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District Thermal Systems: State of the Art and Promising Evolutive Scenarios. A focus on Italy and Switzerland.

--Manuscript Draft--

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Abstract:	In the framework of the built environment enhancement towards energy strategy 2050, interesting debates have been developed at building and district scale. In relation to thermal energy end-uses, that are the most impacting in buildings, district thermal systems (DTS) offer a great flexibility in terms of heat generation technologies and renewable resources integration, resulting, in case of proper management and supply conditions, in primary energy and greenhouse gases savings compared to the most diffuse technologies operating at building scale. Recent progresses in DTS have followed over the years the development of technologies and energy policies resulting in different configurations and operative schemes. The present contribution reviews the different classifications of DTS provided in the technical literature. The European framework of DTS is then analysed, with particular insights to the Italian and Swiss operative context. Currently, DTS have a marginal role in these two countries and can mainly be classified as high-temperature or mid-generation systems. However, there are also innovative systems, on which the attention of the involved stakeholders is focusing. The technological features of DTS are discussed, in order to provide possible challenging evolutive scenarios to enhance their performance and economic appeal through the evaluation of successful recent examples.
Suggested Reviewers:	simone buffa simone.buffa@eurac.edu expertise in the field
	Joachim Ködel Hochschule Luzern joachim.koedel@hslu.ch expertise in the field
	vittorio verda Politecnico di Torino vittorio.verda@polito.it
Response to Reviewers:	

Esteemed Editor,

The research here presented aims to investigate the state of the art of district thermal systems in Europe and in particular in Italy and Switzerland. These systems are analyzed in the framework of the future energy scenarios toward a drastic decarbonization, following two different methods of classification. A further focus about challenging experiences of innovative low temperature systems is reported, providing insights for a proper evolution of these systems. One added value of the work is the involvement of the authors in associations and working groups in the fields, a condition that makes our research “a bridge” between companies, users and scholars. Further, the attempt to transfer the lesson learnt analysing different cases and contexts to the readers can be another important feature of the work.

The treated topics are in accordance with the multi-disciplinary scope of *Sustainable Cities and Society*; can be appealing to energy scientists and affordable also to a wider audience of other stakeholders of the energy systems and buildings sector.

Sincerely,

The authors

Highlights

1. District thermal systems (DTS), promising for 2030 and 2050 goals, are investigated.
2. A review of the technical literature concerning different classifications of DTS is presented.
3. European DTS are analysed, with particular insights on Italian and Swiss operative context.
4. 5^{th} generation DTS are investigated, with insights on Italian and Swiss examples.
5. Technological features of DTS and their possible evolutive scenarios are discussed.

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The authors thank Editor and reviewers for their precious work and for appreciating the research.
The answers are reported in blue in the following.
Sincerely,
the authors

Editor and Reviewer comments:

Reviewer #1: Subject addressed in this article is worthy of investigation. District heating topic is very important for studied regions, because there is high potential for the development of DH in these regions.
Many thanks for your appreciation.

Figure 1 is not described in the text.
We have added the description in the revised version.

Rather many data are presented and analysed, but this set of data is provided in other references (not in English).
Actually few references cited are not available in English. We have tried to minimize references not available in English reporting and citing only those that, in our opinion, are relevant for the issues treated.

5th generation DH concept is added to 4th generation DH, however according to definition 4GDH includes both LTDH and Ultra-low DH too.
https://vbn.aau.dk/ws/portalfiles/portal/280710833/1_4GDH_progression_revised_May2018.pdf
We agree with you about. However, according to recent researches (see recent references) we have preferred to introduce also 5GDH, modified in 5GDHC as clarified in the further comments and answers and in the revised version of the manuscript.
In the text we have specified that 5GDHC refers to "*grids operating at temperatures close to the ground etc…*".

It is not clear, how the maps on Figure 5 have been created.
We have added the description of the map in the revised version (see text above Figure 5).

Mistake: Figure 4 mentioned on page 11, actualy is Figure 6/Figure 12 reference to Figure 7.
We are sorry for this mistake. Figures were not numbered and cited correctly. We have corrected the mistakes in the revised version.

Table numbering is not correct. There is no Table 1 in the text, there are two Tables 3
We are sorry for this mistake. There are 5 tables in total; tables 1 and 2 were not numbered correctly. We have corrected the mistake in the revised version.

Figure 4 is not clear: If 4th generation is lower, then 70°C, it means, that LT can be only 4th generation, because it will be less, then 60°C
According to our research and cited references, the three sub-classes of LT can be both 4GDH and 5GDHC. Figure 4 and its caption have been improved in order to explain better this point.

By the way, further clarification about this issues are reported in the revised version of the paper (see in particular the definition of 5GDHC in section 2.1).

Figure 7- Evolution suggested- how this evolution has been suggested?
In this case, evolution means the process of lowering temperature of grid in operation together with the renovation of the buildings sector (envelope, services, storage, systems for heating, cooling and electricity, thermal network management). It is the same concept described in the 2nd page of https://vbn.aau.dk/ws/portalfiles/portal/280710833/1_4GDH_progression_revised_May2018.pdf
However, in order to avoid to be misleading, in the revised version, we have removed the dashed arrow and the text in red on figures 8 and 11.

Figure 12 doesn't provide any additional information: it is allocation of selected DH by type of heat sources, described in the text.
We understood *"Figure 12. Swiss LT-DTS according to the selected cases (percentages refer to total 25 selected cases)"*. In this case, the classification by sources of the set of the 25 selected cases is actually an added information, not reported elsewhere in the text. Therefore, we would rather maintain this figure in order to show the sources adopted for the operation of the HP of the Swiss LT DTS.

Additional comments:
*District thermal systems is term, that is not used too often. Actually if we look to Scopus database, we will not find any paper, mentioning it. Only five papers, mentioning „district thermal networks". Thermal grids could be used instead. For sure, it is the choice of authors, but in case, this term will be used, clear definition of this term should be presented in the beginning of the paper, focusing on the difference between DTS and DH, or DTS and thermal grids. It there is no difference, it is better use more traditional term. In current version of the paper DTS and DHS are used in the same paragraph and for one type systems. However DTS expression is explained in the conclusion part.
We agree with you and, for sure, we discussed many times about this issue writing our manuscript.
In the Introduction (section 1), we have updated the definition as it follows:
"In the following, DTS is adopted, where appropriate, to indicate a larger concept of thermal networks able to satisfy or integrate thermal uses in buildings (space heating, domestic hot water, space cooling) by means of networks of pipe connected one side to final users/prosumer and other side to available heat sources."
In the Conclusion (section 5), we have kept as it was the phrase:
"The expression DTS has been here adopted, instead of DH and/or DC, indicating a system of pipe connected one side to final users (that can be also a prosumer) for each type of thermal uses and other side to available heat sources, regardless of their level of temperature, size and complexity. To that end, the possibility of managing DTS in bidirectional and unmanaged way can bring interesting opportunities."
This option (DTS) allows us to indicate each typology of district systems devoted to thermal purpose in buildings.
In the revised version of the paper we have corrected the use of DH, DHS and DTS accordingly, deleting DHS, adopting DH when dealing only with district heating (or DC when dealing only with district cooling), and respecting also the terminology reported in the references cited and commented.
We hope that now our option is enough "robust".

*It is not clear, what reference is used for defining of three sub-classes among LT DTS. If it is reference 27 (which is in German and can not be checked by the reviewer), it should be underlined.
This point is treated in section 2.2. that, in the revised version, has been further clarified.
As written above, we have tried to minimize references not available in English reporting and citing only those that, in our opinion, are relevant for the issues treated, e.g. [27].
In order to underline this aspect, in section 2.3 we have added also the following:

“As anticipated in section 2.2, after a deep technical review (not only in the Scopus database, i.e. in English, but also among the available local references in Italian and German),…”
Moreover, reference [27] is in German, but the topic treated is similar to that of reference [28], where there is also one author in common and the citation of web site https://www.energieschweiz.ch/home.aspx?p=22949 from which is possible to download reference [27].
In addition, analogous references in German are cited in the recent technical literature in this filed (e.g. in [25] there are many references in German, one of them is by the same authors of [27] and deals with the same issue).
Analogous considerations can be reported for [29] that cites other references in German, authored by one of the authors of reference [27].
25. S. Buffa, M. Cozzini, M. D’Antonia, M. Baratieri, R. Fedrizzi, (2019) 5th generation district heating and cooling systems: A review of existing cases in Europe. Renewable and Sustainable Energy Reviews 104, 504–522.
27. D. Hangartner, J. Ködel, S. Mennel, M. Sulzer (2018) Grundlagen und Erläuterungen zu Thermischen Netzen. 1121499 Swiss Federal Office of Energy SFOE. In German
28. Sommer, T., Sulzer, M., Wetter, M., Sotnikov, A., Mennel, S., & Stettler, C. (2020). The reservoir network: A new network topology for district heating and cooling. Energy, 117418.
29. Wirtz, M., Kivilip, L., Remmen, P., & Müller, D. (2020). 5th Generation District Heating: A novel design approach based on mathematical optimization. Applied Energy, 260, 114158.

*Please explain each acronym after first mentioning in the text. It is defined by paper authors some more expanded explanations should be added.
We modified the text as requested.

*I am not sure, that there is need to include Figure 1. By my opinion it does not provide any additional value.
We agree that the figure is not fundamental, but we reported it to show the geographic location of the investigated regions, useful to contextualize the research and also to understand the climatic conditions to every reader.

*Please, add explanation to reference [8]
Actually, this source represents a fundamental reference for DH in Italy.
Therefore, in the revised version of the paper (footnote 1) we have added the phrase:
“The reference [8] corresponds to the yearbook published by AIRU, the association of urban (district) heating in Italy. For many years, the association has actively promoted district heating based on different energy resources. The yearbook contains the essential data of the district heating networks present on the national territory.”

*It is not clear why 2.5 pages is devoted to results of one reference- Italian DH annual report in 3.1. section. Later in discussion session- all data are related to the north Italy, but in 3.1. it is not clear.
Section 3.1 is devoted to describe the state of the art of DH in Italy, so [8] is cited properly. According to the climatic conditions, most of the DH systems are located in northern Italy.
We revised part of sections 3.1 and 4 and Tables 1 and 5 to be clearer.

*I don't understand, why in 3.1. number of DHS is 239, but in discussion part 368.
We clarified this point in section 3.1 with the footnote 6 to be clearer. See also previous answer.

*In 3.1.1. may be some additional explanation regarding more then 5 cases of DHS with supply temperature lower, then 20°C can be added.
If we understood correctly, the reviewer suggests to describe the Italian LT cases.

In the revised version, we modified the text as it follows:
"Further insights related to the 4GDH and 5GDHC cases will be provided in section 3.3."
Therefore, the description of these cases is included in section 3.3.

*Once acronyms is explained, it should not be repeated (asi in 3.1.2. (space heating and domestic hot water - DHW)).
We corrected the mistake according to your comment.

*5GDH is not Danish classification, Danish researchers were the authors of the 4th generation DH, and actually many Danish researchers does not agree with the idea of 5th generation DH and consider it as 4th generation DH. So please dont use term "Danish classification "(as in Figure 13)
We agree with you. Indeed, we adopt the definition "classification based on generation" and not "Danish classification" in the paper. We are sorry for the mistake; in the revised version, we have corrected figure 13 accordingly.

Reviewer #2: The topic of the work is very interesting for the reviewer. It refers to a state of the art description of the district heating and cooling sector in Italy and Switzerland with a comparison of recent classification about this technology. The quality of the content, paper structure and writing is very good. For this, I suggest publishing it in Sustainable Cities and Society with minor revisions.
Many thanks for your appreciation.

In the following I reported minor shortcomings for further improvement of the work:
* To review the punctuation:
o space should be removed at line 2 of pag. 3;
o parenthesis should be removed at line 32 of pag. 7;
o parenthesis should be removed at line 53 of pag. 15;
The text has been corrected accordingly.

* To review the figure 4:
o Please use 5GDHC instead of only 5GDH (these networks are mainly conceived when there is the need to cover the cooling load);
o For 5GDHC use the same network for heating and cooling (delete the separate cooling DH at the top right scheme);
o Correct the value of Ts<30°C for 5GDHC so that it includes both 3C-LT and 4C-LT classification;
Figure 4 and its caption have been improved in order to explain better this point.

* As far as I know the 5GDHC system of Torbole Casaglia has not been realised. Please check with the utility company;
Thank for your comment. We realized that the system is not in operation and therefore we have removed this case from the manuscript.

* Please correct the number of the footnote from 6 to 7 at line 43 of pag.17;
There was a mistake in the footnotes. The text has been corrected accordingly.

* Use the uppercase for the first letter for the word "Figure 12" (line 27 at pag. 18);
The text has been corrected accordingly.

* UTDH is in general referred to 4GDH networks supplying heat at 40-35°C that allows direct space heating supply with radiant floor/ceiling heating solutions and where booster HPs are used only for DHW. (see: Ostergaard D, Svendsen S, Space heating with ultra-low-temperature district heating - a case study of four single-family houses from 1980s. In: Proceedings of the 15th international symposium on district heating and cooling, Energy Procedia 116 (2017) 226-235.).
We agree with you and we have modified the text and Figure 4 accordingly.

Thus, for 5GDHC, I suggest to use the nomenclature of neutral temperature DHC (NTDHC) covering space heating & cooling and DHW demands with a supply temperature (below 30°C) that is close to the ground one thus "neutral" from thermal losses point of view.
We adopted the acronym 5GDHC in the revised version, according to your previous comment. However, we would rather avoid the acronym NTDHC, in order to be less misleading in our research. We pointed out in the revised version that 5GDHC operate at temperature in the range 15-30°C (also in Figure 4).

* In the study (line 50 at pag. 24) it is mentioned that a few examples of 5GDHC systems realised include demand side response with advanced control strategies. However, no references are provided for this. I suggest the authors read and eventually cite the following papers:
o M. Brennenstuhl, R. Zeh, R. Otto, R. Pesch, V. Stockinger, and D. Pietruschka, "Report on a Plus-Energy District with Low-Temperature DHC Network, Novel Agrothermal Heat Source, and Applied Demand Response," Appl. Sci., vol. 9, no. 23, p. 5059, Nov. 2019, doi: 10.3390/app9235059;
o S. Buffa, A. Soppelsa, M. Pipiciello, G. Henze, and R. Fedrizzi, "Fifth-Generation District Heating and Cooling Substations: Demand Response with Artificial Neural Network-Based Model Predictive Control," Energies, vol. 13, no. 17, p. 4339, Aug. 2020, doi: 10.3390/en13174339.
We thank you for your suggestions. In the revised version, we integrated the two references and we modified the text accordingly.

District Thermal Systems: State of the Art and Promising Evolutive Scenarios. A focus on Italy and Switzerland.

NOMENCLATURE

EU: European Union;
GHG: Greenhouse Gases
~~RE: Renewable Energy~~
RES: Renewable Energy Source/Sources
HP: Heat Pump/Pumps
~~GSHP: Ground Source Heat Pump/Pumps~~
~~GWHP: Ground Water Heat Pump/Pumps~~
~~PV: Photovoltaics~~
~~SH: Space Heating~~
SC: Space Cooling
DH: District Heating
~~CHP: Combined Heat and Power~~
DTS: District Thermal System/Systems
~~DHS: District Heating System/Systems~~
DC: District Cooling
~~DH: District Heating~~
~~DHC: District Heating and Cooling~~
GIS: Geographic Information System
4GDH: 4th Generation District Heating
5GDHC: 5th Generation District Heating and Cooling
1GDH: 1st Generation District Heating
2GDH: 2nd Generation District Heating
3GDH: 3rd Generation District Heating
~~LT: Low Temperature~~
~~HT: High Temperature~~
MES: Multi Energy System/Systems
DHW: Domestic Hot Water
HT: High Temperature
LT: Low Temperature
1C-HT: Case 1 - High Temperature
2C-LT: Case 2 - Low Temperature
3C-LT: Case 3 - Low Temperature
4C-LT: Case 4 - Low Temperature
VAT: Value Added Tax
CHP: Combined Heat and Power
SH: Space Heating
GSHP: Ground Source Heat Pump/Pumps
HX: Heat Exchanger
GWHP: Ground Water Heat Pump/Pumps
PV: Photovoltaics

1. Introduction

Achieving the European Union (EU) climate objectives (i.e. a reduction of the overall greenhouse gas (GHG) emissions by 80-95% by 2050 compared to 1990 levels) requires a complete transformation of the energy system [1].

One of the main challenges is the decarbonisation of the heating and cooling sector, that, dominated by space heating, accounts for approximately 50% of EU-28 final energy demand and around the 80% of the end-use energy in European buildings [2]. For example, the share of space heating is 61% in Italy and 71% in Switzerland [3].

To move to a sustainable heating and cooling sector, it is essential to invest to lower overall demand, to increase energy conversion efficiencies and to replace fossil fuels with ~~renewable energy sources~~Renewable Energy Sources (RES). Currently, heating is largely supplied by fossil-fuelled individual heating solutions (e.g. natural gas fuelled condensing boilers) at building level, while cooling is mainly provided by electric appliances such as compression chillers. Among the available RES, only biomass was used substantially for heating purposes (12%), while solar thermal, geothermal and ~~heat pumps~~Heat Pumps (HP) are still marginal in many countries [4]. Space ~~cooling~~Cooling (SC) accounts for less than 2% of total end-use energy in building [1] and nowadays it is mainly relevant in southern countries; however, it is expected to more than double towards 2050, as it has already done between 1990 and 2016 according to [4].

District heating (DH) supplies only the 12% of the needs in Europe, involving about 6,000 DH networks, 200,000 km of grids, 60 million citizens and an additional 140 million living in cities with at least one DH system [5]. However, DH has been largely indicated a promising solution [6]. The Heat Roadmap Europe studies [2] show that a future energy system with 50% DH and sector integration (the so-called sector coupling approach) is more efficient than a decentralised/conventional system and allows for higher shares of renewable energy at a lower cost and for integrating Combined Heat and Power (CHP) plants, waste heat from industry and services and use of electricity in large-scale HP. In fact, according to [5], the contribution of fossil fuels in DH mix in EU is expected to decrease from the 85% in 2016 to the 35% in 2050 and, in parallel, large size HP and industrial waste heat are expected to have a share of 30% and 25% respectively, in the same mix.

In Europe, the establishment of scenarios with high amounts of DH in their energy supply by 2050 is in line also with the current urbanization trend. Indeed, in urban areas the demand for heating and cooling assumes the highest density and, at the same time, a huge amount of low-grade waste heat is diffused within the urban landscape. Moreover, as demonstrated by [7] for a case of waste heat from data centres, such free and largely available heat source in urban settlements can be easily exploited in ~~district thermal systems~~District Thermal Systems (DTS) achieving both environmental and economic benefits.

In the following, DTS is ~~preferred~~adopted, where appropriate, to ~~DH or district cooling and~~ indicate ~~district systems~~a larger concept of thermal networks able to satisfy or integrate thermal uses in buildings (space heating, domestic hot water, space cooling) by means of networks of pipe connected one side to final users/prosumer and other side to available heat sources.

However, the pathway to 2050 scenarios depends on the present situation and context of each country. Indeed, DH is generally more developed in Central, Eastern and Northern Europe, where in some countries it has reached a share around 50%. Conversely, in Italy DH represents the 3% of space heating [8][1] and in Switzerland the 5% [3]. However, according to [1] in the 2050 scenarios, these figures are expected to raise in a range of 50-80% in Italy and, according to [3], to raise at least at 40% in Switzerland. This trend will involve also ~~DC~~District Cooling (DC) that is expected to increase given the vast untapped potential of the sector, especially in Mediterranean climates.

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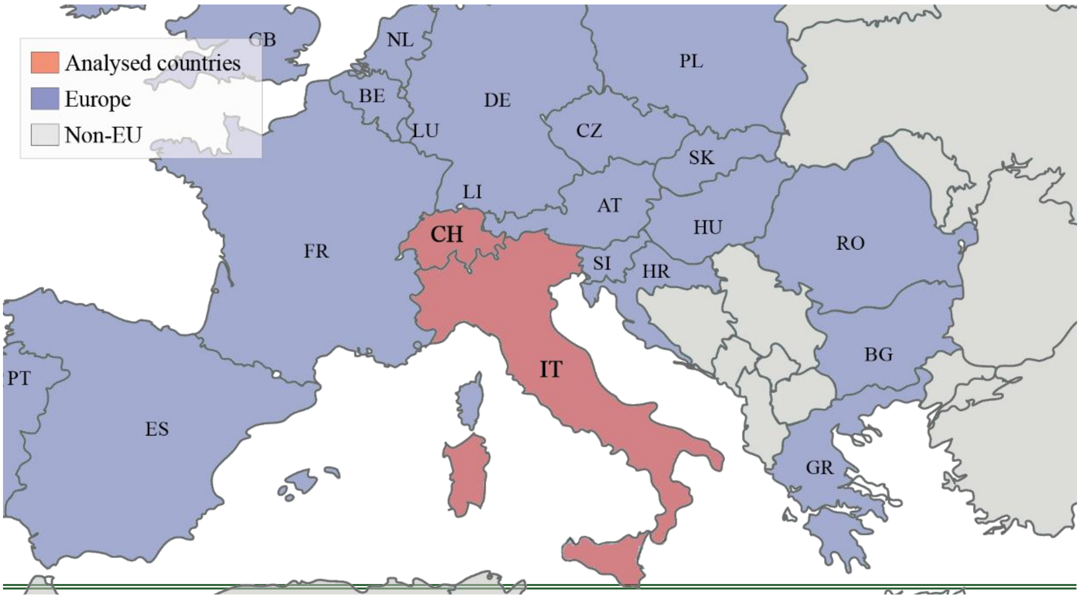
[1] The reference [8] corresponds to the yearbook published by AIRU, the association of urban (district) heating in Italy. For many years, the association has actively promoted district heating based on different energy resources. The yearbook contains the essential data of the district heating networks present on the national territory.



~~Figure 1. Italy and Switzerland in the European geographical framework~~

The study here presented is in line with the precedent researches carried out by the same research group: in [3] a tool for mapping DTS potential has been developed; in [9] the performance of a large sample of Italian biomass DTS has been evaluated; in [10] a procedure to select possible district cooling expansion has been defined and mapped in ~~GIS;~~Geographic Information System (GIS); in [11] the effect of the Italian energy policies linked to district heating development have been analysed. Considering this background in research, along with the expertise of the involved authors, the research here presented investigates northern Italy and Switzerland, where geographic and climatic conditions and density of thermal needs are mutually comparable. Figure 1 shows the geographical position of the two analysed countries within the European context.

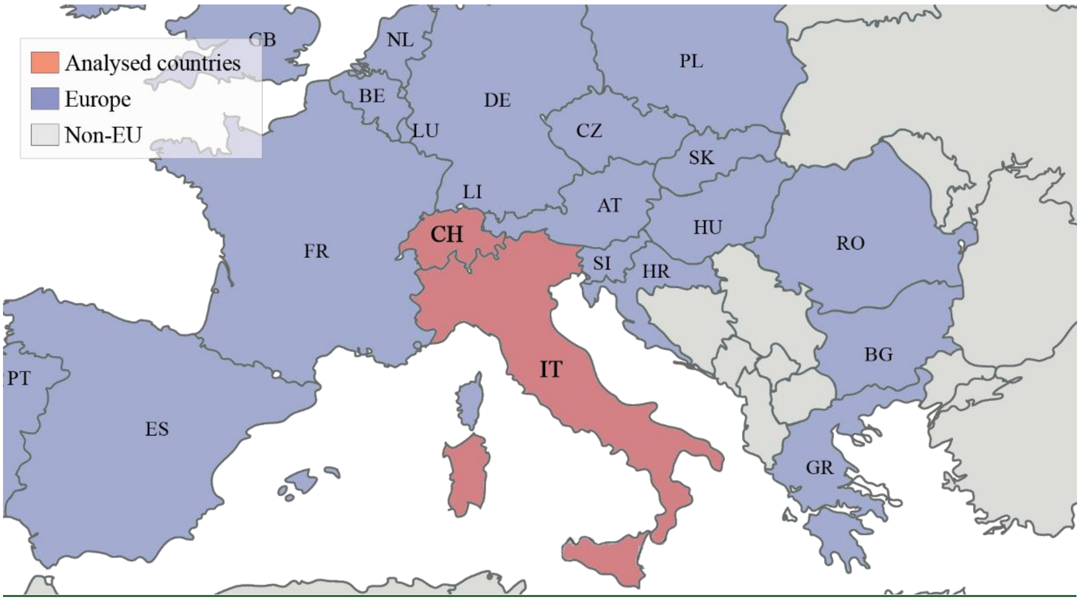


Figure 1. Italy and Switzerland in the European geographical framework

The main aims are: to describe the state of the art of DTS in both the countries; to analyse the schemes available in the technical literature for the classification of DTS; to analyse and classify the Italian and Swiss innovative systems in operations~~-~~; and to provide indications for the evolution of the sector toward 2050 scenarios.

