Comparison of CHP systems for the paper industry in the context of High-efficiency cogeneration

Marco Gambini
Department of Industrial Engineering
University of Rome Tor Vergata, Rome, Italy
e-mail: gambini@ing.uniroma2.it

Michela Vellini*
Department of Industrial Engineering
University of Rome Tor Vergata, Rome, Italy
e-mail: vellini@ing.uniroma2.it

Tommaso Stilo
Department of Industrial Engineering
University of Rome Tor Vergata, Rome, Italy
e-mail: tommaso.stilo@alumni.uniroma2.eu

Michele Manno
Department of Industrial Engineering
University of Rome Tor Vergata, Rome, Italy
e-mail: michele.manno@uniroma2.it

Sara Bellocchi
Department of Industrial Engineering
University of Rome Tor Vergata, Rome, Italy
e-mail: sara.bellocchi@uniroma2.it

ABSTRACT

In January 2011, the incentive scheme for cogeneration power plants changed radically by the introduction of high-efficiency cogeneration (HEC) in Europe. As a consequence of the establishment of this directive, the techno-economic feasibility of new cogeneration plants in different areas of application (industry, service, residential etc.) and their optimal operation have been deeply modified. The previous legislation considered the entire electricity production as cogeneration electricity if two parameters, primary energy saving and thermal limit, evaluated on an annual level, exceeded specific limit values. This old incentive scheme made the sizing of Italian cogeneration power plants be focused on the maximum electricity output. According to the new incentive scheme, however, if cogeneration power plants do not reach an established value of overall efficiency, it is necessary to split them in a CHP portion and a non-CHP portion and the incentives are proportional to the energy quantities pertaining to CHP portion only. This situation implies that cogeneration power plants designed on the basis of thermal demand are more rewarded, as opposed to what happened in the past.

The main area of application of CHP systems is industry and, among the various sectors, paper industry appears the most suited to be matched with cogeneration. Since the choice of the most appropriate technology and the sizing are essential in industry, the present study

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[*] Corresponding author

considers a particular industrial reality and aims at comparing different cogeneration solutions to be coupled to it. This will be accomplished thanks to the definition and analysis of energy, environmental and economic performance parameters, always bearing in mind the high-efficiency cogeneration framework and making use of GateCycle software as the main calculation tool.

KEYWORDS

High-efficiency cogeneration, Primary Energy Saving, Electricity from Cogeneration, paper industry, GateCycle, CO_2 emissions avoided.

1. INTRODUCTION

The term "cogeneration" refers to the simultaneous production of different forms of energy (more than one) and it is generally applied to the generation of process heat and electricity from a single energy source. This is accomplished thanks to a plant that, in its conventional setup, is composed of an engine, provided with its own electric generator, and a heat exchanger system capable of delivering useful heat. All types of power plants can be employed (steam plants, gas turbines, combined cycle plants and internal combustion engines); the extracted heat largely varies in entity and temperature depending on technology, size and final use.

Such a system has the valuable property to enhance the efficiency of fuel use: the combined production of electricity and heat turns out to be more efficient than a separate production of these two forms of energy. Therefore industry facilities have every interest in equipping themselves with combined heat and power (CHP) plants, given their large electric power and process heat requirements. These qualities are a fact, but a difficulty in evaluating the efficiency of CHP has been observed since the breakout of this technology. Havelský pointed out the problem back in 1999 [1]; a strict regulation of such plants had thus to be created.

In the European Union, a well-structured incentive scheme made a contribution to the growth of cogeneration. In 2004, the Directive 2004/8 EC [2] introduced the concept of *high-efficiency cogeneration* (HEC); the Annexes II and III of the Directive provided it with a quantitative definition establishing that a cogeneration production characterised by *primary energy savings* (PES) of at least 10% compared to the reference values for separate production (or >0% for small scale cogeneration units, with installed capacity below 1 MWe, and for micro cogeneration units) is highly-efficient and has the right of access to incentives.

After the publication of the Directive, the Commission Decision of November 19, 2008 [3] stated that a cogeneration unit operates in *full cogeneration mode* when the maximum technically possible heat recovery is attained and all produced electricity is thus considered CHP electricity. When a plant does not operate in full cogeneration mode, it is required to distinguish the amount of electricity and heat not produced under cogeneration mode from CHP electricity and heat, which are the only quantities able to receive incentives. The Directive 2017/27/EU [4] repealed the Directive 2004/8, confirming all of its points in the Annexes I and II.

Italy implemented the Directive by enacting three decrees [5-7], followed by the publication of ministerial guidelines [8]. As a consequence, whereas cogeneration production was at first more electricity-oriented, after 2011 the sizing of Italian cogeneration plants began to be based on thermal demand, given the possibility to split them in a CHP portion and a non-CHP portion.

Authors studied the transposition of the Directive 2004/8 EC in the Italian context, referring to the methodology indicated in the abovementioned guidelines for dealing with cogeneration units in Ref. [9]. That paper was an opportunity to better clarify the methodology to evaluate plants in a high-efficiency cogeneration framework and do the groundwork for estimating their primary energy savings, in a similar fashion as the studies carried out by Kanoglu and Dincer [10]. Starting from this, in Ref. [11] authors assessed the performance of Italian cogeneration plants in terms of the effects of the power loss coefficient on CHP electricity and power-to-heat ratio. Plants with a non-zero power loss coefficient display a lower CHP electricity production, in an equivalent total electric output: among these plants, the influence of the increase of the power loss coefficient can be perceived especially on steam condensing extraction turbine-based plants and combined cycles with heat recovery, whose power-to-heat ratio decreases significantly because of it.

The calculation of the power loss coefficient and the definition of the referred efficiency are critical aspects of the implementation of the Directive, as verified by Gvozdenac et al. In Ref. [12] they studied an actual 150 MW capacity CCGT plant of Independent Power Producers (IPPs) in Thailand; the investigation showed that the referred value of high-efficiency cogeneration has a large effect on the percentage of CHP electricity output, decreasing from 42% to 19% with the referred efficiency varying from 0.7 to 0.9; the impact of the power loss coefficient is not as large, but it influences CHP electricity and CHP fuel energy. These factors are crucial in determining a plant's profitability, so Gvozdenac et al. proposed a modified procedure for the assessment of a CHP plant's efficiency, based on daily calculation and industrial measurement of important parameters, in line with the work of Urošević et al. [13].

It is obvious to state that cogeneration is an advantageous technology; however it can still be improved and research must keep focus on it. For example, CHP plants can perform better if provided with an operation manager (running for example a thermal energy storage device or a backup heater); in this way they become able to make use of fluctuating RES and, as a consequence, much more attractive. An analysis of such a management approach has been conducted by Wolfrum et al. [14]. CHP also casts a glance at the future, thanks to the suitability of this technology for supplying power to microgrids [15].

Coupling an industrial facility with a combined heat and power system in order to increase the overall efficiency of the plant is now very common practice. For instance, Wang et al. [16] optimised the performance of different cogeneration plants to be implemented in the cement industry, in order to recover the available waste heat.

Authors reviewed several industry sectors, identifying the most appropriate CHP technology for each of them, according to the facility size. The pulp and paper industry is characterised by large electric and heat consumptions but also by the opportunity of generating power by burning byproducts of production processes; this means that it lends itself to the implementation of high efficiency production technologies, with cogeneration being the most interesting and proper.

