International Journal of
Sustainable Energy Planning and Management

A spatial approach for future-oriented heat planning in urban areas

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ABSTRACT

The current climate protection goals will lead to unprecedented and profound changes to energy systems. The transition to a decarbonized heat supply system will be complex and the process will have deep impact on the urban subsystems (technical, economic, social and planning subsystems) with different spatial extents. For decision making in this context, the level of individual buildings provides a perspective which is too narrow. On the other hand a very broad view is also unhelpful for the local transition process. There is a tension between individual decisions at the building level and a large-scale implementation strategy for heating grids. This article shows an innovative way to analyse heat demand data with the help of fuzzy logic and spatial mapping of the suitability of different heat supply systems. At the subsequent planning level, the results can be used as guard rails to make the urban planning process more consistent and transparent.

Keywords:

Future heat supply systems;
Suitability maps;
Energy planning;

URL:
dx.doi.org/10.5278/ijsepm.2018.16.2

1. Introduction

In 2015 the energy consumption in the EU (28) was about 68.14 EJ (1,627.5 Mt of oil equivalent) with a share of 13% from renewable energy sources [1]. Space heating and hot water supply is responsible for 31% of the energy consumption [2]. In Germany, the share is 27% for space heating and 5% for domestic hot water (DHW) of energy consumption in 2015 [3].

However, the energy transition in Germany has mainly focussed on power generation so far. Technological development was largely in the area of wind plants and photovoltaic, so the political and the public debate was on the power sector too. Related issues, like a nationwide power grid, funding policy and acceptance were also mainly triggered by renewable power developments [4].

By increasing renewable and volatile power generation, the storage gap grows too. The term 'storage gap' describes a lack of flexibility in the power grid to store surplus energy during light load periods and to supply this stored energy during peak load periods [5].

However, developments in the power sector are not sufficient to achieve climate protection goals alone – heating is equally important. The share of renewable energy in the heating sector in Germany (2015) is around 7.5% [6]. Measures required in the heating sector are of two main types [7]:

- Reducing the heat demand, and
- Integrating renewable energy

Renewable energy sources such as biomass, solar-thermal or deep geothermal plants can be integrated directly. The indirect way is to use power to increase low temperature sources up to a usable heat level, e.g. heat pumps for geothermal plants. If sustainably-generated power is used for this so-called 'sector-coupling', then the integration of renewable energy in the heating sector can be improved.

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Abbreviations:

cDH:	Classic district heating
CHP:	Combined heat and power plant
DH:	District Heating
DHW:	Domestic Hot Water
EN:	Energetic Neighbourhood
HP:	Heating period
MWh/a:	Megawatt hours per year
MWh/(m x a):	Linear Heat Density in megawatt hours per meter and year
nHP:	Non-heating period
PV:	Photovoltaic
TWh/a:	Terawatt hours per year

Now, the power sector sees, in the heating sector, a very good sink for surplus power and a convenient way to solve the problems in the grids. The heating sector sees the power sector as a supplier to meet their needs. Rarely, however, does sector-coupling take the potential and the spatial reference of each sector into account.

The integration of renewable energy sources into the power system is a first step – but the process is far from being completed. The transition to a decarbonized heat supply system will be even more complex, because the process will have an even deeper impact on the urban system consisting, as it does, of various complex subsystems with different spatial extents (technical, economic, social and planning systems).

To achieve the climate protection goals in all sectors and domains (heating, industry, mobility etc.) in Germany by 2050, the renewable power generation required will increase up to 3.000 TWh/a [8]. With sophisticated efficiency measures the actual power required will be around 1.320 TWh/a [9], nearly twice as much as in 2016 (647 TWh/a, including fossil and renewable sources) [10]. Competition for renewable power is to be expected.

So the configuration of a renewable energy system is complex, but has to be implemented at a local level. In Germany, modelling approaches [11, 12] and urban redevelopment projects start from the building level and use a district definition without questioning the spatial context [13]. In the end, a technical solution which reflects this complexity and which takes into account the usual working level of a municipality is to be recommended. However, for the decision making process in the context of system change, the level of individual buildings or districts provides a perspective which is too narrow. On the other hand, a perspective which is too broad is not very helpful for the local transition process either. The challenge is to find an appropriate shaping and sizing method to facilitate the transition process in the built environment.

