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Assessment of waste and renewable heat recovery in DH through GIS mapping: The national potential in Italy

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ABSTRACT

This work aims at showing the unexploited potential of waste and renewable heat in Italy through detailed mapping of these sources. The ambition is to highlight the areas with an important heat recovery potential that could be exploited through DH expansion. The recoverable heat sources have been analysed in terms of geographical location, and recovery aspects with a special focus on temperature levels and technological implications for temperature upgrades. The methodology presented in this work addresses not only the theoretical potential of waste heat and renewable heat use in DH, but also several technical aspects to get a result as closer as possible to the realistic potential at national level. Two different approaches have been used to map potential heat: one to quantify existing waste heat recovery from industrial processes, waste to energy plants, wastewater treatment plants and one to estimate the energy coming from potential new plants based on biomass, geothermal energy and solar thermal. Results shows that for a total heat demand for the civil sector of 329 TWh, out of which 114 TWh come out being suitable for a DH connection, the national available waste and renewable heat that could be integrated in DH amounts to 156 TWh. These results show the significant unexpressed potential of waste heat use in Italy and how its mapping is essential to properly estimate the utilization potential. This work has been commissioned by AIRU, Italian DH association.

1. Introduction

District heating systems (DH) can play a key role in the decarbonisation of energy systems being a measure of efficiency at urban level that uses renewables and excess heat that would otherwise be wasted [1,2].

The evidence of this opportunity has been highlighted by EU policies [3] after the results of several European projects such as Ecoheatcool [4], Heat Roadmap Europe and its follow up Stratego [2,5] and Hotmaps [6]. The merit of these studies is to emphasize the unexpressed potential of waste heat recovery [5] through DH at sustainable costs [7]: this is obtained by the elaboration of heat atlas and maps aimed at identifying synergic areas for DH extension as supportive local planning tools [8].

The European targets for decarbonisation are ambitious [9] and mainly focuses on buildings' retrofit and on the increase of renewables in the power sector [10]: the Italian implementation of EU goals in the NECP sets the target for renewables at 30% on the overall energy consumption, which implies a 33.9% penetration of renewables in the thermal sector [11]. Even though the goals are ambitious, the potential supportive role played by DH in Italian future energy scenarios and waste heat recovery is not identified in these documents neither emphasized mostly because of the marginal role of DH in the current national energy mix. Even if the market share of DH and the waste heat recovery is higher in northern countries [12–17], the Heat Roadmap Europe project [5,7] and a local research work have [18] identified Italy as a strategic potential market for DH based on waste heat and renewables.

This work is therefore developed with the purpose to emphasize the important untapped national potential of waste heat and renewables that could be recovered through the diffusion of DH at national level: DH is in fact one of the key technologies enabling the realization of Smart National Energy System [19] characterized by greater flexibility and cheaper energy efficiency solutions derived by sector coupling. In this framework, the idea is to show the

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Abbreviations

ADEME	Agence de l'environnement et de la maîtrise de l'énergie
AIRU	Associazione Italiana Riscaldamento Urbano
CHP	Combined Heat and Power
COP	Coefficient of performance
DEA	Danish Energy Agency
DH	District Heating
E-PRTR	European Pollutant Release and Transfer Register
ETS	Emissions Trading System
EU	European Union
GIS	Geographic Information System
HP	Heat pump
HRE	Heat Roadmap Europe
HX	Heat Exchanger
IPCC	Intergovernmental Panel on Climate Change
ISPRA	Istituto Superiore per la Protezione e la Ricerca Ambientale
NECP	National Energy and Climate Plan
NUTS	Nomenclature of Territorial Units for Statistics
QGIS	Quantum Geographic Information System
RES	Renewable Energy Source
WTE	Waste-to-energy
WWTP	Wastewater Treatment Plant
XHT	Excess Heat Temperature

Nomenclature

E_{prim}	primary thermal energy input, kWh
E_{abs}	thermal energy absorbed by the production process, kWh
E_{excess}	thermal energy not embedded in the final product, kWh
E_{heat}	waste heat, kWh
E_{el}	electric energy consumption, kWh
E_{bio}	primary thermal energy input from biomass, kWh
E_{need}	heating energy demand, kWh
E_{ww}	thermal energy recovery from wastewater treatment plants, kWh
η	recovery coefficient, %
T_E	evaporation temperature, °C
T_C	condensation temperature, °C
hh	equivalent hours
m	mass, kg
f	emission factor, g/MWh
V	volume, m^3
c	heating value, J/kgK
ΔT	temperature difference, °C
k	percentage of coverage of the heating demand, %
$n_{centralized}$	number of residential units equipped with a centralized heating system
n_{tot}	total number of residential units

Subscripts

steam	steam process
HT	high temperature
LT	low temperature
lost	fraction of irreversible losses
tech	technical
th	theoretical
HP	heat pump
DH	district heating
process	production process
waste	urban waste
ww	wastewater
civil	civil sector

important waste and renewable heat use that could be enabled by the interaction of civil, industrial and power sector though DH and storages. Within this goal, the main purpose of the work is to present a methodology aimed at quantifying the technical realistic potential of exploitation of these heat sources resulting in a GIS map of available sustainable sources for DH. These outcomes represents inputs data that could be used in the simulation of national energy systems with a Smart Energy System approach [19].

1.1. Previous studies

The first comprehensive study of industrial waste heat recovery in Danish DH is presented in Ref. [15]: Bühler et al. present a comprehensive georeferenced assessment in Refs. [20,21], while a focus on waste to energy plant can be found in Ref. [22]. Some follow up studies focusing on some specific Danish case studies can be found in Refs. [23,24], while [25] extends the spatial and thermodynamic analysis, considering also the temporal match between industrial excess heat and DH demand profiles.

Another country in which DH is a mature market and where several studies have been developed about DH [16] and industrial waste heat [17,26,27] is Sweden.

Similar studies trying to estimate the potential of waste heat at national level have been performed in the UK: an important reference for this work regarding the estimation of industrial waste heat to be used in DH is represented by the study of McKenna [28] where a spatial model of technical DH recovery of industrial waste heat in the UK is presented. Starting from ETS database the waste heat is estimated for every site considering temperature levels and industrial sector. The same author has also investigated the role of DH as a way to increase flexibility and storage ability of industrial waste heat reuse in city planning [29].

Another relevant study for this work can be found in Ref. [30] where Berthou and Bory developed an analysis of the France industry sector in 2012 to assess the amount of excess heat in the country. The proposed method has a bottom-up approach based on statistical data collected through questionnaires, covering 70% of the total industrial sector. The importance of this study lies in the level of detail of excess heat analyses: energy data are in fact analysed by industrial sector, effluent type (i.e. combustion gases, steam and cooling fluids) and temperature levels. An updated study on the waste heat in French industrial sector is represented by the report of ADEME [31] while an overall mapping of the suitable heat demand for DH expansion in France can be found in Ref. [32].

Other national potential analysis of waste heat recovery in DH can be found in Ref. [33] for Spain [34,35], for Switzerland and [36] for Germany where industrial waste heat is combined with solar thermal energy.

With the increased presence of low temperature DH networks [37], many researches on the exploitation of low temperature waste heat sources are currently carried out [38]. In Ref. [20] a mapping of low temperature heat sources for DH is performed for Denmark. Similar studies have been performed also in Finland and Sweden [39,40]. The majority of these studies focuses on heat pumps using ambient heat, but several researches are currently developed in relation to their application to less conventional low temperature heat sources such as wastewater treatment plants [6,41], datacentres [42,43], power transformers [44], supermarkets and metro stations [45]. In Ref. [46] the work developed in the EU project ReUseHeat, related to the assessment methodology for waste heat in low temperature processes, is presented. The first comprehensive EU level map of industrial waste heat has been carried out in Ref. [5] where Persson et al. have presented a methodology to assess theoretical annual excess heat potential based on CO_2 emission data from the European Pollutant Release and Transfer Register (E-PRTR) at European level.

A more recent work has presented a tool for exploring the potential availability for industrial excess heat recovery named the “excess heat temperature signature” [47]; in Ref. [48] the influence of temperature levels and other design aspect on the cost of heat recovery are analysed while in Ref. [49] a first matching between waste heat sources together with heat demand in terms of spatial and temporal allocation is performed.

