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District heating potential in the case of low-grade waste heat recovery from energy intensive industries

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# 2 **District Heating potential in the case of low-grade Waste Heat**

## 3 **Recovery from energy intensive industries**

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### 18 **ABSTRACT**

19 Waste Heat Recovery (WHR) from energy intensive industries has a great potential in curbing CO<sub>2</sub>  
20 emissions. Among the different solutions, District Heating (DH) is considered of major interest,  
21 satisfying the heating demand of users in the proximity of power plants. Considering the energy  
22 intensity of the pulp and paper industry, a methodology for evaluating the recovery potential of its  
23 low-grade waste heat from cogeneration plants in DH is presented. The proposed methodology allows  
24 to evaluate the thermal power by cogeneration plants to end users and to assess the potential maximum  
25 number of residential buildings that could be connected to each DH network. Based on the proposed  
26 methodology, the benefits of the WHR are evaluated from both energy and environmental points of  
27 view. More precisely, considering 50 pulp and paper mills in Italy under investigation in the present  
28 analysis, a yearly natural gas saving corresponding to 143.76 kTonnes of Oil Equivalent (TOE) and  
29 333.11 ktCO<sub>2</sub> is obtained. In case of WHR, the average Primary Energy Saving (PES) of the  
30 cogeneration plants increases from 0.14 up to 0.22. In particular, cogeneration units based on steam  
31 turbine technology show the greatest improvement, since its average PES moved from 0 up to almost  
32 0.1.

### 33 **KEYWORDS**

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

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### 37 **NOMENCLATURE**

38  $A_{floor,avg}$  = Average floor area of a building [m<sup>2</sup>]

39  $A_{floor,avg-h}$  = Average heated floor area of a building [m<sup>2</sup>]

40  $A_{bldng,ovrll}$  = Overall surface of a building [m<sup>2</sup>]

41  $C_d$  = Thermal power lost by transmission per unit volume and degree temperature [kW/m<sup>3</sup>K]

42  $C_v$  = Thermal power required to heat the exchanged air per unit volume and degree temperature [kW/m<sup>3</sup>K]

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

58  $V_{NG,WHR}$  = Volume of natural gas saved through Waste Heat Recovery [m<sup>3</sup>]

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

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

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

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

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

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

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

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

67 [MW]

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

69  $\Delta T$  = Temperature difference of the hot water between the inlet and the outlet sections of a heat

70 exchanger [°C]

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

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

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

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

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

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

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

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

79  $\eta_{CHP}$  = Total efficiency of the cogeneration unit [-]

80  $\eta_{e,CHP\_avg}$  = Average electric efficiency of the cogeneration units considering the 50 Italian paper

81 mills [-]

82  $\eta_{th,CHP\_avg}$  = Average thermal efficiency of the cogeneration units considering the 50 Italian paper

83 mills [-]

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

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

86

87 *Acronyms*

88 CHP = Combined Heat and Power

89 DH = District Heating

90 DHT = Direct Heat Transfer

91 EEC = Energy Efficiency Class

92 EPI = Energy Performance Index

93 HDD = Heating Degree Days

94 HEN = Heat Energy Network

- 95 HRES = Hybrid Renewable Energy Systems  
96 ICE = Internal Combustion Engine  
97 LNG = Liquid Natural Gas  
98 ORC = Organic Rankine Cycle  
99 PES = Primary Energy Saving  
100 SFS = Specific Fuel Saving [ $\text{m}^3/\text{kW}$ ]  
101 WHR = Waste Heat Recovery  
102  $LHV_{fuel}$  = Lower Heating Value of the fuel [ $\text{kWh}/\text{kg}$ ]

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## 126 **1. INTRODUCTION**

127 Climate change effects are affecting more and more both the environment and human beings, despite  
128 several measures have been taken so far to contrast them. Emissions of CO<sub>2</sub>, which is the main  
129 greenhouse gas produced by human activities, need to be reduced in order to mitigate the increasing  
130 global warming. As reported in [1], CO<sub>2</sub> emissions flattened in 2018 and 2019 at around 33 Gt; in  
131 2019, advanced economies lowered the CO<sub>2</sub> production from the power sector of about 3.5% with  
132 respect to 2018 due to the expanding role of renewables [2]. According to Brandoni et al. [3], a  
133 reduction of almost 58% on CO<sub>2</sub> emissions has to be achieved by 2050 to prevent the global  
134 temperature rise beyond the threshold of 3°C. To this aim, the use of Hybrid Renewable Energy  
135 Systems (HRESs), which consist of multiple renewable-based energy conversion technologies  
136 usually combined with storage systems to provide a more reliable power supply, is considered a  
137 suitable pathway to have self-sufficient districts for both electric and thermal demand, thus making  
138 cities efficient, carbon-neutral and climate-resilient [4, 5]. Therefore, the application of these systems  
139 leads to the so-called modern energy districts, where the local energy production matches the local  
140 demand required by residential buildings and industrial activities. Besides the use of HRESs, also  
141 energy efficiency measures would give an important contribution to this goal.

