reaches 100% in contrast to Case 1. Furthermore, cooling generation in Case 2 offers no CO_2 emission.

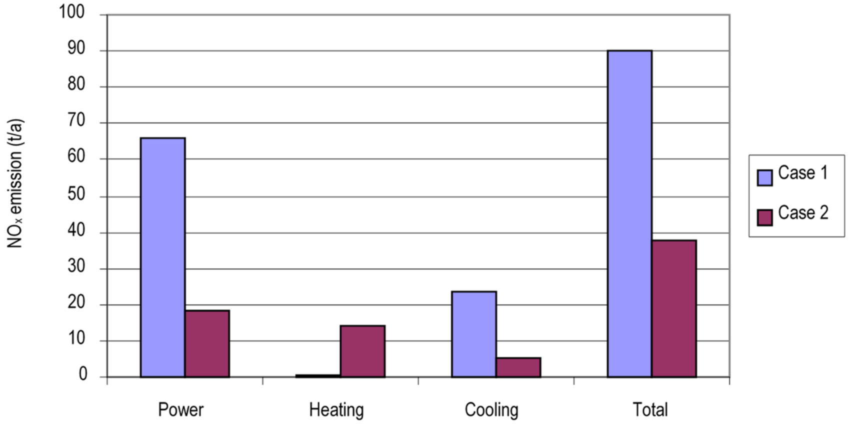

Fig. 9. Annual NO_x emissions. Cases 1 and 2

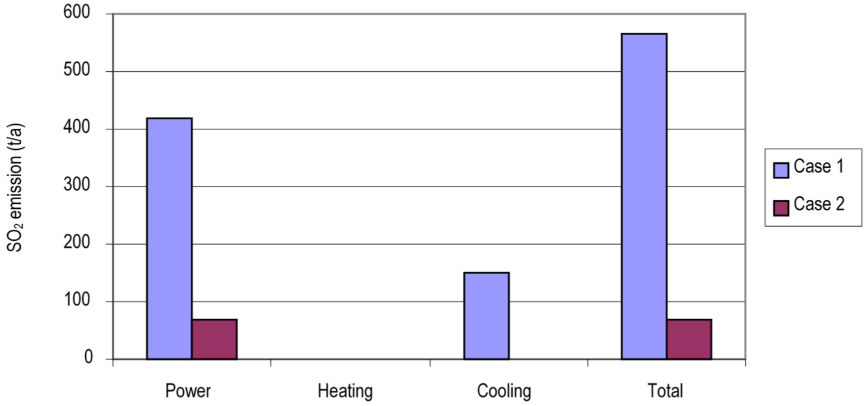

Fig. 10. Annual SO_2 emissions. Cases 1 and 2

Figure 9 presents the annual NO_x emissions for Cases 1 and 2. The total emissions of NO_x are similarly assigned to power, heating, and cooling installations. The entire annual emissions in the CCHP system is almost 60% lower than in the conventional system. The emission reduction in power utilization in Case 2 is over 70% lower than in Case 1. Then, in heating energy production, we have the opposite situation with almost non-existent emission in Case 1 due to gas-fired boilers. Cooling generation in Case 2 offers 74% lower emission than in Case 1.

Figure 10 shows annual SO_2 emissions for Cases 1 and 2. The complete annual emissions in the CCHP system is almost 90% lower than in the conventional system. A similar proportion applies to power usage. SO_2 emission is absent in heating and cooling energy production.

Overall, there is quite evident that the CCHP system has a better environmental impact than the conventional system.

5. CONCLUSIONS

This paper offers energy and environmental evaluation of the CCHP system (Case 2) and the conventional system (Case 1) in an industrial facility. Those two cases have been analyzed in terms of annual primary energy usage as well as annual emissions of CO_2, NO_x, and SO_2. According to some results of the evaluation, the following conclusions should be drawn.

- A relatively stable power demand and technological cooling and heating needs associated with the HVAC loads can match in a quite favorable way with the CCHP system operation. Therefore, the industrial facility could be rather a suitable site for CCHP applications.
- The energy performance assessment based on the comparison of primary energy consumption in the two systems indicates that the CCHP system attains better performance than the conventional one. That is, the CCHP system consumes a smaller amount of primary energy.
- Likewise, the environmental performance appraisal based on the total annual CO_2, NO_x, SO_2 emissions proves that the CCHP system is more environmentally benign than the conventional one.
- Additionally, there also exist several other opportunities to optimize the operation of the proposed CCHP system in this particular industrial facility. One of these measures could be a replacement of a single-effect absorption unit with a two-effect unit with increasing effectiveness of cooling generation almost twofold and reducing primary consumption for cooling energy generation by half. Another operation optimizing measure would be an improvement of demand-side management on the site, especially with grid electricity and backup boilers.

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