High-resolution transformation strategies towards carbon-free heat supply in German municipalities

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Abstract

The decarbonization of the heating sector has become a major focus of energy policy in recent years. Almost 50 % of final energy consumption in Germany is accounted for heating, hot water or process energy with only 15 % share of renewable energies. District heating infrastructure provides an opportunity for municipalities to reduce GHG emissions significantly by developing large scale renewable energy heating technologies, such as geothermal, heat pumps or solar thermal plants. However, the potentials for these technologies are often locally limited and can only be used in a spatial proximity to the heat demand. Therefore, municipal heat planning plays a decisive role by taking regional characteristics into account.

As part of the reports for the European Energy Efficiency Directive (EED), we were commissioned by the German Federal Environment Agency to analyse the potential for efficient heating and cooling at municipal level in order to derive transformation strategies for municipalities. First, we analysed the locally available potentials of renewable heat in the over 4,500 German municipalities and compared them to the municipal heat consumption. The results are prepared in a GIS online platform for local stakeholders and used for the development of transformation strategies at municipal level. These can fulfil the energy efficiency target of a 30 % primary energy reduction by 2030 and the minimum renewable share of 40 % in heat supply. Second, a cost-benefit analysis was performed to evaluate all available technologies for each municipality from both a micro- and a macroeconomic perspective. The latter considered socio-economic and environmental factors and the well-being of society as a whole. Compared with the reference development, the transformation strategies have lower costs and lower greenhouse gas emissions. The results of this paper can help local actors for an initial assessment of local potentials by accessing the developed GIS online platform and thus serve as an important basis for the implementation of carbon-free heating strategies.

Introduction

The design of a high-resolution carbon-free heat supply in Germany was achieved based on the following key pillars:

1. District heating and supply potentials in municipalities
2. Heat supply scenarios
3. Economic Impact and Cost-Benefit Analysis

The first step consists in an in-depth potential analysis including the identification of the heat demand potential suitable for the usage in district heating infrastructure and the different carbon-free heat sources available in a spatial proximity to that heat demand. These key variables being determined for each of a total of 4,670 municipalities[1] in Germany offers a high-resolution overall picture of sustainable heat potential. Using

1. The analysis is conducted for the 'associated municipalities' in Germany. In this spatial resolution, multiple communities are aggregate. Thus, the number of analysed municipalities is 4,670 instead of almost 11.000. For a clear presentation, the visualisation was carried out on NUTS3-Level.

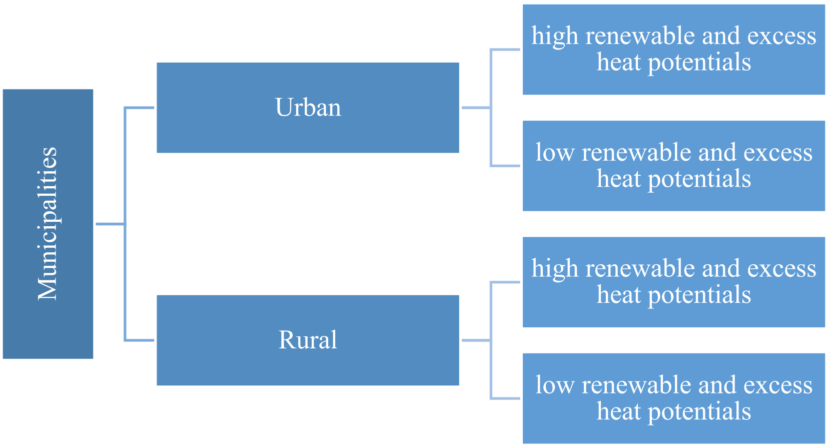

Figure 1. Procedure for the clustering of municipalities.

relevant assumptions optimising the use of these potential in heat networks, several heat supply scenarios based on different technologies mixes were developed in line with the National Energy and Climate Plan (NECP). In the last step, a cost-benefit analysis was carried out to estimate whether the developed transformation scenarios successfully achieve socioeconomic and environmental benefits while preserving resources.

Considering the large amount of data obtained, the results in the following chapters are classified in four different clusters of municipalities: urban or rural and with a low or high renewable and excess heat potential (REHP). The criteria used for clustering the municipalities are the size (urban/rural) and the availability of local potentials as shown in Figure 1.

Compared to the previous assessment in 2014 (Wünsch, M. et. al. (2014)) which focussed on CHP plants this evaluation includes focusses on renewable and excess heat potentials. New in this analysis is the level of detail of the spatially disaggregation and the presentation in maps which enables the analysis on municipality level throughout Germany. The applied method for the cost-benefit analysis was supplemented by the inclusion of environmental costs.

Data and Methodology

POTENTIALS ANALYSIS

In this study[2], spatially available information is used to identify whether relevant renewable potentials or excess heat potentials can be tapped within the municipalities. As a result, the technical potentials are visualized, whereby – depending on heat source – the supply potentials (potentials that can be tapped by known technologies) or demand potentials (potentials that can additionally be used for grid-bound heat supply) are used.

