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# Analysis of the district heating potential in French regions using a geographic information system

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## Abstract

With increasing pressure to meet sustainability and reduced greenhouse gas emission targets, district heating has become widely acknowledged as the future option for the urban heating sector. In France, public subsidies allocated to the development of such systems should reach 350 million euros by 2020, representing a 36% increase compared with 2018. Yet surprisingly little has been done to assess the district heating potential in this country. The purpose of this paper is therefore to provide this assessment. The demand for space heating and domestic hot water in residential and commercial buildings is first determined using data with a resolution of 200m×200m. The linear heat density of the potential district heating networks is then calculated for each of the 5,356,608 grid cells. The 43,565 agglomerations where district heating could reach a linear heat density exceeding 1.5 MWh<sub>th</sub>/m.a represent 62% of the total heat demand. Even in a scenario where the heat demand uniformly decreases by 50% due to the penetration of energy-efficient buildings, the district heating potential remains 5 times greater than current district heating deliveries. However, the identified potential cannot be fully unlocked due to the widespread use of individual heating systems. French legislation should evolve so as to discourage people from equipping new urban dwellings with individual electric or gas boilers and to encourage the development of district heating networks in dense areas.

## Keywords

District heating, Geographic Information System, Heat mapping, Urban

## Highlights

- A spatial analysis of the district heating potential in France
- District heating of 1.5-4.0 MWh<sub>th</sub>/m.a could supply 26% of the 2015 heat demand
- District heating of 4.0-8.0 MWh<sub>th</sub>/m.a could supply 17% of the 2015 heat demand
- District heating exceeding 8.0 MWh<sub>th</sub>/m.a could supply 19% of the 2015 heat demand

## 1. Introduction

The fundamental idea of district heating (DH) is *“to use local fuel or heat resources that would otherwise be wasted in order to satisfy local customer demands for heating, by using a heat distribution network of pipes as a local market place”* [1]. The DH systems in the European Union have been faithful to this notion, achieving 27% renewable and excess heat sources (geothermal, biomass, waste, solar and biogas) and 56% recycled heat from fossil cogeneration plants [1]. In France, these sources represent 53% and 16% of the respective DH sources mentioned above [2].

While France is considered by many historians as the country to have implemented the first DH system (in Chaudes-Aigues, a small town close to Lyon in the 14<sup>th</sup> century [3]), it has since become a ‘DH learning-country’ compared with northern and eastern European countries. DH systems supply only 7% of the French national demand for space heating and domestic hot water in residential and commercial buildings (hereafter simply referred to as ‘heat demand’) [4].

However, French DH deliveries are rapidly increasing. Deliveries of renewable or excess DH sources increased from 7.9 TWh<sub>th</sub>/a in 2009 to 13.8 TWh<sub>th</sub>/a in 2017 [2]. This leap can be partly attributed to the public DH support set up by the government in 2009 [5]. The ‘Fond Chaleur’ offers a financial contribution of about €5/MWh<sub>th</sub> to DH projects aiming to use more than 50% renewable or excess heat sources, provided that the linear heat density exceeds 1.5 MWh<sub>th</sub>/m.a [5]. Within this context, our knowledge of the DH potential in France needs to be further expanded.

## 2. Research scope

This paper aims at providing a clearer understanding of the DH potential in France with the final objective of encouraging its development. For this reason, the DH potential has been assessed using a geographic information system (GIS). With increasing focus on the importance of local conditions for heat planning and the progress made in GIS and computer technology, the need for spatial methods such as GIS in heat planning is gaining ground. GIS-based analysis of the DH potential has been used by several countries. [6] revealed that 63% of the Danish built-up area is suitable for DH, and [7] showed that 5.1% of the current Danish DH demand could be supplied by industrial excess heat from thermal processes, using direct heat transfer or heat pumps. Regarding the United States, [8] highlighted that 43% of residential and commercial heating could be cost-effectively supplied by DH systems. A heat atlas for Baden-Württemberg in Germany was produced by [9] to identify model regions for heat supply. Similarly, [10] has prepared an excess heat atlas for Saxony, while [11] has developed commercial software for a heat atlas for all of Germany. In the UK, national heat atlases [12] as well as atlases for London [13], Scotland [14] have been produced, and [15] have evaluated the local DH potential in Matlock, Bakewell and Darley Dale. Concerning Switzerland, [16] has showed that DH systems could supply 40% of the current built-up area (representing 66% of the

current national heat demand) and 26% of the built-up area (representing 53% of the national heat demand in this scenario) in an energy saving scenario where the heat demand of building is uniformly reduced by 50%. An interesting study focuses on the potential of DH in Europe [17], examining possibilities based on the NUTS3 classification instead of using the usual national perspective. The recent heat roadmap for Europe [18] has provided valuable information for GIS-based DH research. [19] and [20] have drawn on [18] to assess local heat supply strategy and DH distribution cost in the European Union. [19] highlighted that 71% of the heat demand within the 14 studied European countries could be cost-effectively supplied with DH. [19] also provides interesting indication on the amount of excess heat, solar, geothermal and biomass resources which could be mobilised to supply the identified DH potential. [20] evaluates a setting where DH is individually expanded in each member state for reaching a common 50% heat market proportion in the European Union at lowest cost. At this saturation rate, the aggregated DH deliveries would increase to 1500 TWh<sub>th</sub>/a at current heat demands and represents an expansion investment volume, starting from current level of 361 TWh<sub>th</sub>/a, of approximately 270 billion euro for heat distribution pipes.

Surprisingly, however, little effort has been made to analyze the potential expansion of DH in France. This paper sets out to fill this research gap by answering two key questions:

- What is the DH potential in the current context in France, both on a regional and a national level?
- What is the DH potential if the heat demand in buildings is uniformly reduced by 50% (the target set by national authorities for 2050; see [21])?