1.1. Reducing energy consumption

Reducing consumption only by increasing efficiency is a critical point, because of the so-called "Efficiency Limit" (preservation orders, physical condition, distance regulations etc.). Merely integrating renewable energy sources into heat supply systems without undertaking any building refurbishment is also not practicable, because in reality there are often no adequate, realistic potentials. The reduction by at least 40% and by a maximum of 60% is a benchmark which buildings have to reach by 2050. Furthermore, a reduction of heat demand by 20 to 30% in the industrial sector is anticipated. These scenarios are described in the strategy paper "Energy Efficiency Strategy Building of Germany" [14].

Thamling et al. (2015) point out that there are two thresholds for reduction measures to achieve the climate protection goals by 2050 and describe two scenarios [7]:

1.) Scenario Efficiency (A):
   - Use of the realistic potential of renewable energy resources
   - Ambitious refurbishment and building activities
   - Reduction of heat demand by around 60%.
2.) Scenario Renewable Heating (B):
   - Ambitious use of the realistic potential of renewable energy resources
   - Coupling heat and power sector, moderate building refurbishment
   - Reduction of heat demand by around 40%.

The reduction of energy consumption at individual building level is important, but a wider perspective, i.e. at area level, has the potential for even greater efficiencies. The concept of an Energetic Neighbourhood [15] is based on the idea of intelligent interconnectivity between different buildings (residential, commercial, etc.).

This approach, the Energetic Neighbourhood (EN), aims to put the concept of hybrid grids [5] into practice at a local level:

"The approach aims to minimize the distances in all energy processes and the number of wasteful energy conversion processes as far as possible. Here, a variety of approaches can be combined:

- Direct coupling within an energy domain
- Reduction of the number of transformation processes

- Reduction of losses by spatial proximity
- Consideration of the various energy levels" [15, p. 41]

"Only district scale intervention will permit the achievement of the much higher energy efficiency targets required by optimising the use of energy at different levels… " [16, p. 11]

1.2. Renewable heating in urban areas

The integration of renewable energy into the heating system will be increasingly based on power. A distinction can be drawn between building-related and grid-related heat supply.

1.2.1. Building-related heat supply:

High-efficiency buildings can be supplied with renewable heat directly. Here, heat pumps in combination with solar and/or geothermal energy play a very important role. The only external connection is to the power grid. In cases with a higher heat demand, CHP – based on renewable sources – comes into play.

The think-tank Agora describes transition paths in the heating sector and does not exclude the possibility of reaching the reduction target of -95% of CO_2-emisions by 2050. They point out a short-fall in the number of heat pumps needed to achieve the 2050 targets in Germany of around 4 million up to 2030 [17].

1.2.2. Grid-related heat supply:

Currently, the grid-related heat supply system is mainly based on natural gas and district heating systems of the older generation. It is unlikely that the entire gas grid will be fed exclusively with renewable gas. With modern district heating systems, it is possible to supply different types of urban areas with renewable heat, depending on the demand level and given resources. The district heating definition and experience from Denmark provide helpful benchmarks for future developments [18]. They underscore the interplay between, and the spatial interdependency of, individual heat pumps in district heating systems. The 4th Generation District Heating (4GDH) "is defined as a coherent technological and institutional concept" and "provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems." [19, p. 10] This definition describes a target state with high and essential standards. The challenge is to design the transformation process in the built environment while taking into account spatially uneven developments and, in a way, uncertainty (see next chapter). This article addresses the question "where to have DH" [19, p. 8] and adds the point "where not to have DH".

The supply of DHW and the associated operation in summer is a very important cause of overall energy losses in district heating systems. Currently, different approaches which take the legionella issue into consideration are being discussed and tested [20].

Lund et al. (2017) investigated the long-term potential of low-temperature District Heating concepts [21]. They recommend that "the supply temperature should be reduced as much as possible until electric boosting of DHW becomes necessary." [21, p. 16] They recommend a temperature of 55 °C in combination with a small storage unit to avert legionella. In some LowEx-projects with low supply temperatures (20 °C / 40 °C), a separate supply of DHW and space heating is preferred in order to run each system economically and prevent legionella [22]. New technology to filter legionella out of DHW systems is currently under development, so the heat supply could be lowered to 45 °C [23] all year round to supply both space heating and DHW.

