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Comparative economical analysis of a small scale trigenerative plant: a case study

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Abstract – In this paper a mixed integer linear model is proposed to solve the problem of the optimal energy management of a system composed by several kind of loads (electrical, thermal, cooling) and energy sources (external network, CHPs, boilers, chillers). The optimizer manages on/off status of CHPs and boilers and their level of power production and power rate of chillers. A realistic scenario of trigenerative plant is studied focusing the attention to the economical analysis of different CHP size.

I. INTRODUCTION

A Combined Heat and Power (CHP) node is a generating power unit where electrical and thermal power are generated together. The presence of loads requiring at the same time electric and thermal power allows to partially recover the heat dissipated in the thermodynamic cycle. In this way the integrated power source has an energy efficiency higher than using two separated units: one for electric and one for thermal power.

The operational planning of the integrated unit must supply in time both electric and thermal requirements of the loads which often have different scheduling and, when it is economically convenient, it can buy or sell electrical power to the electrical local utility. Examples of this application can be found in district heating and in industrial processes. The management of this energy production unit is not an easy task when energy prices are time varying on a daily or weekly basis, thus requiring an optimal management of production scheduling.

With the addition of one or more absorption chillers it is possible to get a trigenerative system. This kind of system is referred to as Combined Heat Cooling and Power [1]. Besides compressor chillers can be used as auxiliary systems to supply cooling power.

II. MODEL AND SIMULATION DESCRIPTION

In this Section the modelization devoted to the optimal management of a energy system and the description of the test case are presented.

The model includes power systems made by several components: CHPs, boilers, absorption chillers and electrical chillers. It may happen that one or more of these components is omitted. CHPs supply both electrical and thermal power to electrical and thermal loads. Exceeding electrical power can be sold to external network, or can be use to make a compressor chiller work if cooling power is required. Exceeding thermal power can be used to feed absorption chillers or can be wasted into the environment. Boilers can give thermal power to the thermal load, or to the absorption chillers.

A realistic case regarding the electrical and thermal plant of Arquata district in Turin is studied as test case. The study is developed in the ambit of the European project POLYCITY [2]. Loads are supplied with a CHP, three boilers, one absorption chiller and one compressor chiller. The system is shown in Figure 1.

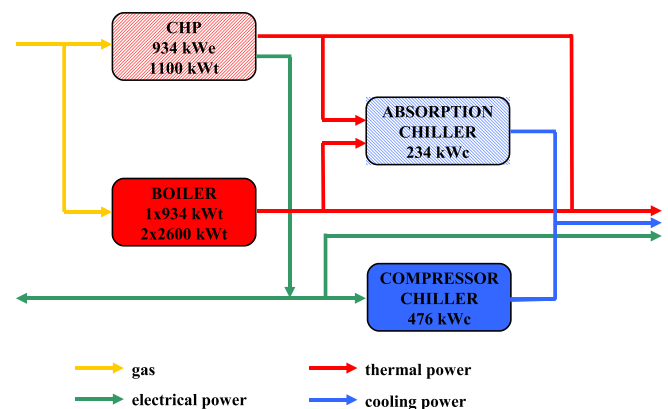


Figure 1: Scheme of power system

This test case represents a particular scenario because request of thermal load is out of proportion with electrical load: the thermal load is about ten times the electrical load.

It happens because electrical load regards only an office building, while thermal loads include district heating of Arquata.

The proposed optimization procedure is based on the *Mixed Integer Linear Programming* (MILP) formulation, adopted from [3]. This class of problems have a linear formulation of both constraints and objective function. When some decision variables are restricted to be integer (e.g. ON/OFF status of machine) standard continuous variable linear solvers are coupled with branch and bound-like techniques [4]. The proposed procedure is time dependent and the optimization is performed for N_t time intervals, with length Δt . Table 1 and Table 2 summarize the variables and parameters of the model.

Table 1 -Variables of optimization model

| | |
|------------|---|
| (i) | time interval |
| P_e^j | electrical power produced by the j -th CHP [kW] |
| P_p | electrical power purchased from the external network [kW] |
| P_s | electrical power sold to the external network [kW] |
| P_{cc}^j | electrical power required by the j -th compressor chiller [kW] |
| P_c^j | power of input fuel required by the j -th CHP [kW] |
| U_e | electrical load [kW] |
| P_t^j | thermal power produced by the j -th CHP [kW] |
| B_t^j | thermal power produced by the j -th boiler [kW] |
| D_t^j | thermal power produced by the j -th CHP and wasted into the atmosphere [kW] |
| B_{ac}^j | thermal power required by the j -th absorption chiller [kW] |
| U_t | thermal load [kW] |
| U_c | cooling load [kW] |
| δ^j | Binary variable setting on/off status of j -th CHP |