This study focuses on the linear heat density (MWh<sub>th</sub>/m.a) of potential DH systems in order to determine the economic feasibility of the distribution side [6]. This approach has the advantage of allowing each stakeholder to form its own opinion of the DH potential based on transparent indicators. The drawback is that it does not allow us to determine whether implementing DH networks in the identified areas will have a greater economic potential than individual heating solutions. To answer this question, future analysis could consider comparing the DH cost (including production, transmission and distribution costs) for each area against the least-expensive individual option (i.e. heat pumps in Denmark, see [6]).

The key added value of the paper is the quality of the data used, i.e. a resolution of 200m ×200m (see Section 3). Such a refined scale is crucial to reduce the uncertainty affecting GIS-based analysis of DH potential [22]. In a nutshell, this paper applies a known methodology (see Section 4) to the best available set of data for France. Results presented in Section 5 thus represent the most accurate estimation of the DH potential in France. Next steps and recommendations are discussed in Section 6.

### 3. Data collection

Most of the data used in this article were from [23], which provides the spatialized residential and commercial heat consumption (kWh<sub>th</sub>/a) for France in 2008 (data made available in 2015) using a resolution of 200m×200m. Data concern the entire space heating and domestic hot water consumption in French residential and commercial buildings, and can thus be covered by any type of heating system. This represents a total of 5,356,608 grid cells, thus implying time-consuming GIS calculations. Data from [23] concerned the 13 new French regions (there were 22 regions in France prior to 2015).

Given the method adopted in this paper (see Section 4), information on the specific heat demand (kWh<sub>th</sub>/m<sup>2</sup>.a) of buildings on a regional level also appeared to be crucial. Data collection was, however, difficult due to large variations in the quality of data sources from region to region. The change in number and geographic boundaries of the French regions in 2015 has made collecting data an even more complex task. Regional residential and commercial heat demands and building performance levels are not analyzed on a regular basis. Thus, the most recent studies often dated prior to the new regional configuration. Given that the spatialized heat demand from [23] is given for

the new regions only, the specific heat demand of these regions was required. Provided that the new regions always strictly comprised one or several of the previous regions,  $Q_N$ , the specific heat demand of residential and commercial buildings in these new regions ( $\text{kWh}_{\text{th}}/\text{m}^2.\text{a}$ ) was calculated according to equation (1):

$$Q_N = \sum_{i=1}^n w_i \cdot Q_{P,i} \quad (1)$$

where  $n$  is the number of previous regions composing the new region,  $Q_{P,i}$  is the specific heat demand of buildings in the previous region  $i$ , and  $w_i$  is the share of the heat demand of the previous region  $i$  in the total heat demand of the new region.

Table 1 shows the specific heat demand ( $\text{kWh}_{\text{th}}/\text{m}^2.\text{a}$ ; resulting from formula (1)), along with the population (millions capita) and heat demand ( $\text{TWh}_{\text{th}}/\text{a}$ ) of the new regions. While the specific heat demand will be used in the methodology presented in Section 4, the two other parameters are given only for informative purpose. For the sake of brevity, the 22 references of studies carried out by the public authorities in the 22 previous French regions (providing  $Q_{P,i}$  and  $w_i$  values) are not given in this paper. There were found on the official websites of the previous regional authorities. The publication dates of these 22 reports varied from 2005 to 2015. Due to the refurbishment and replacement of buildings, specific heat demands in 2015 can, however, be slightly different from what there were in 2010 or 2005. The values in Table 1 were extrapolated to 2015 to standardize the specific heat demands, taking into account the publication dates of reports and a 0.5%/year decreasing rate. Building heating consumption has been predicted to decrease by 0.5%/year during the 2008-2020 period in France according to the business-as-usual scenario in the ENTRANZE study [24], a research program supported by the European Commission.

	Population (millions)	Heat demand [23] ( $\text{TWh}_{\text{th}}/\text{a}$ )	Specific heat demand ( $\text{kWh}_{\text{th}}/\text{m}^2.\text{a}$ )
Auvergne-Rhône-Alpes	7.7	50.6	158
Bourgogne-Franche-Comté	2.8	31.7	201
Bretagne	3.3	17.6	144
Centre-Val de Loire	2.6	72.7	150
Corse	0.3	2.0	129
Grand Est	5.6	42.9	155
Hauts-de-France	6.0	73.7	160
Île-de-France	12.0	57.4	158
Normandie	3.3	25.4	175
Nouvelle Aquitaine	5.8	51.7	129
Occitanie	5.7	38.2	149
Pays de la Loire	3.7	30.7	145
Provence-Alpes-Côte d'Azur	5.0	29.4	122

**Table 1:** Population, heat demand and average specific heat demand by regions.

*Note: In this paper, the 'heat demand' refers to space heating and the domestic hot water demand for residential and commercial buildings.*

## 4. Methodology

### 4.1. DH distribution model

This paper uses the concept of effective width,  $w$  (m), to model the linear heat density of DH networks even in areas where no DH network is implemented, as defined in equation (2):

$$w = \frac{A_L}{L} \quad (2)$$

where  $A_L$  is the total surface area ( $m^2$ ), and  $L$  is the total length of DH pipes required to heat the buildings in the area. Based on real data from 83 EU cities (including 31 in France) in which DH provides on average 21% of the heat load, [25] shows that  $w$  can also be expressed as in equation (3):

$$w = 61.8 \left( \frac{A_B}{A_L} \right)^{-0.15} \quad (3)$$

where  $A_B$  is the total building space area ( $m^2$ ).  $A_B$  can be computed using equation (4):

$$A_B = \frac{Q_s}{Q_N} \quad (4)$$

where  $Q_s$  is the annual heat consumption in the given area ( $kWh_{th}/a$ ), and  $Q_N$  is the specific heat demand of buildings ( $kWh_{th}/m^2.a$ ). As explained in Section 3,  $Q_s$  is provided by [23] at a resolution of  $200m \times 200m$ , and  $Q_N$  is shown in Table 1 on a regional level.

