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Study and Analysis of a Cogeneration System with Microturbines in a Food Farming of Dry Pasta

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The Main purpose of this paper is to assess the possibility of installing a cogeneration plant in a food industry for dry pasta production. In particular, it was verified the feasibility of implementation of microturbines assembled in cluster, for a medium size cogeneration plant.
This way it was seen that it is possible to combine the advantages in terms of the heat recovery at high temperatures of medium size turbines and of the greater flexibility of internal combustion engines.
A preliminary analysis was carried out about the energy needs of the farm, mainly focusing on the thermal and electrical loads and the current methods of both energy supply and production.
Several simulations were carried out for the preliminary design of the cogeneration plant, using suitable programming codes developed in Matlab and referring to the technical documentation for each machine used in the plant.
It was shown that this plant allows for energy savings in all tested configurations. However, a good balance among various parameters leads to choose a size that is around the annual average value of the requested electric power (corresponding to 13 microturbines) or more. This is also confirmed by the analysis of the annual energy costs, which present a minimum in correspondence of the above chosen size.
In addition to the energy and economic advantages, the system proposed in this paper also presents greater flexibility of use than that of individual engines and turbines. In fact, a peculiar characteristic of a cluster of microturbines is the possibility to efficiently meet the variability of the load and also to follow the expansion of the plant, gradually increasing the installed power.
Therefore, the system studied in this paper shows that it is possible to use small machines, not only in the context of micro-cogeneration, but also in medium-sized applications, resulting advantageous in energy terms.

1. Introduction

Today, energy has become an indispensable element for the economy, and now research for several years is routed in favour of alternative energy resources, in order to have cleaner energy and in large amounts. Different socio-economic indicators show that there is a strong correlation between energy consumption, Gross National Product per capita and quality of life.
With regard to the European energy policies, for which global warming is considered a priority issue (Andersen and Lund, 2007), CHP (Combined Heat Power) units are taken as an excellent technical alternative to reduce greenhouse emissions.
CHP comes from the opportunity to recover waste heat from machines primarily designed to produce mechanical and/or electrical energy, allowing to optimize the primary energy use, such as fossil fuels. Also it is possible to choose among available technologies the one that best fits the ratio between thermal and electrical energy required by the industrial process. Some of the machines used in cogeneration (e.g. Microturbine)

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allow a variation in production of energy as a function of the load demand variability, without running into significant efficiency loss.
In particular, pasta production farms have quite high demand for electrical power and heat, and a suitable CHP plant should be of medium size with heat tracking (Panno D. et al, 2007). It is generally excluded the possibility of any combined cycle as dried pasta process does not require direct use of superheated steam. On the contrary, this choice provides for the possibility of a cycle combined with an post-burner: in fact it is not appropriate to size the cogeneration plant to meet the whole needed heat power because this would result in to high surplus of electrical energy produced such as not to justify the economic convenience.
Furthermore, the amount of heat energy required at temperatures lower than 100 °C is equal to about 10 % of the total heat load. This implies the need to size the cogeneration plant in order to have heat at a temperature as high as possible (Colak N. et al, 2013).
Another issue is related to the variability of the heat load. This leads to some difficulties in choosing the suitable CHP plant as it often necessary to use to partialize the CHP plant.
Particularly interesting is the solution that involves gas turbines or microturbines (Bhargava R.K. et al, 2007), as the thermal energy of the combustion gases is only available at high temperatures. In particular, gas microturbines, have moderate inlet temperatures (below 900 ÷ 950 ° C) and, not being made of ceramic material, they are gradually cooled with air at ambient temperature. This allows shutting down and switching on gradually each system downtime weekly scheduled in the pasta factory under study.
In addition, the flexibility of micro-turbines allows to reduce the total power produced without having a breakdown of performance: in fact, just turning on at full nominal power only those microturbines enough for heat demand and partially using only one allow to optimize global plant performance.
Of course, as the nominal power of each microturbine is less than or equal to 200 kWe, then the partialization of only one of them involves a small increase of fuel to be used with respect to that necessary in the case a single 1 MW turbine (or more) is installed and partialized.
Aim of this paper is to evaluate the possibility of installing a CHP plant in a dry pasta factory. In particular, it is wished to verify the feasibility of the application of microturbines assembled in clusters to implement a medium size cogeneration plant. In fact, it is highlighted that it is possible to combine the advantages in terms of heat recovery at high temperatures of the medium size turbines and greater ignition flexibility and typical shutdown of internal combustion engines, using microturbines. This dynamical study was performed for the first time at a pasta factory.

