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Classification through analytic hierarchy process of the barriers in the revamping of traditional district heating networks into low temperature district heating: an Italian case study

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ABSTRACT

The revamping of existing high temperature district heating systems with low temperature solutions will ensure a better usage of primary energy thanks to the reduction of thermal losses through the networks and to the possibility of using low grade enthalpy heat for the purpose, including renewables and waste heat. However, several criticalities are present that make the evolution from the 3rd to the 4th generation of district heating not immediate.

The paper aims to identify general technological and non-technological barriers in the revamping of traditional district heating networks into low temperature ones, with a particular focus on the Italian framework. Possible solutions are suggested, including relevant advice for decision makers. The paper also analyses how the possible solutions required for the up-grade of the existing district heating network can be classified through the Analytic Hierarchy Process (AHP) to prioritize the ones that prove best for more advanced evaluation.

Keywords:

Low temperature district heating (LTDH);
Revamping DH systems;
Barriers;
Analytic Hierarchy Process (AHP);

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1. Introduction

The introduction includes a brief overview of DH systems to give an insight on district heating general framework, with a focus on low temperature district heating concept. In particular, the Italian DH framework is analysed through a state of the art survey.

1.1. General framework

Thanks to the adoption of the Paris Agreement, new and challenging energy strategies were promoted with the aim of reducing fossil fuel consumption and of limiting the global temperature increase to within 1.5 °C above pre-industrial levels [1]. The implementation of several technologies based on renewables were studied to gradually reduce the penetration of traditional fossil fuels in the energy sector such as, for example, photovoltaic cells [2], solar thermal collectors and concentrators [3,4], wind turbines [5], biomass plants [6] and heat pumps [7]. However, although the potentialities, the implementation of renewables is limited by economic considerations requiring therefore new business models and regulatory frameworks based, for example, on environmental impact [8].

In particular, since the domestic/residential sector [9] accounts for one third of the total world energy consumption , new solutions are needed that are able to address space heating and cooling demand with a lower consumption of primary energy, a higher efficiency and a relevant renewable energy fraction.

District Heating (DH) can be considered as one of the most interesting solutions able to improve the entire efficiency of heat production and to reduce

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Abbreviations

A	Alternative	EDH	Existing District Heating
AHP	Analytic Hierarchy Process	EPBD	Energy Performance of Buildings Directive
CLTDH	Cold Low Temperature District Heating	LTDH	Low Temperature District Heating
C	Criteria	NG	Natural Gas
CI	Consistency Index	OPEX	Operative Expenditures
COP	Coefficient of Performance	Q	Question
CR	Consistency Ratio	RI	Random Index
CW	Composite Weight	RW	Relative Weight
DH	District Heating	WLTDH	Warm Low Temperature District Heating
DHW	Domestic Hot Water	WTE	Waste-to-energy

environmental impact if compared with traditional decentralized heating systems [10–12]. From the first commercial application in 1877 at Lockport (New York), several improve ments have been made over the years, totalling more than 80,000 DH networks worldwide [13]. Among these improvements, attempts to foster the environmental sustainability were made in several retrofitting projects by increasing the utilisation of high enthalpy renewables such as biomass plants [14].

Therefore, although developments have been made with respect to the first application, a reduction of the operative temperature was encouraged over the years to reduce thermal losses and to increase the utilization of lower enthalpy energy sources. Furthermore, as reported in [15], the reduction of district heating competitiveness with the decrease of its linear heat density requires high distribution efficiency to ensure operations economic feasibility. In particular, four different DH generations are recognized by the literature according to the characteristics of the heating transfer fluid, such as the operating temperature and the thermodynamic state [16,17].

The 4th DH generation, also called “Low Temperature District Heating” (LTDH), was firstly proposed by [18]: the minimum requirements fulfilled are the ability i) to supply low-temperature thermal energy to new and existing customers, ii) to minimize thermal losses, iii) to integrate low enthalpy heat and iv) to become part of smart energy systems contributing to the transition towards a 100% renewable energy supply system characterized by the integration of different energy sectors [19,20].

The LTDH definition identifies a wide range of temperatures: for example, a preliminary classification is proposed in [21] where “warm LTDH” and “cold LTDH” systems are introduced based on the need or not to locally boost the temperature to customer level. In [22] three different LTDH systems are defined on the basis of distributing temperature: “Low temperature” systems (55/25 °C), “Ultra-low temperature with electric boosting” systems (45/25 °C), and “Ultra-low temperature with heat pump boosting” systems (35/20 °C). In [15] LTDH systems (70/40 °C) are compared with ULTDH systems (40/25 °C): the annual heat distribution costs and the specific distribution costs are lower in the case of ULTDH. In both cases centralized ground source heat pumps are defined, while decentralized air-to-water heat pumps are considered only for ULTDH case.

However, even if advantages can be achieved through the implementation of DH systems [23] many technical and non-technical challenges have to be solved to fully apply the 4th DH concept in existing systems [24]:

- *Flow recirculation*. In traditional DH systems the supply fluid is recirculated to reduce temperature decrease due to heat dispersion in the network in stagnant conditions. Recirculation, however, causes return temperature increase - a phenomenon known as return contamination - and consequently a system performance reduction. Since this is not acceptable in LTDH, an integrated solution consisting of a three-pipe distribution network is proposed in [25]. Three independent solutions are instead proposed by [26], consisting of the recirculation of the supply flow through service pipes, of bathroom floor heating and of the cooling by heat pumps to produce domestic hot water.