2. Materials and methods

Aside the gained expertise of the authors, northern Italy and Switzerland share many features in terms of climate and technological development and can be representative for a larger sample of southern Europe countries. In order to have an analytic and systematic overview of the DTS state of the art, the technical literature has been consulted with particular attention to contributions dealing with methods for analysing and classifying DTS in operation. These methods are useful in order to define clusters of DTS, challenges and strategies for their future improvements. According to the available literature, besides the operational and technological features, the main adopted metrics are the network operative temperatures for supply and return, but, considering the strong site-dependency of DTS [12], other parameters are considered in order to cluster systems in operation and to propose insights for their smart evolution in the future.
The selection of the scientific and technical literature has been carried out in order to:

- Define the technological and operative features of existing DTS;
- Review the methods for analysing and classifying DTS;
- Investigate the barriers and drivers for a smart evolution of the existing DTS and for the development of innovative ones.

The review of the technical literature has involved in particular:

- the Scopus database using specific keywords in the field of DH, e.g.: district heating, DH classification, fourth and fifth generation DH (4GDH and ~~5GDH~~5GDHC[2]), low temperature DH, district thermal networks,);
- national and international technical reports;
- expertise of the authors and their participation in trade associations, working groups and research programs, that is an evident added value of the research.

In particular, the scheme of the method followed is described in Figure 2 together with the main contributions selected that are grouped by: method of analysis and classification schemes; theory and cases of high temperature DTS; theory and cases of low-temperature DTS.
In the following sub-sections, the methods for analysing and classifying district heating networks are discussed dividing them into two group. The first (section 2.1) origins with the work of [13] with particular reference to the Danish DTS, even if other well documented contributions have updated the framework in the last years. The second (section 2.2) is coherent with the previous one, but is more focused on the supply temperature level and on the equipment buildings side. It is particularly referred to the Swiss DTS, even if, also in this case, other well documented contributions have recently updated the framework.
In section 3, these methods are applied for describing and clustering DTS in operation in Italy and Switzerland. Furthermore, a focus on recent low temperature DTS is reported, underlining the penetration in Italy and Switzerland, the main characteristics and the possible strategies for a future spread.
In order to get a full portrait, the documented energy data of DTS have been collected and elaborated in a dataset. Since the available ~~main DH~~ databases (e.g. [8] for Italy and [14] for Switzerland) may contain lacks of technical data due to the dimension of the sample of ~~DHS~~systems considered, elaborations and related graphs and tables in the following may regard different samples of plants, according to the data available for a given parameter studied, as specified case by case.

[2] According to recent contributions in the technical literature that will be cited in the following, 5GDHC is adopted instead of 5GDH in order to underline the intrinsic possibility of such systems to provide heating and cooling.

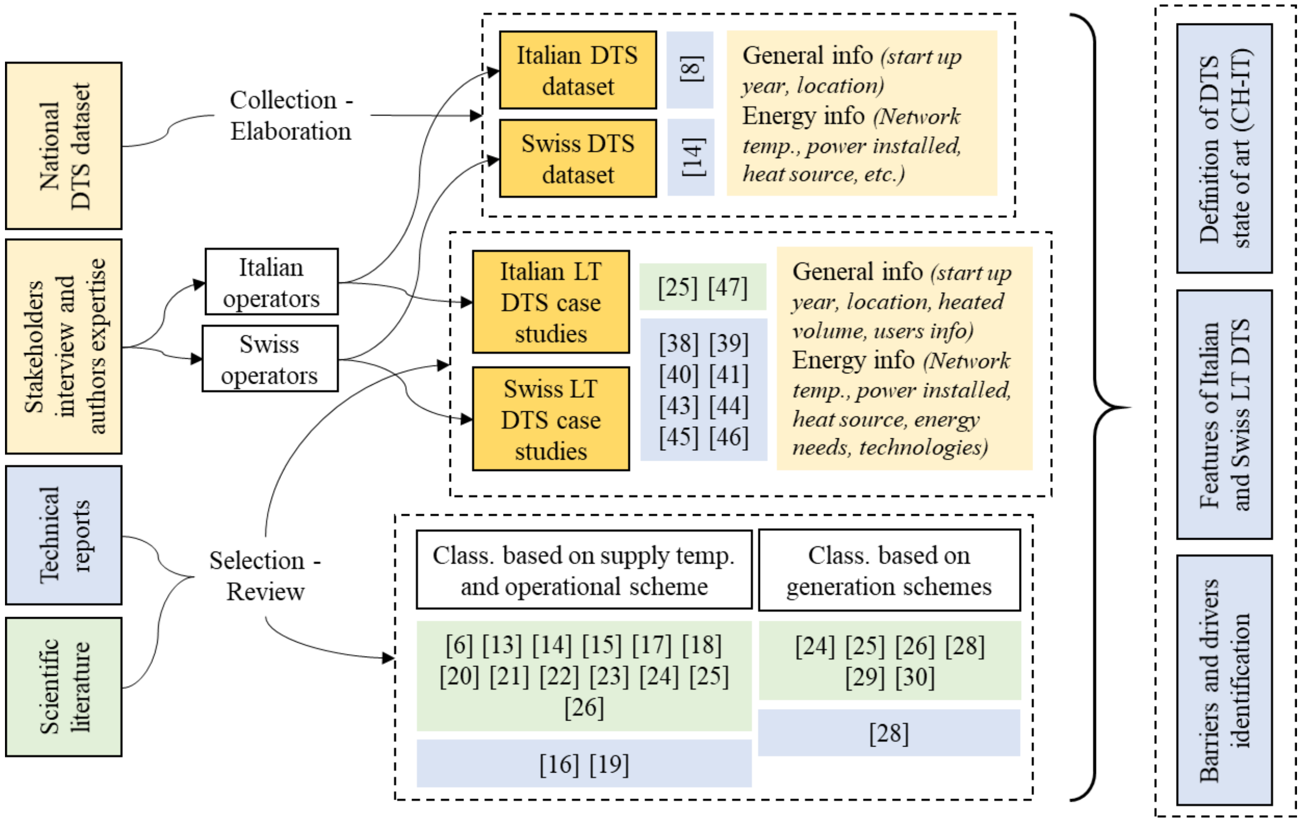


Figure 2. Scheme of the research and main technical references considered

2.1. Method of classification based on DH generations

~~District heating is~~DH refers to a mature technology; in fact, first examples in EU appeared around 1920 [15]. Considering the increasing global urbanization trends and the suitability of ~~DHS~~district systems with the implementation of low carbon paradigms and circular economy in the energy sector [15], ~~DHS~~DTS have been recently addressed as a key point for the EU decarbonization roadmaps toward 2030 and 2050 as reported, e.g., in [16] and [5]. Throughout the years these systems have undergone a considerable spread and a deep technological development in favour of lower distribution temperature, improved materials and components and prefabrication [17]. Nevertheless, the many examples currently in operation present a consistent range of different features, schemes and stages across Europe in terms of technologies, energy resources, built environment, etc. [18].
The classification in different generations has been a robust reference for stakeholders and researchers in order to analyse the existing ~~DHS~~DTS and shape scenarios for their evolution.
This classification, at that time of its definition, consisted in four generations of ~~DHS~~DH, divided in terms of period of maximum spread and technological maturation, operative temperatures, technologies and configurations [19]. A complete and updated state of art review on DH ~~systems~~ is reported in [20], focusing on the operational characteristics (sources, components etc.) of each DH generation.
The first generation of ~~DHS~~DH (1GDH) was characterized by coal steam boilers and the hot water on the users' side were directly heated up with high temperature steam (over 100°C) and distributed to end users through concrete steam pipes.
A second generation of ~~DHS~~DH (2GDH) appeared and diffused between 1930 and 1970 and was characterized by pressurised hot water distributed in steel pipes in place of steam as the heat carrier to overcome the problem of condensation drops.

Following the technological evolution of emission systems and the reduction in the heat demand of buildings, the third generation~~,~~ (3GDH), mainly diffused after 1980 mostly in Europe, is characterized by the adoption of hot water at temperatures in the range of 80-90 °C, control and management technologies as well as plastic jacket pipes to eliminate corrosion of the steel carrier pipes.

The evolution toward the recent fourth generation (4GDH) implies a further lowering of the distribution temperatures (in the range of 30-70 °C), higher energy efficiencies and integration of RES. Many contributions are available in the literature referring to different territories; e.g. [6] for large-scale ~~DHS~~DTS in Estonia; [21] about technological and non-technological barriers in the revamping of traditional ~~DHS~~DTS into low temperature one in Italy.

~~Even if [13] point out 2020-2050 as period of best available technology for the 4GDH, the increasing research interest on DHS and the rapid technological advancements of HP laid the basis for a further decrease of water temperature in the distribution network below 30 °C, an issues explored by many recent studies.~~The authors of [13] specify some properties that future generation ~~DTS~~DH should have in order to fulfil their role in sustainable energy systems, such as: the ability to supply low temperature heat to both existing, renovated, and new buildings; having low grid losses; the ability to recycle heat and integrate renewable sources; the ability to be an integrated part of a renewable ~~multi-energy system~~Multi-Energy System (MES), including cooling; having a sound business model, also in the transition to renewable energy sources. Even if [13] point out 2020-2050 as period of best available technology for the 4GDH, the increasing interest on low-temperature DTS and the rapid technological advancements of HP laid the basis for a further decrease of water temperature in the distribution network below 30 °C. This new generation of DTS has specific features that differs from the ones proposed by [13] in defining 4GDH. For this reason, according to other recent researches, the distinction between 4th and 5th generation is consider in the present study. Precursory insights of this novel concept are reported in [22~~] ,~~], providing a literature review about the innovative concept of "cold DH networks~~"~~", and in [23], clarifying that "bi-directional decentralized district heating and cooling grids" have the potential of turning each connection into a "prosumer" and not have return flows as such, but warm and ~~a~~ cold pipes. More precisely, according to [24], ~~5G~~the 5th generation district heating and cooling (called 5GDHC) combines the properties of local renewable energy systems with the principles of future district heating as defined by [13], therefore are a solution for renewable urban thermal energy supply. The authors of [25], through the review of scientific contributions investigating the features of these systems, provide a common definition of ~~fifth generation DH (5GDH).~~5GDHC. This is defined as a thermal energy supply grid operating at temperatures so close to the ground that is not suitable for direct heating purpose. The low distribution temperature (in the range of 10-25°C) allows instead to exploit directly industrial and urban excess heat, to use renewable and low-exergy heat sources and to provide heating, cooling and ~~domestic hot water~~Domestic Hot Water (DHW) to users by mean of decentralised HP. This is deepened also by [24] that provide a definition for 5GDHC and show how this concept differs from ~~conventional district heating systems~~the concept of 4GDH, since 5GDHC are decentralized, bidirectional, close to ground temperature networks that use direct exchange of warm and cold return flows and thermal storage to balance thermal demand as much as possible. Also [26] underline the novelty of ~~5GDH~~5GDHC and the different possible topology, comprising decentralized heat pumps rather than a single large energy centre, giving opportunities for sharing (prosuming) heating and cooling across ~~an ultra-~~a very low temperature loop.

~~Considering~~Moreover, considering the actual technological features of the existing DTS in Europe [1] and the wide differences between countries in terms of technological development, climate and renewable penetration, a different approach, more adopted in southern Europe DTS, is considered and discussed in the following section.

2.2. Method of classification based on supply temperature and operational scheme

In addition to the classification based on five generation, another approach has been developed, more focused on the levels of operating temperature and components users' side. This approach is adopted as method of classification in Switzerland according to [27], but is available also in other contributions such as [28] and in [29], providing a consistent design framework based on mathematical optimization, and in the references cited therein about "bidirectional Low Temperature Networks", "Cold District Heating Networks (in German *Kalte Nahwärme*)" and "Anergy Networks (in German *Anergienetze*). This approach is mostly adopted in Germany, Austria and Switzerland and mainly devoted to explore DTS belonging to 4GDH and ~~5GDH~~5GDHC focusing on networks operating at supply temperatures below 60-70°C. The interest in this sample of plants is motivated by the possibility to exploit waste heat and local renewables, reducing also heat losses along the grid due to lower temperatures[3]. Based on these considerations, ~~[27] suggests~~ the following operational cases~~ resulting~~, identifiable in four classes~~ for which~~, have been described according to [27]. Every class reports the necessary technologic components, characteristic parameters, grid morphology and configuration, energy balance calculation (input and output heat flows along the network) and requirements for operation~~ are reported.~~. This typological classification cannot be framed directly by the previous approach, which is mainly based on level of supply temperature and on the age of the DTS, and it is connected to the energy efficiency of the served built environment. ~~In~~According to [27] ~~DHS~~DTS are classified in:

- High temperature (HT): systems operating at temperatures above 60°C, which most often use waste to energy plants or wood chips boilers as heat sources. In this category there is one case (named 1C);
- Low temperature (LT): systems operating at temperatures below 60°C that, at least in the Swiss context, are spreading more and more implying new supply concepts and technologies. In this category there are three sub-classes (named 2C, 3C, 4C).

In case of HT (here named~~ consequently~~ 1C-HT), heat can be supplied directly through heat exchangers for space heating and DHW. This type of network is not suitable for cooling buildings. Heat losses along the network are in the range 7-13% of heat supplied. Conversely energy requested for pumping can vary in a wide range, from 1 to 13% of heat supplied.

LT cases are particularly suitable for new or recently renovated buildings that have higher energy performance and lower energy requirements than older buildings and can be heated with lower temperatures systems coupled by radiant emitting components inside buildings. When the temperature of the supply network is not sufficient, e.g. for DHW supply or in case of radiators as emitting components inside buildings, HP can be integrated, buildings side, to upgrade the temperature to the levels requested.

Therefore, since temperature levels influence the technologies that should be used in buildings, three sub-classes among LT DTS have been defined, depending also on technologies required for each operating temperature:

- 2C-LT (Supply temperature from 30°C to 60°C):
  Heat can be supplied directly for space heating. For DHW, the temperature must usually be increased, for example, using a HP. In order to cool the building a cooling system is required and excess heat is not reused. Heat losses along the network are in the range 3-7% of heat supplied. Energy requested for pumping is around 1-2% of heat supplied.

- 3C-LT (Supply temperature from 20°C to 30°C):

[3] Thermal dispersions are proportional to the difference of temperature between the carrier and the medium (i.e. the underground). The smaller the difference of temperature, the lower are the heat losses through the pipes.

Heat cannot be supplied directly for space heating and DHW; a HP is required. In order to cool the building, a cooling system is required, but the heat produced is directly injected into the network and can be reused. Heat losses along the network are lower than 3% of heat supplied. Energy requested for pumping is around 1-2% of heat supplied.

- 4C-LT (Supply temperature lower than 20°C):
  Heat cannot be supplied directly for space heating and DHW; a HP is required. The network temperatures are adapted to the direct cooling of the building by means of a heat exchanger. Excess heat is injected and reused. Heat losses along the network are negligible. Energy requested for pumping is around 2-3% of heat supplied.

The classification of DTS depending on the adopted operating model, taking into account the temperature levels and the technical concept, is reported also in other contributions dealing with ~~5GDH~~5GDHC such as the already mentioned [24], [25], [26], [28] and [29], underlining the recent relevance of the topic and the complementarity of the two approaches for classifying DTS.
According to [27] and analogously to [24], [26], [29] and two criteria for defining the operating mode are the direction of water flow (managed or unmanaged) and the energy flow in the system (unidirectional or bidirectional).
In particular, a DTS can be called managed network if there is only one direction of the water flow from the network to the consumers. Because of this, a centralized pump is installed at the supplier's site. In addition, a DTS can be called unidirectional network if there is only one direction of the energy flow. Energy flow always originates completely from the heat source and moves towards the consumers. In unidirectional networks, the source and the consumers are unambiguously and definitively distinct (e.g. widespread high-temperature networks generally use a directed and unidirectional mode of operation).
Conversely, a DTS can be called unmanaged network if there is not only one direction of the water flow from the network to the consumers. Water is moved with pumps either from the supply pipe (heating) or from the return pipe (cooling). This is in accordance also to [25], where it is reported that in 5GDHC networks with decentralized pumping stations (one for substation) some user can be in heating and others in cooling mode at the same time, considering multiple types of hydraulic configurations. In addition, a DTS can be called bidirectional network if the consumer can become also a heat source. When the energy flows in the building are not balanced (i.e. heating needs are much higher than cooling needs or the other way around), deficits and surpluses might be compensated into the network. Ultra-low temperature networks are often unmanaged and bidirectional~~)~~.. This is a key point for shallow geothermal energy systems, using borehole heat exchangers [30].
The two operative modes are represented in the following Figure 3.

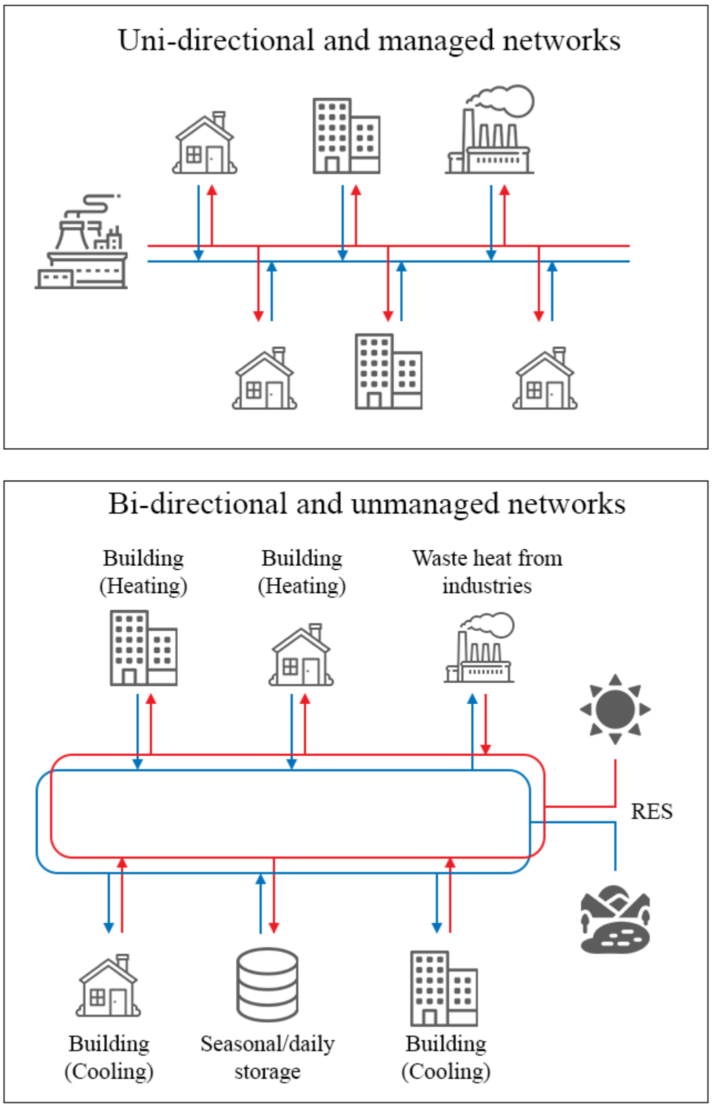


Figure 3. DH networks modes: unidirectional and managed (above picture), bidirectional and unmanaged (below picture).

2.3. Complementarity of the two approaches

The two schemes of classifications are based on common parameters such as heat carriers, temperature levels for supply and return and type of energies adopted. However, in addition, different parameters are considered. For example, the first classification takes into account also the age of the ~~DHS~~DTS, technical details such as materials of pipes and precast components, the relationship with energy performance of the served buildings, available RES and distribute cogeneration. Conversely, the second classification is mainly focused on final uses in buildings and on the available components for providing and emitting heating and cooling inside buildings.

Considering the description reported in sections 2.1 and 2.2 and that for the most part of the ~~DHS~~DTS in operation the heat carrier is hot water with a supply temperature of 90°C or less, the following comparison is mainly focused on 3GDH, 4GDH and ~~5GDH~~5GDHC.Therefore, 1GDH and 2GDH are not taken into account in the following scheme (Figure 4).

The 3GDH is entirely included in the 1C-HT class[4] because: the temperature levels allow covering thermal purposes in buildings by means of heat exchangers (without other technological components

[4] 1GDH, 2GDH and 3GDH are distinguished in the first classification scheme, while all of them are included in the 1C-HT class of the second scheme, without particular differences.

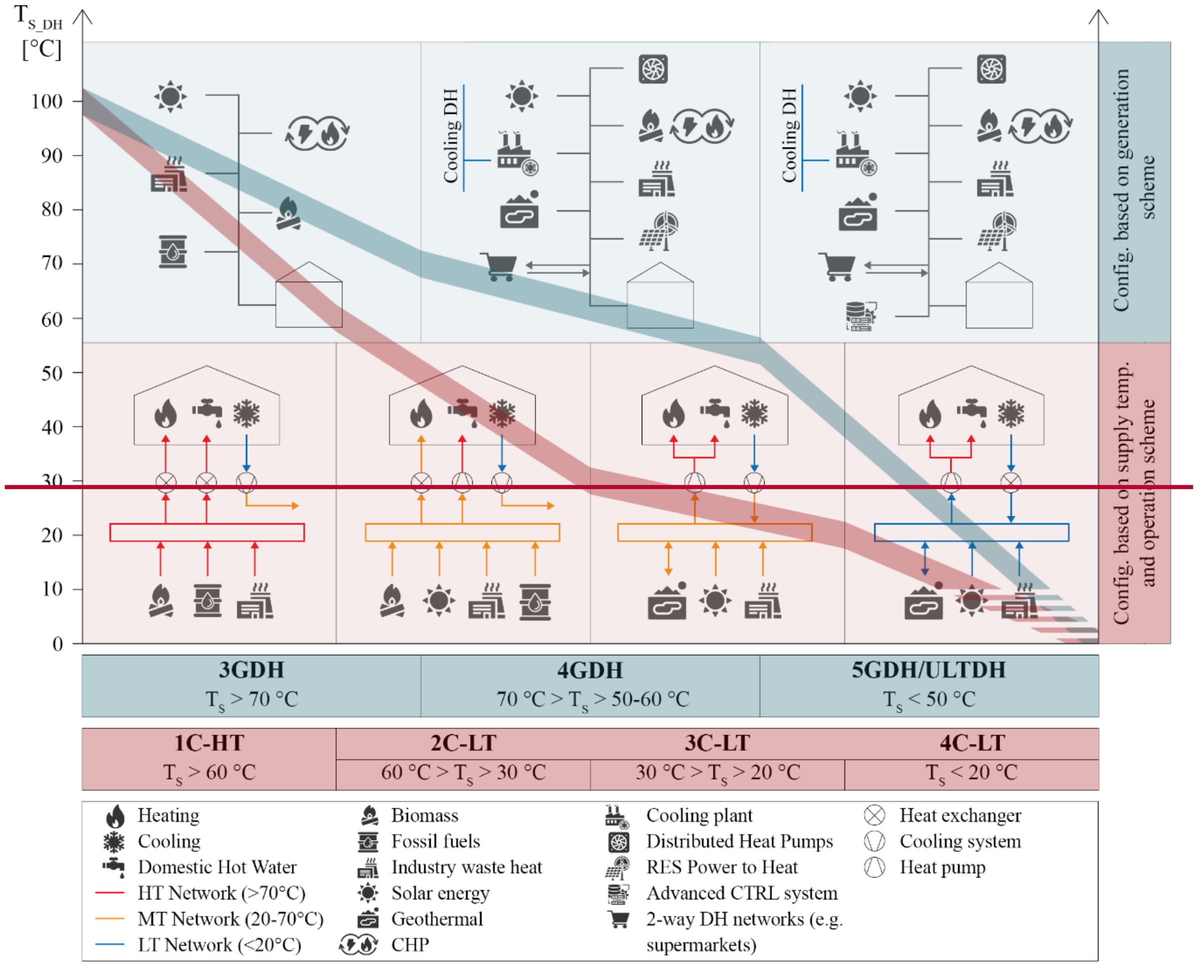
as HP); the contribution of RES is negligible (except biomass DTS); and these grids are not able to provide also DC.

Conversely, the second scheme of classification is more detailed for the LT DTS: in fact, 4GDH and 5GDH5GDHC are split in three classes of operation, because 4GDH can belong to two different types of LT DTS depending on the presence of the components at buildings side (heat exchangers and reversible HP).

-As anticipated in section 2.2, after a deep technical review, (not only in the Scopus database, i.e. in English, but also among the available local references in Italian and German), the second classification, widely described in [27] and cited in [28], defines different typologies, energy balance calculation, and, , classified DHS classifies DTS in four groups, providing also standard diagrams that describe components and technologies needed to supply thermal energy in buildings, the operating details and requirements [27].

The result of the deepening on classification schemes and on their comparison is reported in Figure 4 that resumes information about the temperature level, the energy sources, the components at building side and the energy uses satisfied[5].

[5] For space reasons, only thermal energy areis reported; the electricity input to HP is not represented.



