Heat Roadmap Europe

Towards EU-Wide, local heat supply strategies

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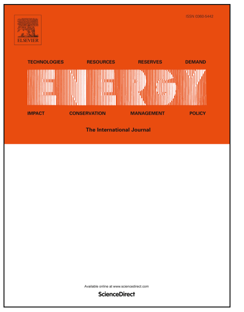

Heat Roadmap Europe: Towards EU-Wide, local heat supply strategies

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Heat Roadmap Europe: Towards EU-Wide, Local Heat Supply Strategies

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Abstract
The present paper describes a quantitative method for preparing local heat supply strategies. Detailed spatial data on heat demand and supply are generated using combined top-down and bottom-up modelling for 14 member states of the European Union, which constitute 91% of its heat demand in buildings. Spatial analysis is used for zoning of heat supply into individual and collective heating. Continuous cost curves are used to model economically feasible district heating shares within prospective supply districts. Excess heat is appraised and allocated to prospective district heating systems by means of a two-stage network allocation process. Access to renewable energy sources such as geothermal, large-scale solar thermal, as well as sustainable biomass, is analysed. The result is a comprehensive and detailed set of heat supply strategies in a spatially discrete manner. The findings indicate that in the 14 European Union member states, up to 71% of building heat demand in urban areas can be met with district heating. Of this, up to 78% can be covered with excess heat, while the remainder can be covered with low enthalpy renewable energy sources. The conclusion shows the possibility of a largely de-carbonised heat sector as part of a smart energy system for Europe.

Keywords
Heat Roadmap Europe, District heating, GIS, allocation

Nomenclature

C_{pipe}	specific investments costs of pipes	€/m
C_w	weighted total transmission pipe cost	€
$\eta_{\mathrm{DH\ grid}}$	district heating distribution network efficiency	[]
HDD_{annual}	annual heating degree days	K d
HDD_{month}	monthly heating degree days	K d
$HDD_{month,\ min}$	minimum of monthly heating degree days	K d
k	thermal conductivity of pipe	W m^{-1}
k_s	thermal conductivity of the insulation	W m^{-1}
$\dot{Q}$	heat transport capacity of a pipe, heat flow rate	MJ/s
q	heat loss in a pipe	W/m
$Q_{loss\ base}$	baseload induced district heat distribution losses	TJ/a
$Q_{loss\ seasonal}$	seasonal load induced district heat distribution losses	TJ/a
$Q_{baseload}$	baseload district heat demand	TJ/a
Q_{DH}	district heat supply /demand	TJ/a
$Q_{DH\ econ}$	economic district heat demand	TJ/a
$Q_{DH\ gross}$	gross district heat demand	TJ/a
q_L	heat demand density	GJ/ha
$Q_{seasonal}$	seasonal district heat demand	TJ/a
r_i	inner pipe radius	m
r_o	outer pipe radius	m
r_s	outer pipe insulation radius	m
δ_{base}	share of climate-dependent baseload	[]
t_a	outer temperature	K
t_i	inner temperature	K

1. Introduction

Heat is the most important secondary energy in Europe [1]. It comprises 51% of the final energy demand in the 28 member states of the European Union (EU28), while space heating and hot water account for 30% [2]. Transition to a sustainable heating sector reduces environmental impact from emissions; shifts energy economics from fuel import to investments; and addresses social sustainability through affordable heating.

1.1. Existing research

Research in the heating sector has increased attention and heat is now recognised as vital in the European energy system and its transition [3]. In smart and sustainable energy systems [4], it is conditional to reduce heat demands (HD). The built environment may see reductions by 25 % [5], according to moderate scenarios. In progressive studies, up to 60% may be saved [6]. District heating (DH) may be extended to 40-70% of current HD [7]. Low-enthalpy geothermal, solar thermal and excess heat sources may cover 30-80% of DH supply [8]. Sectoral integration between renewable electricity, heating, and synthetic fuel sectors (i.e. power to gas, electro-fuels) may provide system flexibility while maintaining efficiency [9]. These combined measures need an inclusive information base. However, currently no coherent and comprehensive model exists [10], which would allow specifying national or regional heat supply strategies as required by the EU Directive on Energy Efficiency, Article 14 [11]. What is needed, therefore, is a heat supply planning methodology, which addresses these elements all at once.

Heat generation, transmission, distribution, and consumption are geographical processes. Their location and dispersal provide technical and economic constraints; DH requires infrastructure investments and causes heat losses. The economics of heat distribution highly depend on linear heat density [12]. Excess heat is accessible, where thermal processes release useable heat within economical distance to consumers [13].

Existing research in the Heat Roadmap Europe (HRE) initiative comprises mapping and systems analysis. In 2012, Connolly *et al.* [14] mapped the European heating sector at local level, followed up by Connolly *et al.* in 2013 [6] with a 1km² resolution model of HD. A first 1 hectare resolution model of HD and supply was presented in 2015 [15], and further refined in 2017, see Möller *et al.* [16]. Available excess heat has been located and quantified [11]; and heat synergy regions have been identified [8]. DH network costs have been assessed at high resolution [17]; and the spatio-economic allocation of excess heat to potential DH areas has been discussed in Möller et al., 2017 [18].

Internationally, few studies exist which aim at mapping HD and supply at similar scale and resolution. Set aside numerous papers that map local areas, particular building types, or specific heat supply technologies, few attempts of comprehensive and cross-sectoral spatial analysis exist. Sørensen and Meibom presented an early global GIS-based energy model [19]. Gils *et al.* [20] studied DH potentials in the USA. For the Middle East, Nematollahi *et al.* [21] presented a GIS-based mapping approach of energy demand and renewable energy supply. Recently the H^{O}TMAPS project published an open source heat atlas for Europe [22].

1.2. Objectives

The present paper presents a coherent approach to re-design European heat supply on secondary energy and local levels. A "what-if" approach assumes a "clean slate" and disregards existing DH systems, behavioural, organisational, and regulatory constraints. The objective is to provide a quantitative benchmark for policymaking, which includes an assessment of where DH is feasible. The local economic potential of DH is assessed using a cost-supply approach. Potential sources of DH are modelled using temporal and spatial allocations, taking into account HD seasonality, locally limited excess heat supply, and transmission. The aim is a techno-economic quantification of local heat markets, understood as physical entities of geographically connected areas with HD densities above a technical minimum.

While investment cost calculations for DH are explained in [23], and excess heat activities (EHA) are identified in [8], a method for delineating prospective supply districts (PSD) for collective heat solutions [16] is presented in [17]. Based on this work, the determination of local, economic DH shares, and the allocation of potential excess heat from industrial processes, waste incineration by means of waste-to-energy (WtE) plants, and current power-only producers, like proposed in [18], is to be addressed in the present paper. Paramount is to allocate appropriately, in time and space, the potentially available excess heat. At this scale, excess heat can only be utilised in DH schemes; the availability of such heat sinks near EHA needs to be evaluated. The difficulty is the temporal and spatial mismatch between demand and supply. Excess heat from industry and waste-to-energy plants is constrained by volume, spatially and temporally, as industrial facilities are seldom established and operated considering the opportunities to utilize excess heat. Current thermal power-only plants, on the other hand, may merely provide locations for future heat supply clusters if located near HD.

The paper offers a coherent and consistent methodology by which HD can be met by sustainable supply on local levels for all of Europe. Such approach may integrate the heating sector vertically (geographically) as well as horizontally (inter-sectorally). The methodology will integrate several tools and methods into an epistemologically connected approach for the preparation of local heat supply strategies.

1.3. Scope

The scope of the paper is the techno-economic assessment of potential local heat markets. In these, HD is assumed non-elastic and delivered DH is understood as supply in a partial equilibrium. This is fulfilled assuming a natural (i.e. without knowing the costs) merit order of supply. Excess heat from industry and WtE is capacity and distance constrained. Access to agglomerated DH areas near existing power plants (PP) is merely distance constrained because the capacities of these are subject to change. Required installations to make excess heat available for DH are excluded at this level.