142 Among the different solutions to improve the overall energy efficiency of the industrial sector,  
143 cogeneration, which is the simultaneous production of electricity and heat where the latter is  
144 considered as a useful effect, has a huge potential [6, 7]. The technologies to be used for power  
145 generation, energy recovery and distribution depend on many factors, such as the amount of electric  
146 and thermal energy demands as well as the related temperatures required by the end users [8-10]. The  
147 operation of cogeneration units is widely analysed in literature, but at present, even in presence of  
148 energy recovery solutions, there are still several energy intensive industries worldwide wasting  
149 significant amounts of low-grade heat downstream their processes [11, 12]. Such waste heat could be  
150 recovered, at least partially, for further electric power generation and/or thermal power applications  
151 [13], thus playing a key role in curbing CO<sub>2</sub> emissions in modern energy districts [14]. Industrial  
152 sectors such as petrochemical, food-processing, textile, pulp and paper, marine transportation and  
153 Liquid Natural Gas (LNG) supply have the highest potential for low-grade waste heat recovery. In  
154 this regard, the pulp and paper sector is characterised by a large amount of raw materials and high  
155 energy consumption that account for almost half of the paper mill costs [15]. Precisely, the sector is  
156 the fourth-largest energy intensive industry worldwide consuming about 6% of the global industrial  
157 energy [16]. Despite the energy intensity of the sector has been reduced in the last decade thanks to  
158 several energy efficiency improvements on both papermaking processes and equipment (fans, pumps,

159 motors and air compressors), the power generation and distribution systems still have some  
160 operational inefficiencies [17]. For instance, Marshman et al. [18] have investigated the energy  
161 management of a steam turbine cogeneration unit having the two-fold goal of supplying heat to the  
162 pulping process and generating electricity, whose surplus is sold to providers nearby. More precisely,  
163 the authors of this paper have developed an optimization algorithm that took into account several  
164 aspects, including the electricity price fluctuation, to improve the energy efficiency of the analysed  
165 pulp mill. In the past, instead, some of the authors of the present paper [19] presented a survey on the  
166 state-of-the-art of the Combined Heat and Power (CHP) plants installed in the Italian pulp and paper  
167 industries from 1986 to 2010. Results showed that nearly all the considered plants (61 in total) worked  
168 with a positive PES index, meaning that they were using less primary energy compared to the separate  
169 production of both electric and thermal energy. Nevertheless, the authors found out that benefits for  
170 the competitiveness of the sector could be achieved through further recovering the excess thermal  
171 energy. Hence, the pulp and paper sector has high potential in curbing energy consumptions: indeed,  
172 Pandey et al. [16] found out that the yearly energy saving potential is about 6% of the yearly energy  
173 consumption. In this context, Costa et al. [20] carried out a study related to the use of eucalyptus,  
174 which undergoes to a gasification process in a bubbling fluidized bed in order to obtain biomass to  
175 feed a 50 MW thermal power plant of a pulp and paper mill in Portugal. The heat is then used to  
176 produce the steam that is required by the papermaking process. Eventually, Ruohonen et al. [21]  
177 investigated the use of the low temperature secondary heat in different heat exchanger networks  
178 retrofits. In this regard, fuel drying can increase the heating value of fuels and, as a consequence, the  
179 energy efficiency of both heat and power production.

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

188 Among the different applications, District Heating (DH) is considered one of the best solutions [24].  
189 Indeed, DH is able to provide multiple benefits i) to the environment by increasing the overall  
190 efficiency of centralised plants, thus lowering the harmful emissions into the atmosphere; ii) from an  
191 economic point of view by reducing the primary energy consumptions and taking advantages of the

192 long lifetime up to 50 years; iii) in terms of safety since no flue gases nor fuel-related risks are present  
193 at end users premises; iv) from the reliability point of view due to the interconnection of multiple heat  
194 sources and, eventually, v) from the maintenance side since the centralised plants can be continuously  
195 monitored and pro-actively maintained. For these reasons, in the recent years many researchers have  
196 focused their attention on DH networks. For example, Fitó et al. [25] studied the design of a DH  
197 network in Grenoble (France) by investigating three different waste heat temperatures, namely 35°C,  
198 50°C and 85°C. Two different results were obtained: the demand-oriented optimal design suggested  
199 to recover waste heat at 35°C in order to supply 49% of the residential need, while the source-oriented  
200 optimal design recommended a waste heat temperature of 85°C with the final aim of maximizing the  
201 waste recovery up to 55%. Among them, the first one was selected since the highest global exergy  
202 efficiency of 27% was possible to be achieved. Sun et al. [26], instead, proposed a DH network based  
203 on WHR from industries, where natural gas fired boilers with absorption heat exchangers are present.  
204 In particular, the decrease of the return temperature of the heat transfer fluid doubled the primary  
205 energy efficiency of the DH system analysed in their work. Pelda et al. [27] assessed the potential of  
206 both industrial waste heat and solar thermal power in DH networks, showing high unused industrial  
207 waste heat sources and solar thermal power that could satisfy the end users' demand completely.  
208 Wang et al. [28] investigated the WHR potential in DH systems and used the tangency analysis, which  
209 is a kind of pinch analysis optimizing the interconnections between multiple-grade industrial waste  
210 heat sources, to enhance the direct-heat-exchange systems with multi-heat sources through the exergy  
211 analysis of heat recovery systems with heat pumps. Results showed that the developed process  
212 optimization principles led to the decrease of the energy input by more than 70%. Along the same  
213 line, Fang et al. [29] discussed issues related to a DH system using two or more kinds of low-grade  
214 industrial waste heat, ranging from 20°C to 90°C and applying three different approaches i) tangency  
215 analysis; ii) lowering the return temperature of the water in the primary circuit and iii) using systems  
216 able to integrate both industrial waste heat for the base load and fossil-fuel heat in DH networks.  
217 Results showed that overall 390,000 GJ of waste heat was recovered and thus 35,000 tCO<sub>2</sub> were  
218 saved.

