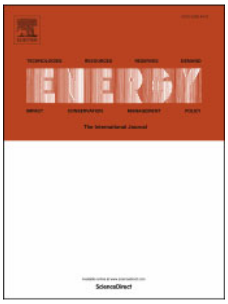

Industrial excess heat recovery in district heating: data assessment methodology and application to a real case study in Milano, Italy

A. Dénarié, M. Muscherà, M. Calderoni, M. Motta

PII: S0360-5442(18)31925-X
DOI: 10.1016/j.energy.2018.09.153
Reference: EGY 13847

To appear in: *Energy*

Received Date: 30 October 2017
Revised Date: 19 September 2018
Accepted Date: 22 September 2018

Please cite this article as: Dénarié A, Muscherà M, Calderoni M, Motta M, Industrial excess heat recovery in district heating: data assessment methodology and application to a real case study in Milano, Italy, *Energy* (2018), doi: https://doi.org/10.1016/j.energy.2018.09.153.

Title

Industrial excess heat recovery in district heating: data assessment methodology and application to a real case study in Milano, Italy

Authors

A. Dénarié [a] ([1]), M. Muscherà [b], M. Calderoni [c], M. Motta [a].

a - Department of Energy, Politecnico di Milano, 20156 Milano, Italy

b - Enersem, Politecnico di Milano Spin off, P.za Leonardo da Vinci, 32 – 20133 Milano

c - R2M solution, Polo tecnologico, Via Fratelli Cuzio, 42, 27100 Pavia

Highlights

- Mapping of potential industrial excess heat recovery through district heating
- Multicriteria Decision Analysis technique used to handle input data uncertainty
- Application of the methodology to real case study in Italy

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[1] Corresponding author (A. Dénarié). Tel.: +39 02 2399 3850; e-mail address: alice.denarie@polimi.it.

Abstract

This work deals with the mapping of industrial excess heat recovery through district heating. In this paper a methodology to estimate industrial waste heat recovery in a given territory is presented and applied. The method is particularly suitable for a relatively large, but limited, geographical region, with a significant number of industrial facilities. The multiplicity of available methodologies to calculate heat recovery from industrial energy consumptions and the related input data variety generate a wide range of results. The intent is to handle the variety of results and to include the uncertainty related to input data quality thanks to the application of Multicriteria Decision Analysis techniques. The presented methodology is then applied to a real case study of new district heating project in Italy. The plan is to connect the city of Milano to a large CHP plant 25 km far, which is currently wasting 80% of its rejected heat. The aim of the case study is to quantify the industrial excess heat that could be recovered along the new district heating. The elaborated methodology has been applied to estimate the recoverable heat potential in five alternative paths and to find the one allowing maximum recovery.

Keywords

District heating, Industrial excess heat recovery, Energy mapping, MCDA

Summary

Abbreviations

AIA	Autorizzazione Integrata Ambientale (Environmental authorisation)
CH	Chemicals industry
CHP	Combined Heat and Power
DH	District Heating
EGHR	Exhaust Gases Heat Recovery
ETS	Emission Trading System
EU	European Union
F	Food industry
HRE	Heat Roadmap Europe
P	Power company
PP	Pulp-paper industry
RES	Renewable Energy Sources
TH	Thermal energy

1 FRAMEWORK

DH is an urban energy infrastructure which enables the use of heat that would otherwise be wasted [1] by distributing it to users across the territory. Cogenerated heat, waste to energy, industrial recovery heat, as well as renewable heat from biomass and solar thermal are energy sources that can reduce the primary energy consumption of this system [1].

In 2004, with the European Directive 2004/8/EC [2], the European Union promoted for the first time cogeneration as a measure of efficiency and mentioned the excess heat recovery as a way to reduce primary energy consumption. An important contribution to acknowledge DH as a strategic system to recover all this excess heat was provided by the European project Ecoheatcool [3]. The main outcome of this project was that the European net heat demand in 2003 was equivalent to the heat lost in the energy conversion from primary[2] to final[3] (updated data for 2007 can be found in [1]). The second main outcome of Ecoheatcool was that all this amount of excess heat could be "retrieved" thanks to DH. DH was consequently presented as a way to meet customer demand with heat that would otherwise be lost, as an efficient means to move heat through the city to suitable customers. The efficiency of this system is however subordinated to certain conditions, such as energy losses, heat densities and heat production costs [4]. Ecoheatcool is considered the first comprehensive evaluation of heat recovery potential through DH; since then the use of DH to increase urban energy efficiency has been investigated by different researches and analysis. Central research themes are the recovered heat from power plants and industrial processes [5] [6] [7] [8] [9], the renewable energies' exploitation [10] [11] [12] and the DH role in reducing energy consumption in present and future energy scenarios [13].

In 2012, the European directive on energy efficiency [14] has included DH among measures of urban energy efficiency and it has pushed member states to evaluate costs, benefits and potential diffusion of this technology. The directive has also outlined the importance of increasing efficiency in industrial facilities through energy audits, of the implementation of suggested efficiency measures and of the connection to DH. Excess heat recovery from industrial processes through DH networks has become more and more important in energy planning in Europe.

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[2] Primary energy: energy extracted or captured directly from natural resources
[3] Final energy: energy available for consumers' end use (corresponding to gross customer heat and power demands)

Nevertheless, later years EU policies have promoted energy efficiency particularly in the power sector with less attention to the heating and cooling sector [15], [16]. Many member states have witnessed a great development of efficiency measures and a growth of RES in electricity sector, which share has averaged 28.8% in EU 28 in 2015 [17]. No equivalent development can be noticed in the heating and cooling sector, which RES share was 18.6% in average in EU 28 in 2015, although it's worth noticing that the thermal energy represents the biggest demand of final energy in Europe, accounting for the 50% of annual energy consumption [18]. It's with the 2016 EU strategy for heating and cooling, that EU really commits in energy efficiency of the thermal sector [18] in order to reduce energy waste; this document states that a shift to RES and excess heat recovery is possible and necessary and it highlights the role of DH in supplying heat.

In the background of this recent EU communication, the Heat Roadmap Europe project [19] has shown the potential energy reuse end emissions reductions in the residential heating and cooling sector thanks to DH. The project has given a different perspective of the future development of the energy sector: with respect to the electrification objectives and the huge reduction of buildings' heat demand promoted by EU strategies, the project shows that another scenario with increased efficiency of energy supply and high exploitation of RES and industrial excess heat is possible through the expansion of DH. This new scenario is based on the exploitation of local synergies between heat rejection and heat demand [20], [21]. The project aims at identifying European strategic areas for DH development highlighted by the combination of geographical mapping of energy demand and supply with energy system modelling. The analysis of these local synergies creates opportunities of local heat recovery, possible thanks to DH, which were not considered in previous studies. The project's follow-up, Stratego, [21] is the national level implementation of the analyses performed at EU level in the two first studies.

It's worth noticing that one of the NUTS[4] 3 region that was highlighted by the project mapping in [20] to have a relevant presence of excess heat is the Milano area, a highly populated area which offers extended expansion possibilities for excess heat recovery and use of RES by district heat distribution. With these premises, in the framework of the EU project SmartReFlex [22], the case study developed in this paper has the intent to be a continuation of the analyses started in the framework of the HRE, as a further more detailed analysis at local level in the perspective of the future DH development in this area.