By referring to formulas (2), (3) and (4),  $L$ , the total length of DH pipes required to connect all buildings in a given grid cell (m) can be calculated.  $Q_s/L$ , the linear heat density ( $MWh_{th}/m.a$ ), results directly from these computations.

#### 4.2. Identification of potential DH areas

Combined with the data collected in Section 3, the DH distribution model in Section 4.1 allowed us to identify grid cells in which the connection of all residential and commercial buildings to a DH network would result in a high linear heat density ( $MWh_{th}/m.a$ ). A high linear heat density is crucial for the economic viability of DH systems, since the capital costs of the distribution network dominate the DH system costs [25]. However, perceptions of DH feasibility thresholds are very diverse depending on stakeholder objectives. French public authorities consider that there is DH potential when the linear heat density exceeds  $1.5 MWh_{th}/m.a$  [4]. Above this threshold, low-carbon DH networks can apply for public subsidies [4]. It worth stressing that  $1.5 MWh_{th}/m.a$  is often seen as a conservative assumption by the DH literature. For instance, [7] has considered a feasibility threshold of  $5 GWh_{th}/km^2$  (about  $0.4 MWh_{th}/m.a$  with the method given in Section 4.1) to assess the DH potential in the United States.

In France, however, the average linear heat density of current DH networks varies from  $2.5 MWh_{th}/m.a$  in Corsica to  $6.7 MWh_{th}/m.a$  in Île-de-France [26]. To provide additional insight, this article considers three ranges of linear heat density,  $1.5-4.0 MWh_{th}/m.a$ ,  $4.0-8.0 MWh_{th}/m.a$  and above  $8.0 MWh_{th}/m.a$ . After eliminating all grid cells with a potential linear heat density falling outside the selected range, neighboring cells of corresponding linear heat density were grouped into agglomerations. In metropolitan areas, these agglomerations can have sizes representing many square kilometers, but there are also examples comprising a single cell. For further analysis, each agglomeration was assigned to one region before the annual heat demand ( $TWh_{th}/a$ ), the share of potential DH in the total heat consumption (%), and the average size of agglomerations ( $km^2$ ) were all determined. These parameters provide the basis for our analysis of the DH potential in France.

### 5. Results

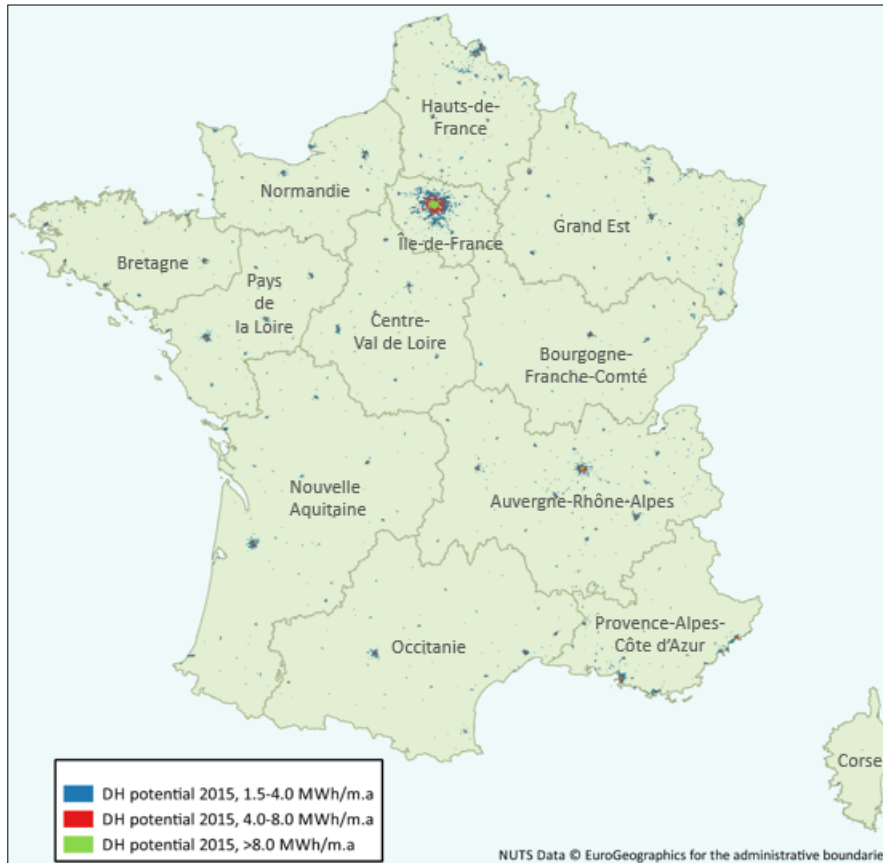
Considering the heat demand in 2015 and a minimum linear heat density of  $1.5 MWh_{th}/m.a$ , the overall DH potential was estimated at  $323 TWh_{th}/a$ , i.e. 62% of the total demand for space and hot water heating in residential and commercial buildings. The 43,565 agglomerations and the supplied heat are distributed rather unevenly across the country; half of the potential – around  $162 TWh_{th}/a$  – is located in the regions of Centre-Val de Loire, Hauts-de-France and Île-de-France (see Figures 1, 2, 3, 4, 5 and 6). Very little potential - less than  $1 TWh_{th}/a$  - is available in Corsica. Climate

conditions, specific heat demands and population urban densities explain the significant differences in the potential. This distribution of the potential is also reflected by the potential DH share in the total heat demand. It ranges between 40% in Bretagne to 86% in Île-de-France.