- *Need to implement ICT solutions and distributed instrumentation in the system*. Because of the possibility to consume and to introduce thermal energy into the DH network by prosumers as described in [27], more stringent requirements regarding metering and control will be present in LTDH networks both at customer level and along the network in order to help distributors take operating decisions, for example in the presence of substation faults [28,29].
- *Size of existing heat exchangers and radiators*. By reducing supply temperature, a reduction of heat transfer is expected, resulting in possible uncomfortable conditions for customers. Even if usually oversized, a possible solution is the substitution of existing radiators whose performance cannot be satisfactory for the new operating conditions as reported in [30], where a case study is analysed considering heating demands in four Danish single-family houses from the 1930s. A similar analysis was performed in [31] where thermal performance of Danish single-family houses from the 1980s supplied by LTDH was simulated resulting in an acceptable condition for most of the year. Another proposed solution is the increase of DH temperature during the coldest season as proposed by [32].
- *Legionella issue in domestic hot water production systems*. To reduce the risk of legionella contamination in domestic hot water (DHW) storage systems, national regulations require high water temperature in order to inhibit bacterial growth. However, thermal, chemical and physical treatments are available against legionella issue as reviewed by [33], reducing the concentration of bacteria or preventing them from entering into the system operated at low temperature. From a design point of view, two configurations of decentralized substations to produce DHW in LTDH systems based on the minimization of the available volume for bacteria proliferation, the Instantaneous Heat Exchanger Unit (IHEU) and the District Heating Storage Unit (DHSU), are proposed in the literature [34].

In addition to these solutions, five different substation configurations applicable to single-family cases supplied with Ultra-Low Temperature District Heating (ULTDH), consisting of an additional heating device, are proposed and compared in terms of total energy consumption in [35].

Because of the identified issues, the application of LTDH is easier in new networks as shown by the low number of existing system renovations. In fact, very few cases were found in the literature. For example, in Sønderborg (Denmark), 975 MWh/y of thermal energy are supplied by an LTDH network operating at a supply temperature between 50 °C and 55 °C in place of an existing network previously operated at 70/75 °C [36]. In Lystrup (Denmark), a demonstration LTDH network supplying heat to forty terraced low energy houses is operated at a supply temperature of 55 °C in a place of the initially envisaged traditional system [32]. In Aarhus (Denmark), LTDH systems will be demonstrated in single and multi-family buildings, reducing the supply temperature from around 72–83 °C towards 60 °C during summer and 70 °C during winter [37]. In Albertslund (Denmark), the renovation of the existing DH is encouraged by the local municipality to apply the concept of LTDH by 2026, reducing the supply temperature from 85 °C to 60 °C [38].

Instead, many new LTDH systems have been designed and supplied by different types of renewable sources, such as in Slough (UK), in Ackermannbogen (Germany) [39], and in Okotoks (Canada) [40]. Among low enthalpy sources, many geothermal applications are located in Switzerland as reported in [41]. For example, 960 kW of thermal power are supplied to 177 apartments in the city of Oberwald through an LTDH network supplied by geothermal heat pumps fed by a water source at 16 °C. Another example of new LTDH systems is present in Airolo, where 1.9 MW are supplied by heat pumps to the highway's buildings, exploiting a water source at 15 °C cooled down by 2.3 °C. A heat pump is used in the village of Kaltbrunn to supply 156 kW utilising a heat source at 12 °C. A low capacity system consisting of a heat pump is located in the community of Minusio (canton Ticino), exploiting an available source at 16 °C. A Coefficient of Performance (COP) of 4.0 is obtained in the village of Trimbach (canton

Solothurn) where 150 apartments are supplied by a heat pump and traditional boilers.

In Italy, instead, two LTDH pilot projects were developed by Cogeme, an Italian communal holding company operating in the energy sector, exploiting a geothermal source and the lake of Iseo [41]. A similar approach is implemented at PortoPiccolo (near Trieste) where 4.5 MW are centrally extracted by seawater at a temperature between 9 °C and 28 °C and used to produce heat up to 40 °C through decentralized heat pumps [42].

Other examples of successful implementation of geothermal source in LTDH are also found in Ulstein [39] and Stavanger [43] (Norway), and in Heerlen (Netherlands) [44]. The integration of renewable sources proves easier in LTDH, making the concept of the Smart Energy Systems effective [45]: a case study regarding the possibility to maximize the use of locally produced electricity by photovoltaic panels through the use of electric storage and heat pumps connected to a thermal storage in the municipality of Bressanone-Brixen is analysed in [46]. In Nottingham (UK) a LTDH project (the REMOURBAN project) was developed aiming to connect 94 properties in the demo site supplying heat at approximately 50 °C to 60 °C and return temperature approximately at 30 °C by exchanging heat with the primary return pipeline [47].

The need to apply the concept of the Smart Energy Systems approach to contribute to a future 100% renewable energy system is highlighted in [48], requiring a new approach to energy generation and consumption. So, LTDH implementation in future years is crucial to contribute to the worldwide energy efficiency goals and to create interconnected energy systems.

The paper analyses the existing barriers for the renovation of existing DH systems for transformation into LTDH, with a particular focus on the Italian DH sector, considered as representative also for Southern Europe. There are very few reports in the literature about LTDH development in European Southern regions, thus making it very difficult to plan and to invest in such renovation action. Furthermore, the technological solutions suggested for Northern regions moving towards LTDH systems are often not applicable to Southern regions because of the presence of different framework conditions, in particular as regards building characteristics.

The paper shows an overview of the Italian DH state-of-the-art in order to identify the main characteristics of the sector. Possible technological and non-technological barriers to the renovation of existing Italian DH systems are then identified and critically analysed. The Analytic Hierarchy Process (AHP) method is applied using the identified barriers as criteria to rank cold and warm LTDH systems with respect to existing DH systems.