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[4] The NUTS classification (Nomenclature d'Unités Territoriales Statistiques) is a geographical system to divide the administrative territory of EU countries for statistical purposes developed by Eurostat

1.1 SCOPE OF THE WORK

Scope of this work is to develop a relatively simple approach to estimate the industrial excess heat potential which can be recovered in a DH network in a given territory. Such task is in between a potential analysis and a pre-feasibility study. As a matter of fact, on one hand considering large numbers of facilities requires a general approach and, on the other hand, the complexity and diversity of industrial processes calls for a detailed analysis of each process. In order to be simple and little resource-consuming, the presented approach bases on public-available data from industrial processes, thus avoiding the need for direct communication with industrial owners. A methodology, based on the review of existing works and methods, is elaborated to manage the uncertainty of input data and to choose the best approach to calculate a potential, according to input data type. In this process, three basic steps can be identified:

- input data collection, to calculate the heat recovery potential from each industry;
- calculation of heat recovery from the input data for each industry;
- final potential recoverable heat in district heating line assessment.

The drawback of this process is that public available data may be not fully reliable if not constantly updated. Another source of uncertainty is given by the variety and diversity resulting from the heat recovery calculation methodologies that can be found in literature.

For this reason, Multicriteria Decision Analysis (MCDA) techniques have been used with the double aim of:

1. handling low input-data reliability;
2. comparing different methodologies found in literature for estimating the amount of excess heat.

MCDA gives in fact a valuable support in finding one single value of heat recovery from the different results provided by each methodology.

The novelty of this work is therefore the field of application of this well know technique (MCDA): starting from existing algorithms for estimating available excess heat from a given industrial process, the elaborated methodology selects and quantifies suitable criteria to be applied to the MCDA, so as to come up with one value of recoverable excess heat from each industrial process. Afterwards, the total potential in the given region, in this case along a given path of a DH network, is calculated.

1.2 HEAT RECOVERY

Excess heat can be defined as the amount of energy used in industrial processes that is emitted again to the environment in the form of heat: all forms of sensible and latent heat escaping a system without being a purpose of the system are considered as excess heat [23].

Multiple factors affect the potential for excess heat recovery. These include the characteristics of the excess heat source and sink, the compatibility of sources and sinks (i.e. temperatures, capacity, timing and location), the available heat recovery technologies (costs and efficiency), energy prices, investor priorities and site-specific issues. Based on these, it is possible to define different levels of excess heat potential: theoretical, technical, economic and commercial potential [23],[24]. According to [23], waste heat recovery potential can be mainly distinguished in three different types:

- the theoretical potential, which considers physical constraints;
- the technical potentials, which depends on implemented technologies;
- the economic potential, that defines the feasibility considering financial aspects.

The present work focuses on theoretical and technical potentials of heat recovery, without taking into account economic or commercial issues. The transition between theoretical to technical potential is driven by exergy availability and technologies efficiency [25]. It is straightforward that two streams with the same energy content but different exergy value offer different opportunities in terms of heat recovery. In addition to that, heat recovery technologies, such as heat exchangers, strongly affect the amount of recoverable heat. In this study, potential heat recovery at low temperature (<70°C) that needs a temperature upgrade by heat pumps to be recovered in DH return line (60°C) is not considered since it would require an economic assessment, which is out of the focus of this study. Moreover, past experiences show that heat recovery investments including heat pumps are riskier than investments with simple high temperature heat recovery [26].

1.3 MULTI CRITERIA DECISION ANALYSIS

The estimation of potential heat recovery in a given area develops in an uncertain environment. The uncertainty here is related both to input data quality and to the results' variability of heat recovery calculation methods. To face this type of problems, decision science [27] support the analyses. Science of decision-making allows critical and mathematical rigorous assessments in dealing with problems of choice among alternative scenarios, especially in a not fully clearly determined context. For input data evaluation, decision theory in non-deterministic environment [28] can be used. The indeterminacy, in this case, arises from the inaccuracy or lack of measured data and in the nature itself of the potential analysis. Decision making in uncertain domain is based on the concepts of probability and utility [28]. Both these concepts are used in this works to assess input data reliability, namely the probability that data used corresponds to reality. Decisions theory methods applications to assess data quality can be found in [29] and [30]. Among decision theory techniques, Multi Criteria Decision Analysis [27] can help in finding the best calculation methodology to assess heat recovery potential from input data. MCDA is a decision support tool to face complex problems, which can break down the problem of decision making into steps evaluated with respect to different criteria meanwhile giving a mathematical robustness even to subjective evaluations [31]. MCDA techniques are commonly used in energy related researches: several studies regarding energy planning [32], [33], energy performances of buildings [34] and district heating [35–38] have been published. Here the MCDA is applied in DH systems analysis but with a different goal, as a support tool to choose the best heat recovery calculation methods in relation to several criteria.

2 METHODOLOGY

In this chapter, a description of the methodology to assess theoretical and technical potential of industrial excess heat recovery in DH is presented.