2. THE PULP AND PAPER INDUSTRY IN EUROPE

2.1 Production and energy consumptions

Pulp is a cellulose-based material produced by separating lignin and cellulose fibres from wood and it is the basic constituent for the preparation of paper. The process of separation is chemical when pulp is obtained by cooking chipped wood in an autoclave, with the addition of sodium sulphate (Kraft or sulphate pulping process) or magnesium bisulphite (sulphite pulping process); the process is mechanical when fibres are separated from the trunk by means of an abrasive rotary grindstone. The Joint Research Centre (JRC) of the European Commission released the BAT Reference Document for the Production of Pulp, Paper and Board [17] to make each of the above processes more efficient and CHP systems, based on different thermal power plants, are one of the main available techniques in this respect.

Europe is one of the main actors in the pulp and paper industry. The JRC BAT Reference Document reported very interesting data concerning the European pulp and paper industry in the year 2008. The annual production of pulp in Europe was about 41.8 million t/y, constituting 22% of world's total wood pulp production of 194.4 million t/y; this made Europe the second largest pulp producer. As for the different types of pulp, mechanical and semi-chemical pulp production amounted to 13.6 million t/y and chemical pulp production amounted to 27.4 million t/y (2.2 through the sulphite process and 25.2 through the sulphate process), leading to a total wood pulp for papermaking of 40.9 t/y. Finland and Sweden together covered 57% of European total wood pulp production.

Paper and board production totalled 390.9 million t/y worldwide; 25.3% of this amount (98.9 million t/y) was produced in Europe. The leading paper and paperboard producers were Germany (22.8%), Finland (13.1%), Sweden (11.7%), Italy (9.5%) and Spain (9.4%). The number of papermills in Europe was 887, located mainly in Italy, Germany, France, Spain and the UK.

Paper production is a set of very energy-consuming processes: it follows that energy consumption (both electricity and heat) of European pulp and paper industry is huge. Depending on the employed production technology, a paper mill consumes 400-2100 kWh of electric energy and 1000-4500 kWh of heat (e.g. steam) per paper unit (tonne).

Concerning kraft mills, thermal consumptions amount to 10-15 GJ/ADt pulp and electric consumptions amount to 600-1200 kWh/ADt pulp; the energy consumption required by pulp drying is about 25% of heat energy and 15-20% of electric energy; over 50% of the electrical consumption is used for pumping. Kraft mills are equipped with a back-pressure turbine powered by the combustion of a byproduct called black liquor; in order to decrease power consumption, modern mills are provided with a small condensing tail to their back-pressure turbine. Therefore, a typical modern market kraft mill is able to generate up to 22.2 GJ/t pulp of heat energy, 820 kWh/t pulp of back-pressure electrical energy (up to 1150 kWh/t pulp if the system is integrated with a bark burner) and 800 kWh/t pulp of condensing electric energy (340 in a bark-fired integrated setup). Much the same applies to sulphite process mills, which consume 7.5-13.5 GJ/ADt of process heat and 550-880 kWh/t of electric energy.

Electric energy in mechanical mills is consumed essentially for grinding and depends on the quality requirements of the end product such as bulk, strength, opacity, and surface smoothness; its amount varies from 1100 kWh/t to 2200 kWh/t. Heat consumption varies widely over the range of 1500-5500 MJ/ADt.

Also general services are present in a paper production process, including mechanical and aerobic treatment, raw water treatment, compressed air, transport and finishing; their consumptions total about 40-100 kWh/t and must be added to the above values.

In order to clarify how much energy this industry sector consumes, it is possible to refer to IEA's "Energy Technology Perspectives" 2017 report [18], which states that OECD Europe final energy use by pulp, paper and printing, a quantity adding up all energy supplied to the final consumer, was 1.36 EJ in the year 2014, representing 1.7% of world total industry energy consumption.

Electric and thermal energy demand of the pulp and paper industry in Europe is bound to increase. Szabó et al. [19] elaborated a world model to reproduce technology and market developments of the pulp and paper industry (PULPSIM) starting from current trends. According to their results, paper demand in Europe is expected to grow up to 120 million t/y by 2030; this increase will be accompanied by a 5.9% decrease in energy consumption (0.4% if carbon tax and sustainable forest management policies are applied), being known a current reference value of 4.54 MWh/t of produced paper.

At national level, the most recent data regarding the Italian pulp and paper industry come from Assocarta's "Rapporto ambientale dell'industria cartaria" 2016 report [20]. According to this document, 154 paper facilities are present on Italian territory, which produced 8650 t/y of paper and 410 t/y of pulp in the year 2014; the majority of the facilities are small and medium-sized, producing less than 25000 t/y of paper each [17]. The pulp and paper industry consumed 7.01 TWh in the year 2014; however, this sector also generated 5.54 TWh of electric energy, of which 95.6% was produced by CHP systems. Also 43000 TJ of steam were employed in the production processes, of which 96% self-produced.

The pulp and paper industry is obviously responsible for the emission of greenhouse gases in the atmosphere; Italian paper mills emitted 4.88 million t of CO_2 from energy production and 0.71 million t of CO_2 from energy purchase (indirect emission) in the year 2014.

The need for an environmental optimisation of paper mills is a long felt concern, since Thompson's works on paper mills [21]. Monte et al. [22] analysed different paper industry production processes, proposing, for each of them, beneficial waste management approaches. Furthermore, considering the issue of emissions from a paper industry facility, Bhander and Jozewicz [23] developed a model to estimate changes in emission when switching fuel, installing air pollution equipment and implementing energy efficiency measures.

The perception of the need for improved efficiency is now well established in the management of production processes; so, the harsh international competition to which the pulp and paper industry is subjected made energy management a necessary practice for preserving competitiveness. Kong et al. [24] reviewed different energy-efficient technologies to be implemented in the paper industry, creating a data collection useful to assess the most suited ones to each process: CHP systems are perfectly placed in this context, having the ability to improve the global efficiency of the plant. Cogeneration systems, with their improved overall efficiency, can also be a solution to the problems raised by Posch et al. [25], who analysed the Austrian case and ascertained that energy costs are the main factor negatively affecting energy management, therefore their minimization must be a target.

CHP systems make a contribution when it comes to complying with the Kyoto Protocol as well: as observed by Chen et al. [26], the pulp and paper industry is characterised by high fossil energy consumption which is strictly linked to high emission of greenhouse gases; they studied the case of Taiwan, which must be prepared to adopt efficient energy production systems in this industry sector, given the possibility of being forced to accept the responsibilities set out for Annex I signatory countries. In the wake of this, Boharb et al. [27] outlined a methodology to perform energy audits in the pulp and paper industry, referring to the Moroccan case.

Returning to the European case, the Joint Research Centre estimates, in its BAT Reference Document for the paper industry, that CHP systems enable paper mills to save about 30% of the energy consumption of a separate production conventional technology and to reduce greenhouse gas emissions. Especially gas turbine-based CHP plants are efficient in this respect and several installations have been built around Europe. Therefore, the present paper aims at proposing and comparing the most efficient CHP setups which can be employed in the pulp and paper industry, taking into consideration a particular industrial reality; so this study will be a sort of extension of the work by Shabbir et al. [28], who did not take into account internal combustion engines.

2.2 Quantitative definition of the analysed process

As seen in the previous sections, the pulp and paper industry is characterised by large electric and heat requirements. Electricity is employed to operate machines and heat is employed, in the form of steam, in two processes, pulp production and drying. In this paper, a methodology for analysing different CHP technologies suitable for paper mills and evaluating them in a HEC framework will be illustrated. For this reason, operation parameters of the process here discussed will be defined in the following.

A kraft fully integrated bark-fired pulp and paper mill is considered. The JRC BAT Document reports the typical electric ($C_{s,e}$) and thermal ($C_{s,t}$) specific consumptions for this kind of mill; they are shown in Table 1.