Looking at similar work dedicated to mapping and potential estimation of renewables, no equivalent detail or methodological uniformity can be found. In Ref. [49] renewable energy sources such as geothermal, large-scale solar thermal, as well as sustainable biomass, are analysed in a qualitative way, looking at land use maps.

The assessment of the potential energy from renewables depend not only on its availability but, due to their limit in use, also from the foreseen final destination. The use of biomass for the heating sector competes in fact with transports and electricity, while solar thermal requires some surface availability for which it competes with photovoltaic or agriculture considering ground installation [49]. No uniform approach can be found about renewables potential. Considering solar thermal use [20,49], and [6] starts from available areas for solar thermal collectors. Geothermal energy potential quantification is hardly assessed: just mapping of the characteristics of the underground layers are available [49,50]. Most of the available works focus on specific cases aimed to estimate the role and the cost of these sources in existing DH networks or in future ones towards complete decarbonisation of the system [51–55]. A reference paper for this work, even if not regarding DH specifically, is given by the study [56] in which, starting from the spatial distribution of wind energy supply in Crete, this method is used to evaluate the technological and economically exploitable potential of this source and, once combined with the energy demand profile, to point out actions and interventions needed to improve the existing energy system.

For renewable energies, as well as for industrial waste heat, the main difficulty lies in the evaluation of the realistic useable amount of energy from the identified source, and this work is aimed at supporting stakeholders and local energy planners in this task. Lots of maps exist on availability resources potential, the aim of this work is to provide method to calculate useable data from them for the scope of the paper.

1.2. Motivation of this work

This work lies in the framework of a wider project, funded by the Italian DH association AIRU, which has as main focus the estimation of national renewable based DH potential in Italy [57]. Being this the final goal of the overall estimation, this paper presents the project activity related to the assessment of sustainable heat sources.

The analysis of the existing literature shows a gap between high level analysis and detailed studies on single projects: this work is positioned between these two levels of analysis trying to reduce their distance addressing the technical aspects which leads closer to the realistic potential of renewables and waste heat at national level in a GIS environment in order to be linked to suitable heat demand for DH expansion.

Starting from the theoretical potential, several steps have been considered to calculate the realistic potential and among them:

- Temperature levels and recovery efficiencies
- Limited time correspondence
- Boundaries to consider theoretical demand suitability

The added value of this work is to have developed a schematic methodology, which is therefore simplified in certain aspects, but clear, reproducible and explicit that allows to recognize all the steps that make possible to move from a theoretical to a realistic potential application of heat that can be integrated into a DH system. The methodology is therefore useful as a planning support for operators in the sector and local planners.

The results of this work are used in the consequent phase of the project [57] in the matching phase of heat demand and sources to identify potential expansion areas for renewable based DH.

2. Methodology

This section presents the methodology used to assess the potential available waste and renewable heat sources for DH: the final result is a GIS map of available sustainable sources for DH. The elaborated methodology starts from existing methods that have been combined and extended in order to quantify the realistic useable potential of sustainable heat to be exploited in DH networks, starting from the theoretical potential expressed by input data. In order to do this, the methodology consider temperature levels, technological aspects and temporal match between energy profiles. Considering renewables, the methodology includes a way to allow the estimation of useful energy starting from availability maps of natural resources such as biomass, geothermal energy and solar thermal related to heat demand.

Due to the local nature of DH systems technology, the research questions addressed in this work are the location and the amount of sustainable DH sources, so that the approach methodology is performed in a GIS environment. Being this the final objective of this research, the work has the following intermediate consecutive steps which starts from the georeferenced availability of the source:

1. Theoretical potential – the estimation of waste heat availability
2. Technical potential – the estimation of the recoverable heat, thus the fraction of waste heat considering its quality and the recovery efficiency due to temperature levels
3. Practical potential – the estimation of the useable heat, which is the results of the matching between the time profile of the recoverable heat and the heat demand

The methodology developed to address these steps differentiate according to the type of the heat sources, namely waste heat and renewables, because of the nature and origin of the input data.

Concerning the estimation of waste heat potential, the analysis focuses on the mapping and on the assessment of waste heat from already existing production sites which are analysed singularly, having as a results a map of punctual distributed energy sources for DH. The analysed processes are.

- Industrial sites
- Power plants
- Waste to energy plants
- Wastewater treatment plants

Looking at renewable energy sources, the starting point is the map of the availability of natural resources concerning geothermal energy and biomass which is defined on extended surface bases, on heat demand map for solar thermal. The practical potential from them is analysed on the basis of the heat demand for DH. The analysed sources are:

- Biomass
- Geothermal heat
- Solar thermal energy

The methodology to assess these sources is described in the following.

2.1. Waste heat

Since there is not an available database collecting measured data on waste or excess heat availability [58], it is necessary to rely on available dataset on energy inputs, site specific emissions, fuel consumption or other kind of available data on the process inputs which are more likely to be found. The first step of the analysis is therefore the definition of primary energy consumption of the identified heat sources and the consequent step is the assessment of waste heat availability.

Fig. 1 schematically shows the procedure used to estimate the DH recoverable waste heat from the energy input of the heat source.

The definition of the quantities with which to express and estimate the potentially recoverable excess heat is essentially based on the principles of thermodynamics shown in equation (2.1):

$$E_{prim} = E_{abs} + E_{excess}[kWh] \tag{2.1}$$

where E_{prim} is the primary energy input consumed by the production site, E_{abs} represent the energy absorbed by the production process, so the process energy used for the realization of the final product and finally E_{excess} indicates all the waste heat which is not embedded in the final product and that is usually dissipated in the environment. Out of this final term, which is the one of interest for this work, an additional discrimination can be done according to the temperature level at which this waste heat is produced which is represented by equation (2.2)

$$E_{excess} = E_{heat,steam} + E_{heat,HT} + E_{heat,LT} + E_{heat,lost}\ [kWh] \tag{2.2}$$

where the excess heat E_{excess} is divided in steam processes, high and low temperature water recoverable waste heat, $E_{heat,steam}$, $E_{heat,HT}$ and $E_{heat,LT}$ respectively and a fraction of irreversible losses $E_{heat,lost}$. The level of temperature here considered is relative to the purpose of the recovery, so considering average operational temperature of DH around approximately 90 °C. According to the effluent temperature levels, Berthou et al. [30] divide the excess heat in these three category which usually correspond to high temperature excess heat coming from steam processes, above 200 °C and suitable for internal recovery, medium temperature heat coming from combustion gases at a temperature above 90 °C and finally the excess heat resulting from cooling processes with a temperature around 40 °C that requires a temperature lift through heat pumps to be used in DH. In the same paper a bottom-up approach has been derived to identify the amount of every component of equation (2.2) for each industrial sector investigated, so that it has been possible to identify the coefficients η_{steam}, η_{HT}, η_{LT} and η_{loss} allowing the calculation of each component starting from primary energy according to eq. (2.3)

$$E_{excess} = E_{prim} \cdot (\eta_{steam} + \eta_{HT} + \eta_{LT} + \eta_{lost})\ [kWh] \tag{2.3}$$

Thanks to the data of the four components of waste heat for each sector, the coefficients can be calculated as the ratio of the relative excess heat amount over total excess heat.