2. Methods

2.1 Theoretical aspects

The main parameter used for evaluating the efficiency of these systems is the PES (Primary Energy Saving) representing the savings of primary energy produced by cogeneration plant compared to the separate production of heat and electrical power in conventional power plants. The overall energy saved ΔE_c is the difference between the amounts required in the two cases.
In the case of separate production, applying the first law of thermodynamics is necessary to consider that the thermal energy E_t is produced by a conventional heat generator characterized by its overall performance η_{te} therefore requires the use of primary energy E_t/η_t. The same applies to the separate production of electrical power E_e requiring primary energy E_e/η_e where η_e is the efficiency of conventional machine. Therefore, said E_c the primary energy required by the CHP to produce E_t and E_e, PES is obtained as follows:

$$\Delta E_c = \left(\frac{E_e}{\eta_{es}} + \frac{E_t}{\eta_{ts}}\right) - E_c \qquad (1) \tag{1}$$

$$PES = \left(\frac{\Delta E_c}{\frac{E_e}{\eta_e p} + \frac{E_t}{\eta_t}}\right) = 1 - \frac{E_c}{\frac{E_e}{\eta_e p} + \frac{E_t}{\eta_t}} > PES_{min} \tag{2}$$

where, on an annual basis, $E_c = M_c H_i$ is the primary energy input cogeneration plant (M_c is the mass of the fuel and H_i its lower heating value), while the amount in parenthesis is the total primary energy input in conventional installations.
The coefficient p takes into account the savings related to the electrical energy transport losses.
The European regulation defines a “high efficiency” CHP plant if the PES value higher than 10 %. However, the overall efficiency must be greater than 75 % or 80 %, depending on the type of CHP plant.

2.2 The case study

The productive activity of the company allows constant quality control during all the stages, from the production of the pasta to the packaging. Production, packaging and storing are fully automated. The main energy resources used by the company are:

- electric power for indoor and outdoor lighting, for service machines (e.g. washing machines, refrigerators, compressors, office), and for summer and winter air conditioning systems (e.g. condensing groups, pumps);
- hot water at 60 °C for heating systems, for production of water for sanitary use for all buildings and process water;
- superheated water at 130 ° C and at 5 bar, required by some processes.

The evaluation of the energy needs of the company was carried out through the following quantities:

- average electric power consumption during every month;
- hourly heat required to overheated water at 130 °C and 5 bar;
- monthly average heat output required to produce water at 60 °C;
- monthly consumption of natural gas;

To meet the needs of electric power, the company is connected to the power grid in Medium Voltage (MV); while in order to meet the requirements of hot water at 60 °C, two hot water boilers are used, and other six boilers (five with a nominal power of 1.744 MW and one with a nominal power of 2.093 MW) are installed for the production of superheated water at 130 °C and 5 bar.

The hourly heat $\dot{Q}_R$ required for superheated water was calculated using the hourly trends of the inlet and outlet temperature (respectively T_i and $T_u^{(k)}$) of superheated water as well as the average hourly flow rate for each boiler. Therefore, power calculation was carried out on an hourly basis by applying the mass and energy balance to each boiler and adding the individual powers obtained:

$$\dot{Q}_k = \dot{m}\, c_p \left(T_u^{(k)} - T_i\right); \quad k = 1 \div 6 \tag{3}$$

$$\dot{Q}_R = \sum_{k=1}^{6} \dot{Q}_k \tag{4}$$

where $\dot{m}$ is the water flow rate and c_p is the specific heat.

In view of these considerations, we chose to simulate a medium size cogeneration plant consisting of a microturbines system assembled in cluster and heat tracking. In addition being the electric power demand between 2 MW and 2.8 MW, several CHP configurations were simulated for powers ranging from 2 MW to 3 MW (10 to 15 C200 microturbines). This choice also provides the use of the post-burner to meet the thermal needs eventually not covered by the microturbines alone.

Figure 1 shows the cogeneration plant scheme: the microturbines cluster was represented as a single microturbine, and the exhausted gases are the sum of those leaving each machine as they are conveyed in single pipe.