Table 1. Electric and heat specific consumptions of a typical kraft fully integrated bark-fired pulp and paper mill.

	Heat consumption [GJ/t]	**Power consumption [kWh/t]**
Pulp mill process	8.5	550
Paper mill process	6.0	650
Total	14.5	1200

In a kraft paper mill, while steam is required at specific conditions (temperature of 170°C and pressure of 8 bar) for pulp production, it is required at different temperature levels for drying, in order not to jeopardise the mechanical strength and the integrity of the product; this is achieved by extracting steam from the turbine at different enthalpy levels. However, since the aim of this work is to propose a plant focusing on HEC main parameters, a plant modelling with such a level of detail is not fundamental. Therefore, a single extraction is considered, at 8 bar, supplying heat to a generic user, and it is assumed that the extracted steam, after the heat exchange, will condense and be put back in the cycle. After defining the most appropriate plant design, a more thorough simulation can still be carried out, in order to take into account the satisfaction of all heating loads. The returned condensate is assumed to be saturated liquid at 1 bar.

According to Ref. [20], 154 facilities are in Italy and their production amounts to 56000 t/y of paper. Supposing an average value of 7200 operating hours (equivalent to 300 days a year), it can be stated that the average hourly production of a single Italian paper mill is about 8 t/h ($\dot{m}_{paper}$). This value allows for the calculation of electric and thermal power requirements of the plant:

$$P_t = C_{s,t} * \dot{m}_{paper} = 32\ MW_t$$

$$P_e = C_{s,e} * \dot{m}_{paper} = 9.6\ MW_e$$

The above values can be considered constant, since industrial users are different from domestic ones: their consumptions do not depend on the time of the year and are easily predictable; this statement particularly applies to paper mills.

Table 2 shows the input data common to all plant types.

Table 2. Input data common to all plant types.

Input data common to all plants	
Operating hours [h/y]	7200
Daily paper production [t/d]	192
Steam pressure required by user [bar]	8
Steam temperature required by user [°C]	170
Returned condensate enthalpy [kJ/kg]	417.5
HEC referred enthalpy (1 bar, 15°C) [kJ/kg]	63
Specific thermal consumption [kWh/t]	4000
Specific electric consumption [kWh/t]	1200
Annual heat demand [MWh/y]	280320
Annual self-consumed electric energy [MWh/y]	69120

In the following section, the procedures to carry out a design and a HEC and economic analysis of the CHP technologies taken into consideration will be illustrated.

3. METHODOLOGY

3.1 Design

When designing a CHP plant, it is essential to set a mode of operation: in fact, a CHP plant can be operated satisfying electric demands or thermal demands.

A plant operated satisfying electric demands is capable of covering the electric demand of the user at full load. In this case there is the possibility of the heat demand not being fully covered - this implies the presence of an auxiliary boiler aimed at supplying the remainder of the heat demand. This mode of operation is bound to make the plant self-sufficient in terms of electric loads, avoiding energy exchanges with the grid. A plant operated satisfying thermal demands, instead, is sized on the basis of a full satisfaction of the heat demand. The potential portion of electric demand not supplied by the plant is purchased, whereas the possible surplus of electric energy is fed into the grid.

Depending on power values, the components of the system are selected from specialized catalogues; given the relevant operational parameters of the components, the operation of the plant is simulated by means of GateCycle software. The outcome of the simulation is the calculation of all pressure, temperature and enthalpy conditions of the working fluid in the system and, as a consequence, a quantitative evaulation of the plant's performance in terms of net power, overall efficiency, primary fuel flow rate and supplementary fuel flow rate.

The variation of the performance parameters of the system in off-design conditions is evaluated as well, by modelling it in different seasonal situations with GateCycle software.

3.2 HEC analysis

The HEC analysis is conducted by following the guidelines reported in Refs. [9, 11, 29]. In short, the overall efficiency η_g must be calculated through the formula:

$$\eta_g = \frac{E + H_{CHP}}{F - F_{non-CHP,H}} \qquad (1)$$

where E is the total electrical/mechanical energy, H_{CHP} is the CHP useful heat energy (total useful heat energy H reduced by the amount of non-combined useful heat energy $H_{non-CHP}$) and F - $F_{non-CHP,H}$ is the amount of fuel energy used in cogeneration. If η_g achieves or exceeds the values of 0.80 for combined cycle gas turbines with heat recovery and steam condensing extraction turbine-based plants or 0.75 for other types of cogeneration units, the plant does not produce non-CHP electric energy $E_{non-CHP}$.

Otherwise it is necessary to assess the non-CHP electric energy $E_{non-CHP}$ and the related fuel energy $F_{non-CHP,E}$. This is accomplished through the evaluation of the power loss coefficient β representing the electricity loss caused by steam extraction for heat production. This parameter allows for the calculation of the efficiency of non-combined electric energy generation $\eta_{non-CHP,E}$ and the power-to-heat ratio C_{eff} (C_{actual} in the European legislation). C_{eff} is required to calculate CHP electric energy E_{CHP} starting from H_{CHP}. Being known $\eta_{non-CHP,E}$, fuel energy for non-CHP electric energy generation $F_{non-CHP,E}$ can be evaluated; fuel energy for CHP electric energy generation F_{CHP} is then determined by residual. It is possible to calculate the primary energy saving PES as:

$$PES = \left[1 - \frac{1}{\frac{CHP\ H\eta}{Ref\ H\eta} + \frac{CHP\ E\eta}{Ref\ E\eta}}\right] * 100 \qquad (2)$$

where $CHP\ E\eta$ is the electric efficiency of the CHP portion and $CHP\ H\eta$ is the thermal efficiency of the CHP portion and $Ref\ H\eta$ and $Ref\ E\eta$ are the referred efficiencies for heat and electric production, respectively, provided by the guidelines.

Fig. 1 shows a schematised CHP unit with all energy flows named according to the Directive.

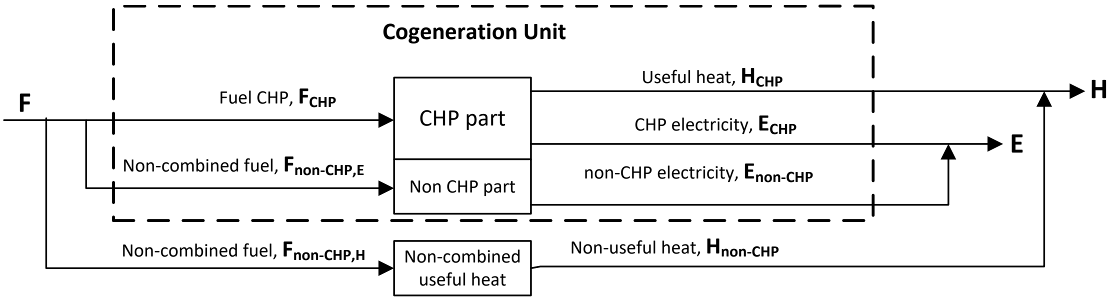

Fig. 1. Scheme of a CHP unit with energy flows.

3.3 Economic analysis

A preliminary step in evaluating the economic yield of a CHP unit consists in the calculation of *RISP* parameter, an expression of the savings fundamental to determine the number of white certificates *WC* (the securities attesting the savings, in toe, subjected to the incentive scheme):

$$RISP = \frac{E_{CHP}}{\eta_{E,ref}} + \frac{H_{CHP}}{\eta_{H,ref}} - F_{CHP} \qquad (3)$$

$$WC = RISP * 0.086 * K \qquad (4)$$

where K is the harmonisation factor, depending on the size of the plant, and $\eta_{E,ref}$ and $\eta_{H,ref}$ are the actual reference efficiencies.