T_{S_DH} [°C]
100
90
80
70
60
50
40
30
20
10
0
Cooling DH
Cooling DH
Config. based on generation scheme
Config. based on supply temp. and operation scheme
3GDH
T_s > 70 °C
4GDH
70 °C > T_s > 50-60 °C
5GDH/ULTDH
T_s < 50 °C
1C-HT
T_s > 60 °C
2C-LT
60 °C > T_s > 30 °C
3C-LT
30 °C > T_s > 20 °C
4C-LT
T_s < 20 °C
Heating
Cooling
Domestic Hot Water
HT Network (>70°C)
MT Network (20-70°C)
LT Network (<20°C)
Biomass
Fossil fuels
Industry waste heat
Solar energy
Geothermal
CHP
Cooling plant
Distributed Heat Pumps
RES Power to Heat
Advanced CTRL system
2-way DH networks (e.g. supermarkets)
Heat exchanger
Cooling system
Heat pump

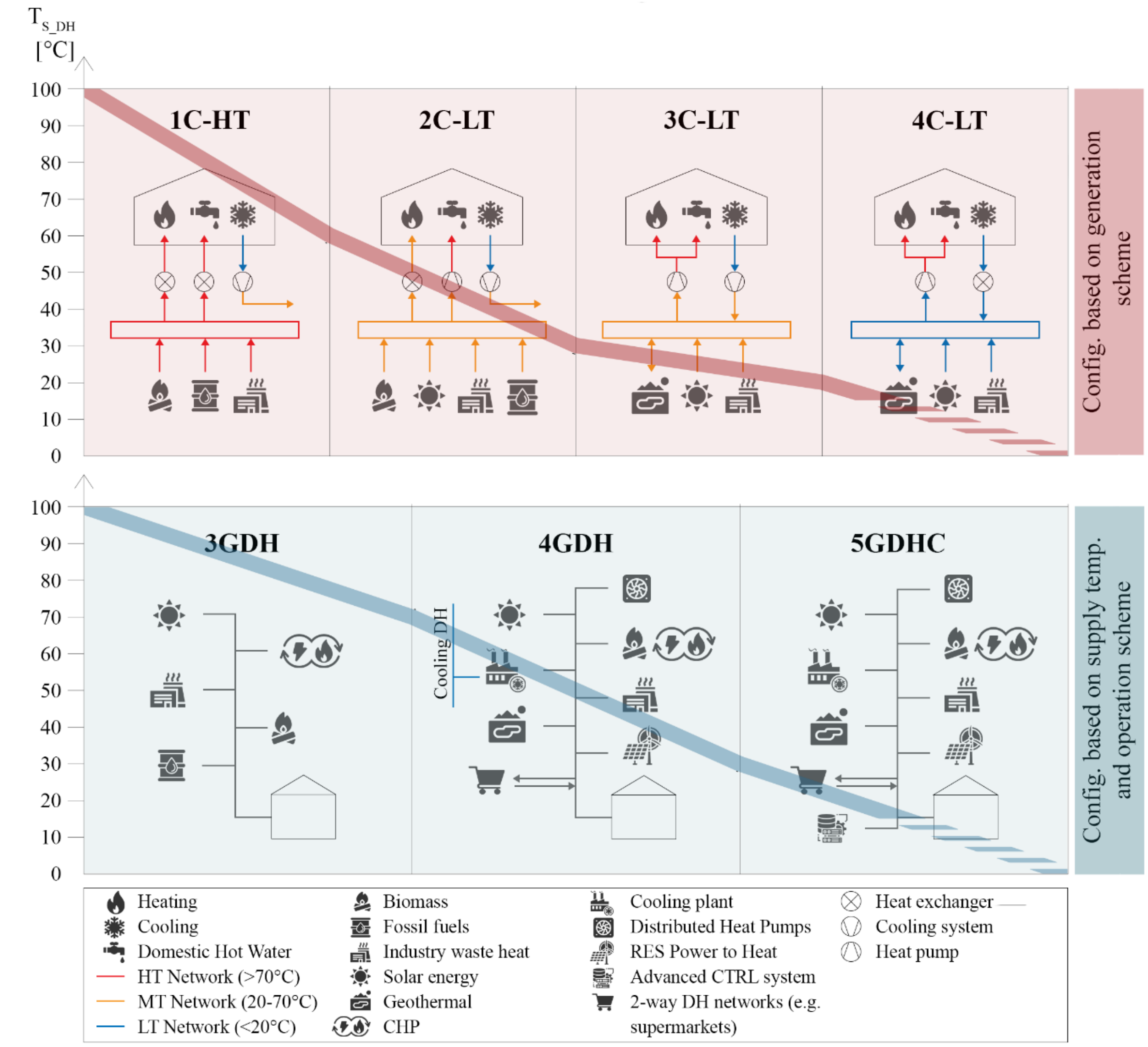


Figure 4. Comparison of the two classification methods in terms of technological configuration (boxes behind the graph area) and network operative temperatures (ordinate axis on the left). Red shaded objects refer to the classification based on supply temperature and operation scheme, while blue shaded objects refer to the classification based on generation scheme (arrows in red, orange and blue means heat provided to or extracted from the buildings)).

3. Results

An overview of the state of the art of the Italian and Swiss DTS is presented based on [3, 9, 10, 31, 11] and on other technical reports published by DH institutions in Italy ([32]; [8]) and in Switzerland [27], [33] and [14]. It is possible to summarise that in Italy:

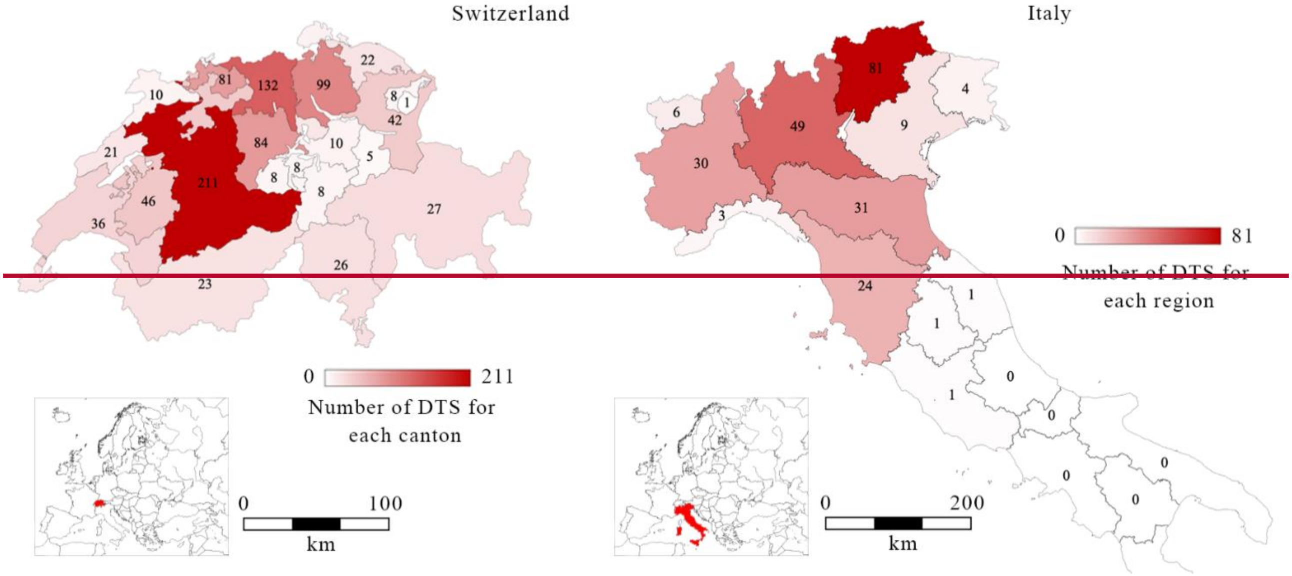
- most of the systems can be classified as high temperature DH;
- some interesting cases of low/ultra-low temperature are available;
- currently these last represent, in number, the 2% of the total, but there is a growing interest in this field;

while in Switzerland:

- one thousand DTS are spread within a small territory; most of the systems have very small sizes, in half of the cases with thermal power lower than 1 MW_{th};

- supply temperatures are not officially available, but an estimation is possible based on the technical features of the systems;
- it is possible to argue that 97% in number are high temperature systems, while 3% in number are low/ultra-low temperature systems and, also in this case, there is a growing interest for these last cases.

The penetration of ~~DHS~~DTS in the analysed areas is reported in Figure ~~9, while~~5 that, for both the countries, reports the dimensions and geographic positions, the distributions of the systems in the different cantons and regions and the comparison between the densities of distribution.
The two national operative contexts are deepened with the available details in section 3.1 and 3.2, respectively. An attempt of classification is presented in sections 3.1.1 and 3.2.1 and a focus on LT-DTS is reported in section 3.3.



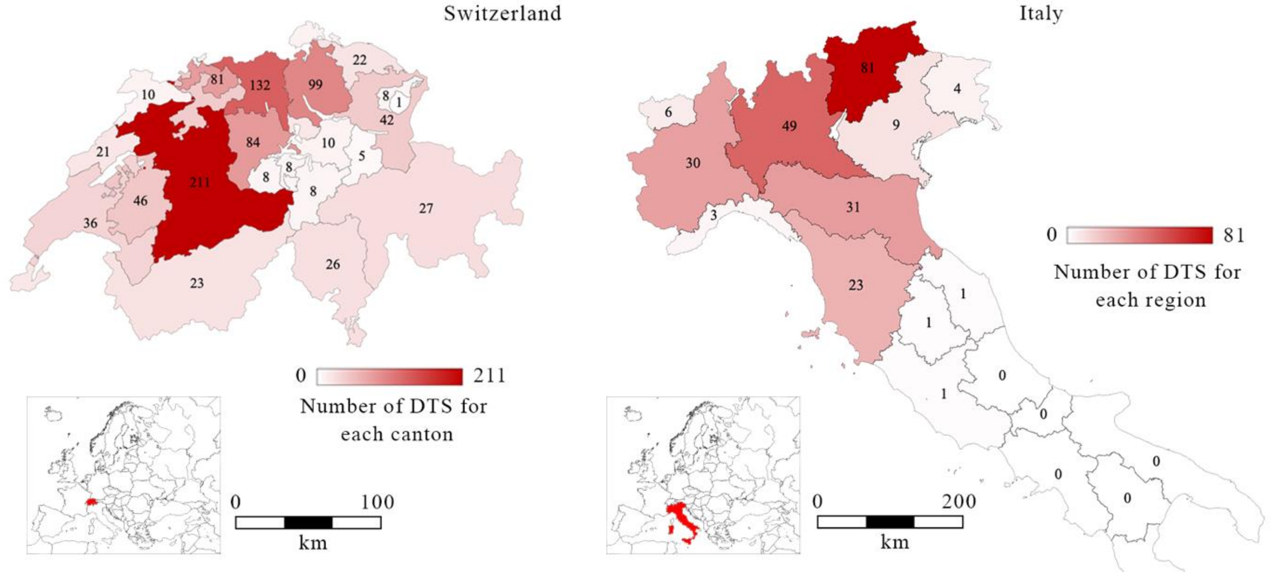


Figure 5. Geographical distribution of DTS in ~~Italy and~~ Switzerland and Italy, grouped by Cantons (CH) and Regions ~~and Cantons, respectively~~(IT). Elaboration based on [14] for Switzerland and [8] for Italy.

3.1. DTS in Italy

Italy is a country of 301,338 km^2; approximately, half territory is characterized by cold winter (more than 2,100 degree-days), while one third is covered by forests. Heating and cooling are dominated by individual solutions, mainly based on natural gas and electricity, respectively. According to [8], 368 DH networks ~~(129 of them are very small systems, while 198 are cities supplied by DH)~~[6] were in operation in 2018 with a total length of the networks of 4,446 km and a total heated volume of 350 million m^3.

The most part of ~~DHS~~them are fuelled by fossil fuels, even if about the 27% of them are fuelled by wood biomass and adopt hot water as carrier (on average: 90°C supply and 60°C return). These systems are mainly ~~located~~operating in ~~the Northern regions (about~~ northern Italy (120,~~000~~260 km^2), ~~where~~especially in mountain areas, due to the cold climatic conditions. However, few plants are also operating in the central part of Italy, especially in Tuscany (22,985 km^2), due to the large availability of geothermal heat. Regions in central/south part of Italy could be promising for the opportunity of providing cooling services during summer.

Moreover, it can be underlined that 198 Italian cities are served by DH networks. Among these, the cities of Brescia, Milan and Turin currently represent 42 % of the total national DH, managed under public-private partnerships.

Stakeholders involved in DH admit that it is generally perceived as a rather old and inefficient technology and that there is a great potential for improving DTS, including also cooling purposes.

DH operation takes place in a highly competitive environment where the choice of heat supplier is principally based on prices. The main alternative to DH is the use of natural gas boilers (or oil boilers in the few areas not yet reached by the natural gas grid), which dominate the heating market. There are no many national incentives to DH and DC, e.g. there are no specific investment grants for DH, despite the long payback time of these systems (above 20 years). Until 2016, district heating and cooling (DHC) projects were supported by white certificates (corresponding to the primary energy saved), but this support scheme has recently been changed and in some cases the incentive has been significantly reduced. As minor support, a reduced Value Added Tax (VAT) is applied to heat sales to residential users supplied with ~~RE sources~~RES or Combined Heat and Power (CHP) and other minor mechanisms are available for particular cases (biomass, geothermal, cogeneration and micro-systems). The effects of the national and regional supporting mechanisms can be perceived in Figure ~~4~~6, where the number of DTS per year and the cumulative number are represented. The figure describes only DTS of which start-up year information were available (i.e. 245 on 368) and evidences a rapid growth during the period 2000-2016 and a decreasing interest in this technology in recent years.

[6] Of these 368 DTS, for 239 cases there are available information while for 129 there are very few information.

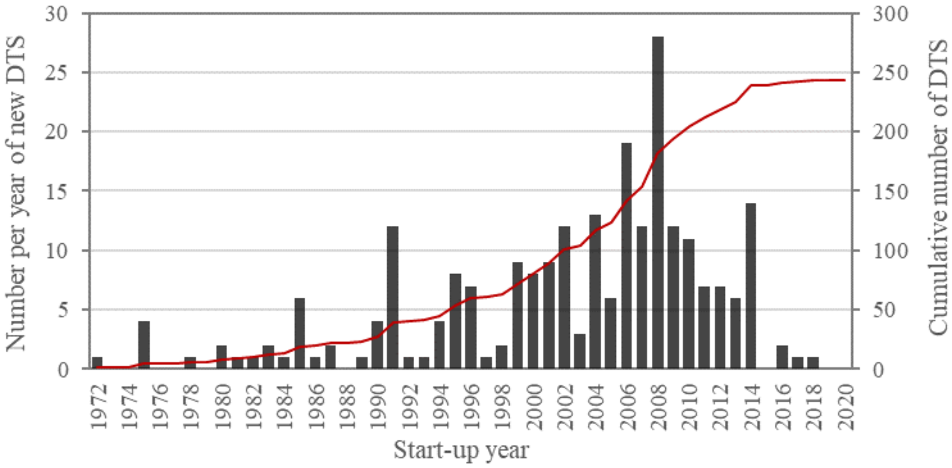


Figure 6. Number of Italian municipalities with ~~DHS~~DTS per year and as cumulative result (elaboration based on [8])

According to [8], DTS in Italy provide Space Heating (SH) and DHW (9,289 GWh and 11.8 GW of installed thermal power) and SC (131 GWh). This last corresponds to a total installed capacity of 205 MW and is provided for the 70% by compression chillers and for the 30% by absorption chillers that are mainly located in substation rather than in the central plant.

The average size of the plant is quite small, as reported by [34], which, based on the involved operators, figures that 54% of the plants have an installed thermal power lower than 6 MW, 31 % from 6 to 50 MW and only 16% over 50 MW. Indeed, this is in accordance to the fact that 64% of the cities with DTS has a population with less than 10,000 inhabitants [35].

Regard the adopted energy sources, natural gas, waste to energy and biomass represent the most diffuse options, while waste heat, geothermal heat and other thermal RES are still marginal. This is described in Figure 7, where primary energies adopted in 2018 are reported, underlining that only one fourth are renewables.

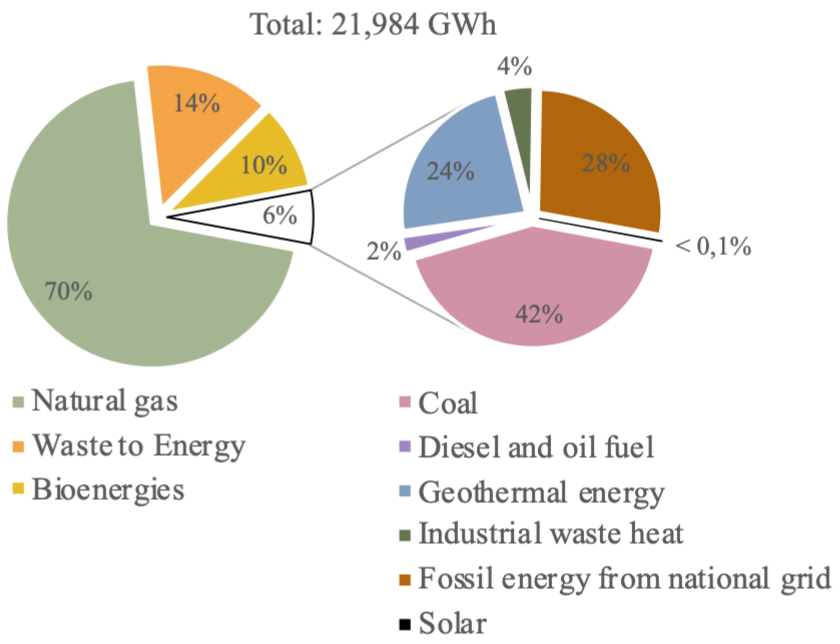


Figure 7. Primary energy sources used in the Italian DTS, elaboration from [8]

Referring to the operative conditions, 66% of the plants work in cogeneration mainly fuelled by fossil fuels, while the rest provide only heat. The diffusion of HP (both large scale in the thermal station or distributed at buildings side) is still marginal in Italy, while a consolidation of the geothermal plants is experienced in 2018 [8].
Data of [8] and dated end 2018 were elaborated; the most important figures are summarized in Table ~~2~~1.

Table ~~2~~1. Summary of the figures of the Italian DTS

Number of cities with DTS	198	-
Number of DTS owners	148	-
Number of DTS with available information	239	-
Total length of networks	4,446	km
Number of Substations	82,853	-
Number of DTS using as heat carrier:		
Hot water (<100°C)	198	-
Pressurized hot water (> 100°C)	35	-
Steam	6	-
Overall heated volume	358	Mm^3
Overall cooled volume	9	Mm^3
Installed thermal power	8,908	MW_{th}
Installed electric power (CHP)	885	MW_{el}
Installed thermal power (CHP)	2,871	MW_{th}
Thermal energy sold to users	9,289	GWh_{th}
from RES	25	%
from fossil fuels CHP	51	%
direct production from fossil fuels	24	%
Estimated thermal losses along the networks	20	%
Cooling energy sold to users	130.8	GWh_{th}
Electricity sold to the national electric network	5,945	GWh_{el}

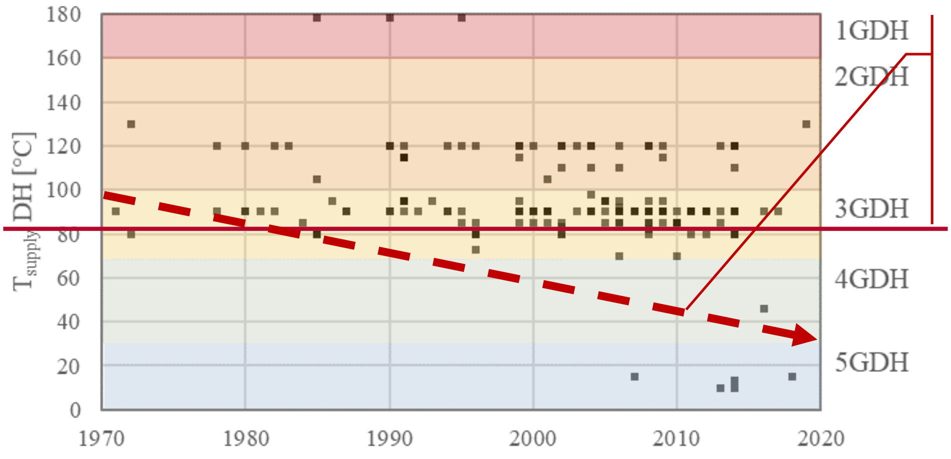
3.1.1. *Evolutive stage of ~~DH~~DTS in Italy and attempt of classification*

In Figure ~~12~~8 the supply temperature ~~and the energy carries, available for 188 DTS[7] on 239 (while not available for the 129 smallest ones), are~~is compared to the age ~~(Figure 8)~~ of each system. Starting from the total of 368 systems, supply temperature was available only for 188 cases[8].
The first attempt of classification according to data availability follows the generation approach. Within the analysed Italian dataset, 6 examples of 1GDH are listed, but very few data were available for them~~.~~ (only for 3 of them, operative temperature were available). These plant use steam as heat carriers and are mainly fuelled by geothermal energy at high temperature, diffused practice in Tuscany, in central Italy. 2GDH networks, operating with pressurized hot water at an average supply temperature of 120 °C, represent the 24% of the sample. The 3GDH ones instead, supply hot water

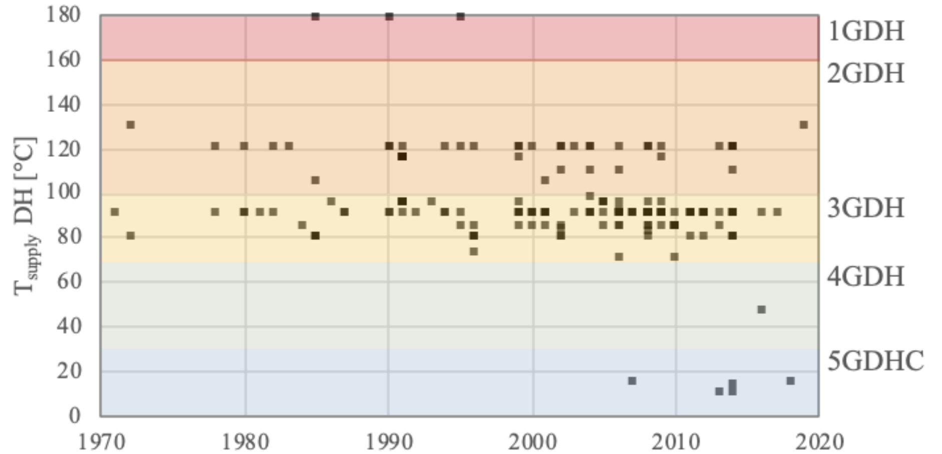
~~[7] From the initial dataset, the supply temperature information was available for 188 plants. In 22 cases more than one network with different distribution temperature is connected to one thermal station and may appear in the graph with different dots.~~

[8] From the initial dataset, the supply temperature information was available for 188 plants. In 22 cases more than one network with different distribution temperature is connected to one thermal station and may appear in the graph with different dots.

averagely around 85-90 °C and amount to the 70% of the total. 4GDH and ~~5GDH~~5GDHC are very few~~,~~ (6 plants), small size and not systematically documented in the available national databases.
Despite the limits related to lack of information, a first consideration is that the chronological evolution of DTS foreseen by the classification based on generation does not match the one observed in Italy (Figure ~~12~~8). Indeed, even the most recent DTS, besides few examples, are still identified as 2GDH-3GDH according to this approach.
If the approach based on supply temperature and operational scheme is applied, it is possible to note that the almost part of the Italian DTS are high temperature (HT, i.e. supply temperature > 60°C). Heat is generated in the thermal station and supplied through the network; heat exchangers for space heating and DHW are integrated at users' side. Heat flow is unidirectional even if different energy sources are adopted (e.g. wood biomass and natural gas combusted in two separate thermal stations). Further insights related to the 4GDH and 5GDHC cases will be ~~discussed~~provided in section 3.3.



~~Evolution by ages suggested together with the improvement of the buildings energy performance~~



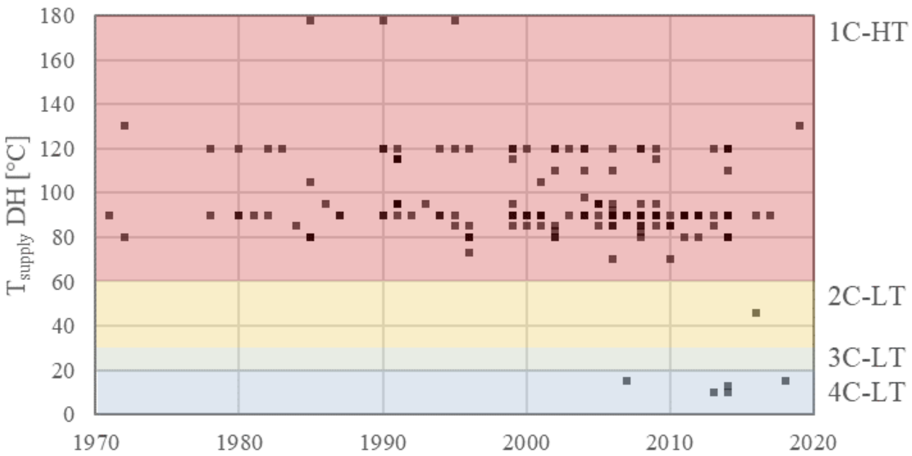


Figure 8. Distribution of the Italian DTS according to the two different classification approaches

3.2. DTS in Switzerland

As anticipated, space heating in Switzerland is reliant on oil (42%) and natural gas (26%), therefore decarbonizing the Swiss heating supply is fundamental for reaching the defined targets for the next future.