A cost-supply relationship is established, providing the basis of a market in the sense that potential supply of DH only depends on the investment cost of distribution. Supply means here providing heat to buildings, not generating DH from primary energy, which is beyond the scope, as is the direct comparison between collective and individual heat supply. Current institutional, organisational, and administrative barriers are excluded, as they are believed to be obstacles to reform the heating sector.

A validation of the HD and PSD mapping is extrinsic. References are given in the text. A validation of the main findings must be restricted to plausibility and balances by nature.

The analysis is limited to the 14 EU member states, which comprise the extent of the HRE project: Austria (AT), Belgium (BE), the Czech Republic (CZ), Germany (DE), Spain (ES), Finland (FI), France (FR), Hungary (HU), Italy (IT), the Netherlands (NL), Poland (PO), Romania (RO), Sweden (SE) and the United Kingdom (UK). These represent 91% of the total HD in the EU28 [2].

2. Methods

High-resolution HD mapping is used to delineate supply districts, estimate the economic potential of district heating within these, and calculate heat distribution losses. Excess heat and renewable heat are allocated in time and space to potential DH systems.

2.1. General considerations

There is often a spatial mismatch between HD and EHA locations. A preliminary distance analysis between the centroids of PSD and EHA located in Persson et al. [17] has been carried out; see Figure 1, where 96% of HD is located within 50 km straight-line distance from an EHA. At merely 20 km distance, 75 % of HD is located. However, simple nearness alone is not sufficient to appraise the coverage of HD with excess heat. It is a question of temporal and spatial alignment of demand and supply, to be addressed by means of allocation analysis.

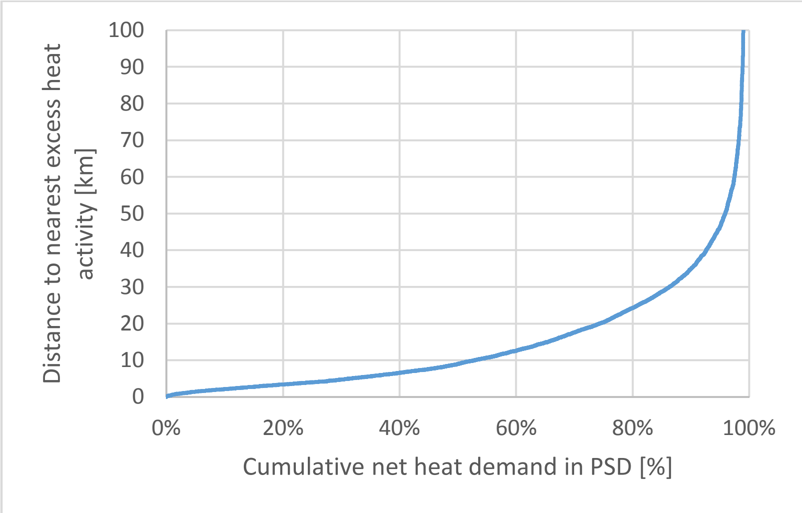

Figure 1: Distance relationship between cumulative HD [16] in prospective heat supply districts (PSD) of the 14 countries represented in the HRE project and the nearest excess heat activity (EHA) [15], measured in planar distance.

The allocation of excess heat assumes relative nearness of raw materials as production factors, formulated in Alfred Weber's basic industrial location model [24]. Analog to Newtonian gravity, the product of mass and distance determines the location of production units. Minimal distance between demand and supply provides least cost solutions. Stewart [25] utilised the strong link between volume of resources and transport distance in retail planning, laying the basis for mapping opportunities of interaction in accessibility modelling [26]. The gravity-based transport problem [27] recognises that larger volumes are less costly to transport over long distances than smaller volumes if the means of transportation has a positive economy of scale of volume and distance. Heat is transported in pipes, and costs occur as investment and operation costs. Investments are the required DH pipes and associated fittings; heat recovery at EHA is excluded. Operation costs are pumping costs and heat losses. Investment costs C_{pipe} approximately increase with the heat transport capacity $\dot{Q}$ (the heat flow rate in MJ/s) as in Equation 1, which has been derived from [12].

$$C_{pipe} \cong 356\ \dot{Q}^{0.223} \qquad [€/m]$$

Equation 1

Losses q are a function of $\dot{Q}$; see Equation 2, where heat loss is calculated per metre of pipe length.

$$q = 5 \cdot 10^{-6}\dot{Q}^{-0.724} \qquad [W/m]$$

Equation 2

Gravity allocation models seek to minimise costs over network distances, and therefore give priority to high volumes at short distances, subsequently increasing coverage by allocating larger plants in the vicinity before extending pipe networks to larger distances. This behaviour favours dense clusters. The transport problem seeks to minimise the total costs of all heat volumes transported. A sub-problem is related to the location and allocation: the p-median problem aims at minimising the total costs for transporting heat from a given number *p* of EHA to a specified number of PSD. Each possible connection *i,j* between facilities and consumers has a distance-weighted heat transmission pipe cost C_w and a local heat demand Q_{dh} [28]:

$$min \sum_{i,j} C_{w,ij} Q_{dh,ij}$$

Equation 3

The decision variable of this optimisation problem is $Q_{dh,ij}$, i.e. the EHA at a location is either being allocated to cover the heat demand in a PSD or not.

A modification is to maximise capacitated coverage, where the capacity of EHA is limited, and all of the capacity is to be utilised while minimizing transport distance. ArcGIS Network Analyst uses Teitz-Bart heuristics to solve the very large solution space of the p-median problem. For the Maximize Capacitated Coverage problem, the so-called Hillsman editing transforms the problem to a p-median before applying the heuristic [29].

EHA and PSD demand do usually not overlap in time, as HD pertains to the cold months of the year. Industrial processes usually have little seasonality; they are considered baseload. The same is assumed for waste-to-energy plants, designed to operate at full capacity. Excess heat from PP is treated differently. In the year 2015, 66% of all European coal-fired PP had been in operation for 30 years or more [30]. The largest and oldest will therefore (subject to coal price, carbon price, competitive alternatives, and political will) disappear within years. If so, some of them may be replaced by CHP units located near HD. Therefore, current PP locations are input to the allocation as candidates for future CHP, assuming that location factors such as electric and gas grids exist. Current PP will therefore be allocated minimising overall impedance, ranked by estimated transmission pipeline costs, and with no capacity limit.

The flow of modelling is shown in Figure 2. Based on HD density at high spatial resolution, the boundaries of PSD are drawn as in [16]. The annualised average investment costs in distribution networks are calculated. Then, local cost-supply curves are drawn to define local heat markets. A cut-off average cost separates the economic from the technical potential. Furthermore, using heating degree-day maps, the climatically defined baseload share is mapped to calculate the annual baseload HD as the temporal constraint to using excess heat from industry and WtE. A network allocation model allocates capacitated baseload EHA to baseload demands. A second network allocation model identifies locations of current power generation plants with heat markets in their vicinity by minimised impedance. Geothermal heat, solar thermal energy, and local biomass are mapped and assigned to the prospective supply districts. Lastly, for each PSD the opportunities for an annual mix of heat supply are generated based on natural merit order.