The economic analysis is performed through the assessment of net present value (NPV) and pay-back period (PBP) for the considered plants, taking into account all positive and negative cash flows. However, the parameter being better able to give a sense of the profitability of a plant, in a comparison of different technologies, is NPV/I that is the ratio of the net present value to the total investment: it is obvious that a plant for which the profit, after a set period of time, carries more weight than the initial outlay is a solution to be preferred.

3.4 Total key performance indicator

The most interesting contribution of Ref. [30] that has been reapplied in this paper is the definition of the total key performance indicator (*TKPI*):

$$TKPI_i = \frac{PES_i}{PES_{max}} + \frac{PBP_{min}}{PBP_i} + \frac{(NPV/I)_i}{(NPV/I)_{max}} + \frac{CO_{2,a,i}}{CO_{2,a,max}} \qquad (5)$$

where $CO_{2,a}$ represents the avoided CO_2 emissions, subscript i indicates a generic CHP technology and subscript *max* (*min*) refers to the maximum (minimum) value attainable considering all plant types. *TKPI* cannot exceed the value of 4 and it is a measure of a plant's performance as it takes into account the parameters that must be evaluated to select a technology when an investment has to be made.

4. RESULTS

The outcome of the design of a CHP plant for supplying energy to a paper mill, conteplating all plant technologies, will be shown in the follwing, along with related performance analyses.

4.1 Preliminary design and performance of CHP technologies for the paper industry

In order to evaluate the performance of a CHP unit implemented in a pulp and paper mill, it is necessary to determine an operation mode on the basis of which the plant is to be designed.

First of all, the ratio P_t/P_e of the specific process must be calculated; using the values reported in section 2.2, the result is $P_t/P_e = 3.33$.

Average values of useful-heat-to-electricity ratio ($R_{H/E}$) for Italian plants are taken from Ref. [31] and are similar to the ones calculated by authors in Ref. [30]. It is essential to refer to these values in order to design CHP plants in line with the current national state of the art.

If the plant is operated satisfying the electric load, after setting the rated electric power equal to P_e, the rated thermal power is calculated through the value of $R_{H/E}$ corresponding to the chosen technology. If the calculated value is lower than P_t, a supplementary steam flow rate must be estimated.

If the plant is operated satisfying the thermal load, after setting the rated thermal power equal to P_t, the rated electric power is calculated through the value of $R_{H/E}$ corresponding to the chosen technology. If the calculated value is lower than P_e, the resulting electric power deficiency must be compensated for by purchasing electricity from the grid; if the calculated value is higher than P_e, the resulting electric power surplus must be released to the grid.

The design must be carried out bearing in mind two hypoteses:

- the useful heat produced by the CHP unit has to be exploited at its most, granting the cogenerator the achievement of the maximum H_{CHP}/E ratio, with this condition being essential to access the best HEC performances;
- electricity has not to be fed into the national grid; this means that the plant size cannot exceed an electric power equal to the electric demand of the process.

In the light of this, the calculated value of the process ratio P_t/P_e must be compared to the ratios $R_{H/E}$ taken from Ref. [31] related to each CHP technology.

As a consequence of the two hypoteses, if:

$$\frac{P_t}{P_e} > R_{H/E}$$

the considered cogeneration technology is able to satisfy the electric demand of the production process, but not the thermal demand; this implies that the CHP unit has to be designed following the electric loads and auxiliary boilers shall be provided;

Otherwise, if:

$$\frac{P_t}{P_e} < R_{H/E}$$

the considered cogeneration technology is able to satisfy the thermal demand of the production process, but not the electric demand; this implies that the CHP unit has to be designed following the thermal loads and additional electricity shall be drawn from the national grid.

Concerning internal combustion engines, the result is $\frac{P_t}{P_e} > R_{H/E,ICE}$. This inequality means that an internal combustion engine must be sized satisfying the electric load in order to be coupled with a pulp and paper mill.

Concerning gas turbines, the result is $\frac{P_t}{P_e} > R_{H/E,GT}$, indicating a design based on the electric load.

Concerning steam power plants with backpressure turbine, the result is $\frac{P_t}{P_e} < R_{H/E,SPP-BPT}$, indicating a design based on the thermal load.

Concerning steam power plants with condensing turbine, the result is $\frac{P_t}{P_e} > R_{H/E,SPP-CT}$, indicating a design based on the electric load.

Concerning combined cycle power plants, the result is $\frac{P_t}{P_e} > R_{H/E,CCPP}$, indicating a design based on the electric load.

Fig. 2 displays the results of preliminary calculations done as in Ref. [30], breaking down TKPI values into the sum of the different contrubutions. It must be noted that, proceeding with this methodology, combined cycle power plants would show a resulting size too small for this kind of plant to be practically designed: because of this, a sizing based on thermal loads should be preferred. Nevertheless, this would result in an oversizing of the plant which would cause the overall efficiency to be lower than the established threshold efficiency; this means that such a technical solution cannot be taken into consideration.

In accordance with Ref. [30], ICEs and GTs prove to be particularly suited to medium paper production processes - the considered paper mill is characterised by an annual production of about 60000 t of paper. As said before, combined cycle power plants are not a viable solution; they would be suitable for large paper production processes (> 400000 t/y).

In view of the analysis conducted in Ref. [30], ICEs appear to be the winning CHP technology for a market kraft paper mill. However, in the following subsections, a more in-depth investigation will be presented: a detailed design of cogeneration units based on the various CHP technologies will be carried out; this will be possible because the features of a specific paper mill, also concerning thermal load diagram and related pressure and temperature levels, are here known. Besides, updated values for electricity and fuel cost will be adopted. Such a follow-up study will be a way to confirm or deny the above statement about ICEs.

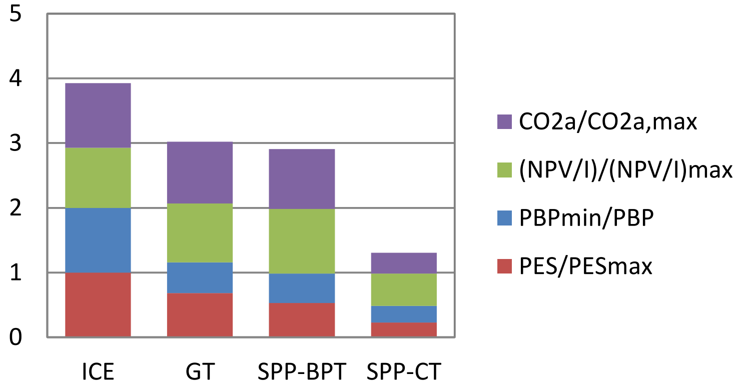

Fig. 2. Total key performance indicator calculated for internal combustion engines, gas turbines and steam power plants, according to the methodology of Ref. [30].

4.2 Detailed optimal design of cogeneration units for a paper mill

ICE-based cogeneration unit. The cogeneration unit has been designed selecting an internal combustion engine model from a Wärtsilä catalogue [32]. The chosen model is W 9L46DF, which is a 4-stroke, non-reversible turbocharged and intercooled engine with direct fuel injection, characterised by a rated power of 10.305 MW. According to the methodology described in subsection 4.1, such a plant must be designed depending on the electric load; its scheme is shown in Fig. 3. This system was modelled by means of GateCycle software starting from the parameters reported in section 2.2. As the plant is sized according to the electric load, the heat production is insufficient and then it must be integrated with an auxiliary boiler in order to fully satisfy the demand ("non-cogeneration heat production").

