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A spatially-explicit method for generating prospective district heating scenarios

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ABSTRACT

District Heating Networks (DHNs) constitute a potentially powerful lever to decarbonise the heating supply and provide flexibility to power systems soon to be dominated by solar and wind production. To accurately quantify this potential, one needs to project the development of DHNs and their production mix. This article proposes a method for generating large-scale district heating development scenarios based on geographical data. The main inputs used to project DHN development are: spatial datasets of heat demand, spatial datasets of local low-carbon heating sources, spatial datasets of existing DHNs associated with corresponding supplied energy, and representative DHN cases. Taking these factors into account narrows the range of possibilities for the DHN production mix, providing more realistic scenarios while keeping the option to explore contrasted development paths. This method represents an advancement in DHN prospective as it combines precise local source potential assessment with scenario generation. As a case study, we apply the method on European Union countries and the United Kingdom (EU27+UK) for 2050 by generating three DHN scenarios: supplied energies of 820 TWh, 631 TWh, and 555 TWh, against 370 TWh currently. These three scenarios feature very diverse levels of local low-carbon source integration (accounting for excess heat, geothermal, biomass and solar): respectively 485 TWh, 388 TWh, and 337 TWh are harnessed; demonstrating how developing DHNs is crucial to harness local low-carbon heat sources. A focus on Denmark is performed to compare these results with established literature, and better understand what drives them. We complete this analysis by testing the sensitivity of local source potentials to various assumptions.

1. Introduction

1.1. The need for large-scale DHN scenarios

The objective to build a decarbonised, resilient, and cost-effective energy system is causing a paradigm shift in energy systems research. Moving from a previously segmented view of the different sub-sectors, the idea of studying the energy system as a whole to benefit from all of its synergies is now widely shared [1–14]. This approach of endogenously modelling the different energy carriers takes several names in the literature: multi-energy systems [1], smart energy systems [2], sector coupling [3], integrated energy systems [4], whole-energy systems [5] etc. Despite subtle differences, the main idea remains to model not only one energy carrier/sector but also other relevant components of the energy system. The main driver of this literature is to

assess the flexibility offered by coupled energy systems to meet energy demands using low-carbon resources cost-effectively. In particular, the potential benefits of more closely integrating District Heating Networks (DHNs) into the rest of the energy system are underlined by a series of studies [6,8,11,15–18]. Indeed, DHNs could offer flexibility to the power system through several means: flexible cogeneration plants (CHPs) [8,15,16], Heat Pumps (HPs) associated with heat storage [6, 11,17,18], DHN intrinsic flexibility,¹ and DHN thermal inertia [19–22]. These studies highlight the flexibility potential of DHN but do not precisely quantify the sensitivity of DHN flexibility contribution to DHN development paths, which is a crucial issue for energy planning. More generally, these studies would benefit from having a method for generating realist large-scale DHN scenarios.² These scenarios should

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¹ Production means are sized to meet annual peak demand so that they compete to produce the rest of the year. Therefore, if an energy vector is stressed and is more expensive than usual, the heat can be supplied with other sources.

² Here, a DHN scenario is a volume of heat demand supplied by DHNs and a production mix (sources and technologies).

Nomenclature

γ^{city}	Random draw from Gamma law for city. A law to be parameterized depending on the case study.
ADEME	Agence de l'Environnement et de la Transition Ecologique, French environmental agency
CAPEX	Capital expenditure
CHP	Combined Heat and Power
CLC	Corine Land Cover
DCN	District Cooling Network
DD_{2050}^{city}	Heat dense demand in the city in 2050
DHN	District Heating Network
dim^{size}	Energy produced by a unitary DHN. Size can be <i>large</i> or <i>small</i> . If there is a subscript s , it indicates the energy produced by the source s in this unitary DHN. If there is a subscript <i>case</i> , it is the energy produced in a DHN of type <i>case</i> .
E^{city}	Energy produced currently by city's existing DHNs. Equals to 0 if no DHNs.
E_{2050}^{city}	Energy produced by city's DHNs in 2050. Equals to 0 if no DHNs.
E_r^{2050}	Energy produced by DHNs in a region r in 2050. Subscript <i>local</i> restrains it to the energy produced by DHNs featuring local sources.
EU27 + UK	European Union countries and the UK
HOP	Heat-Only Plant
HP	Heat Pump
HRE	Heat Roadmap Europe
MILP	Mixed-Integer Linear Programming
nb_{city}^{size}	Number of potential DHNs in the city. Size can be large or small. If there is a subscript s , it indicates the number of potential DHNs supplied by heating source s . If there is a subscript <i>case</i> , it restrains the number to DHNs of type <i>case</i> .
P2H	Power-to-Heat
$pot_{city,s}^x$	Local potential of the source s for the DHNs of the city. Four types of potentials are described : $x \in [MAX; DD; DHN; DIM; COMP]$
SOFC	Solid Oxide Fuel Cell
TES	Thermal Energy Storage
UA	Urban Area
WWTP	Waste Water Treatment Plant

be geographically-detailed to feed precise DHN models and be parameterisable to quantify the impacts of different DHN production mix on the energy system's operation. Still, they should also cover a large perimeter as flexibility in multi-energy systems needs to be assessed with large-scale simulations.³ This paper addresses the need for geographically-detailed, parameterisable large-scale DHN scenarios.

³ For example, the power system cannot be modelled on a perimeter smaller than the European continent, or large parts of it, without blurring the flexibility provided by interconnections [6,23].

1.2. Literature review: projecting DHN development

1.2.1. National DHN scenarios

Existing DHN scenarios are mainly proposed by institutions at national levels. We review scenarios for Denmark and France. In the reports reviewed, [24–26] for France and [27–29] for Denmark, the design of DHN scenarios is part of a scenario for the whole national energy system. As a result, the method used to generate these DHN scenarios is often scantily described, and outputs' resolution is too limited to feed multi-energy simulations. Furthermore, there is no accurate spatial assessment of local sources: the IDA scenario [29] relies on expert assumptions for geothermal and solar thermal potentials for example. Therefore, the methods to produce DHN scenarios on a national scale seem not enough geographically-detailed and parameterisable to be used in large-scale multi-energy studies.

1.2.2. Geographical analysis to assess DHN potential

While the academic literature is relatively scarce on large-scale DHN scenarios, many studies assess DHN technical potential based on geographical analysis on a reduced perimeter (national or smaller perimeter). We analyse this literature to better understand the ins and outs of DHN prospective.

The first and foremost step to identify potential DHN zones is to map current total heat demand [30–35]. Indeed, heat demand density is the main parameter determining the competition between DHNs and individual heating: in a given zone (a neighbourhood typically), if total heat demand is beyond a certain threshold, then district heating is considered more economical than individual heating [36]. However, total heat demand is expected to significantly decrease due to climate change, thermal insulation politics and sufficiency behaviours. As DHNs are capital-intensive assets that will last for decades, projecting future heat demand is required to assess the relevance of DHN deployment or extension [30,33].

Once the mapping of (future) heat demand is completed, other geographical criteria may be considered to assess DHN potential more precisely. At the city scale, it is possible to consider local energy resources [35,37] or the street layout [37,38]. On a national scale, geographical analysis becomes more challenging as data may be lacking and computation time may become prohibitive. Nevertheless, some studies try to refine DHN potential analysis by taking more geographical criteria into account: insulation characteristics and share of residential consumption in [32], production transmission and distribution costs in [30,34].

Then, the heat demand is filtered to retain only the areas where DHNs are relevant. The aggregation of this heat demand gives a DHN deployment energy potential. All these geographical analyses give a maximum economic potential for DHN development as all these areas are conducive to developing cost-effective DHNs.

1.2.3. Extending the scope of DHN potential assessment studies: Heat Roadmap Europe and sEEnergies scenarios

Two European projects, Heat Roadmap Europe (HRE) [39] and sEEnergies [40] expand the DHN potential geographical analysis for several European countries with a standardised method: for each country, they create a decarbonised scenario for its 2050 energy system, with the purpose of fully harnessing the DHN flexibility potential [41–45].