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

225 Italian pulp and paper sector, a methodology to assess the potential of the waste heat from the installed  
226 cogeneration plants for DH application has been developed. Precisely, the DH potential of the existing  
227 cogeneration units has been investigated from both energy and environmental points of view using  
228 operational data of 50 Italian paper mills. The waste heat of the cogeneration plants and the net one  
229 available to DH networks have been assessed taking into account the related heat losses. Then, the  
230 thermal energy required by the end users, according to the building Energy Efficiency Classes  
231 (EECs), and the maximum number of buildings connected to each DH network have been obtained.  
232 Eventually, a detailed analysis of the PES and of the tCO<sub>2</sub> avoided has been performed. Hence, the  
233 main novelties of the present work rely on i) a methodology to assess the low-grade waste heat from  
234 cogeneration plants of energy intensive industries for DH applications and ii) a methodology to  
235 preliminary evaluate the benefits of the DH network in terms of end users to be connected and energy  
236 and environmental savings.

237 Therefore, the paper is organized as follows: after the Introduction, Section 2 provides an overview  
238 of the European and Italian pulp and paper industry, while Section 3 reports the WHR potential for  
239 end users to be connected to the DH networks. Section 4 describes the methodology applied to this  
240 study in order to assess the energy savings deriving from the use of the WHR in DH networks. Section  
241 5 presents and discusses the main findings of the work, focusing the attention on the profitability of  
242 coupling cogeneration units with DH networks and eventually Section 6 reports the conclusions.

243

244

## 245 **2. THE EUROPEAN AND ITALIAN PULP AND PAPER INDUSTRY**

246 Europe is the second largest producer and the third consumer of paper and board, reaching about  
247 41.8% Mt/year of wood pulp that correspond to about 22% of the total production worldwide. The  
248 main grades of wood pulp for papermaking are sulphate pulp (60% of total production), mechanical  
249 and semi-chemical pulp (32% of total production) and sulphite pulp (5% of total production) [31].  
250 Among the European countries, Sweden, Finland, Germany and Portugal are the four biggest pulp  
251 producers (Sweden and Finland produce together about 57% of the total pulp production), while Italy,  
252 Germany, France and the UK are the four biggest markets. Italy produces only 0.7 Mt/year of pulp  
253 that is obtained mainly from mechanical and semi-chemical pulping processes, while the remaining  
254 comes from sulphate pulping. Regarding the paper sector (graphic papers, sanitary, household paper  
255 and packaging paper), Germany, Finland, Sweden and Italy are the four biggest producers with a total  
256 production of 22.8 Mt/year, 13.1 Mt/year, 11.7 Mt/year and 9.1 Mt/year, respectively [31]. With

257 reference to the size, more than 50% of the paper mills in Italy have a paper production <25 kt/year  
258 and many of them belong to private or family-owned businesses.

259 Despite the production of the pulp and paper industry increased between 2000 and 2018 worldwide  
260 [32], the European production continued the negative trend with a reduction of about 3% in 2019. In  
261 particular, the EU paper and board production followed the 2019 EU economy downward trend due  
262 to the global instability and trade tensions, in contrast with a significant uptick of the market pulp  
263 production (+0.8%) as a result of the export market demand and investments in new capacities [33].  
264 According to ASSOCARTA [34], in 2019 the Italian pulp and paper production accounted for almost  
265 9.1 Mt, which represented about 7.2% of the EU production. Although the EU and Italian economic  
266 crisis, the pulp and paper industry still plays a key role in the EU and Italian industry sector.

267 The pulp and paper industry is considered a high energy intensive one and, as a consequence, the  
268 competitiveness of the sector is strongly affected by the energy bills [35]. The used fuels depend on  
269 the location of the pulp and paper mills. For example, the Italian pulp and paper mills make use of  
270 natural gas (95%) and oil (5%) according to [36]. With regard to the energy consumptions, in 2019  
271 the overall natural gas and electric energy consumptions of the pulp and paper sector in Italy were  
272 about 2.40 Gm<sup>3</sup> and 7.00 TWh respectively [37]. With reference to the energy production, 85 out of  
273 153 [38] Italian pulp and paper mills have cogeneration plants and 50 of them have been analysed in  
274 detail in this study. In 2019, their overall natural gas and electricity consumptions were around 0.45  
275 Gm<sup>3</sup> and 1.46 GWh, which correspond to almost 19% and 2.1% of the natural gas and electricity  
276 requirements, respectively, of the entire Italian pulp and paper industry. Particular attention has been  
277 paid to the CHP plants of the analysed paper mills, whose electric power capacity ranges between 1-  
278 105 MW, for a total amount of 613 MW that corresponds to about 13% of the overall electric power  
279 capacity installed in the pulp and paper sector in Italy. Hence, the considered paper mills constitute a  
280 representative sample of the Italian pulp and paper sector and the analysis provides reliable  
281 estimations on the further exploitation of the low-grade waste heat recovered from CHP systems.

282

283

### 284 **3. DISTRICT HEATING POTENTIAL**

285 District heating has a great potential in exploiting huge amounts of low temperature waste heat [39].  
286 Currently, both 4<sup>th</sup> and 5<sup>th</sup> DH generations networks are based on inlet fluid temperatures lower than  
287 70°C, which both makes the direct use of the low-grade waste heat possible and reduces the energy  
288 losses of DH networks [40].