1.2. Analysis of the Italian District Heating sector

Italian DH systems are relatively recent, since the first system was installed in 1971 in Modena. A rapid development of the DH sector occurred between 2000 and 2015 in Italy, thus reaching a total number of 236 DH networks in 2016, with a total pipelines nstalled covering 4270 km, distributed in 193 cities. On the other hand, the heated volume increase is concentrated in the years 2004–2007, while in the last 10 years a decreasing trend in the yearly percentage increase of heated volume can be observed [49].

Table 1 shows that the majority of Italian DH systems (77.5%) have been operating for less than 20 years: therefore, it is very difficult to justify a renovation in accordance with the LTDH concept while the DH system is still being depreciated. Most DH systems can be classified as 3rd generation (81.4%), while very few can be included in the 2nd (16.1%) and 1st (2.5%) generations.

Moreover, the Italian DH framework is characterized by the following heat generation plants: cogeneration plants, natural gas (NG) boilers and renewable plants, including also waste-to-energy (WTE) power plants. In 2016, most of the heat was still produced by cogeneration, followed by NG boilers and renewable sources. Nevertheless, a significant decrease of cogeneration penetration occurs with respect to 1995, while an increasing of renewable sources can be highlighted: this fact can be justified by the combined effect of i) energy efficiency policies (including renewables incentives) and ii) the reduction of profitability in electricity production by fossil fuel cogeneration.

An increase (+226.9%) of the supplied thermal energy occurred between 1995 (2687 GWh) and 2016 (8784 GWh), justified by the heated volume increase (+360.1%) in the same period. However, a reduction of the specific consumption from 36.1 kWh/(m^{3}y) to 25.7 kWh/(m^{3}y) can be observed. Instead, only 121 GWh of cooling energy were delivered in 2016 [49].

Table 1: Development and characterization of the Italian DH framework since 1995. (Based on [49])

Parameter	1995	2000	2015	2016
Number of cities with a DH system	27	27	182	193
Number of DH networks	45	53	216	236
Hot water (90 °C)	26	27	174	192
Superheated water (120 °C)	17	22	37	38
Steam	2	4	6	6
Heated volume (Mm^3)	74.4	117.0	329.8	342.3
Heat delivered (GWh th/year)	2,687	3,854	8,551	8,784
Cogeneration (%)	76.0	66.0	51.2	50.7
NG boilers (%)	18.0	22.0	23.1	23.2
Renewable sources including waste-to-energy power plant (%)	6.0	12.0	25.7	26.1
DH network length (km)	648	1,091	4,098	4,270
Number of DH substations	10,148	18,594	77,482	79,991

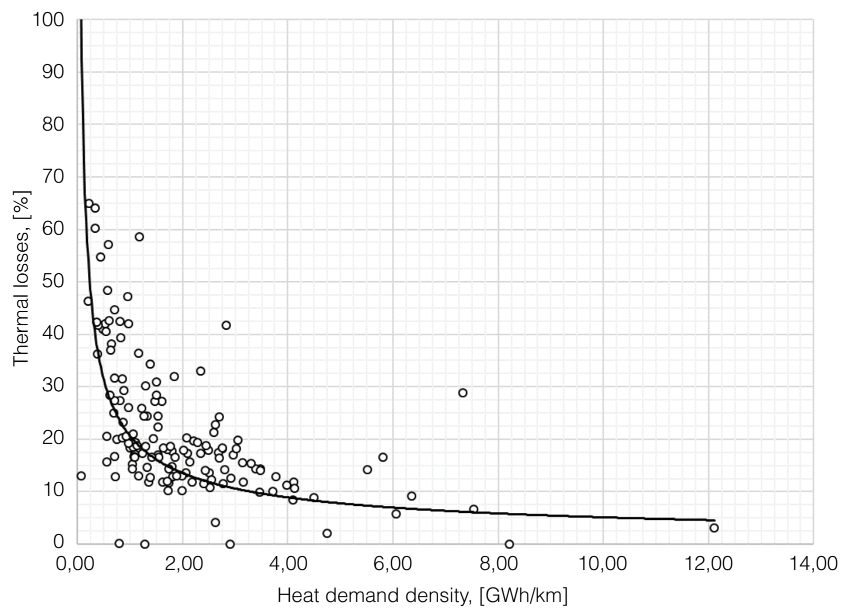

Figure 1: Thermal losses according to the heat demand density in Italian DH networks. (Based on data of [49])

Another relevant fact about Italian DH existing networks concerns distribution heat losses: an average value equal to 21.7% of the total produced heat is currently dispersed in Italian DH networks. The highest heat losses are concentrated in low density distribution networks as resulting from the processing of data shown in Figure 1.

Hence, the strategies to increase DH system efficiency in Italy should include a reduction of fossil fuel dependence, an increase in renewable sources and a reduction of distributing thermal losses. Nevertheless, the current solutions identified by Italian DH operators seem unable to ensure on their own the economic profitability of the DH sector in accordance with the market's evolution due to climate change and to the variation of customers' energy demands.

Among these, in fact, the optimization of the circulating flowrate through the installation of pumps with inverters or the increase of temperature difference between supply and return pipes to reduce the thermal losses through the return pipes seem to be not enough to support DH investments in the future, and disruptive solutions such as the introduction of the LTDH concept are expected to be necessary.

The LTDH concept seems to be really appropriate to the Italian DH framework since it can contribute both to integrate low enthalpy renewable sources and to reduce the distribution heat losses. However, the feasibility of the transition from traditional DH to LTDH systems needs to also consider the characteristics of the buildings connected to the DH networks, since some criticalities at customer level may arise from the changes in DH operating conditions.

