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► To cite this version:

Rémi Patureau, Cong Toan Tran, Valentin Gavan, Pascal Stabat. The new generation of District heating & cooling networks and their potential development in France. *Energy*, 2021, 236, pp.121477. <10.1016/j.energy.2021.121477>. <hal-03381772>

HAL Id: hal-03381772

<https://hal.science/hal-03381772v1>

Submitted on 2 Aug 2023

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The New Generation of District Heating & Cooling Networks and their potential development in France

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Abstract

In order to contribute to the decarbonization of heating consumption, France has set some objectives to develop District heating and/or cooling networks (DHCN). In this context, it is useful to identify the most appropriate district areas for implementing DHCN, and to assess their potential of development.

After introducing the situation of DHCN in France, this paper presents a typology to assess the potential of development of those networks in France, based on an original method that involves the calculation of 3 variables: the linear heating/cooling density (LHD/LCD), the Proportion of Buildings anterior to 1990 and the share of energy consumption from the residential sector, to assess respectively the energy density, the supply temperatures and the energy mix between the different sectors of activities. LHD and LCD are calculated using a Delaunay triangulation and Kruskal's algorithm applied to buildings whose heating and cooling demands are calculated at a local scale.

18 different types of districts are defined for both DHN and DCN, among which 9 have a sufficient LHD/LCD. Then, the potential of development for DHN and DCN is calculated on the French territory. Thus, the DHN potential is assessed to 132 TWh/y while the DCN potential is assessed to 7.8 TWh/y.

Keywords: District heating and cooling, Geographic information system, Heat and cold mapping

Nomenclature

Abbreviations

DCN	District Cooling Network
DHCN	District Heating and/or Cooling Network
DHN	District Heating Network

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IGN	French National Institute of Geographic and Forest Information
INSEE	French National Institute of Statistics and Economic Studies
IRIS	<i>Îlots Regroupés pour l'Information Statistique</i> , aggregated zones for statistical information
MAEP	Multi-Annual Energy Plan
NUTS	Nomenclature of territorial units for statistics

Subscripts

B	Commercial building equipped with cooling equipment
b	Building
b_i	Building i
sub	Subsector
Dep	Department
I	IRIS
n	Network
s	Sector of activity

Variables

α_{Dep}	Climatic harshness per Department for heating	-
β	Proportion of appartments on the overall dwellings	%
δ	Share of the heating consumption on the overall energy consumption for a sub-sector of activity	%
γ	Share of the heating consumption on the overall energy consumption for a dwelling	%
λ	Actual cooled surface	%
C_N	Cooling demand over a network	MWh/y
EC	Energy consumption	MWh/y
EC_E	Electricity consumption	MWh/y
EC_G	Gas consumption	MWh/y

H_N	Heating demand over a network	MWh/y
$S_{cooling}$	Buildings equipped with cooling equipment floor area	m ²
<i>actual rate</i>	Portion of the commercial sector floor area equipped with cooling devices	%
C	Cooling demand	MWh/y
H'	Heating consumption	MWh/y
H	Heating demand	MWh/y
L	Length of a network	m
V	Volume of buildings	m ³
CDD	Cooling Degree Days	-
CDI	Cooling Demand Intensity	kWh/m ²
DHW	Domestic Hot Water	MWh/y
LCD	Linear Cooling Density	MWh/m/y
LHD	Linear Heating Density	MWh/m/y
PBA90	Proportion of Buildings anterior to 1990	%
PNT	Percentage of potentially cooled floor area	%
RS	Residential Share	%
S	Building floor area	m ²
SH	Space Heating	MWh/y

1. Introduction

A District Heating and/or Cooling Network (DHCN) is a system distributing heat and cold energy to several users, with better operation and maintenance than individual heating/cooling solutions and fostering the integration of waste and renewable heat sources. The evolution of the DHCN and the refurbishment/construction of new buildings with higher efficiency standards lead to a decrease in temperatures of the networks.

The total number of District Heating Networks (DHN) is estimated to be around 80,000 throughout the world, covering 3% of the final energy consumption, among which 4500 are located in Europe, that cover

between 11 and 12% of its thermal needs [1]. In 2016, cold deliveries are estimated to be 85 TWh per year, 3 TWh being delivered in Europe [2].

In 2017, heating represented 42.3% of the final energy consumption in France, that is 741 TWh, and the residential and commercial sectors 65% of this heating consumption [3]. France is the sixth European country regarding heat delivered by DHN (among 21 reviewed) [4]. The country possesses 780 DHN (23 District Cooling Networks (DCN)) that delivered 26.1 TWh (0.9 TWh, respectively) of heat (cold) energy in 2018 [5]. Incentives started being implemented at the end of the 2000s, such as a reduced VAT for DHN with a share of renewable in their energy mix higher than 50% or the creation of a “Heat fund program” to help developing DHN. Moreover, the connection of a building to a network can be made compulsory if it has more than 50% of renewable energy. Furthermore, a long-term energy plan sets as an objective that the heat delivered thanks to renewable energies via DHN shall be of 24.4 TWh in 2023 and between 31 and 36 TWh by 2028. To reach this objective, it is recommended to ask cities with more than 10,000 inhabitants to carry out a feasibility study on a heating and cooling network.

There is a need to assess the potential of DHCN in France. To do so, the first step consists in calculating the heating and cooling demands in the country, splitting the territory in homogeneous areas. This is usually achieved using either a top-down approach, as in [6] that disaggregates national heat demand to a local scale (grid cells with a resolution of 100 m²) or a bottom-up approach, as in [7] and [8] that calculate the heat demand per building based on its characteristics and aggregate those buildings to respectively grid cells scale or according to built-up areas. Then the potential is calculated for each area, based on either a linear threshold [9], or a combination of linear density, heat demand and heat demand density, see [7], or an economic threshold [8, 10].

Those studies focus on the thermal demands and on the floor area of the buildings, but do not consider the actual distance between those buildings. Besides, none of the previously mentioned studies considers the construction period nor the economic sector (residential, commercial, industrial...) of the buildings to be connected to the network. Yet, those parameters matter since they have an impact on the architecture of the network that developers will adopt. For instance, [11] shows that old dwellings require refurbishment to have lower temperature levels for space heating.

The aim of this paper is to propose a methodology based on the construction of a typology of districts to study the development potential of DHCN. First, the historical evolution DHCN up to today is presented in Section 2. Then, in Section 3, a method to assess the potential of French districts to host DHCN is introduced. This methodology uses data at a local scale to calculate the heating and cooling demands density, based on building thermal demand and on the calculation of the distance between those buildings via a Delaunay triangulation and Kruskal’s algorithm. In addition, the proportion of old buildings and the mix between residential and commercial are also assessed. Finally, the potential of development of DHCN is analysed through the proposed method in Section 4.

2. Evolution of the DHCN in France

The first French DHN appeared in the 1930s and then properly developed from the 1960s to the 1970s simultaneously with urbanization. Following the second oil crisis, and with the objective of decreasing French dependence on imported energy, the number of new installations briefly rose. After a slowdown in subsequent years, the number of newly built DHCN increases again along with French policies offering more importance to this energy system (see Fig. 1). Those energy policies are for instance a VAT reduced to 5.5% (against 20%) of both the flat and the variable costs if the share of renewable energies on the network exceeds 50%, a program "Heat fund" created by French government to help develop DHN and a coercive measure to potentially impose the connection of a building to a network if it is powered by more than 50% of renewable energy [12]. With 5% of the total heating energy delivered by DHN, France is far from some of its European counterparts, as for instance Denmark where the ratio reaches 64%, or Sweden and Norway with a share superior to 50%, according to [13].

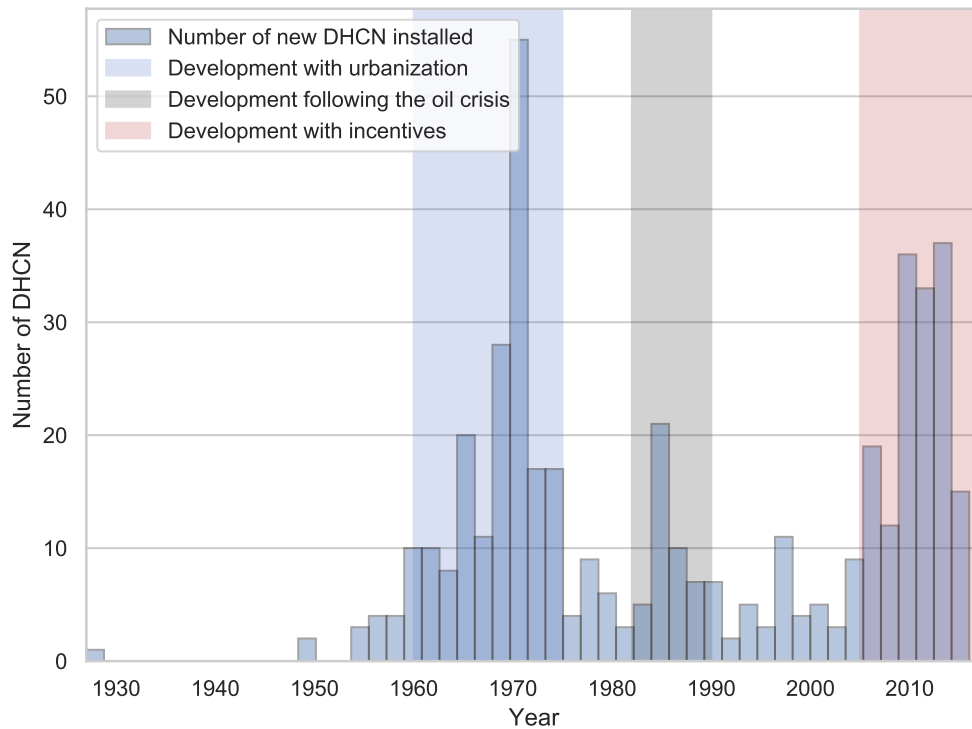


Fig. 1: Evolution of the installation of new DHCN in France from the 1930s

Our review study is based on 456 DHCN systems [14, 15] that represent 24.3 TWh of energy consumption in 2018, among which 289 (that account for 22 TWh) are prior to 2000 and 167 (that account for 2.3 TWh) subsequent to 2000. 2000 was chosen as the splitting year since from that moment DHCN were created to meet the needs of new buildings with a lower energy consumption.