289

290 In Europe, the residential sector accounts for almost 40% of the total energy consumption, thus having  
291 a significant impact on the overall CO<sub>2</sub> emissions [41]. In the rest of the World, despite the fact that  
292 such amounts may differ, the building sector has an important impact in the total energy consumption  
293 as well. Therefore, the use of DH networks in urban areas would contribute to mitigate the energy  
294 consumptions of the building sector and, at the same time, to reduce both installation and maintenance  
295 costs of traditional boilers and heating systems. In Italy, DH networks are installed in more than  
296 hundred city centers mainly located in the North. In particular, five regions (Lombardy, Piedmont,  
297 Veneto, Emilia Romagna and Trentino-South Tyrol) account for almost 95% of the build volume  
298 connected to DH networks in Italy. At present, DH networks extend for almost 4,600 km, where hot  
299 water is used as heat transfer fluid. According to [42], almost 292 Mm<sup>3</sup> of hot streams in Italy have  
300 been used in residential, tertiary and industrial sectors in 2019. In the same year, almost 11.5 TWh,  
301 which correspond to 726 kTOE, have been saved by means of the thermal energy supplied by DH  
302 networks, whose 66% has derived from CHP plants [43].

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

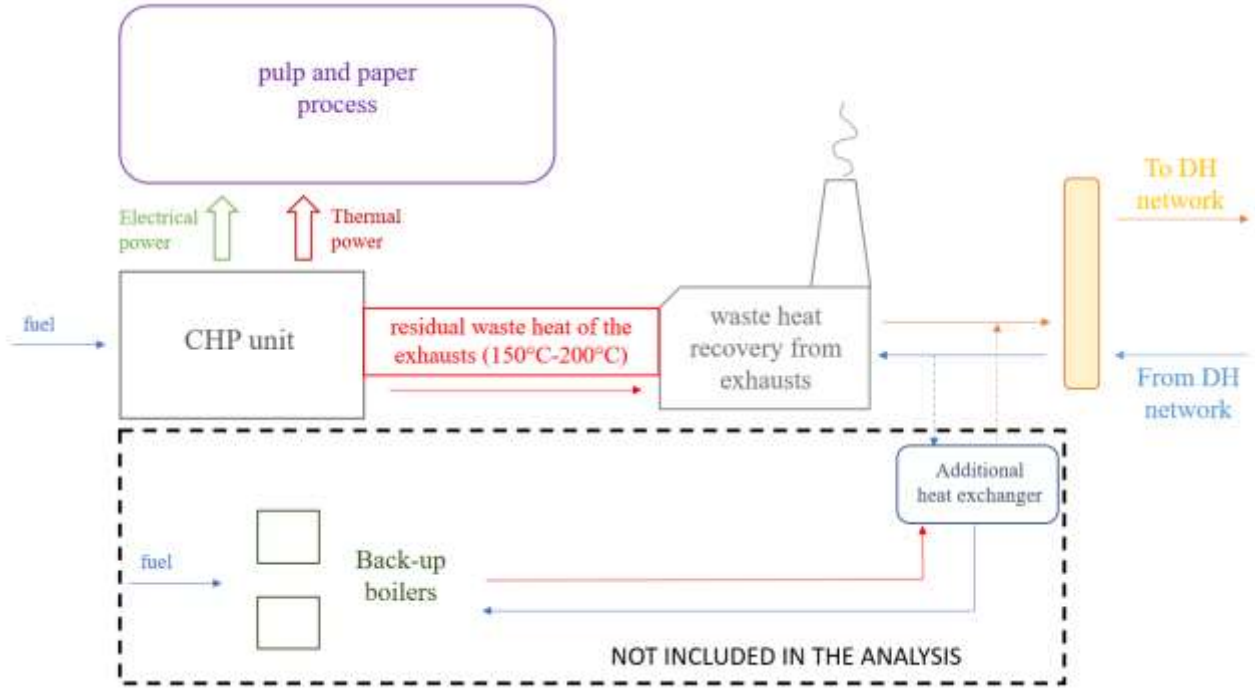


Figure 1: Scheme of the waste heat recovery from CHP plants for DH applications

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## 327 4. METHODOLOGY

328 For the sake of the present analysis, the DH potential has been assessed according to the following  
 329 procedure. Initially, the low-grade waste heat discharged by the CHP plant of each paper mill has  
 330 been evaluated; hence, the heat available to the residential buildings by means of a DH network is  
 331 calculated taking into account the related thermal losses of the network. Then, the overall amount of  
 332 the heated floor area together with the maximum number of buildings connected to the DH network  
 333 are assessed and, eventually, both energy and emissions savings in terms of TOE and tCO<sub>2</sub> have been  
 334 evaluated considering the replacement of traditional residential boilers with DH networks.

335

### 336 4.1 Assessment of the thermal power available to end users

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

339

$$340 P_{th,gross} = P_{input,CHP} - (P_{e,CHP} + P_{th,CHP}) = P_{input,CHP} \cdot (1 - \eta_{e,CHP} - \eta_{th,CHP}) [MW] \quad (1)$$

341

342 where  $P_{e,CHP}$  and  $P_{th,CHP}$  are the electric and thermal powers of the CHP unit,  $\eta_e$  and  $\eta_{th}$  are the electric  
 343 and thermal efficiencies of the CHP unit, respectively, and  $P_{input,CHP}$  is the input power to the CHP

344 unit. However, since the exhausts from a CHP unit cannot be cooled down to the ambient temperature,  
 345 only part of this waste heat can be usefully recovered. Precisely, the percentage of the recoverable  
 346 waste heat to be supplied in the DH network has been calculated considering the following  
 347 assumptions:

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

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

$$362 \quad WHR = \frac{\dot{m}_{exs} \cdot c_{p,exs} \cdot [T_{ex,CHP} - (T_{DH,supplied} + \Delta T)]}{\dot{m}_{exs} \cdot c_{p,exs} \cdot (T_{ex,CHP} - T_{amb})} = \frac{T_{ex,CHP} - (T_{DH,supplied} + \Delta T)}{T_{ex,CHP} - T_{amb}} [\%] \quad (2)$$