The sum of the three recoverable components represents the previously mentioned theoretical potential shown in equation (2.4):

$$E_{heat.th} = E_{prim} \cdot (\eta_{steam} + \eta_{HT} + \eta_{LT})\ [kWh] \tag{2.4}$$

In order to calculate the technical potential, some recovery factors η_{tech} need to be applied; they consider the technological efficiencies in the recovery process, such has heat exchanger efficiency, and the eventual temperature upgrade so that the equation can be rewritten as:

$$E_{heat,tech} = \eta_{tech} \cdot (E_{heat,steam} + E_{heat,HT} + \eta_{HP} \cdot E_{heat,LT})\ [kWh] \tag{2.5}$$

Considering low temperature cooling process waste heat, the recovery coefficient η_{HP} depending on the coefficient of performance of the heat pump is included so that $\eta_{HP} = \frac{COP}{(COP-1)}$ with an additional terms of energy consumption due to electrical power calculated as:

$$E_{el,LT} = \frac{E_{heat,LT}}{(COP-1)}\ [kWh] \tag{2.6}$$

where the *COP* is calculated according to the empirical correlation of Martinovsky [59] depending on evaporator and condenser temperatures T_E and T_C.

$$COP = 0.74\frac{T_C}{T_C - T_E} - \left(0.0032T_E + 0.765\frac{T_E}{T_C}\right) + 0.9 \tag{2.7}$$

The technical recovery potential of waste heat calculated through (2.5) represents the fully recoverable waste heat considering heat quality and technological efficiency. A final step that has been here taken is a simplified method to take into account the time correspondence between the waste heat availability and the heat demand in DH. In fact, the time dependent profile of heat effluents in the analysed production plants is often quite flat and so it does not match with the heat required profile by users in a DH system. Therefore, to have a full recovery of $E_{heat,tech}$ an important storage capacity would be required. In this work the recovery in DH is precautionary considered without the inclusion of a seasonal

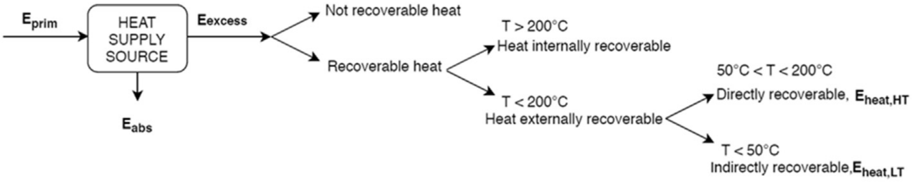

Fig. 1. Procedure used to calculate the excess heat recoverable in a district heating system, starting from the primary energy consumed by the heat source.

storage so that the correspondence in time is taken into account by considering the ratio between the equivalent operating hours *hh* of the industrial process, usually around 7000, and of DH, which have been considered 3500 for Italy, so that the practical potential heat recovery in DH is calculated according to eq. (2.8). In addition to this, as previously mentioned, the high level temperature waste heat coming from steam processes makes sense to be considered for internal recovery so that just a small fraction of it remains available for external waste heat recovery, here estimated in 25%.

$$E_{heat,DH} = \eta_{tech} \cdot \left(25\% E_{heat,steam} + E_{heat,HT} + \eta_{HP} \cdot E_{heat,LT}\right) \cdot \frac{hh_{DH}}{hh_{process}} \; [MWh] \tag{2.8}$$

The equation can be rewritten considering the technological integration in DH, which is direct in case of high temperature levels of waste heat, or indirect, needing a heat pump, in case of low temperature waste heat so that the final heat recoverable in DH can be calculated through equation (2.9):

$$E_{heat,DH} = E_{heat,HT,DH} + \eta_{HP} \cdot E_{heat,HT,DH} = E_{prim} \cdot \left(\eta_{DH,\,HT} + \eta_{DH,\,LT} \cdot \eta_{HP}\right) \cdot \frac{hh_{DH}}{hh_{process}} \; [MWh] \tag{2.9}$$

where $\eta_{DH,\,HT} = \eta_{tech} \cdot (25\% \eta_{steam} + \eta_{HT})$ and $\eta_{DH,\,LT} = \eta_{tech} \cdot \eta_{LT}$.

The following sections present how the methodology is declined for each analysed source.

2.1.1. Industrial processes, power plants and waste to energy plants

Similarly to Ref. [28] the industrial primary energy consumptions are calculated starting from site-specific data contained in the EU Emissions Trading Scheme related to 2018 which have been provided in this study by ISPRA, the national Italian institute for environmental protection and research, to the authors.

The database contains the CO_2 emissions each production plant which are categorized in 17 industrial sectors such as e.g. power producers, fuel supply and refineries, food and beverages and others.

As in Ref. [58] the primary energy consumptions form each site E_{prim} is calculated from data on annual production of CO_2 emissions from fuel combustions m_{CO_2}[kg] with equation (2.10).

$$E_{prim} = \frac{m_{CO_2}}{f_{CO_2}} \; [MWh] \tag{2.10}$$

The emission factor f_{CO_2} is calculated for every industrial sector with the same methodology used in Ref. [58], so combining data from standard carbon dioxide emission factors f_{CO_2} [g,CO2/J] from stationary combustion of fuels [60] associated to corresponding fuels and national annual fuel consumption per sector from Eurostat in 2018 [61] to produce weighted mean average values which are presented for Italy in Table 1:

Table 1
Weighted mean average values of the emission factor f_{CO_2}, representative for Italy, for each industrial sector considered.

Industrial sector	Acronym	f_{CO_2} [g,CO2/J]
Thermal power Main Activity	TP-MA	50.65
Thermal power Autoproducer	TP-AP	70.39
Fuel refineries	FSR	73.63
Chemical and petrochemical	CPC	57.38
Iron and steel	IS	69.99
Non-ferrous metals (N-FM),	N-FM	65.92
Non-metallic minerals	N-MM	67.54
Paper, pulp and printing	PPP	46.08
Food and beverage	FB	56.87
Textile	TEXT	63.95

2.1.1.1. Industrial sites.

Thanks to the application of equation (2.10), primary energy consumption of all the sites have been derived. The calculation of excess heat according to different temperature levels is calculated through the coefficients η_{steam}, η_{HT}, η_{LT} and η_{loss} which have been derived by the study of Berthou and Bory [30] for the industrial categories analysed in the study shown in Table 2, while for power production plants another approach has been used as shown in next section. The interesting aspects of using the results of the French analysis by Berthou is that, being energy data analysed by temperature levels, the outcomes help to better identify the directly recoverable fraction of waste energy, from steam and combustion, and the fraction that needs a thermal lift with heat pumps, form cooling processes. It is important to highlight that for certain categories, namely Iron and steel, Fabricated metals products and Textile, no detail on the temperature levels is given, just the total amount of waste heat which has been therefore equally divided in the 3 components. In the French study just one industrial category related to Fuel supply and refineries is not analysed, so that the coefficients are taken form HRE study [58]. Here a η_{tec} of 75% is considered and equivalent hours of industrial processes constantly equal to 7000.

2.1.1.2. Power plants.

In the ETS register on CO_2 emissions, also power plants are included so that the primary energy inputs can be calculated according to equation (2.10), but the efficiency factors for the estimation of heat recovery has been derived with a different approach. It is in fact necessary to perform a distinction from power plants which already exploit the waste heat in a cogeneration asset from power plants which haven't been conceived with this double purpose and so that are currently dissipating heat in the environment.

This second category is surely as interesting as the first one even though the modification of the production cycle could require additional costs and lower heat recovery than in a power plant that has been designed with cogeneration purposes. A first preliminary identification of the type of power plant is therefore required. The ETS database includes approximately 190 power plants in Italy divided in two main categories: CHP plants and simple power plants.

In order to properly define the heat recovery factors for the purpose of this work, the 190 power plants detected in ETS database has been divided in four categories: a further investigation has been required aimed at defining four categories:

1. CHP serving DH systems
2. CHP supplying heat to a close industrial site or cluster
3. Power plants with a CHP layout but currently wasting heat in the environment
4. Simple power plants with a layout that does not allow for heat recovery

The final category includes all the power plants which are not CHP and that would need a modification of the last turbine stage or the integration of a steam recovery boiler in order to recover dissipated heat. On these categories the heat recovery coefficients have been defined on the basis of bibliographic surveys ([62,63]) and are presented in Table 3:

Table 4 shows the difference in the obtained results with the ones obtained in the framework of the HRE project. The useful recoverable energy that can be used in DH can be calculated inserting these parameters in the following equation:

Table 2
Recovery coefficients defined by industrial sector, according to the temperatures of both the heat source and DH.

Activity Sector	Waste heat				DH recovery	
	η_{steam}	η_{HT}	η_{LT}	η_{loss}	$\eta_{DH,\ HT}$	$\eta_{DH,\ LT}$
Fuel supply and refineriesa	–	–	–	–	28.1%	–
Food products and beverages	18.2%	3.6%	28.1%	2.1%	6.1%	21.1%
Pulp, papers and edi tion	36.1%	7.9%	0.5%	1.8%	12.7%	0.3%
Basic chemicals	8.3%	11.2%	6.5%	–	9.9%	4.9%
Other non metallic mineral products	6.4%	11.0%	2.6%	–	9.5%	2.0%
Capital goods Manuf	7.8%	7.8%	7.8%	2.6%	7.3%	5.9%
Fine chemical products	12.5%	16.8%	9.8%	–	14.9%	7.3%
Iron and steel	3.5%	3.5%	3.5%	1.2%	3.3%	2.7%
Fabricated metals products	4.5%	4.5%	4.5%	1.5%	4.2%	3.3%
Textile	7.8%	7.8%	7.8%	2.6%	7.3%	5.9%
Others	15.6%	15.6%	15.6%	5.2%	14.6%	11.7%

Table 3
Recovery coefficients and number of equivalent operating hours per power plant category.