The Swiss Energy Strategy 2050 [36] sets out the objectives for future energy supply: an end to nuclear power and a significant reduction in CO_2 emissions. It has been estimated that up to 40% of the thermal needs (~~space heating and domestic hot water~~ SH and DHW) could be satisfied by thermal networks (high and low temperature), also considering the buildings renovation rate and the consequence reduction of the heating needs [33]. Of course, these estimations and goals must be verified in the local territorial conditions.

The Swiss territory amounts to 41,285 km^2, most of them occupied by mountains, forests and lakes. However, according to the official Swiss dataset [14], containing energy data of the national DTS sector, a set of 1,010 DH networks were in operation in 2018.

Figure ~~5~~9 shows the annual grow of DTS in Switzerland with the limit that the first year of operation is available only in the 80% of the plants surveyed. A first increase can be clearly seen from the early 1990s onwards, a second one in the first decade of 2000 and a third in recent years, demonstrating a growing interest in this technology. E.g. the number of DTS has more than doubled in the last 10 years.

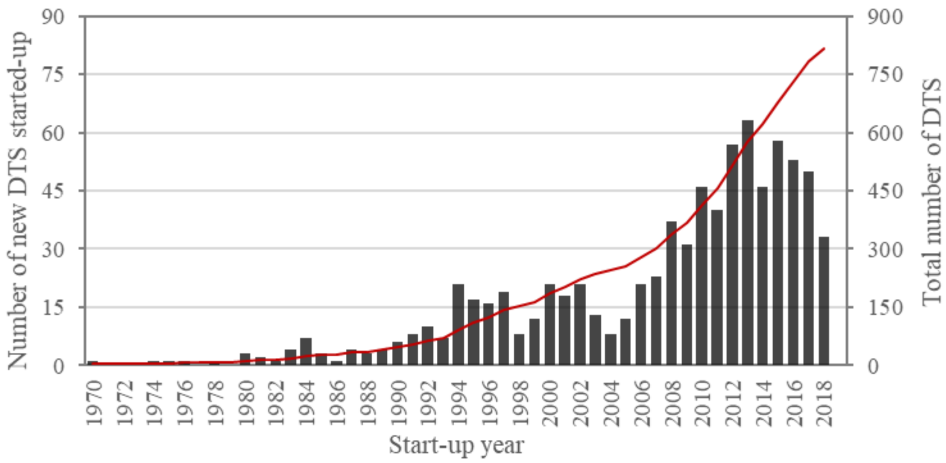


Figure 9. Number of Swiss DHS plants, cumulative data. Elaboration based on [14~~]~~].

According to the definition of ~~DHS~~DH in force in Switzerland[9] and to data available in [14], thermal power information is sufficiently complete only for 852 of the total. Generally Swiss DTS have very small sizes; in fact, half of them have thermal powers lower than 1 MW (Table ~~3~~2). This is a peculiar case characterized by small plants densely distributed over a quite sparsely populated territory.

Table ~~3~~2. Swiss ~~DHS~~DTS with available data grouped by thermal power

Lower than 0.5 MW	0.5-1 MW	1-5 MW	5-10 MW	Higher than 10 MW	Total
265	157	303	65	62	852
31%	18%	36%	8%	7%	100%

In terms of number of DTS, the 66% are fuelled by wood biomass, the 11% are based on Ground Source HP (GSHP~~,~~), the 7% take heat from waste to energy, the 6% are fuelled by natural gas and the remain part relies on a set sources with negligible contribution.
In terms of energy sources adopted the situation is different, because waste to energy and bioenergies represent the most part of the total (Figure 10).

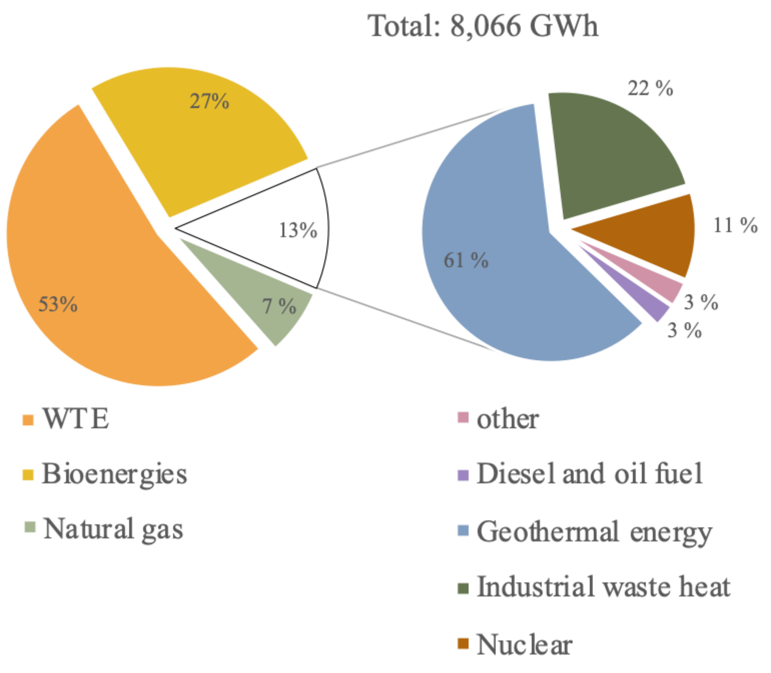


Figure 10. Energy sources used in the Swiss DTS; percentages based on heat sold to final users; elaborations from [14][10]

3.2.1. *Evolutive stage of ~~DH~~DTS in Switzerland and attempt of classification*

Recently, in Swiss neighbourhoods and small towns, DH has increasingly moved towards DTS fuelled by bioenergies that currently allow providing the 27% of the total heat supplied (Figure 10).

[9] Thermal grid is defined as a grid adopted for providing DH by means of a carrier for direct or indirect use of heat in buildings. Heat supplier and heat receiver (final users; at least one) have to be separated and connected by the grid. Thermal losses are expected along the grid, depending on the operative conditions.

[10] Data about adopted primary energy are not available for each DTS. In case of lack of data, the installed thermal power has been considered and multiplied by a realistic number of equivalent hours of operation in a year (an average value of 2000 hours has been assumed).

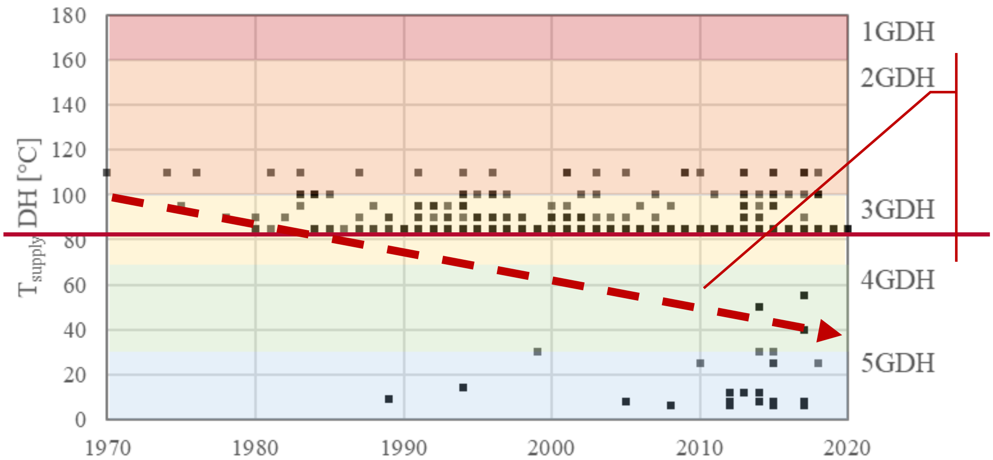
On the other hand, Switzerland is following a parallel technological evolution that is the installation of HP connected to an *anergy* network distributed throughout the territory. This trend is potentially applicable also in other countries like Italy, where however, due to a series of barriers (recent experience in the field of HP, different energy policy, well established infrastructure and market for natural gas etc.), it has developed in a very limited way.

The Swiss databases report many information about geographic coordinates, energy sources, owners, installed power, etc. However, no data about supply temperature and technologic components users' side are available, making any attempt of classification unsuccessful. Nevertheless, considering the adopted energy sources and the typical conversion technologies available for their conversion, it is possible to argue that about the 90% of ~~DHS~~DTS are high temperature (HT, i.e. supply temperature > 60°C).

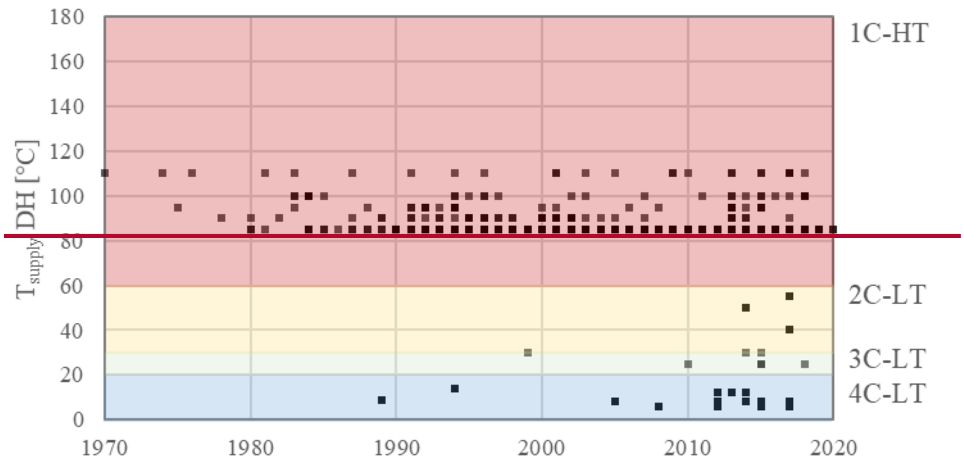
Based on these assumptions, a first attempt of classification according to the generation approach has been developed, revealing that there are no cases of 1GDH, while there are few cases of 2GDH and 4GDH, a few dozen are ~~5GDH~~5GDHC and the most part of the ~~DHS~~DTS in operation belong to 3GDH.

Also in this case, the chronological evolution of DTS foreseen by this method of classification does not match the one observed in Swiss (Figure 11), except the few dozen of ~~5GDH~~5GDHC installed in recent years.

If the approach based on supply temperature and operational scheme is applied, it is possible to note that also in Switzerland the almost part of the DTS are HT, but there is a representative set of LT DTS belonging to the three subclasses 1C, 2C and 3C; further insights will be discussed in section 3.3 since the authors have deeply analysed this set of DTS.



~~Evolution by ages suggested together with the improvement of the building's energy performance~~



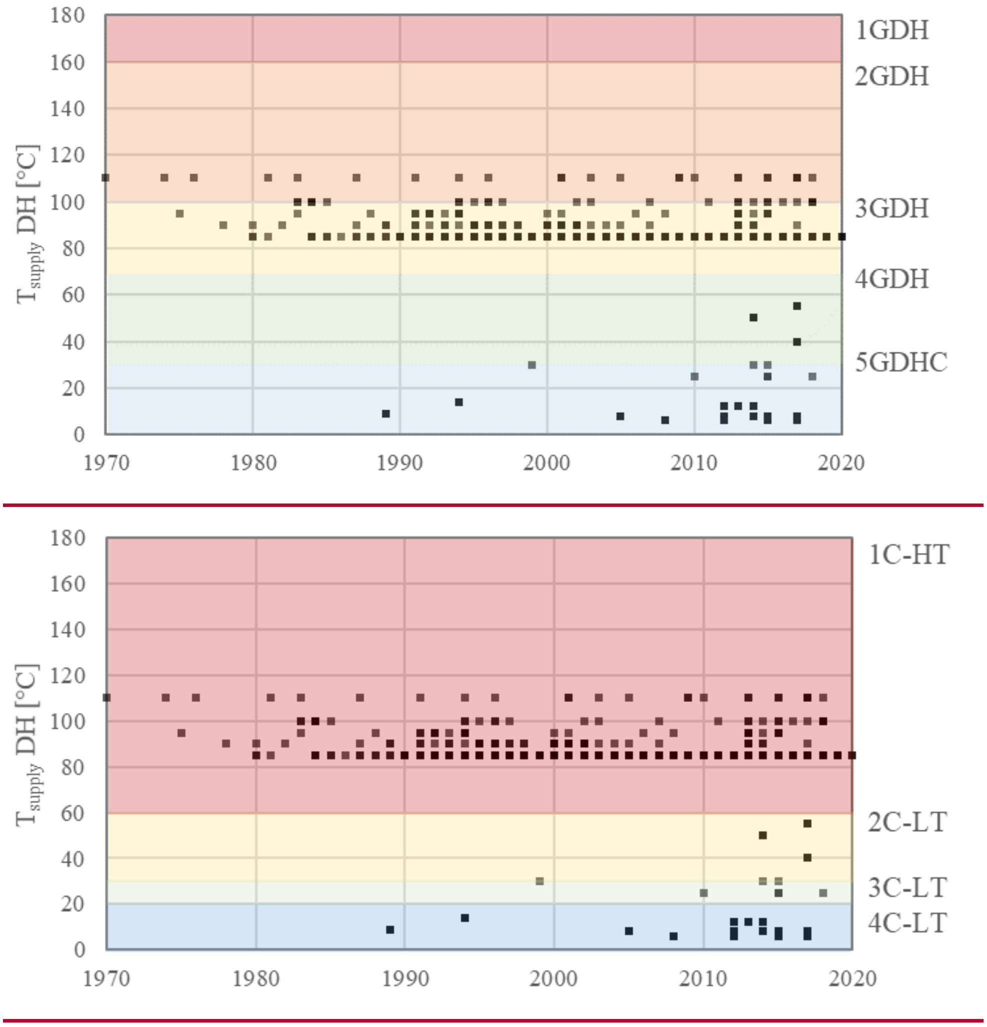


Figure 11. Distribution of the Swiss DTS according to the two different classification approaches (temperature based on estimations by the authors)

3.3. Selection of low temperature case studies and synoptic classification

After a desk research by specific keywords in the Scopus database, taking into account the expertise of the authors and their participation in trade associations, working groups and research programs, the available and documented case studies of innovative DTS in Italy and Switzerland, i.e. ~~5GDH~~5GDHC generation or low/ultra-low temperature, are described and classified in the following. The low temperature Italian systems are almost recent and, despite few cases, they are representative of different operating conditions. Generally, these systems are small size, with a short network, located in flat lands and with moderate climatic conditions (in locations with 2100-2500 heating degree-days except one case).

For example, they use different environmental sources such as groundwater, geothermal, waste heat and seawater. Supply side, four cases can be classified as low temperature systems, while the other two as ultra-low temperature systems. User side, temperature can be low, high or mixed, depending on the cases, but the most part operate at high temperature, demonstrating the possibility to connect also old and/or building with low energy performance to ~~these~~this type of systems. Users can be public or private buildings and final uses can be space heating or heating and DHW or heating and cooling, depending on the situation. The main features are summarised in Table 3. In the case of Sale Marasino (1), in operation since 2014, a thermal annual energy need of 277 MWh is ensured by means of a groundwater loop coupled with HP at building level (300 kW_{th} installed) that allow, in winter, supplying final users (a school and a library) with high temperature water. In summer ~~cooling~~SC is also provided.

~~In the case of Torbole Casaglia (2), an annual thermal energy need of 1335.8 MWh is satisfied by means of HP at building level (1.5 MW_{th} installed) coupled with a groundwater loop that allows, in winter, to supply final users (schools, canteen, sport centre and library) with low (45°C) and high (70°C) temperature water (for both radiant panels and radiators), for space heating (SH) and DHW.~~

In the case of Ospitaletto (~~3~~2), in operation since 2018, 2090 MWh of annual energy needs are covered with a 1.6 MW Heat Exchanger (HX) for waste heat recovering by a local industry and a 1.2 MW ground water HX. A heat distribution network of 2.5 km is then coupled with HP at building level and allows, in winter, to provide high and low (70°C and 45°C) temperature water to final users (schools, sport centre and households) for SH.

In the case of Grado (~~4~~3)[11], in operation since 2016 after a long-lasting project and implementation, by means of borehole heat exchangers, hot water is distributed in the thermal network of 2 km coupled with ~~heat pumps~~HP and ~~heat exchanger~~HX at building level, supplying final users (schools, sport centre, households and auditorium) with high temperatures water for ~~space heating~~SH.

The case of Porto Piccolo - Sistiana (~~5)~~[6]~~,~~4), in operation since 2014, is very interesting because adopts sea water as heat source for providing ~~heating~~SH and ~~cooling~~SC in big residential buildings, with a thermal power of 5.8 MW. 20 HP are located at building level providing warm water for ~~space heating~~SH at 40°C and chilled water for ~~space cooling~~SC at 7°C, while the network (3 km of length) has a ring operating between 8 °C in winter and 30°C in summer. The temperature levels, the source and the concept of the system, in which space cooling for holyday buildings is the main purpose, make this case a clear example of ~~5GDH~~5GDHC. Also the case of Savona – Torre Orsero (~~6~~5), in operation since 2007, adopt sea water as heat source for providing ~~heating~~SH and ~~cooling~~SC in households with an installed thermal power of 5.8 MW. The sea water loop is connected by a HX to a technical water one. The thermal station includes also two backup condensing boilers fuelled by natural gas and HP at building level. In this way all the buildings are equipped for ~~heating~~SH, DHW and ~~cooling~~SC.

Also the case of Venezia (~~7~~6), in operation since 2013, adopt the water of "Laguna di Venezia" as heat source for providing heating and cooling in households. A thermal station equipped with a 9 MWth HX and fossil backup boilers connects the sea water loop with the technical water one (about 0.8 km long). The latter supplies water at 15 °C in winter and 25 °C in summer to each building's substation by means of HP (5 MW_{th} installed in total). The system provides DHW, SC and SH to 530,000 m^3 of industrial and office users for a total of 210 MWh_{th} annual energy needs. The configuration of the system, the low variability of sea water temperature and the availability of LT heat emission subsystem ensure high energy performances.

Another interesting case, still in the design stage and therefore not included in Table 3, regards the development of a new nearly zero energy settlement near Milan equipped by a LT-DTS fuelled by a small size biomass CHP system and Ground Water HP (GWHP) at building level coupled with building integrated Photovoltaic (PV) systems [37].

As anticipated, the Swiss database [14] does not include the level of the temperature but provides precise information about the energy source adopted. For this reason, a consequent method has been followed: the sources compatible with LT-DTS have been selected (i.e. geothermal, lake water, ~~underground water~~groundwater, waste heat including tunnels), finding 84 DTS in the mentioned database. Among these, some systems are actually LT, while the others are equipped by a central HP in the thermal station and a HT district network. Based on the expertise of the involved authors, 25 DTS have been selected due to the possibility of finding reliable information. To that end, a challenging phase of collection, comparison and elaboration of the available data set has been accomplished. In addition to the technical literature (e.g. [25]; [28]), the association for the

[11] Information provided by the engineering office, www.simming.it

enhancement of the energy produced by waste water, ~~waste~~wastes, residual heat and drinking water[12] and the association for promoting geothermal energy[13] have been consulted together with information available at proper web sites[14] and consequently investigated.

The final set of LT DTS represents an impressive number compared to the dimension of the territory. A distribution of the set (25 DTS) according to the adopted energy sources is reported in ~~figure~~Figure 12, where the spread of systems based on lakes and ground is evident.

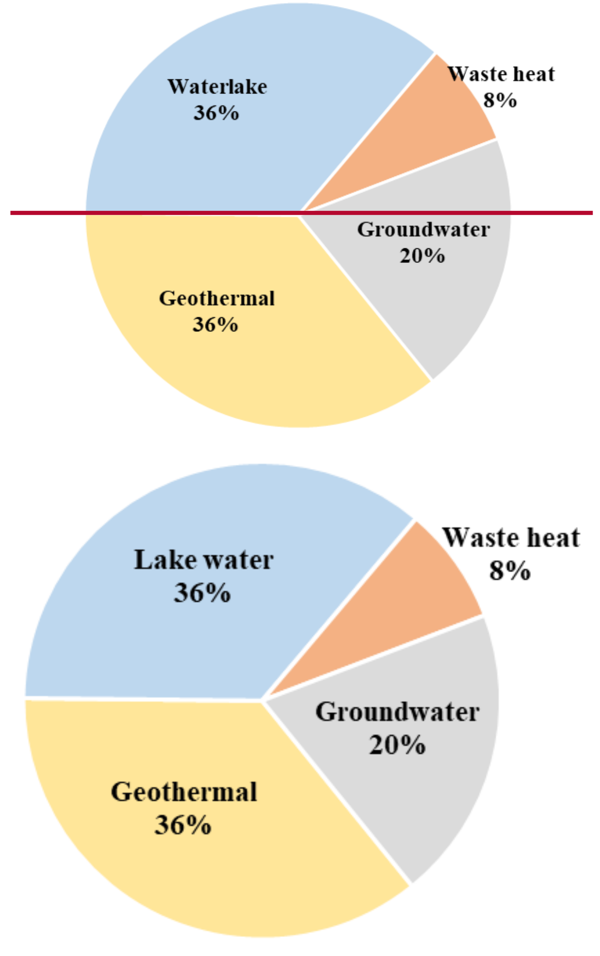


Figure 12. Swiss LT-DTS according to the selected cases (percentages refer to total 25 selected cases)

[12] www.infrawatt.ch
[13] geothermie-schweiz.ch/
[14] www.frauchiger.be/stadtrat/anergienetz/; www.lsta.lt/files/events/~~2016-0418EHPkonfer/~~20160418EHPkonfer/ Pranesimai/Stadtekongress/T.Gautschi.pdf; www.hevs.ch/media/document/2/lauberiwisa_simonsummermatter-1.pdf; www.svizzeraenergia.ch/page/it-ch/reti-termiche

Table 3. Low temperature DTS case studies in Italy

General				Generation subsystem			Distribution subsystem			Users side											Classification		Ref.
n.	Country	Degree Days	Start-up	Technology		Heat source	T_s heating	T_s cooling	Length	Typology	Technology	Pth	sCOP	sEER	Temp. Level	Heated/cooled volume	Energy needs	H	C	DHW			
-		k day	year	-	MWh_{th}	-	°C	°C	km	-	-	MWh_{th}	-	-	-	m^3	MWh_{th}	-	-	-	-	-	-
1	IT	2,497	2014			GW	13	17	0.1	SCH	HTHP	0.3	5	*n/a*	Mixed	*n/a*	277.1	●	●	●	~~5GDH~~5GDHC	4C-LT	[25,38,39]
~~2~~	~~IT~~	~~2,410~~	~~*n/a*~~			~~GW~~	~~15~~		~~*n/a*~~	~~SCH~~	~~LTHP and HTHP~~	~~1.5~~	~~4.3~~		~~Mixed~~	~~46,097~~	~~1,335.8~~	~~●~~		~~●~~	~~5GDH~~	~~4C-LT~~	~~[40,41]~~
~~3~~2	IT	2,446	2018	HX	1.2; 1.6	GW; LTWH	15		2.5	SCH; GYM; RES	LTHP and HTHP	2	4.1		HT	80,000	2,090	●		●	~~5GDH~~5GDHC	4C-LT	[25,1]
~~4~~3	IT	2,239	2016	DBHE	3	GEO	46		2	SCH; GYM; THT	HX and HTHP	*n/a*	*n/a*		HT	*n/a*	*n/a*	●			4GDH	2C-LT	[41]
~~5~~4	IT	2,102	2014	HX	5.8	SW	10	25	*n/a*	RES; COM; HOS; REST	HX	*n/a*	4.7	*n/a*	LT	200,000	*n/a*	●	●		~~5GDH~~5GDHC	4C-LT	[42,25]
~~6~~5	IT	1,481	2007	HX	4.8	SW	15	25	*n/a*	RES; COM; HOS	HTHP	7.4	*n/a*	*n/a*	HT	67,424	*n/a*	●	●	●	~~5GDH~~ 5GDHC	4C-LT	[43,44]
~~7~~6	IT	2,345	2013	HX	5	SW (lagoon); FOS	15	25	0.8	IND; OFF	HTHP	6	5	6	LT	530,000	210	●	●	●	~~5GDH~~5GDHC	4C-LT	[25,45]

Legenda: Ts: Supply temperature in the distribution network; HT: High Temperature; LT: Low Temperature; sCOP: HP seasonal Coefficient of Performance; sEER: HP seasonal Energy Efficiency Ratio; H: Heating; C: Cooling; DHW: Domestic Hot Water; HX: Heat Exchanger; DBHE: Deep Borehole heat exchanger; GW: Ground Water; LTWT: LT Waste Heat (industries); GEO: Geothermal; SW: Sea Water; FOS: Fossil Fuels; SCH: Schools; GYM: Gyms; RES: Residential; THT: Theatres, auditoriums; COM: Commercial; HOS: Hospitality (Hotels, etc.); REST: Restaurants; IND: Industrial; OFF: Offices; HP: Heat Pump.