The following approach is chosen to identify the technical potential for all sources in generals, the procedure for district heating and two selected renewable heat sources is described in more detail below:

- For all municipalities, the theoretical potential is determined and it is evaluated which share of the theoretical potential can be tapped by means of known technologies (supply potentials).
- The heat demand in 2030 on municipal level is derived from the NECP and spatially disaggregated according to the shares of the individual buildings in the total building stock from a national heat demand scenario from the NECP (Kemmler et. al. 2020) and result in information on heat demand per municipality. Since the disaggregation is conducted using a building-specific heat atlas, the heat demand is also categorized in heat densities and allows the prequalification of possible district heating areas based on thresholds.
- In addition, an initial comparison is made of the distance of the heat source to possible heat sinks.
- Assumptions on sink temperatures that are relevant for the determination of the potentials are varied - if possible – in order to be able to take into account the prospective transformation of the heat grids to low-temperature grids. This primarily concerns the use of deep geothermal energy and industrial excess heat.

The local potentials were derived for excess heat, thermal waste treatment plants, deep geothermal energy, solar thermal energy, energy from sewage or sewage treatment plants and large heat pumps using various heat sources. Furthermore, district heating potentials were identified based on heat densities. The approach is shown exemplary for the potential of district heating, industrial excess heat and deep geothermal energy. The results are shown for all heat sources and visualized for industrial excess heat and deep geothermal energy.

District heating potentials:

To derive district heating potentials, the heat densities for space heating and domestic hot water in building for each municipality are analysed. Based on the national development of the heating and cooling demand according to the NECP and a

2. The study behind this paper was conducted by the same authors as this paper within the comprehensive assessment of the potential for the use of high efficiency combined heat and power (CHP) and efficient district heating and cooling called by European Energy Efficiency Directive 2012/27/EU (EED) in paragraph 1 of Article 14 on the promotion of efficiency in heating and cooling.

building heat atlas, heat densities as 100x100 m grid cells[3] are determined. Among others, building types, building age classes and climate zones in Germany were taken into account. Each cell indicates the heat demand per hectare. Various sources indicate that grid-bound energy supply is particularly suitable in areas where the heat density is above 15 GWh/km² (Hausladen & Hambacher, 2011 and Hertle et. al. 2015). Against this background, the heat demand per density class (<15 GWh/km² and >15 GWh/km²) and municipality is summarized.

Industrial excess heat:

The potential of industrial excess heat is analysed based on data from the German Federal Immission Control Act (11. BImSchV) and from the Pollutant Release and Transfer Register (E-PRTR). The site-specific data contain, among other georeferenced information on operating hours, volume flow and temperature of flue gas, which allows to determine the theoretical industrial excess heat potentials (for details see Ortner et a. (2021) and Blömer et al (2019)). Based on the site-specific results of the theoretical potentials, the technical potentials are determined based on a spatial approach. For the locations identified in the previous step, it is analysed whether there is a potential district heating area (heat density over >15 GWh/km² and heat sales of at least 1 GWh without considering the inertia of system) within the maximum permissible distance of 1 km, as this distance usually does not affect the economic viability of the integration of the heat source[4].

Deep geothermal energy:

In order to derive spatially allocated technical supply potentials for geothermal energy, information from the geothermal information system GEotIS is used, in which proven hydrothermal reservoirs are shown according to the temperature level (Agemar et al. (2014), LIAG (2020)). In addition to measured data, the data is also based on derived subsurface models for the spatial interpolation of geological parameters. Using the information on the temperature of the hot water, the mass flow of the reservoir and assumptions regarding the specific heat capacity of water and the reinjection temperature, the supply potential is derived.

Other Renewable energy sources:

The technical potential for the other renewable energy sources takes the source specific restrictions into account (e. g. required land area for solar thermal, distance from waste water treatment plants to heat sinks).

HEAT SUPPLY SCENARIOS

Based on the results of the potential analysis, different heating supply options for the grid-connected heat supply have been calculated, including the following technologies:

- Industrial excess heat and cooling
- Waste incineration
- High-efficient CHP
- Deep geothermal plants
- Solar thermal plants, with/without seasonal storage systems
- Biomass heating plants
- Large-scale heat pumps
- Power to heat
- Fossil heat plants

For these technologies, technical and economic framework parameters have been set based on existing studies such as Fichtner et al. (2019) and Grosse, R. et. al. (2017). These include for instance the minimum runtime and efficiency for each technology, installation, operating and fuel costs, district heating distribution costs, GHG emissions and primary energy factors. Assumptions were also made about the costs and the necessary length of new pipes, connecting the local district heating system with plants that are normally located outside of the city (e. g. solar thermal, deep geothermal plants or excess heat integration from industrial facilities). Some of the assumptions can be found in the annex.

For each municipality the potential of district heating was assessed depending on the heat density and the share of existing heat networks. Then, the share of the REHP that can be used in district heating systems was assessed. This share is limited by factors such as a minimal temperature or a minimum power plant size for an economically viable integration in a heat network. For the analysis the following assumptions were made:

- The realistic district heat potential of 137 TWh respectively 156 TWh (including grid losses) in about 1,640 municipalities is taken into account;
- Industrial excess heat: The potential for high- and low-temperature networks >=75 °C is taken into account, consideration of specific operating hours per municipality;
- Deep geothermal energy: utilization of the potential from a reinjection temperature of 65 °C as described above, which can be used directly in networks of 90 °C;
- Power to heat: The potential exists in northern states of Germany with renewable electricity surplus from wind power plants (Schleswig-Holstein, Mecklenburg-Western Pomerania, Lower Saxony, and Brandenburg) at a maximum of 10 % of the community's required heating load;
- Assumption of a minimum thermal capacity of the plants to be integrated into heat grids, e.g. 1 MW for solar thermal plants, 5 MW for deep geothermal plants:
- Heat pumps: Heat sources that are locally limited and can be made accessible for district heating by means of heat pumps. Excess heat from sewage and wastewater treatment plants, surface water and industrial excess heat between 35 and 75 °C is taken into account. In addition, air heat pumps can be used regardless of the local potential.