Figures 4 and 5 reflect the variation in the number and size ( $\text{km}^2$ ) respectively of the agglomerations in which DH is feasible. The average heat supply per agglomeration varies from 7.2 and 7.6  $\text{TWh}_{\text{th}}/\text{a}$  in Bretagne and Bourgogne-Franche-Comté respectively, to 31.6, 31.9 and 41.1  $\text{TWh}_{\text{th}}/\text{a}$  in Hauts-de-France, Centre-Val de Loire and Île-de-France respectively. Larger agglomerations offer greater opportunities for efficient DH systems regarding both the distribution side (larger agglomerations imply, on average, higher linear heat densities and lower heat losses) and the production side (larger agglomerations imply, on average, larger heat supply and production units, leading to higher efficiencies and economies of scale). These locations are thus particularly attractive for DH development in the short run.

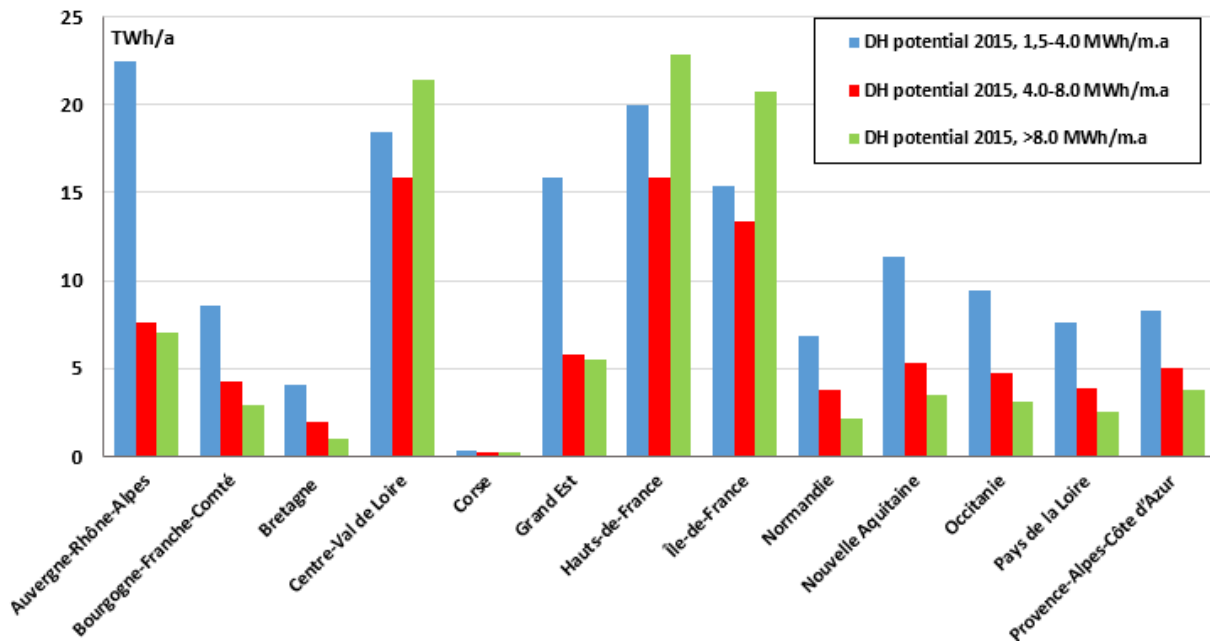
Taking into account the national policy objective of reducing the national heat demand by 50% in 2050 compared with 2015 [21], the DH potential has been assessed considering a uniform decrease in building consumption by 50% and a fixed population urban density. In this scenario (see Figure 6), the DH potential above 1.5  $\text{MWh}_{\text{th}}/\text{m}^2\cdot\text{a}$  is 122  $\text{TWh}_{\text{th}}/\text{a}$ , i.e. 46% of the total reduced heat demand. This is 5 times larger than current DH deliveries to French networks, which are shown in Table 2.

A fixed population urban density and a uniform decrease in building consumption by 50% was considered in order to provide a lower limit for the 2050 DH potential. In reality, the 2050 DH potential would likely be larger for at least three reasons. Firstly, the population urban density is increasing [27]. Secondly, a 50% reduction in the building consumption by 2050 relative to 2015 is an ambitious objective. If the renovation rate remains at 1% per year [28] and if all new buildings respect the French energy efficiency standards ( $40 \text{ kWh}_{\text{th}}/\text{m}^2$ ), the heat demand would be reduced by 15% and 30% towards 2030 and 2050, respectively. Yet, all new buildings do not respect the energy efficiency standards [4]. Besides, human behavior (e.g. windows being open or closed, temperature setting of the thermostatic valves in radiators) can lead to heat demand levels that are higher than those anticipated in prospective studies [29]. For example, the average temperature of French dwellings rose from 19°C to 21°C between 1986 and 2003 [30], implying that the heat demand reduction was lower than what could have been expected in 1986. If the effort to increase the rate of renovation and to inform consumers is not increased significantly, it is reasonable to expect a lower heat demand reduction than the 50% targeted by the French Energy Act [21]. Thirdly, the assessed 2050 DH potential (see Figure 6) does not consider the fact that the heat density thresholds for DH feasibility may decrease in the future. DH systems could indeed benefit from higher efficiency in buildings. If adequate measures are taken to minimize the return temperatures, lower temperature requirements in radiators would make it possible to reduce DH grid losses and pipe diameters [31]. In addition, DH utilities would be able to use plastic piping, which can be more cost-effective than conventional DH metal-based pipes [32]. Lower supply and return temperatures would also enable the further integration of renewable and excess heat sources, as well as a higher level of efficiency for conventional production units.