Below is a summary of their methods used to quantify European DHN potential and determine an optimal development scenario, considering the whole energy system.⁴

First, future heat demand is mapped on European scale at a granularity of 100 m * 100 m. With a model detailed in [44], the heat

⁴ Several slightly different methods are tested in the two projects but the idea remains the same at the level of details considered.

demand raster is used to create a distribution cost curve at national scale (cumulative costs depending on the amount of heat supplied by DHN). Thanks to this curve, an optimisation is performed for each country, by running several simulations of the multi-energy model EnergyPLAN [46] with different levels of heat savings and DHN shares, and retaining the configuration minimising total costs. If this approach constitutes an improvement to DHN potential assessment methods as it considers heat savings, it still only generates one scenario per country and does not endogenously consider local heat sources.

1.2.4. Assessment of local heat source potentials

Another parallel approach developed in the HRE and sEnergies projects involves allocating local low-carbon heat sources (geothermal, solar, excess heat and biomass) to potential DHNs. Moller et al. [45] thus quantify the local heat suitable for supplying potential DHN, accounting for competition between sources and for some technical constraints such as heat demand seasonality. Their results constitute an upper limit to total local source potentials as they are computed assuming that all feasible DHNs are fully developed. A similar method is applied by Persson et al. [42] and Manz et al. [47], also involved in HRE and sEnergies projects, but focusing on how to recover excess heat to satisfy building heat demands, thus increasing European energy efficiency. They also use a European DHN database to compare excess heat currently potentially recoverable by existing DHNs with that potentially recoverable by new DHNs. Moreno et al. [35] refined this excess heat potential quantification for Denmark by taking into account the DHN's available baseload capacity. This is a major improvement as most local low-carbon sources are baseload and this characteristic effectively limits the potential that can be used in real DHNs.

To sum up, the HRE and sEnergies projects propose, on the one hand, optimised national 2050 DHN development scenarios within a European perimeter based on geographical analysis methods and, on the other hand, technical potential assessments of local DHN sources. A lack arises from the difficulty of linking these two parallel approaches. We address this gap in this article by developing a method combining precise potential assessments with scenario generation.

1.3. Research approach

This article presents a method for generating parametrisable DHN 2050 scenarios at large-scale that builds on literature's geographical analyses. The main idea is not to optimise DHN development at national scale, as HRE and sEnergies projects did, but to obtain parametrisable DHN scenarios based on explicit geographical assumptions. Hence, the research question addressed in this article is: **How to build large-scale DHN scenarios taking into account major local technical parameters, and especially precisely assess local source potentials?** Output scenarios are composed, for each city, of a DHN supplied energy and a production mix to supply the DHNs. The novelty of our approach is that large-scale results are constrained by the key local parameters of heat demand density, availability of local DHN heat sources, source production shares, and existing DHNs. The method jointly develops DHNs and corresponding local low-carbon sources. This approach ensures that assessments of potential sources are geographically coherent with DHN development.

Section 2 describes the method in detail. In Section 3, we first generate three European scenarios and analyse them. Then, we compare the Danish results with the literature. Finally, we perform a sensitivity analysis on French local source potentials to test the robustness of the results.

2. Description of a method for generating large-scale detailed DHN scenarios

2.1. Overview of the method

The core of the method is to project the development of DHN at city granularity to better consider the constraints of individual DHNs and their potential local sources.

We retain four different types of data necessary to project DHN development at the city scale:

- A heat demand spatial dataset to determine zones favourable to DHN development. Two attributes are necessary for each city: total heat demand and total dense demand. Dense demand is defined as the sum of heat demand in hectares with a demand above a certain threshold. *A priori*, dense zones can cost-effectively develop DHNs [36].
- A spatial dataset of local heat source potentials to identify synergies between heat availability and demand.
- A set of representative DHN cases with production shares for each source. It gives a simplified representation of real and prospective DHN temporal dynamics and consequently helps to assess the valuable potential of local heat sources more precisely. See an example in Table 1. A justification of the relevance of such representative cases can be found in [48].
- A spatial dataset of existing DHN and their current energy supplies. Indeed, to project DHN development it is essential to distinguish between cities where DHNs already exist and could be extended, from those where DHNs would be created from scratch.

This data constitutes the four "Technical datasets" in the remainder of the paper. An example of these will be displayed in the case study (Section 3.1.1).

To generate DHN development scenarios based on this data, we design a process that can be divided into 4 steps (see Fig. 1):

- Step 1. City classification according to their potential to develop DHN.
- Step 2. Differentiated DHN development in each city by 2050 according to their categories and modeller assumptions.
- Step 3. Reduction of local low-carbon heat source potentials for each city by successively considering spatial matching between demand and sources, production share of each source in a real DHN, and the competition between different local sources.
- Step 4. Aggregation of results at national scale and constitution of DHN national production mix depending on modeller inputs.

All of these steps are detailed in the following section.

2.2. Detailed method description

2.2.1. Step 1: City classification

The first step of the method is to classify cities into n mutually exclusive categories according to their theoretical suitability to develop DHN.

The default classification proposed in the method is in $n = 5$ categories. The two first categories feature cities with currently operational DHN: in the first category, cities with a ratio of local heat sources to dense demand above a certain threshold *thres*, and in the second one, cities below this ratio. This split aims at favouring the development of DHNs in cities where local sources are available in larger quantities. The value *thres* may be tuned depending on the studied region (see an example in Section 3.1.2). The third and fourth categories feature cities currently without DHNs, but with an annual dense demand volume sufficient to develop at least small DHNs i.e. with an annual dense demand (losses included) over 3.4 GWh in the method. This low limit is necessary to avoid developing extremely small DHNs that would not

