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Original
District heating potential in the case of low-grade waste heat recovery from energy intensive industries / Cioccolanti, L.; Renzi, M.; Comodi, G.; Rossi, M.. - In: APPLIED THERMAL ENGINEERING. - ISSN 1359-4311. - 191:(2021). [10.1016/j.applthermaleng.2021.116851]

Published
DOI:10.1016/j.applthermaleng.2021.116851

District Heating potential in the case of low-grade Waste Heat Recovery from energy intensive industries

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ABSTRACT

Waste Heat Recovery (WHR) from energy intensive industries has a great potential in curbing CO_2 emissions. Among the different solutions, District Heating (DH) is considered of major interest, satisfying the heating demand of users in the proximity of power plants. Considering the energy intensity of the pulp and paper industry, a methodology for evaluating the recovery potential of its low-grade waste heat from cogeneration plants in DH is presented. The proposed methodology allows to evaluate the thermal power by cogeneration plants to end users and to assess the potential maximum number of residential buildings that could be connected to each DH network. Based on the proposed methodology, the benefits of the WHR are evaluated from both energy and environmental points of view. More precisely, considering 50 pulp and paper mills in Italy under investigation in the present analysis, a yearly natural gas saving corresponding to 143.76 kTonnes of Oil Equivalent (TOE) and 333.11 $ktCO_2$ is obtained. In case of WHR, the average Primary Energy Saving (PES) of the cogeneration plants increases from 0.14 up to 0.22. In particular, cogeneration units based on steam turbine technology show the greatest improvement, since its average PES moved from 0 up to almost 0.1.

KEYWORDS

Combined Heat and Power; Cogeneration; District Heating; Low-Carbon Districts; Energy Efficiency; Primary Energy Savings;

NOMENCLATURE

$A_{floor,avg}$ = Average floor area of a building [m^2]

A_{floor,avg_h} = Average heated floor area of a building [m^2]

$A_{bldng,ovrll}$ = Overall surface of a building [m^2]

C_d = Thermal power lost by transmission per unit volume and degree temperature [kW/m^{3}K]

C_v = Thermal power required to heat the exchanged air per unit volume and degree temperature [kW/m^{3}K]

$c_{p,exs}$ = Specific heat transfer capacity of the exhausts [kW/kgK]

$E_{input,CHP}$ = Input energy to the cogeneration unit [MWh]

$E_{e,CHP}$ = Electric energy output from the cogeneration unit [MWh]

$E_{th,CHP}$ = Thermal energy output from the cogeneration unit [MWh]

E_{input} = Input energy to a power plant or an industrial boiler [MWh]

E_e = Electric energy output from a power plant [MWh]

E_{th} = Thermal energy output from an industrial boiler [MWh]

$E_{th,end\ users}$ = Available thermal energy for end users connected to a District Heating network [MWh]

$E_{th,max}$ = Maximum thermal energy required by a building [MWh]

h_{bldng} = Average height of a residential building [m]

h_{hs} = Heating hours in the winter season [h]

$L_{th,DH}$ = Heat losses along the DH network and at the heat exchangers [kW]

$L_{l,DH}$ = Linear heat losses along the pipes of a DH network [kW/km]

Le_{DH} = Maximum length of a District Heating network [km]

$m_{fuel,CHP}$ = Mass of the fuel entering the cogeneration unit [kg]

$V_{NG,WHR}$ = Volume of natural gas saved through Waste Heat Recovery [m^3]

$\dot{m}_{exs}$ = Mass flow rate of the exhausts from the cogeneration unit [kg/s]

N_{bldng} = Maximum number of buildings connected to a DH network [-]

P_{input} = Input power to the paper mill plant [MW]

$P_{input,CHP}$ = Input power to the cogeneration unit [MW]

$P_{th,gross}$ = Available thermal power from the cogeneration unit [MW]

$P_{th,net}$ = Available thermal power downstream the process [MW]

$P_{e,CHP}$ = Electric power provided by the cogeneration unit [MW]

$P_{th,end\ users}$ = Available thermal power for end users connected to a District Heating network [MW]

$P_{th,max}$ = Maximum thermal power required by a building [kW]

ΔT = Temperature difference of the hot water between the inlet and the outlet sections of a heat exchanger [°C]

T_{amb} = Mean ambient temperature during winter season [°C]

$T_{DH,supplied}$ = Transfer medium inlet temperature to a DH network [°C]

$T_{ex,CHP}$ = Average outlet temperature of the waste heat from the cogeneration unit [°C]

T_{min} = Minimum outdoor temperature [°C]

T_{indoor} = Indoor temperature of a building [°C]

S/V = Shape factor of a building [1/m]

$\eta_{e,CHP}$ = Electric efficiency of the cogeneration unit [-]

$\eta_{th,CHP}$ = Thermal efficiency of the cogeneration unit [-]

η_{CHP} = Total efficiency of the cogeneration unit [-]

η_{e,CHP_avg} = Average electric efficiency of the cogeneration units considering the 50 Italian paper mills [-]

η_{th,CHP_avg} = Average thermal efficiency of the cogeneration units considering the 50 Italian paper mills [-]

$\eta_{e,ref}$ = Reference electric efficiency of power plants [-]

$\eta_{th,ref}$ = Reference thermal efficiency of industrial boilers [-]

Acronyms

CHP = Combined Heat and Power

DH = District Heating

DHT = Direct Heat Transfer

EEC = Energy Efficiency Class

EPI = Energy Performance Index

HDD = Heating Degree Days

HEN = Heat Energy Network

HRES = Hybrid Renewable Energy Systems
ICE = Internal Combustion Engine
LNG = Liquid Natural Gas
ORC = Organic Rankine Cycle
PES = Primary Energy Saving
SFS = Specific Fuel Saving [m^3/kW]
WHR = Waste Heat Recovery
LHV_{fuel} = Lower Heating Value of the fuel [kWh/kg]

1. INTRODUCTION

Climate change effects are affecting more and more both the environment and human beings, despite several measures have been taken so far to contrast them. Emissions of CO_2, which is the main greenhouse gas produced by human activities, need to be reduced in order to mitigate the increasing global warming. As reported in [1], CO_2 emissions flattened in 2018 and 2019 at around 33 Gt; in 2019, advanced economies lowered the CO_2 production from the power sector of about 3.5% with respect to 2018 due to the expanding role of renewables [2]. According to Brandoni et al. [3], a reduction of almost 58% on CO_2 emissions has to be achieved by 2050 to prevent the global temperature rise beyond the threshold of 3°C. To this aim, the use of Hybrid Renewable Energy Systems (HRESs), which consist of multiple renewable-based energy conversion technologies usually combined with storage systems to provide a more reliable power supply, is considered a suitable pathway to have self-sufficient districts for both electric and thermal demand, thus making cities efficient, carbon-neutral and climate-resilient [4, 5]. Therefore, the application of these systems leads to the so-called modern energy districts, where the local energy production matches the local demand required by residential buildings and industrial activities. Besides the use of HRESs, also energy efficiency measures would give an important contribution to this goal.