As reported by [50], 7.3 million residential buildings (about 60% of the total) in Italy were constructed before 1976, when the first Italian law about energy efficiency in buildings was promulgated. Furthermore, a decline in construction activities began in the 1990s, as shown in Figure 2. The effect of the combination of an old buildings stock and of a decreasing trend in the construction sector is that only a very small percentage of Italian buildings is characterized by good energy performances (<8%) [51].

Furthermore, no particular improvements in energy efficiency in the building sector are expected in the near future. In fact, Italy is characterized by a major renovation rate (defined as the number of major renovations divided by the total number of buildings) of about 0.75% [52], which is relatively low if compared with other European countries (i.e. Germany is about 1.5%, France is 2.0% and Norway 2.4%).

In addition to previous concerns, in the current Italian situation only 0.8 million residential buildings are public (housing less than 2 million people) [53], and so public housing renovation can only play a marginal role in the transition to higher efficiency building stock. Therefore, renovation actions must be taken mainly by private customers in order to have an impact, meaning that higher economic incentives or the introduction of taxes based on CO_2 emissions should be put in place by policy makers to stimulate a wider adoption of building efficiency actions.

In conclusion, the DH framework in Italy seems to be promising for LTDH application, but some limitations are expected due to the buildings' characteristics of age and of low energy efficiency, meaning that low temperature heating systems are not commonly found at customer level.

2. Material and methods

The materials and methods section presents the method applied by the authors to identify and classify the barriers to the development of LTDH in Italy. The AHP method is fully described to ensure the replicability of the analysis also to other European contexts.

2.1. Identification of barriers in the development of LTDH in Italy

Relevant barriers have to be identified to pave the way for the renovation of existing Italian DH systems in accordance with the LTDH concept. In fact, even if several solutions are present in the literature, their direct application to Italy and more generically to Southern European countries may be not effective since different framework conditions can be found. The following questions (Qs) have been defined to identify these barriers:

1) The traditional DH system is a well-known system: why should we change existing DH configurations into new ones?

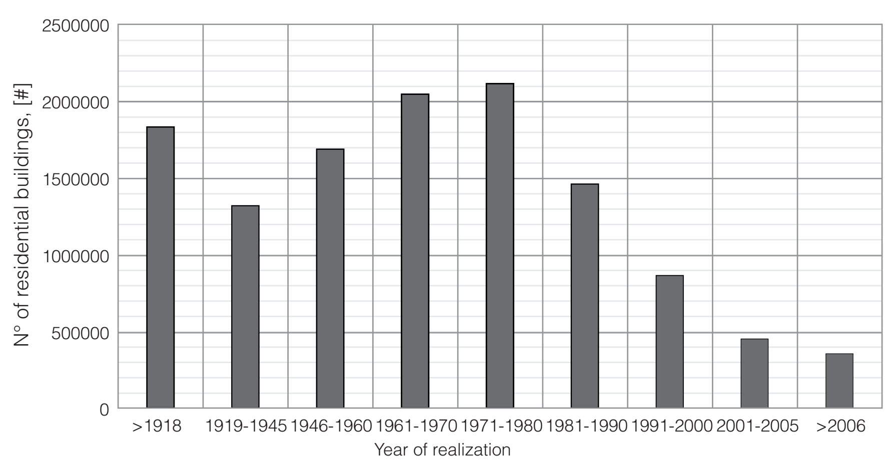

Figure 2: Number of residential buildings in Italy. (Based on [50])

2) The Italian DH market decreased in the last 10 years: why invest in it?
3) Investment uncertainty: how much does the renovation of a DH system to an LTDH system cost?
4) The Italian building stock is old and characterized by low energy efficiency: what are the solutions to ensure thermal comfort also in low energy performance buildings?
5) What interventions should be made to ensure the respect of contractual obligations by DH operators?
6) DH supply limits: what are the technical issues?
7) DH supply limits: what are the business/legal issues?
8) What are the new skills required in the design, realization, commissioning and operation phases?
9) What can be the issues due to the integration with District Cooling (DC) systems?
10) What are the main potential impacts on customers?

In the discussion section, answers are given to the proposed list of questions.

2.2. The Analytic Hierarchy Process (AHP) method

A comparison was made between different possible solutions to overcome the identified barriers. A quantitative comparative analysis did not seem to be appropriate at this early stage of the analysis, and a qualitative multi criteria approach was thus considered in the paper through the Analytic Hierarchy Process (AHP) [54]. AHP is a qualitative comparative method [55] structured in the following four steps:

1) In the first step a hierarchical model is designed to aggregate elements according to their common characteristics at separate levels. The highest level represents the aim of the analysis, the middle ones correspond to the criteria and sub criteria, while the lowest one contains possible alternatives.
2) In the second step, a pair-wise comparison between elements of the same levels is required based on a specific element of the upper level. A comparative matrix A, in which each elements $a_{i,j}$ represents the comparison between the row element a_i and the column element a_j *as* reported in Eq. (1), is constructed:

$$A = (a_{i,j}) \ \ where\ i, j = 1, 2,\ \dots\dots,\ number\ of\ criteria \quad (1)$$

Eq. (2) has also to be respected:

$$a_{i,j} > 0; a_{j,i} = \frac{1}{a_{i,j}};\ \ a_{ii} = 1 \quad (2)$$

The following question: "of the two elements, which is more important with respect to the criterion and how much?" has to be answered to compare two elements with respect to a common criterion. A nine-point scale is used to convert qualitative judgments into numerical ones as defined in Table 2.