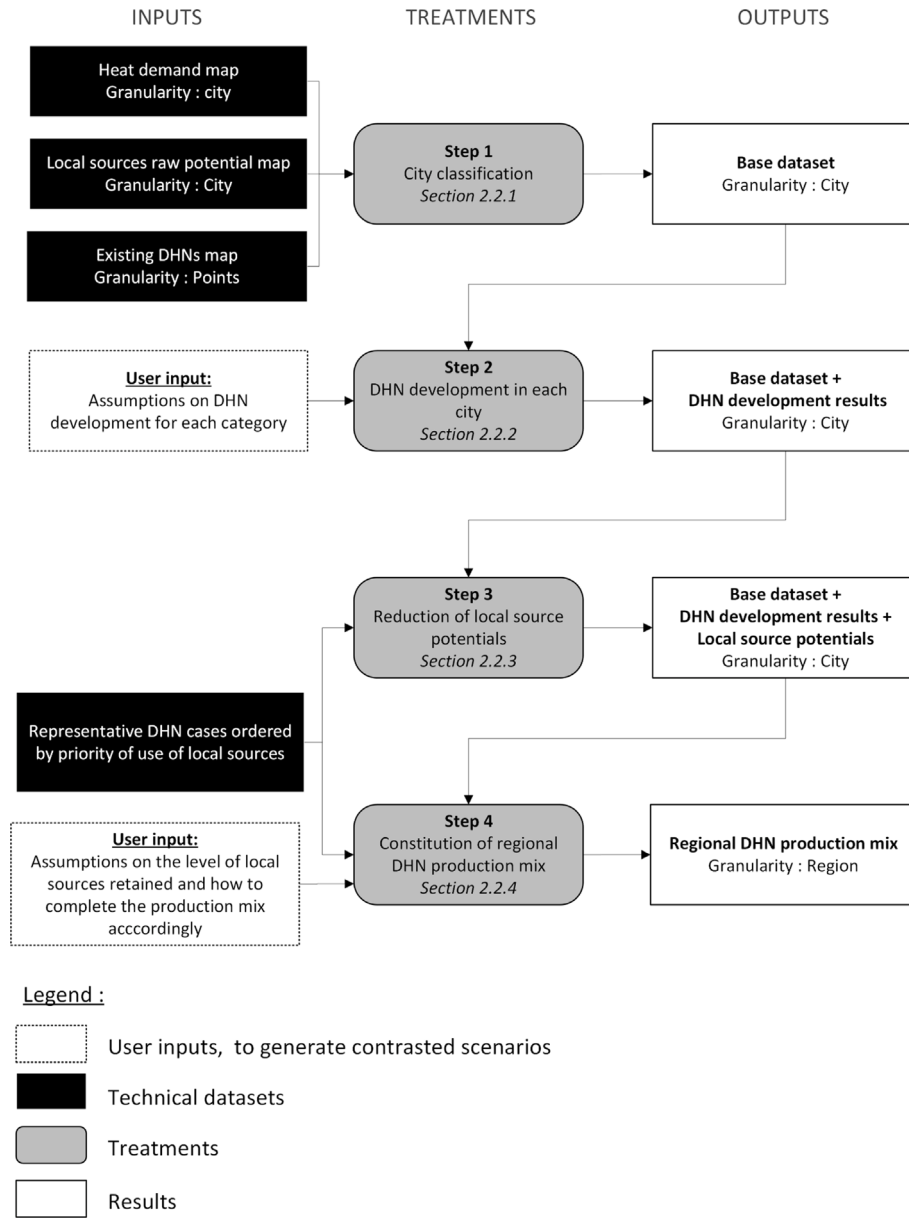


Fig. 1. Overview of the method.

be economically viable. This default value, 3.4 GWh, is an assumption based on current observations. Category 3 cities (respectively category 4 cities) have a ratio of local heat sources to dense demand above (resp. below) *thres*. All remaining cities fall into the fifth category. These cities will not develop DHNs in the method, but in practice, some could develop and operate small competitive DHNs.

2.2.2. Step 2: DHN development in each city

Once cities are categorised, DHNs are developed according to two inputs:

- The probability of DHN creation in each category.
- The expected percentage of dense demand covered by DHN (new or existing) in each category.

DHN creation in a city is randomly determined by the probability assumed for its category. Then, for each city with a DHN, the coverage of dense demand DD_{2050}^{city} is probabilistically drawn from a Gamma law (assumptions of scale and shape parameters are made for each category and scenario). The gamma law has been chosen by observing that,

for France, the ratio of supplied energy by DHN on dense demand was distributed accordingly. Depending on its parameters, the random draw from Gamma law γ^{city} can exceed 1 or can render energy produced lower than the existing DHN-produced energy E^{city} . Hence, the resulting DHN-produced energy is capped:

$$E_{2050}^{city} = \max \left(\min(1, \gamma^{city}) * DD_{2050}^{city}, E^{city} \right) \quad (1)$$

Another restriction is operated when the produced energy E_{2050}^{city} obtained is under 3.4 GWh yr⁻¹, considered as the smallest technically viable DHN. In this case, no DHN is created in the city. It should be noted that this threshold is applied to DHN-produced heat; transmission losses reduce the effective heat supplied to the consumer. In the following, a distinction is made between the **energy produced** by DHN, mainly used when working on local source potential, and the **energy supplied** by DHN, used when focusing on heat demand. In this paper, these two quantities are directly related by a loss factor of 15%, an assumption based on [24].

At the end of this step, all considered cities have a projection of their DHN-supplied energy in 2050.

2.2.3. Step 3: Reduction of local low-carbon heat source potentials

Many low-carbon sources are local: geothermal heat, excess heat, solar thermal... Starting for each source from a technical maximum potential, we compute four new “potentials” to more precisely quantify how much energy could supply DHN. Rigorously, these four new quantities are not technical potentials as they do not only consider the technology to harness the source but also the system, the DHN, in which the technology can be deployed. In the following, we will continue to name “potential” the energy that a local source can deliver, and we will specify for each “potential” which DHN system constraints are considered.

At this stage, each city is assigned a produced energy by DHN, E_{2050}^{city} and for each source and city, we have a technical maximum potential $pot_{city,s}^{MAX}$.

Reduction due to annual energy supply–demand matching. First, a local source cannot supply more energy than the neighbouring DHN supplies to customers. Hence, we compute two refined potentials:

- A potential capped by local dense demand DD_{2050}^{city} , which gives the maximum potential of the source if DHN covers all the dense demand:

$$pot_{city,s}^{DD} = \min \left(DD_{2050}^{city}, pot_{city,s}^{MAX} \right) \quad (2)$$

- A potential capped by DHN-produced energy E_{2050}^{UA} , which gives the maximum potential of the source under given DHN development:

$$pot_{city,s}^{DHN} = \min \left(E_{2050}^{city}, pot_{city,s}^{MAX} \right) \quad (3)$$

Reduction due to the structure of a DHN production mix. Each DHN must satisfy the supply–demand balance, *i.e.* production means must meet heat demand at all times, modulo storage exchanges. The fact that heat demand in the residential and tertiary sectors has specific dynamics/cycles constrains the production mix. Indeed, production means are selected and dimensioned to supply this variable demand while minimising investment and operational costs [16,49]. Typically, a DHN would include baseload plants supplying the flat part of demand and peakload plants supplying the variable part. A local source alone cannot supply a variable demand; it should be part of a mix. To operate this reduction due to operation constraints, we distribute the 2050 produced energy for each DHN to virtual DHNs. Two sizing options for virtual DHNs are used: $dim^{large} = 500$ GWh and $dim^{small} = 5$ GWh. This distinction will be useful later as the production mix of large DHNs can differ from smaller ones. Sizing values were set based on current DHN observations. For each city, where possible, large DHNs are developed first, followed by the smaller ones. $x \rightarrow [x]$ is the integer rounding function.

$$nb_{city}^{large} = \left\lceil \frac{E_{2050}^{city}}{dim^{large}} \right\rceil \quad (4)$$

If $\frac{E_{2050}^{city}}{dim^{large}}$ is rounded to superior integer, DHN produced energy E_{2050}^{city} is updated :

$$E_{2050}^{city} = nb_{city}^{large} * dim^{large} \quad (5)$$

This rounding is done to avoid developing a large number of small DHN instead of one large DHN, which is more realist.

$$nb_{city}^{small} = \left\lceil \frac{E_{2050}^{city} \bmod dim^{large}}{dim^{small}} \right\rceil \quad (6)$$

$x \rightarrow [x]$ is the floor function and $x \rightarrow \bmod(x)$ is the modulo.

At this stage, the production mix of these virtual DHNs remains undetermined. The last technical dataset features DHN representative

cases supplied energies for each source dim_s^{large} , and $share_s$ the production share of source s in a representative DHN (see Table 1), which are linked by:

$$share_s = \frac{dim_s^{large}}{dim^{large}} \quad (7)$$

We use this information to compute the numbers of possible DHNs for each source in each city:

$$nb_{city,s}^{large} = \min \left(\left\lceil \frac{pot_{city,s}^{MAX}}{dim_s^{large}} \right\rceil; nb_{city}^{large} \right) \quad (8)$$

$$nb_{city,s}^{small} = \min \left(\left\lceil \frac{pot_{city,s}^{MAX} \bmod dim_s^{large}}{dim_s^{small}} \right\rceil; nb_{city}^{small} \right) \quad (9)$$

For instance, let us consider the representative case of a large geothermal DHN: it supplies $dim^{large} = 500$ GWh annually, of which $dim_{geothermal}^{large} = 234$ GWh are geothermal heat. If a city has a DHN supplied energy of 1100 GWh and has a geothermal potential of 300 GWh, it can develop two large DHNs, but only one can be a geothermal DHN:

$$nb_{city}^{large} = 2 \text{ but } nb_{city,geothermal}^{large} = 1 \text{ because } \left\lceil \frac{pot_{city,s}^{MAX}}{dim_s^{large}} \right\rceil = 1.$$

These numbers are then used to compute new potentials that integrate the production shares of a real DHN:

$$pot_{city,s}^{DIM} = nb_{city,s}^{large} * dim_s^{large} + nb_{city,s}^{small} * dim_s^{small} \quad (10)$$

To illustrate how this affects the potential, here is another case study: if a city still supplies 1100 GWh by DHN in 2050 but has a geothermal potential of 800 GWh. Then, its $pot_{city,geothermal}^{DHN}$ is equal to 800 GWh but it can only develop 2 large geothermal DHNs, although it has the geothermal potential to supply 3 large DHNs ($dim_{geo}^{large} = 234$ GWh) because $nb_{city}^{large} = 2$. Here the local heating potential is limited by its supply share in the production mix and the resulting effective potential is $pot_{city,geothermal}^{DIM} = 468$ GWh.