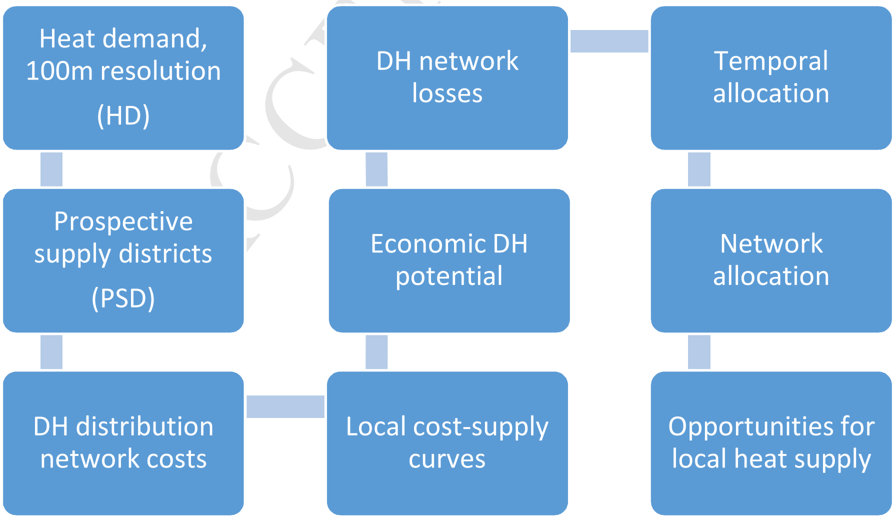

Figure 2: Workflow presented in the paper. A HD raster forms the basis for the formulation of opportunities for local heat supply. PSD are formed and heat distribution investment costs calculated in order to arrive at local economic DH potentials via cost-supply studies. The supply of potential excess heat to cover gross DH demands is allocated to PSD using a temporal and a spatial allocation to arrive at local heat supply strategies.

2.2. Mapping heat demands and prospective heat supply districts

HD (2015) is mapped at 100m grid resolution using modelled plot ratios for single and multi-family as well as service sector buildings. National HD from the FORECAST model [31], have been distributed by means of population density per hectare [32] using the modelled plot ratios, and per-capita floor areas derived from Eurostat [33]. For a detailed description of the mapping of HD, see Persson *et al.*, 2017 [17].

DH may be technically feasible in connected and contiguous areas where HD density is sufficient, and where investment costs of DH distribution networks are low. PSD are areas with HD density > 20 TJ/km² [16] and formed of contiguous cells and coherent settlements likely to represent potential DH supply areas. PSD are solely based on technical criteria and do not include a cost assessment. They are connected if there is a distance of less than 400m between individual clusters of cells. Larger agglomerations of areas are split into smaller units using the NUTS3 (Nomenclature of Territorial Units for Statistics, level 3) areas. In addition, PSDs are split into smaller sections of up to 8km² because the capacitated coverage allocation tool cannot handle demands that exceed facility capacities.

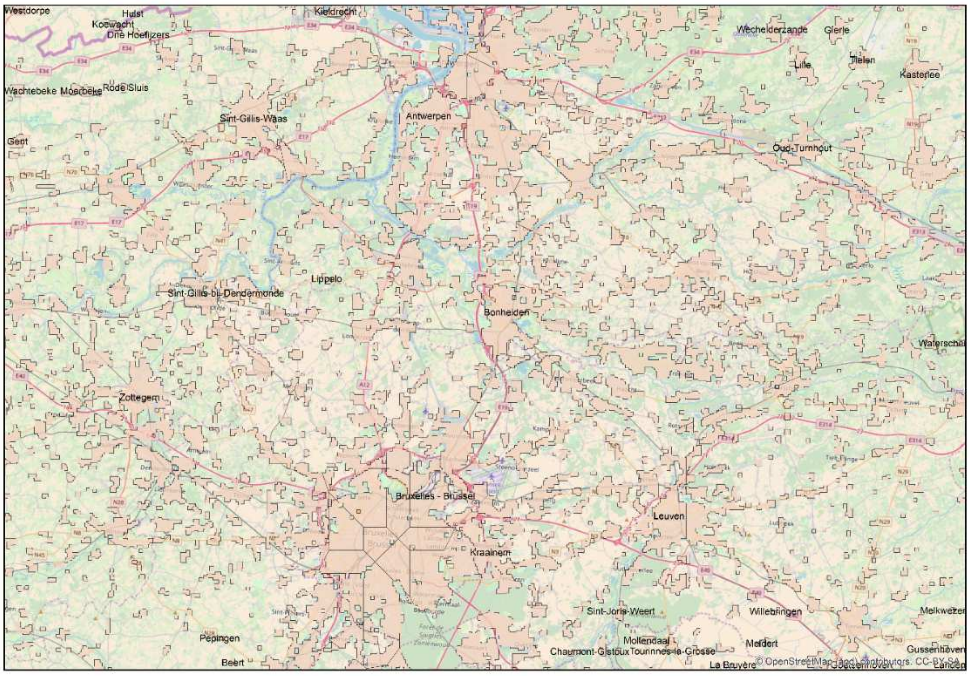

Figure 3: Map of PSDs in the area of Brussels and Antwerp. PSDs larger than 8 km² have been split into smaller sections because the capacitated coverage allocation tool cannot handle demands higher than facility capacities.

The result is a total number of 52,112 PSD for allocation, for which HD, DH network efficiency, and DH supply are being calculated for the spatial allocation process, see Figure 3.

The Halmstad University District Heating and Cooling (HUDHC) database [8] contains descriptive information about 3,104 DH systems in 2,360 urban areas. The present study omits this data, because the point-based HUDHC database is not geo-referenced to the 52,112 PSD polygons identified in the present paper: the actual supply areas of current DH systems are not mapped.

2.3. Cost-supply relations for DH potential in individual PSD

Cost-supply (CS) curves show the costs of exploiting cumulative resources, in this case the potential to develop DH. CS curves facilitate the analysis of policy scenarios as they relate resources and the associated, often spatially defined costs [34]. CS curves can be drawn with marginal costs over cumulative HD, or the average costs of utilising a share of the cumulative resource. A CS curve therefore tells how much of a resource can be utilised at a given cost. The total cost of utilizing this resource is the product of the amount and the average cost.

CS curves have been produced for all HRE countries, on the level of individual PSD. DH distribution capital costs are calculated from HD density and the plot ratio; see [17], as a 100m grid. The cost calculations assume a lifetime of 30 years and a discount rate of 3%.

Practically, the method combines 52,112 PSD with 36 cost values in a geometric sequence in one grid. HD was summarised for the resulting 751,344 individual areas of combined PSD code and cost code, each with a unique combine-ID. Then, a pivot table summarises HD by costs for each PSD, deriving the PSD as well as the cost interval back from the combine-ID via a database relation. In a spreadsheet, accumulated HD, accumulated cost, average cost, and economic potentials were calculated. The economic DH potential $Q_{dh, econ}$ is here assumed to be the cumulative DH potential at average costs below 5 €/GJ annual heat delivered.

2.4. A spatial model of district heating network efficiency

Specific annual heat losses in a DH grid are related to the linear heat density, i.e. the proportion of annual heat sold per trench length. In a pipe, heat loss increases with its diameter according to Equation 4 [35],

$$q = \frac{t_i - t_a}{\frac{\ln(\frac{r_0}{r_i})}{2\pi k} + \frac{\ln(\frac{r_s}{r_0})}{2\pi k_s}} \qquad \text{[W/m]}$$

Equation 4

where q is the heat loss per meter of pipe, t_i the inner and t_a the outer temperature, r_o the outer pipe radius, r_i the inner pipe radius and r_s the outer pipe insulation radius. k is the thermal conductivity (W m^{-1} K^{-1}) of the pipe (steel) and k_s the thermal conductivity of the insulation. Here, k_s is assumed 0.023 W m^{-1} K^{-1} (polyurethane).

Pipe dimensions are correlated to the HD density in an area. Using empirical data on average pipe dimensions used for different HD densities [36], Equation 5 was derived by regression to establish a relation between pipe radius r_0 and the HD density q_L.

$$q_L = 11.455\, e^{45{,}89\, r_0} \qquad \text{[GJ/ha]}$$

Equation 5

Finally, the efficiency $\eta_{DH\ grid}$ of a DH distribution grid can be estimated using Equation 6, which is derived by adjusting parameters q and q_L using an estimated factor 20:

$$\eta_{DH\ grid} \cong 1 - (20\frac{q}{q_L})$$

Equation 6

Plotting values of $\eta_{DH\ grid}$ against q_L, a regression function like Equation 7 can be derived to calculate DH grid efficiency as a function of HD density on a cell-by-cell basis.

$$\eta_{DH\ grid} = 0.0586\ Ln\ (q_L) + 0.4318$$

Equation 7

The result is a continuous spatial model for the efficiency of DH distribution networks. Efficiencies range from 82% in areas with 50 TJ/km² in suburban areas to 98% in highly dense urban centres with HD densities of 1,200 TJ/km². This reflects the lower grid losses of modern DH systems with higher efficiencies [10]. Subsequently, the efficiency of prospective DH grids will be used to calculate the necessary DH supply.