Activity Sector	DH recovery	
	$\eta_{DH,\ HT}$	***hh***
1. CHP DH	45%	3500
2. CHP industry	20%	7000
3. Potential CHP no heat recovery	40%	7000
4. Simple power plant	30%	7000

$$E_{heat,DH} = E_{prim} \cdot \eta_{DH,\ HT} \cdot \frac{hh_{DH}}{hh_{process}} \tag{2.11}$$

2.1.2. *Waste to energy plants*

The evaluation of the heat recovery from waste-to-energy plants follows the same approach used for CHP plants in equation (2.11) with a recovery efficiency assumed as $\eta_{DH,\ HT}$ = 30% retrieved from the average performances of similar plants contained in the annual DH networks report [62] generated by the Italian Association DH AIRU. The input data to calculate primary energy E_{prim} is the quantity of burnt wastes m_{waste}[kg] from the national cadastre of waste management [59], which is then divided by the specific heat value c_{waste} of waste [MWh/kg] equal here to 32 MWh/kg (2.12):

$$E_{prim} = m_{waste} \cdot c_{waste}\ [MWh] \tag{2.12}$$

2.1.3. *Wastewater treatment plants*

The input data for the estimation of the excess heat potentially recoverable in DH network from wastewater treatment plants (WWTP) has been taken by the Hotmaps EU project [6]. From the online Hotmaps Toolbox [64], the average excess heat power thus computed can be downloaded for each of the existing wastewater treatment plants in the EU28 zone. The recoverable energy $E_{ww}$is calculated according to equation (2.13)

$$E_{ww} = c_{ww} \cdot V \cdot \Delta T \cdot hh_{ww}[MWh] \tag{2.13}$$

The assumptions of this calculation are the heating value of wastewater c_{ww} equal to 1.16 kWh/m^{3}K, ΔT equal to 5 K and the volume V equal to the product of the daily flow rate, considered of 200 l/day/inhabitants, and the number of equivalent hours per day, set equal to 18 h/day [65]. Data are drawn from the European Environment Agency database. This amount of energy represents

Table 4
Overall demand and heat sources results of the present work in comparison with HRE project.

Regions	Heat demand HRE TWh]	Excess heat HRE [TWh]	Heat demand [TWh]	DH potential heat demand [TWh]	Excess heat [TWh]	Renewables + WWTP [TWh]
Abruzzo	3.87	1.01	7.07	2.08	0.60	1.51
Basilicata	2.91	1.09	2.88	0.79	0.77	0.66
Calabria	9.03	3.94	7.55	2.09	2.51	2.41
Campania	26.45	3.67	19.21	4.55	1.68	3.23
Emilia Romagna	27.35	12.48	30.48	9.11	8.09	6.45
Friuli Venezia Giulia	6.61	7.09	6.68	2.60	4.69	1.40
Lazio	30.34	23.90	30.10	10.60	6.03	14.86
Liguria	9.60	14.22	8.83	3.30	1.96	1.21
Lombardia	66.38	39.42	65.56	25.89	15.33	15.34
Marche	4.73	1.21	9.09	2.02	0.57	1.50
Molise	1.24	0.63	1.32	0.48	0.39	0.36
Piemonte	26.83	12.52	30.56	15.51	10.85	9.13
Puglia	21.19	54.78	14.85	4.01	11.63	2.98
Sardegna	8.41	23.92	9.11	3.91	7.35	4.69
Sicilia	15.71	31.95	15.43	4.37	8.15	4.12
Toscana	18.84	9.08	21.97	5.97	3.20	7.28
Trentino Alto Adige	7.81	0.98	7.09	3.27	0.89	1.48
Umbria	5.06	3.12	5.54	1.50	0.82	1.00
Valle d'Aosta	0.90	0.09	0.93	0.47	0.07	0.17
Veneto	34.31	13.59	34.77	11.38	5.05	7.39
Total	**327.57**	**258.69**	**329.02**	**113.90**	**90.64**	**87.18**

the low-temperature recoverable excess heat from the source, $E_{heat,LT}$ [kWh/year], that can be considered as source for DH.

Eventually, by applying equation (2.5) with COP equal to 3.1 (obtained by the empirical Martynovsky [59] equation (2.7) with $T_E = 19$ °C, $T_C = 90$ °C) and $\eta_{tech} = 0.8$, the amount of thermal energy actually recoverable in DH networks is obtained.

2.2. Renewables

Differently from waste heat sources which are locally and punctually assessed, the useful thermal energy from renewable energy sources calculation is based onto biomass and geothermal resources availability maps. Starting from the maps, the useful thermal energy production from the natural resources is calculated based on average production efficiencies and technological limitations, together with some constraints in accordance with long-term strategies for sustainable deployment of the biomass source. The output of this renewables assessment therefore consist in a threshold value of the maximum possible use of the renewable sources. The amount of energy that can be used in single specific implementations is subject to the design of individual production plants whose position and size remains to be evaluated in the phase of matching between supply and demand, future development of this work.

The geothermal and biomass maps used in this study have been provided by Halmsatd university and retrieved from the European project Heat Roadmap Europe 3 (also known as Stratego [66,67]), focused precisely on the mapping of the renewable heat sources in Europe. For each EU member states the maps have been created on NUTS[1] 3 level, which for Italy correspond to provinces. Concerning solar thermal, a different approach based on the coverage of heat demand has been followed and it's detailed in the following.

2.2.1. Biomass

The input data for the calculation of potential DH heat coming from biomass plants are represented by in biomass for energy purposes availability maps. These maps, coming from Ref. [66], consist in multiple layers concerning the biomass coverage all over Europe in terms of their energy content [MWh] with a NUTS3 regions geographical distribution. In this work, in accordance with local policies, only the biomass coming from the forestry maintenance and pruning have been considered so that a primary energy input from biomass is defined, E_{bio} [MWh], as the sum of these two components.

The available resource has been then analysed according to the uses foreseen by the long-term national strategy document [68]. Here, based on national energy simulations of a 2050 decarbonized scenario, the national total available biomass is foreseen to be used for the majority, 54%, for power generation, 32% for civil and industrial sector and 13% for hydrogen production and carbon capture.

Since the scope of this study is to privilege energy efficiency and waste heat recovery, only waste heat from biomass power generation has been considered to be integrated in DH, so 54% of the total resource with an average value of thermal recovery efficiency set to $\eta_{DH,\ HT} = 41\%$ [62] so that the annual technical potential by province level, NUTS3 region, is calculated as equation (2.14):

$$E_{heat,\ bio,DH} = E_{prim,bio,el} \bullet \eta_{DH,\ HT} \bullet \frac{hh_{DH}}{hh_{process}}\ [MWh] \qquad (2.14)$$

with $E_{prim,bio,el} = 54\% E_{prim,bioTOT}$. The hypothesis of neglecting heat only plants considering only waste heat from power production is quite strong, but is here taken motivated by the fact that, even if in Italy approximately 40% of the biomass used in DH systems is consumed by heat only generation plants, considering the heat losses in these rural areas ranging from 35 to 45%, it would be more resource efficient to cover building heating needs with high efficiency individual system rather than simple boilers DH systems.

2.2.2. Geothermal energy

The input data are the maps assessing the availability of the resource on the national territory, outcomes of the European GeoDH project [69], to whom technical recovery coefficients are consequently applied. Generally, it is difficult to uniquely quantify the magnitude of potentially recoverable heat from geothermal reservoirs. There exist different geological parameters indicating the presence of a geothermal potential in the ground, such as the soil temperature gradient, but there are also different elements that influence the actual possibility of exploiting this useable heat such as the permeability of the rock bed or the presence of water that affects the quality and quantity of the heat flow [67]. Nevertheless, some estimations have been performed.

Among the geographical layers of GeoDH map, three have been considered interesting for DH application and used in this study:

- High temperature areas – with underground temperature of at least 90 °C, to a depth of 2 km.
- Medium temperature area - with underground temperature of at least 50 °C, to a depth of 1 km.
- Low temperature area – Shallow geothermal resource at low temperature (e.g. sedimentary aquifers and likely hydrothermal area)

These maps allow to spatially define the geothermal potential exploitable in DH networks directly (high temperature area) and indirectly through the use of heat pumps (medium and low temperature areas).