Further comments to the Swiss LT DTS are reported in [28]. The primary energies adopted in the LT-DTS sample ~~analyzed~~analysed mainly consist in low-temperature renewable sources (waste heat from laboratories and data centres, environmental heat from geothermal plants, ground water and lakes). The exploitation of such renewable sources has been made possible by to the adoption of novel GSHP that, after a rapid technological development, is currently a mature technology and a promising opportunity for coupling ground water, sea water and geothermal heat with DTS [46].
Within the sample, the network topologies of DTS differ from case to case: the conventional network topology with a central source, a main circulation pump and throttling valves at each transfer; networks topology with distributed circulation pumps that increased thermal efficiency by minimizing mixing losses and are bidirectional. The most part of the cases can be classified as ~~5GDH~~5GDHC or ultra-low temperature while only 2 cases can be classified as 4GDH (18 and 21 in Table 4). It is evident that the approach based on supply temperature and operational scheme allows a more refined classification for LT cases (e.g. cases 13, 18, and 21 in Table 4).

Table 4. Low temperature DTS case studies in Switzerland

Generation			**Distribution subsystem**			**User side**						**Classification**	
n.	Start-up	Technology	Heat source	T_s heating	T_s cooling	Length		Technology	H	C	DHW		
-	year	-	-	°C	°C	km	MWth		-	-	-		
1	2012	BHE	GEO	8	18	1.5	8.0	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
2	1989	HX	LW		9	4	n.a.	HX and HP		•		~~5GDH~~5GDHC	4C-LT
3	2012	HX	GW	12	16	n.a.	1.3	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
4	2013	HX	GW	12	16	n.a.	n.a.	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
5	2013	HX	GW	12	16	4.2	3.5	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
6	2015	BHE	GEO	8	18	0.4	n.a.	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
7	2014	BHE	GEO	8	18	1.5	n.a.	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
8	2008	HX	LW	6	12	6	3.5	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
9	2017	HX	LW	6	12	n.a.	3.6	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
10	2005	HX	LTWT	8		3.7	1.9	HTHP	•		•	~~5GDH~~5GDHC	4C-LT
11	2014	HX	GW	12		n.a.	0.2	HTHP	•		•	~~5GDH~~5GDHC	4C-LT
12	1994	TU	GEO	14		2.2	n.a.	HTHP	•		•	~~5GDH~~5GDHC	4C-LT
13	2017	mixed	GEO-W-S	40	5	n.a.	n.a.	mixed	•	•	•	~~5GDH~~5GDHC	3C-LT
14	2017	BHE	GEO	8	18	n.a.	1.6	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
15	2012	HX	GW	12	12	0.85	2.0	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
16	2012	BHE	GEO	8	18	2.5	6.7	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT

17	2015	HX	LW	6	12	7	8.9	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
18	2014	BHE	GEO	35 - 65		n.a.	0.3	HX	•		•	4GDH / ~~5GDH~~5GDHC	1C-HT / 2C-LT
19	2013	HX	LTWT	12	16	0.48	n.a.	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
20	2014	BHE	GEO	8	18	n.a.	2.5	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
21	2017	HX	LW	50 - 70		n.a.	2.5	HTHP and HX	•		•	4GDH	2C-LT
22	2012	HX	LW	6	12	5	16.0	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
23	2015	HX	LW	6	12	n.a.	5.5	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
24	2017	HX	LW	6	12	n.a.	20.0	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT
25	2008	HX	LW	6	12	n.a.	3.0	HTHP and HX	•	•	•	~~5GDH~~5GDHC	4C-LT

Legenda: Ts: Supply temperature in the distribution network; HT: High Temperature; LT: Low Temperature; H: Heating; C: Cooling; DHW: Domestic Hot Water; HX: Heat Exchanger; BHE: Borehole heat exchangers; GW: Ground Water; LTWT: LT Waste Heat (industries); GEO: Geothermal; LW: Lake Water; HP: Heat Pump.

The Italian and Swiss cases analyzed above are reported in Figure 13 where the labels are referred to the suggested classes according to the two approaches considered.

It is evident that the most part of the systems are ~~5GDH~~5GDHC or 4C, due to the congruence between these two classes. The 4GDH class, which can coincide with the class 2C or 3C, is very rare in the analyzed territory, meaning that in the last years DTS are evolving from the 3GDH or HT DTS to ~~5GDH~~5GDHC or ultra-LT DTS, skipping intermediate configurations. The technical components, used side, are HP and HX in order to make possible every type of energy end-use.

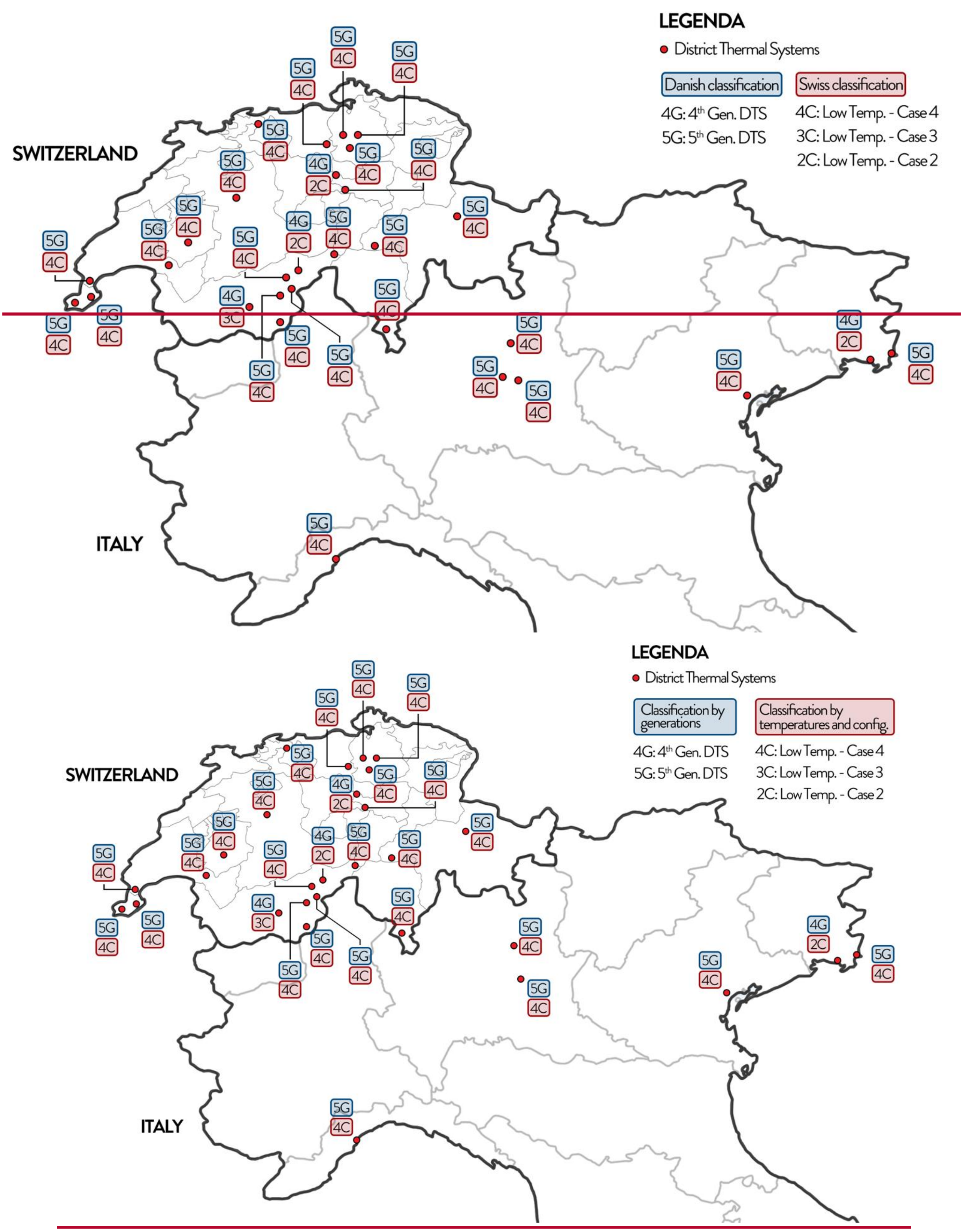


Figure 13. Distribution of the Italian and Swiss LT-DTS and proposal of classification

4. Discussion and possible evolution for DTS

Many issues and figures are reported in the previous sections, therefore a recap and discussion is needed.

The state of the art of DTS is summarised in Table 5, where similar and different operative conditions are underlined. In Italy DH has an older history and is still low efficient and based on fossil fuels. The overall system appears more inertial and less inclined to a radical evolution. In Switzerland DH is more recent and mainly based on heat locally available, be it from waste to energy plants or from lakes and ground. DTS are really small size, compatible to the exploitation of local sources in small and often low-dense areas.

Table 5. Comparison of the state of the art of DTS in Italy and Switzerland

	Parameter	Italy	Switzerland
A	Territorial dimension, km^2	120,000 (north)301,338 (*)	41,285 (all)
B	NumberTotal number of DTS	368	1,010
C	Primary energy for DTS, GWh	21,984	n.a
D	Of which fossil energy	72%	7% (*)(**)
E	Of which heat from Waste to Energy	7%	53% (*)(**)
F	Specific primary energy, MWh/km^2 (C/A)	183	195
G	Mean installed thermal power, MW (C/(B×eq. hours))	30	4
H	Peculiarities	2GDH and 3GDH prevail; Few recent 5GDH5GDHC with information difficult to be collected; Energy from lakes and ground available but scarcely exploited; Presence of metropolitan areas high-density populated	3GDH prevail; Recent evident spread of 5GDH5GDHC with information available even if consulting different DBdatabase; Energy from lakes and ground available and exploited; Few and small metropolitan areas high-density populated

(*)(*) most part in northern regions (120,260 km^2) and Tuscany (22,985 km^2).
(**) based on 8,066 GWh per year of heat sold to users.

DTS have been analysed referring to two complementary classifications, underlining that the one based on generation allows a more detailed analysis about older systems (1GDH, 2GDH and 3GDH instead of the only 1C-HT class), while the one based on supply temperature and operational scheme allows a more detailed analysis about most recent systems (2C-LT, 3C-LT and 3C-LT instead of 4GDH and 5GDH5GDHC). Therefore, the first scheme can support the analysis of the most part of the existing cases for defining their future scenarios of operation, while the second ones can support the technical feasibility of those scenarios with particular regard to the relation with the users/prosumers.

Dealing with feasibility, economic barriers have to be considered. A barrier that regard all the classes of DTS is the involvement of final user in order to increase their willingness to be connected. Indeed, the obligation to sign binding and long-lasting contracts in advance is an obstacle not only for the final users, but also for other stakeholders that could finally renounce to the initiative. In this context, to make mandatory the connection of public buildings could be an important help for the investors and an example to be emulated. Moreover, considering the barrier of high investments, a great help can be to have precise and flexible economic and energy models, in addition to economic support by central and local governments. About investments, the payback time should be considered not *per se*, but in comparison to the lifetime of buildings and components of the ~~DHS~~system. However, a payback time of 10-15 years can be very disheartening and unaffordable for the investors involved in a DTS project [47]; therefore, supporting mechanisms should promote technologies and sources otherwise not economically interesting. As evolution, innovative LT-DTS may bring new billing challenges, which go far beyond the simple sale of heat to final users. In fact, the presence of different components and energy carriers, the possibility to become also suppliers (in power to heat configuration), the balancing of the electric and thermal needs open new opportunities that can bring also economic benefits, on the long term. For example, in the case ground source heat pumps, a reduction of the number of probes regenerating the soil can imply a reduction of the initial investment as also the possibility to experiment cooling and free-cooling. Economic barriers are also connected to the political ones. Political instability, in particular changes in legislative conditions or incentives, should be faced and can be a strong barrier for all the involved stakeholders. E.g., considering the two national contexts explored, from Table 5 it is possible to argue that in Switzerland there is a more robust energy policy, while in Italy the economic and regulative instability and the bureaucratic complexity are strong brakes to the spread of DTS.

Moreover, to plan the evolution of DTS implies the need of a deep knowledge of the current state of the art. Considering the efforts carried out for data collection and elaboration, the need to improve the knowledge about the existing cases emerges. In addition, new dedicated tools are needed mapping of the territory, its thermal demand evolution, identifying quickly particularly interesting areas where to concentrate possible studies and financial investments. The more detailed this mapping is, the more it is able to favour small and neighbourhood systems.

Despite the barriers above mentioned, several drivers that can be activated to facilitate the evolution of HT DTS to LT DTS, both for new plants and for extensions and expansion of existing ones, as well as for the transformation and optimization of old plants. The goals about renewable sources for thermal uses in addition to energy retrofit measures represent an effective driver. LT DTS (in particular 4C-LT DTS) could be equipped also in order to satisfy the ever~~-~~-increasing cooling purposes and network systems, if properly managed, can make the distribution and exploitation of renewable energy sources more efficient. According to [48], ~~multi-energy systems (~~MES~~)~~ can be promising in low-temperature DTS, where prosumers participation is facilitated through a double loop heat pipe configuration, allowing consumers to be both buyers and sellers of heat. In addition, the use of renewable energy generation and energy storage allows reducing operational costs, heat losses, energy consumption and carbon emissions. This option allows also controlling the issue of the large-scale penetration of individual domestic HP, due to their strong impact on the national or local electric grid, which could be not suitable to manage power peaks determined by thermal needs. In this context, DTS can help the balance of the overall system, considering the electric grids currently available.

Moreover, it has been learnt that all the components of the system should be perfectly integrated and controlled, i.e. ~~heat exchanger~~HX, HP, storage and heat emitting systems in buildings, considering also the energy performance of the served buildings that influences the requested thermal power and the heat density along the grid. If radiators, coils or fan coils are the emitting systems in buildings, DTS operating at 40-50°C providing heat directly through heat exchanger (4GDH or 2C-LT) can be very critical. Conversely, the matching is less critical for DTS operating at lower temperature providing heat indirectly through HP (~~5GDH~~5GDHC or 3C-LT and 4C-LT). In fact, HP can upgrade heat to high temperatures (60-70°C), buildings side. Analogous considerations may regard DHW production because, as mentioned for the protection to Legionella, it is necessary to reach, at least occasionally, temperatures of about 65°C.

5. Conclusions and further developments

As demonstrated in the previous sections, DTS have still a small role that is expected to grow impressively to 2050 by means of the following modes:

- To connect new development areas to existing DTS;
- To connect existing areas to existing DTS;
- To develop new small size DTS for new development areas;
- To renovate existing DTS making them more efficient.

Since DTS imply big investments, it is fundamental to have a systematic frame of analysis in order to guide their evolution and penetration effectively and possibly without committing errors and waste of resources. In order to study more in details key issues of DTS, two classifications have been considered and an attempt of comparing and matching the two methods has been here presented.
The expression DTS has been here adopted, instead of DH and/or DC, indicating a system of pipe connected one side to final users (that can be also a prosumer) for each type of thermal uses and other side to available heat sources, regardless of their level of temperature, size and complexity. To that end, the possibility of managing DTS in bidirectional and unmanaged way can bring interesting opportunities.
Currently, the European debate is dealing with the 4GDH and ~~5GDH DTS, but few examples have been already realized, integrating demand side response through advanced control systems in order to supply and store heat in a more effective way, reducing emissions and energy costs.~~ 5GDHC. Indeed, thanks to the possibility of having a single and low temperature network both for heating and cooling, the novel concept of 5GDHC allow to improve flexibility of DTS through the optimal management of the energy fluxes. The variety and complexity of system configurations and interactions between connected customers, key difference between 4th and 5th generation, poses a challenge in modelling and integrating advanced control systems for optimizing electric and thermal energy fluxes in a DTS. Actually, few examples have been already realized integrating demand side response through advanced control systems, but progresses in this field are available in very recent contributions in the technical literature, e.g. [49], that implements a model predictive control method based on recurrent artificial neural networks to shift electricity consumption from peak-hours and [50], that show the application of a demand side response control in a 5GHDC network enabling an optimized management of electricity production-consumption, stressing also the economic benefits.
As important driver, favouring the cascade use of heat, the evolution of DTS towards LT will allow an increasing of the linear heat density[15] with a reduction of heat losses. Further, LT DTS are intrinsically characterized by lower heat losses and allow the use of cost effective non-insulated pipes. According to [1], the following points can be cited in addition to those already discussed for supporting the evolution of DTS in the mid-term:

- To activate local governments and municipalities in the transition. Heating is a local energy demand and it is important to enable coordination between national and local levels;
- To end investment in new individual fossil fuel heating capacity such as gas boilers and instead support transition to heat pumps that can utilize renewable electricity and district heat;
- To start investigating the potential of DC, because cooling is the fastest growing thermal sector, of free-cooling and thermal storage in order to provide solutions by DTS;
- To support investments in thermal grids and multidimensional infrastructure and construction sites, that are very promising for energy transition;
- To promote a systemic approach, finding synergies between sectors and enabling the energy value chain. This means exploiting waste heat source for DTS and providing flexibility to the electric sector. Indeed, the challenging issue of sector coupling (i.e. to interconnect/integrate the different sectors of energy users, such as buildings, transport, and industry, with the power

[15] It describes the average amount of energy supplied considering the length of the network.

producing sector resulting in energy and environmental benefits [5]) can be a promising chance;

- To train the operators involved in the whole chain of DTS: investors have to be informed about opportunities and supporting mechanisms; technicians about the technical solution for improving existing thermal stations and grids and for installing innovative and flexible systems. Since operators have to design and manage new DTS that do not follow the usual and scalable management logics, it is necessary that they are supported to face innovative alternatives.

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District Thermal Systems: State of the Art and Promising Evolutive Scenarios. A focus on Italy and Switzerland.

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NOMENCLATURE

EU: European Union;
GHG: Greenhouse Gases
RES: Renewable Energy Source/Sources
HP: Heat Pump/Pumps
SC: Space Cooling
DH: District Heating
DTS: District Thermal System/Systems
DC: District Cooling
GIS: Geographic Information System
4GDH: 4th Generation District Heating
5GDHC: 5th Generation District Heating and Cooling
1GDH: 1st Generation District Heating
2GDH: 2nd Generation District Heating
3GDH: 3rd Generation District Heating
MES: Multi Energy System/Systems
DHW: Domestic Hot Water
HT: High Temperature
LT: Low Temperature
1C-HT: Case 1 - High Temperature
2C-LT: Case 2 - Low Temperature
3C-LT: Case 3 - Low Temperature
4C-LT: Case 4 - Low Temperature
VAT: Value Added Tax
CHP: Combined Heat and Power
SH: Space Heating
GSHP: Ground Source Heat Pump/Pumps
HX: Heat Exchanger
GWHP: Ground Water Heat Pump/Pumps
PV: Photovoltaics

1. Introduction

Achieving the European Union (EU) climate objectives (i.e. a reduction of the overall greenhouse gas (GHG) emissions by 80-95% by 2050 compared to 1990 levels) requires a complete transformation of the energy system [1].
One of the main challenges is the decarbonisation of the heating and cooling sector, that, dominated by space heating, accounts for approximately 50% of EU-28 final energy demand and around the 80% of the end-use energy in European buildings [2]. For example, the share of space heating is 61% in Italy and 71% in Switzerland [3].
To move to a sustainable heating and cooling sector, it is essential to invest to lower overall demand, to increase energy conversion efficiencies and to replace fossil fuels with Renewable Energy Sources (RES). Currently, heating is largely supplied by fossil-fuelled individual heating solutions (e.g. natural gas fuelled condensing boilers) at building level, while cooling is mainly provided by electric appliances such as compression chillers. Among the available RES, only biomass was used substantially for heating purposes (12%), while solar thermal, geothermal and Heat Pumps (HP) are still marginal in many countries [4]. Space Cooling (SC) accounts for less than 2% of total end-use

energy in building [1] and nowadays it is mainly relevant in southern countries; however, it is expected to more than double towards 2050, as it has already done between 1990 and 2016 according to [4].

District heating (DH) supplies only the 12% of the needs in Europe, involving about 6,000 DH networks, 200,000 km of grids, 60 million citizens and an additional 140 million living in cities with at least one DH system [5]. However, DH has been largely indicated a promising solution [6]. The Heat Roadmap Europe studies [2] show that a future energy system with 50% DH and sector integration (the so-called sector coupling approach) is more efficient than a decentralised/conventional system and allows for higher shares of renewable energy at a lower cost and for integrating Combined Heat and Power (CHP) plants, waste heat from industry and services and use of electricity in large-scale HP. In fact, according to [5], the contribution of fossil fuels in DH mix in EU is expected to decrease from the 85% in 2016 to the 35% in 2050 and, in parallel, large size HP and industrial waste heat are expected to have a share of 30% and 25% respectively, in the same mix.

In Europe, the establishment of scenarios with high amounts of DH in their energy supply by 2050 is in line also with the current urbanization trend. Indeed, in urban areas the demand for heating and cooling assumes the highest density and, at the same time, a huge amount of low-grade waste heat is diffused within the urban landscape. Moreover, as demonstrated by [7] for a case of waste heat from data centres, such free and largely available heat source in urban settlements can be easily exploited in District Thermal Systems (DTS) achieving both environmental and economic benefits.

In the following, DTS is adopted, where appropriate, to indicate a larger concept of thermal networks able to satisfy or integrate thermal uses in buildings (space heating, domestic hot water, space cooling) by means of networks of pipe connected one side to final users/prosumer and other side to available heat sources.

However, the pathway to 2050 scenarios depends on the present situation and context of each country. Indeed, DH is generally more developed in Central, Eastern and Northern Europe, where in some countries it has reached a share around 50%. Conversely, in Italy DH represents the 3% of space heating [8][1] and in Switzerland the 5% [3]. However, according to [1] in the 2050 scenarios, these figures are expected to raise in a range of 50-80% in Italy and, according to [3], to raise at least at 40% in Switzerland. This trend will involve also District Cooling (DC) that is expected to increase given the vast untapped potential of the sector, especially in Mediterranean climates. The study here presented is in line with the precedent researches carried out by the same research group: in [3] a tool for mapping DTS potential has been developed; in [9] the performance of a large sample of Italian biomass DTS has been evaluated; in [10] a procedure to select possible district cooling expansion has been defined and mapped in Geographic Information System (GIS); in [11] the effect of the Italian energy policies linked to district heating development have been analysed. Considering this background in research, along with the expertise of the involved authors, the research here presented investigates northern Italy and Switzerland, where geographic and climatic conditions and density of thermal needs are mutually comparable. Figure 1 shows the geographical position of the two analysed countries within the European context.

[1] The reference [8] corresponds to the yearbook published by AIRU, the association of urban (district) heating in Italy. For many years, the association has actively promoted district heating based on different energy resources. The yearbook contains the essential data of the district heating networks present on the national territory.

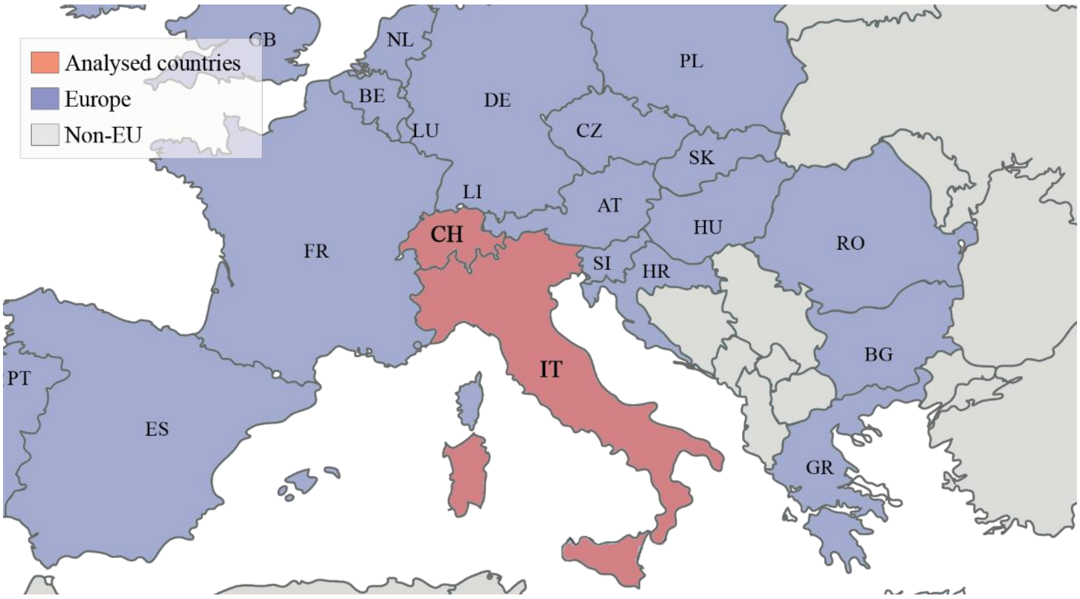

Figure 1. Italy and Switzerland in the European geographical framework

The main aims are: to describe the state of the art of DTS in both the countries; to analyse the schemes available in the technical literature for the classification of DTS; to analyse and classify the Italian and Swiss innovative systems in operations; and to provide indications for the evolution of the sector toward 2050 scenarios.

2. Materials and methods

Aside the gained expertise of the authors, northern Italy and Switzerland share many features in terms of climate and technological development and can be representative for a larger sample of southern Europe countries. In order to have an analytic and systematic overview of the DTS state of the art, the technical literature has been consulted with particular attention to contributions dealing with methods for analysing and classifying DTS in operation. These methods are useful in order to define clusters of DTS, challenges and strategies for their future improvements. According to the available literature, besides the operational and technological features, the main adopted metrics are the network operative temperatures for supply and return, but, considering the strong site-dependency of DTS [12], other parameters are considered in order to cluster systems in operation and to propose insights for their smart evolution in the future.