One could question the assumptions made on DHN cases sizing and exhibit counter-examples of geothermal DHN supplied at 80% by geothermal heat. This would be fair as DHN operational dynamics are highly dependent on diverse local parameters and an infinite number of situations exist. But, to develop this method on a large-scale perimeter, it was necessary to ‘average’ the sizing and use rather conservative representative cases, which can be applied to diverse contexts. This approach is coherent with the purpose of our method, which is to develop realistic large-scale scenarios, and not to assess technical potentials for low-carbon heating in a specific city.

Reduction due to competition between local heat sources. In the previous steps, we obtained the potentials by considering the local heat sources independently. However, each city may have potentials from different sources, and if these potentials are larger than DHN-supplied energy, it may be necessary to arbitrate between them. Our method implements this by a priority order (modeller input) between representative cases with local sources. The first case in the priority order is developed using a part of local source potentials, then the second case, etc. For instance, let us consider two representative DHN cases: C_1 and C_2 with the priority order $C_1 > C_2$. They have a local source in common s_c and a distinct local source s_1 and s_2 . We introduce the new notation: $nb_{city,s,C}^{large}$ which is the number of possible DHNs of type C considering only the source s and is computed the same way as $nb_{city,s}^{large}$.

The algorithm will first develop as many cases C_1 as possible constrained by the corresponding local source potential:

$$nb_{city,C_1}^{large} = \min \left(nb_{city,s_c,C_1}^{large}; nb_{city,s_1,C_1}^{large} \right) \quad (11)$$

Then, it develops C_2 cases taking into account that C_1 cases have already been developed (which reduces the common source potential but also the global number of potential DHNs):

$$nb_{city,C_2}^{large} = \min \left(\min \left(nb_{city,s_c,C_2}^{large} - nb_{city,s_c,C_1}^{large} * \frac{dim_{s_c,C_1}^{large}}{dim_{s_c,C_2}^{large}}; \right. \right. \\ \left. \left. nb_{city,s_2,C_2}^{large} \right); \right. \\ \left. nb_{city}^{large} - nb_{city,C_1}^{large} \right) \quad (12)$$

This approach is extended to compute the number of virtual DHNs with local sources for several cases, $nb_{city,s,case}^{large}$ and $nb_{city,s,case}^{small}$. Then the potentials for local sources are updated in pot^{COMP} :

$$pot_{city,s,case}^{COMP} = nb_{city,s,case}^{large} * dim_{s,case}^{large} + nb_{city,s,case}^{small} * dim_{s,case}^{small} \quad (13)$$

To sum up, the potentials obtained are arranged, by construction, in the following order:

$$pot_{city,s}^{COMP} \leq pot_{city,s}^{DIM} \leq pot_{city,s}^{DHN} \leq pot_{city,s}^{DD} \leq pot_{city,s}^{MAX} \quad (14)$$

This method improves on the literature as the potentials obtained consider local DHNs, local heat resources, local source production shares and local source competition.

2.2.4. Step 4: Production mix constitution

The final step to obtain national DHN scenarios is to build a production mix to meet the overall DHN national demands. Local low-carbon resources that could effectively supply DHN were assessed and assumed to be used in priority to supply DHN in the following process.

For each region r with an annual produced energy by DHN in 2050 E_{2050}^r :

- Substep 1. Computation of the number of virtual DHNs that local low-carbon sources can supply.
- Substep 2. Translation of these DHNs into a production mix supplying an energy $E_{local,2050}^r$. DHNs supply this energy with local low-carbon sources but not entirely as they are only a part of the mix. What remains to be supplied by DHNs without local sources is equal to $E_{2050}^r - E_{local,2050}^r$.
- Substep 3. To meet the remaining demand, other DHNs are added (not relying on local low-carbon sources). Depending on which representative cases are chosen, the final production mix will be different.

To contrast the DHN production mix, the modeller has three options. The first one is to choose radically different DHN cases in substep 3. Typically, the modeller can generate two variants, one with many electrified DHN cases and the other with biomass-based cases instead. Another option to further contrast the scenarios is intentionally not fully exploiting the local potential and reducing $E_{local,2050}^r$. This gives greater latitude to choose DHN cases at substep 3. In the reference process, a priority was given to local-heat DHNs to better assess the local source potential in a national mix, as these sources are generally a privileged choice to decarbonise heating. However, it does not mean local-heat DHNs are always superior to other DHNs considering carbon emissions, material footprint, and economic performance... And some sources, biomass principally, may be used for other purposes than DHN supply. The last option is to modify the priority order between local sources defined in Section 2.2.3.

3. Case study: 2050 DHN scenarios for Europe

This section is composed of four parts. First, we describe the inputs used to generate three 2050 DHN scenarios for Europe. Second, we proceed to a global analysis of the results at a European scale. Then, we focus on Denmark to compare the scenarios generated with the literature. Finally, we perform a sensitivity analysis on the French local source potentials.

3.1. Inputs

3.1.1. Technical datasets

Heat demand atlas. Regarding heat demand datasets, we use a 2050 European spatial dataset generated in the sEnergies project [40] to capture the fact that heat-saving policies and climate change will reduce DHN potential in the future. This data only considers the heat demand of the residential and service sectors, not industry and agriculture.

Regarding data granularity, two levels are available in the European project. The first level consists of heat demand rasters at 100 m granularity [40], computed using 2050 projections for population and built surfaces. For the second level, this heat demand is aggregated on Urban Areas (UA), which are defined as “coherent and contiguous areas with urban land use and with population living within” [50]. The UA concept is more relevant than administrative city boundaries to study heat demand as it is standardised at European scale. We used the UA granularity in this case study to identify potential DHN zones.

As a conservative assumption according to [36], only demand superior to 14 kWh/m² is considered to be “dense demand” in this case study, i.e demand dense enough so that DHNs are, with high confidence, more cost-effective than individual heating. This leads to a probable underestimation of DHN potential as 4th generation DHNs could be developed in less dense zones [51].

Heat demand atlases greatly depend on population projections, restructuring of built surfaces, heat savings, and sufficiency behaviours. Two scenarios were built for 2050 heat demand in the sEnergies project: a scenario with a frozen efficiency, without any building renovation measures, and a scenario named Baseline 2050 which is built on the eponymous European Commission scenario [52]. The latter is a prudent demographic and economic growth scenario that integrates renovation measures currently in place in Europe: 2367 TWh of heat demand in Europe 2050 against 3121 TWh in case of frozen efficiency and 3149 TWh in 2015. We chose to work with the Baseline 2050 scenario as it is coherent with current legislation.