Nevertheless the maps give no indication for the quantification of useable geothermal energy. An empirical approach has been used here based on the analysis of existing geothermal DH plants: a maximum percentage of coverage k_{RES} of the heating demand of DH, $E_{need,DH}$, is defined so that the useable geothermal heat in DH $E_{heat,DH,geo}$ is calculated as equation (2.15):

$$E_{heat,DH,geo} = E_{need,DH} \bullet k_{RES}\ [MWh] \qquad (2.15)$$

with the fraction k_{RES}here assumed being:

- High temperature area – $k_{RES} = 100\%$
- Medium and low temperature area – $k_{RES} = 30\%$

This approach is simplified and empirical: usually in areas with a high temperature level of geothermal energy (above 100 °C) the total heat demand is fully covered by geothermal energy (e.g Toscana region or Iceland plants) so that a full coverage of DH demand is reasonable. For lower temperature geothermal energy plants, only the base load of the heat demand is usually covered by geothermal energy, approximately 30%. In case of medium and low temperature heat, also the efficiency of the heat pump correlated to the temperature upgrade has been considered and defined by equations (2.6) and (2.7).

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[1] **NUTS (Nomenclature of Territorial Units for Statistics)** is a geocode standard for referencing the subdivisions of countries for statistical purposes.

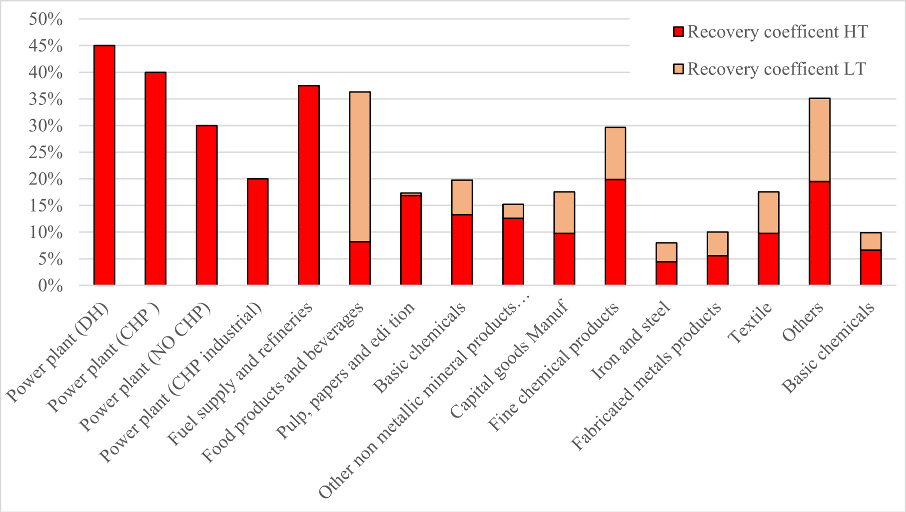

Fig. 2. Obtained recovery coefficients at HT and LT, per industrial process and power plant typology.

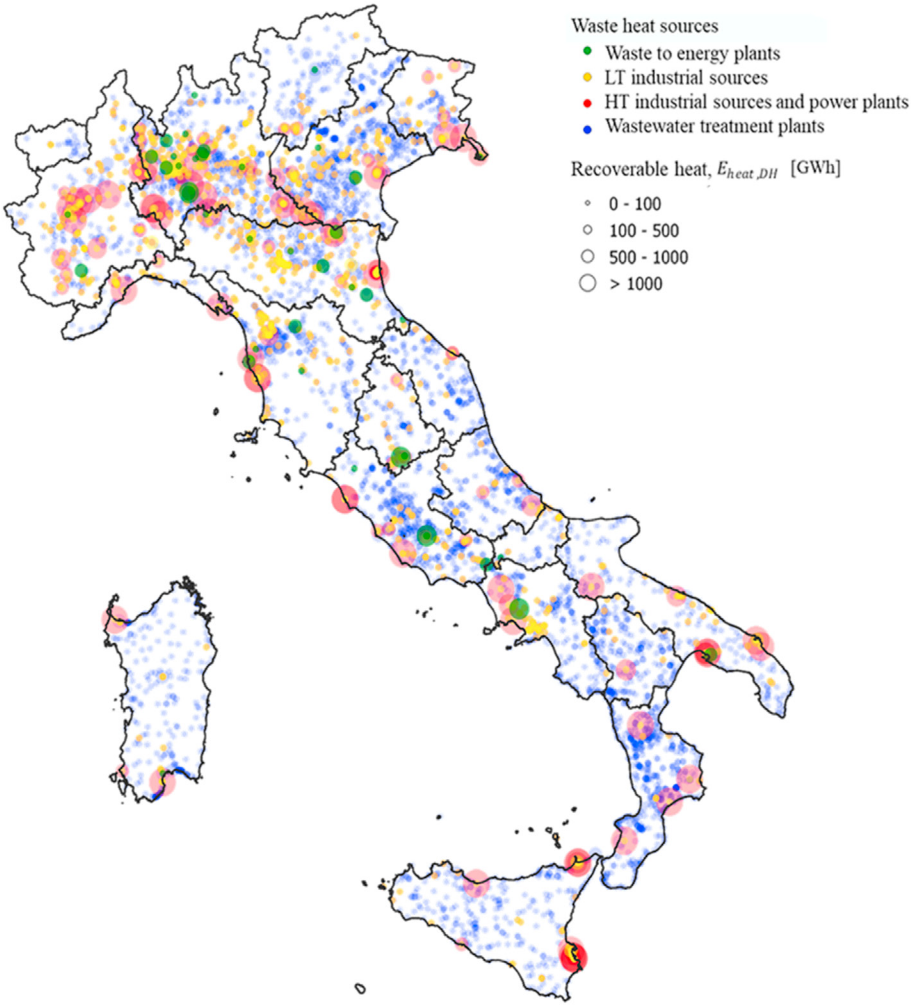

Fig. 3. Waste heat sources map: high temperature industrial sources and power plants in red, low temperature industrial sources in yellow, waste to energy plants in green and wastewater treatment plants in blue.

According to this method, also the heat demand map is required as input for this calculation. Being the objective of this work the evaluation of energy sources in the framework of full potential development of DH in the territory, the overall national potential

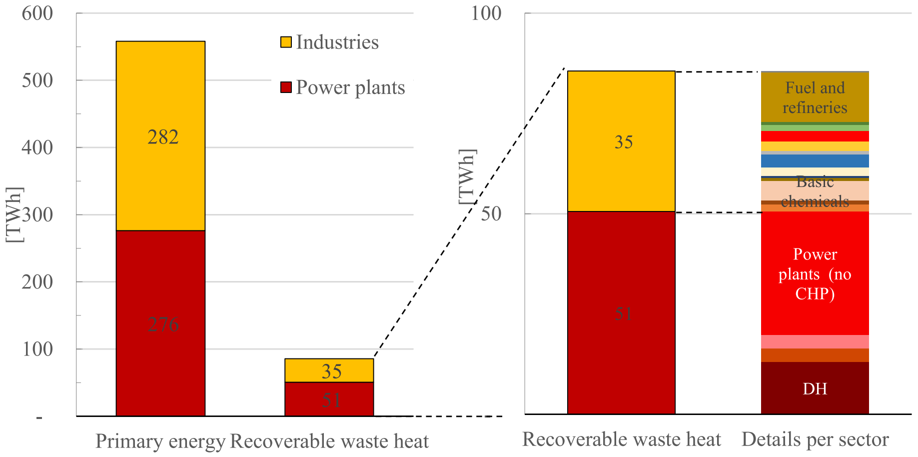

Fig. 4. Graphic representation of the fractions of recoverable heat $E_{heat,DH}$ by type of industry and power plant in comparison with primary energy input.E_{prim}