The selection of the scientific and technical literature has been carried out in order to:

- Define the technological and operative features of existing DTS;
- Review the methods for analysing and classifying DTS;
- Investigate the barriers and drivers for a smart evolution of the existing DTS and for the development of innovative ones.

The review of the technical literature has involved in particular:

- the Scopus database using specific keywords in the field of DH, e.g.: district heating, DH classification, fourth and fifth generation DH (4GDH and 5GDHC[2]), low temperature DH, district thermal networks,);
- national and international technical reports;
- expertise of the authors and their participation in trade associations, working groups and research programs, that is an evident added value of the research.

[2] According to recent contributions in the technical literature that will be cited in the following, 5GDHC is adopted instead of 5GDH in order to underline the intrinsic possibility of such systems to provide heating and cooling.

In particular, the scheme of the method followed is described in Figure 2 together with the main contributions selected that are grouped by: method of analysis and classification schemes; theory and cases of high temperature DTS; theory and cases of low-temperature DTS.
In the following sub-sections, the methods for analysing and classifying district heating networks are discussed dividing them into two group. The first (section 2.1) origins with the work of [13] with particular reference to the Danish DTS, even if other well documented contributions have updated the framework in the last years. The second (section 2.2) is coherent with the previous one, but is more focused on the supply temperature level and on the equipment buildings side. It is particularly referred to the Swiss DTS, even if, also in this case, other well documented contributions have recently updated the framework.
In section 3, these methods are applied for describing and clustering DTS in operation in Italy and Switzerland. Furthermore, a focus on recent low temperature DTS is reported, underlining the penetration in Italy and Switzerland, the main characteristics and the possible strategies for a future spread.
In order to get a full portrait, the documented energy data of DTS have been collected and elaborated in a dataset. Since the available databases (e.g. [8] for Italy and [14] for Switzerland) may contain lacks of technical data due to the dimension of the sample of systems considered, elaborations and related graphs and tables in the following may regard different samples of plants, according to the data available for a given parameter studied, as specified case by case.

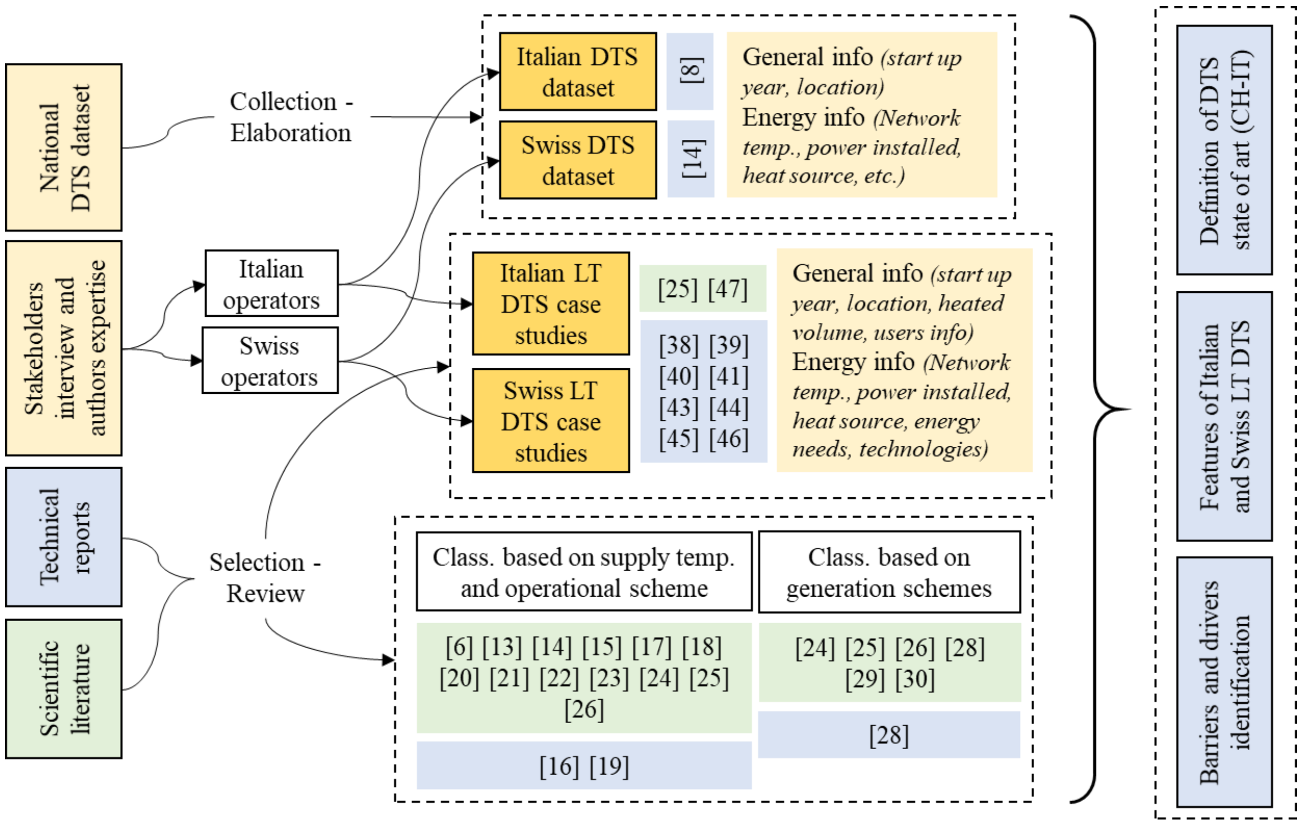

Figure 2. Scheme of the research and main technical references considered

2.1. Method of classification based on DH generations

DH refers to a mature technology; in fact, first examples in EU appeared around 1920 [15]. Considering the increasing global urbanization trends and the suitability of district systems with the implementation of low carbon paradigms and circular economy in the energy sector [15], DTS have been recently addressed as a key point for the EU decarbonization roadmaps toward 2030 and 2050 as reported, e.g., in [16] and [5]. Throughout the years these systems have undergone a considerable spread and a deep technological development in favour of lower distribution temperature, improved materials and components and prefabrication [17]. Nevertheless, the many examples currently in operation present a consistent range of different features, schemes and stages across Europe in terms of technologies, energy resources, built environment, etc. [18].

The classification in different generations has been a robust reference for stakeholders and researchers in order to analyse the existing DTS and shape scenarios for their evolution.

This classification, at that time of its definition, consisted in four generations of DH, divided in terms of period of maximum spread and technological maturation, operative temperatures, technologies and configurations [19]. A complete and updated state of art review on DH is reported in [20], focusing on the operational characteristics (sources, components etc.) of each DH generation.

The first generation of DH (1GDH) was characterized by coal steam boilers and the hot water on the users' side were directly heated up with high temperature steam (over 100°C) and distributed to end users through concrete steam pipes.

A second generation of DH (2GDH) appeared and diffused between 1930 and 1970 and was characterized by pressurised hot water distributed in steel pipes in place of steam as the heat carrier to overcome the problem of condensation drops.

Following the technological evolution of emission systems and the reduction in the heat demand of buildings, the third generation (3GDH), mainly diffused after 1980 mostly in Europe, is characterized by the adoption of hot water at temperatures in the range of 80-90 °C, control and management technologies as well as plastic jacket pipes to eliminate corrosion of the steel carrier pipes.

The evolution toward the recent fourth generation (4GDH) implies a further lowering of the distribution temperatures (in the range of 30-70 °C), higher energy efficiencies and integration of RES. Many contributions are available in the literature referring to different territories; e.g. [6] for large-scale DTS in Estonia; [21] about technological and non-technological barriers in the revamping of traditional DTS into low temperature one in Italy.

The authors of [13] specify some properties that future generation DH should have in order to fulfil their role in sustainable energy systems, such as: the ability to supply low temperature heat to both existing, renovated, and new buildings; having low grid losses; the ability to recycle heat and integrate renewable sources; the ability to be an integrated part of a renewable Multi-Energy System (MES), including cooling; having a sound business model, also in the transition to renewable energy sources.

Even if [13] point out 2020-2050 as period of best available technology for the 4GDH, the increasing interest on low-temperature DTS and the rapid technological advancements of HP laid the basis for a further decrease of water temperature in the distribution network below 30 °C. This new generation of DTS has specific features that differs from the ones proposed by [13] in defining 4GDH. For this reason, according to other recent researches, the distinction between 4th and 5th generation is consider in the present study. Precursory insights of this novel concept are reported in [22], providing a literature review about the innovative concept of "cold DH networks", and in [23], clarifying that "bi-directional decentralized district heating and cooling grids" have the potential of turning each connection into a "prosumer" and not have return flows as such, but warm and cold pipes. More precisely, according to [24], the 5th generation district heating and cooling (called 5GDHC) combines the properties of local renewable energy systems with the principles of future district heating as defined by [13], therefore are a solution for renewable urban thermal energy supply. The authors of [25], through the review of scientific contributions investigating the features of these systems, provide a common definition of 5GDHC. This is defined as a thermal energy supply grid operating at temperatures so close to the ground that is not suitable for direct heating purpose. The low distribution temperature (in the range of 10-25°C) allows instead to exploit directly industrial and urban excess heat, to use renewable and low-exergy heat sources and to provide heating, cooling and Domestic Hot Water (DHW) to users by mean of decentralised HP. This is deepened also by [24] that provide a definition for 5GDHC and show how this concept differs from the concept of 4GDH, since 5GDHC

are decentralized, bidirectional, close to ground temperature networks that use direct exchange of warm and cold return flows and thermal storage to balance thermal demand as much as possible. Also [26] underline the novelty of 5GDHC and the different possible topology, comprising decentralized heat pumps rather than a single large energy centre, giving opportunities for sharing (prosuming) heating and cooling across a very low temperature loop.
Moreover, considering the actual technological features of the existing DTS in Europe [1] and the wide differences between countries in terms of technological development, climate and renewable penetration, a different approach, more adopted in southern Europe DTS, is considered and discussed in the following section.

2.2. Method of classification based on supply temperature and operational scheme

In addition to the classification based on five generation, another approach has been developed, more focused on the levels of operating temperature and components users' side. This approach is adopted as method of classification in Switzerland according to [27], but is available also in other contributions such as [28] and in [29], providing a consistent design framework based on mathematical optimization, and in the references cited therein about "bidirectional Low Temperature Networks", "Cold District Heating Networks (in German *Kalte Nahwärme*)" and "Anergy Networks (in German *Anergienetze*). This approach is mostly adopted in Germany, Austria and Switzerland and mainly devoted to explore DTS belonging to 4GDH and 5GDHC focusing on networks operating at supply temperatures below 60-70°C. The interest in this sample of plants is motivated by the possibility to exploit waste heat and local renewables, reducing also heat losses along the grid due to lower temperatures[3]. Based on these considerations, the following operational cases, identifiable in four classes, have been described according to [27]. Every class reports the necessary technologic components, characteristic parameters, grid morphology and configuration, energy balance calculation (input and output heat flows along the network) and requirements for operation. This typological classification cannot be framed directly by the previous approach, which is mainly based on level of supply temperature and on the age of the DTS, and it is connected to the energy efficiency of the served built environment. According to [27] DTS are classified in:

- High temperature (HT): systems operating at temperatures above 60°C, which most often use waste to energy plants or wood chips boilers as heat sources. In this category there is one case (named 1C);
- Low temperature (LT): systems operating at temperatures below 60°C that, at least in the Swiss context, are spreading more and more implying new supply concepts and technologies. In this category there are three sub-classes (named 2C, 3C, 4C).

In case of HT (here named 1C-HT), heat can be supplied directly through heat exchangers for space heating and DHW. This type of network is not suitable for cooling buildings. Heat losses along the network are in the range 7-13% of heat supplied. Conversely energy requested for pumping can vary in a wide range, from 1 to 13% of heat supplied.
LT cases are particularly suitable for new or recently renovated buildings that have higher energy performance and lower energy requirements than older buildings and can be heated with lower temperatures systems coupled by radiant emitting components inside buildings. When the temperature of the supply network is not sufficient, e.g. for DHW supply or in case of radiators as emitting components inside buildings, HP can be integrated, buildings side, to upgrade the temperature to the levels requested.
Therefore, since temperature levels influence the technologies that should be used in buildings, three sub-classes among LT DTS have been defined, depending also on technologies required for each operating temperature:

[3] Thermal dispersions are proportional to the difference of temperature between the carrier and the medium (i.e. the underground). The smaller the difference of temperature, the lower are the heat losses through the pipes.

- 2C-LT (Supply temperature from 30°C to 60°C):
  Heat can be supplied directly for space heating. For DHW, the temperature must usually be increased, for example, using a HP. In order to cool the building a cooling system is required and excess heat is not reused. Heat losses along the network are in the range 3-7% of heat supplied. Energy requested for pumping is around 1-2% of heat supplied.
- 3C-LT (Supply temperature from 20°C to 30°C):
  Heat cannot be supplied directly for space heating and DHW; a HP is required. In order to cool the building, a cooling system is required, but the heat produced is directly injected into the network and can be reused. Heat losses along the network are lower than 3% of heat supplied. Energy requested for pumping is around 1-2% of heat supplied.
- 4C-LT (Supply temperature lower than 20°C):
  Heat cannot be supplied directly for space heating and DHW; a HP is required. The network temperatures are adapted to the direct cooling of the building by means of a heat exchanger. Excess heat is injected and reused. Heat losses along the network are negligible. Energy requested for pumping is around 2-3% of heat supplied.

The classification of DTS depending on the adopted operating model, taking into account the temperature levels and the technical concept, is reported also in other contributions dealing with 5GDHC such as the already mentioned [24], [25], [26], [28] and [29], underlining the recent relevance of the topic and the complementarity of the two approaches for classifying DTS.
According to [27] and analogously to [24], [26], [29] and two criteria for defining the operating mode are the direction of water flow (managed or unmanaged) and the energy flow in the system (unidirectional or bidirectional).
In particular, a DTS can be called managed network if there is only one direction of the water flow from the network to the consumers. Because of this, a centralized pump is installed at the supplier's site. In addition, a DTS can be called unidirectional network if there is only one direction of the energy flow. Energy flow always originates completely from the heat source and moves towards the consumers. In unidirectional networks, the source and the consumers are unambiguously and definitively distinct (e.g. widespread high-temperature networks generally use a directed and unidirectional mode of operation).
Conversely, a DTS can be called unmanaged network if there is not only one direction of the water flow from the network to the consumers. Water is moved with pumps either from the supply pipe (heating) or from the return pipe (cooling). This is in accordance also to [25], where it is reported that in 5GDHC networks with decentralized pumping stations (one for substation) some user can be in heating and others in cooling mode at the same time, considering multiple types of hydraulic configurations. In addition, a DTS can be called bidirectional network if the consumer can become also a heat source. When the energy flows in the building are not balanced (i.e. heating needs are much higher than cooling needs or the other way around), deficits and surpluses might be compensated into the network. Ultra-low temperature networks are often unmanaged and bidirectional. This is a key point for shallow geothermal energy systems, using borehole heat exchangers [30].
The two operative modes are represented in the following Figure 3.

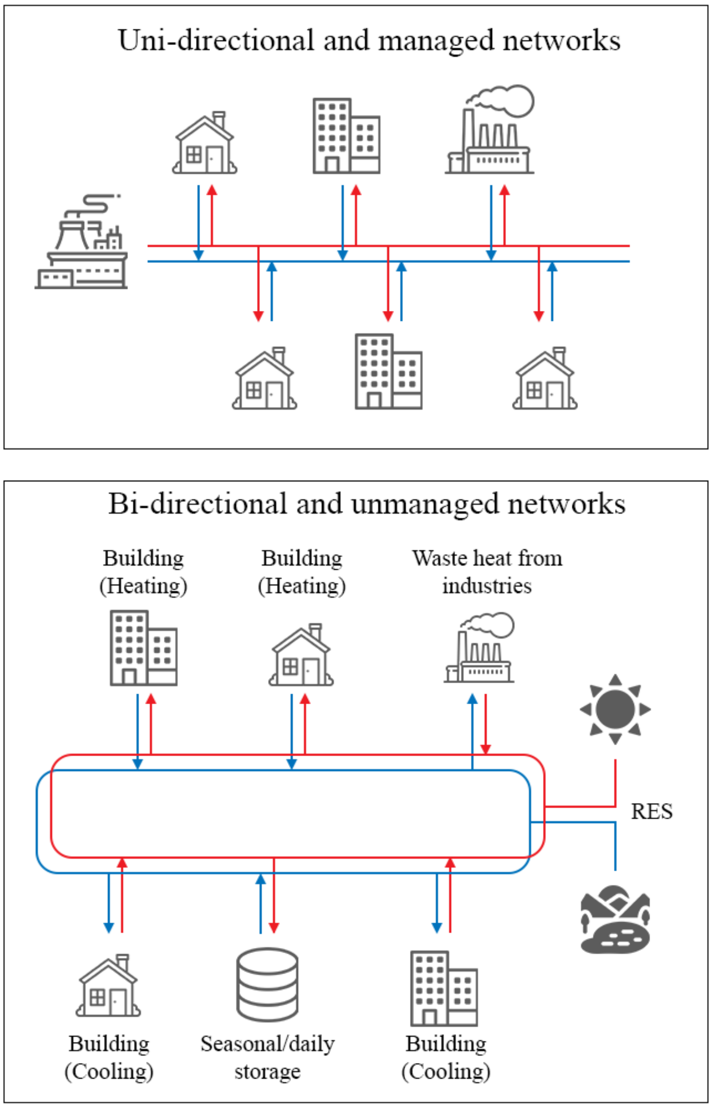

Figure 3. DH networks modes: unidirectional and managed (above picture), bidirectional and unmanaged (below picture).

2.3. Complementarity of the two approaches

The two schemes of classifications are based on common parameters such as heat carriers, temperature levels for supply and return and type of energies adopted. However, in addition, different parameters are considered. For example, the first classification takes into account also the age of the DTS, technical details such as materials of pipes and precast components, the relationship with energy performance of the served buildings, available RES and distribute cogeneration. Conversely, the second classification is mainly focused on final uses in buildings and on the available components for providing and emitting heating and cooling inside buildings.
Considering the description reported in sections 2.1 and 2.2 and that for the most part of the DTS in operation the heat carrier is hot water with a supply temperature of 90°C or less, the following comparison is mainly focused on 3GDH, 4GDH and 5GDHC.Therefore, 1GDH and 2GDH are not taken into account in the following scheme (Figure 4).
The 3GDH is entirely included in the 1C-HT class[4] because: the temperature levels allow covering thermal purposes in buildings by means of heat exchangers (without other technological components

[4] 1GDH, 2GDH and 3GDH are distinguished in the first classification scheme, while all of them are included in the 1C-HT class of the second scheme, without particular differences.

as HP); the contribution of RES is negligible (except biomass DTS); and these grids are not able to provide also DC.

Conversely, the second scheme of classification is more detailed for the LT DTS: in fact, 4GDH and 5GDHC are split in three classes of operation, because 4GDH can belong to two different types of LT DTS depending on the presence of the components at buildings side (heat exchangers and reversible HP).

As anticipated in section 2.2, after a deep technical review (not only in the Scopus database, i.e. in English, but also among the available local references in Italian and German), the second classification, widely described in [27] and cited in [28], defines different typologies, energy balance calculation, and classifies DTS in four groups, providing also standard diagrams that describe components and technologies needed to supply thermal energy in buildings, the operating details and requirements [27].

The result of the deepening on classification schemes and on their comparison is reported in Figure 4 that resumes information about the temperature level, the energy sources, the components at building side and the energy uses satisfied[5].

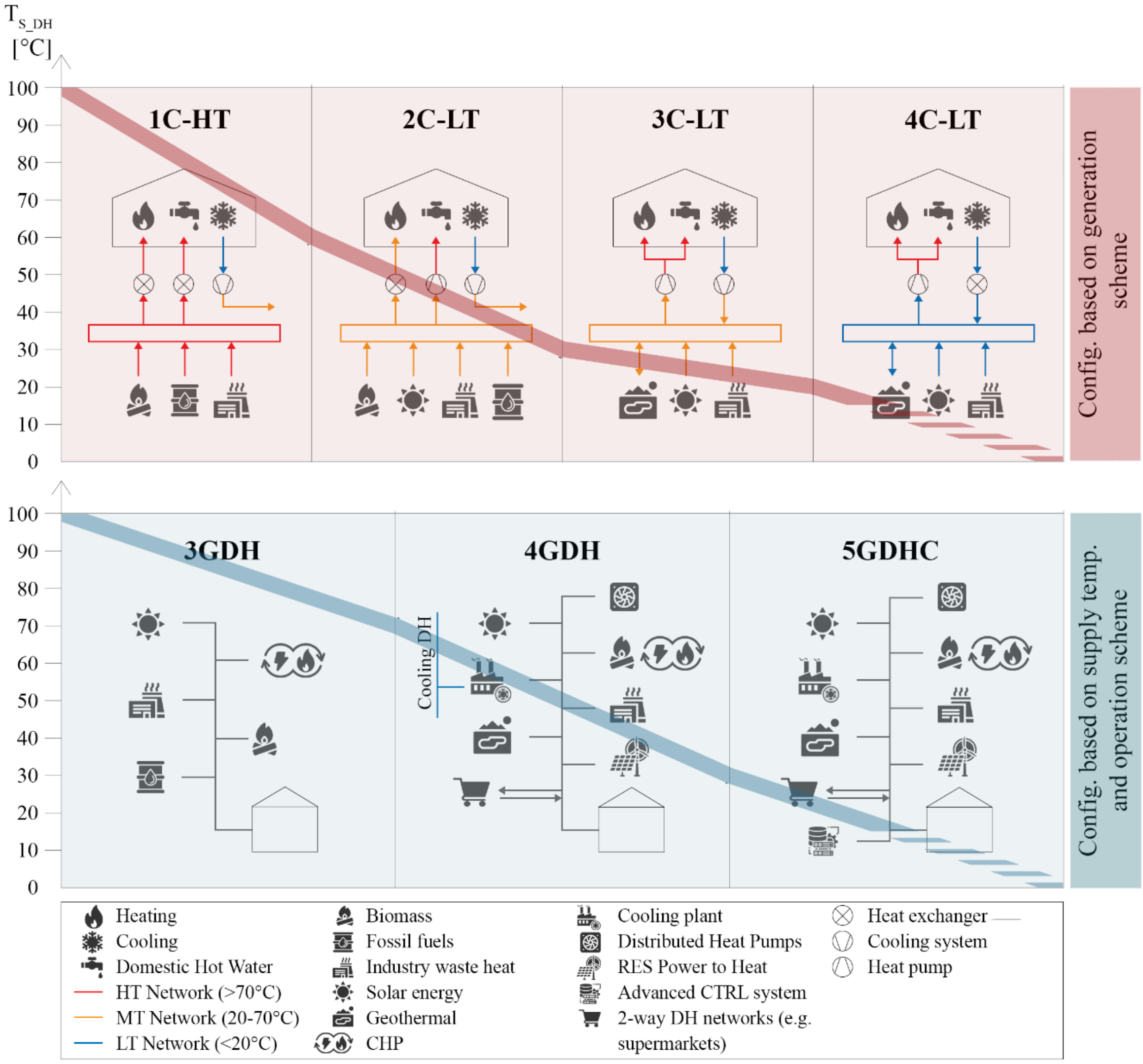

Figure 4. Comparison of the two classification methods in terms of technological configuration (boxes behind the graph area) and network operative temperatures (ordinate axis on the left). Red shaded objects refer to the classification based on supply temperature and operation scheme, while

[5] For space reasons, only thermal energy is reported; the electricity input to HP is not represented.

blue shaded objects refer to the classification based on generation scheme (arrows in red, orange and blue means heat provided to or extracted from the buildings).

3. Results

An overview of the state of the art of the Italian and Swiss DTS is presented based on [3, 9, 10, 31, 11] and on other technical reports published by DH institutions in Italy ([32]; [8]) and in Switzerland [27], [33] and [14]. It is possible to summarise that in Italy:

- most of the systems can be classified as high temperature DH;
- some interesting cases of low/ultra-low temperature are available;
- currently these last represent, in number, the 2% of the total, but there is a growing interest in this field;

while in Switzerland:

- one thousand DTS are spread within a small territory; most of the systems have very small sizes, in half of the cases with thermal power lower than 1 MW_{th};
- supply temperatures are not officially available, but an estimation is possible based on the technical features of the systems;
- it is possible to argue that 97% in number are high temperature systems, while 3% in number are low/ultra-low temperature systems and, also in this case, there is a growing interest for these last cases.

The penetration of DTS in the analysed areas is reported in Figure 5 that, for both the countries, reports the dimensions and geographic positions, the distributions of the systems in the different cantons and regions and the comparison between the densities of distribution.

The two national operative contexts are deepened with the available details in section 3.1 and 3.2, respectively. An attempt of classification is presented in sections 3.1.1 and 3.2.1 and a focus on LT-DTS is reported in section 3.3.