Heat sources. To quantify how much energy local sources can supply to a DHN, we mainly use a heat source spatial dataset also provided by the sEnergies project [36]. This dataset compiles the results of various European projects, each focusing on a particular source. All heat sources considered are allocated to the previously described UAs, facilitating data merging. In sEnergies data, the considered local sources are:

- Geothermal heat
- Excess heat from industry (glass, cement, iron and steel, primary aluminium, pulp and paper, chemical, and the refinery industries)
- Excess heat from Waste Water Treatment Plants (WWTPs)
- Available residual biomass (straw and wood residues)
- Solar thermal

Except for excess heat potentials, sEnergies data is not usable as such and needs to be transformed to estimate the maximum technical potential of each source s at UA granularity: $pot_{UA,s}^{MAX}$. An overview of the transformations can be found in Appendix.

Note that these source potentials are those evaluated in 2022. One should use 2050 data if available on the studied region, especially for biomass and excess heat sources, which are the most likely to evolve depending on external factors (climate change, agriculture, industry, urban development...).

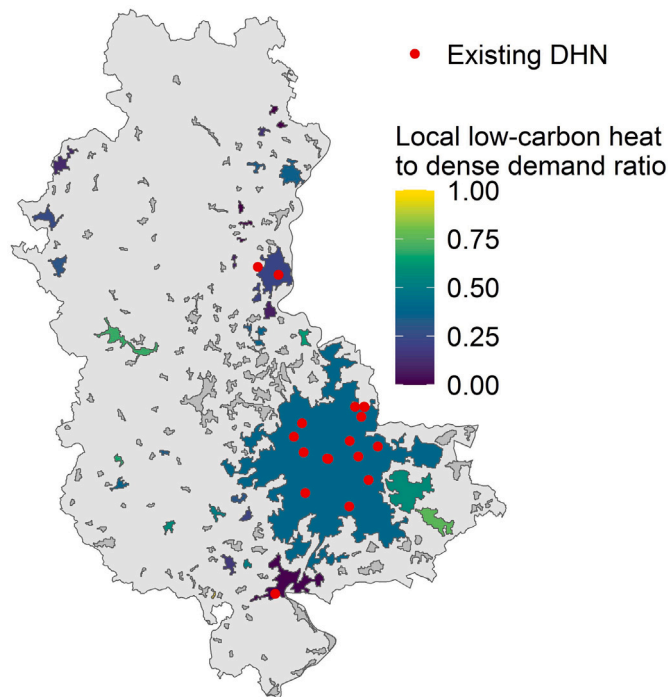


Fig. 2. Map of existing DHNs in the Rhone area (Lyon province, France) (source: CEREMA [53]) and the excess heat to dense demand ratio.

Existing district heating networks. DHNs are capital-intensive assets with long lifetimes. Consequently, existing DHNs will likely still be operational in 2050, and such information can be used to obtain consistent scenarios. The DHN map is also taken from the sEnergies project [40]. It features existing DHN locations for all EU27+UK. Other key information about existing DHNs is their current supplied energy. The current level strongly determines future energy supplied by an existing DHN as infrastructures are sized for a given level of demand. For DHN operators, it is advantageous to maintain at least the level of energy supplied to consumers to preserve their business model. To estimate energy supplied by each DHN, we redistributed the national DHN energy (gathered by [49]) proportionally to the dense demand in DHN-cities. Fig. 2 features these three geographical datasets by displaying the existing DHNs and the local low-carbon heat to dense demand ration in a French region.

DHN representative cases. 12 types of representative DHN were designed in previous works related to the thesis of Marie-Alix Dupré la Tour [54]. They all are coherent sets of heating plants that meet heating demands hourly. A simulation of the supply–demand of these cases on a Mixed-Integer Linear Programming (MILP) tool gave the production shares visible in Table 1, which are used to obtain the effective potentials for each source (Section 2.2.3). These cases do not aim to be exhaustive but rather to allow an aggregated representation of DHN diversity at a large scale without blurring the dynamics of heat demand, heat production, and other vector interactions throughout the year.

As the possibilities for designing a DHN production mix, in terms of technologies and sizing, are infinite, these cases were built by choosing a technology or set of technologies and then adapting the complementary technologies and their sizing accordingly, *i.e.* all cases were built to respect constraints on the security of supply, CAPEX limitations, etc. Most cases were largely inspired by existing state-of-the-art European DHNs. A sensitivity analysis is performed in Section 3.4 to quantify the influence of the production share assumptions on the local sources' final potential.

3.1.2. Other parameters

For this case study, cities are classified into 5 categories using reference classification exposed in Section 2.2.1. The threshold *thres*, respectively discriminating categories 1 and 2/categories 3 and 4, is set at 30%. This value gives categories 1 and 2 (respectively 3 and 4) with comparable overall dense demand, which is helpful to differentiate the DHN development depending on the scenarios.

As biomass is a transportable local source, we designed an algorithm to redistribute biomass resources after DHN development. The original data allocates biomass to the nearest UA, leading to UAs with no DHN but a lot of available biomass. Our algorithm thus reallocates biomass from UAs without DHNs to UA with DHNs in a given radius. We used a radius of 10 km in this case study; it proved to be a good compromise between keeping local consistency and redistributing a large part of the resource.

3.1.3. Specific scenarios assumptions

DHN development scenarios. Three scenarios with contrasted DHN developments are defined:

- Conservative: no new DHNs are created. Further development of existing DHNs is limited, only easily attainable heat demand is connected.
- Local: DHNs are developed in priority in cities where local low-carbon heat is available (categories 1 and 3) as these DHNs are expected to be the most economical and low-carbon.
- Ambitious: DHNs are developed in categories 1 to 4 at levels that would require a political effort in countries that do not already have a large share of DHNs.

These scenarios are common for all European countries. They do not pretend to forecast DHN development in Europe, which significantly depends on political willingness. They should rather be interpreted as exploratory development paths, considered as technically and economically relevant.

Local sources priority order. A priority order between local sources must be set to obtain refined potentials, see Section 2.2.3. Of the 12 representative cases presented in Section 3.3.1, 10 involve local sources. But, several only have biomass so we retained the following priority order (adapted from French Energy Agency policy [55]).⁵

1. C3: excess heat from industry and local biomass
2. C4: excess heat from WWTP and local biomass
3. C11: geothermal heat and local biomass
4. C6: solar thermal and local biomass
5. C3b: excess heat from industry and non-local biomass or power-to-heat
6. C4b: excess heat from WWTP and non-local biomass or power-to-heat
7. C7: geothermal heat and gas
8. C6b: solar thermal and non-local biomass or power-to-heat
9. C2: local biomass, waste-to-energy and gas

The first four cases combine two local sources whereas the five others only feature one.

Production mix. In this case study, the production mix is built following the pre-implemented process exposed in Section 2.2.4: first, all accessible local low-carbon sources are harnessed and, then the mix is completed with electrified cases.

3.2. Results: local source potentials for europe

Fig. 3 depicts the production mix for the three scenarios generated.

⁵ Suffix “b” cases are the DHN cases featuring a local source and non-local biomass if the remaining local biomass is insufficient to supply the case.

Table 1
Representative district heating networks cases - Composition and production shares.