**Figure 1:** Spatial mapping of the DH potential in France according to the three linear heat density ranges

*Note: For computational reasons, Figure 1 uses grid cells of 1 km<sup>2</sup>. All results and other figures in this paper are based on 200×200m grid cells (25 smaller), as explained in Section 3.*



**Figure 2:** Potential DH heat consumption (TWh<sub>th</sub>/a) for three ranges of linear heat density



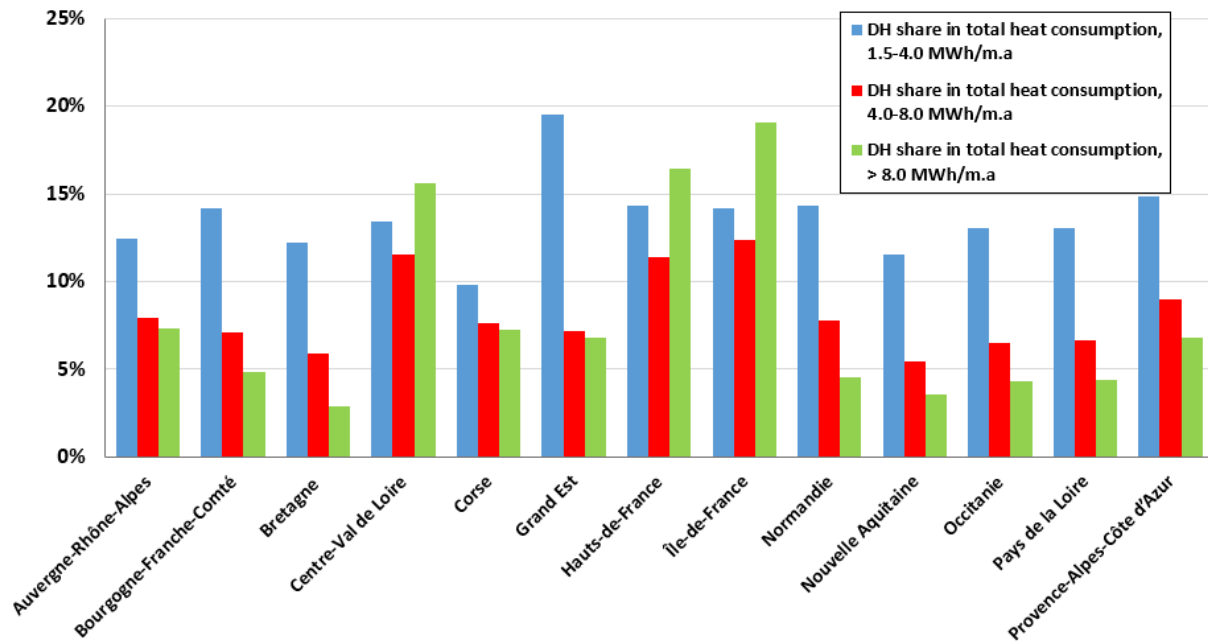


Figure 3: DH share in the total heat demand (%) for three ranges of linear heat density