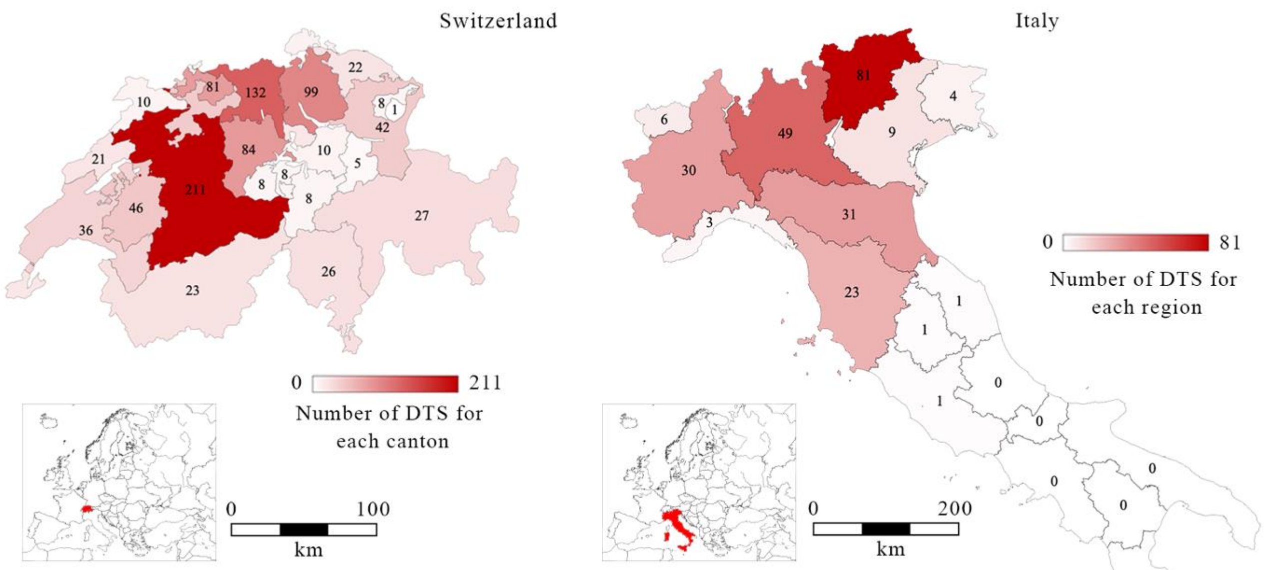

Figure 5. Geographical distribution of DTS in Switzerland and Italy, grouped by Cantons (CH) and Regions (IT). Elaboration based on [14] for Switzerland and [8] for Italy.

3.1. DTS in Italy

Italy is a country of 301,338 km^2; approximately, half territory is characterized by cold winter (more than 2,100 degree-days), while one third is covered by forests. Heating and cooling are dominated by individual solutions, mainly based on natural gas and electricity, respectively. According to [8], 368 DH networks[6] were in operation in 2018 with a total length of the networks of 4,446 km and a total heated volume of 350 million m^3. The most part of them are fuelled by fossil fuels, even if about the 27% of them are fuelled by wood biomass and adopt hot water as carrier (on average: 90°C supply and 60°C return). These systems are mainly operating in northern Italy (120,260 km^2), especially in mountain areas, due to the cold climatic conditions. However, few plants are also operating in the central part of Italy, especially in Tuscany (22,985 km^2), due to the large availability of geothermal heat. Regions in central/south part of Italy could be promising for the opportunity of providing cooling services during summer.

Moreover, it can be underlined that 198 Italian cities are served by DH networks. Among these, the cities of Brescia, Milan and Turin currently represent 42 % of the total national DH, managed under public-private partnerships.

Stakeholders involved in DH admit that it is generally perceived as a rather old and inefficient technology and that there is a great potential for improving DTS, including also cooling purposes.

DH operation takes place in a highly competitive environment where the choice of heat supplier is principally based on prices. The main alternative to DH is the use of natural gas boilers (or oil boilers in the few areas not yet reached by the natural gas grid), which dominate the heating market. There are no many national incentives to DH and DC, e.g. there are no specific investment grants for DH, despite the long payback time of these systems (above 20 years). Until 2016, district heating and cooling (DHC) projects were supported by white certificates (corresponding to the primary energy saved), but this support scheme has recently been changed and in some cases the incentive has been significantly reduced. As minor support, a reduced Value Added Tax (VAT) is applied to heat sales to residential users supplied with RES or Combined Heat and Power (CHP) and other minor mechanisms are available for particular cases (biomass, geothermal, cogeneration and micro-systems). The effects of the national and regional supporting mechanisms can be perceived in Figure 6, where the number of DTS per year and the cumulative number are represented. The figure describes only DTS of which start-up year information were available (i.e. 245 on 368) and evidences a rapid growth during the period 2000-2016 and a decreasing interest in this technology in recent years.

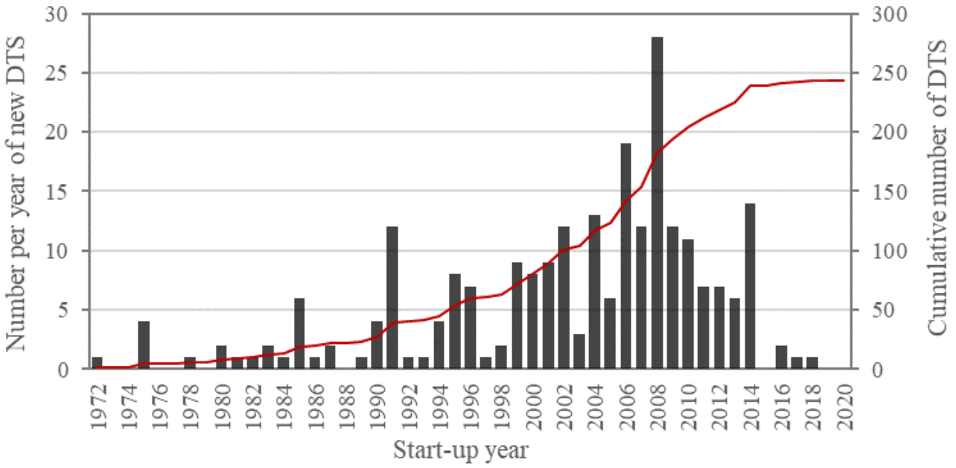

Figure 6. Number of Italian municipalities with DTS per year and as cumulative result (elaboration based on [8])

[6] Of these 368 DTS, for 239 cases there are available information while for 129 there are very few information.

According to [8], DTS in Italy provide Space Heating (SH) and DHW (9,289 GWh and 11.8 GW of installed thermal power) and SC (131 GWh). This last corresponds to a total installed capacity of 205 MW and is provided for the 70% by compression chillers and for the 30% by absorption chillers that are mainly located in substation rather than in the central plant.
The average size of the plant is quite small, as reported by [34], which, based on the involved operators, figures that 54% of the plants have an installed thermal power lower than 6 MW, 31 % from 6 to 50 MW and only 16% over 50 MW. Indeed, this is in accordance to the fact that 64% of the cities with DTS has a population with less than 10,000 inhabitants [35].
Regard the adopted energy sources, natural gas, waste to energy and biomass represent the most diffuse options, while waste heat, geothermal heat and other thermal RES are still marginal. This is described in Figure 7, where primary energies adopted in 2018 are reported, underlining that only one fourth are renewables.

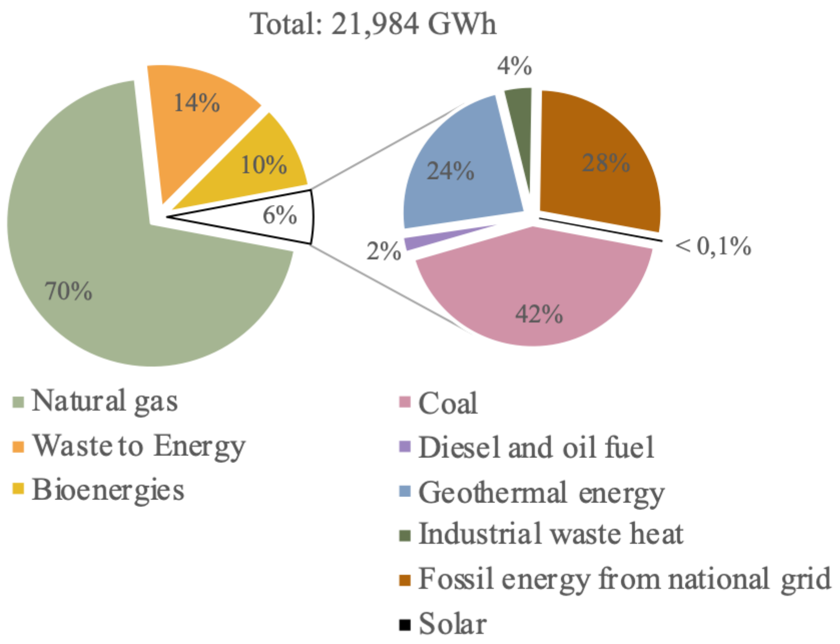

Figure 7. Primary energy sources used in the Italian DTS, elaboration from [8]

Referring to the operative conditions, 66% of the plants work in cogeneration mainly fuelled by fossil fuels, while the rest provide only heat. The diffusion of HP (both large scale in the thermal station or distributed at buildings side) is still marginal in Italy, while a consolidation of the geothermal plants is experienced in 2018 [8].
Data of [8] and dated end 2018 were elaborated; the most important figures are summarized in Table 1.

Table 1. Summary of the figures of the Italian DTS

Number of cities with DTS	198	-
Number of DTS owners	148	-
Number of DTS with available information	239	-
Total length of networks	4,446	km
Number of Substations	82,853	-
Number of DTS using as heat carrier:		
Hot water (<100°C)	198	-
Pressurized hot water (> 100°C)	35	-

Steam	6	-
Overall heated volume	358	Mm^3
Overall cooled volume	9	Mm^3
Installed thermal power	8,908	MW_{th}
Installed electric power (CHP)	885	MW_{el}
Installed thermal power (CHP)	2,871	MW_{th}
Thermal energy sold to users	9,289	GWh_{th}
from RES	25	%
from fossil fuels CHP	51	%
direct production from fossil fuels	24	%
Estimated thermal losses along the networks	20	%
Cooling energy sold to users	130.8	GWh_{th}
Electricity sold to the national electric network	5,945	GWh_{el}

3.1.1. *Evolutive stage of DTS in Italy and attempt of classification*

In Figure 8 the supply temperature is compared to the age of each system. Starting from the total of 368 systems, supply temperature was available only for 188 cases[7].

The first attempt of classification according to data availability follows the generation approach. Within the analysed Italian dataset, 6 examples of 1GDH are listed, but very few data were available for them (only for 3 of them, operative temperature were available). These plant use steam as heat carriers and are mainly fuelled by geothermal energy at high temperature, diffused practice in Tuscany, in central Italy. 2GDH networks, operating with pressurized hot water at an average supply temperature of 120 °C, represent the 24% of the sample. The 3GDH ones instead, supply hot water averagely around 85-90 °C and amount to the 70% of the total. 4GDH and 5GDHC are very few (6 plants), small size and not systematically documented in the available national databases.

Despite the limits related to lack of information, a first consideration is that the chronological evolution of DTS foreseen by the classification based on generation does not match the one observed in Italy (Figure 8). Indeed, even the most recent DTS, besides few examples, are still identified as 2GDH-3GDH according to this approach.

If the approach based on supply temperature and operational scheme is applied, it is possible to note that the almost part of the Italian DTS are high temperature (HT, i.e. supply temperature > 60°C). Heat is generated in the thermal station and supplied through the network; heat exchangers for space heating and DHW are integrated at users' side. Heat flow is unidirectional even if different energy sources are adopted (e.g. wood biomass and natural gas combusted in two separate thermal stations). Further insights related to the 4GDH and 5GDHC cases will be provided in section 3.3.

[7] From the initial dataset, the supply temperature information was available for 188 plants. In 22 cases more than one network with different distribution temperature is connected to one thermal station and may appear in the graph with different dots.

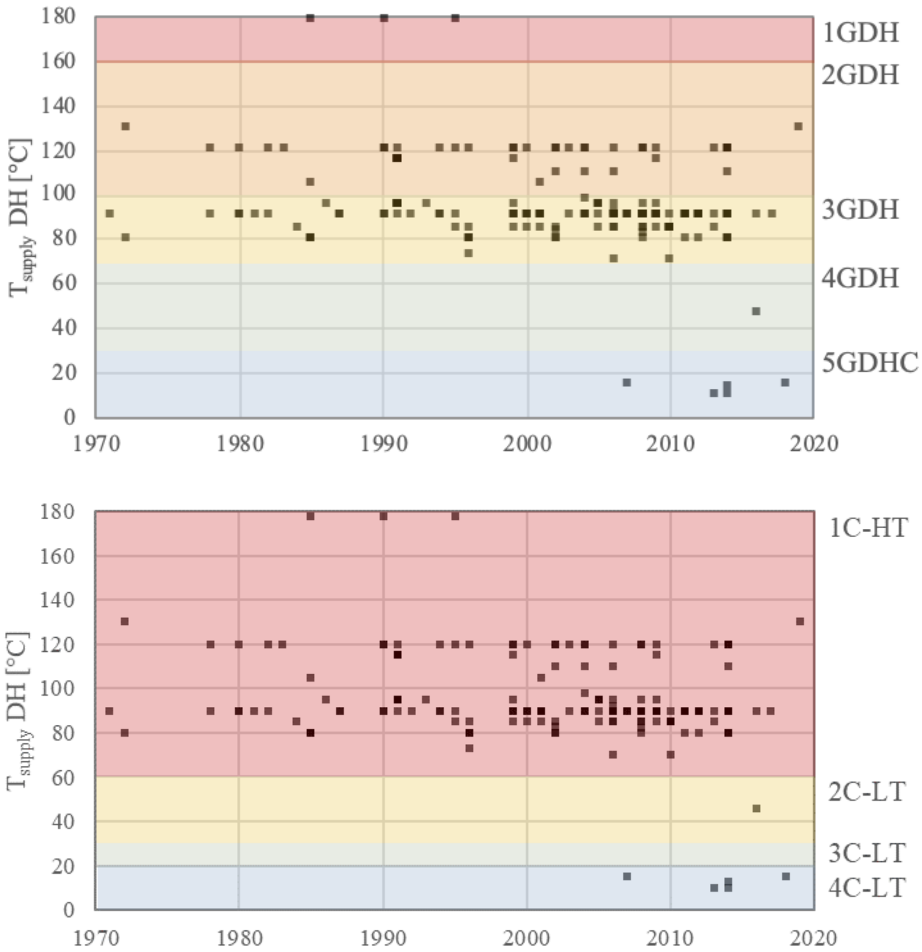

Figure 8. Distribution of the Italian DTS according to the two different classification approaches

3.2. DTS in Switzerland

As anticipated, space heating in Switzerland is reliant on oil (42%) and natural gas (26%), therefore decarbonizing the Swiss heating supply is fundamental for reaching the defined targets for the next future.

The Swiss Energy Strategy 2050 [36] sets out the objectives for future energy supply: an end to nuclear power and a significant reduction in CO_2 emissions. It has been estimated that up to 40% of the thermal needs (SH and DHW) could be satisfied by thermal networks (high and low temperature), also considering the buildings renovation rate and the consequence reduction of the heating needs [33]. Of course, these estimations and goals must be verified in the local territorial conditions.

The Swiss territory amounts to 41,285 km^2, most of them occupied by mountains, forests and lakes. However, according to the official Swiss dataset [14], containing energy data of the national DTS sector, a set of 1,010 DH networks were in operation in 2018.

Figure 9 shows the annual grow of DTS in Switzerland with the limit that the first year of operation is available only in the 80% of the plants surveyed. A first increase can be clearly seen from the early 1990s onwards, a second one in the first decade of 2000 and a third in recent years, demonstrating a growing interest in this technology. E.g. the number of DTS has more than doubled in the last 10 years.

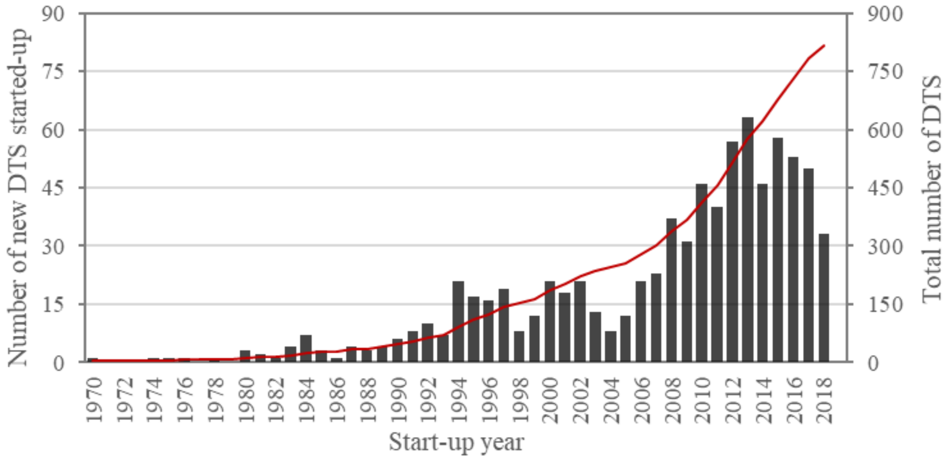

Figure 9. Number of Swiss DHS plants, cumulative data. Elaboration based on [14].

According to the definition of DH in force in Switzerland[8] and to data available in [14], thermal power information is sufficiently complete only for 852 of the total. Generally Swiss DTS have very small sizes; in fact, half of them have thermal powers lower than 1 MW (Table 2). This is a peculiar case characterized by small plants densely distributed over a quite sparsely populated territory.

Table 2. Swiss DTS with available data grouped by thermal power

Lower than 0.5 MW	0.5-1 MW	1-5 MW	5-10 MW	Higher than 10 MW	Total
265	157	303	65	62	852
31%	18%	36%	8%	7%	100%

In terms of number of DTS, the 66% are fuelled by wood biomass, the 11% are based on Ground Source HP (GSHP), the 7% take heat from waste to energy, the 6% are fuelled by natural gas and the remain part relies on a set sources with negligible contribution.

In terms of energy sources adopted the situation is different, because waste to energy and bioenergies represent the most part of the total (Figure 10).

[8] Thermal grid is defined as a grid adopted for providing DH by means of a carrier for direct or indirect use of heat in buildings. Heat supplier and heat receiver (final users; at least one) have to be separated and connected by the grid. Thermal losses are expected along the grid, depending on the operative conditions.

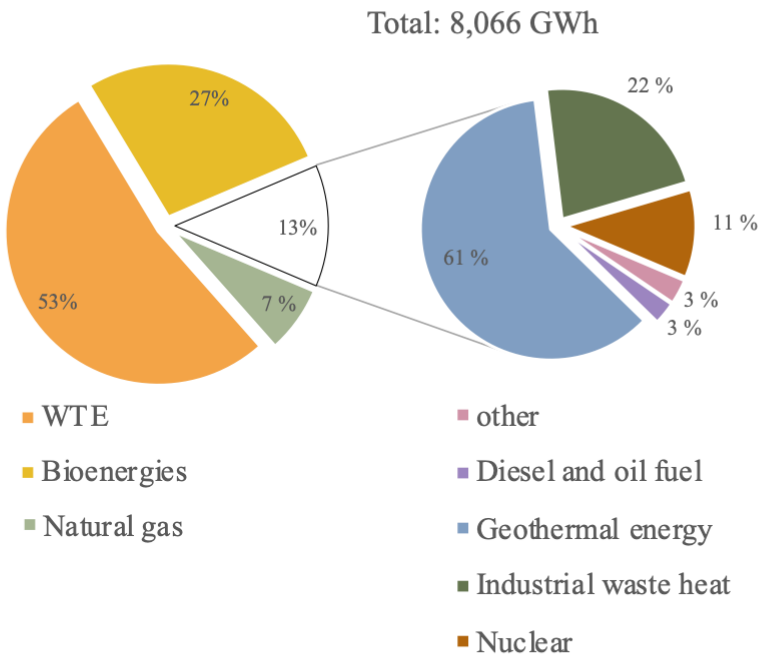

Figure 10. Energy sources used in the Swiss DTS; percentages based on heat sold to final users; elaborations from [14][9]

3.2.1. Evolutive stage of DTS in Switzerland and attempt of classification

Recently, in Swiss neighbourhoods and small towns, DH has increasingly moved towards DTS fuelled by bioenergies that currently allow providing the 27% of the total heat supplied (Figure 10). On the other hand, Switzerland is following a parallel technological evolution that is the installation of HP connected to an *anergy* network distributed throughout the territory. This trend is potentially applicable also in other countries like Italy, where however, due to a series of barriers (recent experience in the field of HP, different energy policy, well established infrastructure and market for natural gas etc.), it has developed in a very limited way.

The Swiss databases report many information about geographic coordinates, energy sources, owners, installed power, etc. However, no data about supply temperature and technologic components users' side are available, making any attempt of classification unsuccessful. Nevertheless, considering the adopted energy sources and the typical conversion technologies available for their conversion, it is possible to argue that about the 90% of DTS are high temperature (HT, i.e. supply temperature > 60°C).

Based on these assumptions, a first attempt of classification according to the generation approach has been developed, revealing that there are no cases of 1GDH, while there are few cases of 2GDH and 4GDH, a few dozen are 5GDHC and the most part of the DTS in operation belong to 3GDH.

Also in this case, the chronological evolution of DTS foreseen by this method of classification does not match the one observed in Swiss (Figure 11), except the few dozen of 5GDHC installed in recent years.

If the approach based on supply temperature and operational scheme is applied, it is possible to note that also in Switzerland the almost part of the DTS are HT, but there is a representative set of LT DTS belonging to the three subclasses 1C, 2C and 3C; further insights will be discussed in section 3.3 since the authors have deeply analysed this set of DTS.

[9] Data about adopted primary energy are not available for each DTS. In case of lack of data, the installed thermal power has been considered and multiplied by a realistic number of equivalent hours of operation in a year (an average value of 2000 hours has been assumed).

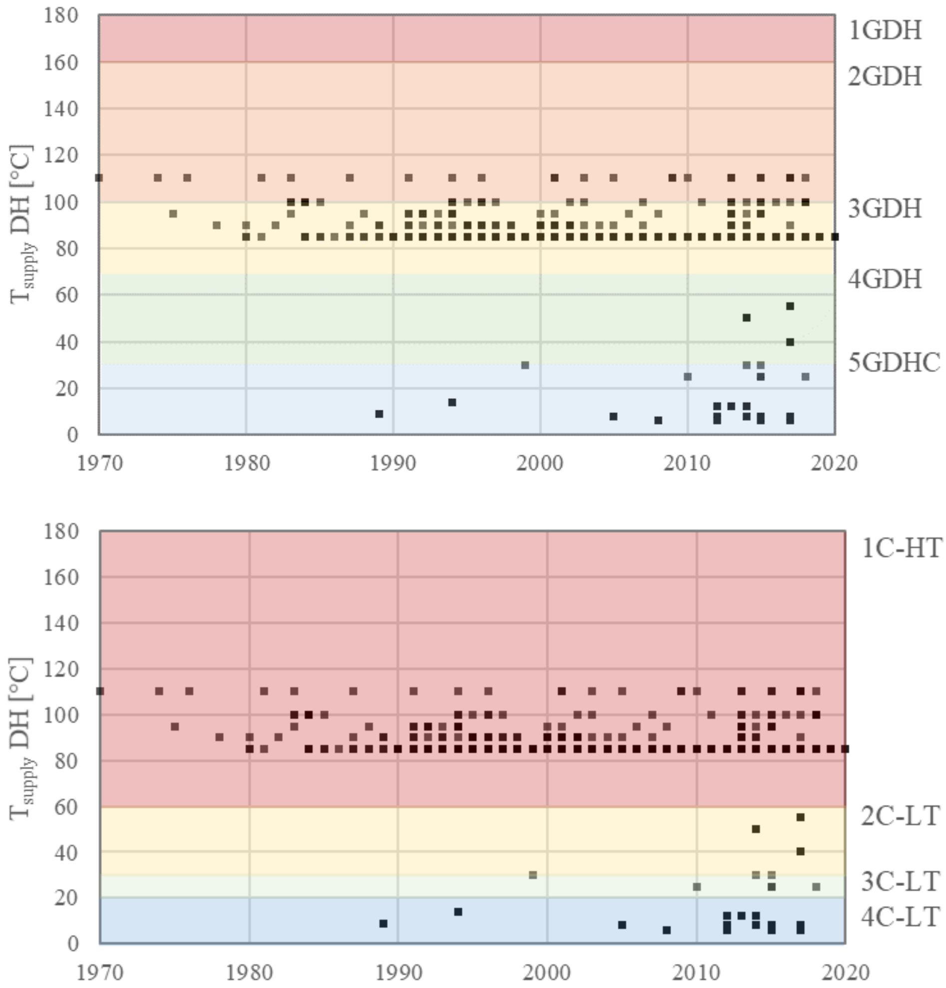

Figure 11. Distribution of the Swiss DTS according to the two different classification approaches (temperature based on estimations by the authors)

3.3. Selection of low temperature case studies and synoptic classification

After a desk research by specific keywords in the Scopus database, taking into account the expertise of the authors and their participation in trade associations, working groups and research programs, the available and documented case studies of innovative DTS in Italy and Switzerland, i.e. 5GDHC generation or low/ultra-low temperature, are described and classified in the following.

The low temperature Italian systems are almost recent and, despite few cases, they are representative of different operating conditions. Generally, these systems are small size, with a short network, located in flat lands and with moderate climatic conditions (in locations with 2100-2500 heating degree-days except one case).