Table 2: Parameters of optimization models

| | |
|-------------|---|
| N_{boil} | numbers of boilers |
| η_{cc} | efficiency of compressor chiller |
| η_{ac} | efficiency of absorption chiller |
| η_h^j | efficiency of j -th boiler |
| a_0, a_1 | coefficients regarding efficiency of CHP ($P_c = a_0 + a_1 P_e$) |
| H | inferior thermal power of fuel used for CHP and boilers [kg/kWh] |
| c_e | cost of fuel used for CHP [€/m ³] |
| c_t | cost of fuel used for boilers [€/m ³] |
| $c_p(i)$ | cost of an electrical kWh bought from the external network [€/kWh] |
| $c_s(i)$ | earn for an electrical kWh sold to the external network [€/kWh] |

From now on apexes on variables regarding CHP, absorption chiller and compressor chiller will be omitted because test case introduced before has just one for each of them.

The main constraints of the problem are the satisfaction of electrical, thermal and cooling energy conservative equations:

- Electrical balance: CHP and external network must supply electrical load and compressor chiller. If exceeding electrical power is produced by CHP it is sold to external network

$$P_e(i) + P_p(i) - P_s(i) - P_{cc}(i) = U_e(i)$$

- Thermal balance: thermal power is needed by thermal load and absorption chiller. During summer season power can be supplied only by CHP. If exceeding thermal power is produced by the CHP it can be wasted in the environment

$$P_t(i) + \sum_{j=1}^{N_{boil}} B_t^j(i) - D_t(i) - B_{ac}(i) = U_t(i)$$

- Cooling balance: cooling load can be supplied just by absorption and compressor chillers

$$\eta_{cc} P_{cc}(i) + \eta_{ac} B_{ac}(i) = U_c(i)$$

The objective function is defined as the minimization of the global production costs

$$\min \sum_{i=1}^{N_t} \left[c_e (a_0 \delta(i) + a_1 P_e(i)) \frac{1}{H} + \sum_{j=1}^{N_{boil}} \left[c_t \eta_h^j B_t^j(i) \frac{1}{H} \right] + c_p(i) P_p(i) - c_s(i) P_s(i) \right] \Delta t$$

For further details about the model see [3] and [5]. The optimization procedure provides the generation profile of each source which can be operatively used to set their actual behavior. Figure 2 and Figure 3 show an example of the optimal management of a typical autumn day with 1 MW CHP installation.

Electrical request is supplied by CHP from 4 a.m. to 12 p.m. Exceeding electrical power is sold to external network, while night load is fulfilled by purchasing electrical power from the external network.

Thermal request is partially supplied by CHP, the peak load is covered by boilers.

The economical analysis of investment is performed for seven Internal Combustion Engines (ICE) CHPs with different size (see Figure 4).

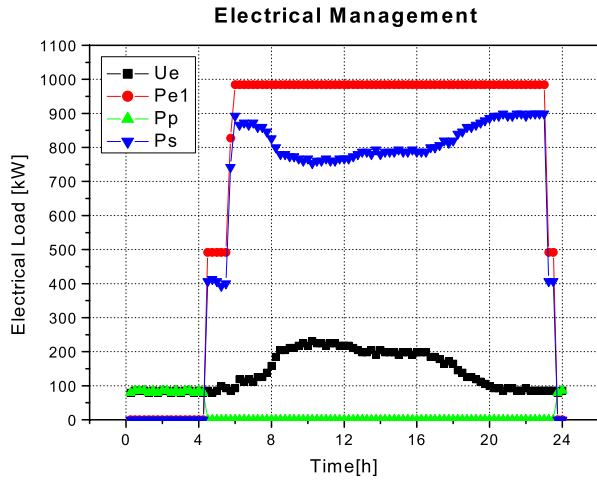


Figure 2: Electrical management of plant of test case.

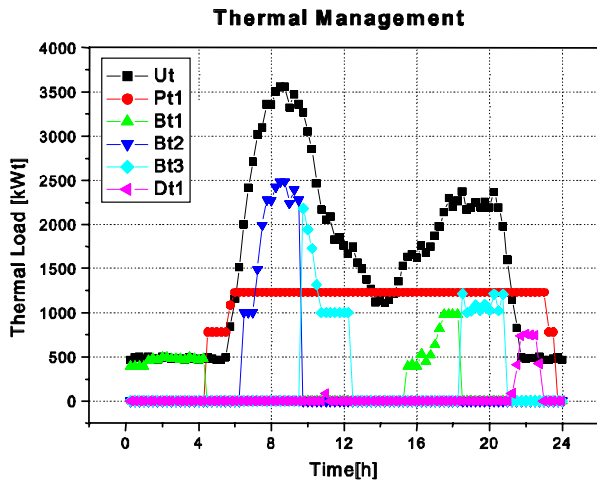


Figure 3: Thermal management of plant of test case.

A yearly production is simulated by aggregating the load profiles into four typical days. Each day is representative of a season with a proper recurrence. Once the optimal power fluxes are known, it is possible to estimate money cash flows and evaluate economical indicators as proposed in [6].