The presence of the residential sector in the energy demand has decreased in the new DHCN due to the creation of new districts with a higher diversity of use. The residential sector represents at least 71% of the energy consumption for more than half of the networks prior to 2000, whereas the median goes down to 49% (Fig. 2) for the networks built from 2000.

The opposite can be seen for the commercial sector. For half of the networks prior to 2000, the commercial sector accounts for a maximum of 24% of the network consumption, whereas the median goes up to 43% for the networks from 2000.

The networks post 2000 tend to be more mixed and oriented to the commercial sector. Thus, only 8 DHCN built from 2000 provide energy exclusively to the residential sector while 24 provide energy exclusively to the commercial sector. The industrial sector is present only in 37 out of 456 networks.

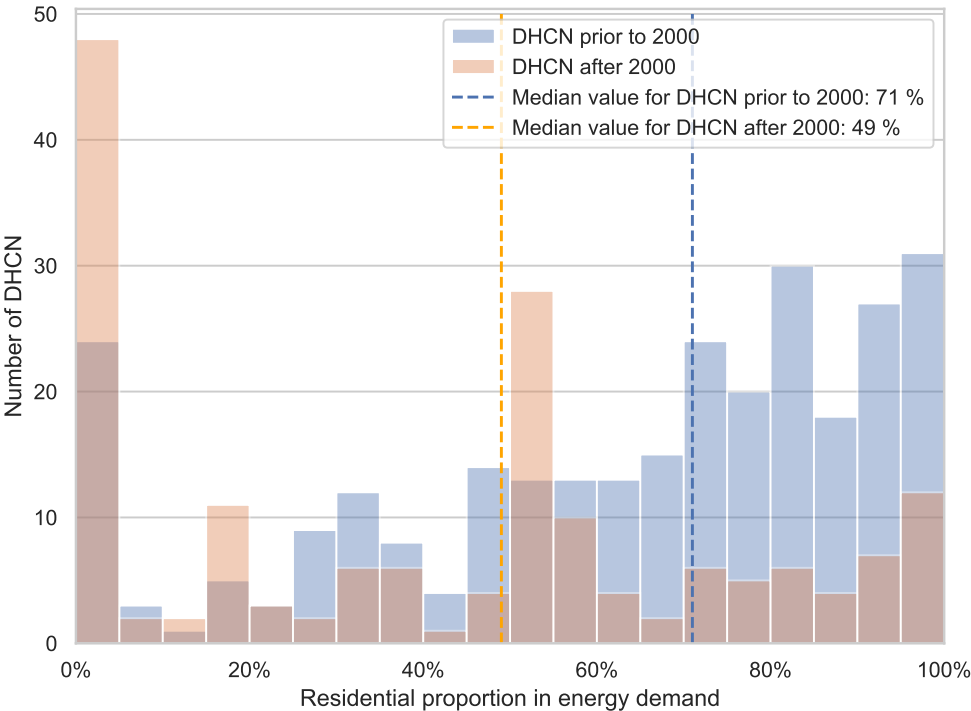


Fig. 2: Energy consumption from DHCN per sector

Since 2000, the size of the networks has decreased dramatically. There is less energy delivered, a smaller length per network, fewer substations and a lower linear density (Fig. 3). Thus, regarding the median values, if the linear density decreased by 48%, the number of substations decreased by 60%, the length of the networks by 72% and the energy delivered by 83%. These results are conform with the observations presented in [4]: new networks are smaller, with less substations, and connected to new buildings with a better energy efficiency.

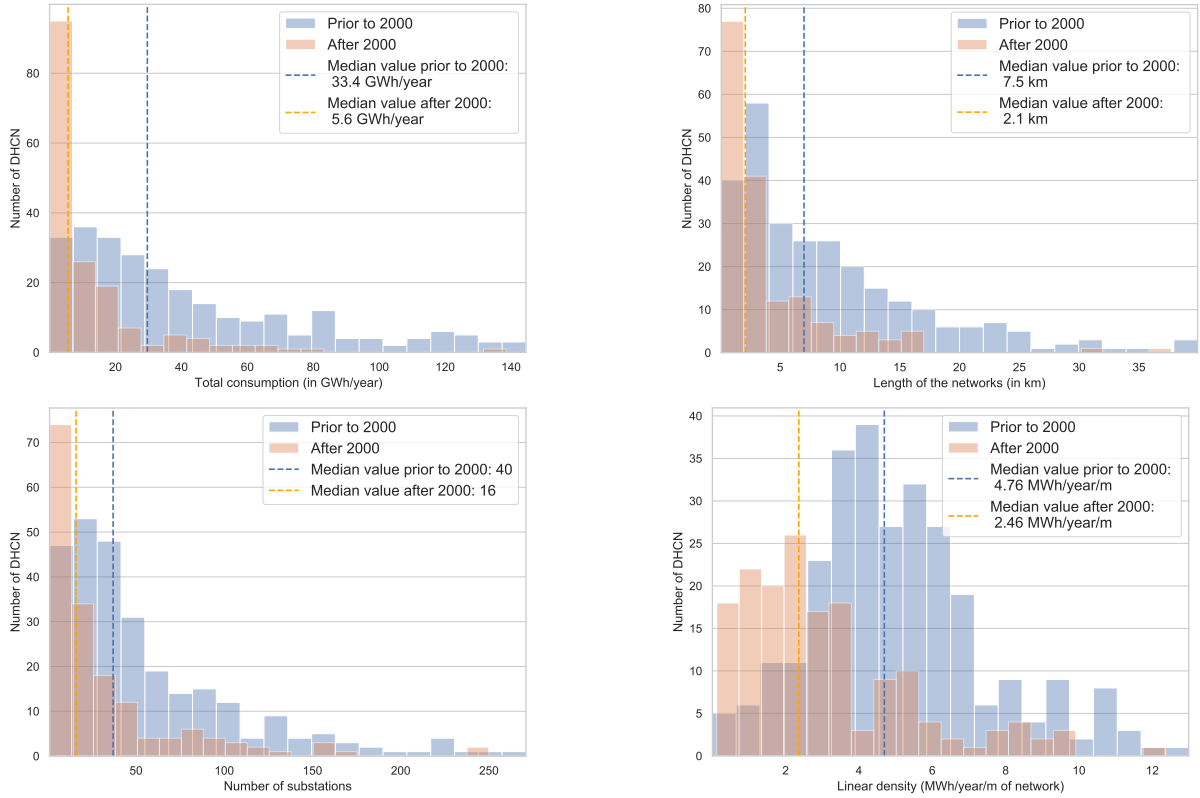


Fig. 3: Comparison between the DHCN prior to and posterior to 2000, regarding the energy consumption, the networks length, the number of substations and the linear density for the year 2018

As shown in [14], biomass, gas, Waste-to-Energy and geothermal energy represent 90% of the overall sources of energy for DHN. The share of renewable energies in DHN increased from 56% in the networks built prior to 2000 to 75% in the ones created from 2000, mostly thanks to an increase of the share of biomass and geothermal energy while the consumption of gas decreased, see Fig. 4.

The DCN are likely to mobilize renewable energy sources, in particular through electrical chillers which are mainly connected to a water source such as a river or the sea, and also through the direct use of a naturally cold water source, such as deep sea water or river water during winter to cool the network down (free cooling). In [4], water-cooled electrical chillers produce 71.9% of cooling from DCN in France, while electric chillers associated to wet cooling towers account for 21%. Excess heat from industry, waste incinerators or solar energy can be used to produce cold water via absorption chillers, but the process is marginal at the present time (0.6%). Moreover, heat pumps producing simultaneously cooling and heating are being developed in DHCN (1.7%).