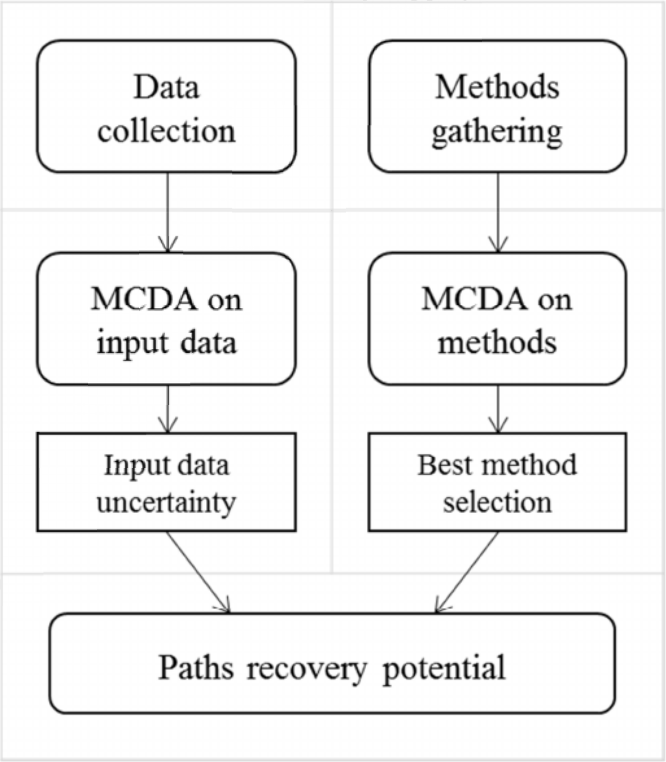


Figure 2.1 describes the workflow followed from data collection to the result. The first step is the collection of all necessary data, in other words, the elaboration of a database gathering all companies operating in the analysed area, including their location and related energy consumption values. Data collected often have uncertain data quality: some data can be missing, not homogenous in terms of units, not updated or exposed to subjectivity, either in the monitoring or collection phase. After having defined the energy consumptions and pollutant emissions of every industry and after having analysed all technological aspects of their industrial processes, the heat recovery potentials need to be calculated. Investigating a wide area regarding several companies, a site visits with detailed energy audits would be time consuming and not cost effective. Dealing with potential analysis, a calculation methodology should be applied in order to estimate the potential of the area. Several methodologies can be found in literature [23]: the second step of the analysis therefore consists in the collection of the methodologies that can be applied to the different input data. At this point of the analysis, multiple input data can be used and different methodologies with different approaches can be applied. Input data can be: energy consumptions (final, primary), pollutant emissions, ETS data (Emission Trading System), final products' amount, measured or estimated. Recoverable potential calculation methodologies, on the other side, could be statistical, formulas deriving from monitoring data, theoretical methodologies. The described process though shows two weak points that needs further analysis: the uncertainty related to input data quality and the multiplicity of heat recovery calculation methodologies which bring to a variety of different results. While dealing with these two uncertainties, a decision support method has been applied in the two steps previously described: first to heat recovery calculation methodologies and then to input data, in order to face multiplicity and uncertainties of results respectively (Figure 2.1). To support the choice of the best heat recovery methodology which best fits with the purpose of this work, MCDA, Multi Criteria Decisions Analysis [27] has been used to rank and chose the best methodology to be applied in the framework of the project. The uncertainty of input data has been taken into account by "scoring" in a similar way the input data according to different criteria assessing their quality. The aim of this step is to give a mathematical form, a coefficient, quantifying input data uncertainty and quality. At the end of these three steps' analysis, a final value of potential recoverable heat for every industrial process has been obtained.

At this point, only the final step must be taken, namely the calculation of the potential heat recoverable in the district heating line which is the simple sum of the values obtained from the industries that can be touched by the district heating network's path. Chapter 2.1 describes in detail the double application of MCDA that has been used in the two final steps of the methodology.

2.1 APPLICATION OF MCDA

At the end of the data collection phase, literature offers a wide set of different methodologies that can be applied to estimate the heat recovery potential in the DH line. MCDA is proposed here to be applied to support the calculation procedure to the final result, to manage complexity, variety and uncertainty related to it. By applying the recovery calculation methods for each industry according to the data provided, a set of different recovery potential values for each company can be obtained. Given the set of results for each industry, the evaluation of the potential excess heat recovery in the DH line can be represented by two questions:

1. Which heat recovery potential result is closer to reality for each industry? Choice of best method.
2. How can I consider input data quality? Uncertainty coefficient

Answering the first question, means finding a way to choose among all the results given by the different recovery methods used, in order to have a single value per industry.

The second question implies finding a way to consider not only the final result, but also its reliability which lies in the uncertainty of the input data. As described in the following paragraphs, this aspect has been taken into account by an "uncertainty coefficient", which multiplies the input data, increasing with the quality and the trustfulness of the collected data.

2.1.1 MCDA applied to heat recovery estimations methods.

In the framework of the here presented work, the pertinence and representativeness of methods and the application scale in relation to a DH project are examples of criteria that can be used to find the most suitable methodology. This phase is necessary because the methods can differ from data origin, volumes of data, representativeness, approach and application field; these attributes are definitely more qualitative than quantitative. In this framework, MCDA is a powerful tool able to translate considerations affected by the decision maker's sensitivity (such as professional experience, confidence in the data and in the method) into a formal and objective model [27]. After defining the goal, here the identification of the most suitable excess heat recovery calculation method, the MCDA is applied following these steps:

- Definition of alternatives: Methods
- Identification of criteria: Approach, data source, representativeness..
- Calculation of performances for every alternatives according to chosen criteria: Scoring of the methods
- Determination of criteria weights
- Determination of preference orders MCDA techniques

The MCDA technique is applied to the performance matrix $\underline{\underline{x}}$ resulting after the first preliminary steps :

$$\begin{array}{ccc|ccc} & & & a_1 & a_j & a_m \\ \hline C_1 & & w_1 & x_{11} & x_{1j} & x_{1m} \\ C_i & \rightarrow & w_i & x_{i1} & x_{ij} & x_{im} \\ C_n & & w_n & x_{n1} & x_{nj} & x_{nm} \end{array} \qquad (2.1)$$

In the decision matrix each element describes the performance of the different alternatives, in this case heat recovery calculation methods, according to each criterion.

The criteria with respect to which they are evaluated can be:

- approach type: top down or bottom up [23];
- data source: statistical analysis, surveys, or monitoring data;
- representativeness: if the field of application is the same, the number of industries investigated is high.

For what concerns performance assessment of every method with respect to each criterion , they could be either numbers and figures or subjective considerations. When objective criteria are available, a numeric score is defined through linear normalization; the lowest value in the scale correspond to zero, while the highest to one, thus all intermediate values are linearly normalized. In case of subjective opinions, alternatives are scored as suggested in [30] by a scale of subjective quality evaluation for , where 0=very low - 0.25=low - 0.50=medium - 0.75=high - 1=very high.

Every criterion is therefore weighted through a weighting assignment method. Here the SMARTER [39] method has been used, Simple Multi-Attribute Rating Technique Exploiting Ranks, as a weighting criteria based on criteria rating. According to this method, the decision maker ranks the criteria importance from best to worst. The centroid method is afterward used to give criteria weights for which:

$$w_i = \frac{1}{n}\sum^{n} {}_{i}\,\frac{1}{k} \qquad (2.2)$$

For every criterion and ranking position [39]

The final ranking is based on the linear weighted sum for which final weighted performance is

$$X_j = \sum_i^n \; w_i \cdot x_{ij} \qquad (2.3$$

For every alternative .

The resulting weighted score gives the ranking of the alternatives, being the first the most suitable to the application

2.1.2 MCDA applied to Input Data quality

As stated before, the heat recovery potential needs to consider the uncertainty of the input data, being all the process based on them. On the perspective of drawing the DH line according to the path that would maximize the heat recovery in the DH line, not just the value of estimated recoverable heat itself is important, but also its input data quality. Being this calculation based on the collected input data, also their reliability, namely the probability that these results correspond to real values, is crucial. In this step the quality of input data is assessed. Considering the high investment costs of such infrastructure, the attitude of the decision maker, in this case the DH manager, is usually risk adverse: this means that, for him, a lower but certain result could be more significant than a higher but uncertain one. Criteria weighting, like subjective scoring, are heavily influenced by decision maker’s attitude.

As done for the heat recovery calculation methods in the previous paragraph, a scoring on data quality is done in order to give a quality, certainty coefficient to input data for each industry, here defined as . The criteria according to which the data are scored can be:

- data origin;
- completeness;
- update.