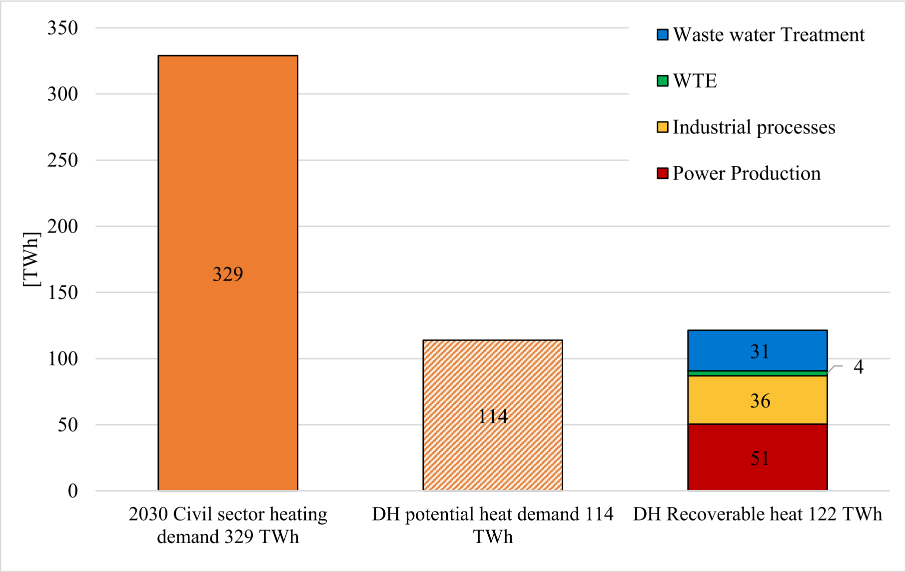

Fig. 5. Total recoverable heat in DH from all the excess heat sources in comparison with national civil sector heat demand and potential heat demand to be served by DH.

heat demand coverable by DH is considered in this calculation. This has been calculated in the framework of this project and presented in a concurrent work [70]. The heat demand suitable for DH connection $E_{need,DH}$ map is elaborated starting from the national heat demand map and from national census database which indicates for every census section the number n and type, centralized or individual, of heating systems serving each building. The potential heat demand for DH, $E_{need,DH}$, is therefore calculated as the fraction of the overall civil sector demand (residential and tertiary) with a heating system suitable to be substituted by DH substation without the need to retrofit the internal distribution heating system: centralized heating system for multifamily buildings and single houses. The calculation is therefore done as equation (2.16):

$$E_{need,DH} = E_{need,civil} \cdot \frac{n_{centralized}}{n_{tot}} \; [MWh] \tag{2.16}$$

Future steps of this work will be the analysis of the same potential but in a future scenario characterized by refurbished buildings in terms of retrofitted envelopes and also emission and distribution systems so that if the $E_{need,civil}$ terms is foreseen to be decreasing, the $n_{centralized}$ term is supposed to be increasing.

2.2.3. Solar thermal

Regarding the evaluation of the solar thermal energy potential to be integrated in DH, no uniform methodology has been fund in literature. It depends on the used technology, space availability and temperature levels. Since the objective of this work is to give support to decision makers, the surface needed for solar field is not considered as the input constraint, but the eventually a consequent result. The goal here is to calculate the feasible solar energy integration in DH system. It's up to the decision maker to decide the technology and the space to allocate to this technology to realise it. The technically feasible solar integration in DH $E_{heat,DH,ST}$ is calculated as equation (2.17):

$$E_{heat,DH,ST} = E_{need,DH} \cdot k_{RES} \; [MWh] \tag{2.17}$$

with [71]:

- k_{RES} = 50% in case of seasonal storage
- k_{RES} = 10% in case of daily or no storage

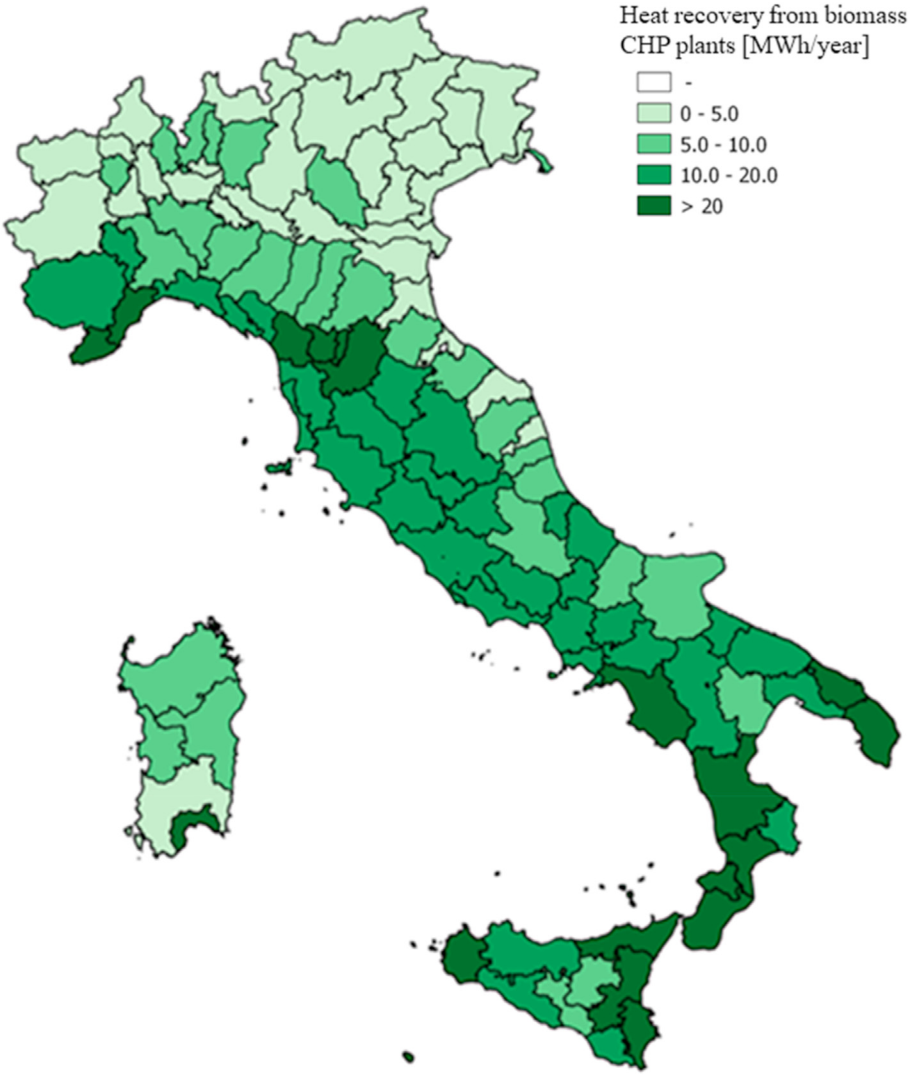

Fig. 6. Annual heat recovery from biomass cogeneration plants (forest maintenance and pruning residues) in Italy, at NUTS3 level (provinces).

Based on existing DH networks exploiting solar thermal energy without the use of seasonal storages, the coverage factor has been assumed to be equal to 10% in this project, leaving the hypothesis of seasonal storage to application also in combination of its use together with the other sources in sector coupling simulation scenarios, future step of this work.

3. Results

The results of the application of the formerly presented methodology to assess waste and renewable heat sources in Italy are presented. These have been analysed in terms of their quantity and their geographical position. The outcome of this analysis is therefore a map of available heat sources for DH elaborated in QGIS software [72].

3.1. Waste heat sources

The resulting coefficients $\eta_{DH,\,HT}$ for the analysed ETS sectors are presented in Fig. 2.

The categories allowing a higher recovery of high temperature waste heat, thus allowing a direct recovery, are power plants and refineries, followed by pulp and papers and chemicals sector. Food and beverages and fine chemical allow also important amount of waste heat but for the majority at low temperature thus requiring a temperature upgrade here foreseen by a heat pump. It has to be noticed that these categories include a broad variety of industrial processes so that the average value of heat recovery for the single industrial site could be found under or overestimated in comparison with site specific energy audit results.

The map of the available waste heat sources identified at national level is then shown in Fig. 3.

It can be noticed that the high temperature waste heat sources, red points, and waste to energy plants, green points, are in general less numerous than other categories but they generally provide the biggest quantity of energy per single site. The regions with the majority of these sources are in the north of Italy, but several among the biggest production plants are located in the south of Italy. Apart from one plant located in the south, all the waste-to-energy plants are located in the northern part of the country. It is interesting to notice instead that, even if the single sources of heat per site is smaller, wastewater treatment plants, in blue, are widely distributed along the territory being somehow correlated with the population presence so that in every portion of area where there's a heat demand, one of these sources can be surely found.