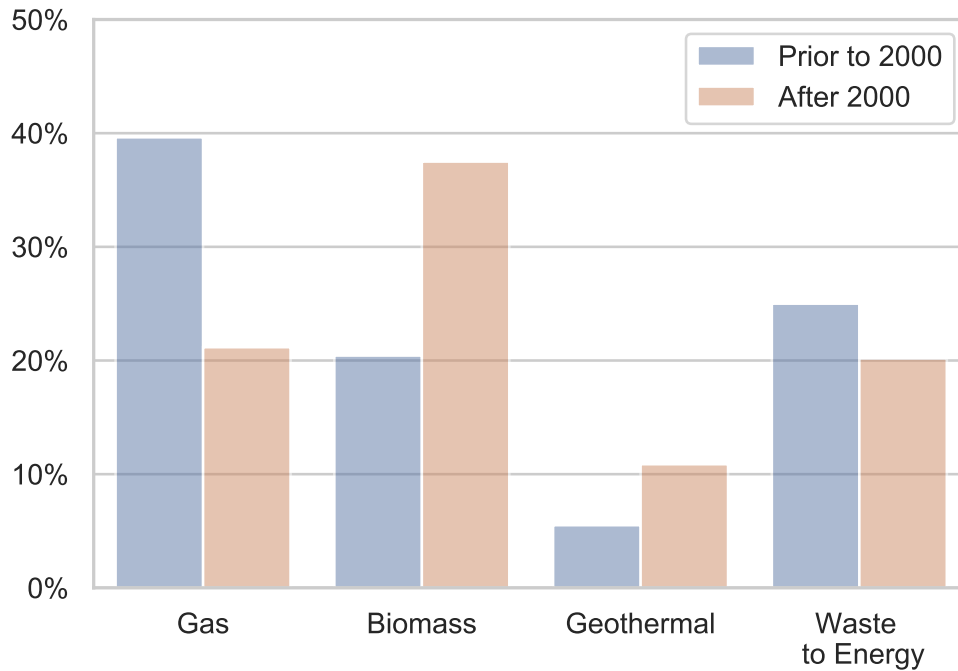


Fig. 4: Share of the most common heat sources for DHN built prior to and after 2000

The present study shows the evolution of the situation for the DHCN in France regarding the energy perspective. It appears, firstly, that if the residential and commercial sectors represent the vast majority of the energy demand over the networks, the share of each of these sectors in the networks evolved. Thus, the share of the residential sector that was predominant in most of the districts is in the recent DHCN more spread. Also the recent networks are now smaller than the old ones, in terms of energy consumption over the network, size and density. The reason is most of the recent networks have been installed in the new districts that generally correspond to areas more diverse and less energy intensive.

This diversity of needs leads to a variety of potential districts for the installation of DHCN that will be studied via the definition of a typology oriented towards the potential of installation of DHCN taking into account the needs of the districts.

3. Construction of an urban heating and cooling district typology

The typology is performed for the entire metropolitan France. The country is split in small areas called IRIS (defined in Section 3.1) on which the study is performed.

Given the data provided in national databases, three variables are used to classify the IRISs in different groups:

- The Linear Heating/Cooling Density (LHD/LCD): it is a key factor for DHCN since a district with a

high energy density allows to increase the profitability of a district network, reducing the investments and maintenance costs per kWh distributed

- The Residential Share (RS): the RS corresponds to the proportion of energy consumption from the residential sector in the IRIS. A very high proportion of the residential consumers induces similar load profiles between users degrading the load factor on the network, whereas a lower proportion of buildings from the residential sector will lead to more diverse load profiles. A very low proportion induces a high share of consumption from the commercial sector.
- The Proportion of Buildings Anterior to 1990 (PBA90): this variable accounts for the temperature constraints for a DHN since old buildings generally require higher temperatures for space heating. 1990 is used as the splitting year because it corresponds to the introduction of the second French thermal regulation for building construction (RT 1988) which aimed to reduce the energy consumption related to heating and domestic hot water (DHW) for both residential and commercial buildings.

In what follows, we explain how to calculate these three categorical variables at the IRIS scale and how they lead to the definition of our typology.

3.1. Use of the IRIS scale

Two meshes were considered: the use of a geographic grid or the use of aggregated zones for statistical information so-called *Îlots Regroupés pour l'Information Statistique (IRIS)* [16], which is a division of the French territory by the French National Institute of Statistics and Economic Studies (INSEE) in order to “respect geographic and demographic criteria and have borders which are clearly identifiable and stable in the long term. Towns of more than 10,000 inhabitants, and a large proportion of towns of between 5,000 and 10,000 inhabitants, are divided into several IRIS units”. So, an IRIS corresponds roughly to a district. The IRIS borders were defined following three criteria: if the IRIS is in a residential area (92% of the total number of IRIS), an IRIS comprises from 1,800 to 5,000 inhabitants, if the IRIS is in a commercial area (at least two times more employees than inhabitants, 5% of the total number of IRIS), an IRIS comprises at least 1,000 employees, and finally the remaining IRIS are in low population density areas and their edges are the towns administrative borders. In total, metropolitan France is divided into 50,153 IRIS.

The IRIS mesh is selected for the study since the database sources we exploit are either given at this scale or easily scalable to this scale. Another mesh would imply disaggregating the data.

IRISs are included in the 96 metropolitan departments (a department is a NUTS-3 region, the NUTS classification (Nomenclature of territorial units for statistics) being “a hierarchical system for dividing up the economic territory of the EU” [17])

3.2. Databases

This study was made possible by the use of databases recently published, at a local scale. The databases used in this study are:

- The BD Topo vector dataset provided by the IGN (the French National Institute of Geographic and Forest Information) [18]. Specifically, the database includes the buildings properties for the entire territory: their surface footprint, their height (making it possible to calculate their volume) and, when available, the year of their construction and their sector of activity (residential, commercial, agricultural, industrial).
- The IRIS GE database [19], also provided by the IGN, which is the georeferenced subdivision of the French territory at the IRIS scale.
- The database “housing” by the INSEE [20] that shows the total number of dwellings per IRIS and the periods those dwellings were built: before 1918, from 1919 to 1945, from 1946 to 1970, from 1971 to 1990, from 1991 to 2005 and from 2006 to 2012.
- the energy databases that provides at the IRIS scale (for electricity and gas) or at the network scale (for heat and cold consumption) the energy consumption by sector of use (agricultural, industrial, commercial, residential and other) for the year 2018 [15].
- The data from the French association Via Sèva [14], from where the existing DHCN layouts were extracted
- The data from the *Direction Régionale et Interdépartementale de l’Environnement et de l’Énergie (DRIEE)*, that provided complementary layouts for the region Île-de-France [21]
- The SIRENE database [22], georeferenced in [23]. This database comprises information about all the French companies, and in particular the subsectors of activity of each one of them for the commercial sector. The subsectors include hotels, restaurants, insurances, public administration... The definition of the subsectors is based on the definition by INSEE, similar to the Statistical Classification of Economic Activities in the European Community (NACE) [24].

Fig. 5 provides an overview of how to get the categorical variables (LHD, LCD, RS, PBA90) at IRIS scale from the presented databases. In what follows, we detail the calculation method.

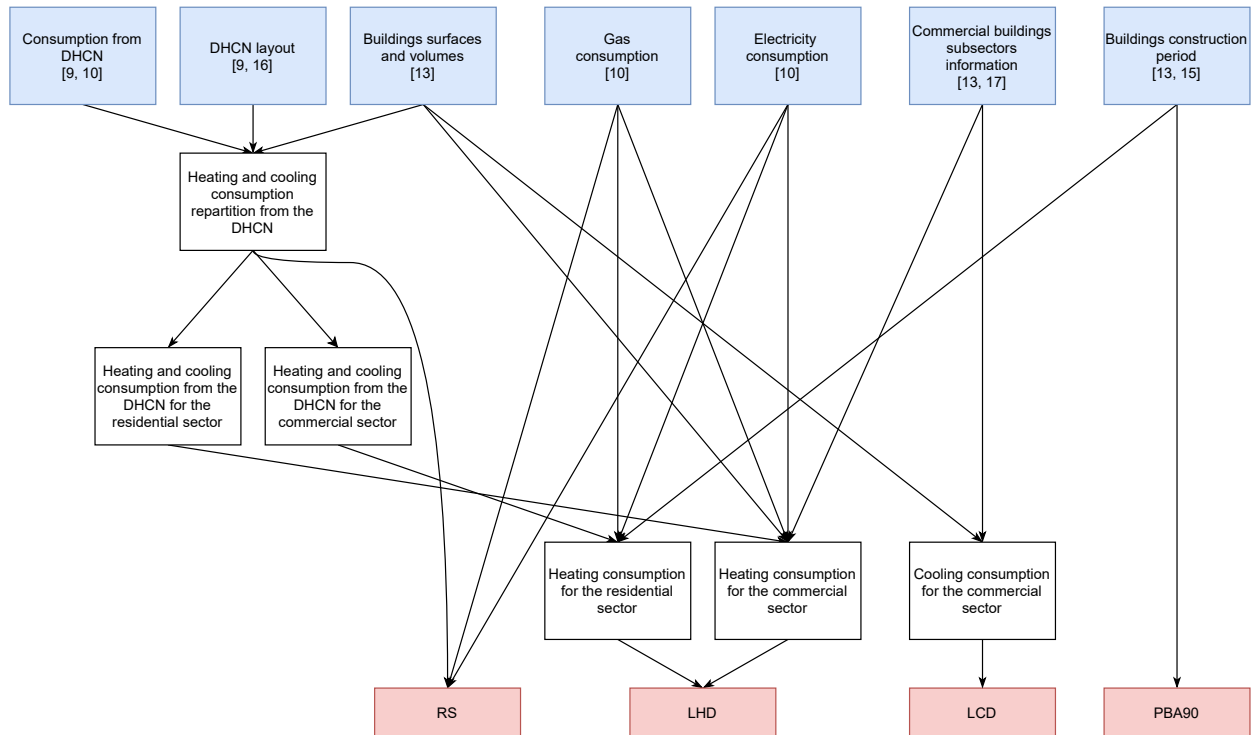


Fig. 5: Diagram of the data used to get the variables

3.3. Calculation of energy demand

In France, gas, electricity, heat energy from DHNs, wood and heating oil are the main sources of energy for heating systems. The heating demand (defined as the energy required for Space Heating (SH) and DHW) at the IRIS scale, estimated from the final energy consumption at that scale. In our study, we consider only heat from DHNs, electricity and gas, because of two main reasons. First, there is a lack of data at IRIS scale regarding the heating oil and wood. Secondly, these two sources are mainly used in France for individual households, which are generally poor candidates to be connected to DHC due to their low energy densities. Indeed, individual households account for 98% (90%) of the floor area heated with wood (heating oil), according to [25]. In contrast, for the commercial sector, in 2018, electricity, gas and heat from the networks represent 81.3% of the heated surface and more than 90% of the heating consumption [26].