Based on a typical monthly load profile of a district heating system, different district heating options were calculated and evaluated by their economic and ecological impact. As a re-

3. The spatial data are compliant with the EU directive INSPIRE.

4. The actual economic assessment takes place within the framework of the heat supply scenarios and the threshold is only used to prequalify the technical demand potentials.

Table 1. Results for district heating potential in municipalities on cluster level.

Cluster	Number of municipalities	Description	District heating potential [TWh]
1	506	urban, low REHP (≤ 40 %)	97.9
2	240	urban, high REHP (>40 %)	27.0
3	678	rural, low REHP (≤ 40 %)	9.1
4	216	rural, high REHP (>40 %)	2.9
Total	1,640		136.9

sult, the optimal technology mix was determined for each municipality based on its optimal heat production costs. It means that the cheapest existing technology was prioritized over the more expensive ones, without impact on the overall national goal of a 40 % Renewable and Excess Heat Share and 30 % primary energy reduction by 2030 according to the energy efficiency targets set by the EED (European Commission (2021)).

COST-BENEFIT ANALYSIS (CBA)

The cost-benefit analysis (CBA) includes according to the EED definition in Annex VIII the evaluation of the scenario on a macroeconomic and microeconomic perspective. The macroeconomic analysis takes into account socio-economic and environmental factors to assess the well-being of society as a whole and is thus used for policy-making. The microeconomic cost-benefit analysis takes the perspective of a private investor. In the the results of the microeconomic perspective evaluation are discussed later in this paper as it serves stakeholders in municipalities for planning purposes and decision making (Ortner et al. 2021). Therefore, the economic efficiency and resulting GHG emissions of the district heating supply scenarios on municipal level are compared to an alternative decentralised heat supply. The evaluation of economic efficiency is based on the discounted cash flow method, whereby levelized costs of heating (LCOH) are calculated considering capital CAPEX and OPEX of the respective supply systems[5] and heating networks. The analysis considers discounted energy prices over a period of 20 years. The development of fossil fuel and electricity prices until 2040 as well as the development of CO_2 prices in the ETS and the German Fuel Emission Trading Act (BEHG) is taken from the assumptions of the NECP of the German Government 2020 (Kemmler et. al. 2020; Ortner et al. 2021). A discount rate of 5.5 % and an deprecation time of 20 years are assumed in the micro-economic cost benefit analysis representing the perspective of local utilities that are operating district heating networks in Germany. Furthermore, a heat loss of 12 % is considered in the analysis that is the average heat loss of district heating networks in Germany (AGFW, 2019)

5. Within the study for the Comprehensive Assessment Heating and Cooling, a micro and macro-economic cost benefit analysis have been performed (see Umweltbundesamt (2021) and IREES et al. (2021)).

Results of District heating and supply potentials in municipalities

District heating potentials:

Assuming a connection rate of 100 % in suitable areas, 47 % of the total heat consumption in 2030 (466 TWh potential in buildings plus 50 TWh district heating consumption in industry) would prequalify for district heating supply. Taking into account the inertia of the system and assuming that an increase of the connection rate by a maximum of 50 % is possible by 2030 in municipalities with existing district heating infrastructures and a district heating share of 15 % is possible in about 100 municipalities without district heating, this results in a realistic potential of 137 TWh (without grid losses) in about 1,640 out of 4,670 municipalities.

The 1,640 German municipalities with a potential for district heating were analysed and clustered by their size and potential in four different clusters. Municipalities with more than 40 % renewable and excess heat potentials in relation to the heat demand to be covered in heating networks were classified as high potential. The number of municipalities and the results for the district heating potentials are shown in Table 1.

Industrial excess heat:

The total technical demand thus determined is 32.1 TWh, which breaks down as follows depending on the heat sink temperature:

- The technical excess heat potential that can be used without additional upgrading by means of heat pumps in existing heat networks (Tref >=125 °C) is 22.3 TWh.
- The technical excess heat potential that can be used without additional upgrading by means of heat pumps in local heating networks or low-temperature networks (75 °C<=Tref<125 °C) is 6.2 TWh.
- The technical excess heat potential that can be used in heat grids by means of heat pumps (30 °C <= Tref<75 °C) is 3.6 TWh.

Deep geothermal energy

Overall, this results in a technical supply potential of around 47 GW in Germany based on a reinjection temperature of 65 °C. In the case of active use of geothermal energy by raising the temperature using heat pumps, taking into account a reinjection temperature of 35 °C, the technical supply potential increases to 98 GW. In the previously derived district heating potential regions, the potential accounts for 23 GW.