Given the necessity of heat demand reduction, the importance of 4GDH will increase. Currently, many classic district heating systems of the 2nd and 3rd generation in Germany are under pressure economically. In some towns this is caused by demographic change, but mainly by retrofitting programs for buildings, see also [24].

The current funding announcement – "District Heating 4.0" – issued by the German government defines the new generation of DH with a temperature range between 20 °C and 95 °C [25]. Current studies still do not differentiate between types of district heating, see e.g. [26] and threshold values for cost-effectiveness are defined by a linear heat density of above 1.5 MWh/(m x a) or 1.8 MWh/(m x a) [27]. Nevertheless, there are some projects based on low temperature grids in Germany [28–31].

In fact, there is gradient between building-related and grid-related systems, due to the range of available technological possibilities and seasonal effects.

1.3. Planning levels

Consensus on the spatial reference is essential for the planning process. Generally, the building level is easy to define, but some complex buildings and sites are similar to a small district (campus, hospital etc.). A district could be defined as "a set of connected buildings, public spaces, transport infrastructure, and networks (e.g. electricity, heating, cooling, water and wastewater etc.), including inhabitants, building users and managers" [32, p. 13]. Besides the physical world, this definition also takes into account people and stakeholders. The urban planning research goes further and emphasizes the importance of the socially related setting and shaping of a district by people [33]. Bläser (2015) illustrates the complexity of a district and understands the district as a delimitation of sectoral activities with an undefined, multi-layered boundary [34]. Schnur (2014) defines a district as a constructed and fuzzy socio-geographic term [35].

At first glance, these concepts may not seem to be helpful for energy and infrastructure planning, but on an abstract level the concept of the fuzziness of neighborhoods opens up new possibilities to shape solution areas [36]. An approach becomes possible which allows collaborations and the creation of supply areas for the entire urban area and not just districts as they are conventionally defined. "The term 'neighborhood' is understood more as an energy senseful summarizeable spatial unit than an urban structure." [37, p. 1290]

Bornemann et al. (2016) developed a framework of „spheres of energy-related uncertainties" [38, p. 49] to enable a more sustainable planning process of municipalities. They have developed a "differentiated conceptual framework regarding the ways uncertainties are dealt with by policymakers and planners on the ground." [38, p. 49] Adequate planning instruments are currently lacking for long-term restructuring strategies, which extend beyond the usual planning limits of individual redevelopment areas [39].

This article suggests a methodology for the spatial aspects of handling the uncertainties in the planning process. It could be described as a reshaping-strategy, see [38, pp. 43–44].

1.4. Data protection issues

Data protection has to be treated with the utmost care in such studies. The Guidelines for Data Protection for Geodata Services, published by the Interministerial Committee on Geoinformation [40], provides important information on how to deal with geospatial data. If geodata can be used to derive personal data, so-called resolution thresholds are defined with which data protection can generally be ensured [40, p. 11]

1. Maps with a scale less than 1: 5 000;
2. Satellite or aerial image information with a resolution of 20 cm or greater per pixel;
3. A rasterized area with 100 m x 100 m resolution or larger; or
4. Information aggregated to at least four households

Around 30% of the raster cells represent 1–4 buildings. This means that detailed maps are not created in order to conform with data protection requirements.

Additionally, the data protection of companies has to be considered (see 3.6). So, in such cases, detailed maps are not created either.

2. Approach setting and objectives

The article primarily takes the perspective of a municipality interested in developing an overall spatial strategy for energetic urban redevelopment which is open to all technologies. This follows the spatial planning view of municipalities and can be classified as follows:

The following premises are set:

– Scenarios: The scenarios (chapter 1.1) describe a corridor of the necessary and given reduction path.