Every data is scored, , according to subjective quality evaluation scale from 0 to 1 and the weighting assignment method used is again the SMARTER which gives criteria weights .

$$\begin{array}{cccc|ccc} & & & & I_1 & I_j & I_m \\ \cline{5-7} \zeta_1 & & \omega_1 & & s_{11} & s_{1j} & s_{1m} \\ \zeta_i & \rightarrow & \omega_i & & s_{i1} & s_{ij} & s_{im} \\ \zeta_n & & \omega_n & & s_{n1} & s_{nj} & s_{nm} \end{array} \tag{2.4}$$

The result of this scoring process are probabilities coefficients, , calculated with the weighted sum of every score as defined in (2.5) that gives a measure of the likelihood that the input data collected correspond to reality; the higher the score is, the closer the input data are to onsite visit monitoring data collection.

$$p_j \quad \sum_{=1}^{n} \omega \qquad {}_j \tag{2.5}$$

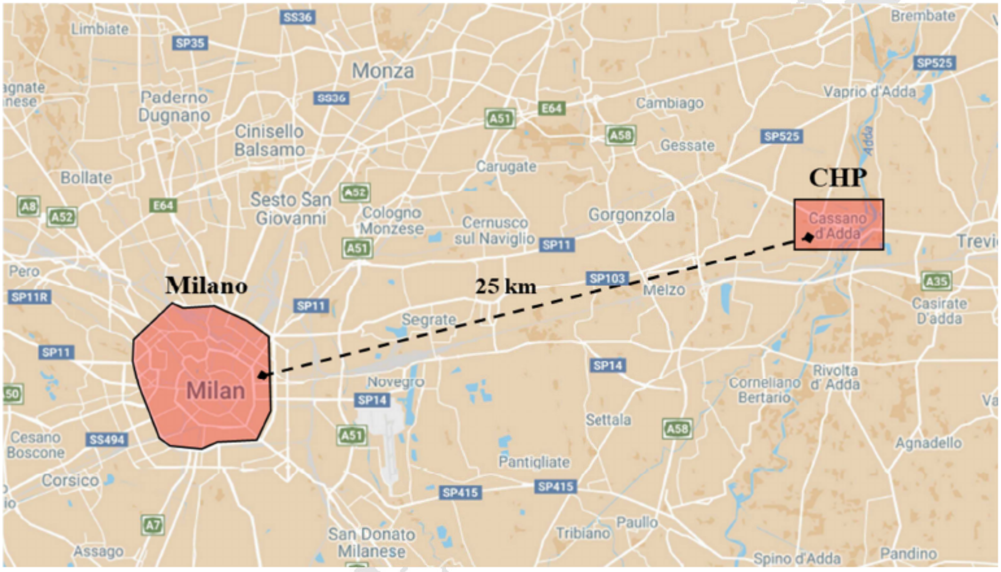
These coefficients are multiplied to input data to reduce their importance in case of high uncertainty. At the end of this phase, the chosen methodology can be applied to input data multiplied by probabilities coefficients, :

$$I \ _j = p_j I_j \tag{2.6}$$

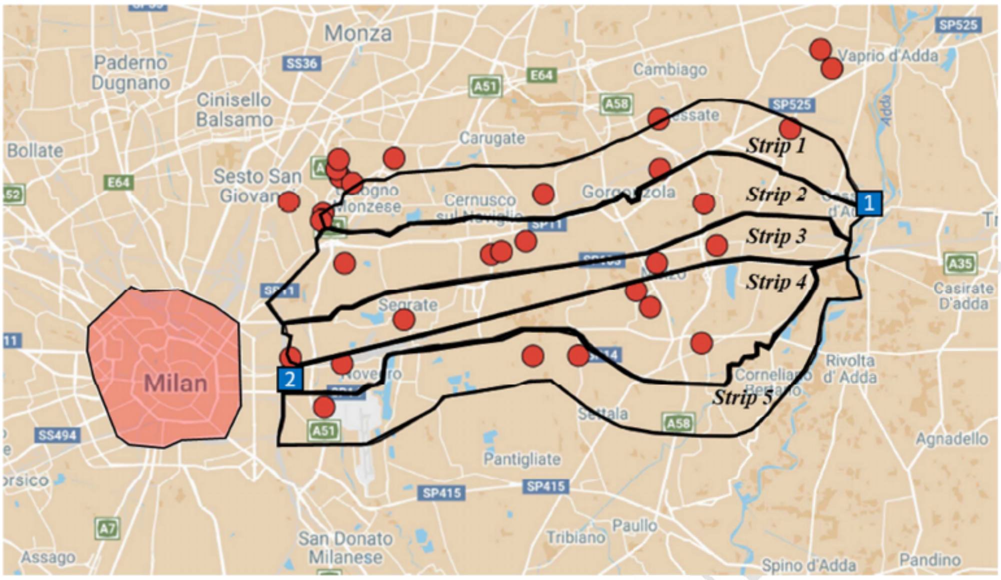
The heat recovery potential for each industry will be than calculated on the bases of instead of . The next chapter describes real case study in which this methodology has been applied.

3 THE CASE STUDY

The present study describes a real application of the presented methodology to Milano DH system. The city has a large district heating system composed by several networks providing approximately 900 GWh, over 5% of the city's heat demand. The utility running the DH system also operates a big CHP plant located 25 km away from Milano. Except for a minor part of heat that is currently feeding a local DH network, the CHP is wasting over 80% of the rejected heat, amounting approximately to 1TWh/year. The utility is therefore evaluating the feasibility of connecting the CHP plant to the DH network of East Milan as a way of reusing excess heat from the power plant. (Figure 3.1).



The aim of this work is the quantification of the heat recovery potential from industrial processes along each possible connection path which the heat provider is currently considering. Such potential could influence the final decision about the best path to choose [22]. Possible connection layouts have been sorted in five strips, as shown in Figure 3.2. Each strip falls between significant infrastructures, such as highways, railways and canals. A maximum distance of 2 km between each path and industrial facilities has been considered acceptable.



The heat recovery potential has been quantified for each strip based on industrial facilities operating in the area: energy consumption has been estimated from either environmental authorisation documents (Autorizzazioni Integrate Ambientali) [40] or Emission Trading System [41]. The potential amount of heat to be recovered from each process has been calculated according to five different methods found in literature and all results are collected to come up with an overall recovery potential for each strip following the methodology presented in previous chapters.

3.1 INPUT DATA

Main input data used in this work come from AIA documents. AIA is an Italian acronym for Autorizzazione Integrata Ambientale meaning Integrated Environmental License [40]. This license is mandatory for companies with a high pollution potential. The “integrated” feature is due to the fact that the document includes all possible environmental impacts of the company: water, energy consumption and pollutants emission. In the framework of the present work, AIA represents a strategic tool. In addition to final and/or primary energy consumption, AIA includes the description of production processes and it lists main emissions’ flowrates and temperatures. These emissions and consumptions values must be monitored, and they are updated with sampling results. The authority which is responsible for AIA documents and data monitoring is the regional Agency for environmental protection, ARPA (Agenzia Regionale per la

Protezione dell'Ambiente). While documents describing the process date back to the moment when the authorization has been given, the monitoring data are updated every year.

For this reason, a possible time offset between processes descriptions used here (2005/2006) and energy values used for recovery potential calculation (till 2014) can occur. In this lapse of time, the analysed companies' asset could have been updated, refurbished and changed. Nevertheless, only few companies actually updated AIA information about the plant's layout, therefore the process information and the energy consumption could be out of phase for many companies. Based on the database and thanks to geo-referenced data, a selection of high-consuming companies in the analysed area has been carried out. A lower limit on site's consumption has been fixed by the DH heat provider to 4 000 MWh/y, in order to select only the companies with a significant potential. This threshold has been calculated by the utility developing the DH project, considering payback time for investment costs and business model with the industries. Below this limit, the recovery has been evaluated as too costly and not profitable. From a list of 30 companies operating in this area, seven sites resulted interesting for the present work's purposes.