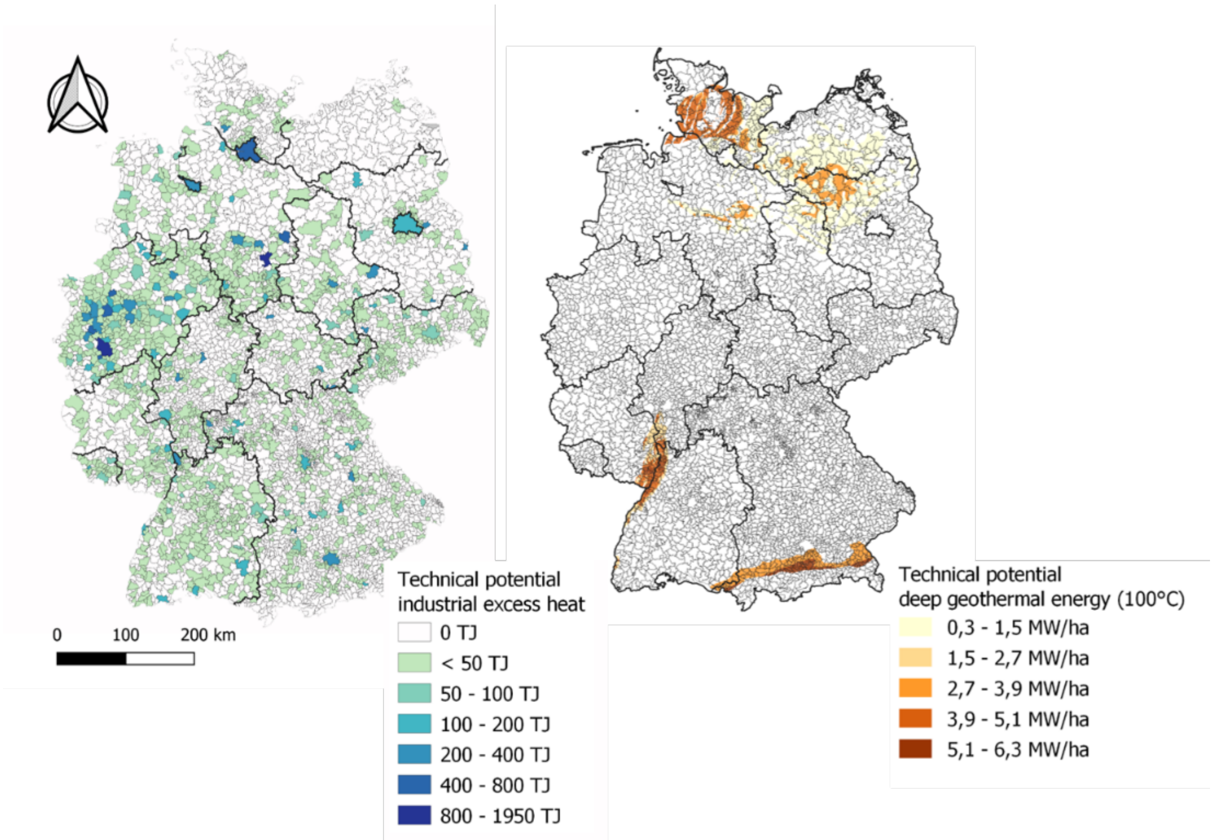

Figure 2. Technical supply potentials of industrial excess heat, that can be used without additional upgrading by means of heat pumps in existing heat networks and deep geothermal energy potential in Germany.

Other renewable energy sources

The potentials were analysed in the same way for the other renewable and excess heat sources and accounted for the municipalities. The technical demand potential for all German municipalities of solar thermal energy amounts to 80 TWh, the potential for heat pumps using energy from sewage water and wastewater treatment plants amounts to 31 TWh and the potential for heat pumps using heat from rivers and sees is almost 80 TWh.

GIS-Visualization

The visualisation of REHP is exemplary shown for the technical potentials of industrial excess heat as well as for deep geothermal energy in Figure 2.

It can be seen that a huge potential for industrial excess heat can be found in the western part of Germany (North Rhine-Westphalia) as well as in and around bigger cities like Berlin, Hamburg, Munich and Mannheim. On the other hand, the potential for deep geothermal energy is available in three regions: the North German Basin, the Upper Rhine Graben in the western part of Germany and the South German Molasse Basin.[6]

The following table summarises the result for the renewable and excess heat potentials in the four cluster, where the inertia of the district heating system is considered.

6. All visualizations developed within the comprehensive assessments can be found here: https://datahub.uba.de/portal/apps/opsdashboard/index.html#/ae128313517548f193a9b72f93ca9db7

Results of the heat supply scenarios

For each municipality a distribution of the technically and economically possible monthly heat production in the year 2030 was determined. Figure 3 shows an example of a small city with high renewable and excess heat potentials. The base load is covered by a deep geothermal plant. In addition, solar thermal and the excess heat of a waste incarnation plant are being used. The peak load in winter times is covered by a fossil high-efficient CHP plant.

This analysis was carried out for each municipality with a potential of district heating and the optimal technology path was selected. Then the results were clusters in the four groups of municipalities recording their size and potentials as described in the previous section. The results of the heat production mixes per cluster and in total are shown in Figure 4. While some municipalities reach a share of renewable and excess heat of 25–30 % in average, others are capable to fulfil their demand with a share of 80 % and more. Nevertheless, this calculation was calibrated to reach an overall share of almost 40 % according to the energy efficiency targets set by the EED. This means that in many municipalities a greater potential could be reached. In fact, a scenario with a 100 % renewable and excess heat share was calculated. The results of that scenario go out of the scope of this paper and can be found in the study (Ortner (2021)).