Case	Baseload plants - Production share	Peakload plants - Production share	Storage
C1	HOP (Heat-Only Plant) Biomass - 76%	HOP Methane - 17% and HOP Methane - 0%	
C2	CHP Waste-to-Energy - 57% and HOP Biomass 39%	HOP Methane - 4% and HOP Methane - 0%	
C3	Heat Pumps on WWTP - 47% (a third being directly WWTP excess heat) and HOP Biomass - 53%	Power-to-Heat boiler - 3%	Short-term storage (tank)
C4	CHP SOFC (Solid Oxide Fuel Cell) - 25% and Power-to-Heat boiler - 75%		Short-term storage (tank)
C5	Heat Pumps on WWTP - 96% (a third being directly WWTP excess heat)	HOP Methane - 4%	Weekly storage (pit)
C6	Solar thermal - 35% and HOP Biomass - 62%	HOP Methane - 3%	Long-term storage (Pit)
C7	Geothermal assisted by Heat Pumps - 83% (half being directly geothermal energy)	HOP Methane - 18%	Short-term storage (tank)
C8	CHP Waste-to-Energy - 51% and HOP Biomass - 40%	CHP Methane - 7% and HOP Methane - 3%	Network storage
C9	Excess heat from industry - 74%	HOP Biomass - 32%	Long-term storage (pit)
C10	Heat Pumps on WWTP - 55% (a third being directly WWTP excess heat)	HOP Biomass or Power-to-Heat boiler - 43%	Long-term storage (pit)
C11	Geothermal assisted by Heat Pumps - 71% (half being directly geothermal energy)	HOP biomass - 29%	Short-term storage (tank)
C12	CHP Biomass - 80%	Power-to-Heat boiler - 20%	Short-term storage (tank)

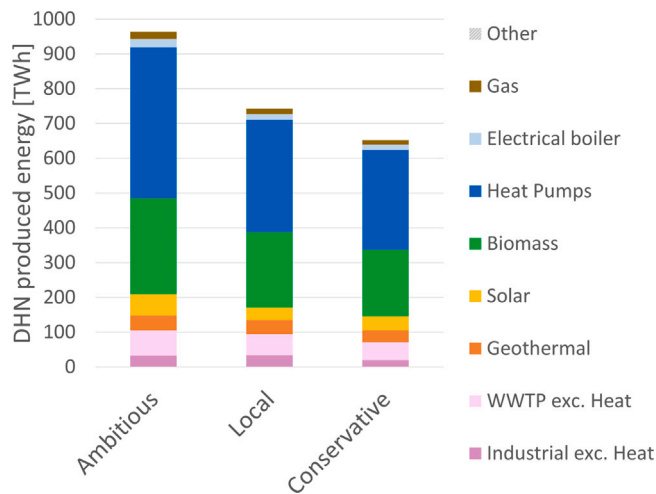


Fig. 3. The production mix of the three EU27+UK scenarios.

All scenarios feature a massive DHN development: supplied energies are respectively 820 TWh, 631 TWh, and 555 TWh, against 370 TWh currently [49]. Even with conservative assumptions, DHN potential is so important and untackled in some cities that the method projects a nearly 200 TWh increase. In this conservative scenario, 287 TWh out of 555 TWh are supplied by local low-carbon sources. The remaining is mainly supplied by heat pumps, low-carbon if electricity is low-carbon, and gas or electrical boilers for peak demand.

Being more ambitious on DHN development allows for harnessing more local low-carbon energy at approximately the same rate:

- Comparing the Local scenario to the Conservative one, a 14% increase in supplied energy results approximately in a 15% increase in supplied energy by local low-carbon sources.

- Comparing the Ambitious scenario to the Conservative one, a 48% increase in supplied energy results approximately in a 44% increase in supplied energy by local low-carbon sources.

Therefore, in order to use more low-carbon energy, the efforts to develop DHNs where local sources are more available (Local scenario) are secondary compared to the global level of DHN development. This is an important result as these sources, except for biomass in some cases, cannot be exploited other than with DHNs. Therefore, massively developing DHNs is a powerful lever to harness more local low-carbon sources.

It should be noted that behind these production mix, heat storage is present in most of the projected DHNs, which is essential to reach this level of baseload capacity and thus this level of low-carbon sources.

3.3. Results: method comparison on Denmark

3.3.1. Denmark mix

Let us compare the scenarios generated with our method to the literature for Denmark, which is the most studied country. Fig. 4 depicts 6 different scenarios for Danish 2050 DHNs:

- *DEA fossil* and *DEA wind* are taken from [28], which is a study aiming at decarbonising the whole energy system under different assumptions of bio-energy consumption.
- *IDA* scenario [29] builds on *DEA wind* scenario, but with significant differences in district heating sector.
- *EA energy* scenarios were proposed by [27] as alternative paths to decarbonise the whole energy system. *Combo* scenario is the reference with moderate electrification to reach ambitious climate goals whereas *Ambitious* scenario shows how accelerated electrification allows to further reduce emissions towards 2050.
- *Elec+* scenario is the electrified ambitious scenario generated by our method. The three scenarios (Ambitious, Local and Conservative) are very similar for Denmark as DHNs are already well-developed, which is not the case for all countries, e.g. France.

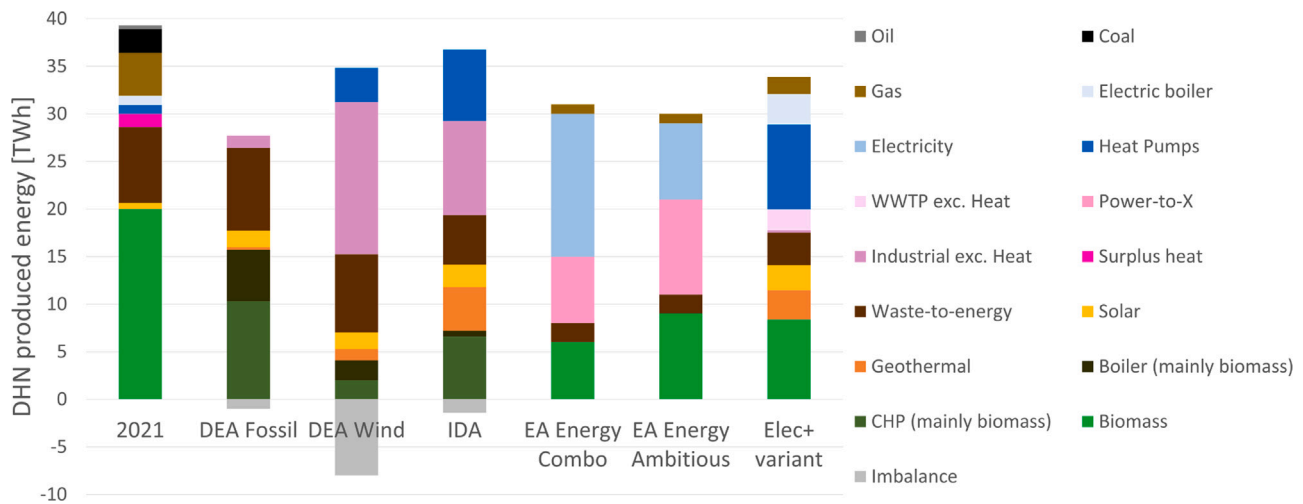


Fig. 4. Comparison of 2050 DHN scenarios for Denmark. *Elec + variant* is our scenario. Other scenarios are from [27–29].

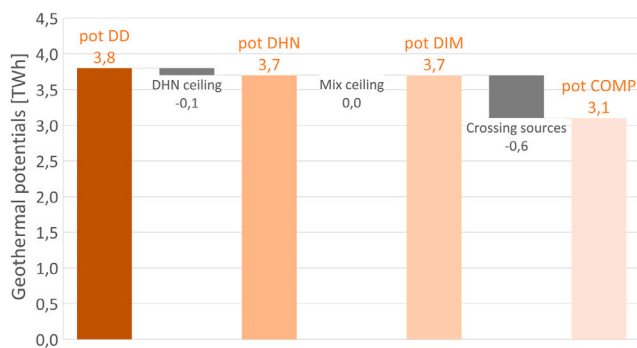


Fig. 5. Geothermal potential reduction - Denmark Ambitious scenario.

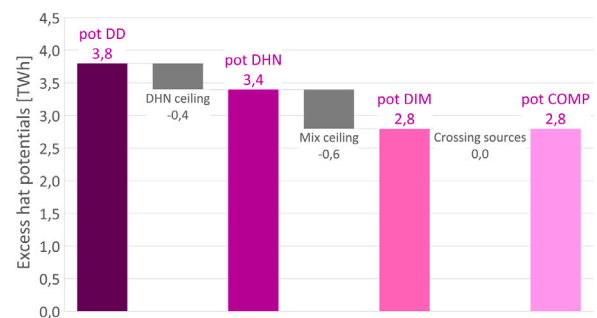


Fig. 6. Excess heat potential reduction - Denmark Ambitious scenario.