3) Because several decisional criteria are present, the third step consists in the ranking of criteria and in the evaluation of judgement consistency. For the purpose, the principal eigenvector *v* of the matrix *A* has to be calculated through the solution of Eq. (3):

$$Av = \lambda_{max} v \quad (3)$$

where λ_{max} is the largest eigenvalue of the matrix A and the corresponding eigenvector v contains only positive entries. The consistency of the matrix is estimated through the calculation of the consistency ratio (CR) defined as in Eq. (4):

$$CR = \frac{CI}{RI} \quad (4)$$

Where *CI* is the consistency index of a randomly generated reciprocal matrix from the nine-point scale and RI is the random index. A higher value of the index *CR* is representative of a poor consistency of the matrix and thus of the judgement. A threshold value equal to 0.10 is usually considered for the acceptability of the analysis [55]. The calculation of *CI* can be done through Eq. (5):

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

Table 2: Relative importance measurement scale

Importance intensity	Definition
1	Equal importance
3	Weak importance
5	Moderate importance
7	Strong importance
9	Extreme importance
2,4,6,8	Intermediate values
Sum	11.00

Table 3: Random index according to the number of elements

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	0.12	1.24	1.32	1.41	1.45	1.49

where n is the number of criteria. RI factor is then tabulated according to the number of element as reported in Table 3.

4) The final step of the method is the calculation of the aggregate priority. Thanks to the local priorities alternatives with respect to each criterion, the total priorities of each alternative are calculated. To calculate the relative weight (RW) for each criterion at each level, Eq. (6) has to be used:

$$RW = \frac{1}{n}\left[\frac{preference\ of\ criterion\ i\ in\ column\ 1}{sum\ of\ the\ entries\ in\ column\ of\ criteria\ 1} + \frac{preference\ of\ criterion\ i\ in\ column\ 2}{sum\ of\ the\ entries\ in\ column\ of\ criteria\ 2} + \cdots + \frac{preference\ of\ criterion\ i\ in\ column\ n}{sum\ of\ the\ entries\ in\ column\ of\ criteria\ n}\right] \tag{6}$$

A composite weight (CW) of the high level alternatives taking into account the RW of low level alternatives and representing their ranking can be lastly calculated as in Eq. (7):

$$CW = \sum_{i=1}^{n} RW_{i,k-1} \times RW_{i,k} \tag{7}$$

Where the subscript k is used to indicate the different level.

3. Results and discussion

The results of the AHP analysis are shown and discussed in the third section of the paper. Comments are given by the authors to suggest effective actions to be carried out for the development of LTDH systems in Italy.

3.1. Barriers and possible solutions for the development of LTDH in Italy

In the previous section, ten questions (Qs) were defined as a track-list to identify the main barriers to the renovation of existing DH systems to 4th generation systems. A preliminary division into technological and non-technological barriers was made as in Table 4.

The first issues to be overcome (Q1, Q2, Q3) are related to the techno-economic feasibility and sustainability of DH operators' investments in DH renovation. The quantification of heat losses reduction, the efficiency gain reached by the substitution of traditional heating systems with more efficient ones (i.e. renewable energy sources), and the current low profitability of existing DH systems are three great drivers moving towards LTDH systems.

Table 4: Technological and non-technological barriers to the integration of the LTDH concept

	Technological	Non-technological
Question	1, 4, 6, 8, 9, 10	2, 3, 5, 7

However, the quantification of the cost for the retrofit of existing DH networks is more critical and is usually perceived as requiring high investment. At the same time, operation benefits depend on several parameters that are not directly under the control of DH operators, like NG and electricity costs, or the presence of dedicated incentives and tax reductions. Because very large investments require a very small range of uncertainty or must offer a potentially high yield on investment capital [56], DH operators consider the retrofitting of the existing DH networks very critical from the economic point of view.

Another critical issue is due to the presence of a great number of low energy efficiency buildings and, consequently, to the possible limitations in ensuring thermal comfort (Q4). In fact, the decrease of transmitted heat due to the reduction of the supply temperature is not always acceptable for final customers that would need to renovate their internal heating systems to ensure thermal comfort conditions in accordance with the new supply conditions [30].

Therefore, DH supply temperatures have to be ensured coherently with existing contracts between operator and customers, otherwise new contracts have to be signed. Temperature boosters (Q5) such as decentralized heat pumps, solar collectors, electric boilers or other solutions should be installed to locally increase the temperature without thermally unbalancing th LTDH network [57,58]. However, a check of available spaces within substations and of the required variations has to be performed to ensure the respect of existing constraints and DH supply limits (Q6) [33]. Although the installation of active latent heat thermal energy storage systems could save spaces in existing DH substation, sensible heat water storage systems are still preferred due to their lower specific cost per cubic meter [59].

Temperature boosters can also be property of the final customers or prosumers: in the last case, thermal energy can be fed-in into the network even if it is produced outside of the DH system's supply limits. The result is a complex bi-directional and decentralized energy system that requires smart management and innovative business models, with relevant legal issues (Q7) related to fiscal energy metering (consumption and production), charge for device maintenance, responsibilities in the case of anomalies, and energy production planning [60,61]. The criticalities can be solved through the application of new contracts, and a different legal framework also seems to be required. Furthermore, new intermediary figures would be introduced in the DH market being responsible for the management of decentralized systems.

To make LTDH revamping of existing DH networks effective, new skills are required (Q8), starting from the design phase, the ability to manage big data and the optimization of control strategies [62]. A new business approach to the DH market is required from the decision makers and from those who will be responsible for the definition of contracts because many more variables will be present in future energy scenarios [61].