Table 3.1 shows the input data obtained by the regional database of final and primary energy consumption for each of the seven selected energy-consuming companies.

Companies	**Final Energy**		**Primary Energy**		
	MWh $_{el}$	**MWh $_{th}$**	**MWh $_{el}$**	**MWh $_{th}$**	**MWh $_{tot}$**
A	23 401	34 423	36 144	56 629	92 774
B	18 464	30 598	32 128	44 682	76 811
C	9 130	30 018	31 519	22 095	53 614
D	20 177	26 217	27 528	48 828	76 357
E	32 490	26 151	27 459	78 625	106 084
F	3 260	10 819	11 360	7 888	19 248
G	-	-	-	-	46 981
Total					**471 869**

The literature review brought to the application of five different calculation methods, in this work named: McKenna [42], Heat Roadmap Europe (HRE) [7], Berthou [43], Ecoheatcool [44] and exhaust gases heat recovery (EGHR). These methods have been chosen to be the most suitable to the application of heat recovery to DH. Each method has a different approach: bottom-up or top-down [23]. Top down approaches start from a high level (regional or national) to derive single company or industrial sector potential, while bottom-up approaches analyse single sites in order to build a statistic to be applied at national level [23]. Each approach is described in detail in the following chapter.

3.2 EXCESS HEAT RECOVERY CALCULATION METHODOLOGIES

Regarding excess heat potential estimation, in literature, a wide variety of methodologies can be found, and their classification can be based on:

- Study scale: a region or a whole country [42], [24] and [45], a town [46] or a single industry [47].
- Data acquisition: estimation or measure. Measured data could be either directly measured or collected via a questionnaire. Estimated data are based on the input of the industrial process, either energy or materials, or on production quantities.
- Approach: bottom-up or top-down.

In the following, a detailed description of the selected methods is presented. All the methods used here are based on the calculation of the recoverable excess heat , to be integrated in DH, through recovery efficiency . As stated in [7], the useful energy used in the process and derived from primary energy input is described by the total conversion efficiency of the process, defined as:

$$\eta \quad = \eta_{\ \ bs} + \eta_{\quad t} = \frac{E_{abs} + E_{heat}}{E_{prim}} \tag{3.1}$$

Where is the energy absorbed in the product during the industrial process. Relationship between primary energy and share of excess heat recovered , is therefore defined through recovery efficiency :

$$E_{heat} = \eta_{heat} \cdot E_{prim} \tag{3.2}$$

represents all the process excess heat, in particular the theoretical heat recovery potential. To obtain technical recovery efficiency , further coefficient should be applied to theoretical values:

$$E_{tech,heat} = \eta_{tech,heat} \cdot E_{prim} = \eta_{tech} \cdot \eta_{heat} \cdot E_{prim} \tag{3.3}$$

Thanks to the methods described in the following, different values of and have been calculated.

3.2.1 McKenna

McKenna et al. developed a methodology [42] to assess excess heat in UK industrial sector. Starting from allocated emissions from EU ETS database, the calculation of combustion emissions is performed. Two calculation processes are defined to estimate the total fuel and electricity use on site, where the discriminating factor is the presence of a CHP unit. The total heat load is the sum of CHP and fuel contribution. At this point, temperature demand profiles are estimated, and the heat load is divided into five temperature bands, based on literature data.

For each temperature band, a theoretical recovery efficiency is calculated based on the ratio between heat sink and heat source temperatures, where the sink is normally the external ambient and source is the process. The higher is process temperature, the higher is the theoretical recovery potential. The technical potential is estimated according to the assumption that half of the sensible heat in an exhaust stream might be technically recoverable, for which =50%. Around this final value, a range of heat recovery fraction is defined and applied to final energy values.

Industry sector	**Heat recovery fraction $\eta_{tech,heat}$**
Food products and beverages	5-10%
Pulp, papers and edition	0-5%
Chemicals	5-10%
Glass	10-20%
Aluminium	5-10%
Cement	10-20%
Gypsum	5-10%
Mineral/rock wool	10-20%

[42]

As heat consumption is immediately available for the considered industrial sites, the first part of the methodology is avoided, and recovery coefficients has been directly applied in order to calculate recovery potential range.

3.2.2 Heat Roadmap Europe (HRE)

This procedure is aimed at ideal recovery potential estimation in EU. From ETS database it is possible to derive annual carbon dioxide emissions from fuel combustion activities, (kg). Based on the considered country, a characteristic carbon dioxide emission factor (g /MJ) has to be chosen. This factor reflects the average national fuel mix for each activity. The annual primary energy, (J), can be calculated as the ratio between CO_2 emissions and country-related emission factor, / (MJ). Depending on the considered activity sector, a default recovery efficiency has been defined to calculate rejected excess heat, as equation (3.1). This value represents the maximum ideal recovery potential.

Industry sector	**Recovery efficiency η_{heat}**	**f_{CO_2} [$g_{,CO_2}$/MJ] for Italy**
Thermal power	50-60%	64.9-71
Fuel supply and refineries	50%	73.3
Chemical and petrochemical	25%	58.2
Iron and steel	25%	77.1
Non-ferrous metals	25%	58.3
Non-metallic minerals	25%	66.7

Paper, pulp and printing	25%	57.3
Food and beverage	10%	58.8

[7]

As the present work is aimed at technical recovery potential calculation, further coefficients should be applied to theoretical values. According to [42], a 50% has been finally applied to .

As above, the heat consumption is immediately available from AIA technical documents. Primary energy consumption can be derived thanks to the combination of used energy sources. This allows skipping the first step of HRE procedure, where allocated emissions have to be converted into primary energy consumption.

3.2.3 Berthou

Berthou and Bory [43] developed in 2012 an analysis of France industry sector to assess the amount of excess heat in the country. The proposed method has a top down approach based on statistics data, covering 70% of the total industrial sector. The advantage of this study lies in the reliability of data origin, survey database, and in the detail level of excess heat analyses: energy data are analysed by effluent type, temperature levels and industrial sector. In particular, the temperature levels help to better identifying the directly recoverable fraction of waste energy and the fraction that needs a thermal lift with heat pumps. The effluent type considered are combustion gases, steam, cooling fluids, cleaning hot water.

The first step of the analysis identifies the excess heat fraction from the primary energy consumption for each analysed industrial sector, thus the energy fraction not embodied in the final product.

Industry sector	**Excess heat fraction** $\eta_{ex,heat}$
Food products and beverages	52%
Pulp, papers and edition	46%
Basic chemicals	13%
Other non-metallic mineral products	20%
Capital goods	26%
Fine chemical products	39%
Iron and steel	12%
Fabricated metals products	15%
Textile	26%

[43]

In a second step, the analysis goes deeper in the major consuming sectors and the excess heat is divided in three sub fractions of recovery according to the type of effluent and temperature level.