In terms of produced energy, our scenario is comparable to other ones. This gives confidence on our projection of future DHN-produced energy as this latter does not depend on DHN development assumptions in Denmark.

Regarding the production mix, what first needs to be noticed is the high level of Power-to-X/Industrial excess heat in all scenarios except *DEA fossil* and *Elec+*. Behind different names, this represents the same heat source: excess heat generated during power-to-X industrial processes. In our approach, no assessment of Power-to-X excess heat is led, as we consider locating future electrolyzers and quantifying their excess heat potential for DHN is highly uncertain [56]. However, our *Elec+* scenario shows that supplying 2050 DHN demand with low-carbon sources may be reachable without requiring a massive development of Power-to-X capacities. However, it will necessitate a massive development of geothermal and solar thermal DHNs. It can be noted that the levels projected by our spatial method for these two sources are quite similar to those given by experts for the *IDA* scenario. Biomass and waste-to-energy will continue to provide a large share of DHN energy. Meanwhile, large heat pumps will mainly supply the remaining demand, as heat pumps are key to raising the temperature from low-temperature sources. Overall, except for power-to-X excess heat, our method features energy mix comparable to what exists in the literature. To better understand what limits the local source potentials for DHN, let us analyse the details of Danish potentials.

3.3.2. Potential reduction on Denmark

Fig. 5 depicts the evolution of geothermal potential in the Ambitious scenario, computed with the method described in Section 2.2.3. As

geothermal potential in Denmark is relatively limited and located in high-demand cities, the first two filters (ceiling by DHN 2050 development and ceiling by geothermal share in supply mix) have no effect. Only the third filter (considering other local sources) significantly affects the geothermal potential. 0.9 TWh of Danish geothermal resources are located in zones where excess heat is available, which is prioritised in the process.

Excess heat potential (industrial and WWTP) behaves oppositely (see Fig. 6). Excess heat sources are more concentrated, leading to high potential in cities where heating demand is not as high. Therefore, the first two filters limit the harnessing of excess heat, while the third one does not affect it as excess heat is first on the priority list. A lesson for public policy drawn from this result is that planners could purposely develop DHNs in zones where excess heat is available but not harnessed because of insufficient DHN demand. In the longer term, planners could jointly optimise heat demand saving efforts and DHN development taking into account local low-carbon sources with geographical studies. Indeed, it may be interesting to neglect heat savings in zones where cheap local energy could be harnessed.

3.4. Sensitivity analysis

In order to test the reliability of our conclusions, we perform a sensitivity analysis on the final local potentials. This section illustrates the method's functioning and demonstrates its ability to generate robust scenarios.

3.4.1. Method

In this analysis, the reference scenario is the Ambitious scenario for France. From this reference, we quantify the impacts of various

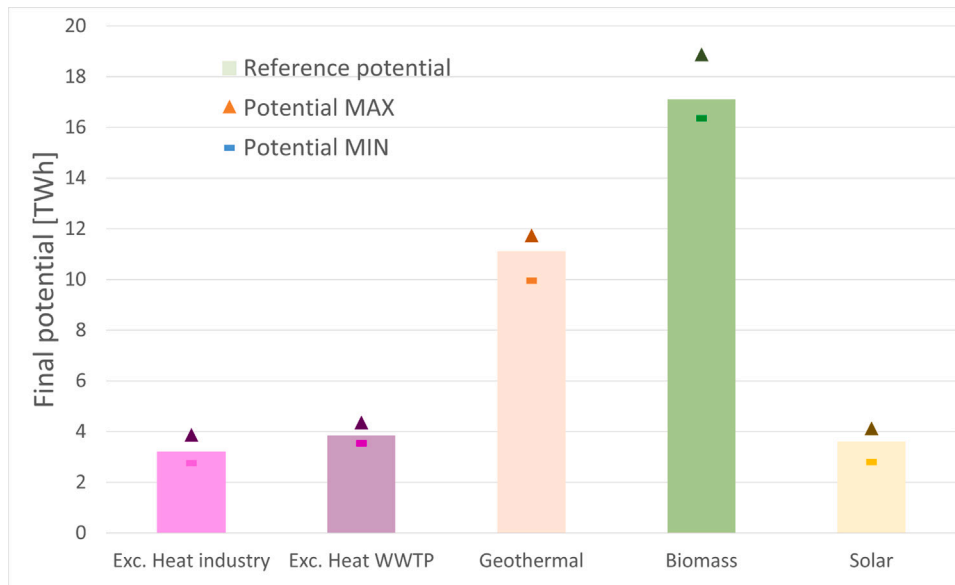


Fig. 7. France Ambitious scenario: local sources' final potentials and their maxima/minima in the sensitivity analysis.

Table 2

Tested assumptions in the sensitivity analysis and their reference value.

	Local source	Reference value
Energy for DHNs [TWh]	X	55.8
Technical maximum potential [TWh]	Geothermal	29.4
	Industrial exc. heat	11.6
	WWTP exc. heat	15.8
	Biomass	322.5
	Solar	496.2
Production shares	Geothermal	See Table 1
	Industrial exc. heat	See Table 1
	WWTP exc. heat	See Table 1
	Biomass	See Table 1
	Solar	See Table 1

assumptions on the final local source potentials. Table 2 lists the tested assumptions. There are three types of tested assumptions: overall DHN produced energy, the technical maximum potential for each source ($pot_{city,s}^{MAX}$ in Section 2.2.3), and production shares in representative cases for each source.⁶ For each studied assumption, we generate two scenarios: one with the assumption raised by 10% at UA granularity and the other with the assumption decreased by 10%. All the studied assumptions are energies, which enables comparison and facilitates results analysis.

This gives 11 assumptions to study with two scenarios for each (+10% / -10%). The final potentials for each source ($pot_{city,s}^{COMP}$ in Section 2.2.3) are then examined to find which assumptions are the most impactful.

3.4.2. Results

Fig. 7 depicts the reference final potentials, with their maximum and minimum values obtained during the sensitivity analysis. Final potentials are moderately sensitive to the assumptions studied, which backs the method's reliability.

Let us examine which assumptions have the greatest influence on each potential, see Fig. 8. Industrial excess heat, WWTP excess heat,

⁶ For instance for solar, we modify the C6 production shares (see Table 1) to raise/decrease solar produced energy by 10%.

and biomass are mainly influenced by the same expected assumptions. Their main driver is the DHN energy; indeed in French cities where excess heat or biomass is available, it is often massively available. What limits its use is therefore the size of the neighbouring DHNs. A 6.8 TWh increase in DHN energy results in a 0.6 TWh increase in excess heat industrial potential. The second most influential assumption is the technical potential of the source: a 1.2 TWh increase in industrial excess heat technical potential results in a 0.4 TWh increase in its final potential. The third one is the share of industrial excess heat in its representative case: a 37 GWh increase (out of 500 GWh DHN produced energy) results in a 0.3 TWh increase in its final potential.

Regarding geothermal and solar, the ranking of the assumptions is less intuitive. For geothermal technical potential variation, only a negative 10% variation modifies the final potential. This is due to a threshold effect: the 10% increase is not sufficient to build new geothermal DHNs while, in four cities, the decrease is enough to lower the potential below the required geothermal energy for building a large geothermal DHN dim_{geo}^{large} . The geothermal final potential is also capped by DHN size and the geothermal production share. However, DHN energy is a relatively less impactful assumption than for other sources. This is explained by the fact that geothermal resources are mainly located in French big cities where excess heat resources are available and have priority. Therefore, the variation of DHN energy is first captured by excess heat DHNs. For solar, the impact of a 10% decrease in WWTP share is surprising. When we delve into the details, we see that the 10% decrease on dim_{WWTP}^{large} and dim_{WWTP}^{small} makes possible the creation of more WWTP DHNs in some cities, reducing the space for solar thermal DHNs (due to the priority order, the WWTP DHNs are developed first). This is another threshold effect that could occur with this method. To overcome this in a study aiming at assessing precisely local potentials, one should induce variations on the most impactful parameters identified here and take the average result.