The aggregated results of the heat recovery analysis on ETS

Fig. 7. Availability of geothermal resource on the Italian territory.

processes, namely industries and power plants, are presented in Fig. 4.

Starting from a primary energy input value of about 558 TWh, according to the previously illustrated assumptions and methodology, the share of waste heat recoverable in DH is reduced to 86 TWh. This figure includes all the considerations of temperature levels, technological efficiencies of heat exchange and heat pumps and temporal correspondence with the energy profiles accounted by the ratio of equivalent hours. The reduction from primary to realistic recoverable amount of waste heat is significant. This is an extremely cautious scenario that could significantly increase assuming the use of even large thermal storages that could affect the best temporal matching of supply and demand and imagining a significant drop in network temperatures in future DH systems.

Out of these 86 TWh, it should be noted that the major share comes from power production plants and specifically from plants in current non-cogeneration assets: in these plants, even if an additional important investment could be required, the recoverable heat could be significant. Considering the other industrial production sectors, most of the recoverable heat is estimated to be present in the oil sector followed by the chemical one.

The reduction from primary to practical realistic recoverable heat in DH is important but the result should not be discouraging, in fact if these numbers are compared to civil sector heat demand the perspective is different. The obtained results are in fact summed with the 3.6 TWh of heat recoverable from WTE plants, and 31 TWh from WWTP for a total of 121 TWh available to be integrated in DH network. Fig. 5 shows these results in comparison with the national heat demand of the civil sector, which is the sum of residential and tertiary sectors energy needs for space heating and domestic hot water, equal to 329 TWh calculated for 2030 [70]. Out of this amount, 114 TWh are the energy needs of buildings which have a suitable heating plant to be connected in DH, which constitutes therefore the potential heat demand expansion for DH.

It means that, looking at the total amount of waste heat recoverable in DH mapped in the country equivalent to 122 TWh, it is higher than the total heat demand for potential full expansion of DH. Even if important, this result does not mean that the full recovery is possible though, since a geographical matching of demand and supply would be required. These results are the input of this phase of analysis of geographical and economic matching between demand and supply considering distribution infrastructure costs, future development of this work.

3.2. Renewable heat

The waste heat recovery potential shown in the previous section, is here summed up with the total potentially useful heat from the analysed renewable sources: biomass, geothermal energy and solar thermal. Looking at the recoverable heat from biomass

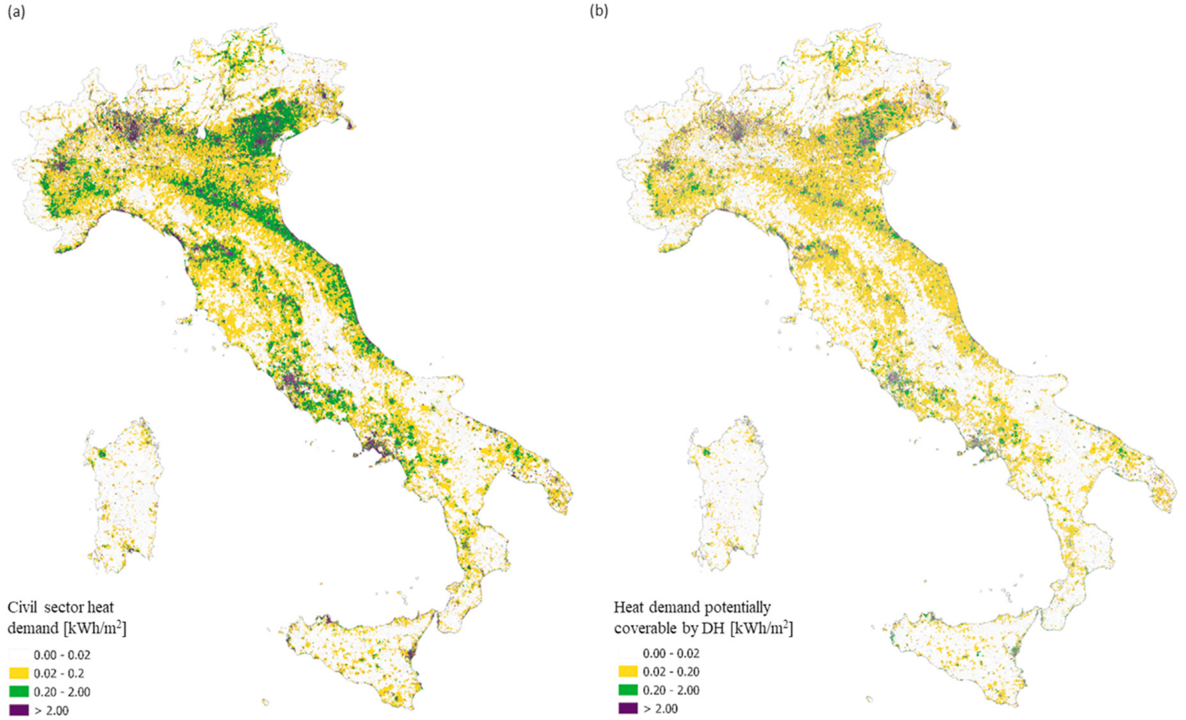

Fig. 8. Map of the national distribution in census section of civil sector heating needs (a) and of heat demand potentially coverable by DH (b) per m^2 of census area [kWh/m^2].

cogeneration, Fig. 6 show the national potential recoverable heat per land area at NUTS3 level, resulting in an overall value of 5.49 TWh for the entire Italian State.

In the case of geothermal energy, the starting point of the analysis is given by the maps assessing the availability of the resource on the national territory.

The maps used in this study, elaborated in Ref. [69], are shown in Fig. 7 for Italy. The colored layers indicate the areas previously defined with potential of geothermal energy at high temperature in red, medium temperature in yellow and low temperature in blue.

The geographical distribution allows to spatially define the geothermal potential in Italy and, according to the geological parameter layers, to distinguish between geothermal potential directly exploitable in DH networks (areas in red and yellow) and indirectly exploitable through the use of heat pumps for temperature upgrade (light blue areas). As previously mentioned, these layers have been juxtaposed with the maps of heat demand in order to define the quota of geothermal heat in proportion with the DH heat demand.

Fig. 8 show the geographic distribution of heat demand and potentially DH demand per area at census section level.

On the basis of these empirical assumptions, the annual geothermal energy potential to cover the heating needs amounts to 7 TWh, at high temperature, and to 11 TWh, at low temperature requiring a heat pump. Using the same map to estimate a 10% coverage of the heat demand by solar thermal plants, the result is that 11 TWh of suitable heating demand can be technically met by solar thermal energy.

These results of the useful renewable energy useable in DH are summed up to the recoverable waste heat in Fig. 9. The amount of sustainable low emission heat sources on the county is therefore 156 TWh, which use in DH is subordinated to the matching between these sources and the DH potential heat demand at geographical level.

In the hypothesis of using seasonal storages to combine all these sources within a framework of sector coupling analysis, a hypothetical heat recovery calculation is shown in the following figure which represents the same results of the previously used methodology but without considering the limitation of equivalent DH running hours, imagining to be able to recover the full available waste heat (see Fig. 10).

3.3. Discussion

In order to assess the potential quantification of the recoverable heat in DH, a parallel phase of analysis pf potential diffusion of DH is required. It is in fact just in the superposition and combination of the heat demand and sources suitability, costs, and geographical proximity that the potential of DH fed by waste heat and renewables can be assessed. This evaluation is part of the current work and future step of this analysis. Nevertheless, the geographical distribution of waste heat and DH heat demand can already be shown at NUTS3 region which is depicted in Fig. 11. It clearly emerges a general mismatch between demand to be covered by DH, in green, and available waste and renewable heat, in red. In fact, being the heat demand influenced by the climate, the northern region have in general a higher request of energy needs than what the available sources can cover. The opposite situation happens in the south of Italy. These results imply that it can be supposed that the entire amount of renewables and waste heat available could be integrated in DH in the north of Italy in a full DH potential deployment scenario, while this could not happen in the south of Italy. Again, this result is not to be seen in a discouraging perspective because it clearly shows some potential future investigation for district cooling potential recovery thanks to heat driven cooling technologies.