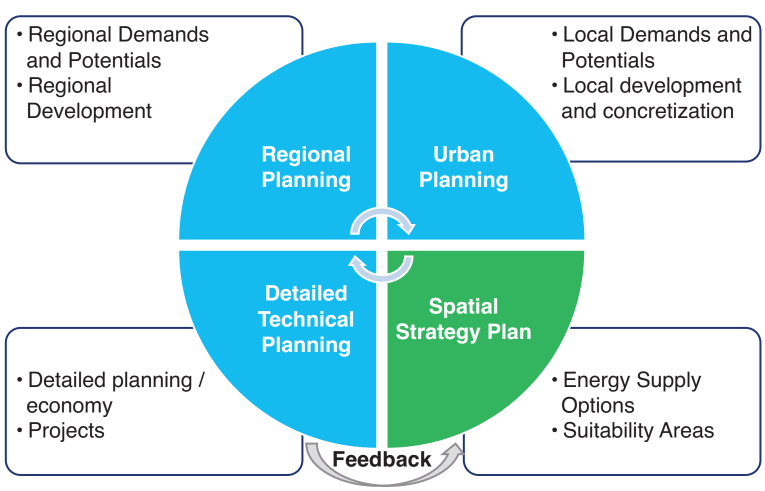

Figure 1: Approach set in the context of planning

- Spatial and content-related level: Due to the planning levels (chapter 1.3), the development statements (considering chapter 1.2) are guidelines for the subsequent technical refinement. If necessary, these refinements could lead to adjustments (Figure 1), which are not part of the article. Also, the local technical configuration and optimization is part of the subsequent planning level.
- Costs: Due to the given scenarios the costs for the implementation are considered indirectly. The ranges of the linear heat density represent the current state of the art for economical operation of LowEx and DH systems (chapter 3.2.).

The article has the following objectives:

- Development of an easy to use approach for the spatial detection of suitability areas for various heat supply options.
- Development of a spatial accounting method for heat supply options, based on the example of industrial excess heat and solar potentials.
- Derivation of recommendations for future municipal energy planning and spatial monitoring of developments.

With exemplary accounting the municipalities get the possibility to cross-check – approximately – the impact of local activities (e.g. PV installation, integration of industrial excess-heat). This can be extended to deep geothermal energy, solar thermal energy in different scales etc.

The article aims to stimulate discussion on the spatial framework of energy supply options that can be used for the necessary optimization and evaluation. At the end, the effects on the planning and funding instruments are discussed from the perspective of municipalities.

3. Materials and methods

3.1. Study areas and heat demand data

The approach is being tested in representative cities in Lower Saxony (Germany):

- City of Oldenburg (164,000 citizens), representing a typical city with a high proportion of residential areas, administration and commercial areas with few industrial areas
- The cities of Bramsche and Wallenhorst (36,000/ 23,000 citizens), represent typical cities with industrial development and related residential areas

This article focusses on the nearby cities of Bramsche and Wallenhorst. The data of the PInA project ("Planungsportal für industrielle Abwärme", planning portal for industrial excess heat [41]) is used (in total around 23,000 points). The County of Osnabrück is involved in the plausibility check.

The heat demand data are derived from models based on the age and construction type of buildings, the number of inhabitants and building usage etc. In addition to the total heat demand per year, the domestic hot water demand per year (DHW) is given separately.

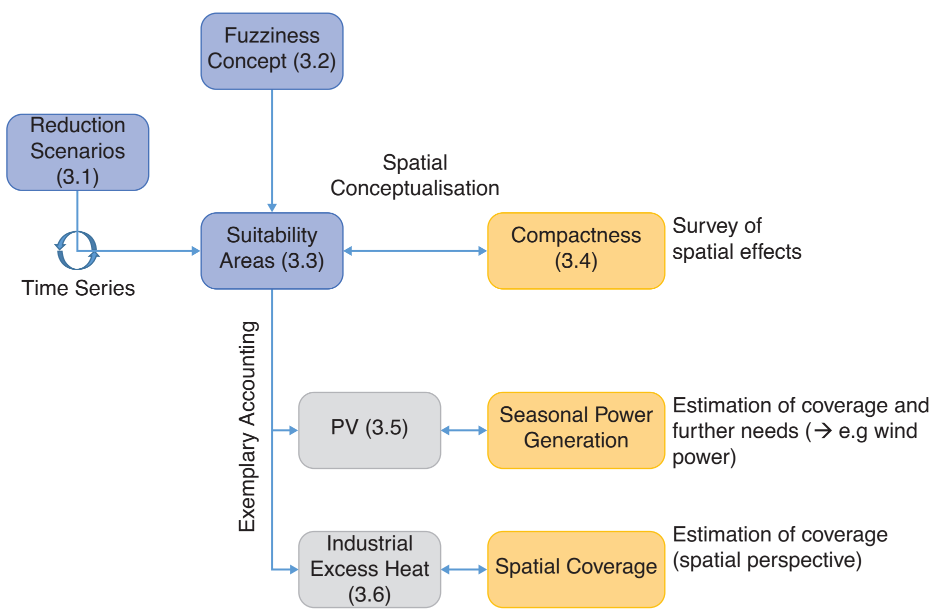

Figure 2: Structure of the article

Heat demand is not heat consumption: Heat consumption depends on personal behaviour and certain structures, so heat demand gives a more objective picture. A high degree of uncertainty is typical for the industrial sector, caused by unknown parameters like the amount of goods produced, see also [15], so heat demand for industrial processes is not considered.