Heating demands are estimated by:

- Calculating the heating energy received by the IRIS from the DHN (Section 3.3.1), if the IRIS hosts part of a DHN
- Adding to this energy, the part of electricity and gas consumption dedicated to the heating demands per IRIS (Section 3.3.2)

The space cooling demands are considered only in commercial buildings and they, are calculated as a ratio of cooling demand by floor area depending on the climatic conditions (Section 3.3.3).

3.3.1. Heating demands from the DHCN

This section aims to quantify, for a given IRIS, the part of heating demand supplied by a DHCN. In order to do so, we will use the available data about the declared DHCN in France [21, 15]. While their energy demand for the entire network is known, the demand at the IRIS scale is not, knowing that in most cases, one DHCN spreads over several IRIS.

For a given DHN, we calculate the heating demands by IRIS as the volume share of the buildings connected to the network that belongs to the IRIS over the total volume of the buildings connected to the network multiplied by the energy consumption over that network. A building is supposed to be part of the DHN if it is at a maximum of 6 m from it.

To spread the heating distributed on the DHCN, the first step (Eq. (1)) involves calculating, the volume ratio of each building b that belongs to the network n :

$$Ratio(b) = \frac{V(b)}{\sum_{ben} V(b)} \quad (1)$$

The heating H_N demands over the network for a given sector s with $s \in \{Commercial, Residential\}$ are then calculated for each building b of the network using Eq. (2):

$$H_N(s, b) = Ratio(b) \times H_{N_total}(s, n) \quad (2)$$

Where $H_{N_total}(s, n)$, given in [15, 14], is the total annual heating demand for a given sector (s) of the network (n).

Finally, the heating demand supplied by a DHCN, for a given sector s and an IRIS I is defined in Eq. (3), by summing up all the buildings belonging to the corresponding network:

$$H_N(s, I) = \sum_{b \in I} H_N(s, b) \quad (3)$$

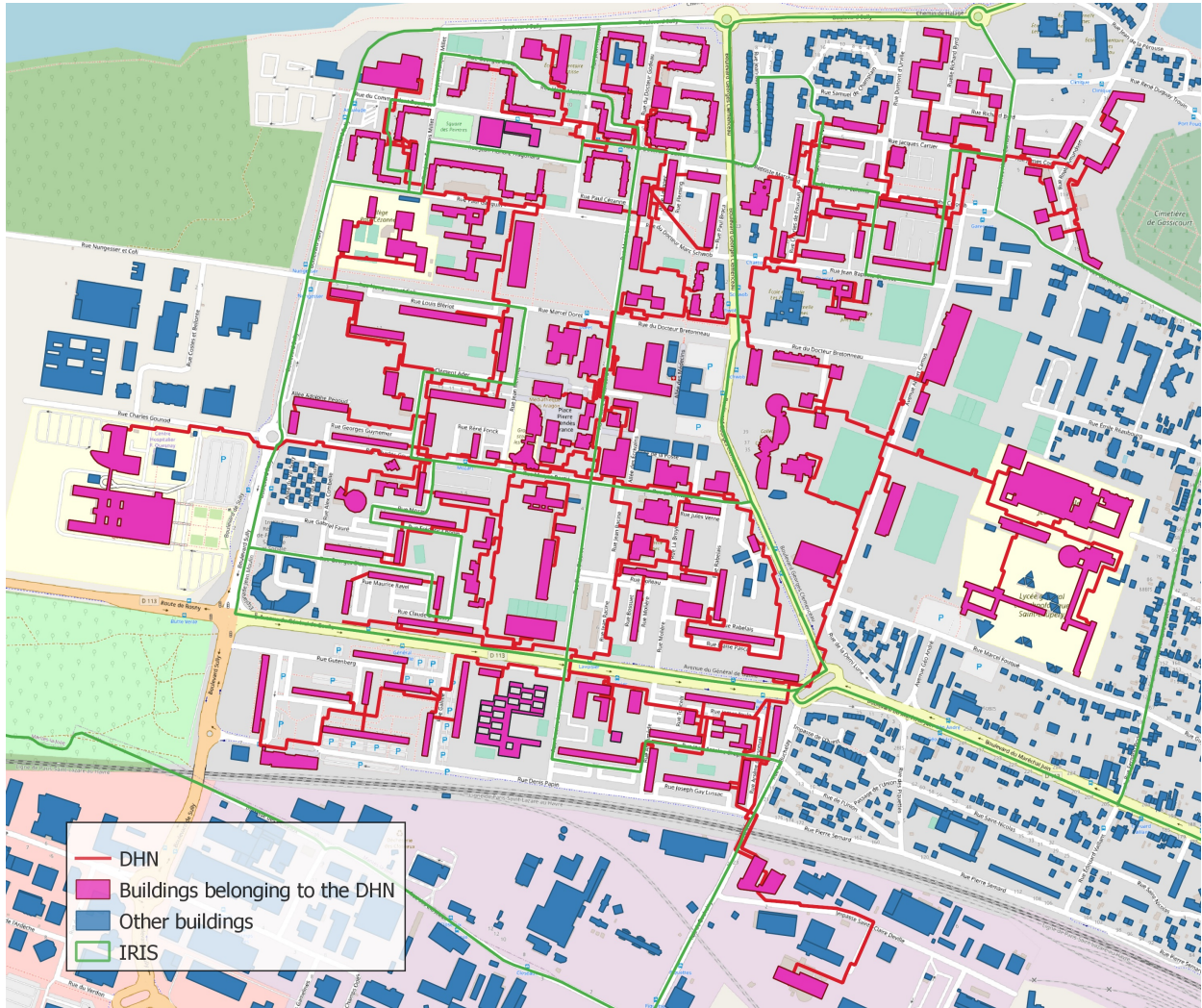


Fig. 6: Buildings connected to the DHN in Mantes-la-Jolie (department 78)

Fig. 6 shows an example of a small city, divided into IRISs (green lines), with the existing network in red and the buildings that are supposed to receive heat from the network (distance lower than 6 m) marked in pink. The presented method is applied for 337 DHN of which the layout is given over 780 DHN declared. They account for 73.6% of the overall DHN consumption in France.

3.3.2. Heating demands

Heating demands at the IRIS scale are calculated based on the heating consumptions from electricity, gas and DHN at that scale. Heating demands from DHN have already been calculated in Section 3.3.1. This section aims to determine heating demands from electricity and gas. Note that in the case of electricity and DHN, heating demand and consumption are equal (i.e. energy conversion efficiency equals 1), whereas it is not in the case for gas due to the efficiency of gas boilers (the gas conversion rate is assumed to be 0.8).

While the total energy consumption of electricity and gas is available, the part related to the heating purposes (space heating and DHW) needs to be estimated. For the residential sector, [27] provides an assessment of the share of energy dedicated to the heating consumption among the total consumption of a dwelling at the national level, per period of construction and per type of dwelling (apartment or house). For the commercial sector, [26] provides an assessment of the heating share among the total consumption per subsector of activity at the national level.

Heating consumption per IRIS for the residential sector $H'(R, I)$ is assessed in Eq. (4) calculating, for each IRIS, the average heating consumption share in the energy consumed multiplied by the electricity and gas consumptions for the residential sector $EC_{E+G}(R, I)$ [15]. The heating consumption share in the energy consumed depends on the proportion of dwellings that are apartments ($\beta(I)$) or houses ($1 - \beta(I)$), on the periods of construction p of those dwellings and on the climatic harshness of each department α_{Dep} . $\gamma(p, a, \alpha_{Dep})$ is the ratio of SH and DHW consumptions on the total electricity and gas consumptions in the apartments built during the period p under the climatic harshness α_{Dep} , $Apa(p, I)$ is the proportion of apartments built during the period p over the total number of apartments for the IRIS I [20]. $\gamma(p, h, \alpha_{Dep})$ and $Hou(p, I)$ are the same variables for the houses.