The simulated plant displays an electric efficiency of 47.5%, a thermal efficiency of 20.5% and an overall efficiency of 68%; the latter value is lower than the threshold efficiency, this meaning that a HEC portion must be extracted from the CHP unit (β=0). The resulting energy balance is illustrated in Table 3. On the basis of the energy balance, knowing from the guidelines that $Ref\ H\eta = 90\%$ and $Ref\ E\eta = 52.5\%$, the calculated PES is equal to 17.37%.

Regarding economic and environmental analysis, the considered input data are reported in Table 4 and Table 5. Table 4 shows parameters common to all considered technologies.

The capital cost of the installed unit and the average O&M cost are derived from Ref. [33]. Fuel is assumed to be natural gas in all cases and its cost is taken from Ref. [34]; fuel cost in CHP arrangement is lower because cogeneration is encouraged by lower excise duties that make fuel, basically, discounted. Fuel cost in separate production arrangement is used to assess the annual cost attributable to the quantity of fuel employed in the production of non-CHP energy amounts; it is also used to evaluate the total annual cost in the reference case of separate production against which the savings produced by cogeneration are estimated. The cost of the electricity purchased from the grid is derived from Ref. [34] as well. The result is a saving of 8.84 M€ per year, which produces a PBP of 1.12 years and a NPV/I ratio equal to 3.69.

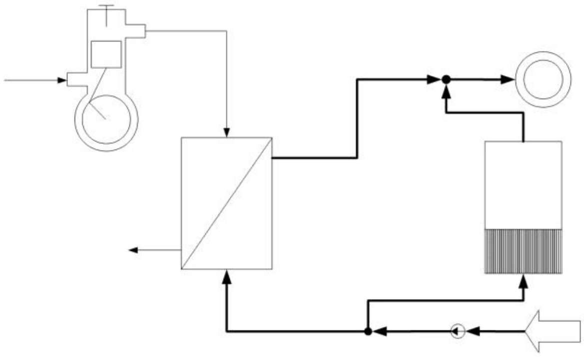

Fig. 3. Scheme of the ICE-based cogeneration unit taken into consideration.

Table 3. Energy balances for the considered cogeneration units (optimal design).

Quantity\Technology	**ICE**	**GT**	**SPP-BPT**	**SPP-CT**
F [GWh]	372.9	309.0	312.1	368.5
F_{unit} [GWh]	145.5	201.9	312.1	298.6
F_{CHP} [GWh]	108.3	201.9	312.1	298.6
$F_{non\text{-}CHP,E}$ [GWh]	37.2	0	0	0
$F_{non\text{-}CHP,H}$ [GWh]	227.4	107.1	0	69.9
E [GWh]	69.1	69.1	69.1	69.1
E_{CHP} [GWh]	51.4	69.1	51.6	69.1
$E_{non\text{-}CHP}$ [GWh]	17.7	0	0	0
E_{aux} [GWh]	0	0	17.5	0
H [GWh]	264.5	264.5	264.5	264.5
H_{CHP} [GWh]	29.8	154.0	264.5	189.3
$H_{non\text{-}CHP}$ [GWh]	234.7	110.5	0	75.2

Table 4. Input data for economic and environmental analysis common to all technologies.

Input data for economic and environmental analysis	
Fuel cost in CHP arrangement [€/kWh]	0.0193
Fuel cost in separate production arrangement [€/kWh]	0.0243
Grid electricity cost [€/kWh]	0.156
Discount rate [%]	6
Emission factor [t_{CO_2}/TJ]	55

Table 5. Input data for economic analysis (different technologies).

Cost \ Technology	**ICE**	**GT**	**SPP-BPT**	**SPP-CT**	**CCPP**
Unit capital cost [€/kW]	900	1165	1600	1800	1000
Average O&M cost as fraction of the installed capital cost [%]	6	6	4	4	4

Concerning environmental analysis, the ICE-based cogeneration plant avoids the emission of 14099 t_{CO2}/y with respect to the case of separate production.

GT-based cogeneration unit. The cogeneration unit has been designed selecting a gas turbine model from a Siemens catalogue [35]. The chosen model is SGT-400, which is a twin-shaft engine characterised by a rated power of 12.9 MW. According to the methodology described in subsection 4.1, such a plant must be designed depending on the electric load; its scheme is shown in Fig. 4. This system was modelled by means of GateCycle software starting from the parameters reported in section 2.2: the outcome of the simulation is the energy balance illustrated in Table 3. As the plant is sized according to the electric load, the heat production is insufficient and then it must be integrated with an auxiliary boiler in order to fully satisfy the demand.

The simulated plant displays an electric efficiency of 34.2%, a thermal efficiency of 76.3% and an overall efficiency exceeding the threshold value. On the basis of the energy balance, knowing from the guidelines that $Ref\ H\eta = 90\%$ and $Ref\ E\eta = 52.5\%$, the calculated PES is equal to 33.31%.

Regarding economic analysis, the considered input data are reported in Table 5 [33].

The result is a saving of 10.52 M€ per year (with respect to the case of separate production), which produces a PBP of 1.54 years and a NPV/I ratio equal to 7.03.

Concerning environmental analysis, the GT-based cogeneration plant avoids the emission of 26751 t_{CO2}/y with respect to the case of separate production.

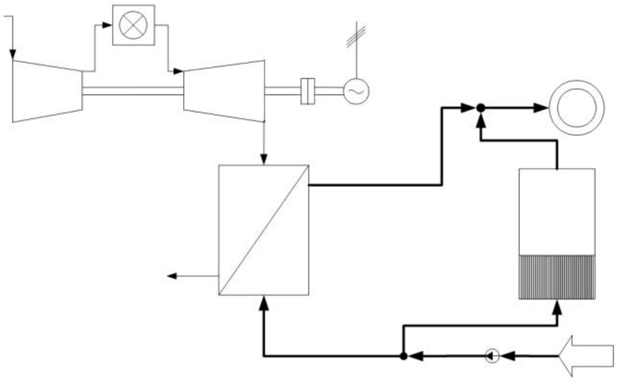

Fig. 4. Scheme of the GT-based cogeneration unit taken into consideration.

SPP-BPT-based cogeneration unit. A steam power plant with backpressure turbine cogeneration unit has been set up with a rated power of 7.17 MW. According to the methodology described in subsection 4.1, such a plant must be designed depending on the thermal load; its scheme is shown in Fig. 5. This system was modelled by means of GateCycle software starting from the parameters reported in section 2.2: the outcome of the simulation is the energy balance illustrated in Table 3. As the plant is sized according to the thermal load, the electricity production is insufficient and then it must be integrated with an auxiliary amount of energy purchased from the grid (E_{aux}) to fully satisfy the demand.

The simulated plant displays an electric efficiency of 16.5%, a thermal efficiency of 84.7% and an overall efficiency exceeding the threshold value. On the basis of the energy balance, knowing from the guidelines that $Ref\ H\eta = 90\%$ and $Ref\ E\eta = 52.5\%$, the calculated PES is equal to 20.42%.

The capital cost of the installed unit reported in Table 5 is estimated in view of the current market.

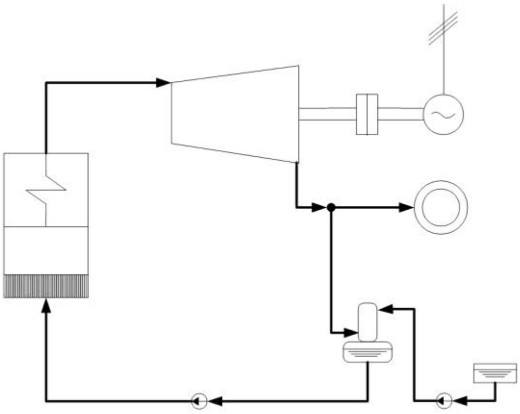

Fig. 5. Scheme of the SPP-BPT-based cogeneration unit taken into consideration.