2.5. Temporal allocation of excess heat

The modelled HD includes space heating and hot water. While hot water consumption is assumed constant throughout the year, space HD follows the seasonal variation of heating degree-days. The climate-dependent baseload is calculated using a 2.5km monthly average temperature grid [37] to arrive at a grid of monthly degree-days. The differences between the monthly mean temperatures and a reference temperature of 17°C times the number of days per month result in monthly heating degree-days, HDD_{month}. The share of climate-dependent baseload HD per cell is the minimum of monthly degree-days, $HDD_{month,\ min}$ divided by the annual sum of degree-days HDD_{annual}; see Equation 8.

$$\varphi_{base} = \frac{12\ HDD_{month,min}}{HDD_{annual}}$$

Equation 8

This climatic baseload factor, see Figure 4, was then assigned to each PSD to describe the seasonally dependent share of space heat to be provided by DH. While large parts of Europe have very low baseload demands, the climatic conditions in Scandinavia, on the British Isles and in mountainous regions result in high heating baseloads even in summer. These locations prove favourable for using baseload excess heat.

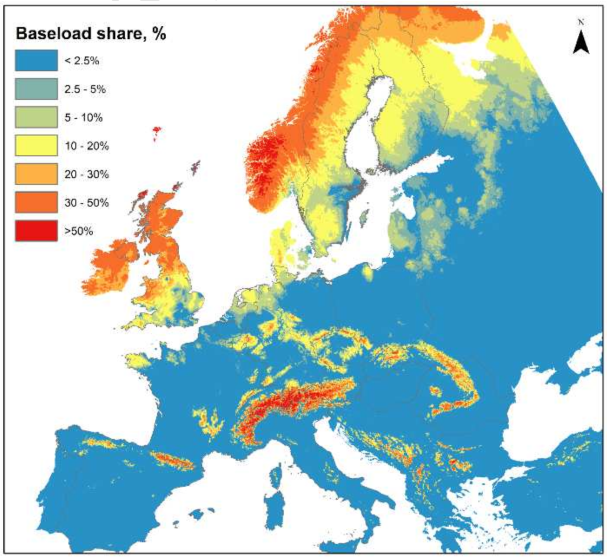

Figure 4: Baseload HD shares, understood as the climate-independent percentage of the annual space HD, calculated continuously for all of Europe.

2.6. Seasonal and baseload district heat delivery and losses

DH supply, including space heat and hot water demands, that may be delivered from the nearest excess heat facilities to PSD with economic DH potential, is composed of baseload and seasonal HD, see Equation 9.

$$Q_{DH} = Q_{baseload} + Q_{seasonal}$$

Equation 9

Baseload DH supply is the share φ_{base} of the economic DH potential $Q_{DH\ econ}$ that is fixed throughout the year:

$$Q_{baseload} = Q_{DH\ econ} * \varphi_{base}$$

Equation 10

Consequentially, the seasonal DH load $Q_{seasonal}$ is:

$$Q_{seasonal} = Q_{DH\ econ} * (1 - \varphi_{base})$$

Equation 11

Hot water demand is assumed constant throughout the year and a fraction of the total annual HD, derived as the ratio between “Hot water delivered” and “Total heating delivered” on national levels from the HRE D3.1 report [2]. Hot water demand is included in the mapped HD, but subtracted from the total DH demand before calculating seasonal demands.

Assuming for simplicity that loss-inducing temperatures are the same throughout the year, losses in the DH distribution network are modelled as fractions of baseload as well as seasonal loads:

$$Q_{DH,gross} = Q_{baseload} + Q_{loss,base} + Q_{seasonal} + Q_{loss,seasonal}$$

Equation 12

Accordingly, baseload and seasonal supply to be delivered to the DH system is calculated as follows, using the DH grid efficiency calculated in Equation 7:

$$Q_{baseload,gross} = \frac{Q_{DH\ econ}\ \varphi_{base}}{\eta_{DH\ grid}}$$

Equation 13

$$Q_{seasonal,gross} = \frac{Q_{DH\ econ}\ (1 - \varphi_{base})}{\eta_{DH\ grid}}$$

Equation 14

These heat loads were calculated for all of the 52,112 PSD and made available for the following allocation process.

2.7. Spatial allocation of excess heat

The allocation of excess heat uses two different, sequentially applied allocation methods, which follow a merit order of excess heat utilization in energy systems. First, baseload excess heat from industry and WtE is allocated with priority given to larger units by assigning the annual capacities as weights in the allocation. The results comprise the excess heat of each facility that can be allocated to a demand point and hence utilised, and vice-versa the possibility for each prospective DH system to cover its baseload demand with excess heat. Second, PSD are allocated to current PP, in heat supply clusters, based on minimum cumulative, weighted transmission pipe length required to connect to a facility. The allocation therefore comprises a method to systematically match demand and supply using an assumed least-cost algorithm that is based on spatial connectedness.

2.7.1. Network allocation data

The connectivity of DH installations is constrained by topography. Water bodies, mountains, forests, and built-up areas affect DH pipe routing in the open landscape. Therefore, as a proxy to DH transmission corridors between EHA and PSD, a road network database of primary and secondary roads was used. The Global Roads Open Access Data Set, Version 1 (gROADSv1) [38], was estimated as appropriate for the purpose, compromising between accuracy and computability.

The gROADS dataset was converted into an ArcGIS Network Analyst network dataset (ND). Connectivity to any vertex of the network features was assumed, which avoids de-routes, and the unit for road distance accumulation was set to metres. 615,000 connecting road elements are included, as well as 216,000 junctions.

As a maximum distance for allocation, 50km road network distance was chosen, based on experiences from large interconnected DH systems such as in Copenhagen.

2.7.2. Network location data: facilities and demand points

Facilities are the 2,189 EHA points, of which 1,389 baseload units have a potential of 2,149 PJ, while 800 seasonal load facilities may deliver up to 4,403 PJ. Demand points are the 23,953 centroids of PSD with an economic DH potential of 5,798 PJ in total.

Results from the allocation are stored in relational tables pertaining to the network data elements facilities, demands and lines. An Access database allows for the extract of allocation results by PSD, facility type, by MS and other dimensions of interest.

Figure 5 visualises the allocation of baseload excess heat to PSD in the area of Erfurt, Germany. Connecting lines are drawn from EHA to PSD centroids. These lines are imaginary, as the transmission pipes are routed along the road network. It shows that while most of the PSD in that area could be supplied with extensive DH networks, some of them are beyond the 50km distance.

Figure 6 visualises the allocation of seasonal HD to current locations of PP in North-West Germany. This allocation is not capacitated; however, the costs of transmission pipelines are calculated. Maximum annualised transmission costs of 0.5 €/GJ heat delivered are estimated to exclude allocations beyond. Green lines are below this threshold, red ones exceed it.