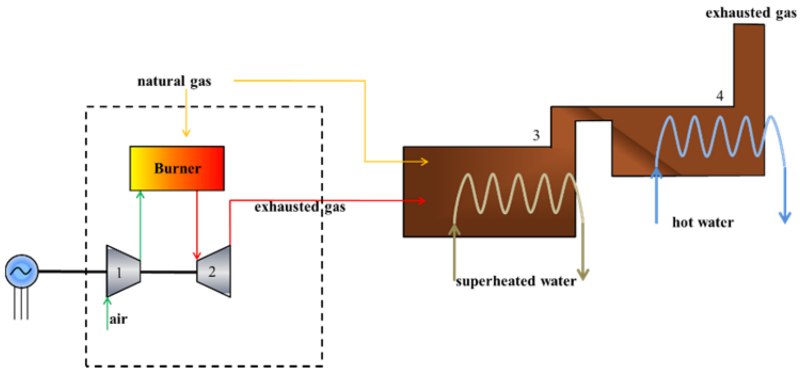

Figure 1: Scheme of the simulated cogeneration plant: 1, 2 - microturbines cluster; 3 - recovery boiler for superheated water with post-burner; 4 - recovery boiler for hot water

Of course, by meeting the heat load demand, the electrical power production will be subject to it, CHP nominal power has to be determined such as to provide an annual output roughly equal to that needed, as it is not convenient to have high surplus of electrical power production.

2.3 Dynamic simulation

The different configurations chosen for the cogeneration plant were simulated using the data of the C200 Capstone microturbine (nominal power 200 kWe) developing appropriate MatLab scripts and according to the macro-steps described below. *h* is the enthalpy, *T* the temperature, $\dot{Q}_{PB}$ is the post-burner (*PB*) required heat, $\dot{Q}_R$ is the total required heat, $G_{eg,GMT}$ exhausted gas (*eg*) flow rate out from the gas microturbine (*GMT*), $G_{b,PB}$ methane flow rate into the post-burner, $P_e(p)$ is the electric power produced by one of the N_{GMT} microturbine operating at partialization *p*, η_{HE} heat exchanger (*HE*) efficiency, η_{GMT} microturbine efficiency, H_i methane lower heating value. The steps below realize a dynamical simulation of the CHP plant allowing an ad-hoc design:

1. Calculating the maximum thermal power $\dot{Q}_{GMT}^{\max}$ available by cooling the exhausted gases out of the turbines without the use of the post-burner and all microturbines running at full load, p = 100%:

$$\dot{Q}_{GMT}^{\max} = \eta_{HE} \cdot G_{eg,GMT}^{p=100\%} \cdot N_{GMT} \cdot \left(h\left(T_{eg,GMT}^{p=100\%}\right) - h\left(T_{eg,HE}\right)\right) \quad (5)$$

2. IF $\dot{Q}_{GMT}^{\max} \leq \dot{Q}_R$ THEN $\dot{Q}_{PB} = \dot{Q}_R - \dot{Q}_{GMT}^{\max}$
   2.1. Calculating the:
   - temperature and flow rate of the exhaust gas leaving the post-burner by solving the following nonlinear system:

$$\begin{cases} \dot{Q}_R = \eta_{HE} \cdot G_{eg,GMT}^{p=100\%} \cdot N_{GMT}^{\min} \cdot \left(h\left(T_{eg,GMT}^{p=100\%}\right) - h\left(T_{eg,HE}\right)\right) \\ G_{eg,GMT}^{p=100\%} \cdot \left(h\left(T_{eg,PB}\right) - h\left(T_{eg,GMT}^{p=100\%}\right)\right) + G_{b,PB} \cdot \left(h\left(T_{eg,PB}\right) - h\left(T_a\right)\right) = \eta_{PB} \cdot G_{b,PB} \cdot H_i \end{cases} \quad (6)$$

   - methane flow rate:

$$G_{b,MTG}\left(p = 100\%\right) = \frac{N_{MTG} \cdot P_e^{p=100\%}}{\eta_{MTG}^{p=100\%} \cdot H_i} \quad (7)$$

   - total power:

$$P_e^{TOT} = N_{MTG} \cdot P_e^{p=100\%} \quad (8)$$

3. ELSE $\dot{Q}_{PB} = 0$
   3.1. Calculating the:
   - minimum number of microturbines to be turned on at full load:

$$N_{GMT}^{\min} = \left\lceil N_{MTG} \cdot \frac{\dot{Q}_{AR}}{\dot{Q}_{GMT}^{\max}} \right\rceil \quad (9)$$