Among the different solutions to improve the overall energy efficiency of the industrial sector, cogeneration, which is the simultaneous production of electricity and heat where the latter is considered as a useful effect, has a huge potential [6, 7]. The technologies to be used for power generation, energy recovery and distribution depend on many factors, such as the amount of electric and thermal energy demands as well as the related temperatures required by the end users [8-10]. The operation of cogeneration units is widely analysed in literature, but at present, even in presence of energy recovery solutions, there are still several energy intensive industries worldwide wasting significant amounts of low-grade heat downstream their processes [11, 12]. Such waste heat could be recovered, at least partially, for further electric power generation and/or thermal power applications [13], thus playing a key role in curbing CO_2 emissions in modern energy districts [14]. Industrial sectors such as petrochemical, food-processing, textile, pulp and paper, marine transportation and Liquid Natural Gas (LNG) supply have the highest potential for low-grade waste heat recovery. In this regard, the pulp and paper sector is characterised by a large amount of raw materials and high energy consumption that account for almost half of the paper mill costs [15]. Precisely, the sector is the fourth-largest energy intensive industry worldwide consuming about 6% of the global industrial energy [16]. Despite the energy intensity of the sector has been reduced in the last decade thanks to several energy efficiency improvements on both papermaking processes and equipment (fans, pumps, motors and air compressors), the power generation and distribution systems still have some operational inefficiencies [17]. For instance, Marshman et al. [18] have investigated the energy management of a steam turbine cogeneration unit having the two-fold goal of supplying heat to the pulping process and generating electricity, whose surplus is sold to providers nearby. More precisely, the authors of this paper have developed an optimization algorithm that took into account several aspects, including the electricity price fluctuation, to improve the energy efficiency of the analysed pulp mill. In the past, instead, some of the authors of the present paper [19] presented a survey on the state-of-the-art of the Combined Heat and Power (CHP) plants installed in the Italian pulp and paper industries from 1986 to 2010. Results showed that nearly all the considered plants (61 in total) worked with a positive PES index, meaning that they were using less primary energy compared to the separate production of both electric and thermal energy. Nevertheless, the authors found out that benefits for the competitiveness of the sector could be achieved through further recovering the excess thermal energy. Hence, the pulp and paper sector has high potential in curbing energy consumptions: indeed, Pandey et al. [16] found out that the yearly energy saving potential is about 6% of the yearly energy consumption. In this context, Costa et al. [20] carried out a study related to the use of eucalyptus, which undergoes to a gasification process in a bubbling fluidized bed in order to obtain biomass to feed a 50 MW thermal power plant of a pulp and paper mill in Portugal. The heat is then used to produce the steam that is required by the papermaking process. Eventually, Ruohonen et al. [21] investigated the use of the low temperature secondary heat in different heat exchanger networks retrofits. In this regard, fuel drying can increase the heating value of fuels and, as a consequence, the energy efficiency of both heat and power production.

Residual waste heat can be used also at low temperatures for producing further electric power through technologies like thermoelectric generators and systems based on Kalina cycle and Organic Rankine Cycle (ORC) [22]. While ORC systems obtained a relative technological maturity and several products are already available in the market, the other technologies have still limited applications. In general, the low penetration of all these technologies is due to the intrinsic low efficiency of the waste-to-energy conversion and the additional complexity of the plant [23]. Therefore, in this perspective the direct exploitation of the low-grade waste heat for further thermal applications represents the easiest and most effective solution on both energy and economic points of view.

Among the different applications, District Heating (DH) is considered one of the best solutions [24]. Indeed, DH is able to provide multiple benefits i) to the environment by increasing the overall efficiency of centralised plants, thus lowering the harmful emissions into the atmosphere; ii) from an economic point of view by reducing the primary energy consumptions and taking advantages of the long lifetime up to 50 years; iii) in terms of safety since no flue gases nor fuel-related risks are present at end users premises; iv) from the reliability point of view due to the interconnection of multiple heat sources and, eventually, v) from the maintenance side since the centralised plants can be continuously monitored and pro-actively maintained. For these reasons, in the recent years many researchers have focused their attention on DH networks. For example, Fitó et al. [25] studied the design of a DH network in Grenoble (France) by investigating three different waste heat temperatures, namely 35°C, 50°C and 85°C. Two different results were obtained: the demand-oriented optimal design suggested to recover waste heat at 35°C in order to supply 49% of the residential need, while the source-oriented optimal design recommended a waste heat temperature of 85°C with the final aim of maximizing the waste recovery up to 55%. Among them, the first one was selected since the highest global exergy efficiency of 27% was possible to be achieved. Sun et al. [26], instead, proposed a DH network based on WHR from industries, where natural gas fired boilers with absorption heat exchangers are present. In particular, the decrease of the return temperature of the heat transfer fluid doubled the primary energy efficiency of the DH system analysed in their work. Pelda et al. [27] assessed the potential of both industrial waste heat and solar thermal power in DH networks, showing high unused industrial waste heat sources and solar thermal power that could satisfy the end users' demand completely. Wang et al. [28] investigated the WHR potential in DH systems and used the tangency analysis, which is a kind of pinch analysis optimizing the interconnections between multiple-grade industrial waste heat sources, to enhance the direct-heat-exchange systems with multi-heat sources through the exergy analysis of heat recovery systems with heat pumps. Results showed that the developed process optimization principles led to the decrease of the energy input by more than 70%. Along the same line, Fang et al. [29] discussed issues related to a DH system using two or more kinds of low-grade industrial waste heat, ranging from 20°C to 90°C and applying three different approaches i) tangency analysis; ii) lowering the return temperature of the water in the primary circuit and iii) using systems able to integrate both industrial waste heat for the base load and fossil-fuel heat in DH networks. Results showed that overall 390,000 GJ of waste heat was recovered and thus 35,000 tCO_2 were saved.

Despite there are several papers in literature that analyse the exploitation of the waste heat from energy intensive industries for DH applications, to the best of the authors’ knowledge there is no work that addresses the potential of the low-grade waste heat from cogeneration plants of energy intensive industries in DH networks. Indeed, the exhausts exit the cogeneration units within a temperature range of 150°C-200°C [30] after the energy conversion process and this waste heat could be further recovered for DH applications. Hence, in this paper, based on the authors’ expertise in the

Italian pulp and paper sector, a methodology to assess the potential of the waste heat from the installed cogeneration plants for DH application has been developed. Precisely, the DH potential of the existing cogeneration units has been investigated from both energy and environmental points of view using operational data of 50 Italian paper mills. The waste heat of the cogeneration plants and the net one available to DH networks have been assessed taking into account the related heat losses. Then, the thermal energy required by the end users, according to the building Energy Efficiency Classes (EECs), and the maximum number of buildings connected to each DH network have been obtained. Eventually, a detailed analysis of the PES and of the tCO_2 avoided has been performed. Hence, the main novelties of the present work rely on i) a methodology to assess the low-grade waste heat from cogeneration plants of energy intensive industries for DH applications and ii) a methodology to preliminary evaluate the benefits of the DH network in terms of end users to be connected and energy and environmental savings.

Therefore, the paper is organized as follows: after the Introduction, Section 2 provides an overview of the European and Italian pulp and paper industry, while Section 3 reports the WHR potential for end users to be connected to the DH networks. Section 4 describes the methodology applied to this study in order to assess the energy savings deriving from the use of the WHR in DH networks. Section 5 presents and discusses the main findings of the work, focusing the attention on the profitability of coupling cogeneration units with DH networks and eventually Section 6 reports the conclusions.

2. THE EUROPEAN AND ITALIAN PULP AND PAPER INDUSTRY

Europe is the second largest producer and the third consumer of paper and board, reaching about 41.8% Mt/year of wood pulp that correspond to about 22% of the total production worldwide. The main grades of wood pulp for papermaking are sulphate pulp (60% of total production), mechanical and semi-chemical pulp (32% of total production) and sulphite pulp (5% of total production) [31]. Among the European countries, Sweden, Finland, Germany and Portugal are the four biggest pulp producers (Sweden and Finland produce together about 57% of the total pulp production), while Italy, Germany, France and the UK are the four biggest markets. Italy produces only 0.7 Mt/year of pulp that is obtained mainly from mechanical and semi-chemical pulping processes, while the remaining comes from sulphate pulping. Regarding the paper sector (graphic papers, sanitary, household paper and packaging paper), Germany, Finland, Sweden and Italy are the four biggest producers with a total production of 22.8 Mt/year, 13.1 Mt/year, 11.7 Mt/year and 9.1 Mt/year, respectively [31]. With reference to the size, more than 50% of the paper mills in Italy have a paper production <25 kt/year and many of them belong to private or family-owned businesses.