All the IRIS of a Department are supposed to be under the same climate α_{Dep} , defined in the French Thermal Regulation [28] as a ratio of the observed climatic harshness over a standard one. α_{Dep} varies between 0.8 and 1.3.

$$H'(R, I) = EC_{E+G}(R, I) \times \left(\beta(I) \times \sum_p \gamma(p, a, \alpha_{Dep}) \times Apa(p, I) + (1 - \beta(I)) \times \sum_p \gamma(p, h, \alpha_{Dep}) \times Hou(p, I) \right) \quad (4)$$

[27] provides for an average flat, for each period p , its heating consumption $H'(p, a)$, its DHW consumption $DHW(p, a)$ and its total energy consumption $EC(p, a)$ at national level. We calculate, in Eq. (5), $\gamma(p, a, \alpha_{Dep})$ per period p , taking into account the variation of the heating consumption in the total energy consumption that depends on the climatic harshness α_{Dep} . We also calculate $\gamma(p, h, \alpha_{Dep})$ as in Eq. (5).

$$\gamma(p, a, \alpha_{Dep}) = \frac{\alpha_{Dep} \times H'(p, a) + DHW(p, a)}{EC(p, a) + (\alpha_{Dep} - 1)H'(p, a)} \quad (5)$$

The next step consists in calculating the heating demands $H(R, I)$. When gas and electricity are present on the IRIS, gas is assumed to be the favoured energy for heating consumption (the consumption not covered by gas being then covered with electricity) since 93.9% of gas energy is used for space heating and hot water

production according to [25]. The heating demand for the residential sector $H(R, I)$ is calculated in Eq. (6):

$$H(R, I) = 0.8 \times EC_G(R, I) + EC_E(R, I) + H_N(R, I) \quad (6)$$

with $EC_E(R, I) = H'(R, I) - EC_G(R, I)$

In Eq. (6), it is assumed that all the electric consumption for SH and DHW is due to electric radiators and electrical water heaters respectively, the heat pumps are considered still negligible in the building stock. $H_N(R, I)$ was calculated in Section 3.3.1.

The heating consumption per IRIS for the commercial sector $H'(C, I)$, is assessed by calculating the average share of the heating consumption in the energy consumed, which is the sum of the share of the heating consumptions per subsector of activity depending on the climatic harshness ($\delta(sub, \alpha_{Dep})$) times the volume share of the buildings of this subsector among all the commercial buildings of the IRIS $V(sub, I)/V(C, I)$, multiplied by the electric and gas consumptions for the commercial sector $EC_{E+G}(C, I)$, see Eq. (7):

$$H'(C, I) = EC_{E+G}(C, I) \times \sum_{sub} \delta(sub, \alpha_{Dep}) \times \frac{V(sub, I)}{V(C, I)} \quad (7)$$

[26] provides for each subsector of activity, the heating consumption $H'(sub)$, the DHW consumption $DHW(sub)$ and the total energy consumption $EC(sub)$. $\delta(sub, \alpha_{Dep})$ is calculated in Eq. (8) considering the variation of the heating consumption in the total energy consumption that depends on α_{Dep} :

$$\delta(sub, \alpha_{Dep}) = \frac{\alpha_{Dep} \times H'(sub) + DHW(sub)}{EC(sub) + (\alpha_{Dep} - 1)H'(sub)} \quad (8)$$

Eq. (6) can be applied to the commercial sector, gas being also assumed to be the favoured energy for heating consumption since 88.6% of gas energy is used for space heating and hot water production according to [25].

Finally the total heating demand per IRIS $H(I)$ is defined in Eq. (9), adding up both sectors:

$$H(I) = H(R, I) + H(C, I) \quad (9)$$

3.3.3. Cooling demands

The cooling demands for the residential sector were assumed to be marginal, since the cooling consumption at country level is only 0.22% (0.9 TWh) of all the energy consumed by residential buildings in 2018 according to [25]. Other studies assess a higher but still marginal value, around 4 TWh according to [29, 30], that accounts for 0.94% of the residential consumption.

Space cooling demand per IRIS for the commercial sector is defined in Eq. (10) as the product of two parameters: the Cooling Demand Intensity (CDI), in kWh/m², and the commercial buildings equipped with

cooling equipment floor area per IRIS $S_{cooling}(C, I)$, in m.

$$C(C, I) = CDI(Dep) \times S_{cooling}(C, I) \quad (10)$$

The average CDI was assessed by [29] for commercial sector buildings for various locations in Europe. Here, these values are spread over the French departments. CDI values are supposed to be the same in each IRIS of a given department.

$S_{cooling}(C, I)$ is not equal to the total commercial surface, since only a portion of the commercial sector floor area, the actual rate, is equipped with cooling devices. In what follows, we show how to estimate $S_{cooling}(C, I)$ and identify the cooled commercial buildings.

First we calculate the percentage of potentially cooled floor area (PNT) in the future, so-called the market saturation rate. A study carried out by [31] suggested a correlation (Eq. (11)) between PNT and the Cooling Degree Days (CDD which is, by definition, the sum over a year of the daily difference between the mean outdoor temperatures, in °C, and a reference temperature, 18 °C in this study). Here, we suppose that PNT in France are equivalent to the US ones for the same CDD. Mean CDD values (expressed in °C) are obtained from meteorological stations located in France for the years 1998–2017, using European Climate Assessment and Dataset [32], and then calculated at the department level using an inverse distance weighted interpolation.

$$PNT(Dep) = 0.0072 \times CDD(Dep) + 64.168 \quad (11)$$

The second step is to calculate the actual rate, knowing that the cooling demand is today far from the market saturation. To do so, a correction factor λ is used, see Eq. (12).

$$Actual\ rate(Dep) = \lambda \times PNT(Dep) \quad (12)$$

The factor λ is supposed to be the same for all the departments in France, and its value is adjusted so that the actual rate is equal to 37.27% at national level, following the value given in [26]. Hence, λ can be calculated from the commercial buildings floor area per department $S(C, Dep)$, Eq. (13):

$$\lambda = \frac{37.27\% \times \sum_{Dep} S(C, Dep)}{\sum_{Dep} PNT(Dep) \times S(C, Dep)} \quad (13)$$

To identify the cooled commercial buildings, the biggest buildings of a given department are assumed to be the most likely to be equipped with cooling equipment. Thus, we select the buildings, gradually from the biggest, until the total area reaches the estimated cooling area of that department. From Eq. (14), we

identify a set B of the cooled commercial buildings in the department.

$$\sum_{b \in B} S(C, b) \approx Actual\ rate(Dep) \times S(C, Dep) \quad (14)$$

Finally, the cooling area at the IRIS scale $S_{cooling}(C, I)$ is determined by adding up all the selected buildings that belong to the corresponding IRIS, as in Eq. (15):

$$S(C, I) = \sum_{b \in B \cap I} S(C, b) \quad (15)$$

3.4. Calculation of the categorical variables

3.4.1. Heating and cooling demands linear density (LHD and LCD)

LHD and LCD per IRIS are defined as being the heating and cooling demands divided by the network length. To access these variables, the method aims first to identify the buildings that could be potentially connected to a district network excluding the isolated and low energy consuming ones. Then, a virtual network is created using the Delaunay triangulation followed by a minimum spanning tree algorithm to connect all these buildings. In what follows, we detail the method.

The first step is to calculate the heating $H(b)$ and cooling $C(b)$ demands per building b . The heating and cooling demands per IRIS are already calculated in Section 3.3. The heating demand is spread among the buildings b that belong to the IRIS depending on the ratio of their volume against the total volume of the buildings as in Eq. (16):

$$H(b) = \frac{V(b)}{\sum_{b \in I} V(b)} \times H(I) \quad (16)$$

The cooling demand per buildings is calculated in Eq. (17), using the same assumption of the previous part, i.e. a cooling demand proportional to CDI and the building surface:

$$C(b) = CDI(Dep) \times S(C, b) \quad (17)$$

For a potential DHN, only the buildings with a floor area superior to 1000 m² are considered, since it can be made mandatory for those buildings to be connected to a future DHN in case of refurbishment [33]. For a potential DCN, all the selected buildings (set B from Eq. (14)) are considered.

The second step is to gather the considered buildings in clusters. To do so, a buffer zone around all the selected buildings is created (Eq. (18) defines the radius of the buffer zone, where H and C are expressed in MWh/y), and then the created buffer zones are merged if an intersection exists between these zones, as described in Eq. (19).

$$buffer_{heating}(b) = \min\left(2000\text{ m}, H(b)\right) \text{ and } buffer_{cooling}(b) = \min\left(2000\text{ m}, C(b)\right) \quad (18)$$

$$Cluster(k) = \bigcup_b buffer(b), \text{ with if } \forall(b_i, b_j), buffer(b_i) \cap buffer(b_j) \neq \emptyset \text{ if } i \neq j \quad (19)$$

It should be noted that the definition of the buffer zone (Eq. (18)) guarantees that the corresponding network will have a LHC/LCD of at least 1 MWh.m⁻¹. In addition, the threshold value 2000 m was chosen as conservative value to limit the longest distance between two neighbours buildings of the same network.

For the DHN, only the surfaces with at least 6 buildings are considered, which is a conservative value given that more than 90% of the networks deliver heating/cooling to at least 6 buildings [14]. For the DCN, we consider the clusters that contain at least 4 commercial buildings, since only the DCN connected to at least 4 buildings are eligible for subsidies [12].

As an example, the clusters that can potentially host a DHN in a department are visible in Fig. 7. We observe a big cluster in the center of the department, around the main city of that department, and a number of smaller clusters in the suburban areas. In total, there are 88 clusters identified, corresponding to as many potential DHN.