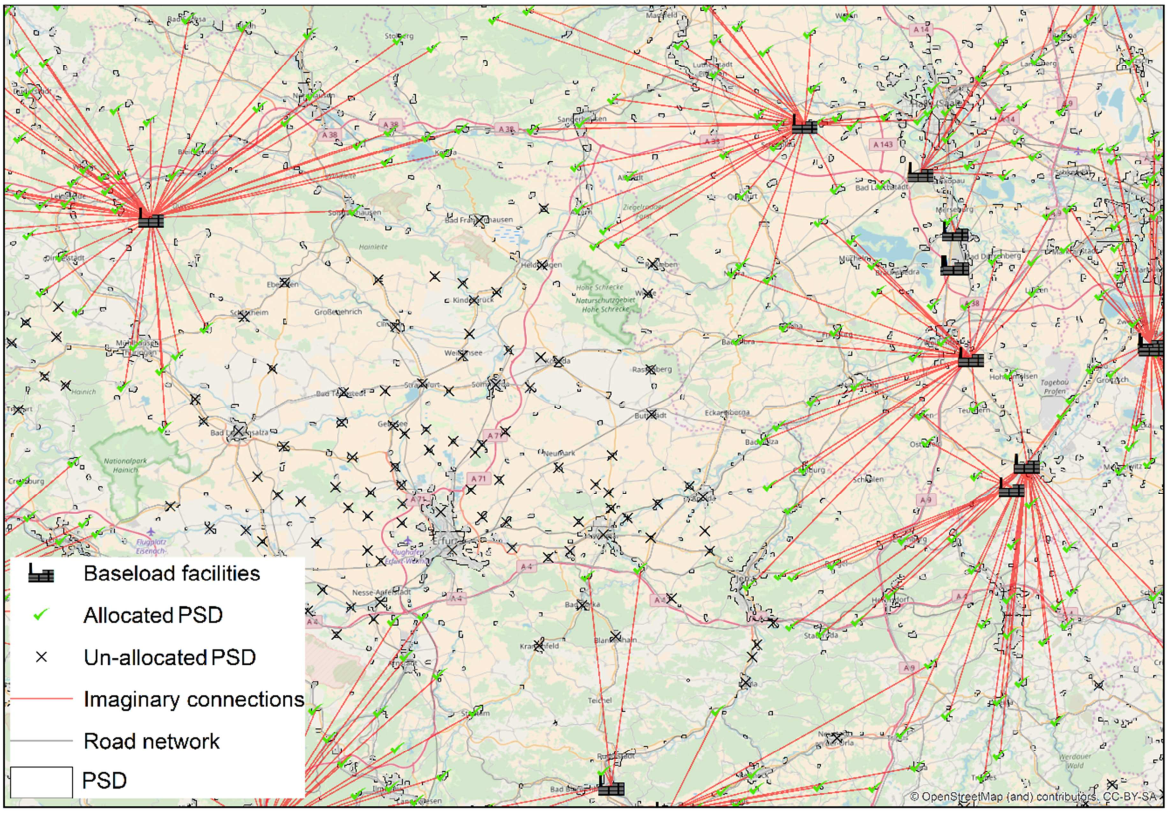

Figure 5: Extract from the map that shows the result of the allocation of baseload demand to industrial excess heat and WtE plants. The map shows the area around Erfurt (centre left of map), state of Thuringia, Germany.

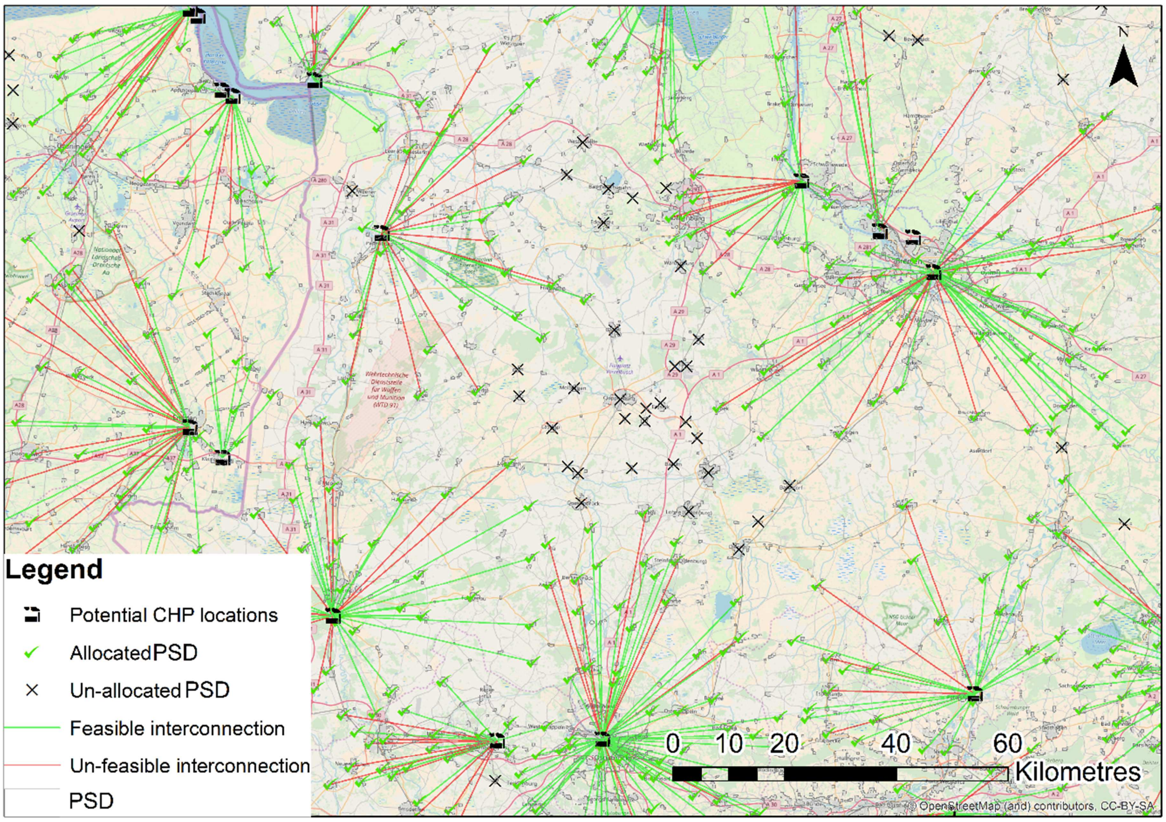

Figure 6: Extract from the map that shows the result of the allocation of seasonal district HD to locations of current PP. The map shows the area of Bremen (centre right), North-West Germany.

2.8. Renewable energy sources

Low-enthalpy renewable heat and marginal biomass are preferred resources for DH systems wherever baseload excess heat is not available. Hence, a geographical analysis of these resources aims at locating and quantifying available renewable energy sources such as geothermal heat, solar thermal energy, and sustainable biomass to PSD.

2.8.1. Geothermal heat

Geothermal heat resources are difficult to map quantitatively. The accessible heat depends on temperature gradient and possible mass flow of hydrothermal water. In addition, the heat rate depends on technology and is therefore difficult to allocate quantitatively to specific PSD [39].

The GeoDH project [40] presented qualitative maps of geothermal potential across Europe. A simple scoring system was developed in the present paper to assign priorities of geothermal potential to PSD, see Table 1. Using the GeoDH spatial layers, see Table 1, a score between 1 and 3 was associated to the PSD, and geothermal shares of DH were assumed. Areas outside the score were given a priority of zero.

Table 1: Scoring system of qualitative geothermal data layers into a prioritisation of available geothermal heat.

Geothermal property	Priority 1 (high)	Priority 2 (medium)	Priority 3 (low)
Heat flow density > 90W/m²	X		
Hot sediment aquifer	X		
Neogene basins	X		
Other potential reservoirs		X	X
Temperature gradient of 90°C at 2000m	X		
Temperature gradient of 50°C at 1000m	X	X	
Assumed share in DH supply	30%	20%	10%

2.8.2. Sustainable biomass

Sustainable biomass potentials from the BioBoost project [41], which show the marginal (i.e. excluding dedicated energy crops), technically and economically feasible biomass resources on a NUTS3-level, were distributed to PSD. Concentrating on the three main sources: straw from agriculture, wood from forestry and biodegradable household waste, the available resources in each NUTS3-district were distributed to a 100m resolution grid. Straw was distributed to CORINE 2012 land use Code 12 [42]. Likewise, forest residues were distributed to all CORINE forest areas, not discriminating between forest type, age, or management practices. Forests located in NATURA 2000 areas [43] are excluded. Finally, within each NUTS3-district, biodegradable household waste was distributed following population density using the JRC 100m population grid [32].