Industry sector	**Combustion gases** η_{comb}	**Cooling fluids** η_{cool}	**Steam process** η_{vap}	**Lost** η_{lost}

Food products and beverages	7%	54%	35%	4%
Pulp, papers and edition	17%	1%	78%	4%
Basic chemicals	44%	24%	32%	-
Other non-metallic mineral products	55%	13%	32%	-

As mentioned in the French paper, the portion of excess heat from the steam processes is normally recovered inside the process because of its very high temperature level (150°-500°C). The excess heat resulting from cooling processes have a temperature around 40°C so they would need a temperature lift, such as heat pumps, to be used in DH. Since the purpose of this work is the study of heat recovery for a DH network, only the fraction of heat coming from combustion gases is considered as directly recoverable, so that . Again, the obtained valued represents the theoretical reusable excess heat; a 50% reduction has been applied to consider technical recovery [42].

3.2.4 Ecoheatcool

A top-down approach used in this paper comes from the already mentioned Ecoheatcool project [44], completed in 2006, that was intended to carry out an analysis of thermal energy demand and supply in Europe.

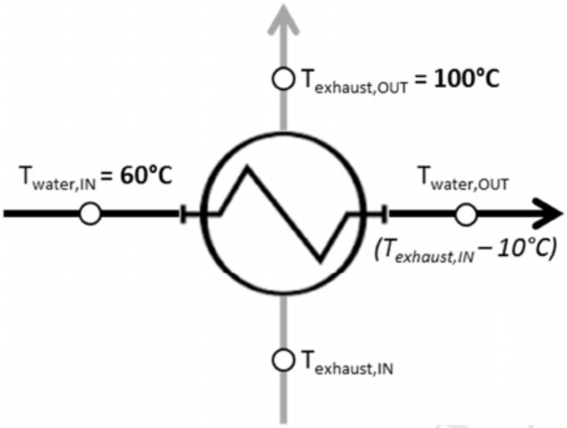
The industrial excess heat recovery potential is assessed through "heat recovery factors" to be applied to primary energy consumption of analysed industrial sectors. The recovery ratios are derived from a 2002 report of the Swedish DH association [48]: the study aim is the promotion of industrial excess heat integration in DH. Data comes from monitoring of industrial excess heat recovery in Swedish DH networks. The heat recovery coefficients resulting from these data are consequently derived from the analysis of real experiences, and not from theoretical considerations. Coefficients are shown in Table 3.6 [48]. For cogeneration plant, international energy statistics are used in this project, which lead to a heat recovery fraction equal to 0.31 of primary energy consumption for gas engine.

Industry sector	**Excess heat fraction** $\eta_{tech,heat}$
Petroleum and refineries	0.6%
Food and tobacco	3.6%
Pulp and paper	2.4%
Chemical	12.2%
Non-metallic minerals	2.9%
Basic metals	17.3%

[48]

3.2.5 Exhaust Gases Heat Recovery (EGHR)

This method consists in the calculation of the heat recoverable from combustion exhaust gases. The inputs needed are temperature, flowrate and duration of exhaust gas' emissions. The following scheme shows method's hypothesis.



The outlet stream temperature at exhaust gas side has been fixed at 100°C, in order to avoid possible condensation of dangerous substances. This implies that if the exhaust temperature at the inlet (input data) is lower than 100°C, the stream is not considered for the evaluation of recoverable heat. At waterside, the inlet temperature is fixed at 60°C, simulating return line of the DH network. The outlet temperature at waterside is considered 10°C under the inlet exhaust temperature, taking into account the exchanger effectiveness. It is therefore possible to calculate the potential for heat recovery from exhaust stream. The instantaneous power is calculated from exhaust gas flowrate and enthalpy change:

$$Q_{rec,exhaust} = \dot{m}_{exhaust} \cdot \left(h_{exhaust,in}\left(T_{exhaust,in}\right) - h_{exhaust,out}\left(T_{exhaust,out}\right)\right) \qquad (3.4)$$

Exhaust gas enthalpy is calculated as follows (considering tabulated values):

$$h_{exhaust} = (972.7 + 10.67\,u) \cdot T' + (166.31 - 3.25\,u) \cdot (T')^2 - (27.98 - 2.443\,u) \cdot (T')^3 \qquad (3.5)$$

Where is in °C and is the humidity in %. The information about duration of emissions is useful to evaluate the recoverable heat, multiplying instantaneous power to the amount of time in hours. The method application leads to following recovery coefficients.

Companies	Recovery coefficient
A	1%
B	7%
C	14%
D	14%

E	8%
F	1%
G	10%

3.3 HEAT RECOVERY POTENTIAL PER INDUSTRY

In Table 3.8, the recovery coefficients calculated according to the presented methods are listed for each industrial sector related to the analysed companies. In the same table, it is specified if the coefficients have to be applied to global primary energy, thermal primary energy or thermal final energy.

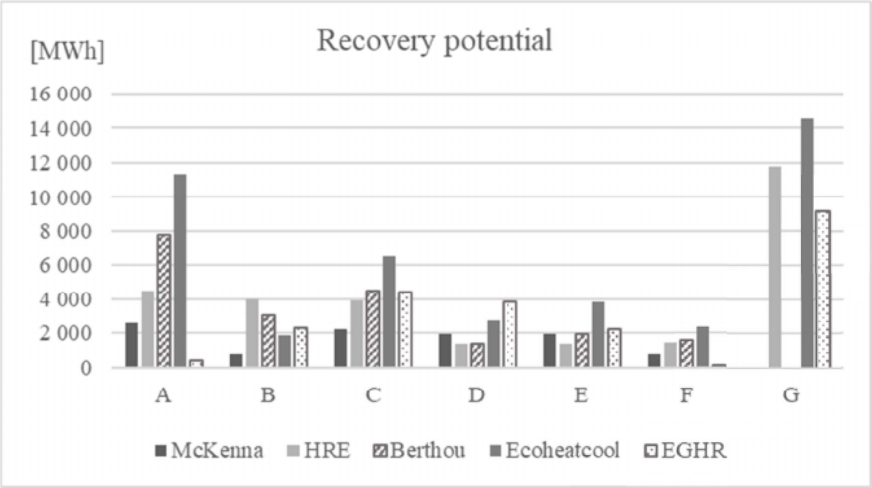
Methods	**Coefficients**				**Application**		
	Food (F)	**Chemicals (CH)**	**Pulp-Paper (PP)**	**Power (P)**	**Primary Energy**	**Primary Energy TH**	**Final Energy TH**
McKenna	5-10%	5-10%	0-5%	-			X
HRE	5%	12.5%	12.5%	25%		X	
Berthou	1.82%	8.39%	3.91%	-	X		
Ecoheatcool	3.6%	12.2%	2.4%	31%	X		

As discussed in the previous chapter, McKenna and HRE approaches start from ETS database to calculate final or primary energy consumptions. From AIA and AIDA, final or primary energy consumptions are directly available, and the first step from emissions to consumptions is not necessary. Furthermore, not for all companies both emissions and consumptions are available.

Coefficients derived from all the presented methods have been applied to final or primary energy based on Table 3.8 indications. Applying the coefficients to energy consumptions, it is possible to estimate the recovery potential with the five described methods. For McKenna method, an arithmetic average between low and high recovery value has been applied. Regarding power generation category (P), only HRE, and Ecoheatcool coefficients are available.