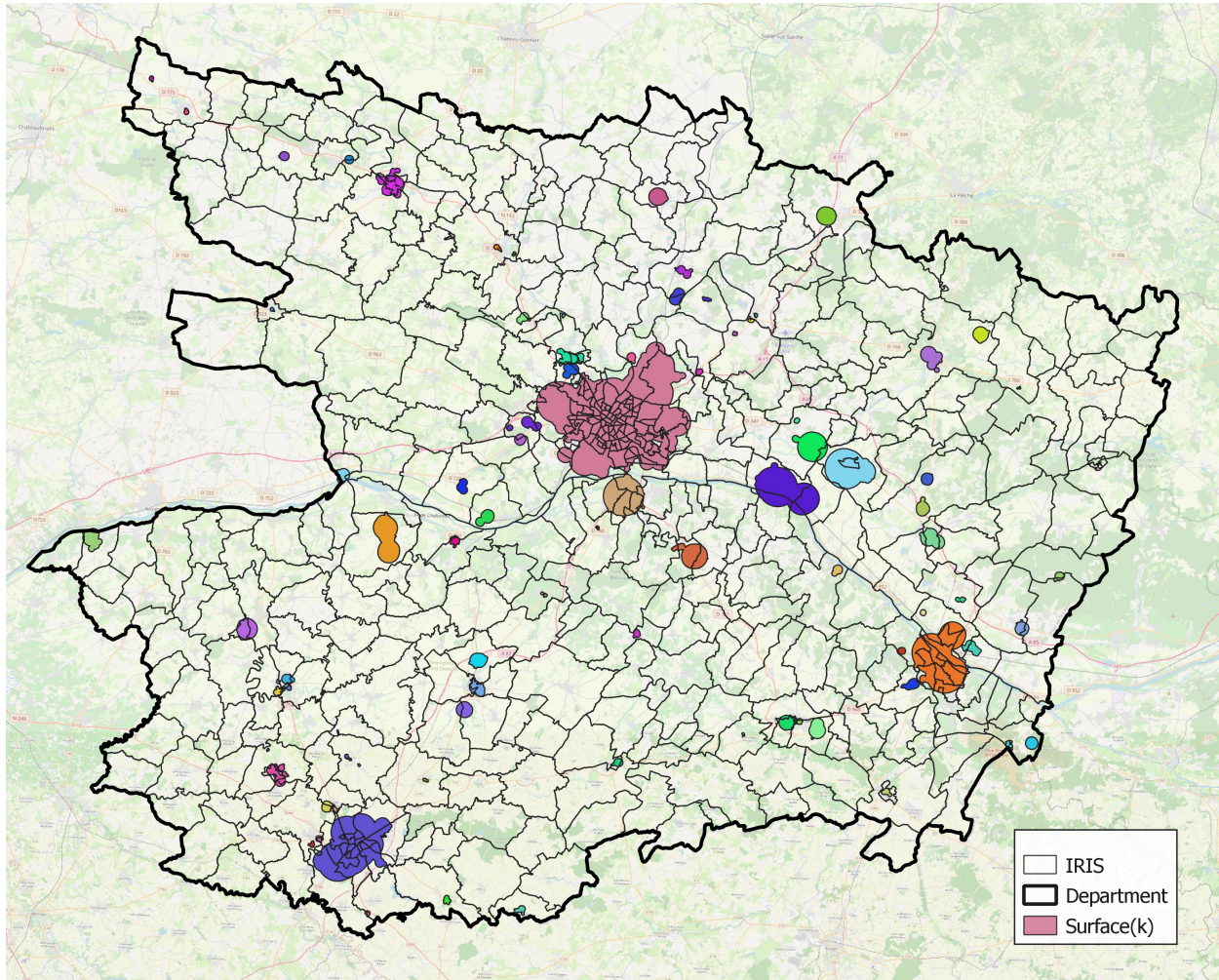


Fig. 7: clusters considered for potential DHN in the department 49

The third step involves creating a network layout to connect all the buildings b that belong to the same cluster. On each cluster, a Delaunay triangulation is run first, to connect each building to the nearest buildings. The result is an undirected graph, where the nodes are the buildings and lengths of the edges can be easily calculated. Then, Kruskal minimum spanning tree algorithm is used to find the path which includes all the nodes/building (without any cycles) and whose length is minimized. Note that the Delaunay triangulation step is necessary because it reduces dramatically the number of potential paths, making possible to run Kruskal's algorithm and get results within a reasonable calculation time

The final step consists in calculating LHD and LCD per IRIS as the sum of the heating (cooling) demands of all the buildings that belong to the virtual heating (cooling) network (n) and to the IRIS (I) divided by

the length of the network present in the IRIS $L(n, I)$, as shown in Eq. (20):

$$LHD(I) = \frac{\sum_{be(n \cap I)} H(I)}{L(n, I)} \quad (20)$$

$$LCD(I) = \frac{\sum_{be(n \cap I)} C(I)}{L(n, I)}$$

Fig. 8 is an example of the use this algorithm applied for a DHN. Buffers were created following Eq. (18) and were merged to obtain the surface in blue. A Delaunay triangulation is then applied to connect all the buildings' centroids. Next Kruskal's minimum spanning tree algorithm calculates the overall shortest way to connect all the buildings with sufficient heating (cooling) demand (i.e. such as the distance between two buildings is inferior to the sum of their heating (cooling) demands).

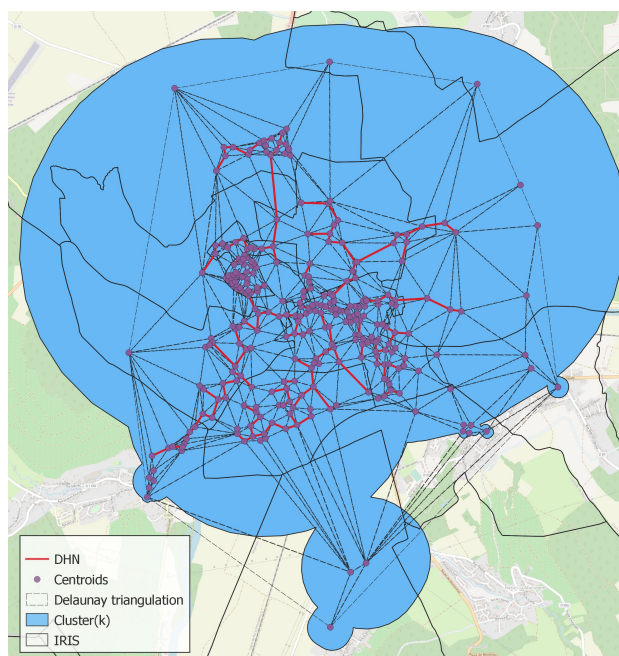


Fig. 8: Focus on a virtual network created

3.4.2. Consumption profile variability

The energy consumption for the residential and the commercial sectors has been calculated in Section 3.3. When most of the energy consumption comes from a unique sector, it can be assumed that the heating demand profiles of the different consumers are similar, whereas when it is split between different sectors, the heating demand profiles of the different consumers vary. The Residential Share (RS) is calculated as being, for each IRIS, the ratio of the energy consumption from the residential sector $EC(R, I)$ over the energy

consumption from all the sectors s (commercial and residential), as shown in Eq. (21):

$$RS(I) = \frac{EC(R, I)}{EC(R, I) + EC(C, I)} \quad (21)$$

3.4.3. Proportion of buildings built before 1990

An assumption has been made that the required temperature to provide the building depends on its period of construction, as shown in [11]. [27] provides the evolution of the heating consumption among the dwellings, depending on the period of their construction. The period of construction is provided for each IRIS by the database BD TOPO and completed, if not available for a particular IRIS, by the INSEE database. From these data, we calculate the proportion of buildings anterior to 1990, hereafter named PBA90. 1990 was chosen as the splitting year since it corresponds to the time new regulations were enforced in France regarding consumption reduction in the residential sector

3.5. Categories

Once the different variables have been calculated per IRIS, they are split in different ranges.

The LHD is split into two categories: the first one where the LHD is sufficient to integrate a DHN, and the second one when the LHD is insufficient. The same split is applied for the LCD. For the DHN, a conservative threshold is set at 1 MWh/m/y, and at 1.5 MWh/m/y for a DCN, since those are the minimum possible density to receive subsidies from the French "Heat fund program" [12].

The PBA90 and the RS, whose values ranging between 0 and 1, are each split into three equal ranges. This results in the three PBA90 categories ranging from a low to a high proportion of old building built before 1990. Concerning the three RS categories, it ranges from a low to a high proportion of residential buildings.

Combining all the categories (RS, PBA90, LHD or LCD), 18 different types of districts ($3 \times 3 \times 2$) are defined, for respectively DHN and DCN.

4. Results

4.1. Heating and cooling demands

The overall heating consumption from electric, gas and DHN is 277.5 TWh for the residential sector (obtained from Eq. (4)), and 103.5 TWh for the commercial sector (Eq. (7)) in 2018, that is in total 381 TWh for both commercial and residential sectors. Heating consumption from wood is 64.5 TWh [34] and heating consumption from heating oil is 36.6 TWh according to [15]. The other power sources are considered negligible. Altogether, the heating consumption for residential and commercial sector is 482.1 TWh, that is very close to the reference heating consumption assessed by the Multi-Annual Energy Plan (MAEP), which is 481.7 TWh. The heating demand was calculated in Eq. (6) and is equal to 346.4 TWh in 2018.

The cooling demand in France for the commercial sector is 27.6 TWh/y using Eq. (10) over all the IRIS. The cooling demand was also estimated in other studies: 58.5 TWh/y in a report from the Joint Research Centre of the European Commission (JRC) [35], 18 TWh/y for [29] and 20.9 TWh/y for [30]. These estimations are far from each other, and that mainly is due to the lack of data requiring to make many assumptions. Our estimation corresponds roughly to the average of the other studies.