Allocating biomass resources to PSD is not trivial. Limited biomass resources should maximise the replacement of fossil fuels while minimising environmental impact. However, socio-economics and the logistics of biomass need consideration. Transport costs may prioritize the nearest consumers. The economy of scale in biomass operations, however, favours long-haul transport of biomass from the most productive source areas to the consumers with the highest ability to pay. Nevertheless, as the Bioboost data comprise marginal resources, biomass may initially be allocated by Euclidean distance to the nearest demand points. Patterns of urban settlement then lead to two main modes of allocation: in rural areas, allocation from a local forest or field to the nearest settlement favours small-scale DH. In urbanised areas, the supply of biomass from agriculture and forestry would be minimal. Therefore, in allocating biomass resources, the local PSD are prioritised if no alternatives to biomass exist and if more than 10% of supply is met. Solar thermal heating is prioritised over biomass. Accordingly, biomass is for smaller DH systems in rural areas without alternatives. Finally, surplus biomass from the local allocation is made available for large-scale biomass economies.

2.8.3. Solar thermal district heating

Large-scale solar DH requires sufficient solar radiation, available space, and the absence of competing baseload supply. Counter-cyclic behaviour of solar to HD disfavours baseload supply, and necessitates significant seasonal storage.

Adapting and further improving the method applied in [43], using CORINE land use grids of agriculture and marginal land use. Natura 2000 areas [44] were excluded. Further, the discrete CORINE land use mapping by majority neglects sparse development in the urban fringe, which effectively rules out large solar collector fields. Accordingly, cells with more than 10% built-up area found in the European Settlement Map 2016 [45] were excluded.

Available land 200m around each PSD was found by expanding by 2 cells, then summarising the suitable area. Mean global horizontal irradiation derived from PVGIS [46] was associated to PSD, and the solar potential was calculated using technical and economic parameters as in Trier *et al.* [43].

2.9. Local heat supply strategies

To provide annual mixes of heat supply from excess heat, potential CHP, marginal biomass, geothermal heat, and solar thermal, available supply options were modelled for each PSD where economic DH potentials exist.

Supply strategies are formulated by prioritisation. After allocating baseload excess heat, residual baseload DH supply was assigned to the spatial allocation of seasonal demand. However, before agglomerating PSD to centralised CHP units, local geothermal supply was investigated. Where neither baseload excess heat nor geothermal heat is available, solar thermal DH is assigned, at an annual solar share of 40%. At this scale, seasonal heat storages are needed.

Furthermore, residual supply is allocated to central CHP locations by impedance-minimizing allocation. As the pipe cost is a weight in the allocation, the total weighted distance represents the pipe costs. Annualised transmission capital costs were calculated assuming the same interest rate and life expectancy as for distribution pipes. A simple threshold of 0.50 €/GJ excludes unfeasible connections.

Where none of the supply options above is available, or where local supply is not sufficient, biomass is used. Finally, the remainder is being specified, for which alternatives have to be found beyond the solutions mentioned. The result is a set of strategies for all 52,112 PSD, defining where DH systems may be feasible and supplied by limited excess heat and local renewable sources. The remainder is subject to individual heating solutions.

3. Results

At 9,908 PJ, the 14 HRE countries comprise 91% of the EU HD, of which 8,154 PJ (82%) is found within PSD, and may be defined as the theoretical maximal DH potential. Applying cost-supply analysis to all 52,112 PSD, the economic potential of DH at average annualised distribution system investment cost of 5 €/GJ is reduced to 5,798 PJ. Table 2 shows the sensitivity to these costs. Austria, Finland, Italy, and Sweden are countries with favourable conditions to develop DH, while Hungary and the UK are initially more expensive to develop. Assuming maximally feasible development costs of 9 €/GJ all countries except Hungary show DH potentials of 80% or more.

Table 2: Percentages of cumulative 2015 HD within PSD, which can be covered with DH at average annualised DH distribution capital costs ranging from 1…9 €/GJ annually delivered heat.

MS	1 €/GJ	2 €/GJ	3 €/GJ	4 €/GJ	5 €/GJ	6 €/GJ	7 €/GJ	8 €/GJ	9 €/GJ
AT	3%	43%	57%	64%	69%	73%	76%	79%	81%
BE	0%	31%	47%	54%	60%	66%	72%	76%	79%
CZ	0%	31%	64%	75%	80%	84%	87%	88%	90%
DE	0%	29%	57%	69%	76%	81%	85%	88%	90%
DK	7%	34%	51%	61%	68%	73%	76%	79%	82%
ES	0%	27%	60%	77%	85%	89%	92%	93%	95%
FI	30%	50%	60%	67%	72%	75%	78%	81%	82%
FR	2%	17%	41%	55%	64%	70%	75%	79%	82%
HU	1%	21%	36%	42%	46%	50%	53%	56%	58%
IT	4%	38%	65%	78%	85%	90%	92%	94%	95%
NL	0%	1%	23%	57%	73%	85%	92%	95%	98%
PL	0%	29%	62%	72%	77%	81%	84%	86%	87%
RO	0%	1%	25%	59%	69%	74%	76%	78%	80%
SE	17%	54%	67%	74%	78%	81%	83%	85%	86%
UK	1%	12%	29%	41%	53%	65%	76%	85%	91%
HRE	2%	26%	50%	63%	71%	77%	82%	86%	88%

HD within those 23,976 PSD, where DH is below the cost threshold, is subjected to local baseload shares and the local DH network efficiency to calculate gross baseload and seasonal DH supply. By means of Maximise Capacitated Coverage Allocation of 1,398 baseload excess heat activities, 1,308 of such activities were allocated to 15,887 PSD. 580 PJ out of 895 PJ (65%) gross baseload demand in these PSD could be covered. The remaining baseload was associated to seasonal excess heat locations. Seasonal and non-allocated baseload gross HD in 14,161 PSD (in total 7,325 PJ) was allocated to 736 out of 800 locations of current thermal PP. These currently have a theoretical excess heat potential of 4,403 PJ, however 5,611 PJ of gross seasonal and -residual baseload demand was allocated. This leaves 9,815 PSD with 1,714 PJ in total out of reach for larger, centralised CHP.

Part of developing heat supply strategies was the utilisation of local renewable energies. If priority is given to excess heat, produced at low or zero variable costs, then capital-intensive renewable sources may not be competitive. Where connection to larger, centralised DH systems is not feasible, biomass may be used. Biomass may comprise a seasonal fuel storage, and be the only choice for small-scale DH.

Table 3: Allocation results per MS. Out of the economically maximal DH potential of 71% of the net HD in 2015, 78% can be covered. From one MS to another, DH potentials and coverages by means of excess heat utilization vary significantly.