Companies	**Category**	**McKenna MWh**	**HRE MWh**	**Berthou MWh**	**Ecoheatcool MWh**	**EGHR MWh**
A	CH	2 582	4 518	7 784	11 318	420
B	PP	765	4 016	3 003	1 843	2 319
C	CH	2 251	3 940	4 498	6 541	4 417
D	F	1 966	1 376	1 390	2 749	3 863
E	F	1 961	1 373	1 931	3 819	2 201
F	CH	811	1 420	1 615	2 348	132

G	P	-	11 745	-	14 564	9 177
Sum industries (A-F)		10 337	16 643	20 221	28 619	13 352



As previously discussed, different methods lead to very heterogeneous results, as can be seen in Figure 3.4. This variety is the reason for MCDA is required. The next chapter describes in detail the application of MCDA, aiming at each company’s potential estimation.

3.4 MCDA APPLIED TO METHODOLOGIES

The multi-criteria analysis has been applied to the five heat recovery methodologies chosen in relation to their relevance and pertinence to the focus of this study. The objective of MCDA is to find the most suitable methodology. The alternatives of the MCDA problem are the five applied methods, McKenna, HRE, Berthou, Ecoheatcool and EGHR. The criteria chosen to assess each methodology are three:

- Type of approach: top-down or bottom-up
- Origin of input data used to elaborate the methodology
- Purpose of the methodology: whether the final result of the application of the methodology is the technical potential, or the theoretical one

The chosen methodologies follow different procedures to reach the final result and they deal with different types of data with different points of view. Table 3.10 summarizes the differences between different methods according to which the MCDA has been applied.

	McKenna	**HRE**	**Berthou**	**Ecoheatcool**	**EGHR**

Approach	Top-down	Top-down	Bottom-up	Top-down	Bottom-up
Data origin	Estimated	Estimated	Estimated	Measured	Estimated
Purpose	Theoretical	Theoretical	Theoretical	Technical	Technical

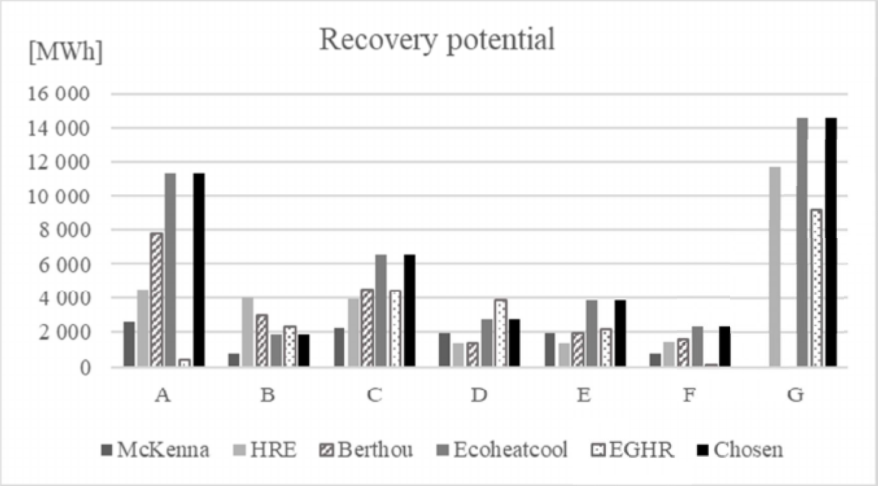
Following the MCDA structure presented in 2.1.1, alternatives have been scored according to the chosen criteria. Using the scoring procedure for subjective evaluations, each alternative's score is a value between 0 and 1.

			a_1	a_2	a_3	a_4	a_5
Criteria - C_i	Criteria Ranking	**Criteria Weights - w_i**	**McKenna**	**HRE**	**Berthou**	**Ecoheatcool**	**EGHR**
Approach: top-down/bottom-up	3°	0.11	0.08	0.08	0.11	0.08	0.11
Data origin: estimated/measured	2°	0.28	0.14	0.14	0.21	0.28	0.21
Purpose	1°	0.61	0.46	0.46	0.46	0.61	0.61
Final scoring - X_j			0.68	0.68	0.78	0.97	0.93

Bottom-up approaches have been given a higher score (alternatives 3, 4, 5), being considered more suitable for potential calculation at city level, with respect to national potential analyses made through top-down approaches. Methods based on measured data (alternative 4) have been considered more reliable and they have received the highest score. Methods based on estimated data received a different score according to their starting point: if starting from ETS they received 0.50, if starting from energy consumption they received 0.75. This considers that to convert emissions to energy consumption it is necessary to apply average coefficients calculated on national basis. Last, concerning representativeness, methods which directly allow for the calculation of technical heat recovery have been given a higher score than the ones allowing calculation of theoretical recovery. As a matter of fact, a corrective factor has been applied to the outputs of such methods, resulting in a less certain result. The weights have been obtained through equation (2.2). The SMARTER method application is based on the following criteria importance:

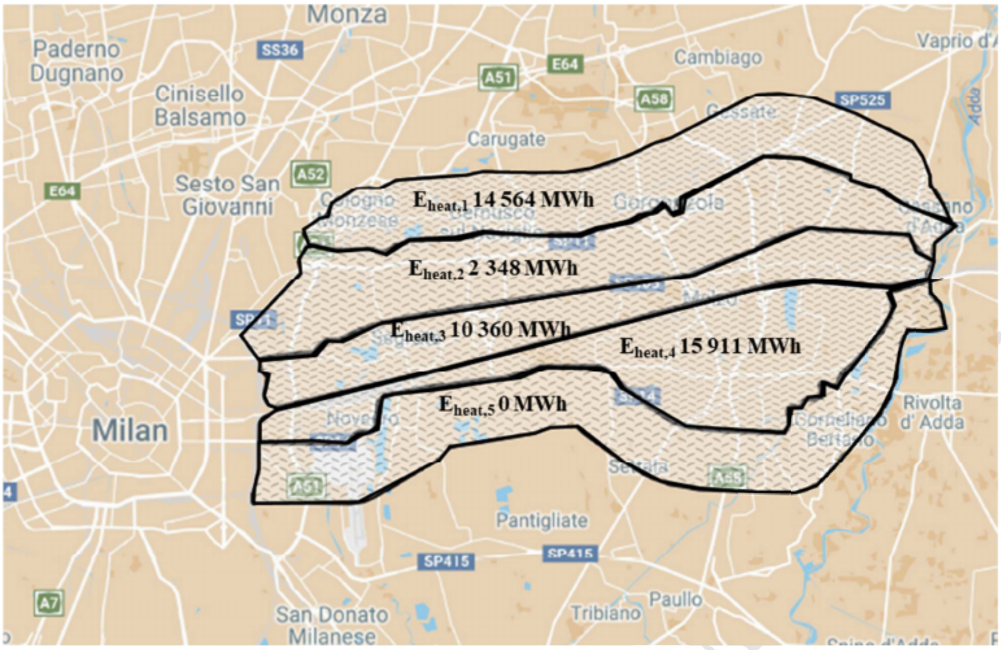
1. Objective 2. Data origin 3. Type of approach

Final scoring for every method has been obtained through equation (2.3). Considering the criteria and the reasoning previously presented, the method with the highest score is Ecoheatcool. Therefore, among the excess heat recovery potentials resulting from all methodologies, the ones resulting from Ecoheatcool methods are chosen.