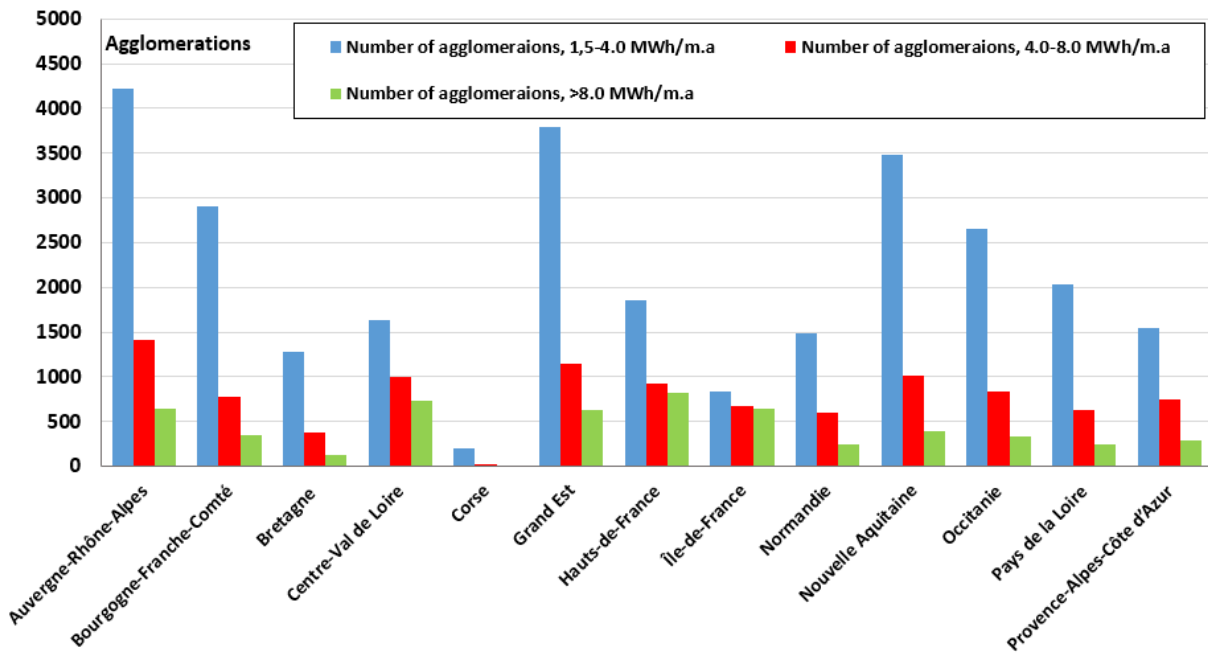
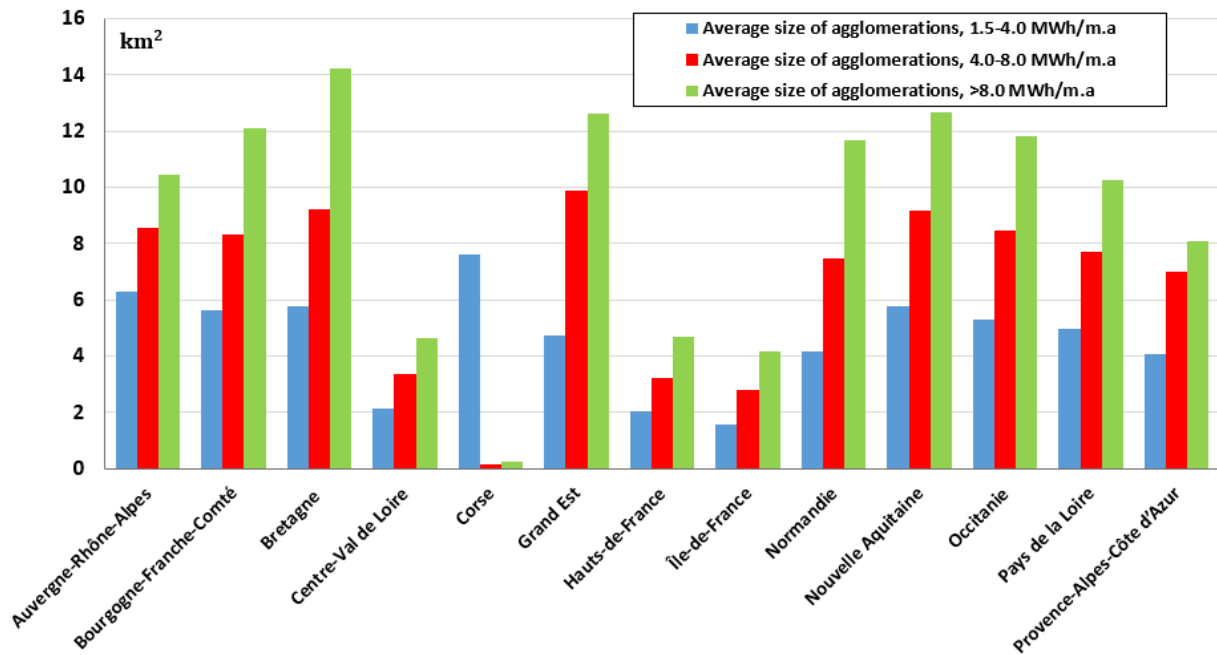
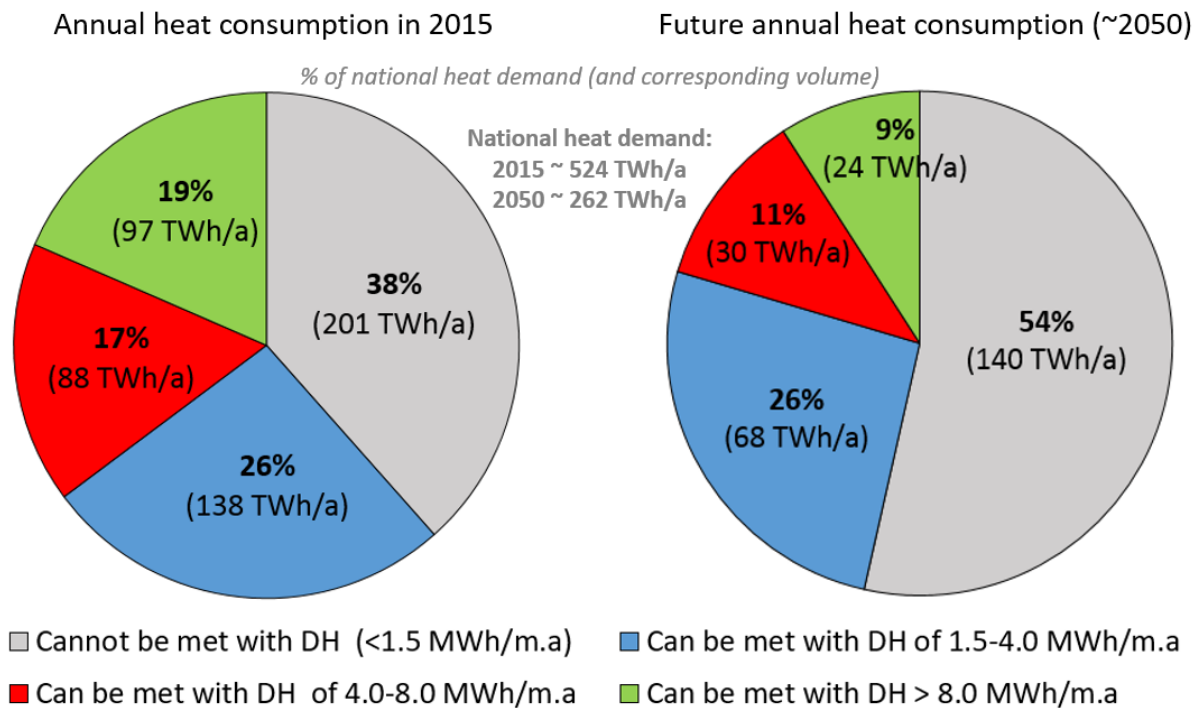


Figure 4: Number of agglomerations corresponding to the DH potential identified in Figure 2



**Figure 5:** Average size of agglomerations (km<sup>2</sup>) corresponding to the DH potential identified in Figure 2



**Figure 6:** Present and future heat consumption that could be met (>1.5 MWh/m.a) or could not be met (<1.5 MWh/m.a) with DH. Left: DH potential based on the 2015 heat demand. Right: DH potential when the 2015 heat demand is uniformly reduced by 50%.