MS	HD within PSD [PJ]	Economic net DH potential [PJ]	Econ. DH share [%]	DH baseload, gross [PJ]	DH seasonal gross [PJ]	Allocated baseload gross [PJ]	Covered baseload [%]	Allocated seasonal gross [PJ]	Covered seasonal load [%]	Covered total gross [PJ]
AT	177	122	69%	15	149	12	82%	119	80%	80%
BE	275	165	60%	6	219	6	99%	217	99%	99%
CZ	184	147	80%	37	168	22	61%	153	91%	86%
DE	2,089	1,589	76%	263	1,884	195	74%	1,605	85%	84%
ES	413	349	85%	45	432	31	70%	300	69%	69%
FI	176	126	72%	19	157	4	22%	132	84%	78%
FR	1,213	779	64%	131	926	92	70%	571	62%	63%
HU	177	82	46%	7	109	4	55%	74	68%	67%
IT	1,081	924	85%	64	1,199	49	76%	923	77%	77%
NL	376	276	73%	33	342	24	71%	314	92%	90%
PL	442	342	77%	52	427	23	45%	351	82%	78%
RO	117	81	69%	15	99	4	26%	58	58%	54%
SE	237	183	78%	47	206	29	63%	157	77%	74%
UK	1,198	630	53%	134	721	85	63%	637	88%	84%
HRE	8,154	5,798	71%	867	7,038	580	67%	5,611	80%	78%

Table 4: Summary of local heat supply strategies on country level. The table distinguishes between rural and urban HD. Where DH is feasible at distribution capital costs below 5 €/GJ, supply from excess heat, solar thermal, and geothermal has been allocated. Where within reach, an urban area may be connected to a central DH system with large-scale CHP. Where none of these options is available, small-scale biomass may be used. Finally, the remainder has to be covered with alternatives. This way, the table is a summary of potential heat supply strategies derived from spatial allocation of excess and renewable heat for 52,112 individual PSD.

MS	Total net HD [PJ]	HD within PSD [PJ]	HD rural [PJ]	PSD DH pot. [PJ]	PSD no DH [PJ]	Base excess [PJ]	Solar therm [PJ]	Geo-therm [PJ]	Cen-tral CHP [PJ]	Bio-mass [PJ]	DH other [PJ]	DH grid loss [PJ]
AT	232	177	55	122	55	12	25	2	96	11	18	42
BE	324	275	49	165	110	6	36	1	129	4	48	59
CZ	237	184	53	147	37	22	27	11	95	34	16	57
DE	2,413	2,089	325	1,589	499	195	255	216	1,035	141	305	558
ES	491	413	78	349	63	31	42	0	298	43	62	127
FI	226	176	50	126	50	4	12	0	149	26	15	49
FR	1,.563	1,213	350	779	434	92	144	117	527	39	138	278
HU	209	177	32	82	95	4	19	11	56	21	4	33
IT	1,285	1,081	203	924	157	49	126	166	673	77	173	339
NL	426	376	50	276	100	24	41	63	134	5	109	100
PL	658	442	216	342	100	23	60	15	294	54	33	137
RO	183	117	66	81	36	4	15	10	71	12	1	33
SE	296	237	59	183	53	29	12	0	185	21	4	69
UK	1,365	1,198	167	630	568	85	127	17	212	27	386	224
HRE	9,909	8,154	1,754	5,798	2,356	579	942	631	3.954	515	1,283	2,107

Table 4 shows national summaries of spatial heat supply based on allocating excess heat and renewable energy sources, plus the rural share. While baseload excess heat may deliver 579 PJ (7%) to the total gross DH supply of 7,905 PJ, solar thermal may contribute with 942 PJ (12%) where no baseload is available, at 40% solar share. Geothermal heat, although difficult to quantify, has been assigned at 631 PJ, being 8% of DH supply. Where investments in transmission pipelines allow, urban areas may receive 3,954 PJ from central CHP stations, which is 50% of the total DH supply. Biomass may contribute with 515 PJ (7%) where no other supply is available. Finally, DH supply of 1,283 PJ (16%) is to be covered by other sources. 2,356 PJ of HD in low-density urban areas, as well as the rural HD of 1,754 PJ is subject to technologies like heat pumps or individual biomass boilers. The mapping of HD is not yet detailed enough to locate small HD clusters, which would allow establishing collective heating systems in neighbourhoods.

4. Conclusions

The present paper describes a coherent and comprehensive methodology to formulate heat supply strategies. At local levels, HD density and distribution capital costs of DH are being mapped with a raster-based approach of 100m cell size. Coherent and contiguous areas with minimal HD densities, the so-called PSD, are being delineated as zones, in which DH systems are technically possible. For the first time, a cost-supply analysis describes local heat markets in a spatially explicit manner. A major result is that geographic zoning of local heat supply leads to lower potentials than estimated by means of national analysis in earlier studies. The reason is that heat markets are local by nature. The method of cost-supply curves effectively confines areas, which appear favourable for implementing local projects. Accordingly, the economic DH potential for the HRE countries could be estimated at 5,798 PJ, equal to 59% of the total HD in 2015. This potential relies on potent policy instruments to promote DH as a resource and cost efficient way of heating. It may be higher if heat could be supplied at very low costs.

Hence, one way to improve the cost-effectiveness of DH is the access to low cost excess heat. However, not all of the HD matches temporally and spatially with excess heat supply. Consequently, the paper proposes a method to allocate temporally the heat supply from EHA. Here, baseload HD in DH systems is composed of a climatically induced summer HD, hot water demands, and losses, mapped for all PSD. The remainder is the seasonal HD, which varies with climate. While assuming that baseload EHA have constrained capacities, seasonal EHA are potential CHP location at current PP, possibly obsolete in a future smart energy system. Therefore, it is assumed that current PP locations near potential heat markets are prioritised in a spatial allocation. Hence, a two-step allocation process, solves baseload EHA as a Capacitated Coverage Allocation problem, while seasonal HD is associated to prospective locations of CHP in a least cost manner as a Minimize Impedance problem, without capacity constraints.

Results show that in the HRE countries, 67% of the baseload gross HD can be covered, while 80% of the remaining baseload and the seasonal demands can be associated to current locations of PP. Combined, this means that 78% of gross HD in potential DH areas can be covered with excess heat and central CHP. Assuming a maximum DH share of 71%, this is 55% of the total HD in the HRE countries, which can be partly or fully decarbonised.

A large part of the remaining 22% of the HD in DH areas may be covered with geothermal heat, with large-scale solar thermal installations and with biomass where none of the other supply options exist. A mere 16% of the DH supply has not been assigned to potential supplies. There is still potential in refining the methods to identify potential supply. This includes the areas where DH is not feasible, which contain 41% of all HD. In further studies, individual supply options may estimate the potentials to utilise heat pumps, individual biomass boilers etc. based on local conditions.

One of the strengths of local cost-supply analyses has not been used yet. As the present model continuously calculates the distribution costs of DH, the share of DH may be increased where supply is available at lower costs, as higher investment costs may be tolerated. An optimization approach may be applied here; however, the interaction with Smart Energy Systems [4] may necessitate connecting advanced energy systems analysis to this approach.

5. Limitations and Discussion

The present analysis cannot be done without numerous limitations. First, data quality issues due to the absence of comprehensive data on the heating sector may compromise the validity of results. Second, costs are derived from empirical studies, and it is uncertain if future costs will be on similar levels. Furthermore, the allocation uses methods from operations research, implying crude assumptions. Finally, the potentials and availability of excess heat and renewable energy sources are based on generic assumptions, which neglect local conditions, primarily temperature levels and extraction rates.

However poor the data basis for carrying out comprehensive and spatially explicit studies of HD and supply on the local level may be, the results of the present paper should be seen as a very first attempt at mapping a coherent heat sector of Europe. If the reader allows drawing on an analogy, the Mercator World map of 1538 only imprecisely showed the newly discovered parts of the World, while Europe and the Orient were rather well depicted. Mapping the heating sector is similar. There are few countries or parts of those, where tradition, political mandate or energy regulation have brought along a comprehensive mapping of heat supply and demand. Meanwhile, in most European countries the heating sector remains largely unchartered waters. Mercator's map has formed the basis for the scientifically sound and comprehensive description of the World. It is the hope of the authors that maps with the authority of Mercator's will emerge, to help formulating strategies for the future heat sector.

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References

(1) Connolly D. Heat Roadmap Europe: Quantitative comparison between the electricity, heating, and cooling sectors for different European countries. Energy-139 (2017) 580-593.

(2) Fleiter T, Elsland R, Rehfeldt M, Steinbach J, Reiter U, Catenazzi G, Jakob M, Rutten C, Harmsen R, Dittmann F, Rivière P, Stabat P. Profile of heating and cooling demand in 2015. Heat Roadmap Europe D3.1 report, Karlsruhe 2017.