The result is a saving of 8.71 M€ per year (with respect to the case of separate production), which produces a PBP of 1.41 years and a NPV/I ratio equal to 9.44. Concerning environmental analysis, the SPP-BPT-based cogeneration plant avoids the emission of 18605 t_{CO2}/y with respect to the case of separate production.

SPP-CT-based cogeneration unit. A steam power plant with condensing turbine cogeneration unit has been set up with a rated power of 10.1 MW. According to the methodology described in subsection 4.1, such a plant must be designed depending on the electric load; its scheme is shown in Fig. 6. This system was modelled by means of GateCycle software starting from the parameters reported in section 2.2: the outcome of the simulation is the energy balance illustrated in Table 3. As the plant is sized according to the electric load, the heat production is insufficient and then it must be integrated with an auxiliary boiler in order to fully satisfy the demand.

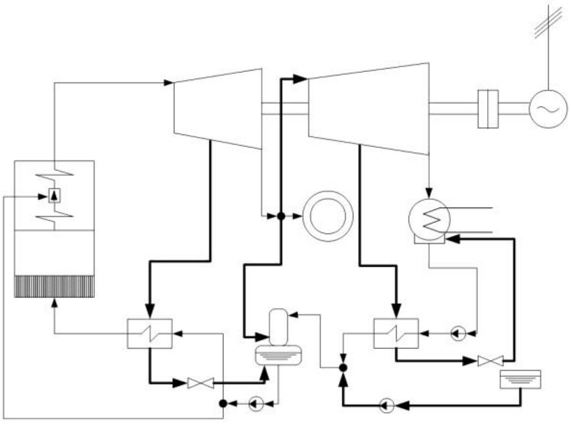

Fig. 6. Scheme of the SPP-CT-based cogeneration unit taken into consideration.

The simulated plant displays an electric efficiency of 23.1%, a thermal efficiency of 63.4% and an overall efficiency of 86.5%, thus exceeding the threshold value. On the basis of the energy balance, knowing from the guidelines that $Ref\ H\eta = 90\%$ and $Ref\ E\eta = 52.5\%$, the calculated PES is equal to 12.68%. The capital cost of the installed unit reported in Table 5 is estimated in view of the current market.

The result is a saving of 9.73 M€ per year (with respect to the case of separate production), which produces a PBP of about 2 years and a NPV/I ratio equal to 6.37. Concerning environmental analysis, the SPP-CT-based cogeneration plant avoids the emission of 14972 t_{CO_2}/y with respect to the case of separate production.

CCPP-based cogeneration unit. On the basis of the methodology described in subsection 4.1, a combined cycle power plant must be designed depending on the electric load; however, the rated electric power, resulting from the typical heat-to-electricity ratio of this technology, would be much lower than the minimum value for such a plant to be viable (that is 20 MW, according to Ref. [36]). Therefore, a CC-based cogeneration unit will not be taken into consideration for the application here discussed.

4.3 Detailed alternative design of cogeneration units for a paper mill

The aim of this section is to study the alternative design of the previously analysed CHP technologies (that is, the plants sized according to the electric load will be sized according to the thermal load and vice versa), in order to corroborate the validity of the design methodology subject of the present paper and to provide a more complete overview of cogeneration units.

ICE-based cogeneration unit. The size of an ICE cogeneration unit designed depending on the thermal load would be too large for this technology, given its typical heat-to-electricity ratio. The cogeneration unit would have to be composed of more engines run in parallel; all engines would operate at maximum electric load (in order to accomplish heat requirements) and a great part of electric power would have to be delivered to the grid. Therefore, being known that this situation is not profitable in HEC context, an ICE-based cogeneration unit shall not be considered for the application here discussed.

GT-based cogeneration unit. A GT-based cogeneration unit designed supplying the thermal load was modelled by means of GateCycle software starting from the assumptions reported previously: the outcome of the simulation is the energy balance illustrated in Table 6.

Table 6. Energy balances for the considered cogeneration units (alternative design).

Quantity\Technology	**GT**	**SPP-CT**	**CCPP**
F [GWh]	452.3	414.4	934.7
F_{unit} [GWh]	452.3	414.4	934.7
F_{CHP} [GWh]	452.3	414.4	727.5
$F_{non\text{-}CHP,E}$ [GWh]	0	0	207.2
$F_{non\text{-}CHP,H}$ [GWh]	0	0	0
E [GWh]	69.1	69.1	69.1
E_{CHP} [GWh]	155.9	95.9	317.5
$E_{non\text{-}CHP}$ [GWh]	0	0	104.1
E_{aux} [GWh]	-86.8	-26.8	-352.5
H [GWh]	264.5	264.5	264.5
H_{CHP} [GWh]	264.5	264.5	264.5
$H_{non\text{-}CHP}$ [GWh]	0	0	0

With reference to the abovementioned assumptions, this plant displays an overall efficiency of 92.9% and a PES equal to 23.4%. This setup shows a negative E_{aux}: this means that it produces a surplus amount of electric energy that must be released to the grid. The economic analysis is carried out by resorting to the reference price for purchased electricity in Italy (*national unique price*, [37]), that is 0.042 €/kWh, to price the electricity fed into the grid (this trade constitutes an incoming cash flow). Taking into account the values reported in Tables 4 and 5, the result is a saving of 11.94 M€ per year (with respect to the case of separate production), which produces a PBP of 1.35 years and a NPV/I ratio equal to 8.11.

Concerning environmental analysis, it is possibile to assume that the release of electricity to the grid causes a decrease in the CO_2 emissions related to the mix of power plants regularly generating electricity: according to Ref. [38], the emission factor attributable to such a mix is 330 g_{CO_2}/kWh. As a consequence, a GT-based cogeneration plant avoids the emission of 60647 t_{CO_2}/y, with respect to the case of separate production.

SPP-BPT-based cogeneration unit. In section 4.2, it was noted that a SPP-BPT-based cogeneration unit requires the purchase of electricity from the grid if designed supplying the thermal load: this means that a design of this kind of plant based on the electric demand would produce a huge waste of exhaust heat, which is pointless in a CHP context. Therefore, a SPP-BPT-based cogeneration unit shall not be considered for the application here discussed.

SPP-CT-based cogeneration unit. A SPP-CT-based cogeneration unit designed supplying the thermal load was modelled by means of GateCycle software starting from the assumptions reported previously: the outcome of the simulation is the energy balance illustrated in Table 6.

With reference to the abovementioned assumptions, this plant displays an overall efficiency of 87% and a PES equal to 13.1%. This setup produces a surplus amount of electric energy that must be released to the grid, whose price is established as previously done. Taking into account the values reported in Tables 4 and 5, the result is a saving of 10.09 M€ per year (with respect to the case of separate production), which produces a PBP of 2.64 years and a NPV/I ratio equal to 4.79.

Environmental analysis is conducted making use of the previously illustrated emission factors: a SPP-CT-based cogeneration plant avoids the emission of 25122 t_{CO_2}/y, with respect to the case of separate production.

CCPP-based cogeneration unit. A CCPP-based cogeneration unit designed supplying the thermal load was modelled by means of GateCycle software starting from the assumptions reported previously: its scheme is shown in Fig. 7 (rated electric power equal to 59.5 MW).