The heating period (HP) in this region is from the beginning of October to the end of April. In this period both space heating and DHW must be supplied. In the non-heating period (nHP; May-September) energy is only needed for DHW. In residential buildings, DHW demand is largely consistent throughout the year. At a residential area level, the holiday-related declines, especially in the summer months, are spread over the holiday season [42]. However, for planning purposes, the standard VDI 6002 (1) [43, p. 81] provides more accurate figures for each month. The DHW demand during the HP can be calculated using the factor 0.38117 and during the nHP using the factor 0.61892 of the annual demand.

Depending on the size and heat demand of the buildings, the spread of potential reduction varies by around +/- 5% [44]; buildings with less demand having lower reduction potential than buildings with higher demand. Due to the lack of further information about the buildings, the heat demand is divided into three sub-groups with a third of the total sum. Each building is assigned to one of these groups according to its current heat demand. For this study, the scenarios for residential houses, trade and services are defined in Table 1. For instance the scenario 2020A represents a spread of the reduction level to between 91% and 81% (+/- 5%). Industrial buildings have a potential reduction of -20% by 2050.

This generalisation cannot take into account the individual situation of each building, and yet it gives a first impression of future development. "A scenario is a story that describes a possible future." [45, p. 8]

3.2. Fuzziness of heat supply options

A very important indicator of economic feasibility is the linear heat density of energy demand. As described above, the established threshold of 1.5 MWh/(m x a) is valid for economical operation of classic district heating systems (90 °C in winter, 70 °C in summer). Low temperature heating systems can operate in different modes:

- permanent low temperature during the year
- alternating temperature (winter/summer mode)

Depending on the DHW supply, the summer supply temperature could be reduced to 60 °C (including DHW preparation) or down to 30–40 °C (DHW supply by heat pumps or electric boosting or legionella filtering). From a municipality point of view, these technical refinements cannot be taken into account at a strategic level. Which solution is preferable or suitable, depends very much on the specific local conditions and heat line densities. Additionally, it is not possible to define tipping points absolutely for heat line densities valid everywhere, because experience gained from other projects indicates a range, e.g. current solar integration projects [46, 47]. Fuzzy logic makes it possible to handle this challenge by describing fuzzy thresholds for heat supply options. "Fuzzy logic represents an extension of the classic binary logic, with the possibility of defining sets without clear boundaries or partial memberships of elements belonging to a given set." [48, p. 38]

Firstly, the following heat supply options are described. Next these heat supply options are linked to fuzzy thresholds described using the concept of fuzzy membership [49]. c. The fuzzy membership functions and the thresholds should be adjusted regionally.

The range for LowEx heating systems could be further subdivided into permanent low temperature supply and seasonal cold/hot system. This refinement should take place at the detailed planning level.

3.3. Suitability areas

The concept of suitability maps has its origins in the field of land use management and ecology [48] and helps to identify the best place according to certain criteria. "A criterion is a measurable aspect of a judgement, which makes it possible to characterize and quantify alternatives in a decision making progress." [51, p. 366] In this article, the criterion used is heat-line

Table 1: Definition of the Scenarios and the Reduction of Heat Demand (based on [7])

Year	2020		2030		2050	
Scenario	A	B	A	B	A	B
Reduction to (+/– 5%)	91%	94%	73%	82%	45%	65%
	86%	89%	68%	77%	40%	60%
	81%	84%	63%	72%	35%	55%

Table 2: Definition of the supply options

Limit/Ranges	Definition
< 0.5 MWh/(m x a)	Single Supply: Heating by fuel cells, air and geothermal heat pumps etc. No connection to a grid, limit for grants [50]
> = 0.5 – <1.5 MWh/(m x a)	LowEx Heating System (LowEx): Seasonal operation management of a grid (summer: 30–40 °C.; electric boosting or heat pumps for DHW, solar thermal and power; winter: 70–90 °C. by (decentralized) CHP, heat pumps) or permanent low temperature all year round; integration of industrial excess heat [28–30].
> =1.5 MWh/(m x a)	Classic District Heating (cDH): 70–90 °C. by (decentralized) CHPs and backed up by heat pumps (industrial heat pumps, solar thermal energy, etc.) [24]. This can also include solutions for large properties (CHPs on site, direct connection to the gas grid, district heating in the form of cellular grids).