## 6. Next steps and recommendations

While this article offers a sound preliminary estimate of the DH potential in France, the fact remains that a certain number of simplifications were used. Firstly, the heat demand density map

tends to underestimate the demand because this analysis is limited to the residential and commercial sector while neglecting the industrial process heat demand. Secondly, the assessed DH potential includes all agglomerations, even those which may be too small for economic exploitation. Future GIS studies should account for these two points if possible. Thirdly, the approach here adopted relies on an empirical correlation between the heat density in a given area ( $\text{GWh}_{\text{th}}/\text{km}^2$ ) and the DH pipes required to connect all buildings in this area (see Section 4.1). This correlation assumes that the geographic properties of areas with the same heat density level are similar, while in reality they can differ significantly. To improve the accuracy of the assessment, future research could use existing geographic entities based on the road network, similar to what was done in [33] and [34].

It must also be noted that the identified DH potential cannot be fully unlocked due to the widespread use of individual heating systems. Buildings without central heating systems cannot be connected to DH without refurbishing the heating infrastructure. In France, only 17.6% of residential buildings are equipped with central heating systems (see Table 2). In collective buildings, individual heating systems (e.g. electrical heater, heat pump, gas boiler) deserving one single apartment are less efficient and generate higher operational costs than central systems designed to deserve the whole building (see Danish Energy Agency reports, or [4]). However, most new French collective buildings still install individual electric or gas boilers [4]. The future French legislation for building energy consumption (under discussion, to be applied from 2020) should encourage the installation of central heating systems in new urban buildings so as to increase efficiency, lower operational costs, and progressively unlock the DH potential.

In 2019, the national authorities decided to increase the public support fund ('Fonds Chaleur') up to 350 million euros by 2020, representing an increase of 36% compared with 2018 [35]. Given the long-term DH potential identified in this paper, it is reasonable to say that this money has been well invested. However, the national scheme [35] nevertheless projects a reduction in government funding from 2022. Such a signal regarding the long-term stability of public involvement may inhibit the development dynamics, which need to be accelerated to reach the national target. If the DH development trend of 2009-2017 is extended, renewable and excess DH deliveries will total 23  $\text{TWh}_{\text{th}}/\text{a}$  in 2030 [3], while the national 2030 objective is 31-36  $\text{TWh}_{\text{th}}/\text{a}$  [35].

To increase connection rates, DH players should focus on building consumer trust. This requires greater transparency in heating tariffs, simplified access to data and smart metering systems [36]. Recent initiatives from DH operators such as Dalkia (implementing a smart digital platform for the Clervia network) or Engie (simplifying heating tariffs for the Sevrans system) can serve as examples of best practices. The process of exchanging knowledge between multiple players and countries is also a crucial aspect of unlocking the DH potential in 'learning countries' such as France.

	DH deliveries ( $\text{GWh}_{\text{th}}/\text{a}$ ) (*)	Average linear heat density ( $\text{MWh}_{\text{th}}/\text{m.a}$ ) (*)	Number of DH networks (*)	DH share in total heat demand (**)	Central heating share in residential buildings [37]
Auvergne-Rhône-Alpes	3024	3.9	145	4.8%	21%
Bourgogne-Franche-Comté	1160	3.3	58	4.5%	16%
Bretagne	577	4.1	22	2.6%	7%
Centre-Val de Loire	857	6.1	23	3.6%	11%
Corse	9	2.5	1	0.3%	4.4%
Grand Est	2610	4.4	85	4.4%	17%
Hauts-de-France	1467	4.0	45	2.7%	11%
Île-de-France	11445	6.7	102	12.0%	38%
Normandie	1253	4.6	44	4.4%	15%
Nouvelle Aquitaine	668	4.1	51	1.3%	7%
Occitanie	548	3.0	41	1.4%	6%
Pays de la Loire	640	2.8	26	2.2%	10%

Provence-Alpes-Côte d’Azur	338	3.3	27	1.2%	19%
<b>TOTAL (or average)</b>	<b>24596</b>	<b>(4.8)</b>	<b>670</b>	<b>(7%)</b>	<b>(15.4%)</b>

**Table 2:** Existing DH networks by region

(\*) All data is from [2] except for the Corsica and Provence-Alpes-Côte d’Azur regions given that this reference not provide separate statistics for these two regions. Data from [26] was used instead.

(\*\*) Data from [2] and [26] was combined with data from the column 3 of Table 1.

## 7. Conclusion

This paper provides the best available assessment of the district heating potential in France on a regional level. In 2015, the 43,565 agglomerations with district heating potential exceeding 1.5 MWh<sub>th</sub>/m.a represented 323 TWh<sub>th</sub>/a, which is about 13 times higher than the current district heating deliveries. Towards 2050, the estimated lower limit for the DH potential is 122 TWh<sub>th</sub>/a, 5 times higher than the current deliveries. The DH potential is distributed rather unevenly across the country. The regions of Centre-Val de Loire, Hauts-de-France and Île-de-France represent half of the potential in volume. Other regions also hold potential for district heating creation or extension. The fact nonetheless remain that a robust life cycle analysis must be led before any implementation in order to determine whether the environmental benefits of the planned district heating schemes are greater than those of efficient individual systems such as heat pumps.