Overall, this sensitivity analysis highlighted how the final potentials behave depending on variations in various assumptions. Especially, we underlined some threshold effects that could affect the results. These threshold effects are the downside of affecting production mix to each DHN, which is essential to consider the competition between local sources when computing the local potentials. Benefiting from this sensitivity analysis, Fig. 7 shows a confidence interval on the different potentials obtained.

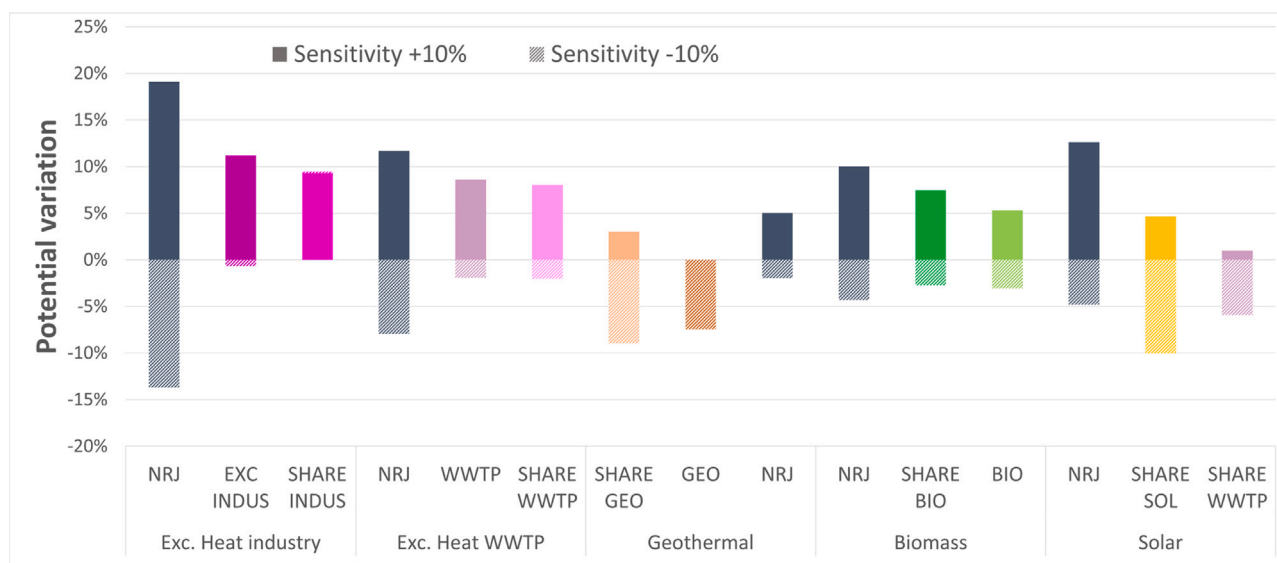


Fig. 8. Sensitivity analysis: for each local source, the three most impactful assumptions.

4. Conclusion

This paper presents a method for generating prospective large-scale DHN scenarios based on explicit geographical assumptions. Its novelty is to consider DHN technical constraints to better assess the amount of local low-carbon energy exploitable depending on DHN development path. Spatially, all DHNs virtually created in the method are coherent with local heat demand, local low-carbon sources, and existing DHNs. Temporally, the virtual DHNs are coherent with the production mix of real DHNs. Therefore, the method combines the best potential assessment techniques available in the literature for generating coherent prospective scenarios.

As a case study, we generated three scenarios for European countries. It illustrated the massive potential for DHN development at horizon 2050: the scenarios feature supplied energies of 820 TWh, 631 TWh, and 555 TWh, against 370 TWh currently. And this level of DHN development is the key driver of DHN low-carbon source integration (accounting for excess heat, geothermal, biomass and solar): respectively 485 TWh, 388 TWh, and 337 TWh are harnessed in the three scenarios.

Though the method builds from the local scale, its results, e.g. for Denmark, are globally aligned with literature scenarios. A sensitivity analysis allows to quantify the impact of the various inputs on the final potentials of the different local sources. These two sections help to understand better how the scenarios and corresponding local source potentials are generated.

Overall, the method fits its purpose which is to generate large-scale DHN scenarios based on local technical parameters. These scenarios can be used as inputs for multi-energies simulations as identified in Section 1.1. This method could also serve other interesting purposes. In our case study, we do not consider the industry heat demand and some industrial excess heat sources (Power-to-X, data centres excess heat etc.) as we consider their future locations as uncertain. We can reverse the reasoning and identify where it would be beneficial to implement the new industries. If the industrial process requires low-temperature heat, it could be located near a city with local sources not fully exploited, easily identifiable with our method. On the other

hand, if the industrial process generates low-temperature heat, it could be located in a city with high heat demand but lacking of local low-carbon sources. More generally, this approach combines a top-down and a bottom-up approach in a way that could inspire other sectors for their projection studies.

CRediT authorship contribution statement

Maxime Vrain: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Virginie Dussartre:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Nicolas Lhuillier:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Robin Girard:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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.

Appendix. European local sources: how quantitative potentials are obtained

See Fig. A.9.

Data availability

Data will be made available on request.

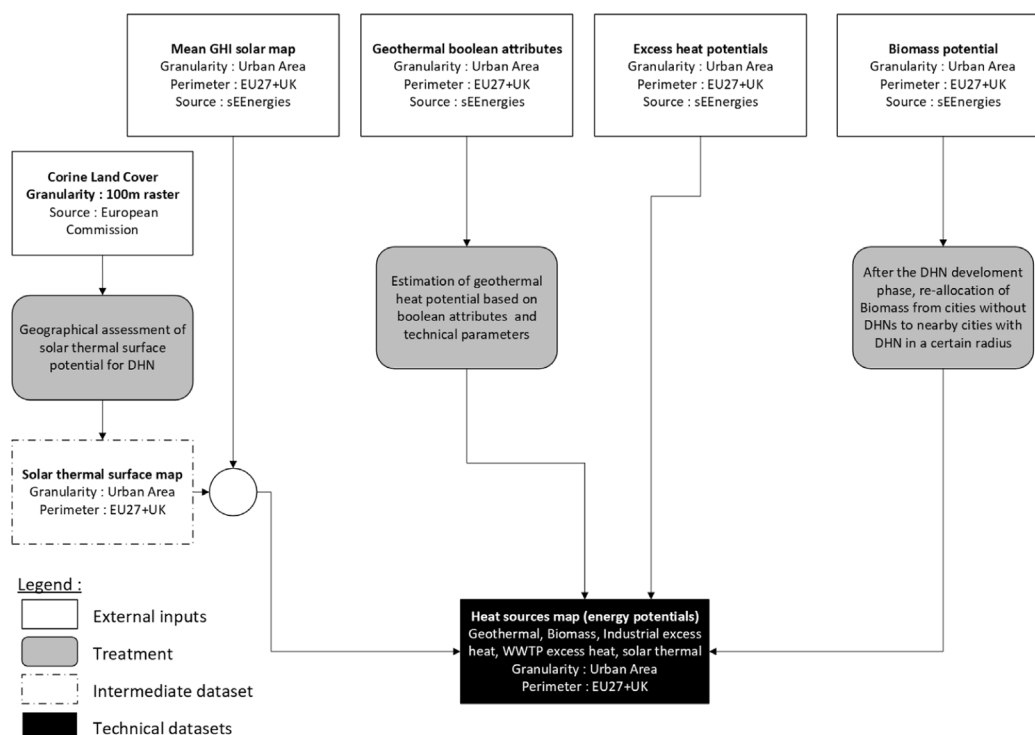


Fig. A.9. Scheme summarising how local source potentials were obtained for the European case study.

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