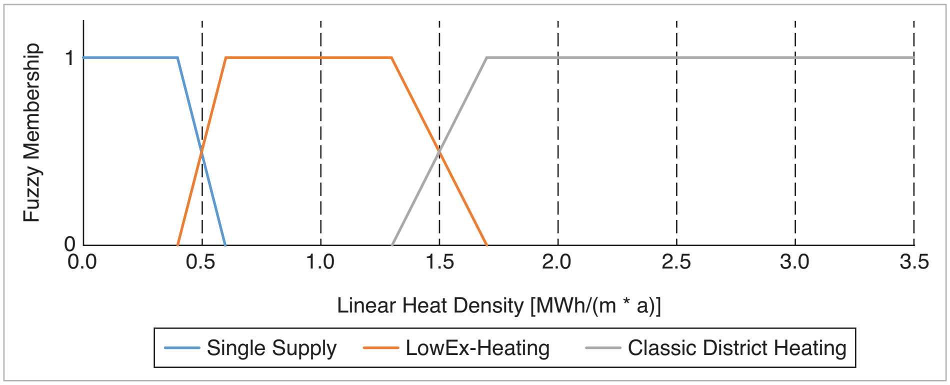

Figure 3: Fuzzy membership of heat supply options

density. It determines the most suitable niche of different heat supply options.

To define neighbourhoods and districts based on purely energy related criteria, it is necessary to cluster the heat-line density in a spatial way. Spatial conceptualisation is a very important step to find an appropriate scale for analysis. This follows Tobler's first law:" everything is related to everything else, but near things are more related than distant things." [52, p. 236]

Sellers and Peters (2016) described and tested raster-based algorithms to calculate heat density [53]. They found out that a raster of 100 m x 100 m describes the situation very well. "The raster tessellation makes for easy comparability of areas as it is based on tiles with equal area sizes." [53, p. 9]

Another way is to evaluate an appropriate analysis scale geo-statistically, e.g. the incremental-spatial-autocorrelation. It measures the spatial autocorrelation for a series of distances while taking into account the annual heat demand. As a result, it shows the z-scores for each distance, reflecting the intensity of spatial clustering. Statistically significant peak z-scores indicate distances where a spatial clustering of annual heat demand is most apparent [54].

To avoid a distortion of the results, the core areas of the urban areas are tested and the first and maximum peak in Oldenburg is at 125 m (z-score: 13.401686) and in Bramsche / Wallenhorst the first peak is at 120 m (z-score: 30.372284) and the maximum peak at 153.31m (z-score: 31.422533). To achieve recommended resolution while conforming to data protection guidelines, the grid resolution is set to 100 m. The resolution of 150 m is considered by the spatial processes described below.

While the spatial perspective is taken into account, the calculation of suitability maps starts from the heat demand of each building. As there are no or only very local district heating systems in the cities under examination, a hypothetical district heating network is modelled.

With reference to Dorfner & Hamacher (2014) [55], a process is developed which calculates the theoretical (pipe)line length using the length of the streets, based on OpenStreetMap data, plus the distance between the streets and demand points (buildings). The process avoids parallel structures of potential pipelines by creating branches. A spatial smoothing filter takes the average length within the immediate neighbourhood (8n) into account to avoid extremes caused by the raster border. No-data raster cells in the neighbourhood are ignored.

This results in a more realistic line length per raster. The pseudo-code of the process is added in the appendix.

Using the sum of the demand within the raster it is possible to express the linear heat density indicator as MWh/(m x a) per raster cell (1 ha).

Next, the spatial transformation of the linear heat density to the fuzzy membership (see above) takes the following aspects into account:

- the degree of suitability for each heat supply option
- the suitability within the raster based neighbourhood (8n) of each cell (focal analysis of suitability/fuzzy membership of each heat supply option)

The focal analysis is a spatial smoothing method which considers the influence of nearby objects. This takes account of the fact that larger buildings are also present in neighbouring cells and that complex buildings represented by some heat demand points are split by the raster boundaries etc. The smoothing allows larger contiguous areas to be created, without losing spatial refinements and corresponds to the double extent of the spatial autocorrelation (2 x 150 m = 300 m = 3 cells).