Despite the production of the pulp and paper industry increased between 2000 and 2018 worldwide [32], the European production continued the negative trend with a reduction of about 3% in 2019. In particular, the EU paper and board production followed the 2019 EU economy downward trend due to the global instability and trade tensions, in contrast with a significant uptick of the market pulp production (+0.8%) as a result of the export market demand and investments in new capacities [33]. According to ASSOCARTA [34], in 2019 the Italian pulp and paper production accounted for almost 9.1 Mt, which represented about 7.2% of the EU production. Although the EU and Italian economic crisis, the pulp and paper industry still plays a key role in the EU and Italian industry sector.

The pulp and paper industry is considered a high energy intensive one and, as a consequence, the competitiveness of the sector is strongly affected by the energy bills [35]. The used fuels depend on the location of the pulp and paper mills. For example, the Italian pulp and paper mills make use of natural gas (95%) and oil (5%) according to [36]. With regard to the energy consumptions, in 2019 the overall natural gas and electric energy consumptions of the pulp and paper sector in Italy were about 2.40 Gm^3 and 7.00 TWh respectively [37]. With reference to the energy production, 85 out of 153 [38] Italian pulp and paper mills have cogeneration plants and 50 of them have been analysed in detail in this study. In 2019, their overall natural gas and electricity consumptions were around 0.45 Gm^3 and 1.46 GWh, which correspond to almost 19% and 2.1% of the natural gas and electricity requirements, respectively, of the entire Italian pulp and paper industry. Particular attention has been paid to the CHP plants of the analysed paper mills, whose electric power capacity ranges between 1-105 MW, for a total amount of 613 MW that corresponds to about 13% of the overall electric power capacity installed in the pulp and paper sector in Italy. Hence, the considered paper mills constitute a representative sample of the Italian pulp and paper sector and the analysis provides reliable estimations on the further exploitation of the low-grade waste heat recovered from CHP systems.

3. DISTRICT HEATING POTENTIAL

District heating has a great potential in exploiting huge amounts of low temperature waste heat [39]. Currently, both 4th and 5th DH generations networks are based on inlet fluid temperatures lower than 70°C, which both makes the direct use of the low-grade waste heat possible and reduces the energy losses of DH networks [40].

In Europe, the residential sector accounts for almost 40% of the total energy consumption, thus having a significant impact on the overall CO_2 emissions [41]. In the rest of the World, despite the fact that such amounts may differ, the building sector has an important impact in the total energy consumption as well. Therefore, the use of DH networks in urban areas would contribute to mitigate the energy consumptions of the building sector and, at the same time, to reduce both installation and maintenance costs of traditional boilers and heating systems. In Italy, DH networks are installed in more than hundred city centers mainly located in the North. In particular, five regions (Lombardy, Piedmont, Veneto, Emilia Romagna and Trentino-South Tyrol) account for almost 95% of the build volume connected to DH networks in Italy. At present, DH networks extend for almost 4,600 km, where hot water is used as heat transfer fluid. According to [42], almost 292 Mm^3 of hot streams in Italy have been used in residential, tertiary and industrial sectors in 2019. In the same year, almost 11.5 TWh, which correspond to 726 kTOE, have been saved by means of the thermal energy supplied by DH networks, whose 66% has derived from CHP plants [43].

As regards DH networks, two different types can be distinguished: open and closed networks. In the former, the heat fluid transfer is extracted through hydraulic pumps and then discharged after the fluid has transferred its thermal energy content. Therefore, in this case the fluid is always renewed after completing a cycle. In the latter type of network, the heat transfer fluid is heated up and exchanges its thermal energy by means of adequate heat exchangers in a closed-loop circuit without being renewed [44]. Hence, the connection with the end users can be either direct or indirect. An intermediate configuration is sometimes adopted, where the main network is divided into different secondary circuits and the thermal energy is transferred by means of several heat exchangers. Despite their huge potential in curbing energy consumptions, present DH networks have some intrinsic criticalities: for instance, the heat demands of the connected end users can fluctuate during the day causing non optimal operating conditions of the generating system and the network. To this purpose, Gopalakrishnan et al. [45] proposed a Mixed-Integer Non-Linear Programming (MINLP) formulation to optimally schedule the system operation, while Gladysz et al. [46] presented a complex algorithm capable of selecting the optimal coefficient of the share of cogeneration in DH systems. Despite some improvements in the operation and control of CHP plants are still needed to enhance their energy efficiency when used in DH networks, it is expected that the cogeneration capacity will play a fundamental role in DH systems also in the next future as in the Croatian case [47]. This study aims at assessing the potential recovery of the unexploited low-grade waste heat from the exhausts of the CHP units in the pulp and paper sector. The recovery scheme is shown in Figure 1 and its potentiality is analysed considering 50 pulp and paper mills in Italy to be used as heat source for DH networks.