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

$$374 \quad P_{th,net} = P_{th,gross} \cdot WHR [MW] \quad (3)$$

375  
 376

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

382

$$383 \quad P_{th,end\ users} = P_{th,net} - L_{th} = 90\% P_{th,net} [MW] \quad (4)$$

384

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

387

$$388 \quad L_{e_{DH}} = \frac{P_{th,end\ users}}{L_{l,DH}} [km] \quad (5)$$

389

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

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

# paper mill	CHP technology	$P_e$ [MW]	$\eta_e$ [-]	$P_{input}$ [MW]	$\eta_{th}$ [-]	WHR [%]	$P_{th,net}$ [MW]	$\eta$ [-]	$T_{amb}$ [°C]	$P_{th,end\ users}$ [MW]	$L_{th,DH}$ [MW]	$L_{eDH}$ [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

## 412 4.2 Assessment of the overall heated floor area served by District Heating network

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

425

$$426 A_{bldng,ovrll} = 2 \cdot \left( \frac{A_{floor,avg} \cdot h_{bldng}}{10} + 10 \cdot h_{bldng} + A_{floor,avg} \right) \quad (6)$$

427

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

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

# paper mill	HDD [-]	S/V [1/m]	$A_{\text{floor,avg}}$ [m <sup>2</sup> ]	$EPI_{\text{lim}}$ [kWh/m <sup>2</sup> year]	EPI [kWh/m <sup>2</sup> 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

446

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

459

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

# paper mill	$A_{\text{floor,avg}}$ [m <sup>2</sup> ] for each EEC of the buildings							Total $A_{\text{floor,avg}}$ [m <sup>2</sup> ]	$EPI_{\text{lim}}$ [kWh/m <sup>2</sup> 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

461

### 462 4.3 Maximum thermal energy available to end users

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

465

466

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

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):

$$N_{bldng} = \frac{P_{th,end\ users}}{P_{th,max}} \quad (8)$$

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 <sup>3</sup> K]	$C_v$ [kW/m <sup>3</sup> 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:

$$A_{floor,avg\ h} = A_{floor,avg} \cdot N_{bldng} \quad (9)$$

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

494 area connected to the DH network [58], as reported in Table 3. These values are summarised in Table  
 495 5.

496

497

Table 5:  $A_{\text{floor,avg}_h}$  [m<sup>2</sup>] and the simultaneity factor

# paper mill	$A_{\text{floor,avg}_h}$ [m <sup>2</sup> ]	Simultaneity factor [-]
1	29,859	1.00
2	10,335	0.79
3	42,591	0.50
4	163,131	0.81

498

#### 499 4.4 Primary energy saving (PES)

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

507

$$508 \quad PES = 1 - \frac{1}{\frac{\eta_{e,CHP}}{\eta_{e,ref}} + \frac{\eta_{th,CHP}}{\eta_{th,ref}}} \quad (10)$$

509

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

513

$$514 \quad E_{input,CHP} = m_{fuel,CHP} \cdot LHV_{fuel} \quad (11)$$

$$515 \quad E_{e,CHP} = \eta_{e,CHP} \cdot E_{input,CHP} \quad (12)$$

$$516 \quad E_{th,CHP} = \eta_{th,CHP} \cdot E_{input,CHP} \quad (13)$$

517

518 Along the same line, the electric and thermal energies obtained through separate technologies are  
 519 calculated through of Eqs. (14) and (15), similarly to Eqs. (12) and (13), respectively. In this case,

520 the only variance is that different amounts of primary energy inputs are considered, based on the same  
521 reference electric and thermal efficiencies.

522

$$523 \quad E_e = \eta_{e,ref} \cdot E_{input} \quad (14)$$

$$524 \quad E_{th} = \eta_{th,ref} \cdot E_{input} \quad (15)$$

525

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

530

531

## 532 **5. RESULTS AND COMMENTS**

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

535

### 536 **5.1 Energy and environmental advantages of CHP units**

537 Independently from the WHR application considered in this analysis, cogeneration is usually able to  
538 provide energy and environmental benefits compared to the separate production of the same amount  
539 of thermal and electrical energies. Table 6 lists the data related to the use of the CHP units installed  
540 in the 50 Italian paper mills for producing electricity and thermal energies simultaneously and their  
541 separate production (boilers) without considering the advantages of the low grade WHR. It is worth  
542 noting that average electric ( $\eta_{e,CHP_{avg}}$ ) and thermal ( $\eta_{th,CHP_{avg}}$ ) efficiencies of the CHP units  
543 analysed in this work are equal to 0.31 and 0.45 respectively, while the reference electric and thermal  
544 efficiencies are 0.46 and 0.9 respectively according to [61]. Despite the lower values of the average  
545 electric and thermal efficiencies of the CHP units compared to the reference ones, the use of  
546 cogeneration allows reducing the fuel consumption significantly. Indeed, the yearly natural gas saving  
547 is equal to 175,322.42 km<sup>3</sup> per year, which means avoided 143.76 kTOE or 333.11 ktCO<sub>2</sub>. As regards  
548 the PES, an average value of 0.14 is obtained, highlighting that the energy efficiency target is  
549 achieved by the considered cogeneration plants also in case the low-grade heat is wasted.