(3) Sayegh MA, Danielewicz J, Nannou T, Miniewicz M, Jadwiszczak P, Piekarska K, Jouhara H. Trends of European research and development in district heating technologies. Renewable and Sustainable Energy Reviews 68 (2017) 1183–1192.

(4) Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 137 (2017) 556-565.

(5) D'Agostino D, Cuniberti B, Bertoldi P. Energy consumption and efficiency technology measures in European non-residential buildings. Energy and Buildings 153 (2017) 72–86.

(6) Connolly D, Lund H, Mathiesen BV, Werner S, Möller B, Persson U, Boermans T, Trier D, Østergaard PA, Nielsen S: Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 65 (2014) 475-489.

(7) Hansen K, Connolly D, Lund H, Drysdale D, Thellufsen JZ. Heat Roadmap Europe: Identifying the balance between saving heat and supplying heat. Energy 115/3 (2016) 1663-1671.

(8) Persson U, Möller B, Werner S. Heat Roadmap Europe: Identifying strategic heat synergy regions. Energy Policy 74 (2014) 663-681.

(9) Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, Nielsen S, Ridjan I, Karnøe P, Sperling K, Hvelplund FK: Smart Energy Systems for coherent 100% renewable energy and transport solutions. Applied Energy 145 (2015) 139-154.

(10) Werner S, International review of district heating and cooling, Energy 137 (2017) 617-631.

(11) European Commission: Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - An EU Strategy on Heating and Cooling. Brussels, 2016.

(12) Persson U, Werner S, Heat distribution and the future competitiveness of district heating. Applied Energy 88 (2011) 568-576.

(13) Persson U, Münster M. Current and future prospects for heat recovery from waste in European district heating systems: A literature and data review. Energy 110 (2016) 116-128.

(14) Connolly D, Mathiesen BV, Østergaard PA, Möller B, Nielsen S, Lund H, Trier D, Persson U, Nilsson D and Werner S: Heat Roadmap Europe 1: First Pre-Study for the EU27. Aalborg University, 2012.

(15) Möller B, Wilke OG, Werner S, Persson U. Heat Roadmap Europe: towards a Pan-European Thermal Atlas (Peta). Archival paper presented at the 10th Conference on Sustainable Development of Energy, Water, and Environment Systems, Dubrovnik (2015).

(16) Möller B, Wiechers E, Persson U, Grundahl L, Connolly D. Heat Roadmap Europe: Identifying Local Heat Demand and Supply Areas with a European Thermal Atlas. Energy 158 (2018) 281-292.

(17) Persson U, Möller B, Wiechers E: Methodologies and assumptions used in the mapping. Heat Roadmap Europe 4 deliverable D2.3 report, Halmstad 2017.

(18) Möller B, Wiechers E, Persson U. Matching district heat demand and excess heat supply using network allocation analysis. Paper presented at the 3rd International Conference on Smart Energy Systems and 4th Generation District Heating. Copenhagen, 2017.

(19) Sørensen B, Meibom P. GIS tools for renewable energy modelling. Renewable Energy 16 (1999) 1262-1267.

(20) Gils HC, Cofala J, Wagner F, Schöpp W: GIS-based assessment of the district heating potential in the USA. Energy 58 (2013) 318-329.

(21) Nematollahi O, Hoghooghi H, Rasti M, Sedaghat A. Energy demands and renewable energy resources in the Middle East. Renewable and Sustainable Energy Reviews 54 (2016) 1172-1181.

(22) The EU HOTMAPS project. https://www.hotmaps-project.eu Accessed Nov 30, 2018

(23) Persson U, Wiechers E, Möller B, Werner S. Heat Roadmap Europe: Heat Distribution Costs. Submitted to Energy, 2018.

(24) Gorter C and Nijkamp P: Location Theory. International Encyclopedia of the Social & Behavioral Sciences 2 (2015) 287–292.

(25) Stewart JQ. Demographic Gravitation: Evidence and Applications. Sociometry 11 (1/2) 1948, 31-58.

(26) Farahani RZ, SteadieSeifi M, Asgari N. Multiple criteria facility location problems: A survey. Applied Mathematical Modelling 34 (2010) 1689–1709.

(27) Horner MW. Location Analysis. International Encyclopedia of Human Geography 2009, 263-269.

(28) Mirchandani P, Francis R. Discrete Location Theory. John Wiley & Sons (1990).

(29) Hillsman EL. The p-median structure as a unified linear model for location-allocation analysis. Environment and Planning A, 16 (3) 1984, 305-318.

(30) Rocha M, Roming N, Parra PY, Ancygier A, Sferra F, Ural U, Schaeffer M, Hare B. A Stress Test for Coal in Europe Under the Paris Agreement. Scientific Goal Posts for a Coordinated Phase-Out and Investment. Climate Analytics, Berlin 2017.

(31) Fraunhofer ISI, Forecasting Energy Consumption Analysis and Simulation Tool (FORECAST). http://www.forecast-model.eu/forecast-en/index.php , last accessed 09-05-18.

(32) JRC, Joint Research Centre of the European Commission, Earth Observation Data and Processing Platform: GHS European population grid, 100m. http://cidportal.jrc.ec.europa.eu, last accessed 09-05-18.

(33) Eurostat Census Hub: Census data. https://ec.europa.eu/CensusHub2, last accessed 09-05-18.

(34) Izquierdo S, Dopazo C, Fueyo N. Supply-cost curves for geographically distributed renewable-energy resources. Energy Policy 38 (2010) 667–672.

(35) Beitz W and Küttner KH. Dubbel; Handbuch für den Maschinenbau. 17th edition. Springer, 1990.

(36) Ahlgren E. IEA ETSAP Technology Brief E16, District Heating. Energy Technology Systems Analysis Programme, 2013.

(37) University of Alberta gridded Climate data for Europe. https://sites.ualberta.ca/~ahamann/data/climateeu.html (last accessed 09-05-2018).

(38) Center for International Earth Science Information Network (CIESIN)/Columbia University, and Information Technology Outreach Services (ITOS)/University of Georgia. 2013. Global Roads Open Access Data Set, Version 1 (gROADSv1). Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). Downloaded from http://sedac.ciesin.columbia.edu/data/set/groads-global-roads-open-access-v1 03-05-17.

(39) Østergaard PA, Mathiesen BV, Möller B, Lund H. A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. Energy 35/12 (2010) 4892-4901.

(40) Dumas P, Angelino L, Latham A, Pinzuti V. Developing geothermal district heating in Europe. GeoDH, Brussels (2013).

(41) The EU Bioboost Project: www.bioboost.eu (last accessed 09-05-2018).

(42) EEA (European Environment Agency) Corine Land Cover 2012 raster data: http://land.copernicus.eu/pan-european/corine-land-cover/clc-2012, last accessed 20-4-17.

(43) Trier D, Skov CK, Sørensen SS. Potentials for ground-mounted SDH in Europe. Paper presented at the Solar District Heating conference in Graz, 2018.

(44) EEA (European Environment Agency) Natura 2000 data - the European network of protected sites. Natura 2000 End 2017 Shapefile: https://www.eea.europa.eu/data-and-maps/data/natura-9#tab-gis-data, last accessed 13-05-18.

(45) JRC, Joint Research Centre of the EC: European Settlement Map 2016. land.copernicus.eu/pan-european/GHSL/EU%20GHSL%202014 (last accessed 13-05-18).

(46) JRC, Joint Research Centre of the EC: Photovoltaic Geographical Information System (PVGIS): http://re.jrc.ec.europa.eu/pvgis/ (last accessed 13-05-18).

Highlights

A comprehensive spatial energy planning model for the European heat sector.

Cost-supply relationships of district heat and investment costs on local levels.

Temporal and spatial allocation of excess heat to potential district heating systems.

Heat supply strategies for 50,000 heat supply districts across Europe.