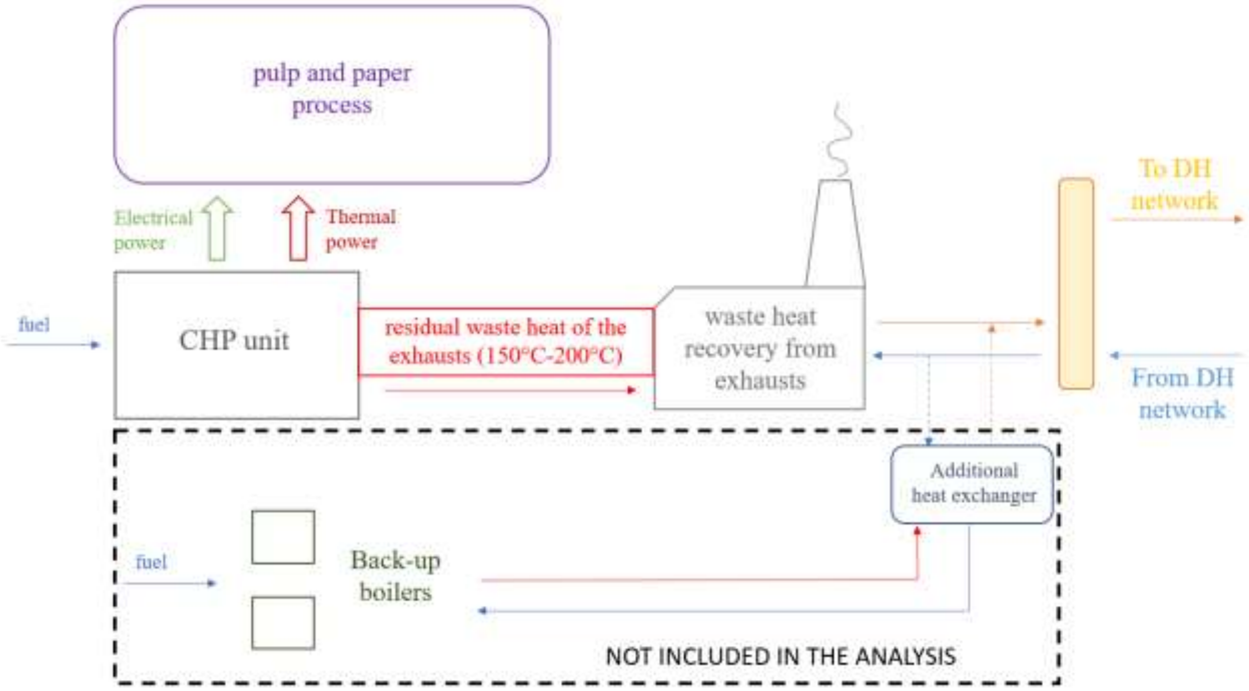

Figure 1: Scheme of the waste heat recovery from CHP plants for DH applications

4. METHODOLOGY

For the sake of the present analysis, the DH potential has been assessed according to the following procedure. Initially, the low-grade waste heat discharged by the CHP plant of each paper mill has been evaluated; hence, the heat available to the residential buildings by means of a DH network is calculated taking into account the related thermal losses of the network. Then, the overall amount of the heated floor area together with the maximum number of buildings connected to the DH network are assessed and, eventually, both energy and emissions savings in terms of TOE and tCO_2 have been evaluated considering the replacement of traditional residential boilers with DH networks.

4.1 Assessment of the thermal power available to end users

In order to evaluate the thermal power potentially available to the end users, the waste heat from a CHP plant ($P_{th,gross}$) has been calculated according to Eq. (1):

$$P_{th,gross} = P_{input,CHP} - (P_{e,CHP} + P_{th,CHP}) = P_{input,CHP} \cdot (1 - \eta_{e,CHP} - \eta_{th,CHP})\ [MW] \quad (1)$$

where $P_{e,CHP}$ and $P_{th,CHP}$ are the electric and thermal powers of the CHP unit, η_e and η_{th} are the electric and thermal efficiencies of the CHP unit, respectively, and $P_{input,CHP}$ is the input power to the CHP unit. However, since the exhausts from a CHP unit cannot be cooled down to the ambient temperature, only part of this waste heat can be usefully recovered. Precisely, the percentage of the recoverable waste heat to be supplied in the DH network has been calculated considering the following assumptions:

- the CHP unit operates at constant load throughout the winter season, which actually occurs in paper mills that have a strong duty cycle;
- an average temperature of the waste heat equal to 170°C $(T_{ex,CHP})$based on the data provided by the 50 paper mills and also according to the literature review [48];
- a transfer medium inlet temperature to the DH network of 100°C $(T_{DH,supplied})$ [48], conservatively considering the case of old generation networks;
- a temperature difference (ΔT) of the hot water between the inlet and the outlet sections of the heat exchanger equal to 10°C according to [48];
- a constant specific heat transfer capacity of the exhausts in the considered temperature range;
- no additional thermal power is introduced in the DH from either the papermaking process or the boilers.

With these hypotheses, the percentage of the low-grade WHR that can be effectively recovered corresponds to:

$$WHR = \frac{\dot{m}_{exs} \cdot c_{p,exs} \cdot [T_{ex,CHP} - (T_{DH,supplied} + \Delta T)]}{\dot{m}_{exs} \cdot c_{p,exs} \cdot (T_{ex,CHP} - T_{amb})} = \frac{T_{ex,CHP} - (T_{DH,supplied} + \Delta T)}{T_{ex,CHP} - T_{amb}} \ [\%] \qquad (2)$$

where, $\dot{m}_{exs}$ and $c_{p,exs}$ are the mass flow rate and the specific heat transfer capacity of the exhausts and T_{amb} is the mean winter temperature of the locations where the paper mills are located, which ranges between 5.9°C and 14.2°C in the considered case. The numerator of Eq. (2) stands for the thermal power recoverable from the exhausts and to be used in DH networks, whereas the denominator of the same equation represents the thermal power related to 100% of WHR from the exhausts. Since both numerator and denominator multiply the same amount of exhausts mass flow rate and the specific heat transfer capacity of the exhausts is constant, Eq. (2) can be written as the ratio between two temperature differences. Hence, the amount of the recovered thermal power from a CHP unit is equal to:

$$P_{th,net} = P_{th,gross} \cdot WHR \ [MW] \qquad (3)$$

The thermal power available to the end users ($P_{th,end\,users}$) has been obtained by subtracting the related thermal losses of the DH network and of the heat exchangers to the $P_{th,net}$ previously calculated. In particular, in this study the heat losses along the DH network and those in the heat exchangers have been accounted equal to 6.5% and 3.5% of the overall available thermal power, respectively, according to [49]. Hence, the $P_{th,end\,users}$ corresponds to:

$$P_{th,end\,users} = P_{th,net} - L_{th} = \ 90\%\, P_{th,net}\ [MW] \qquad (4)$$

As regards the maximum length of the DH network, it has been calculated through Eq. (5), considering a linear heat loss along the pipes ($L_{l,DH}$) of 0.203 kW/km as reported in [48]:

$$Le_{DH} = \frac{P_{th,end\,users}}{L_{l,DH}}\ [km] \qquad (5)$$

Eventually, the thermal energy available to the end users $\left(\mathrm{E_{th,end\,users}}\right)$ is calculated as the product of the thermal power available to the end users and the number of heating hours in the winter season (h_{hs}), which in Italy is defined by the national legislation [50]. For sake of conciseness, data related to 4 out of 50 paper mills investigated in this study, which refer to four different CHP technologies having the highest electric power per each category, are presented hereinafter.

Table 1: Percentage of WHR, $P_{th,net}$ [MW], Le_{DH} [km] and $E_{th,end\ users}$ [MWh] (4 out of 50)

# paper mill	**CHP technology**	**P_e [MW]**	**η_e [-]**	**P_{input} [MW]**	**η_{th} [-]**	**WHR [%]**	**$P_{th,net}$ [MW]**	**η [-]**	**T_{amb} [°C]**	**$P_{th,end\ users}$ [MW]**	**$L_{th,DH}$ [MW]**	**Le_{DH} [km]**	**h_{hs} [h]**	**$E_{th,end\ users}$ [MWh]**
1	Gas turbine	9.2	0.33	27.88	0.44	37.5	2.41	0.86	10.1	2.17	0.24	7.7	2,548	5,517.55
2	Internal Combustion Engine	6.6	0.43	15.49	0.42	37.3	0.87	0.91	9.2	0.78	0.09	2.8	2,548	1,987.41
3	Steam turbine	10.0	0.16	62.50	0.62	36.6	5.03	0.86	9.9	4.52	0.51	15.5	3,582	16,203.017
4	Combined cycle	96.0	0.44	218.18	0.36	37.4	16.32	0.87	9.6	14.69	1.63	52.0	2,548	37,424.85

4.2 Assessment of the overall heated floor area served by District Heating network

The yearly thermal energy demand of a building for heating is usually expressed by the "winter Energy Performance Index" (EPI) [kWh/m^{2}year]. In the present work, this parameter has been used to evaluate the average floor area that can be served by the DH network. In particular, the specific energy consumption has been calculated according to the European Directive on buildings energy performance [51]. For each place where the paper mills are located, the following parameters have been considered i) the average floor area $(A_{floor,avg})$ of a residential building according to the data reported in the last census of the National Statistics [52] and (ii) the Heating Degree Days (HDD) which quantify how cold a location is. The average floor area of a residential building times the minimum height of a residential apartment (h_{bldng}), which is equal to 2.7 m according to [53], leads to the net volume of a building. The gross volume of a building, instead, has been calculated by adding to the net volume its 30% according to the standard UNI 10379/2005. On the other hand, the overall surface of the residential building has been calculated through Eq. (6), according to [54]:

$$A_{bldng,ovrll} = 2 \cdot \left(\frac{A_{floor,avg} \cdot h_{bldng}}{10} + 10 \cdot h_{bldng} + A_{floor,avg}\right) \tag{6}$$

Hence, the shape factor of a building (S/V), which is the ratio between the overall surface of a building and its gross volume, has been evaluated and subsequently the main climatic characteristics of the buildings, based on the HDD and S/V values, have been calculated according to [50]. In particular, the EEC of a building ranges from A (the most performing) to G (the less performing) [54]. Finally, the EPI$_{\text{lim}}$, being a function of HDD, S/V and the main climatic characteristics of the buildings, was obtained for each climatic zone as reported in [50]. Once the EPI$_{\text{lim}}$ has been obtained, the corresponding EPI of each EEC of the buildings has been evaluated by multiplying the EPI$_{\text{lim}}$ with the respective coefficients reported in [54]. For further details on this methodology, interested readers are invited to see the norm UNI/TS 11300. Table 2 reports the values of these parameters for the locations where the 4 paper mills reported in Table 1 are placed.