550

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

Technology	Natural gas consumption [km <sup>3</sup> ]	Tonnes of Oil Equivalent [kTOE]	Tonnes of CO <sub>2</sub> [ktCO <sub>2</sub> ]
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%	

554

555 In case of WHR, an additional amount of 308.45 GWht is still available to the end users for DH  
 556 applications. More precisely, such value has been calculated considering that the heating hours of the  
 557 winter season range between 1,360 h and 3,582 h in the areas where the paper mills are located. In  
 558 particular, this amount corresponds to about 7.1% and 16.2% of the overall input and output thermal  
 559 energies of the CHP units, respectively. Considering the use of conventional boilers with a  $\eta_{th,ref}$  of  
 560 0.9 [61], it also corresponds to a natural gas consumption of 35,924.51 km<sup>3</sup> or, in other terms, to  
 561 avoided 29.46 kTOE or 68.26 ktCO<sub>2</sub>. Therefore, in case of WHR, the thermal efficiency of the CHP  
 562 units increases from an average value of 0.45 up to about 0.54, thus resulting in an increase of the  
 563 PES from 0.14 up to 0.22 that is a very remarkable value. Table 7 highlights the relevance of the  
 564 waste heat from the CHP plants with respect to the separate production through conventional gas  
 565 boilers. It is worth noting that the thermal energy  $E_{th}$  [MWh] of the separate production takes into  
 566 account the heat required by both the papermaking process and the end users of the DH networks.

567

568

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

569

## 570 5.2 Sensibility analysis on the profitability of using District Heating (DH) networks

571 Despite the thermal energy deriving from the low-grade waste heat as evaluated in Subsection 5.1 is  
 572 significant, the convenience of DH cannot be easily determined a priori since new infrastructures are  
 573 required in most of the cases. Based on Eq. (5), the overall maximum length of DH networks that  
 574 would be required in this case study is approximately 470 km, ranging from 1.5 to 56.9 km for the

575 considered paper mills and thus entailing significant economic investments that do not always lead  
 576 to a favourable economic return of the DH application.

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

587

588 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 <sub>avg</sub> [-]
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

589

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

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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 <sup>3</sup> ]	Natural gas consumption by CHP [km <sup>3</sup> ]	Natural gas saving by CHP without WHR [km <sup>3</sup> ]	Natural gas saving by CHP in case of WHR [km <sup>3</sup> ]
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

602

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

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

610

$$611 \quad SFS = \frac{V_{NG,WHR}}{P_{input}} \quad (16)$$

612

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

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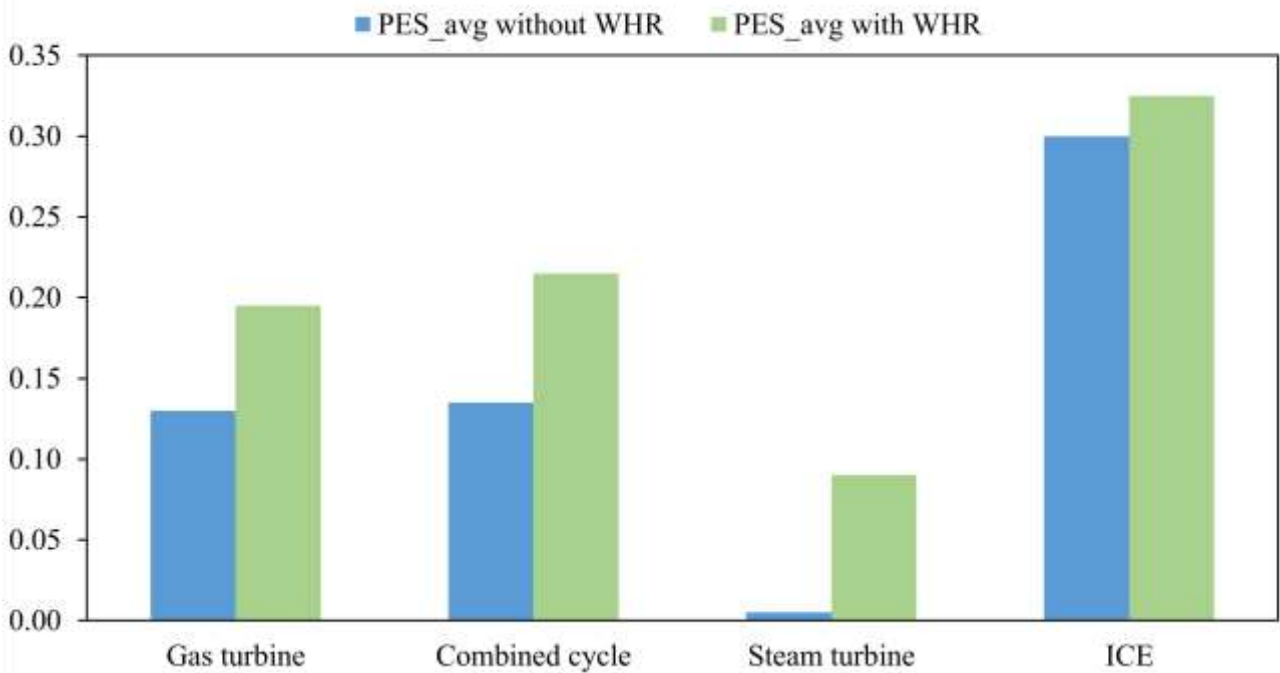
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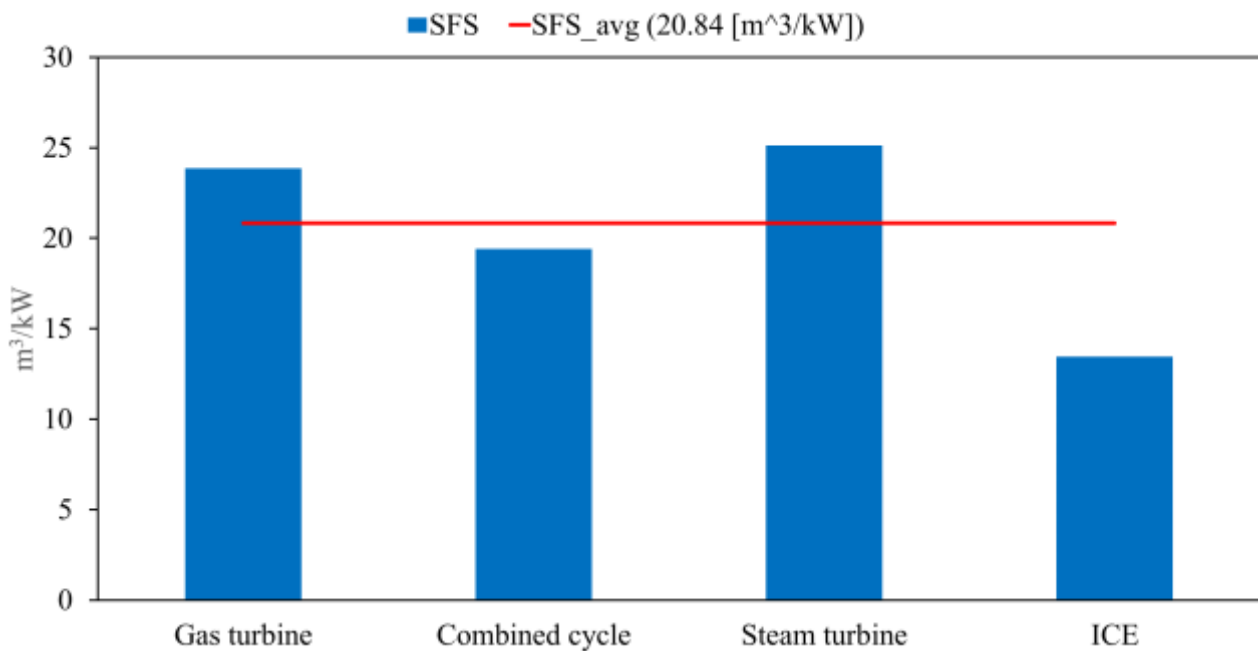
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Figure 2: Comparison between  $PES_{avg}$  obtained without and with WHR