The simulated plant displays an overall efficiency of 73.4%: this value is lower than the threshold efficiency, therfore a HEC portion must be extracted from the CHP unit (β=0.1813). The resulting energy balance is illustrated in Table 6. On the basis of the energy balance, the calculated PES is equal to 19.05%.

Regarding economic and environmental analysis, the considered input data are reported in Tables 4 and 5 [33].

This setup produces a surplus amount of electric energy that must be released to the grid, whose price is established as previously done. The result is a saving of 11.28 M€ per year (with respect to the case of separate production), which produces a PBP of 6.53 years and a NPV/I ratio equal to 0.84. Environmental analysis is conducted making use of the previously illustrated emission factors: a CCPP-based cogeneration plant avoids the emission of 155743 t_{CO_2}/y, with respect to the case of separate production.

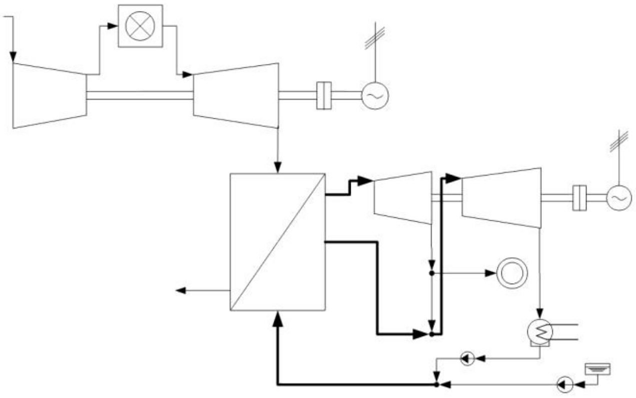

Fig. 7. Scheme of the CC-based cogeneration unit taken into consideration.

5. DISCUSSION

In the light of the performance parameters evaluated in section 4, it is now possibile to calculate the total key performance indicator for each of the examined technologies.

The maximum (minimum) reference values for the indicators appearing in TKPI formula are selected considering the two sizing methodologies (optimal and alternative) separately.

Concerning the optimal design, the resulting total key performance indicator values are reported in Fig. 8, broken down into the sum of their different contributions.

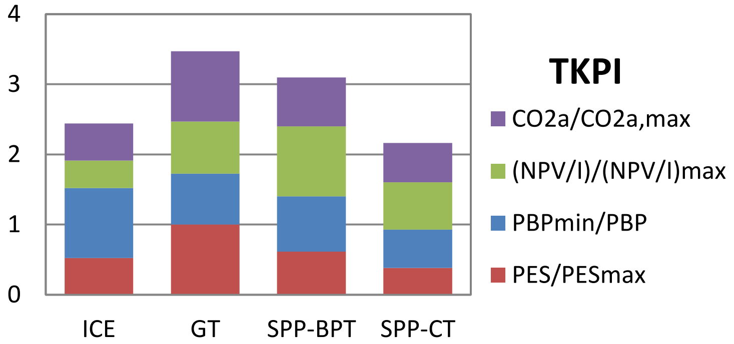

Fig. 8. TKPI values and breakdown for the considered cogeneration technologies (optimal design).

Steam power plants with backpressure turbine, with a TKPI equal to 3.10, and, especially, gas turbines, with a TKPI equal to 3.47, turn out to be the most performing technologies, in spite of the results described in Ref. [30], which indicated ICEs as the most suitable cogeneration units for the paper industry. This is due to the impossibility of exploiting all heat produced by the engine, an hypotesis adopted in Ref. [30], as the amount delivered by the cooling water jacket and the oil system cannot be harnessed because of their temperature levels being much lower than that required by the paper mill processes.

Regarding the alternative design, the breakdown of the resulting total key performance indicators is in Fig. 9. The results indicate gas turbine as the winning technology also in this case and that steam power plants with condensing turbine are the least convenient units for the application here discussed. Combined cycles are extremely favoured by their excellent environmental performance, improved by the huge quantity of electricity fed into the grid, which contributes to the reduction of CO_2 emissions in the model utilized in the present analysis; if it was not for this factor, the total key performance indicator for this technology would be very low because of its poor economic performance, consequence of the very high initial investment. As seen in section 4.2, considering that the only feasible design methodology for combined cycles is not the optimal one, this kind of plant is not viable for being coupled with paper mills.

However, if the two design methodologies are compared, it is clear that the optimal design must be preferred, since it is produces plants displaying higher TKPI values (TKPIs in Fig. 9 would be smaller if calculated by using reference values of TKPIs in Fig. 8). This statement reaffirms the validity of the sizing methodology proposed by authors.

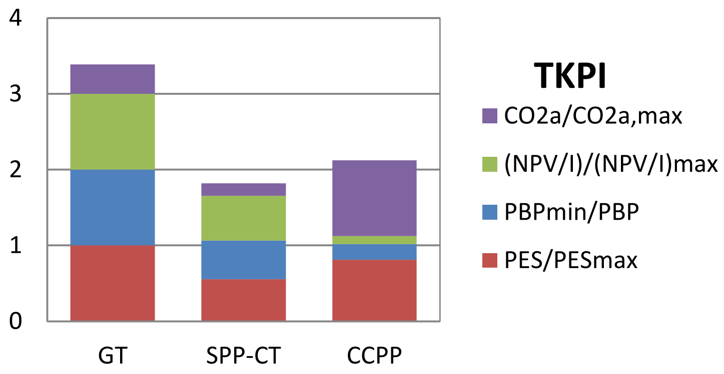

Fig. 9. TKPI values and breakdown for the considered cogeneration technologies (alternative design).

In the analysis conducted thus far, white certificates are not taken into account in the economic analysis. According to GSE's annual report on white certificates [39], the average value of incentive securities is 267 €/toe in the Italian context for the year 2017; on the basis of this value, it is possible to price energy savings for each technology (RISP parameter), generating a further positive cash flow. TKPI parameters can be therefore recalculated: the results are reported in Figs. 10 and 11.

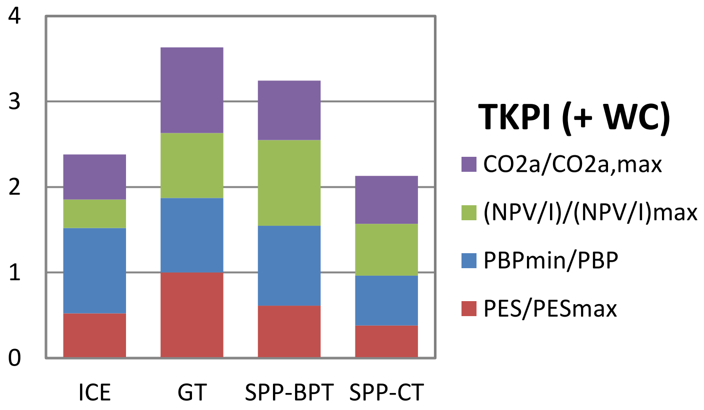

Fig. 10. TKPI values and breakdown for the considered cogeneration technologies with white certificates taken into account (optimal design).

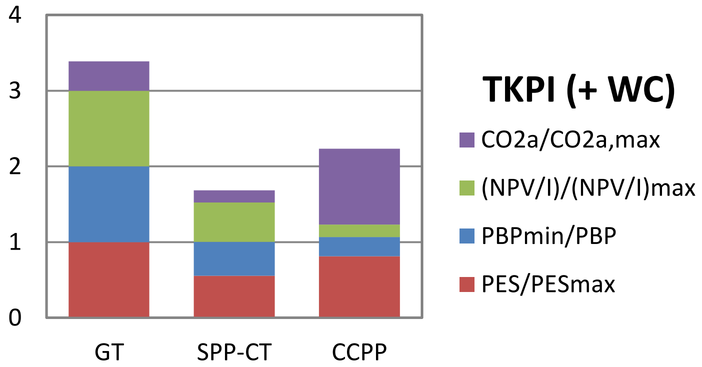

Fig. 11. TKPI values and breakdown for the considered cogeneration technologies with white certificates taken into account (alternative design).