Table 2: HDD, S/V [1/m], $A_{floor,avg}$ [m^2], EPI_{lim} and the EPI [kWh/m^{2}year] per each building EEC (4 out of 50)

# paper mill	**HDD [-]**	**S/V [1/m]**	**$A_{floor,avg}$ [m^2]**	**EPI_{lim} [kWh/m^{2}year]**	**EPI [kWh/m^{2}year] for each EEC of the buildings**						
					A	B	C	D	E	F	G
1	2,892	0.88	96	111	41	70	97	125	166	236	277
2	2,234	0.88	80	92	35	60	83	107	142	202	238
3	3,071	0.86	101	114	42	72	100	129	172	243	286
4	2,936	0.88	97	112	41	70	97	126	167	237	279

Then, the share of the different energy efficiency classes of the buildings has been calculated in terms of the overall average floor area per each location. More precisely, starting from the data made available by the Italian census for the year 2019, the buildings percentage for each EEC has been evaluated taking into account the construction year of the buildings [52] with the related envelops and typologies [55] in order to obtain an overall EPI equal to the national average, which corresponds to 157 kWh/m^{2}year [51]. It is worth noting that the buildings percentage for each EEC was considered the same for all the locations where the analysed paper mills are located. The total floor area of each building EEC has been calculated by dividing the thermal energy available to the end users with the EPI of each building EEC reported in Table 2, while the total average floor area has been assessed by taking into account the percentage previously obtained. Eventually, the ratio between the thermal energy available to the end users and the total average floor area gives the EPI_{lim}. Table 3 sums up the results obtained for the location of the 4 paper mills considered so far.

Table 3: Total $A_{floor,avg}$ [m^2] and EPI_{lim} [kWh/m^{2}year] per each location (4 out of 50)

# paper mill	**$A_{floor,avg}$ [m^2] for each EEC of the buildings**							**Total $A_{floor,avg}$ [m^2]**	**EPI_{lim} [kWh/m^{2}year]**
	A	**B**	**C**	**D**	**E**	**F**	**G**		
	2%	2%	3%	7%	8%	40%	38%		
1	139,798	82,104	59,115	45,978	34,484	24,341	20,690	29,787	192
2	61,576	36,163	26,038	20,252	15,189	10,721	9,113	13,120	157
3	397,462	233,430	168,070	130,721	98,041	69,205	58,824	84,689	199
4	941,633	553,023	398,176	309,692	232,270	163,955	139,362	200,638	194

4.3 Maximum thermal energy available to end users

Independently from the EEC of the building, the maximum thermal power required by a building was calculated through Eq. (7):

$$P_{th,max} = \frac{(C_d + C_v) \cdot V \cdot (T_{indoor} - T_{min})}{1{,}000} \ [MW] \tag{7}$$

where C_d and C_v are the thermal powers per unit volume and degree temperature dispersed by transmission and required to heat the exchanged air respectively, calculated according to the standard UNI 7357/1974, T_{min} is the minimum outdoor temperature defined by [56], while T_{indoor} is the internal comfort temperature of a residential apartment assumed equal to 20°C during the heating season as imposed by the Italian legislation [57]. Hence, the maximum number of residential buildings connected to the DH network has been obtained by dividing the thermal power available to the end users by the maximum thermal power required by a building as in Eq. (8):

$$N_{bldng} = \frac{P_{th,end\ users}}{P_{th,max}} \tag{8}$$

Eventually, the maximum thermal energy required by a building is obtained as the product of the maximum thermal power required by the building and the related heating hours during the winter season. Table 4 reports a summary of these calculations.

Table 4: $P_{th,max}$ [kW], N_{bldng} and $E_{th,max}$ [MWh] required by a residential building

# paper mill	**C_d [kW/m^{3}K]**	**C_v [kW/m^{3}K]**	**T_{min} [°C]**	**T_{indoor} [°C]**	**$P_{th,max}$ [kW]**	**N_{bldng}**	**h_{hs} [h]**	**$E_{th,max}$ [MWh]**
1	0.00072	0.00017	0	20	6.13	306	2,548	15.63
2	0.00076	0.00017	0	20	6.38	106	2,548	16.27
3	0.00070	0.00017	-10	20	10.17	385	2,548	36.43
4	0.00072	0.00017	-5	20	7.91	1,607	3,582	20.16

However, in practice it is quite rare that all the connected end users need the maximum thermal power simultaneously. On the contrary, the average thermal power required by the end users is usually lower than the sum of the maximum thermal powers of each building. Hence, the average heated floor area with a simultaneity factor of 100% has been calculated as follows:

$$A_{floor,avg\ h} = A_{floor,avg} \cdot N_{bldng} \tag{9}$$

and then the effective simultaneity factor has been assessed as the ratio between the average heated floor area with a simultaneity factor of 100%, calculated according to Eq. (9), and the average floor area connected to the DH network [58], as reported in Table 3. These values are summarised in Table 5.

Table 5: $A_{floor,avg\ h}$ [m^2] and the simultaneity factor

# paper mill	**A_{floor,avg_h} [m^2]**	**Simultaneity factor [-]**
1	29,859	1.00
2	10,335	0.79
3	42,591	0.50
4	163,131	0.81

4.4 Primary energy saving (PES)

According to [59], cogeneration stands for the simultaneous production of both electrical and thermal energies, where the latter is considered as a useful effect. Since cogeneration leads benefits from both energy and environmental points of view, the dimensionless index PES is used to quantify the amount of primary energy saved by the simultaneous production. In particular, the PES is calculated through Eq. (10), where both the electric $(\eta_{e,CHP})$ and the thermal $(\eta_{th,CHP})$ efficiencies of the CHP unit are divided by the reference electric $(\eta_{e,ref})$ and thermal $(\eta_{th,ref})$ efficiencies related to power plants and industrial boilers, respectively [59].

$$PES = 1 - \frac{1}{\frac{\eta_{e,CHP}}{\eta_{e,ref}} + \frac{\eta_{th,CHP}}{\eta_{th,ref}}} \tag{10}$$

It is worth noting that Eq. (10) takes into account both input and output energies of a CHP unit; in particular, the input primary energy is evaluated through Eq. (11), while the output electric and thermal ones are calculated through of Eqs. (12) and (13), respectively.

$$E_{input,CHP} = m_{fuel,CHP} \cdot LHV_{fuel} \tag{11}$$

$$E_{e,CHP} = \eta_{e,CHP} \cdot E_{input,CHP} \tag{12}$$

$$E_{th,CHP} = \eta_{th,CHP} \cdot E_{input,CHP} \tag{13}$$

Along the same line, the electric and thermal energies obtained through separate technologies are calculated through of Eqs. (14) and (15), similarly to Eqs. (12) and (13), respectively. In this case, the only variance is that different amounts of primary energy inputs are considered, based on the same reference electric and thermal efficiencies.

$$E_e = \eta_{e,ref} \cdot E_{input} \tag{14}$$

$$E_{th} = \eta_{th,ref} \cdot E_{input} \tag{15}$$

Generally, a CHP unit has a PES higher than zero: if this occurs for a micro or small-scale power plant, the unit is considered a high efficiency cogeneration system. In case of large scale (>1MW), instead, in order to be considered a high efficiency cogeneration system the CHP must have a PES higher than 0.1 [60].