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628  
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Figure 3: SFS values sorted by CHP technologies

630 With reference to Figure 2, the exploitation of the low-grade heat from the CHP units leads to positive  
631 values of the PES in all the analysed cogeneration plants. More precisely, ICEs show the lowest  
632 improvement of the PES, although yet the highest; in case of steam turbines, instead, the average PES  
633 increases from 0.005 to almost 0.1. As a consequence, WHR has the largest impact in case of steam

634 turbine CHP units. This trend is confirmed also when the SFS is considered. Indeed, according to  
 635 Figure 3, steam turbine CHP units have the highest SFS of about 25.15 m<sup>3</sup>/kW in case of WHR,  
 636 followed by gas turbines units that have a SFS of 23.85 m<sup>3</sup>/kW. These values are 20.6% and 14.4%  
 637 higher than the average SFS by all the analysed cogeneration plants (about 20.84 m<sup>3</sup>/kW),  
 638 respectively. On the contrary, the SFS is limited in case of the ICE technology (equal to about 13.46  
 639 m<sup>3</sup>/kW) that could lead to unprofitable results of WHR application.

640 Afterwards, only the paper mills located in the areas with HDD higher than 2,000 have been  
 641 considered. This threshold value has been selected since it corresponds to the HDD of a mid-town  
 642 located in the Centre of Italy, where a DH network already exists and for which some of the authors  
 643 of the present paper have already evaluated both the energy and the economic benefits [19], finding  
 644 out that lower values of HDD may not be sufficient for achieving the overall sustainability of the  
 645 project. Therefore, according to this criterion, 31 out of 49 paper mills have been considered. All  
 646 these paper mills are located in Central and Northern Italy, where both autumn and winter seasons  
 647 are colder. In particular, the benefit of the WHR for DH application has been also analysed with  
 648 reference to three different ranges of the HDD, as reported in Table 10. Among the 31 paper mills,  
 649 20 of them are located in areas with HDD in the range 2,000-2,500, 7 in areas with HDD of 2,500-  
 650 3,000 and eventually 4 in areas with HDD higher than 3,000.

651

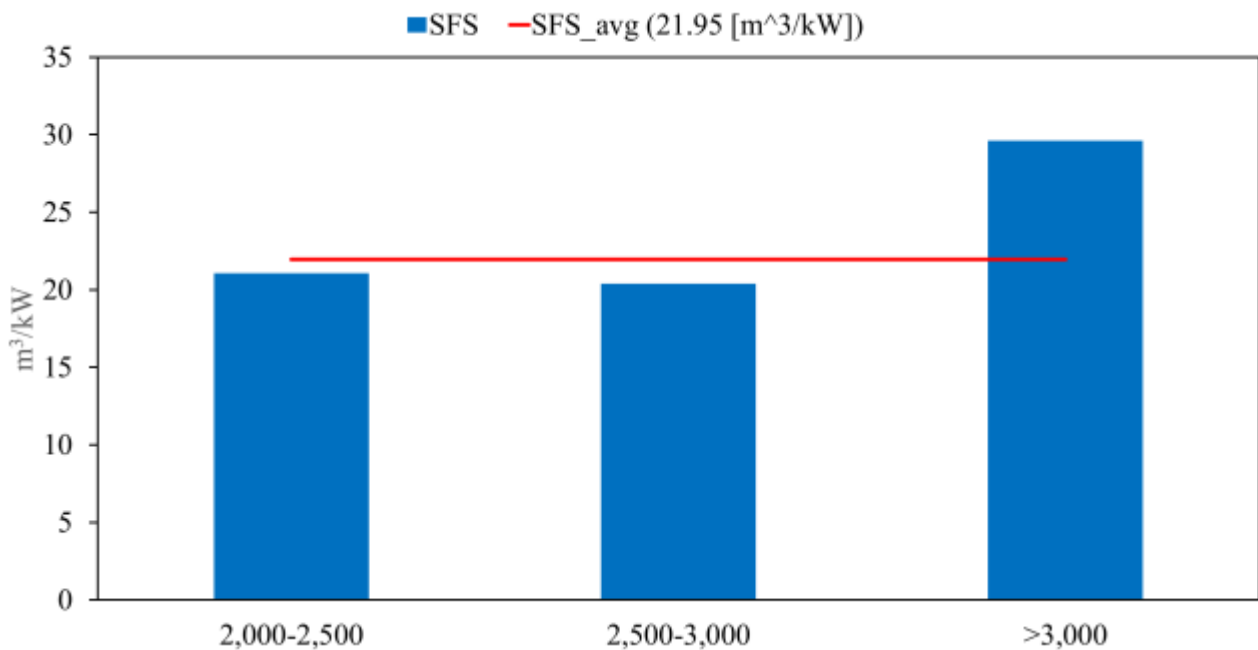
652 *Table 10: Natural gas consumption and saving of 31 paper mills without and with WHR sorted by HDD range*