Municipalities with high renewable and excess heat can cover a major part of their heat supply by locally available sources such as solar or geothermal power plants, excess heat from

Table 2. Results for REH potentials in municipalities with district heating potential on cluster level.

Cluster	Description	Industrial excess heat [TWh]	Deep geothermal energy [GW]	Solar thermal [GW]	Waste incineration [GW]	excess heat from surface water [GW]	wastewater treatment plants [GW]
1	urban, low REHP (≤ 40 %)	10.3	4.5	13.3	1.3	0.6	2.0
2	urban, high REHP (>40 %)	11.1	4.7	11.7	3.3	1.7	2.6
3	rural, low REHP (≤ 40 %)	0.1	11.1	10.6	0.1	1.1	0.4
4	rural, high REHP (>40 %)	0.1	3.2	3.0	0.8	1.1	0.4
Total		21.6	23.5	38.6	5.6	4.5	5.4

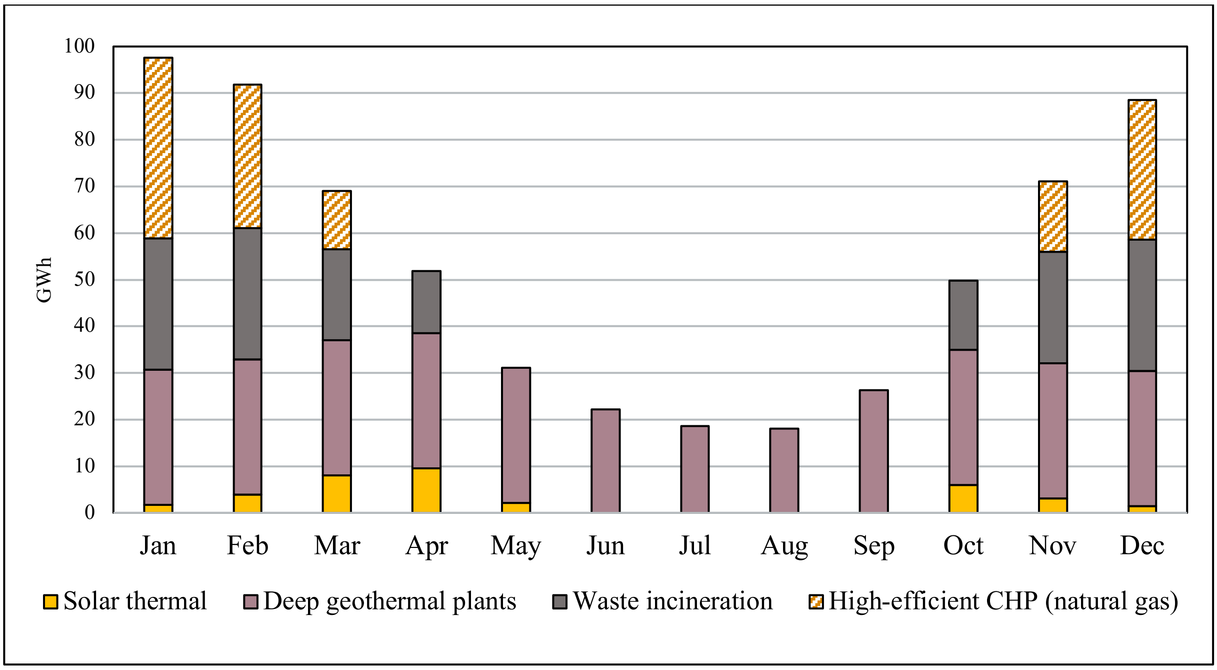

Figure 3. Detailed results of an exemplary municipal heat supply on a monthly basis (located in central Germany).

industry, waste incineration and water bodies. Municipalities with low local potentials, on the other hand, need to use more flexible renewable heat sources such as biomass heating plants, air source heat pumps and electric heating systems. In urban areas, excess heat due to waste incineration and solar power plants contribute a larger share to the heat supply since potentials within a certain radius outside the urban area can also be integrated by connecting pipes. Rural municipalities can make greater use of industrial excess heat, large-scale heat pumps and biomasses. However, a case-by-case assessment must be carried for the obtained potentials of each municipality since the results in Figure 4 are aggregated to a cluster level.

With a share of 11 % in total, the developed heat supply scenario makes a greater use of the solar and deep geothermal potentials in Germany. As a comparison, these energy sources represent today only 1 % of grid-bound heat supply in Germany. Large-scale heat pumps, which are also currently almost non-existent, are given a share of 8 % for 2030. The use of excess heat and (biogenic) waste incineration is slightly higher compared to the status quo. Today, natural gas, coal and oil represent together 68 % of grid-bound heat supply which is being limited to an efficient use of natural gas in the developed scenarios in addition to the already mentioned shift to renewable and excess heat sources (BDEW 2022).