5. RESULTS AND COMMENTS

This section reports the energy and the environmental benefits of the proposed low-grade WHR application taking into account all the 50 Italian paper mills investigated in this work.

5.1 Energy and environmental advantages of CHP units

Independently from the WHR application considered in this analysis, cogeneration is usually able to provide energy and environmental benefits compared to the separate production of the same amount of thermal and electrical energies. Table 6 lists the data related to the use of the CHP units installed in the 50 Italian paper mills for producing electricity and thermal energies simultaneously and their separate production (boilers) without considering the advantages of the low grade WHR. It is worth noting that average electric (η_{e,CHP_avg}) and thermal (η_{th,CHP_avg}) efficiencies of the CHP units analysed in this work are equal to 0.31 and 0.45 respectively, while the reference electric and thermal efficiencies are 0.46 and 0.9 respectively according to [61]. Despite the lower values of the average electric and thermal efficiencies of the CHP units compared to the reference ones, the use of cogeneration allows reducing the fuel consumption significantly. Indeed, the yearly natural gas saving is equal to 175,322.42 km^3 per year, which means avoided 143.76 kTOE or 333.11 $ktCO_2$. As regards the PES, an average value of 0.14 is obtained, highlighting that the energy efficiency target is achieved by the considered cogeneration plants also in case the low-grade heat is wasted.

Table 6: Advantages on the use of cogeneration with respect to the separate production (boilers)

Technology	Natural gas consumption [km^3]	Tonnes of Oil Equivalent [kTOE]	Tonnes of CO_2 [ktCO_2]
CHP units	452,739.43	371.25	860.21
Separate production (boilers)	628,061.85	515.01	1,193.32
CHP vs separate production	-27.91%		

In case of WHR, an additional amount of 308.45 GWht is still available to the end users for DH applications. More precisely, such value has been calculated considering that the heating hours of the winter season range between 1,360 h and 3,582 h in the areas where the paper mills are located. In particular, this amount corresponds to about 7.1% and 16.2% of the overall input and output thermal energies of the CHP units, respectively. Considering the use of conventional boilers with a $\eta_{th,ref}$ of 0.9 [61], it also corresponds to a natural gas consumption of 35,924.51 km^3 or, in other terms, to avoided 29.46 kTOE or 68.26 ktCO_2. Therefore, in case of WHR, the thermal efficiency of the CHP units increases from an average value of 0.45 up to about 0.54, thus resulting in an increase of the PES from 0.14 up to 0.22 that is a very remarkable value. Table 7 highlights the relevance of the waste heat from the CHP plants with respect to the separate production through conventional gas boilers. It is worth noting that the thermal energy E_{th} [MWh] of the separate production takes into account the heat required by both the papermaking process and the end users of the DH networks.

Table 7: Energy consumptions of separate production and cogeneration in case of WHR

Technology	E_{input} [GWh]	E_{th} [GWh]	WHR [GWh]
CHP units	4,319.13	1,898.47	308.45
Separate production (boilers)	5,629.91	2,211.13	0.00

5.2 Sensibility analysis on the profitability of using District Heating (DH) networks

Despite the thermal energy deriving from the low-grade waste heat as evaluated in Subsection 5.1 is significant, the convenience of DH cannot be easily determined a priori since new infrastructures are required in most of the cases. Based on Eq. (5), the overall maximum length of DH networks that would be required in this case study is approximately 470 km, ranging from 1.5 to 56.9 km for the considered paper mills and thus entailing significant economic investments that do not always lead to a favourable economic return of the DH application.

However, in order to better assess the profitability of the DH, two different analyses have been carried out as follows. Firstly, the paper mills have been sorted by technology, namely gas turbine, combined cycle, steam turbine and Internal Combustion Engine (ICE). Since for a given technology both the electric and the thermal efficiencies vary with its size, feasible ranges have been considered for each technology previously mentioned. It is worth noting that the CHP unit having a rated electric power lower than 1 MW has not been considered due to the limited available waste heat; hence, the number of the analysed paper mills has been reduced to 49. Table 8 reports the ranges of the input thermal power, the output electric and thermal powers and the electric and thermal efficiencies, related to the CHP units of the 49 paper mills without considering the recovery of the low-grade waste heat. Furthermore, also the range of the PES values is reported.

Table 8: Main performance of the paper mills analysed in this study sorted by technology

Technology	**#/49**	$\eta_{e,CHP}$	$\eta_{th,CHP}$	$P_{input,CHP}\ [MW]$	$P_{e,CHP}\ [MW]$	$P_{th,CHP}\ [MW]$	**PES [-]**	**PES$_{avg}$ [-]**
Gas turbine	26	0.30 - 0.33	0.40 - 0.46	12.67 - 27.88	3.80 - 9.20	5.07 - 12.27	0.09 - 0.17	0.130
Combined cycle	17	0.24 - 0.44	0.36 - 0.55	18.13 - 236.36	4.35 - 104.00	7.98 - 85.09	0.01 - 0.26	0.135
Steam turbine	3	0.12 - 0.16	0.62 - 0.64	16.67 - 62.50	2.00 - 10.00	10.67 - 38.75	-0.03 - 0.04	0.005
ICE	3	0.43 - 0.44	0.42 - 0.44	4.88 - 15.49	2.15 - 6.66	2.15 – 6.51	0.29 - 0.31	0.300

As regards the PES, the CHP units based on steam turbine technology show the lowest values. Moreover, in some cases PES values lower than zero have been recorded which confirms that in light of the natural gas and electricity prices the use of a CHP unit may be economically convenient also when the primary energy consumption is higher than that of the separate production. Table 9, instead, presents the natural gas consumptions and the related savings, sorted by CHP technology, in the absence of WHR and in case of WHR for DH applications.

Table 9: Natural gas consumption and saving without and with WHR sorted by CHP technology

CHP technology \ Consumption & Saving	**Natural gas consumption in case of separate production [km^3]**	**Natural gas consumption by CHP [km^3]**	**Natural gas saving by CHP without WHR [km^3]**	**Natural gas saving by CHP in case of WHR [km^3]**
Gas turbine	153,641.62	116,801.88	36,839.73	10,907.44
Combined cycle	424,244.94	295,349.22	128,895.73	21,978.25
Steam turbine	39,025.75	33,411.95	5,613.80	2,667.19
ICE	11,149.54	7,176.38	3,973.16	371.63
TOTAL	628,061.85	452,739.43	175,322.42	35,924.51

As it can be clearly noticed, the natural gas savings obtained by the combined cycle cogeneration units are much higher than those of the other technologies. However, data presented in Table 9 strictly depend on the number and the capacity of the cogeneration plants in each category and do not clearly provide any significant insight into the benefits of the WHR with respect to the kind of the CHP technology.