   - degree of partialization *p* of an additional microturbine to meet the residual required thermal energy by solving the following nonlinear equation:

$$\dot{Q}_R = \eta_{he} \cdot \left\{G_{eg,GMT}^{p=100\%} \cdot N_{GMT}^{\min} \cdot \left(h\left(T_{eg,GMT}^{p=100\%}\right) - h\left(T_{eg,HE}\right)\right) + G_{eg,GMT}(p) \cdot \left(h\left(T_{eg,GMT}(p)\right) - h\left(T_{eg,HE}\right)\right)\right\} \quad (10)$$

   - methane flow rate:

$$G_{b,GMT}(p) = \frac{N_{GMT}^{\min} \cdot P_e^{p=100\%}}{\eta_{GMT}^{p=100\%} \cdot H_i} + \frac{p \cdot P_e(p)}{\eta_{GMT}(p) \cdot H_i} \quad (11)$$

   - total power:

$$P_e^{TOT} = N_{GMT}^{\min} \cdot P_e^{p=100\%} + p \cdot P_e(p) \quad (12)$$

The above steps are repeated each hour of the experimental year and using data measured on the production plant as input.

3. Results and Discussion

Figure 2 and 3 show the overall monthly electric power and heat consumption confirming that there is a high demand for electric power and more than twice of thermal energy. Heat required was computed using equations 3, 4 with hot water and superheated water flow rates, pressure and temperatures measured during the production year (data not shown).

Below simulation results for each configuration are shown about methane consumption (Figure 4) and electrical energy surplus (Figure 5). In particular, the last one has been plotted as the difference between the electrical power produced by the CHP plant and the actual electrical load so to determine its surplus that should be on average slightly greater than zero. Figure 5 shows that this result can be reached with 13 microturbines.

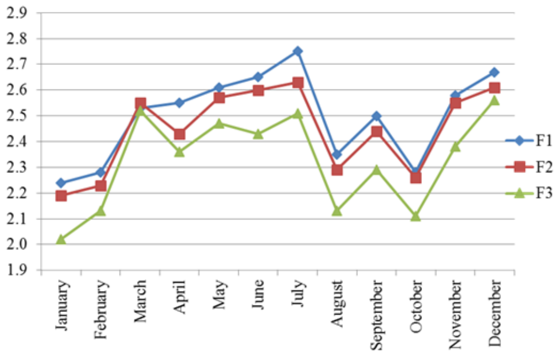

Figure 2: Monthly averaged electric power (MW), for each of the three Italian time rates

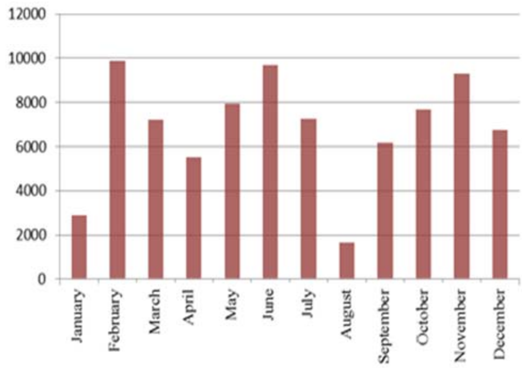

Figure 3: Monthly heat requirements (GJ)

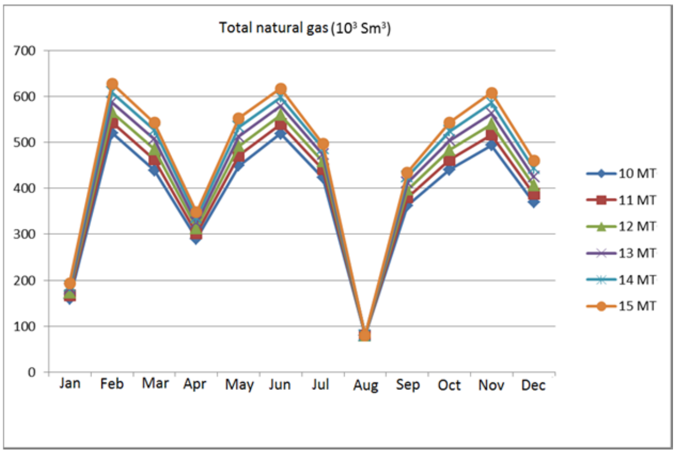

Figure 4: Total natural gas consumption in the different configurations of microturbines (MT)