Results of the Economic Impact and Cost-benefit Analysis

Figure 5 shows the results of the derived average heat supply scenarios on the level of the different clusters as a whole. It relates the specific GHG emissions (y-axis) and the LCOH (x-axis). The LCOH for the clusters are in the range between 62 Euro/MWH and 77 EURO/MWh. The specific GHG emissions result in a higher deviation between the clusters ranging

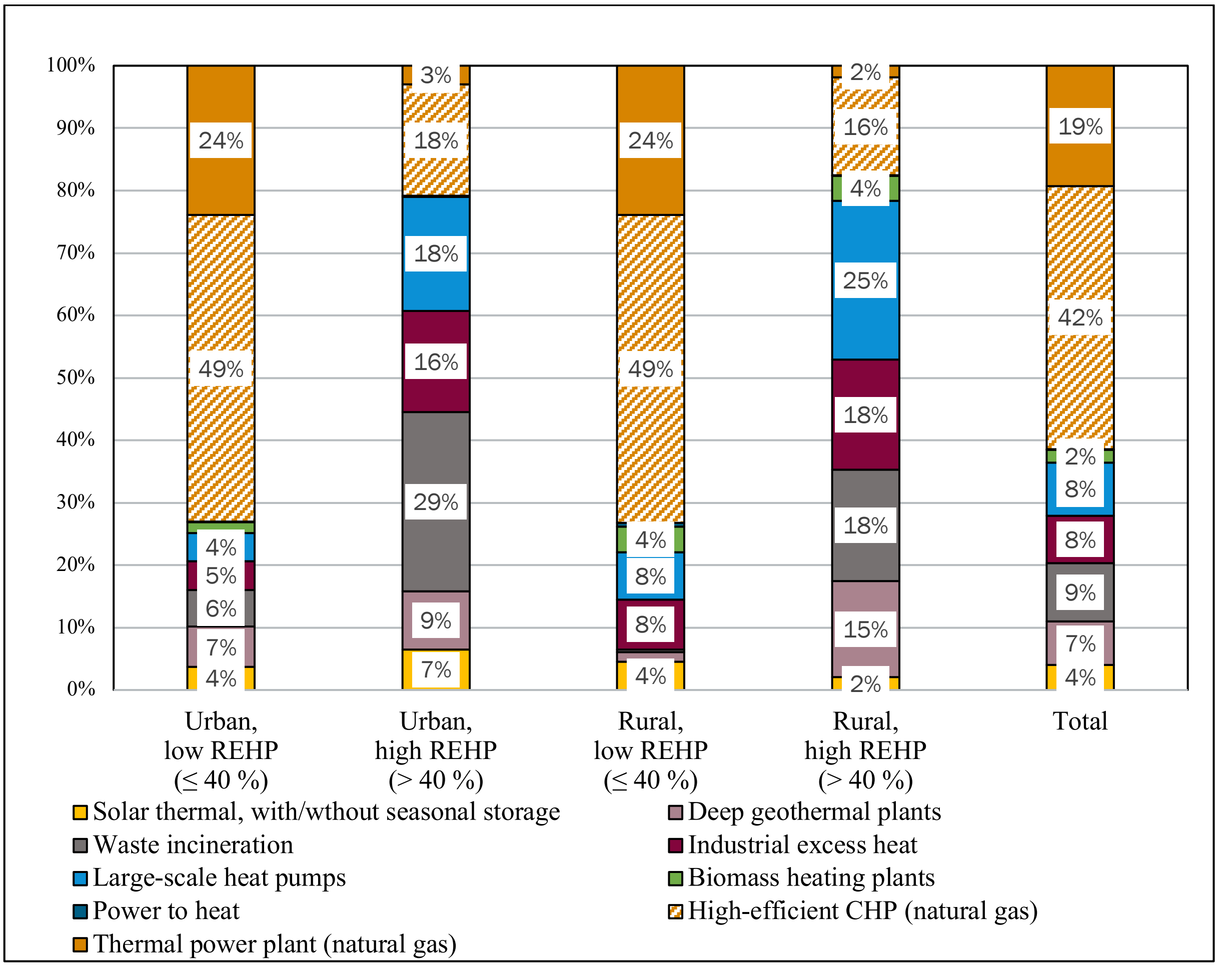

Figure 4. Results of the heat supply of the community clusters in 2030.

from 73 g CO_2eq/kWh to 159 gCO_2eq/kWh. The cluster with low REHP have higher shares of gas CHP systems in the respective district heating mix and thus significant higher GHG emissions and lower LCOH. The GHG emissions are on average 111 % higher whereas LCOH are 11 % lower on average compared the rural and urban clusters with high REHP. The lowest LCOH is reached in the cluster "urban, with low REHP potential". The lowest specific GHG emissions are to be found in the cluster "rural with high REH potential". However, as shown in Figure 5, there is no uniform heating strategy for all municipalities in these cluster which emphasizes the relevance of detailed spatial analysis on municipal level considering the local prerequisites.