As a result, each raster cell represents membership of a certain heat supply option. Before combining, a reclassification is necessary:

The subsequent overlay process produces a raster file in which each cell represents the degree of suitability for each heat supply option, e.g. the code "2025" represents a high degree of suitability for Single Supply (Single Supply ++). In some cases, there is a suitability for two or all three options at once. These indifferent cells represent very important coupling and intermediary areas between heat supply option areas. An overview of the reclassification codes and their interpretation is given in the appendix.

3.4. Spatial compactness

The task of municipalities is to create the framework for a comprehensive and spatially feasible development. So, from a municipality point of view a too close look at individual energy supply issues is not helpful. The point is to derive coherent and spatially compact planning units. The compactness of heat supply option areas can be calculated using patch indices, which are useful in describing the spatial effect of the generalisation (focal analysis) and the reduction scenarios. The indices are calculated and described by Fragstat 4.2 [56]. In this article the normalized Landscape Shape Index is used, see [56]. In order to make the analysis clearer, a re-classification of the options at the higher level is carried out.

Table 3: Membership classification

Membership range	Reclassification for Single Supply	Reclassification for LowEx	Reclassification for cDH and higher
0–0.2	1	20	2000
0.2–0.4	2	40	4000
0.4–0.6	3	60	6000
0.6–0.8	4	80	8000
0.8–1	5	100	10000

3.5. Seasonal power generation

The seasonal balance of heat demand and power generation is an important indicator for identifying the most suitable technology mix.

An easy way to generate power within cities is by photovoltaic (PV) panels on roofs. The County of Osnabrück provides access to the raw data of the solar potential map (2010), which can be used to estimate the PV generation potential. The data is derived from airborne laser scanning data in order to calculate orientation, slope and shadowing of each roof segment [57].

Notwithstanding the calculation derived from the solar potential map, the calculation here is based on the PV GIS system [58], using the older database to achieve more conservative results. Additionally, the system losses are reduced to 21% in total, because an increase in efficiency is to be expected. The solar data can be found in the appendix.

The following calculated data is available:

- Power generation on pitched roofs, differentiated by orientation (east, south-east, south, south-west, west) and period (HP and nHP)
- Power generation on flat roofs, differentiated by period (HP and nHP). The orientation is taken into account using an average value calculated from power generation on pitched roofs. This takes account of the fact that the panels on flat roofs can be oriented so that they provide optimum daytime cover for the power demand of the building.

For the average monthly power generation of wind plants, it is necessary to get real data from plants. The operator database (http://www.btrdb.de/) provides such data and the CEO, Mr. Keiler, kindly supported this study by filtering the database based on the following criteria:

- region 11 (see http://www.btrdb.de/
- > = 2.4 MW per plant (excluding older power plants)
- average generation from 2007–2016 per month

The data was sent by email on 30/08/2017

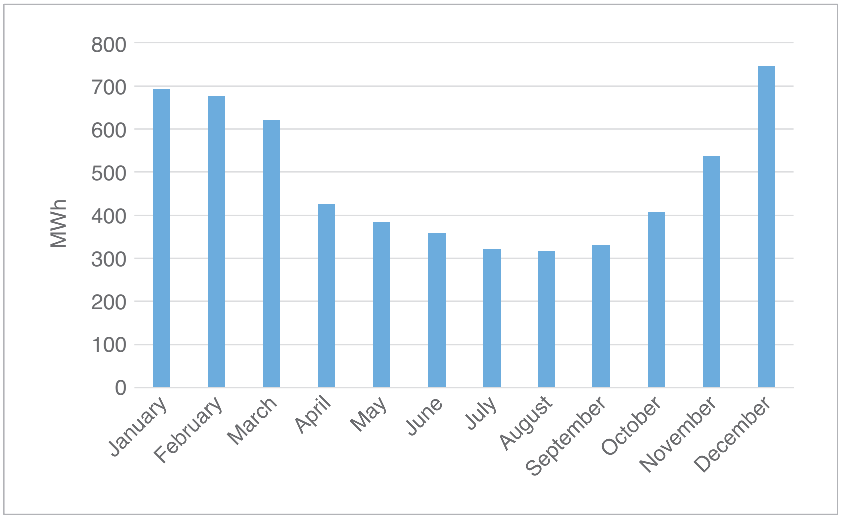

Figure 4: Average wind plant power generation, provided by www.btrdb.de (email: 30/08/2017)

The average power generation per plant within the HP (October–April) is 4,108 MWh and in the nHP (May–September) 1,712 MWh.