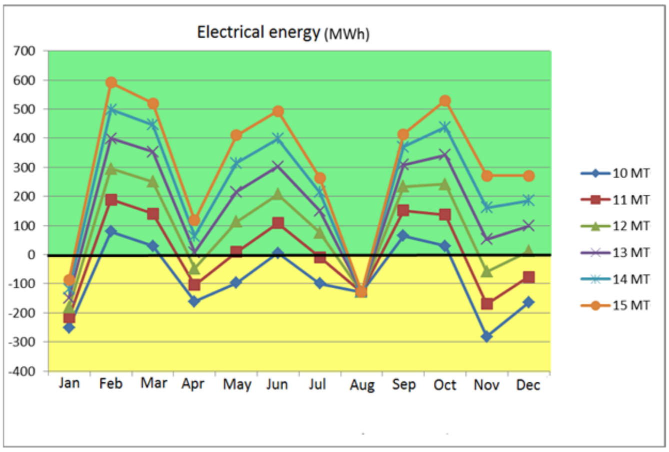

Figure 5: Electrical energy surplus

As shown by previous plots relative to energy use, higher the number of microturbine obviously higher is the total energy production. On the other hand, the electric energy to be purchased by the public electric network

gradually reduces. A cluster with 13 microturbines allows to meet the electric load and to have a surplus during some months that can be fed into the public electric grid.
Figure 6 shows the overall efficiency of the CHP plant calculated for various configurations of the cluster.

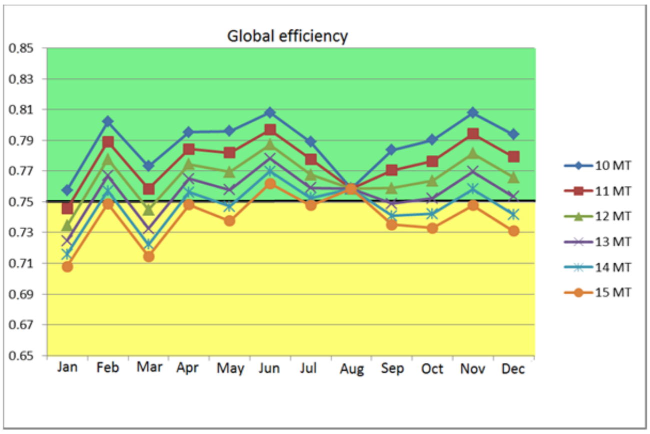

Figure 6: Trend of the global efficiency of the CHP plant

By analyzing the plot in Figure 6, it is clear that as the number of microturbines increases, the overall monthly average efficiency reduces. With a cluster of 13 microturbines, it almost always remains above 75 %, thus satisfying the minimum value that the European regulation allows in order to define a "High efficiency" CHP plant.The total energy savings (PES) calculated comparing each configuration of the cogeneration plant with a traditional production of electricity and heat is shown in Table 1.

Table1: Yearly average of PES

	N. OF MICROTURBINES					
	10	11	12	13	14	15
PES %	16,28	15,38	14,52	13,80	13,24	12,87

4. Conclusions

In this paper has been shown that suitable energy saving could be achieved in a pasta factory with the correct installation of a medium size cogeneration plant obtained assembling in cluster an appropriate number of micro-turbines. The method used here is different from traditional ones using only average monthly data (e.g. typical average day trend of heat and power consumption). In fact the dynamical simulation carried out in this paper has led to an ad-hoc design of the CHP plant adapted just for the particularly variable trend of energy consumption during every day of every month.
It is shown that this type of plant allows for energy savings in all configurations tested (see PES). However, a good balance between the various parameters studied leads to choose a size that is around the average value of the requested annual electric power (corresponding to 13 microturbines) or slightly greater values.
In addition to the significant benefits of energy saving, the plant proposed in this paper also has greater flexibility than that of internal combustion engines and turbines. In fact a peculiar characteristic of a cluster of microturbines is the possibility to efficiently meet the variability of the load and also to follow the expansion of the company, gradually increasing the installed power.

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