The results on cluster level are important for national policy makers in order to set specific framework conditions to support the transition to zero-carbon heat supply. For stakeholders on local level, the comparison among the clusters gives a good indication on potential transition pathways for centralised heat supply. For developing of local heat transition strategies, it is rather important to compare the available alternatives of district heating with decentralised options. Therefore, Figure 6 shows the results all municipalities with an identified demand potential for district heating that have lower LCOH as the decentralised reference technologies. The comparison reveals a wide range among the municipalities concerning specific LCOH and GHG emissions in the derived district heating supply scenarios. As decentralised reference technologies, LCOH of a gas condensing boiler (fossil fuel reference) and average LCOH of decentralised heat pumps and biomass boilers (RES-H reference) is included in the figure. The LCOH of the decentralised supply options represent the average of LCOH calculation for different building types (see Umweltbundesamt (2021) for details). The results indicate that 1,499 out of the total 1,640 municipalities that are suitable for district heating have significantly lower LCOH than the natural gas condensing boiler. Thereby, the assumed CO_2 price development in the National Emission Trading Scheme (BEHG) is an important factor for the economic efficiency of centralised and decentralised RES supply options. According to the assumptions NECP, the CO_2 price in the BEHG was expected to increase to 140 Euro/t CO_2eq. Nevertheless, compared to the decentralised RES-H supply option, the centralised technology systems are also the more favourable option in almost all identified municipalities with district heating demand potential. The comparison shows the relevance of district heating supply for an efficient and climate-friendly heat supply. However, the analysis also highlights the large differences between the municipalities due to the local conditions with regard to heat demand density as well as the regional renewable and excess heat potentials.

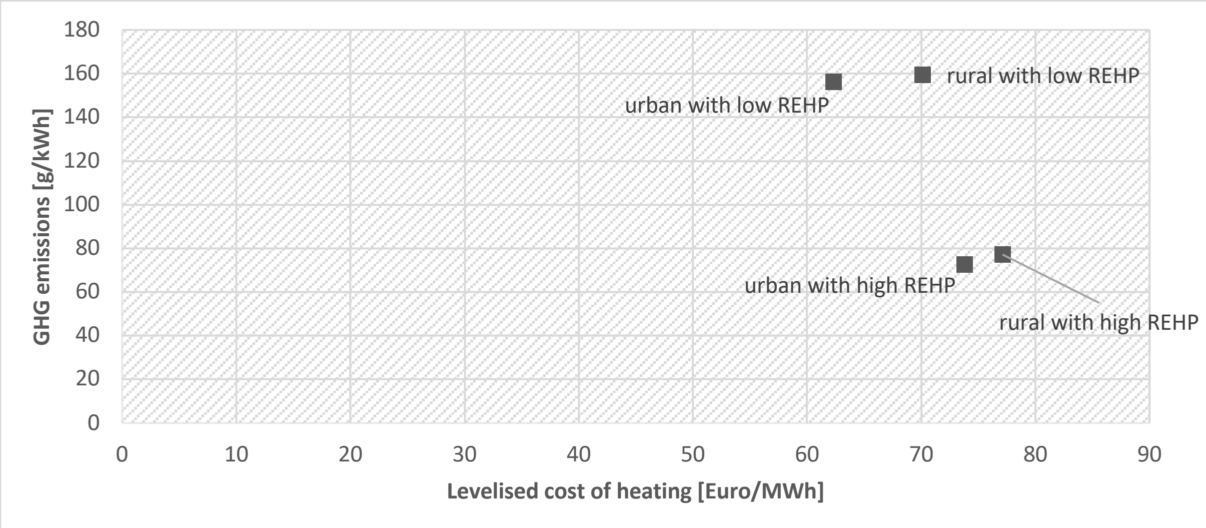

Figure 5. GHG emissions and LCOH for the four municipal clusters.