4.2. Heating and cooling district typologies

PBA90 category	RS category	Insufficient LHD: Number of IRIS	Sufficient LHD: Number of IRIS	Sufficient LHD: % of total IRIS
Lower	Lower	20	98	83.1
	Intermediate	20	97	82.9
	Higher	60	76	55.9
Intermediate	Lower	82	223	73.1
	Intermediate	518	678	56.7
	Higher	7770	1106	12.5
Higher	Lower	262	650	71.3
	Intermediate	1399	3019	68.3
	Higher	23,288	9002	27.9
Total		33,419	14,949	30.9

Table 1: Heating district typology: repartition of the IRIS per variable (PBA90, RS, LHD)

The typology is based on the categories described in Section 3.5. Table 1 gives the number of IRIS associated to each of the 18 possible types of districts for the heating purpose. Among the 18 district types, DHN can be cost effective solutions, with a sufficient linear density, in 9 district types since their LHD are sufficient.

The results from Table 1 can be explained by the repartition and the structure of the IRIS. As mentioned in Section 3.1, each IRIS comprises an equivalent number of inhabitants (for the residential IRIS) or employees (for the commercial ones). Therefore, the lower the surface of the IRIS is, the higher the concentration of inhabitants/employees is, with a higher energy density (an equivalent energy consumption within a smaller surface). Thus, the IRIS with a sufficient LHD have an average surface of 3.7 km², compared to 14.2 km² for those with an insufficient LHD. Moreover, the IRIS with a sufficient LHD are mainly located in the most populated cities in France (the 280 cities with more than 30,000 inhabitants, see[36]). The IRIS with a sufficient LHD are on average 8.3 km away from those city centres versus 28.7 km for the IRIS without a sufficient LHD. IRIS with a high share of old buildings and a high share of energy consumption from the residential sector are the most prevalent. The existing DHN are present on 2898 IRIS and among all those IRIS, 2815 (97.1%) belong to the category of sufficient LHD.

The IRIS with a sufficient LCD have an average surface of 1.5 km², compared to 12 km² for those with an insufficient LCD. Moreover, the IRIS with a sufficient LCD are located close to the biggest cities: the IRIS with a sufficient LCD are on average 4 km away from those city centres versus 24.4 km for the IRIS

PBA90 category	RS category	Insufficient LCD: Number of IRIS	Sufficient LCD: Number of IRIS	Sufficient LCD: % of total IRIS
Lower	Lower	51	67	56.8
	Intermediate	71	46	39.3
	Higher	113	23	16.9
Intermediate	Lower	213	92	30.2
	Intermediate	955	241	20.2
	Higher	8623	253	2.9
Higher	Lower	631	281	30.8
	Intermediate	3151	1267	28.7
	Higher	29,784	2506	7.8
Total		43,592	4776	9.9

Table 2: Cooling district typology: Repartition of the IRIS per variable (PBA90, RS, LCD)

without a sufficient LCD. The IRIS with a sufficient LCD are smaller, closer to the city centres and have a higher share of collective dwellings (in comparison to the IRIS for DHN).

4.3. Heating district potential

The IRIS that belong to the category Sufficient LHD are considered to be a candidate to host a DHN. The potential of DHN development is calculated based on the methodology presented here above and results in an additional heating consumption of 106 TWh/y which could be covered by DHN. Considering the heating demand already covered by the existing DHN [14, 15], the total heating demand that can potentially be supplied by DHN is of 132 TWh/y, which is a more conservative estimation than [9] that estimated the DHN potential to be 330 TWh/y, despite an energy density of at least 1.5 MWh/m²/y. Two reasons explain the lower potential in our study. Firstly, [9] considers a heating consumption is of 524 TWh/y, but only 481.1 TWh/y in our study. Secondly, and more important reason, the density is calculated in a different way: [9] considers the energy density per tile (with a resolution of 200 m × 200 m), calculated from the heat consumption per tile (kWh) and the heat demand density (kWh/m²) per region. Therefore, each tile is considered independently from the others and the number of buildings is not taken into account, a network can potentially be created with a single building. In our methodology, a DHN is created if it connects at least 6 buildings.

Fig. 9 shows that there is a huge potential for the installation of new DHN in a variety of districts. Among the 48,368 IRIS studied, 12,134 (25%) have the potential to host a new DHN, in addition to the 2,898 that already host one. IRIS with a high share of energy consumption from the residential sector, especially the IRIS with old constructions, have the lowest proportion of potential DHN. Those IRIS are found in rural and suburban areas, with many individual dwellings, therefore with a low linear energy density. At the opposite, a high ratio of DHN and potential DHN can be found in recent district and/or districts with a medium to high ratio of commercial buildings. The IRIS with recent constructions are situated in the suburban areas close to the cities, therefore implying a high concentration of buildings. The commercial buildings are on

average bigger making them good candidates to be connected to a DHN.

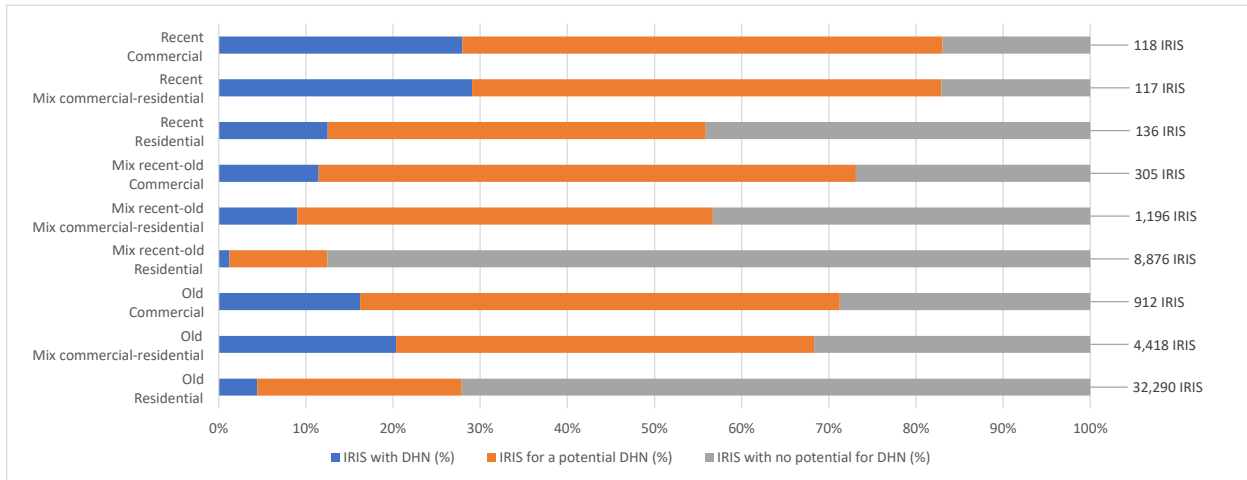


Fig. 9: Share of actual DHN and potential DHN on the IRIS, by district type

Splitting the 15,028 IRIS with a sufficient LHD in terciles, we distinguish: a high category with a LHD superior to 3.5 MWh/m/y, where the IRIS are mostly in or very close to the city center, a medium category with a LHD comprised between 1.7 MWh/m/y and 3.5 MWh/m/y, close to the city center, and a lower category with a LHD comprised between 1 and 1.7 MWh/m/y, mostly found in the suburban area, as shown in Fig. 10.

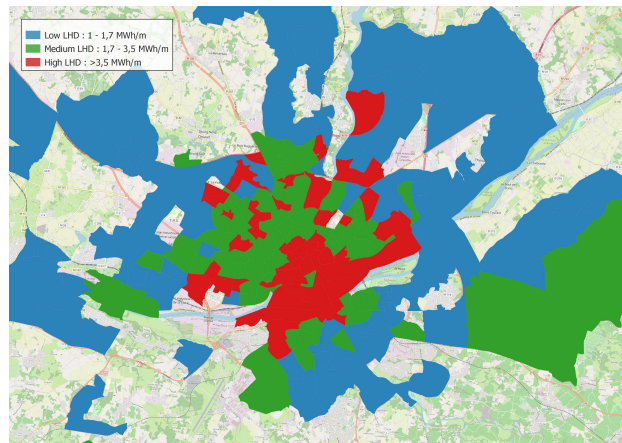


Fig. 10: Example of potential LHD in the City area of Nantes (44)

Almost all the IRIS with a sufficient LHD are situated in urban or suburban areas and in large population bases, along the coast, the French rivers, and the country borders as shown Fig. 11, following the same scheme as for Fig. 10, i.e. a high density in the city centres and in IRIS with a high concentration of commercial buildings, decreasing as the IRIS is further away from the city centres. The IRIS with the highest LHD

are located in the northern part of France, where the climatic harshness is more important, and in highly populated metropolitan areas.