The difference from the previous case is slight: since all technologies benefit from incentives, the hierarchies established in the previous case are maintained. Gas turbines, whose TKPI grows up to 3.63, are confirmed to be the most suitable technology; combined cycle economic performance is enhanced but not enough to make it a winning solution.

Besides, it must be noted that white certificates are subject to certain variability in the individual national context and that incentives vary in different legislative realities: this is an element that can be taken into consideration by carrying out a parametric analysis as shown in Figs. 12 and 13. It is clear that the change in the performance of the individual technology is almost negligible; nevertheless, in the optimal design case, GT and SPP-BPT's performance improves, whereas ICE and SPP-CT's one stays costant or even worsen: this is caused by the growth of maximum NPV/I ratio, which is faster than that of NPV/I ratio for the individual technology, with increasing incentives. In any case, gas turbines are hereby confirmed to be the winning technical solution for a CHP unit coupled with a pulp and paper mill and this statement is in line with the outcome of the research conducted by Shabbir et al. [28].

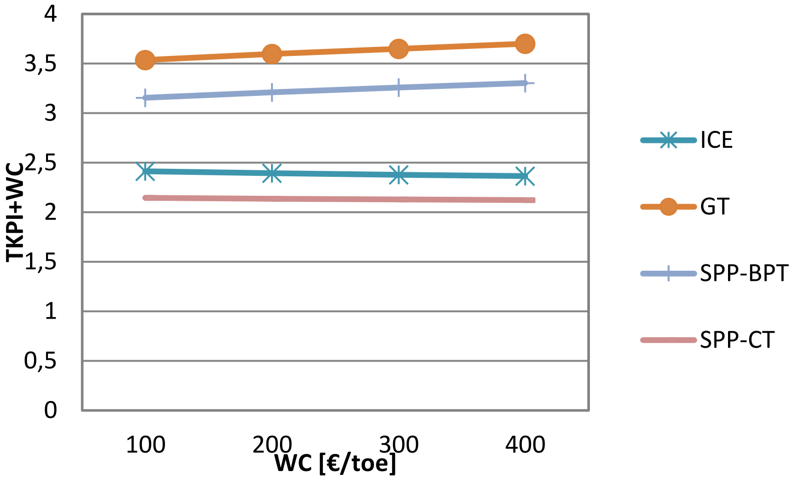

Fig. 12. TKPI sensitivity analysis for varying incentive values (optimal design).

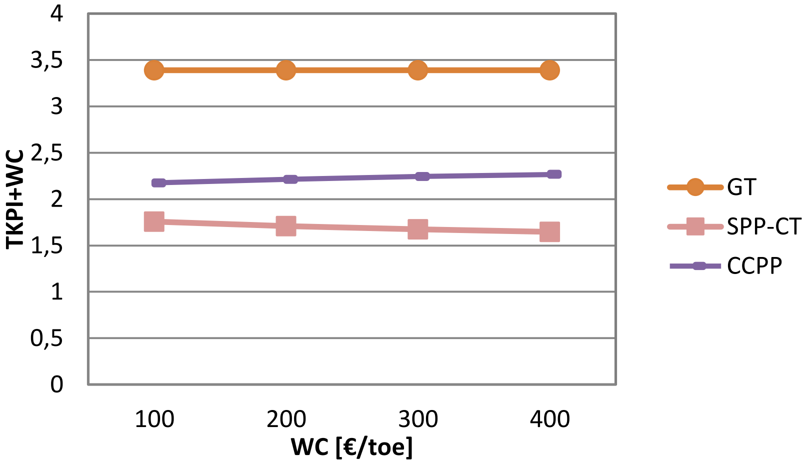

Fig. 13. TKPI sensitivity analysis for varying incentive values (alternative design).

6. CONCLUSIONS

In the present paper, different technologies have been analysed to be coupled with a pulp and paper mill as cogeneration units. The investigation has been conducted from a thermodynamic, economic and environmental point of view, focusing on internal combustion engines, gas turbines, steam power plants with backpressure turbine, steam power plants with condensing turbine and combined cycle power plants. The thermodynamic analysis has been carried out by simulating the plants with GateCycle software, in order to elaborate their energy balances. The economic analysis has been performed in accordance with the principles of high-efficiency cogeneration (HEC), thus following the guidelines issued by the European Commission and making use of the obtained energy balances: this allowed energy savings of cogeneration to be estimated and economically valued with respect to separate energy production. All of these analyses are summed up in the definition of a total key performance indicator: this parameter allows for the evaluation of the various technologies in an objective manner and its calculation is based on the actual production amounts and load diagrams of a particular industrial reality in Italy. Thanks to the known specific data, a plant has been sized, modelled and simulated. The calculations indicate gas turbines as the winning technical solution, with a TKPI of 3.47, which is increased to 3.63 if incentives (white certificates) are taken into account.

The methodology illustrated in this paper applies to a paper mill, but it must not be intended for this limited use. Indeed, the main achievement of the present study is the provision of the means for a simple evaluation of CHP performances of different types of power plant: as the evaluation criteria are general, the research can be extended and the methodology successfully applied to other industry sectors.

NOMENCLATURE

CC combined cycle
CCPP combined cycle power plants with condensing turbine
C_{eff} power-to-heat ratio from the Italian legislation
CHP combined heat and power
CHP Eη electric efficiency of the CHP portion
CHP Hη thermal efficiency of the CHP portion
$C_{O\&M}$ operation and maintenance costs
CO_{2a} CO_2 emissions avoided
$C_{s,e}$ specific electric demand
$C_{s,t}$ specific thermal demand
E electricity
E_{aux} auxiliary electricity
E_{CHP} electricity from cogeneration
$E_{non\text{-}CHP}$ electricity not from cogeneration
F fuel input in a CHP system
F_{CHP} fuel input to produce useful heat and electricity from cogeneration
$F_{non-CHP,E}$ fuel input to produce electricity not from cogeneration
$F_{non-CHP,H}$ fuel input to produce heat not from cogeneration
GT gas turbine
H heat
h specific enthalpy
H_{CHP} useful heat from cogeneration
HEC high-efficiency cogeneration
$H_{non\text{-}CHP}$ useful heat not from cogeneration
I total investment
ICE internal combustion engine
K harmonisation factor
$\dot{m}_{paper}$ produced paper mass flow rate
NPV net present value
PBP pay back period
P_e electric power
PES primary energy saving
P_t thermal power

Ref Eη referred efficiency for electric production according to the guidelines
Ref Hη referred efficiency for heat production according to the guidelines
$R_{H/E}$ useful-heat-to-electricity ratio
RISP parameter expressing energy savings in the Italian legislation
SPP-BPT steam power plants with backpressure turbine
SPP-CT steam power plants with condensing turbine
TKPI total key performance indicator
WC white certificates
Greek letters
β power loss factor by a heat extraction at a steam turbine
η_{CHP} cogeneration efficiency
η_{E} electric efficiency
$\eta_{E,EQ}$ electric equivalent efficiency
$\eta_{E,ref}$ actual referred electric efficiency
η_{g} overall efficiency
$\eta_{H,ref}$ actual referred thermal efficiency
$\eta_{non\text{-}CHP,E}$ efficiency of non-combined electrical/mechanical energy generation
$\eta_{threshold}$ threshold efficiency

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