For example, they use different environmental sources such as groundwater, geothermal, waste heat and seawater. Supply side, four cases can be classified as low temperature systems, while the other two as ultra-low temperature systems. User side, temperature can be low, high or mixed, depending on the cases, but the most part operate at high temperature, demonstrating the possibility to connect also old and/or building with low energy performance to this type of systems. Users can be public or private buildings and final uses can be space heating or heating and DHW or heating and cooling, depending on the situation. The main features are summarised in Table 3. In the case of Sale Marasino (1), in operation since 2014, a thermal annual energy need of 277 MWh is ensured by means of a groundwater loop coupled with HP at building level (300 kW_{th} installed) that allow, in winter,

supplying final users (a school and a library) with high temperature water. In summer SC is also provided.
In the case of Ospitaletto (2), in operation since 2018, 2090 MWh of annual energy needs are covered with a 1.6 MW Heat Exchanger (HX) for waste heat recovering by a local industry and a 1.2 MW ground water HX. A heat distribution network of 2.5 km is then coupled with HP at building level and allows, in winter, to provide high and low (70°C and 45°C) temperature water to final users (schools, sport centre and households) for SH.
In the case of Grado (3)[10], in operation since 2016 after a long-lasting project and implementation, by means of borehole heat exchangers, hot water is distributed in the thermal network of 2 km coupled with HP and HX at building level, supplying final users (schools, sport centre, households and auditorium) with high temperatures water for SH.
The case of Porto Piccolo - Sistiana (4), in operation since 2014, is very interesting because adopts sea water as heat source for providing SH and SC in big residential buildings, with a thermal power of 5.8 MW. 20 HP are located at building level providing warm water for SH at 40°C and chilled water for SC at 7°C, while the network (3 km of length) has a ring operating between 8 °C in winter and 30°C in summer. The temperature levels, the source and the concept of the system, in which space cooling for holyday buildings is the main purpose, make this case a clear example of 5GDHC.
Also the case of Savona – Torre Orsero (5), in operation since 2007, adopt sea water as heat source for providing SH and SC in households with an installed thermal power of 5.8 MW. The sea water loop is connected by a HX to a technical water one. The thermal station includes also two backup condensing boilers fuelled by natural gas and HP at building level. In this way all the buildings are equipped for SH, DHW and SC.
Also the case of Venezia (6), in operation since 2013, adopt the water of "Laguna di Venezia" as heat source for providing heating and cooling in households. A thermal station equipped with a 9 MWth HX and fossil backup boilers connects the sea water loop with the technical water one (about 0.8 km long). The latter supplies water at 15 °C in winter and 25 °C in summer to each building's substation by means of HP (5 MW_{th} installed in total). The system provides DHW, SC and SH to 530,000 m^3 of industrial and office users for a total of 210 MWh_{th} annual energy needs. The configuration of the system, the low variability of sea water temperature and the availability of LT heat emission subsystem ensure high energy performances.
Another interesting case, still in the design stage and therefore not included in Table 3, regards the development of a new nearly zero energy settlement near Milan equipped by a LT-DTS fuelled by a small size biomass CHP system and Ground Water HP (GWHP) at building level coupled with building integrated Photovoltaic (PV) systems [37].
As anticipated, the Swiss database [14] does not include the level of the temperature but provides precise information about the energy source adopted. For this reason, a consequent method has been followed: the sources compatible with LT-DTS have been selected (i.e. geothermal, lake water, groundwater, waste heat including tunnels), finding 84 DTS in the mentioned database. Among these, some systems are actually LT, while the others are equipped by a central HP in the thermal station and a HT district network. Based on the expertise of the involved authors, 25 DTS have been selected due to the possibility of finding reliable information. To that end, a challenging phase of collection, comparison and elaboration of the available data set has been accomplished. In addition to the technical literature (e.g. [25]; [28]), the association for the enhancement of the energy produced by waste water, wastes, residual heat and drinking water[11] and the association for promoting geothermal

[10] Information provided by the engineering office, www.simming.it
[11] www.infrawatt.ch

energy[12] have been consulted together with information available at proper web sites[13] and consequently investigated.

The final set of LT DTS represents an impressive number compared to the dimension of the territory. A distribution of the set (25 DTS) according to the adopted energy sources is reported in Figure 12, where the spread of systems based on lakes and ground is evident.

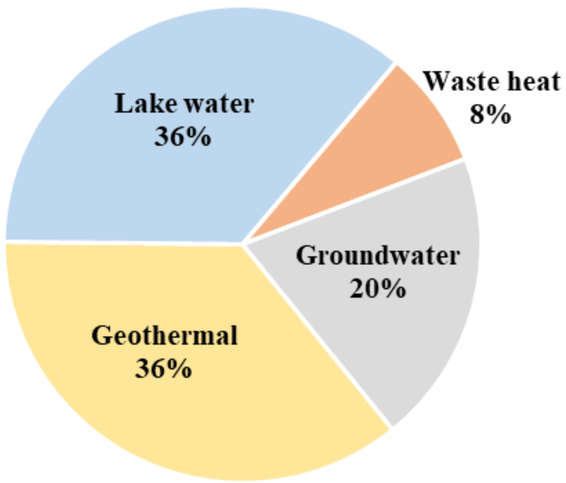

Figure 12. Swiss LT-DTS according to the selected cases (percentages refer to total 25 selected cases)

[12] geothermie-schweiz.ch/

[13] www.frauchiger.be/stadtrat/anergienetz/; www.lsta.lt/files/events/20160418EHPkonfer/Pranesimai/Stadtekongress/T.Gautschi.pdf; www.hevs.ch/media/document/2/lauberiwisa_simonsummermatter-1.pdf; www.svizzeraenergia.ch/page/it-ch/reti-termiche

Table 3. Low temperature DTS case studies in Italy

General				**Generation subsystem**			**Distribution subsystem**			**Users side**											**Classification**		**Ref.**
n.	Country	Degree Days	Start-up	Technology		Heat source	T_s heating	T_s cooling	Length	Typology	Technology	Pth	sCOP	sEER	Temp. Level	Heated/cooled volume	Energy needs	H	C	DHW			
-		k day	year	-	MWh_{th}	-	°C	°C	km	-	-	MWh_{th}	-	-	-	m^3	MWh_{th}	-	-	-	-	-	-
1	IT	2,497	2014			GW	13	17	0.1	SCH	HTHP	0.3	5	*n/a*	Mixed	*n/a*	277.1	●	●	●	5GDHC	4C-LT	[25,38,39]
2	IT	2,446	2018	HX	1.2; 1.6	GW; LTWH	15		2.5	SCH; GYM; RES	LTHP and HTHP	2	4.1		HT	80,000	2,090	●		●	5GDHC	4C-LT	[25,40]
3	IT	2,239	2016	DBHE	3	GEO	46		2	SCH; GYM; THT	HX and HTHP	*n/a*	*n/a*		HT	*n/a*	*n/a*	●			4GDH	2C-LT	[41]
4	IT	2,102	2014	HX	5.8	SW	10	25	*n/a*	RES; COM; HOS; REST	HX	*n/a*	4.7	*n/a*	LT	200,000	*n/a*	●	●		5GDHC	4C-LT	[42,25]
5	IT	1,481	2007	HX	4.8	SW	15	25	*n/a*	RES; COM; HOS	HTHP	7.4	*n/a*	*n/a*	HT	67,424	*n/a*	●	●	●	5GDHC	4C-LT	[43,44]
6	IT	2,345	2013	HX	5	SW (lagoon); FOS	15	25	0.8	IND; OFF	HTHP	6	5	6	LT	530,000	210	●	●	●	5GDHC	4C-LT	[25,45]

Legenda: Ts: Supply temperature in the distribution network; HT: High Temperature; LT: Low Temperature; sCOP: HP seasonal Coefficient of Performance; sEER: HP seasonal Energy Efficiency Ratio; H: Heating; C: Cooling; DHW: Domestic Hot Water; HX: Heat Exchanger; DBHE: Deep Borehole heat exchanger; GW: Ground Water; LTWT: LT Waste Heat (industries); GEO: Geothermal; SW: Sea Water; FOS: Fossil Fuels; SCH: Schools; GYM: Gyms; RES: Residential; THT: Theatres, auditoriums; COM: Commercial; HOS: Hospitality (Hotels, etc.); REST: Restaurants; IND: Industrial; OFF: Offices; HP: Heat Pump.

Further comments to the Swiss LT DTS are reported in [28]. The primary energies adopted in the LT-DTS sample analysed mainly consist in low-temperature renewable sources (waste heat from laboratories and data centres, environmental heat from geothermal plants, ground water and lakes). The exploitation of such renewable sources has been made possible by to the adoption of novel GSHP that, after a rapid technological development, is currently a mature technology and a promising opportunity for coupling ground water, sea water and geothermal heat with DTS [46].
Within the sample, the network topologies of DTS differ from case to case: the conventional network topology with a central source, a main circulation pump and throttling valves at each transfer; networks topology with distributed circulation pumps that increased thermal efficiency by minimizing mixing losses and are bidirectional. The most part of the cases can be classified as 5GDHC or ultra-low temperature while only 2 cases can be classified as 4GDH (18 and 21 in Table 4). It is evident that the approach based on supply temperature and operational scheme allows a more refined classification for LT cases (e.g. cases 13, 18, and 21 in Table 4).

Table 4. Low temperature DTS case studies in Switzerland

Generation			**Distribution subsystem**				**User side**					**Classification**	
n.	Start-up	Technology	Heat source	T_s heating	T_s cooling	Length		Technology	H	C	DHW		
-	year	-	-	°C	°C	km	MWth		-	-	-		
1	2012	BHE	GEO	8	18	1.5	8.0	HTHP and HX	•	•	•	5GDHC	4C-LT
2	1989	HX	LW		9	4	n.a.	HX and HP		•		5GDHC	4C-LT
3	2012	HX	GW	12	16	n.a.	1.3	HTHP and HX	•	•	•	5GDHC	4C-LT
4	2013	HX	GW	12	16	n.a.	n.a.	HTHP and HX	•	•	•	5GDHC	4C-LT
5	2013	HX	GW	12	16	4.2	3.5	HTHP and HX	•	•	•	5GDHC	4C-LT
6	2015	BHE	GEO	8	18	0.4	n.a.	HTHP and HX	•	•	•	5GDHC	4C-LT
7	2014	BHE	GEO	8	18	1.5	n.a.	HTHP and HX	•	•	•	5GDHC	4C-LT
8	2008	HX	LW	6	12	6	3.5	HTHP and HX	•	•	•	5GDHC	4C-LT
9	2017	HX	LW	6	12	n.a.	3.6	HTHP and HX	•	•	•	5GDHC	4C-LT
10	2005	HX	LTWT	8		3.7	1.9	HTHP	•		•	5GDHC	4C-LT
11	2014	HX	GW	12		n.a.	0.2	HTHP	•		•	5GDHC	4C-LT
12	1994	TU	GEO	14		2.2	n.a.	HTHP	•		•	5GDHC	4C-LT
13	2017	mixed	GEO-W-S	40	5	n.a.	n.a.	mixed	•	•	•	5GDHC	3C-LT
14	2017	BHE	GEO	8	18	n.a.	1.6	HTHP and HX	•	•	•	5GDHC	4C-LT
15	2012	HX	GW	12	12	0.85	2.0	HTHP and HX	•	•	•	5GDHC	4C-LT
16	2012	BHE	GEO	8	18	2.5	6.7	HTHP and HX	•	•	•	5GDHC	4C-LT

17	2015	HX	LW	6	12	7	8.9	HTHP and HX	●	●	●	5GDHC	4C-LT
18	2014	BHE	GEO	35 - 65		n.a.	0.3	HX	●		●	4GDH / 5GDHC	1C-HT / 2C-LT
19	2013	HX	LTWT	12	16	0.48	n.a.	HTHP and HX	●	●	●	5GDHC	4C-LT
20	2014	BHE	GEO	8	18	n.a.	2.5	HTHP and HX	●	●	●	5GDHC	4C-LT
21	2017	HX	LW	50 - 70		n.a.	2.5	HTHP and HX	●		●	4GDH	2C-LT
22	2012	HX	LW	6	12	5	16.0	HTHP and HX	●	●	●	5GDHC	4C-LT
23	2015	HX	LW	6	12	n.a.	5.5	HTHP and HX	●	●	●	5GDHC	4C-LT
24	2017	HX	LW	6	12	n.a.	20.0	HTHP and HX	●	●	●	5GDHC	4C-LT
25	2008	HX	LW	6	12	n.a.	3.0	HTHP and HX	●	●	●	5GDHC	4C-LT

Legenda: Ts: Supply temperature in the distribution network; HT: High Temperature; LT: Low Temperature; H: Heating; C: Cooling; DHW: Domestic Hot Water; HX: Heat Exchanger; BHE: Borehole heat exchangers; GW: Ground Water; LTWT: LT Waste Heat (industries); GEO: Geothermal; LW: Lake Water; HP: Heat Pump.

The Italian and Swiss cases analyzed above are reported in Figure 13 where the labels are referred to the suggested classes according to the two approaches considered.

It is evident that the most part of the systems are 5GDHC or 4C, due to the congruence between these two classes. The 4GDH class, which can coincide with the class 2C or 3C, is very rare in the analyzed territory, meaning that in the last years DTS are evolving from the 3GDH or HT DTS to 5GDHC or ultra-LT DTS, skipping intermediate configurations. The technical components, used side, are HP and HX in order to make possible every type of energy end-use.

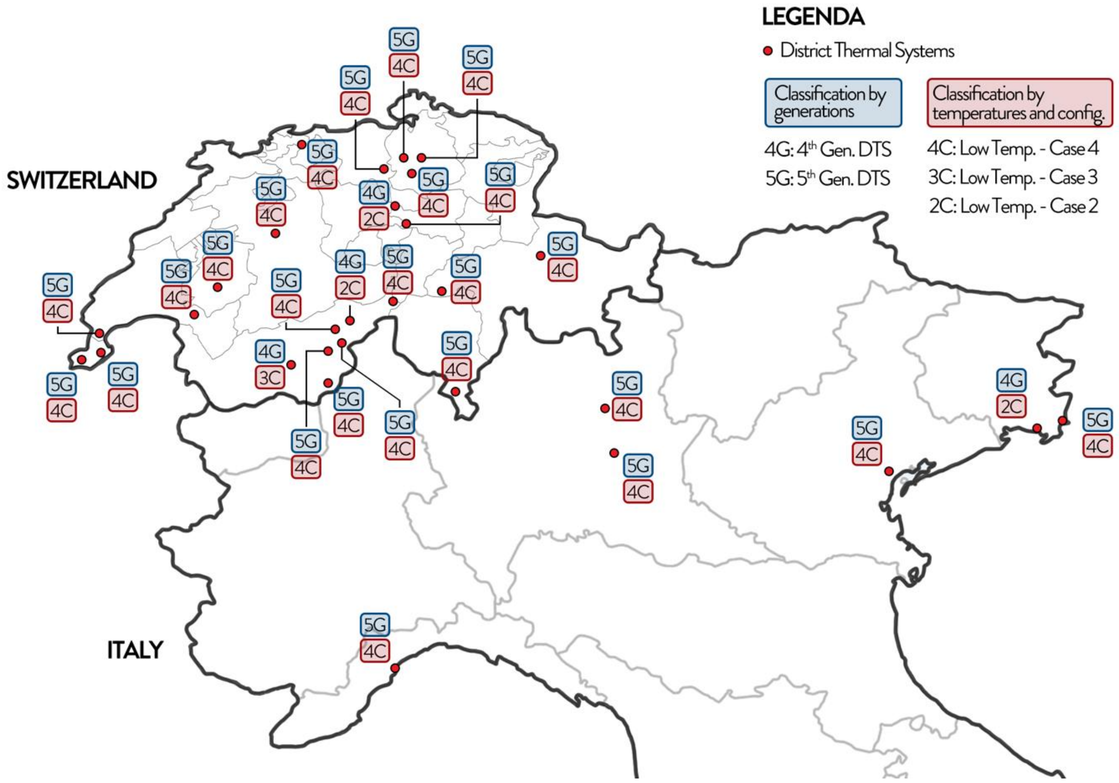

Figure 13. Distribution of the Italian and Swiss LT-DTS and proposal of classification

4. Discussion and possible evolution for DTS

Many issues and figures are reported in the previous sections, therefore a recap and discussion is needed.
The state of the art of DTS is summarised in Table 5, where similar and different operative conditions are underlined. In Italy DH has an older history and is still low efficient and based on fossil fuels. The overall system appears more inertial and less inclined to a radical evolution. In Switzerland DH is more recent and mainly based on heat locally available, be it from waste to energy plants or from lakes and ground. DTS are really small size, compatible to the exploitation of local sources in small and often low-dense areas.

Table 5. Comparison of the state of the art of DTS in Italy and Switzerland

	Parameter	Italy	Switzerland
A	Territorial dimension, km^2	301,338 (*)	41,285
B	Total number of DTS	368	1,010
C	Primary energy for DTS, GWh	21,984	n.a
D	Of which fossil energy	72%	7% (**)
E	Of which heat from Waste to Energy	7%	53% (**)
F	Specific primary energy, MWh/km^2 (C/A)	183	195
G	Mean installed thermal power, MW (C/(B×eq. hours))	30	4
H	Peculiarities	2GDH and 3GDH prevail; Few recent 5GDHC with information difficult to be collected; Energy from lakes and ground available but scarcely exploited; Presence of metropolitan areas high-density populated	3GDH prevail; Recent evident spread of 5GDHC with information available even if consulting different database; Energy from lakes and ground available and exploited; Few and small metropolitan areas high-density populated

(*) most part in northern regions (120,260 km^2) and Tuscany (22,985 km^2).
(**) based on 8,066 GWh per year of heat sold to users.

DTS have been analysed referring to two complementary classifications, underlining that the one based on generation allows a more detailed analysis about older systems (1GDH, 2GDH and 3GDH instead of the only 1C-HT class), while the one based on supply temperature and operational scheme allows a more detailed analysis about most recent systems (2C-LT, 3C-LT and 3C-LT instead of 4GDH and 5GDHC). Therefore, the first scheme can support the analysis of the most part of the existing cases for defining their future scenarios of operation, while the second ones can support the technical feasibility of those scenarios with particular regard to the relation with the users/prosumers. Dealing with feasibility, economic barriers have to be considered. A barrier that regard all the classes of DTS is the involvement of final user in order to increase their willingness to be connected. Indeed, the obligation to sign binding and long-lasting contracts in advance is an obstacle not only for the final users, but also for other stakeholders that could finally renounce to the initiative. In this context, to make mandatory the connection of public buildings could be an important help for the investors and an example to be emulated. Moreover, considering the barrier of high investments, a great help can be to have precise and flexible economic and energy models, in addition to economic support by central and local governments. About investments, the payback time should be considered not *per se*, but in comparison to the lifetime of buildings and components of the system. However, a payback time of 10-15 years can be very disheartening and unaffordable for the investors involved in a DTS project [47]; therefore, supporting mechanisms should promote technologies and sources otherwise not economically interesting. As evolution, innovative LT-DTS may bring new billing challenges, which go far beyond the simple sale of heat to final users. In fact, the presence of different components and energy carriers, the possibility to become also suppliers (in power to heat configuration), the balancing of the electric and thermal needs open new opportunities that can bring also economic benefits, on the long term. For example, in the case ground source heat pumps, a reduction of the number of probes regenerating the soil can imply a reduction of the initial investment as also the possibility to experiment cooling and free-cooling. Economic barriers are also connected to the political ones. Political instability, in particular changes in legislative conditions or incentives, should be faced and can be a strong barrier for all the involved stakeholders. E.g., considering the two national contexts explored, from Table 5 it is possible to argue that in Switzerland there is a more robust energy policy, while in Italy the economic and regulative instability and the bureaucratic complexity are strong brakes to the spread of DTS.

Moreover, to plan the evolution of DTS implies the need of a deep knowledge of the current state of the art. Considering the efforts carried out for data collection and elaboration, the need to improve the knowledge about the existing cases emerges. In addition, new dedicated tools are needed mapping of the territory, its thermal demand evolution, identifying quickly particularly interesting areas where to concentrate possible studies and financial investments. The more detailed this mapping is, the more it is able to favour small and neighbourhood systems.

Despite the barriers above mentioned, several drivers that can be activated to facilitate the evolution of HT DTS to LT DTS, both for new plants and for extensions and expansion of existing ones, as well as for the transformation and optimization of old plants. The goals about renewable sources for thermal uses in addition to energy retrofit measures represent an effective driver. LT DTS (in particular 4C-LT DTS) could be equipped also in order to satisfy the ever-increasing cooling purposes and network systems, if properly managed, can make the distribution and exploitation of renewable energy sources more efficient. According to [48], MES can be promising in low-temperature DTS, where prosumers participation is facilitated through a double loop heat pipe configuration, allowing consumers to be both buyers and sellers of heat. In addition, the use of renewable energy generation and energy storage allows reducing operational costs, heat losses, energy consumption and carbon emissions. This option allows also controlling the issue of the large-scale penetration of individual domestic HP, due to their strong impact on the national or local electric grid, which could be not suitable to manage power peaks determined by thermal needs. In this context, DTS can help the balance of the overall system, considering the electric grids currently available.

Moreover, it has been learnt that all the components of the system should be perfectly integrated and controlled, i.e. HX, HP, storage and heat emitting systems in buildings, considering also the energy performance of the served buildings that influences the requested thermal power and the heat density along the grid. If radiators, coils or fan coils are the emitting systems in buildings, DTS operating at 40-50°C providing heat directly through heat exchanger (4GDH or 2C-LT) can be very critical. Conversely, the matching is less critical for DTS operating at lower temperature providing heat indirectly through HP (5GDHC or 3C-LT and 4C-LT). In fact, HP can upgrade heat to high temperatures (60-70°C), buildings side. Analogous considerations may regard DHW production because, as mentioned for the protection to Legionella, it is necessary to reach, at least occasionally, temperatures of about 65°C.

5. Conclusions and further developments

As demonstrated in the previous sections, DTS have still a small role that is expected to grow impressively to 2050 by means of the following modes:

- To connect new development areas to existing DTS;
- To connect existing areas to existing DTS;
- To develop new small size DTS for new development areas;
- To renovate existing DTS making them more efficient.

Since DTS imply big investments, it is fundamental to have a systematic frame of analysis in order to guide their evolution and penetration effectively and possibly without committing errors and waste of resources. In order to study more in details key issues of DTS, two classifications have been considered and an attempt of comparing and matching the two methods has been here presented.
The expression DTS has been here adopted, instead of DH and/or DC, indicating a system of pipe connected one side to final users (that can be also a prosumer) for each type of thermal uses and other side to available heat sources, regardless of their level of temperature, size and complexity. To that end, the possibility of managing DTS in bidirectional and unmanaged way can bring interesting opportunities.
Currently, the European debate is dealing with the 4GDH and 5GDHC. Indeed, thanks to the possibility of having a single and low temperature network both for heating and cooling, the novel concept of 5GDHC allow to improve flexibility of DTS through the optimal management of the energy fluxes. The variety and complexity of system configurations and interactions between connected customers, key difference between 4th and 5th generation, poses a challenge in modelling and integrating advanced control systems for optimizing electric and thermal energy fluxes in a DTS. Actually, few examples have been already realized integrating demand side response through advanced control systems, but progresses in this field are available in very recent contributions in the technical literature, e.g. [49], that implements a model predictive control method based on recurrent artificial neural networks to shift electricity consumption from peak-hours and [50], that show the application of a demand side response control in a 5GHDC network enabling an optimized management of electricity production-consumption, stressing also the economic benefits.
As important driver, favouring the cascade use of heat, the evolution of DTS towards LT will allow an increasing of the linear heat density[14] with a reduction of heat losses. Further, LT DTS are intrinsically characterized by lower heat losses and allow the use of cost effective non-insulated pipes.
According to [1], the following points can be cited in addition to those already discussed for supporting the evolution of DTS in the mid-term:

- To activate local governments and municipalities in the transition. Heating is a local energy demand and it is important to enable coordination between national and local levels;
- To end investment in new individual fossil fuel heating capacity such as gas boilers and instead support transition to heat pumps that can utilize renewable electricity and district heat;
- To start investigating the potential of DC, because cooling is the fastest growing thermal sector, of free-cooling and thermal storage in order to provide solutions by DTS;
- To support investments in thermal grids and multidimensional infrastructure and construction sites, that are very promising for energy transition;
- To promote a systemic approach, finding synergies between sectors and enabling the energy value chain. This means exploiting waste heat source for DTS and providing flexibility to the electric sector. Indeed, the challenging issue of sector coupling (i.e. to interconnect/integrate the different sectors of energy users, such as buildings, transport, and industry, with the power

[14] It describes the average amount of energy supplied considering the length of the network.

producing sector resulting in energy and environmental benefits [5]) can be a promising chance;

- To train the operators involved in the whole chain of DTS: investors have to be informed about opportunities and supporting mechanisms; technicians about the technical solution for improving existing thermal stations and grids and for installing innovative and flexible systems. Since operators have to design and manage new DTS that do not follow the usual and scalable management logics, it is necessary that they are supported to face innovative alternatives.

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Declaration of interests

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

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