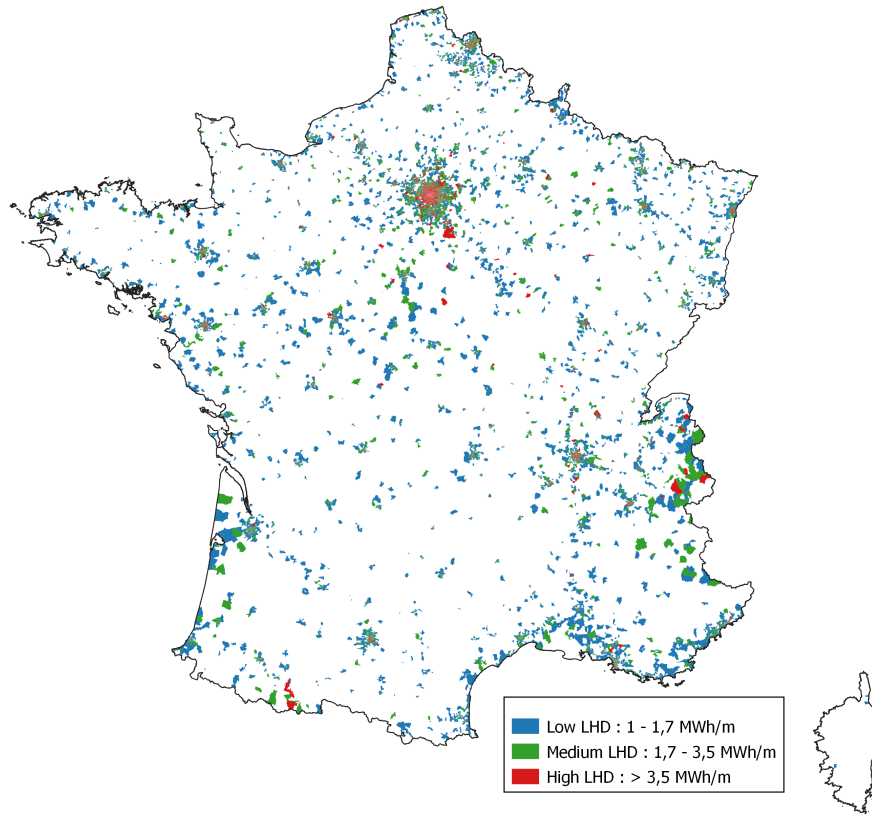


Fig. 11: Potential LHD for France

4.4. Cooling district potential for the commercial sector

The Cooling potential for DCN is way lower than the heating potential. There are only 4776 IRIS that meet the cooling density requirement of 1.5 MWh/m/y, for a total potential of 7.8 TWh/y, which represents a cooling demand of 6.9 TWh/y in addition to the 0.9 TWh/y already covered by current [14, 15]. This represents 28% of the commercial sector cooling demand. Those IRISs are either in commercial suburban areas or in the city centres, with enough commercial buildings to be connected (Fig. 12). As a result, those buildings are prone to have a sufficient cooling demand and to be close enough to other commercial buildings to create a DCN.

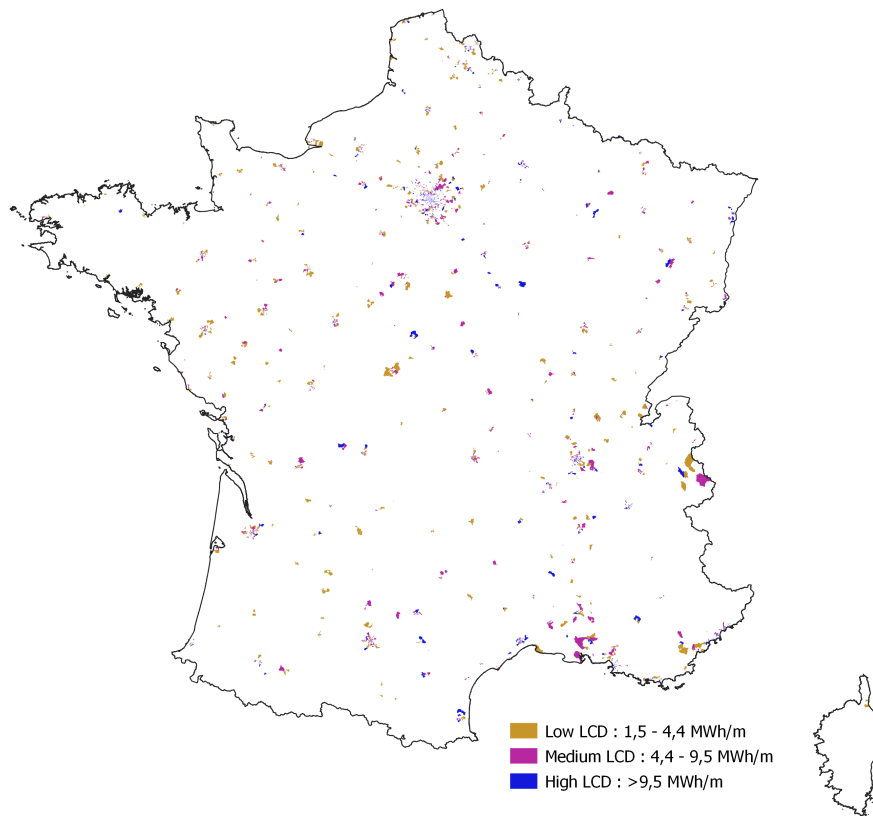


Fig. 12: Potential LCD for France

The IRIS that can host a DCN are concentrated around the most populous cities, as shown in Fig. 12, where the commercial sector areas are located. DCN is sparsely developed: a DCN is currently present only on 40 IRIS.

Splitting those IRIS in terciles, we get a different spatial repartition for the cooling demands, as can be seen in Fig. 13, with the highest potential not being concentrated in the city centers but being more spread in the city and the suburban area. The split between the terciles happens at 4.4 MWh/m/y and 9.5 MWh/m/y. Fewer IRIS have the potential to host a DCN. Those are either in commercial suburban areas or in the city centres, with enough commercial buildings.

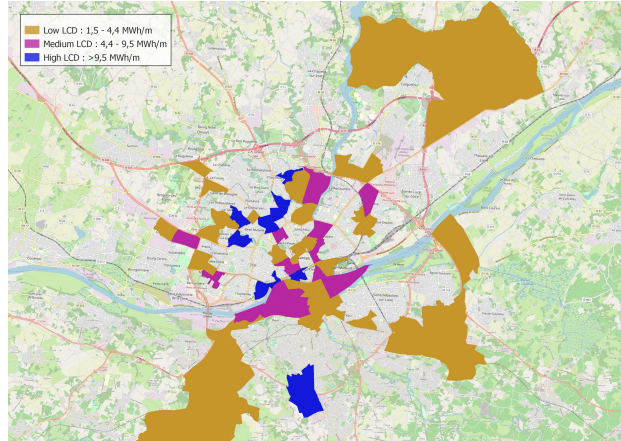


Fig. 13: Example of potential LCD in the City area of Nantes (44)

Among the 4776 IRIS that have potential to host a DCN, 4602 (96.4%) can also host a DHN, creating synergies for simultaneous distribution of heat and cold energy. 61% of those IRIS have a high LHD and 28% have a middle LHD.

5. Discussion

The agricultural sector and the industrial sector were not taken into account in this study. Yet, the agricultural sector is essentially present in rural areas where the DCHN potential is low. The industrial sector is potentially interesting for DHCN applications. [37] estimates that the heating consumption for water under 100°C, comprising space heating, hot water and process heating, is 63 TWh per year in France, whereas [38] calculates a cooling demand of 11.3 TWh per year. Currently, only 7% of the DHCN deliver energy to the industrial sector. Additionally, there is a lack of local data regarding those two sectors.

Assumption was made that heating oil and wood are mostly used in areas with an energy density too low for the implementation of DHCN and therefore were not considered.

The cooling for the residential sector was considered negligible but it is expected to increase in the future. However, the cooling demand in residential is diffuse and limited to short periods during heat waves. The connection of residential buildings to the DCN seems to be poorly cost-effective except in dense cities and in the hottest zones such as south of France. The estimate of cooling demand in residential in France is quite uncertain due to the lack of data. As evidence, [29] estimates a cooling need in France of 4 TWh for residential sector, against only 1 TWh for [25].

This work presents the opportunities for developing DHN/DCN. Almost every network is over several IRIS. Therefore, every IRIS with at least one building that connects to a virtual network was considered in the method developed. Thus each IRIS on its own may not have enough buildings to host a DHN/DCN, but is part of a set of IRIS that together meet the requirements for a DHN/DCN. Those requirements were

defined in this paper as considering solely: buildings with a floor area of at least 1000 m², DHN that connect 6 buildings (DCN that connect 4 buildings) with a heating density of at least 1 MWh/m/y (cooling density of at least 1.5 MWh/m/y).

6. Conclusion

This paper presents first the evolutions of the DHCN in France, in particular concerning the reduction of the networks size, the decrease of their energy density, and the increase of the mix between residential and commercial.

Then, an original method was developed to define a typology of districts from the point of view of the integration potential of DHN and DCN, based not only on the linear energy density, but also taking into account two other parameters important for the networks, the levels of temperature to be delivered (depending on the proportion of old buildings) and the mix between residential and commercial buildings.

Eighteen district types are defined and, among them, nine could have the potential for DHN and/or DCN integration. A study has been carried out in France on the scale of the IRIS corresponding to about 10 000 inhabitants and in which statistical information is provided. The results show a high potential for developing the DHN and DCN. About 24.9% of the IRIS in France could be candidate for implementing a DHN, a potential largely superior to the French objectives to develop the DHN at horizon 2028 [3]. The development potential of DCN seems also very important with about 10,000 new possible IRIS equipped with a network. This potential of new and extension of DHN should be crossed with the availability of renewable energies at local scale since the main objective to develop DHN is to increase the share of renewable energies in the heating consumption.

We defined a district typology which highlights certain district types for their potential for integrating heating and/or cooling networks. It could be interesting to focus on those types of district and to assess, for each type, the best possible network design(s). Then a mapping of available local energy sources would be requested to validate the economic feasibility of the networks. Finally by considering both the district types and the local energy sources, it could be interesting to assess the best possible designs.

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