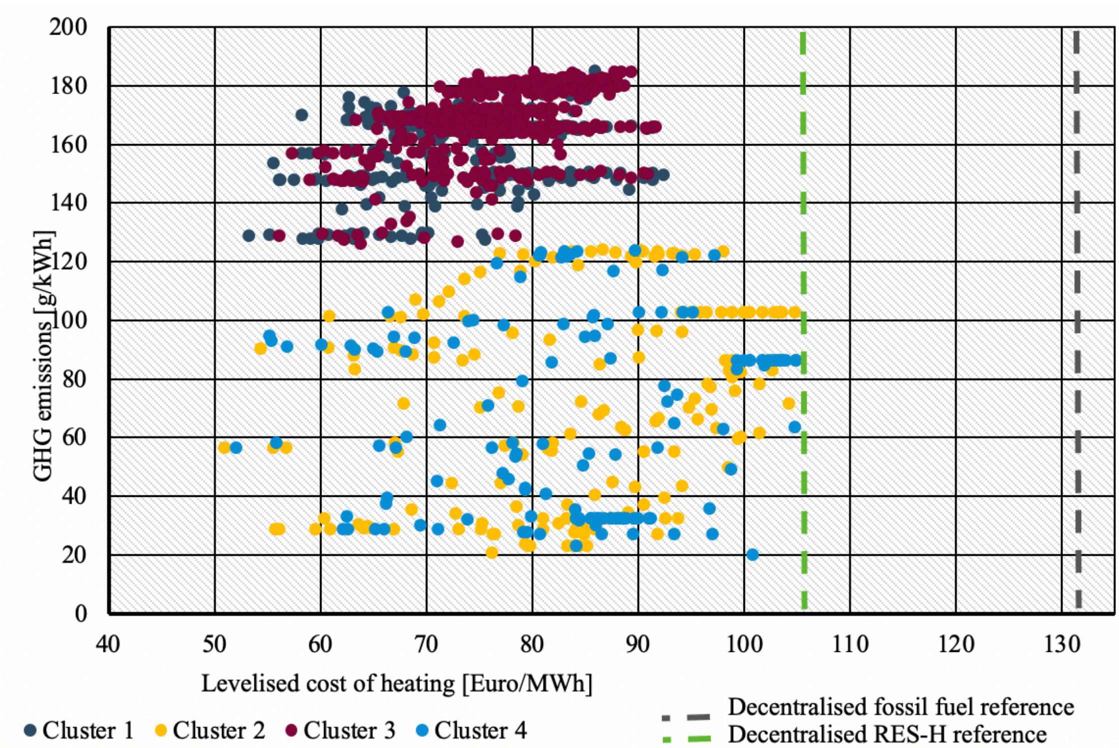

Figure 6. Specific GHG emissions and LCOH of heat supply scenarios in municipalities with district heating demand potential in comparison to decentralised reference technologies.

Summary and conclusions

The results for the different clusters show that a small-scale analysis at municipality level provides insights that cannot be taken into account in an aggregated view. Especially due to locally limited renewable energy and excess heat potential as well as the differences in demand structures on the municipal level, the step-by-step approach with an identification of potentials, optimisation of supply mix and cost benefit analysis is a suitable way to proceed. A challenge in this approach is above all the availability of the required data for such analysis which emphasizes the importance of open-source data and standardised platforms and formats. Although not all data used in this analysis is open available, the maps produced and provided in the project can be used by all interested parties for an initial assessment[7].

7. See: https://datahub.uba.de/portal/apps/opsdashboard/index.html#/ae128313517548f193a9b72f93ca9db7

The results of the heat supply scenarios show that the defined share of 40 % renewable and excess heat on the overall heat supply in German municipalities can be reached. However, the availability of local potentials varies greatly among municipalities. While some reach a REH share of 25–30 % in average, others are capable to fulfil their demand with a share of 80 % and more, depending on the local availability of heat sources. Municipalities with high renewable and excess heat potentials can cover a major part of their heat supply by locally available sources such as solar district heating, geothermal plants or excess heat from industry. Municipalities with low local REH potentials, on the other hand, need to use more other renewable heat sources such as biomass heating plants, large air source heat pumps. Rural municipalities in average make greater use of industrial excess heat, large-scale heat pumps and biomasses. This analysis shows that a sustainable heat supply from renewable energies and excess heat is possible both in urban and rural areas.

In the cost benefit analysis, the resulting GHG emissions and heat costs (LCOH) were examined. Results show that GHG emissions are much lower in municipalities that make greater use of renewable and excess heat. Even if LCOH are higher, the relative costs differences are much lower than the differences in specific GHG emissions compared to the clusters with low RHEP.

Relevant for the municipal strategy is the comparison to decentralized options. The results clearly show that all municipalities that are suitable for district heating have significantly lower LCOH than the natural gas condensing boiler and decentralised renewable heat supply technologies. The centralised technology supply systems in district heating are also the more favourable option in almost all identified municipalities with district heating demand potential. But especially municipalities in rural areas with low heat densities and therefore low potentials for district heating can make greater use of carbon-free decentralized options.

The results on cluster level are important for national policy makers in order to set specific framework conditions to support the transition to zero-carbon heat supply. The spatially unevenly distributed REHP requires policy making and design that enables municipalities to contribute to the overall 30 % energy efficiency target. Given the large diversity of municipalities with regard to the potentials, the policy design must be suitable to incentivise municipalities with very high REHP to realise their potentials, while providing targeted support to municipalities with (very) low potentials in order to enable their contribution to the transformation towards GHG-neutrality. The comparison of centralised and decentralised supply options with regard to the cost benefit analysis must also take into account environmental integrity, for example with regard to biomass.

Regarding the local level, a detailed analysis of REHP and heat sinks is imperative. Comprehensive “municipal heat plans” present a promising way to initiate local transformations. The obligation of municipalities for municipal heat planning by the federal states must be backed by national support measures. The national program for efficient heating and cooling networks as well as the Competence Centre for Municipal Heating, which is currently being set up by the Federal Ministry of Economics and Climate are steps in this direction. Further regulatory laws and support schemes will have to follow in order to implement municipal transformation strategies towards carbon-free heat supplies.

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Annex

A 1: Economic framework for the heat supply technologies, exemplarily calculated for a 10 MW system.

Technology	Investment costs [EUR/kW_{th}]	Fixed operating costs [EUR/kW_{th}]	Variable operating costs [EUR/MWh]	Efficiency	Minimum capacity [MW_{th}]
Industrial excess heat	409	8,2	-	COP: 9	0,2
High-efficient CHP	126	9	7	50 %	0,01
Deep geothermal plants	2.885	27	-	COP: 9,5	5
Solar thermal plants	659	-	1,5	100 %	1
Solar thermal plants with seasonal storage systems	762	-	1,5	87 %	2,5
Biomass heating plants	505	4	0,2	84 %	0,01
Large-scale heat pumps (excess heat)	631	2	2,4	COP: 3	0,4
Large-scale heat pumps (air-based)	799	2	2,4	COP: 2,7	0,4
Power-to-Heat	111	1	0,2	98 %	0,01

The variation of investment and operating costs with the plant capacity was considered by applying cost functions. Due to clarity reasons the above costs refer to 10 MW systems.