Another relevant barrier is related to DH integration with DC, which is a specific issue of Southern Europe (Q9). In traditional DH systems, absorption chillers can be used as refrigeration units in combination with standard compression chillers. The absorption chillers can recover the waste heat produced by cogeneration plants, thus maximizing the investment and considerably reducing the cold energy production costs [63]. Absorption chillers are supplied by relatively high temperature fluid and cannot directly work with supply fluid temperature of LTDH networks.

An effective integration of LTDH and DC can be achieved with a different substation configuration only if the supply temperature is very low, i.e. under 25 °C: in that case it is possible to locally satisfy the cooling demand of each customer through decentralized chillers or reversible heat pumps. Through a further decreasing of LTDH supply temperature under 12 °C, free cooling may be achieved [63].

Finally, depending on the adoption of a warm or cold LTDH model, the impact on customers (Q10) may be different: while a cold LTDH system needs a local booster, and so the customer may not perceive any kind of variation in the DH operation, in a warm LTDH a supply temperature reduction is present in the substation, and so the customer can directly observe different performance levels of the DH system (i.e. temperature reduction in the radiators) [21].

3.2. Alternatives and selection criteria

From the proposed questions regarding existing barriers for the introduction of LTDH, ten criteria (C) were chosen for the AHP analysis to compare possible DH configurations, distinguishing between technological and non-technological alternative:

1) Knowledge about state of the art technology (technological) – C1.
2) Status of DH market (non-technological) – C2.
3) Economic profitability and uncertainty payback time (non-technological) – C3.
4) Supply delivery conditions (technological) – C4.
5) Contractual obligations (non-technological) – C5.
6) DH supply limits (technological) – C6.
7) DH supply limits (non-technological) – C7.
8) Skills required (technological) – C8.
9) Integration with DC (technological) – C9.
10) Impact on customer (technological) – C10.

To perform AHP analysis, compared alternatives (A) also have to be defined. For the purpose, three possible configurations were considered: existing DH (EDH – A1), warm LTDH (WLTDH – A2) and cold LTDH (CLTDH – A3). EDH was introduced to compare existing systems with LTDH ones. A schematic representation of the hierarchal approach is proposed in Figure 3 where the scope of the analysis, criteria and alternatives are shown.

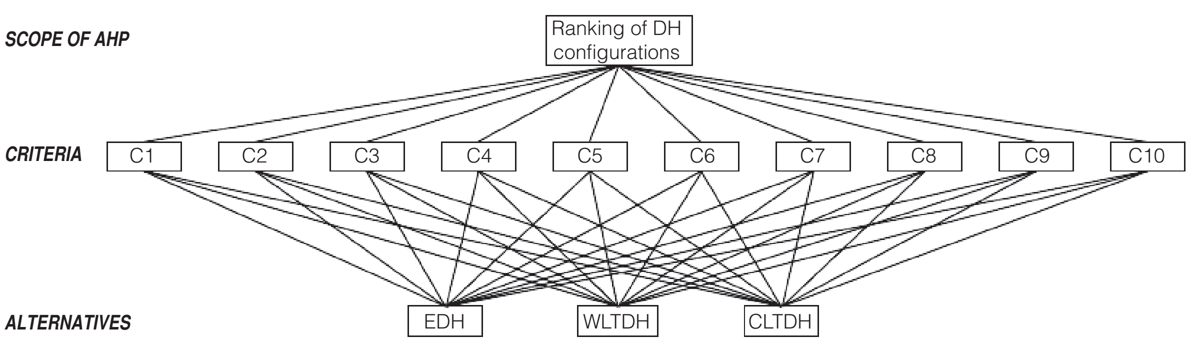

Figure 3: The hierarchal representation of the comparative analysis with ten criteria and three alternatives

Table 5: Impact of different criteria with respect to the implementation of WLTDH and CLTDH

Criteria	Kind	WLTDH	CLTDH
C1	Technological	LOW	LOW
C2	Non-Technological	MEDIUM	HIGH
C3	Non-Technological	LOW	HIGH
C4	Technological	HIGH	LOW
C5	Non-Technological	HIGH	NONE
C6	Technological	NONE	HIGH
C7	Non-Technological	NONE	MEDIUM
C8	Technological	LOW	MEDIUM
C9	Technological	HIGH	LOW
C10	Technological	HIGH	NONE

Table 5 proposes a qualitative assessment of the identified criteria due to the impact of LTDH for WLTDH and CLTDH configurations. As shown, due to the absence of remote temperature boosters in WLTDH configurations, a high possible impact is considered for those criteria that take into account the delivery conditions to the customers. In fact, the absence of remote boosters is responsible for off-design working conditions that can be unacceptable for the end-users.

The same barriers, instead, have a different impact on CLTDH. As shown in Table 5, the main barriers for the implementation are the economic ones (C2 and C3) and those related to the renovation of existing systems to ensure design delivery conditions (C6). As previously reported, in fact, ever-greater guarantees are required by Top Management before making economic investments. This is particularly true in the case of CLTDH for which great efforts are required for their implementation in substitution of the relatively new Italian DH.

Another possible impact is due to the necessity to modify DH substations in order to ensure delivery conditions at the same time as the variation of the DH plant supply conditions. As previously described, the implementation of dedicated devices along the DH network has to be carefully checked both during design and operation. Consequently, the identification of the best solution requires further investigation.