Therefore, to this aim, together with the PES also the Specific Fuel Saving (SFS) [m^3/kW], as expressed in Eq. (16), is considered:

$$SFS = \frac{V_{NG,WHR}}{P_{input}} \tag{16}$$

where $V_{NG,WHR}$ is the natural gas saving by CHP in case of WHR and P_{input} the thermal power input to the related CHP unit. Hence, based on these two indexes, useful considerations can be drawn according to Figures 2 and 3.

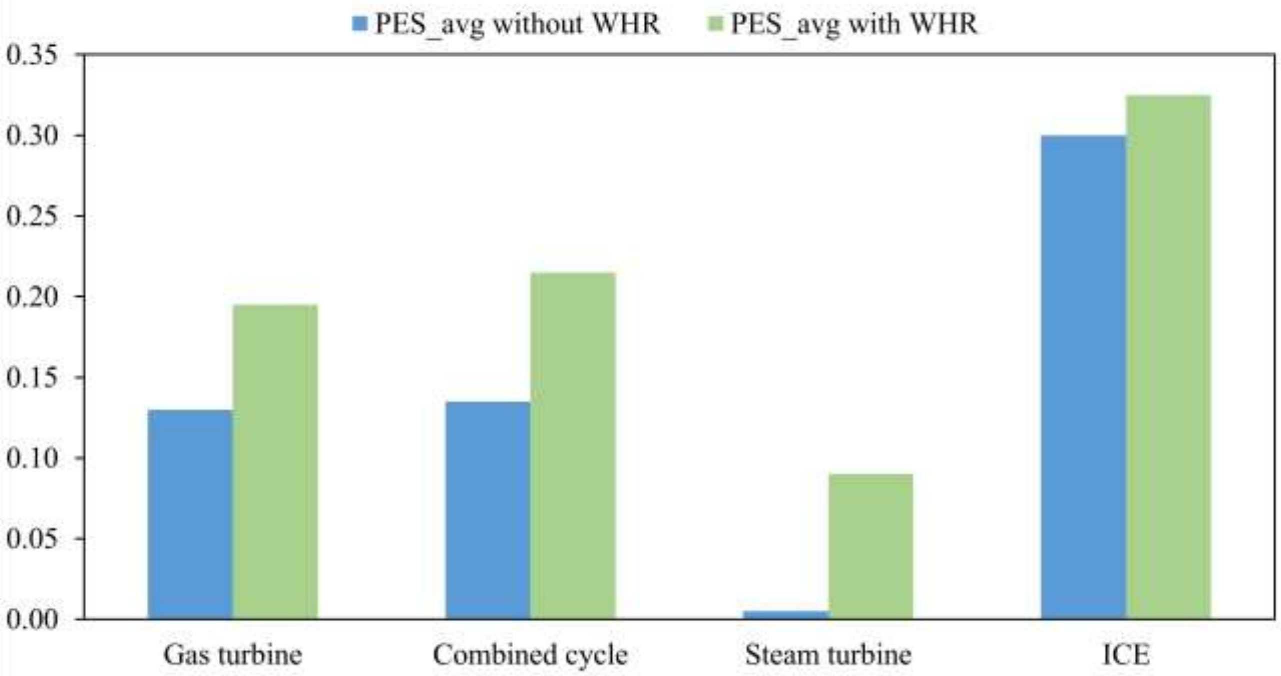

Figure 2: Comparison between PES_{avg} obtained without and with WHR

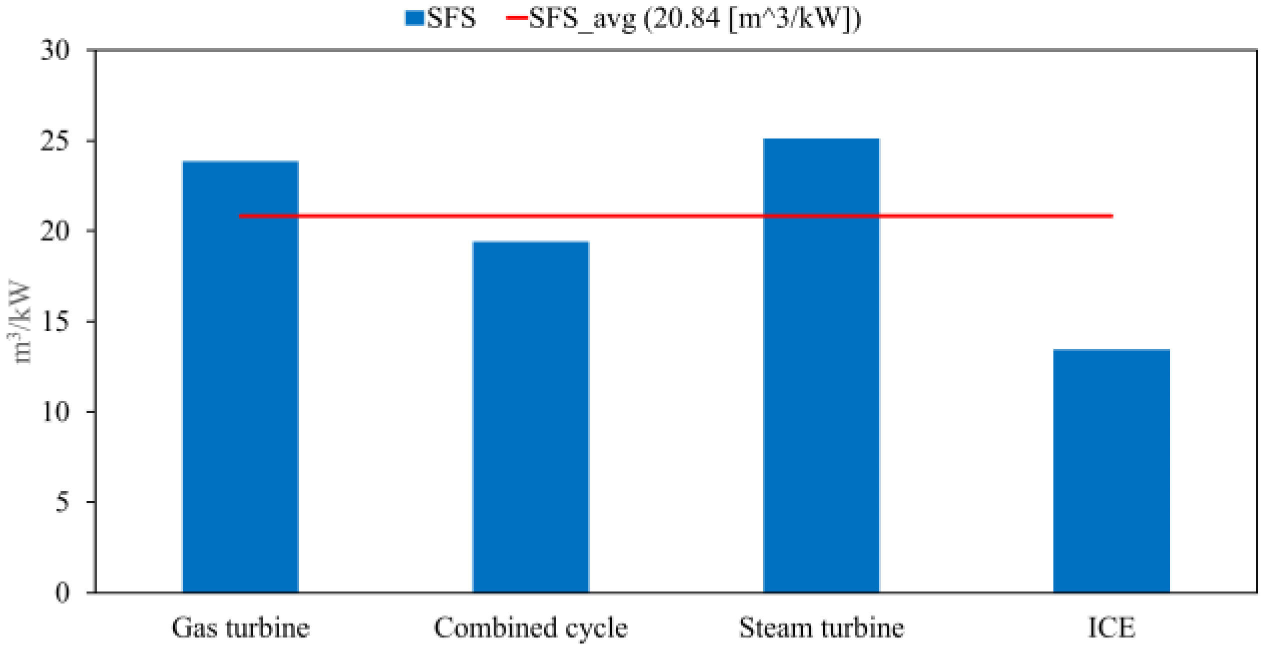

Figure 3: SFS values sorted by CHP technologies

With reference to Figure 2, the exploitation of the low-grade heat from the CHP units leads to positive values of the PES in all the analysed cogeneration plants. More precisely, ICEs show the lowest improvement of the PES, although yet the highest; in case of steam turbines, instead, the average PES increases from 0.005 to almost 0.1. As a consequence, WHR has the largest impact in case of steam turbine CHP units. This trend is confirmed also when the SFS is considered. Indeed, according to Figure 3, steam turbine CHP units have the highest SFS of about 25.15 m^3/kW in case of WHR, followed by gas turbines units that have a SFS of 23.85 m^3/kW. These values are 20.6% and 14.4% higher than the average SFS by all the analysed cogeneration plants (about 20.84 m^3/kW), respectively. On the contrary, the SFS is limited in case of the ICE technology (equal to about 13.46 m^3/kW) that could lead to unprofitable results of WHR application.

Afterwards, only the paper mills located in the areas with HDD higher than 2,000 have been considered. This threshold value has been selected since it corresponds to the HDD of a mid-town located in the Centre of Italy, where a DH network already exists and for which some of the authors of the present paper have already evaluated both the energy and the economic benefits [19], finding out that lower values of HDD may not be sufficient for achieving the overall sustainability of the project. Therefore, according to this criterion, 31 out of 49 paper mills have been considered. All these paper mills are located in Central and Northern Italy, where both autumn and winter seasons are colder. In particular, the benefit of the WHR for DH application has been also analysed with reference to three different ranges of the HDD, as reported in Table 10. Among the 31 paper mills, 20 of them are located in areas with HDD in the range 2,000-2,500, 7 in areas with HDD of 2,500-3,000 and eventually 4 in areas with HDD higher than 3,000.