Italian laws define an indicator for cogeneration plants called “thermal limit” (TL). It is defined as:

$$TL = \frac{E_T}{E_T + E_E}$$

where:

- E_E is the electrical energy generated by a section of CHP production in one year of operation.

- E_T is the thermal energy generated and effectively used for industrial or civil purposes by a section of CHP production in one year of operation.

This means that a lower limit for the real utilization of the heat generated is imposed in order to avoid that people takes the cogeneration incentives without realizing a “real cogeneration” [7].

Italian laws impose different lower limits on the TL depending on the size of the plant. In the present work the TL calculated with the simulation results is higher than 33%, which is the lower limit for a CHP plant up to 10 MW_e.

III. ECONOMICAL ANALYSIS

For each CHP has been conducted a cash flow analysis which provides the pay back period (PBP) of the investment. In Figure 4 the curves of the Net Present Value (NPV) are reported considering a CHP technical life of 20 years. The results show that all the CHPs size have similar PBT of about 4 years, but the larger the size, the higher the final NPV. On the other hand the initial investment is higher and the choice of a CHP of 985 kW is considered a good compromise between the initial risk and the final profit.

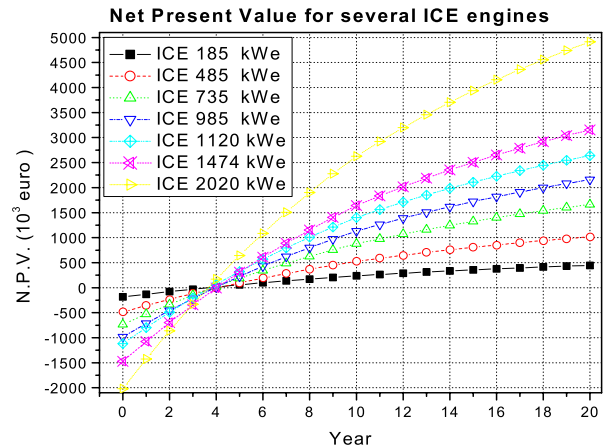


Figure 4: NPV for 20 years

IV. MANAGEMENT STRATEGIES

Effects of different management strategies are investigated for the 985 kW CHP:

- Not optimised management: CHP is ON from 7 a.m to 8 p.m. producing rated electrical power
- Optimization with fixed power management: optimization procedure sets the optimal ON/OFF

status of CHP (turning on just once a day), producing rated electrical power

- Optimized management: optimization sets both CHP optimal ON/OFF status (turning on just once a day) and its production level.

In Figure 5 it is possible to see the NPV versus years for the engine ICE 985 kWe when it is managed with these different strategies.

Besides it was taken into account also two other economical parameter, called Internal Rate of Return (IRR) and PBP. IRR is the discount rate that vanishes the NPV in the investment period. It represents the investment yield. PBP shows the years necessary to return from the initial investment. In Table 3 these parameters are summarized for this engine varying kind of management.

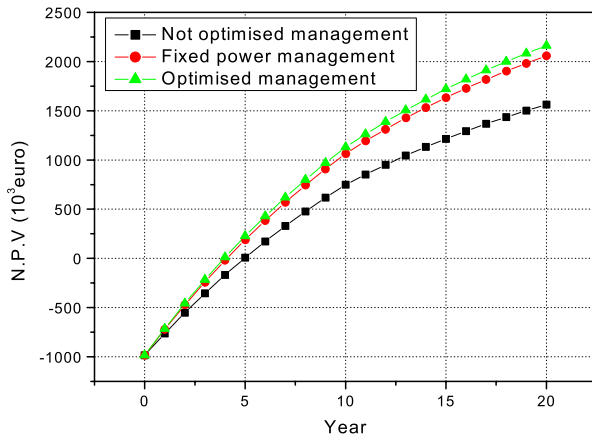


Figure 5: Net Payback Value of CHP at varying kind of optimization

It is possible to observe that the optimized strategy allows reduction of 1 year in the PBP and an increment of about 4.5% in the IRR. Comparing the two optimization strategies, it is worth noting that the ON/OFF status variable play the most important role while the regulation of the generation levels does not improve significantly the optimal management.

V. CONCLUSIONS.

The installation of a CHCP plant requires a deep study about economical investments. This work shows an

optimization procedure to foreseen a management of the system aimed to increase yield of investment.

The optimization procedure seems to work well as foreseen PBP is short if compared with other similar installed plants. Nothing can be said about IRR, whose quality depend on the kind of investment wished by the manager.

Table 3: IRR and PBP for CHP of size 985 kWe with several kind of optimisations

| | IRR [%] | PBP [years] |
|--|------------|----------------|
| No Optimization | 23.1 | 5.0 |
| Optimization with fixed power | 27.8 | 4.1 |
| Optimized Management | 28.7 | 4.0 |

VI. ACKNOWLEDGMENTS

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