3.3. Obtained results

To overcome the identified uncertainty, AHP is the selected method because qualitative judgement can be used as a starting point for a semi-quantitative analysis. The first step of the analysis was the comparison between criteria responding to the following question: "Considering DH systems, what is the importance of criteria A with respect to criteria B?". Table 6 reports the pair wise matrix resulting from the comparison: each number is the preference of each criterion with respect to the others. For example, in the fourth row, C5 (contractual obligations) is compared to all the other criteria. As shown, C5 is considered much more important than C1 (state of the art technology) in the first column but it is considered to have the same importance with respect to C4 (supply delivery conditions). Therefore, the values reported in the intersection between rows and columns are the preference of the first with respect to the second.

The estimation was performed by the authors based on the criticalities identified by the literature and by considering the Italian DH sector peculiarities. More in detail, economic and financial issues as well as the relationship with the customers are generally considered the most critical ones, since both can have high negative impact on a DH project development [23,64–67]. The highest importance (32.3%) given to the impact on customer (C10), as resulting from Table 6, is justified by the specific Italian framework, which is characterized by a larger part of low energy efficiency buildings and the consequent high risks of negative impact on the performance at customer level (i.e. thermal comfort) of the DH system due to supply temperature lowering.

Economic uncertainty (C3) is the second impacting criteria (21.5%), since financing issues always play a decisive role in the DH sector. Contractual obligations (C5) and the supply delivery conditions (C4) have, respectively, the third (14.0%) and fourth (11.9%) importance, since both are related to the Italian customer characteristics (as per C10). Other criteria have an importance almost equal to or lower than 5.0%. As shown in Table 6,

Table 6: Pair-wise comparison of the different criteria and their relative weights (RW)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	RW
C1	1.00	0.33	0.11	0.14	0.11	0.33	0.33	0.33	0.33	0.11	0.015
C2	3.00	1.00	0.20	0.20	0.20	3.00	3.00	3.00	3.00	0.11	0.053
C3	9.00	5.00	1.00	3.00	3.00	9.00	9.00	9.00	9.00	0.20	0.215
C4	7.00	5.00	0.33	1.00	1.00	5.00	5.00	5.00	5.00	0.20	0.119
C5	9.00	5.00	0.33	1.00	1.00	7.00	7.00	5.00	5.00	0.33	0.140
C6	3.00	0.33	0.11	0.20	0.14	1.00	1.00	3.00	3.00	0.14	0.038
C7	3.00	0.33	0.11	0.20	0.14	1.00	1.00	5.00	5.00	0.14	0.048
C8	3.00	0.33	0.11	0.20	0.20	0.33	0.20	1.00	1.00	0.11	0.024
C9	3.00	0.33	0.11	0.20	0.20	0.33	0.20	1.00	1.00	0.11	0.024
C10	9.00	9.00	5.00	5.00	3.00	7.00	7.00	9.00	9.00	1.00	0.323
Sum	50.00	26.67	7.42	11.14	9.00	34.00	33.73	41.33	41.33	2.46	

RI: 1.49
CI: 0.14
CR: 0.095
λmax: 11.28

a good consistency ratio (CR), lower than 0.10, was found, thus ensuring the consistency of the analysis.

Matrices for the pair-wire comparison of the three alternatives based on each criterion are presented in Tables from 7 to 16. The values in the tables are obtained by answering the following question: "with respect to criterion C, what is the impact on alternative A with respect to alternative B?". The answers have been given on the basis of the preliminary qualitative analysis carried out in Table 5. For example:

- in Table 9 economic investment and uncertainty are considered: EDH is assumed to be the most critical solution since several external factors such as fuel cost, electricity selling price and incentives/feed-in tariffs can have a negative impact on expected Operative Expenditures (OPEX);
- in Table 10 and Table 11, supply delivery conditions and contractual obligations have the greatest impact on WLTDH due to the fact that, without the presence of decentralized heat sources, wrong supply conditions could verify during operative conditions, while a lower impact is assumed for CLTDH due to the presence of remote heating devices;
- in Table 12 and Table 13, technological and not technological supply limits are considered: the greatest impact is assumed for CLTDH, since decentralized heat sources and dedicated control systems have to be installed in existing substation where spaces are limited;
- in Table 16, CLTDH and EDH are assumed as the least impacting configurations ensuring the maintenance of existing supply conditions.

Table 7: Pair-wise comparison of the three alternatives with respect to the knowledge about state of the art technology

Criterion C1				
	CLTDH	WLTDH	EDH	RW
CLTDH	1.00	1.00	1.00	0.33
WLTDH	1.00	1.00	1.00	0.33
EDH	1.00	1.00	1.00	0.33
Sum	3.00	3.00	3.00	

RI: 0.58
CI: 0.0
CR: 0.0
λmax: 3.00

Table 8: Pair-wise comparison of the three alternatives with respect to the status of DH market

Criterion C2				
	CLTDH	WLTDH	EDH	RW
CLTDH	1.00	3.00	0.20	0.19
WLTDH	0.33	1.00	0.14	0.08
EDH	5.00	7.00	1.00	0.72
Sum	6.33	11.00	1.34	

RI: 0.58
CI: 0.025
CR: 0.043
λmax: 3.05

From the processing of the obtained results in the pair-wise comparison between criteria and alternatives, the preferred configuration is calculated by Eq. (7) as reported in Table 17. It is interesting to note that CLTDH proves to be most appropriate for the Italian DH

Table 9: Pair-wise comparison of the three alternatives with respect to the economic investment and uncertainty on payback time

Criterion C3				
	CLTDH	**WLTDH**	**EDH**	**RW**
CLTDH	1.00	5.00	0.33	0.28
WLTDH	0.20	1.00	0.14	0.07
EDH	3.00	7.00	1.00	0.64
Sum	4.20	13.00	1.48	