The obtained results are compared to the ones obtained in the Heat Roadmap Europe project as reference in the following table: the heat demand results are completely comparable. It can be noticed instead that the results of conventional excess heat recovery are always much higher in HRE project since they represent

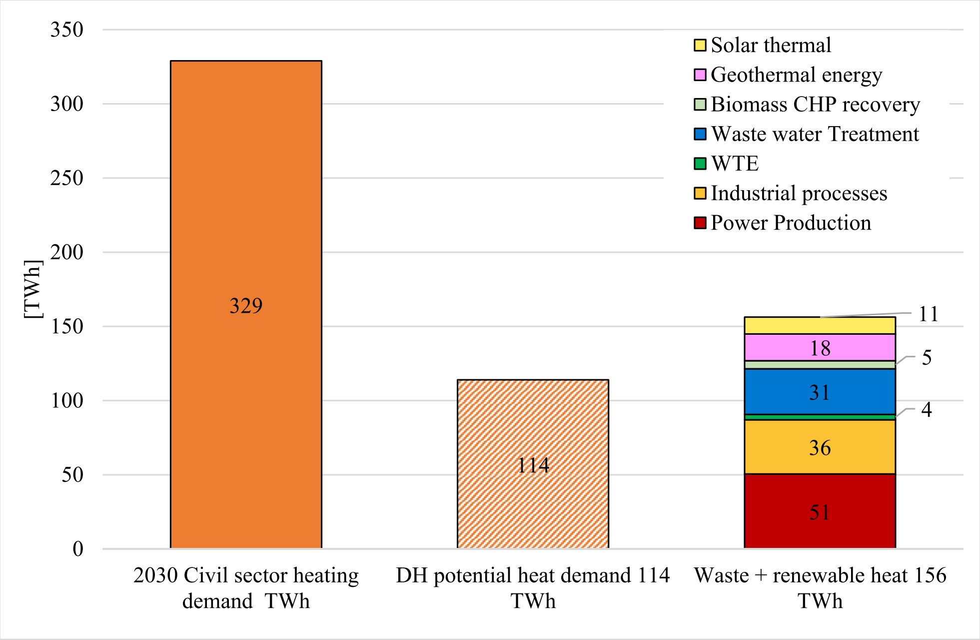

Fig. 9. Total recoverable heat in DH from all the excess heat and renewable sources in comparison with national civil sector heat demand and potential heat demand to be served by DH.

the theoretical recoverable potential, while the approach used in this work aims at calculating the realistic potential. Considering also renewables, the total sustainable sources of heat are more comparable to HRE results even if always lower.

4. Conclusions

In this work the mapping and quantification of waste heat and renewable energy sources suitable for the integration in DH systems in Italy is analysed. The methodology to assess them allow the quantification of the realistic amount of energy recoverable from the input data, considering temperature levels and technological recovery efficiencies. The methodology allows the calculation of recoverable excess heat from industrial existing sites and also the quantification of useful heat deriving by natural renewables sources as biomass geothermal and solar thermal. The outcome is a schematic, clear and reproducible methodology together with the Italian heat map of potential sustainable sources

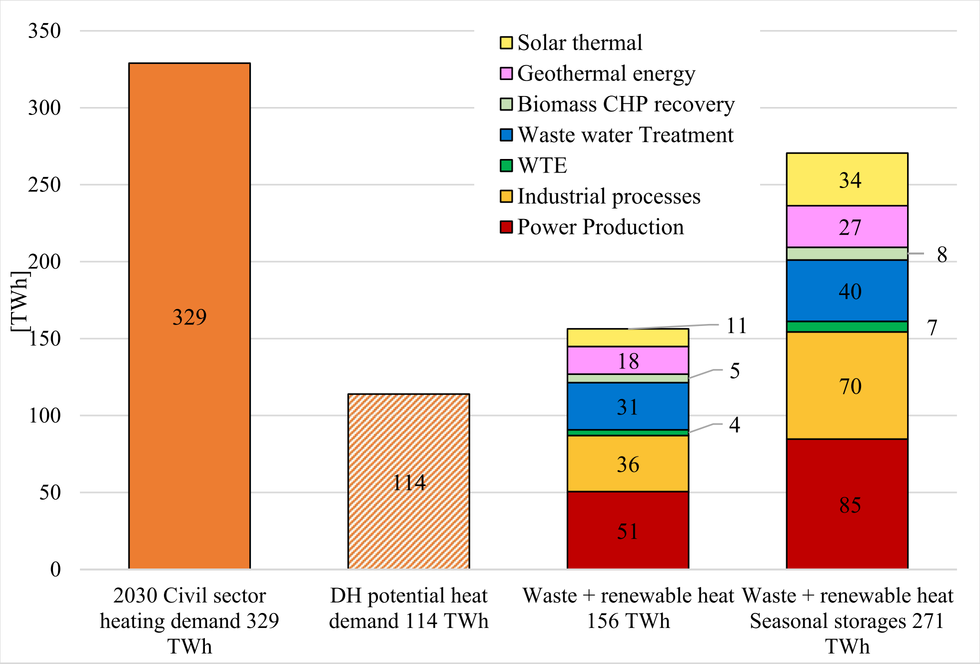

Fig. 10. Total recoverable heat in DH from all the excess heat and renewable considering the use of seasonal storages.

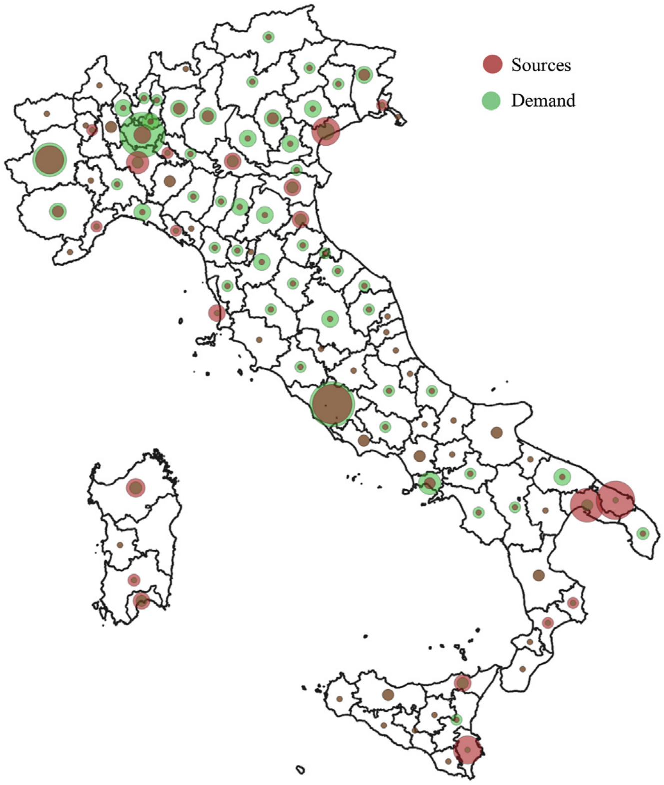

Fig. 11. Geographical national distribution in NUTS3 region of suitable DH heat demand and available waste heat and renewables for DH integration.

for DH. The results show that, in comparison with the total heat demand of the civil sector for space heating and domestic hot water of 329 TWh, 156 TWh of waste and renewable heat can be found along the territory out of which112 TWh from heat recovery of already existing industrial, power and wastewater treatment plants, and 42 TWh from renewable natural resources. This result is even more significant in comparison with the amount of heating needs that are suitable for a DH connection, amounting to 114 TWh.

The balance among the mapped heat sources and the heat needs is not uniform along the country so that it can be deduced that not the overall amount of heat sources energy identified could be actually used. In the northern part of the country in fact the heat demand exceeds the availability of waste and renewable heat identified, weather in the southern regions of the country the opposite outcome is found. Nevertheless, this result highlights some potential opportunities of development of district cooling based on the identified sources.

The methodology and the consequent results consider very precautionary and realistic hypothesis that's reduces significantly the amount of theoretical energy exploitable in DH: if on one hand this aspect adds a certain reliability to the results, on the other hand could imply a certain underestimation by not considering some improving aspects such as the use of large-scale storages or the sharp reduction of network temperatures towards low temperature DH systems.

Further step of the work includes the estimation of the economic potential considering investment and operating costs of the exploitation of these energy sources in combination with infrastructure costs for DH network expansion in order to identify an overall renewable DH potential for the country.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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