## References

- [1] Werner S. International review of district heating and cooling. *Energy* 2017;137:617–31.
- [2] SNCU (French National Union for District Heating). Enquête annuelle sur les réseaux de chaleur et de froid. Rapport 2017. Edition nationale [In French]. 2017.
- [3] Wiltshire R. Advanced district heating and cooling (DHC) systems. Cambridge: Woodhead Publishing Ltd. 2015.
- [4] AMORCE (French district heating association). Comparatif des modes de chauffage et prix de vente de la chaleur. Data for 2014 [in French]. 2015.
- [5] ADEME (French Agency for Environment and Energy Supervision). 13ième Rencontres des réseaux de chaleur (13th national DH meeting). Round Table of the 12/12. Presentation by Rémi Chabrilat [In French]. 2017.
- [6] Nielsen S, Möller B. GIS based analysis of future district heating potential in Denmark. *Energy* 2013; 57:458–68.
- [7] Bühler, F., Petrović, S., Karlsson, K., Elmegaard, B., 2017. Industrial excess heat for district heating in Denmark. *Applied Energy* 205, 991–1001.
- [8] Gils HC, Cofala J, Wagner F, Schöpp W. GIS-based assessment of the district heating potential in the USA. *Energy* 2013; 58:318–29.
- [9] Blesl M, Kempe S, Ohl M, Fahl U, König A, Jenssen T, Eltrop L. W. Armeatlas baden-württemberg, endbericht (Heat atlas for baden-württemberg, final report). University of stuttgart. Institut für Energiewirtschaft und Rationelle Energieanwendung. 2009.
- [10] Sächsische Energieagentur GmbH. Armeatlas Sachsen [in German].
- [11] Geomer: Wärmeatlas Deutschland [in German].
- [12] Centre for Sustainable Energy (CSE): UK Heat Map.
- [13] Mayor of London: London Heat Map.
- [14] Scottish Government: Scotland’s Heat Map.

- [15] Brocklebank, I., Styring, P., Beck, S., 2018. Heat mapping for district heating. *Energy Procedia*, 3rd Annual Conference in Energy Storage and Its Applications, 3rd CDT-ESA-AC, 11–12 September 2018, The University of Sheffield, UK 151, 47–51.
- [16] Chambers, J., Narula, K., Sulzer, M., Patel, M.K., 2019. Mapping district heating potential under evolving thermal demand scenarios and technologies: A case study for Switzerland. *Energy* 176, 682–692.
- [17] Connolly D, Lund H, Mathiesen BV, Werner S, Möller B, Persson U, et al. Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. *Energy Policy* 2014; 65:475–89.
- [18] Heat Roadmap Europe. Heat Roadmap Europe 2050. Research project co-funded by the European Commission. Peta, the Pan-European Thermal Atlas: renewable energy. 2015.
- [19] Möller, B., Wiechers, E., Persson, U., Grundahl, L., Lund, R.S., Mathiesen, B.V., 2019. Heat Roadmap Europe: Towards EU-Wide, local heat supply strategies. *Energy* 177, 554–564.
- [20] Persson, U., Wiechers, E., Möller, B., Werner, S., 2019. Heat Roadmap Europe: Heat distribution costs. *Energy* 176, 604–622.
- [21] Assemblée nationale (French national assembly). Loi n° 2015–992 du 17 août 2015 Relative à la transition énergétique pour la croissance verte, 2015–2992 [In French]. 2015.
- [22] Jalil-Vega, F, Hawkes, A.D, 2018. The effect of spatial resolution on outcomes from energy systems modelling of heat decarbonisation. *Energy* 155, 339–350.
- [23] CEREMA (French Research Centre on Risks, Environment, Mobility and Territorial Planning). Carte nationale de chaleur – France [in French]. 2015.
- [24] ENTRANZE. Policies to ENforce the TRAnSition to Nearly Zero Energy building in the EU27. 2014.
- [25] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. *Applied Energy* 2011; 88:568–76.
- [26] Viaseva. L’annuaire des réseaux de chaleur et de froid. Edition 2016/2017 [in French]. 2017.
- [27] INSEE (French national institute for statistics and economic studies). Projections de population à l’horizon 2050. 2017.
- [28] Chirat, J-P, Denisart, F, 2016. Nouvelles dynamiques de rénovation des logements. Rapport de synthèse et proposition. Jean-Pascal Chirat (Club de l’Amélioration de l’habitat) et Frédéric Denisart (Conseil National de l’Ordre des Architectes) [in French].
- [29] Dalla Rosa, A, Christensen, J.E. Low-energy district heating in energy-efficient building areas. *Energy* 2011; 36:6890–6899.
- [30] ADEME (French Environment and Energy Management Agency), 2008. « Economies d’énergie. Faisons vite, ça chauffe ! » [in French].
- [31] Averfalk H, Werner S. Essential improvements in future district heating systems. *Energy Procedia* 2017; 116:217–25.
- [32] Schmidt D, Kallert A, Blesl M, Svendsen S, Li H, Nord N, et al. Low Temperature District Heating for Future Energy Systems. *Energy Procedia* 2017; 116:26–38.
- [33] Nielsen S. A geographic method for high resolution spatial heat planning. *Energy* 2014; 67:351–62.
- [34] Unternährer J, Moret S, Joost S, Maréchal F. Spatial clustering for district heating integration in urban energy systems: Application to geothermal energy. *Applied Energy* 2017; 190:749–63.
- [35] Ministère de la Transition écologique et Solidaire. Stratégie française pour l’énergie et le climat. Programmation pluriannuelle de l’énergie. 2019–2023. 2024–2028 [in French]. 2019.
- [36] AMORCE. 9 propositions du comité national des acteurs des réseaux de chaleur [in French]. 2017.
- [37] INSEE (French National Institution for Statistics and Economics Studies). Logements en France [in French]. 2014.