RI: 0.58
CI: 0.025
CR: 0.043
$^{\lambda}$max: 3.05

Table 10: Pair-wise comparison of the three alternatives with respect to the supply delivery conditions

Criterion C4				
	CLTDH	**WLTDH**	**EDH**	**RW**
CLTDH	1.00	0.11	1.00	0.09
WLTDH	9.00	1.00	9.00	0.82
EDH	1.00	0.11	1.00	0.09
Sum	11.00	1.22	11.00	

RI: 0.58
CI: 0.00
CR: 0.00
$^{\lambda}$max: 3.00

Table 11: Pair-wise comparison of the three alternatives with respect to the contractual obligations

Criterion C5				
	CLTDH	**WLTDH**	**EDH**	**RW**
CLTDH	1.00	0.14	1.00	0,11
WLTDH	7.00	1.00	9.00	0,80
EDH	1.00	0.11	1.00	0,10
Sum	1.00	0.14	1.00	

RI: 0.58
CI: 0.00
CR: 0.00
$^{\lambda}$max: 3.00

Table 12: Pair-wise comparison of the three alternatives with respect to the supply limits (technological)

Criterion C6				
	CLTDH	**WLTDH**	**EDH**	**RW**
CLTDH	1.00	3.00	9.00	0.69
WLTDH	0.33	1.00	3.00	0.23
EDH	0.11	0.33	1.00	0.08
Sum	1.44	4.33	13.00	

RI: 0.58
CI: 0.0
CR: 0.0
$^{\lambda}$max: 3.00

Table 13: Pair-wise comparison of the three alternatives with respect to the supply limits (not-technological)

Criterion C7				
	CLTDH	**WLTDH**	**EDH**	**RW**
CLTDH	1.00	5.00	9.00	0.72
WLTDH	0.20	1.00	5.00	0.22
EDH	0.11	0.20	1.00	0.06
Sum	1.31	6.20	15.00	

RI: 0.58
CI: 0.055
CR: 0.095
$^{\lambda}$max: 3.11

Table 14: Pair-wise comparison of the three alternatives with respect to the skills required

Criterion C8				
	CLTDH	**WLTDH**	**EDH**	**RW**
CLTDH	1.00	9.00	9.00	0.82
WLTDH	0.11	1.00	1.00	0.09
EDH	0.11	1.00	1.00	0.09
Sum	1.22	11.00	11.00	

RI: 0.58
CI: 0.0
CR: 0.0
$^{\lambda}$max: 3.00

Table 15: Pair-wise comparison of the three alternatives with respect to the integration with DC

Criterion C9				
	CLTDH	**WLTDH**	**EDH**	**RW**
CLTDH	1.00	0.11	0.33	0.07
WLTDH	9.00	1.00	5.00	0.75
EDH	3.00	0.20	1.00	0.18
Sum	13.00	1.31	6.33	

RI: 0.58
CI: 0.010
CR: 0.017
$^{\lambda}$max: 3.02

Table 16: Pair-wise comparison of the three alternatives with respect to the impact on customers

Criterion C10				
	CLTDH	**WLTDH**	**EDH**	**RW**
CLTDH	1.00	0.11	1.00	0.09
WLTDH	9.00	1.00	9.00	0.82
EDH	1.00	0.11	1.00	0.09
Sum	11.00	1.22	11.00	

RI: 0.58
CI: 0.0
CR: 0.0
$^{\lambda}$max: 3.00

Table 17: Final composite weight (CW) of the three DH configurations with respect to identified barriers

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	CW
RW	0.02	0.05	0.22	0.12	0.14	0.04	0.05	0.02	0.02	0.32	
CLTDH	0.33	0.19	0.28	0.09	0.11	0.69	0.72	0.82	0.07	0.09	0.21
WLTDH	0.33	0.08	0.07	0.82	0.80	0.23	0.22	0.09	0.75	0.82	0.54
EDH	0.33	0.72	0.64	0.09	0.10	0.08	0.06	0.09	0.18	0.09	0.25

scenario. WLTDH, instead, is considered the most critical for the Italian DH market, especially for the possible impact on customers that limits its implementation in existing systems.

4. Conclusion

Solutions to improve energy efficiency are required in order to identify energy and emission targets worldwide and particularly in residential and commercial sectors where a greater implementation of district heating (DH) systems is expected in future years. However, even if known for more than a century, a continuous technological development has always characterized the DH sector with the aim of reducing thermal losses, integrating more renewable sources and integrating them with other energy sectors.

The fourth generation of this sector or the so called low temperature district heating (LTDH) represents the novel approach in DH. Nevertheless, many barriers are currently present reducing the development potential of LTDH systems. Furthermore, little research has been done for Southern European regions, and for Italy in particular, where a high potential of renewable sources could be present.

The paper identifies and classifies ten main technological and non-technological barriers to the adoption of LTDH in Italy. The Analytic Hierarchy Process (AHP) method is applied to assess the difficulty to implement cold LTDH and warm LTDH in existing DH networks by considering the identified barriers. The preliminary assessment shows that cold LTDH proves to be the best option for the Italian DH sector, while several concerns are still present for the application of warm LTDH, the possible impact on the customers being the most relevant.

A questionnaire was drawn up and submitted to several experts in Italy and in other European countries, to compare the opinions on barriers and solutions in the development of LTDH and to allow a comparison between the Italian framework and those in other European countries. Once concluded, the findings of the survey will be used to adjust and modify the AHP approach developed in the paper and to validate or to update the current results. Furthermore, a feasibility study will be carried out in one existing and representative Italian DH network to measure technical and economic barriers in the retrofitting into an LTDH network.

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