<b>HDD range \ Consumption &amp; Savings</b>	<b>Natural gas consumption in case of separate production [km<sup>3</sup>]</b>	<b>Natural gas consumption by CHP [km<sup>3</sup>]</b>	<b>Natural gas saving by CHP without WHR [km<sup>3</sup>]</b>	<b>Natural gas saving in case of WHR [km<sup>3</sup>]</b>
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
<b>TOTAL</b>	<b>444,586.07</b>	<b>321,953.23</b>	<b>122,632.84</b>	<b>25,454.70</b>

653

654 The total amount of the natural gas yearly consumed by the CHP units of the selected 31 paper mills  
 655 is equal to 321,953.23 km<sup>3</sup>, which corresponds to 71.11% of the natural gas consumed yearly by the  
 656 CHP units of all the 50 paper mills. Considering the related low-grade waste heat, 224.64 GWh of  
 657 heat is available to the end users of the DH networks, which corresponds to 7% and 15.8% of the  
 658 input and output thermal energies respectively of the 31 out of 49 CHP units. In case the same amount

659 of thermal energy is produced by conventional boilers, a consumption of about 25,454.70 km<sup>3</sup> of  
 660 natural gas is required. In other terms, this natural gas saving corresponds to 20.87 kTOE and 49.56  
 661 ktCO<sub>2</sub> of avoided emissions. Hence, this last analysis has shown that a noticeable increase in the use  
 662 of the low-grade waste heat from CHP units can be obtained by those plants located in areas with  
 663 high HDD values, granting a better exploitation of the recovered heat.  
 664 To better appreciate the impact of the location on the potential saving, the SFS of the 31 paper mills  
 665 are reported in Figure 4 sorted by the HDD range.  
 666



667  
 668 Figure 4: SFS values sorted by HDD ranges

669  
 670 As expected, the SFS due to WHR application increases with HDD. In particular, a SFS value of  
 671 29.60 m<sup>3</sup>/kW is obtained in case of HDD>3,000 which is 34.86% higher than the average SFS. With  
 672 respect to the values reported in Figure 4, it is worth to noticing that the obtained average value of  
 673 the SFS by the CHP units located in areas with HDD in the range 2,500-3,000 is lower than that of  
 674 the CHP units located in areas with HDD in the range 2,000-2,500, because in the former most of the  
 675 capacity is constituted by combined cycle power plants that exhibit a lower SFS than steam turbines  
 676 and gas turbines plants, as reported in Figure 3.  
 677  
 678  
 679  
 680

## 681 **6. CONCLUSIONS**

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

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

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

694 A further analysis, based on the values of the HDD of the locations where the paper mills are placed,  
695 has shown that 31 out of 49 paper mills are located in areas having HDD equal or higher than 2,000 for  
696 which the profitability of DH is proven. These 31 paper mills have a natural gas consumption of  
697 321,953.23 km<sup>3</sup> and, in case of WHR for DH, about 224.64 GWht would be available to the end users  
698 corresponding to a natural gas saving of 25,454.70 km<sup>3</sup>. Obviously, WHR increases the PES of all  
699 the CHP technologies and, in case of steam turbine technology, the benefit is remarkable moving  
700 from 0 to about 0.1, which means that also such plants could take advantage of the incentives offered  
701 by the Italian legislation for the high efficiency cogeneration systems. In other terms, the steam  
702 turbine CHP units exhibit the highest values of SFS equal to 25.15 m<sup>3</sup>/kW in case of WHR  
703 application. Eventually, the average SFS is 29.60 m<sup>3</sup>/kW if paper mills located in areas with  
704 HDD>3,000 are considered.

705 Hence, the proposed methodology has allowed i) to assess the potential of low-grade waste heat  
706 recovery from cogeneration plants of energy intensive industries for DH application and ii) to  
707 preliminary evaluate the number of end users to be connected to the DH network and the  
708 corresponding energy and environmental savings. For example, by roughly extending the proposed  
709 methodology to all the 85 Italian pulp and paper mills having CHP units, about 62,320 km<sup>3</sup> of natural  
710 gas savings could be achieved connecting about 26,037 buildings to the DH networks. Furthermore,  
711 the present analysis could be easily extended to many other energy intensive industries having  
712 cogeneration plants thus obtaining a first estimation of their potential in curbing overall CO<sub>2</sub>  
713 emissions of the residential sector and supporting the implementation of low carbon districts.

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