Table 10: Natural gas consumption and saving of 31 paper mills without and with WHR sorted by HDD range

HDD range \ Consumption & Savings	**Natural gas consumption in case of separate production [km^3]**	**Natural gas consumption by CHP [km^3]**	**Natural gas saving by CHP without WHR [km^3]**	**Natural gas saving in case of WHR [km^3]**
2,000-2,500	242,283.96	174,776.95	67,507.01	14,083.61
2,500-3,000	132,837.54	91,929.37	40,908.17	7,015.54
>3,000	69,464.57	55,246.91	14,217.66	4,355.55
TOTAL	444,586.07	321,953.23	122,632.84	25,454.70

The total amount of the natural gas yearly consumed by the CHP units of the selected 31 paper mills is equal to 321,953.23 km^3, which corresponds to 71.11% of the natural gas consumed yearly by the CHP units of all the 50 paper mills. Considering the related low-grade waste heat, 224.64 GWh of heat is available to the end users of the DH networks, which corresponds to 7% and 15.8% of the input and output thermal energies respectively of the 31 out of 49 CHP units. In case the same amount of thermal energy is produced by conventional boilers, a consumption of about 25,454.70 km^3 of natural gas is required. In other terms, this natural gas saving corresponds to 20.87 kTOE and 49.56 $ktCO_2$ of avoided emissions. Hence, this last analysis has shown that a noticeable increase in the use of the low-grade waste heat from CHP units can be obtained by those plants located in areas with high HDD values, granting a better exploitation of the recovered heat.

To better appreciate the impact of the location on the potential saving, the SFS of the 31 paper mills are reported in Figure 4 sorted by the HDD range.

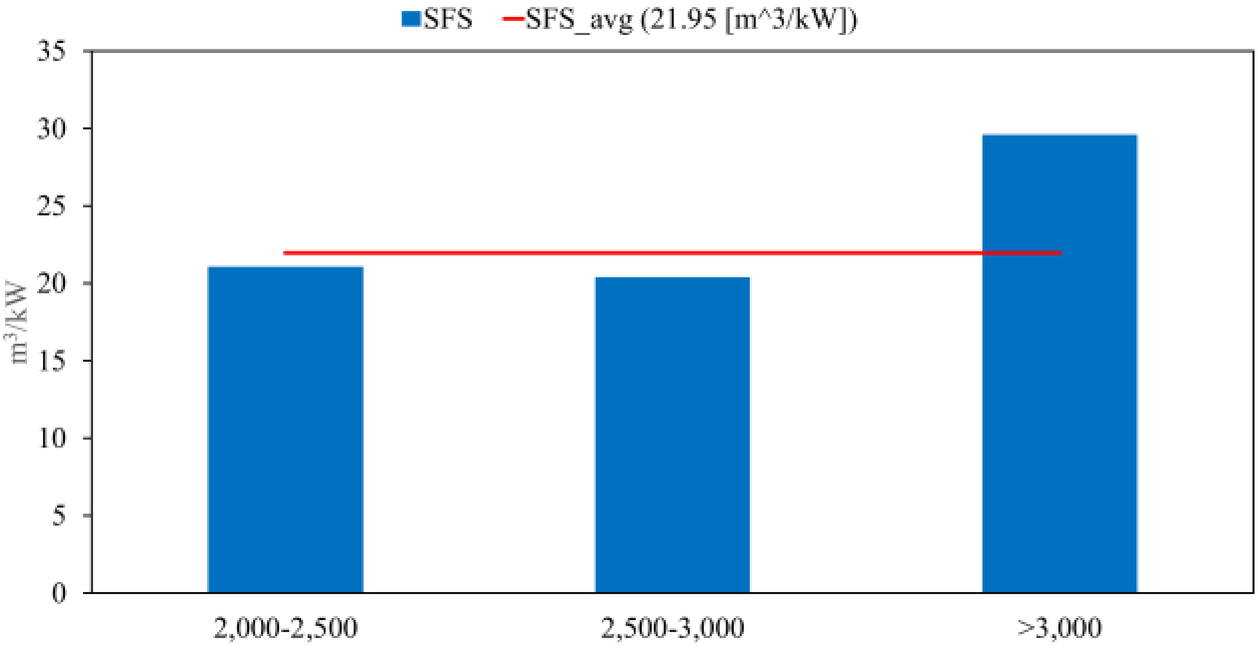

Figure 4: SFS values sorted by HDD ranges

As expected, the SFS due to WHR application increases with HDD. In particular, a SFS value of 29.60 m^3/kW is obtained in case of HDD>3,000 which is 34.86% higher than the average SFS. With respect to the values reported in Figure 4, it is worth to noticing that the obtained average value of the SFS by the CHP units located in areas with HDD in the range 2,500-3,000 is lower than that of the CHP units located in areas with HDD in the range 2,000-2,500, because in the former most of the capacity is constituted by combined cycle power plants that exhibit a lower SFS than steam turbines and gas turbines plants, as reported in Figure 3.

6. CONCLUSIONS

Among the different energy intensive industries, the pulp and paper sector requires a significant amount of process-energy, which accounts for almost half of the overall cost of the production. In pulp and paper mills, cogeneration plants are usually present and, despite positive PES values, the low temperature heat of the exhausts from these plants could be further recovered for other applications.

In this work, the potential of the low-grade waste heat from the CHP units of 50 different Italian paper mills, representing almost 60% of the overall Italian pulp and paper mills having cogeneration plants, for DH application has been evaluated by means of an ad-hoc methodology.

In general, the considered CHP units have an average PES of 0.14 which increases up to 0.22 if low-grade WHR is applied. In this regard, about 308 GWht would be available to end users of DH networks connected to the 50 paper mills considered in this analysis which corresponds to 35,924.51 km^3 of natural gas consumption if conventional boilers were used.

A further analysis, based on the values of the HDD of the locations where the paper mills are placed, has shown that 31 out 49 paper mills are located in areas having HDD equal or higher than 2,000 for which the profitability of DH is proven. These 31 paper mills have a natural gas consumption of 321,953.23 km^3 and, in case of WHR for DH, about 224.64 GWht would be available to the end users corresponding to a natural gas saving of 25,454.70 km^3. Obviously, WHR increases the PES of all the CHP technologies and, in case of steam turbine technology, the benefit is remarkable moving from 0 to about 0.1, which means that also such plants could take advantage of the incentives offered by the Italian legislation for the high efficiency cogeneration systems. In other terms, the steam turbine CHP units exhibit the highest values of SFS equal to 25.15 m^3/kW in case of WHR application. Eventually, the average SFS is 29.60 m^3/kW if paper mills located in areas with HDD>3,000 are considered.

Hence, the proposed methodology has allowed i) to assess the potential of low-grade waste heat recovery from cogeneration plants of energy intensive industries for DH application and ii) to preliminary evaluate the number of end users to be connected to the DH network and the corresponding energy and environmental savings. For example, by roughly extending the proposed methodology to all the 85 Italian pulp and paper mills having CHP units, about 62,320 km^3 of natural gas savings could be achieved connecting about 26,037 buildings to the DH networks. Furthermore, the present analysis could be easily extended to many other energy intensive industries having cogeneration plants thus obtaining a first estimation of their potential in curbing overall CO_2 emissions of the residential sector and supporting the implementation of low carbon districts.

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