According to such results, the final recovery potential along the different DH paths is presented in Figure 3.6. Table 3.12 shows the ratio of potential heat recovery and the heat recoverable from the CHP plant.

Path	**Total recovery [MWh] E_{heat}**	**Ratio industrial E_{heat}/ CHP**
1	14 564	1.46%
2	2 348	0.23%
3	10 360	1.04%
4	15 911	1.59%
5	-	-
Total	**43 183**	**4.32%**



3.5 MCDA APPLIED TO INPUT DATA UNCERTAINTY

The same approach of quantifying numerical scores to subjective considerations [30], used in the previous paragraph, is here applied to the input data, assessed according to thoroughness, update and homogeneity of information. The results of this scoring are certainty, reliability, coefficients according to the procedure explained in 2.1.2. The criteria according to which the data have been scored in Table 3.13 are:

- Data origin: whether figures found in AIA documents were measured (score 1) or estimated (score 0.75) by industrial companies.
- Completeness of the AIA document. Completeness score is defined and normalized following the here listed six criteria (score 0 corresponds to zero fulfilled criteria, score 1 corresponds to six fulfilled criteria):
  Production process description
  Production capacity, nominal and actual
  Description of thermal and electrical energy production
  Nominal power indication for thermal and electric plants
  Energy consumption indication
  Specification of quantity, type and temperature of exhaust gas
- Update: if AIA technical documents are updated with respect to energy consumption data. The score is given according to the time delay between monitoring data and the document: the score is 1 if the

year of the document is the same than monitoring data, score is 0 for the data with the biggest time delay.

- Homogeneity: if the monitoring data of energy consumption have significantly changed over the years, this implies the possibility that the generation systems or the industrial production have changed with respect to the description of the plant of AIA document. Consequently, the hypothesis on recoverable energy based on the technology could be less realistic. The score is normalized considering the highest consumption change (score 0) and the lowest one (score 1)

Again, weights have been obtained through the SMARTER method, through equation (2.3), based on the following criteria ranking:

1. Update 2. Data origin stimation/measurement) 3. Homogeneity 4. Completeness

Industry Sector	Criteria Ranking	Criteria Weights - w_i	A CH	B PP	C CH	D F	E F	F CH	G P
Data origin	2	0.27	0.75	1.00	0.75	0.75	0.75	1.00	0.75
Completeness	4	0.06	1.00	1.00	0.83	0.83	0.83	0.67	1.00
Update	1	0.52	1.00	1.00	1.00	0.00	0.00	0.14	0.00
Homogeneity	3	0.15	0.71	1.00	0.36	0.99	0.83	0.00	1.00
Final scoring probability -			**0.89**	**1.00**	**0.83**	**0.40**	**0.38**	**0.39**	**0.41**

In fact, it's worth recalling that while documents describing the process date back to the moment when the authorization has been given, the monitoring data are kept up-to-date.

The result of the application of (2.5) are a probability coefficients that gives a measure of the likelihood that the input data collected correspond to reality; the higher the scoring is, the closer the input data are to reality.

The entire process of total heat recovery per path has been applied to a second calculation, but this time with the aim of inputting data multiplied by these probability coefficients. Input data of this second calculation are no more primary energy consumption data , but , calculated through equation (2.6), where for each industry:

$$E_{p,prim} = p \cdot E_{prim} \tag{3.6}$$

So that equation (3.2) becomes:

$$E_{p,heat} = \eta_{heat} \cdot E_{p,prim} \tag{3.7}$$

Starting from these new inputs data, paths' results changes.

Path	Total recovery [MWh] E_{heat}	Total recovery [MWh] $E_{p,heat}$
1	14 564	5 992
2	2 348	909
3	10 360	6 861
4	15 911	13 019
5	-	-
Total	**43 183**	**26 781**

Table 3.14 shows the heat recovery potential along each path with and without considering input data quality.

Looking at new values of heat recovery potential, it's worth noticing that the path with the highest heat recovery potential is always number 4, which at the end represents the 1.3% of the total amount of heat rejected by the CHP plant. Considering data quality, path n. 1 has a lower heat recovery potential than path n. 3, and both values of these two paths have decreased with respect to n. 4. These results show how the input data quality can affect the final choice considering that decision makers, as previously stated, prefer a sure and certain value rather than a higher but uncertain one.

4 CONCLUSIONS

The approach described in detail in the present article can be useful in the planning phase of a specific DH project, whether the realization of a new network, or the extension of an existing one. If, in such situation, industrial heat recovery is a criterion for choosing the path of a DH network, several scenarios of heat recovery potential have to be developed. Detailed quantification of available excess heat from an industrial process is relatively complicated, though, as this requires deep knowledge of each process and updated data about production. Several methodologies exist for estimating excess heat based on fewer and simpler-to-obtain data, but each of them provides highly different results. As explained in the text, the quality of data is essential in order to obtain reliable results, but it is generally very difficult to gather data about industrial processes that are enough detailed to enable heat recovery potential calculations. One possible solution is to investigate each single industrial facility, which is very resource-consuming, though. Additionally, private companies may not be interested in making energy consumption and pollution data public.

Sources such as environmental authorisation documents or mandatory pollution-monitoring reports are therefore extremely useful (AIDA and AIA in Italy). Nevertheless, such data may be scarcely updated, which is particularly problematic in the industrial branch, where energy consumption may vary heavily from year to year, according to economic boundary conditions and technical improvements of the plants.

In addition to that, the application of different methodologies available in literature to calculate waste heat recovery values generate a wide range of results which pushes for the need of a decision support tool to manage them.

Considering the above mentioned issues, the approach described in the present article provides a relatively little resource-consuming method for estimating industrial heat recovery potential along different possible paths, when detailed data is available but its quality and updating is questionable. It is important to underline that this approach is particularly suitable for a relatively large, but limited, geographical region, with a significant number of industrial facilities. Looking at the variety of results deriving from the different heat recovery methodologies found in literature, it clearly emerges how the study size and the approach scale of the methodologies have an impact on the results. A methodology to deal with different calculation approaches and data variety becomes therefore very useful to manage results according to the purpose and the size of the project.

Furthermore, it should be noticed that for calculating the real technical heat recovery potential from an industrial process, the knowledge of excess heat temperature becomes very relevant, this information being extremely difficult to gather as long as no analysis of each single industrial process is performed. Consequently, the heat recovery potential may influence the decision about the final path of the DH network, but as soon as the utility operating the network decides to indeed recover such heat, a fully detailed analysis of the process will be required to evaluate whether or not the recovery is technically and economically feasible.

Funding

The case study presented in this paper was commissioned by DH company A2A S.p.A. The work on methodology is resulting also from the activities undertaken in SmartReFlex project (IEE/13/434).

Acknowledgments

The authors would like to thank A2A for the opportunity and the support given in this work. The authors appreciate the help provided by Regione Lombardia in the data collection and the collaboration shown throughout the entire project.

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Highlights

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