3.6. Integration of industrial excess heat

The data to estimate the amount of usable excess heat is delivered by the PInA- Project [41]. Briefly, this approach is based on two principles:

- The search radius depends a) on the amount of usable excess heat [59, p. 33] and b) on the threshold of target heat supply option plus a maximum loss, here: 20 W/(m x a).
- It provides a first sketch for subsequent, more detailed planning.

$$\text{Search Radius (m)} = \frac{\text{Usable Excess Heat}\left[\frac{\text{MWh}}{\text{a}}\right]}{0{,}00002\,\frac{MW}{m} \times 8760\left[\frac{\text{h}}{\text{a}}\right] + \text{Y}\left[\frac{\text{MWh}}{\text{m} \times \text{a}}\right]}$$

$$\text{Y : Threshold of Heat Supply Option}$$

The result for classical DH is similar to other, more complex approaches, and enables easy geographical mapping, first matchmaking and risk assessment [60].

4. Results

4.1. Suitability areas

The effect of focal analysis of a) the linear heat density and b) the suitability, is shown in the following description:

Cell A in Figure 5 has a heat demand of 162.627 MWh/a. The total pipeline length modelled in the cell is about 269 m. However, it is clear that these pipeline segments are not interconnected but connected to nearby cells. Using focal analysis, required pipeline length can be estimated more realistically (average focal length: 396 m).

If the sharp thresholds of the heat supply options are also taken into account, cell A would be suitable for LowEx-systems (0.6 MWh/(m x a) without focal analysis and almost suitable for Single Supply with focal analysis of the pipeline length of the nearby cells (0.41 MWh/(m x a)), see Figure 6 (left).This, however, only takes the pipeline length into account, and not the spatial setting of the suitability. The suitability results of Figure 6 (left) are too patchy and not helpful for spatially aggregated planning areas. With the second focal analysis of the suitability of each cell, broader aggregated areas can be derived (see Figure 6, right). Cell A achieves the suitability for a classic District Heating system due to the surrounding average suitability. So the patchiness can be reduced and results in more useful and compact planning areas.

With focal analysis, in each category the degree of aggregation increases and two categories emerge: indifferent (DH/Single Supply) and overall indifferent.

The distribution of the modelled focal pipeline lengths is shown in Figure 7. The LowEx areas have a marked line length, indicating that these are small-scale settlement structures.

The distribution of the average linear heat density (status quo) is shown in Figure 8. It illustrates that the expected increasing of the density along the suitability classes, the indifferent classes mediates between classes.

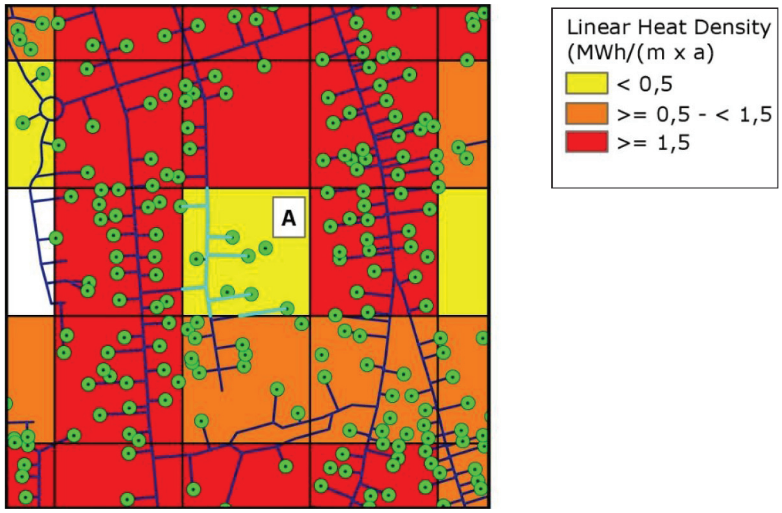

Figure 5: Analysing the linear heat density (unscaled)

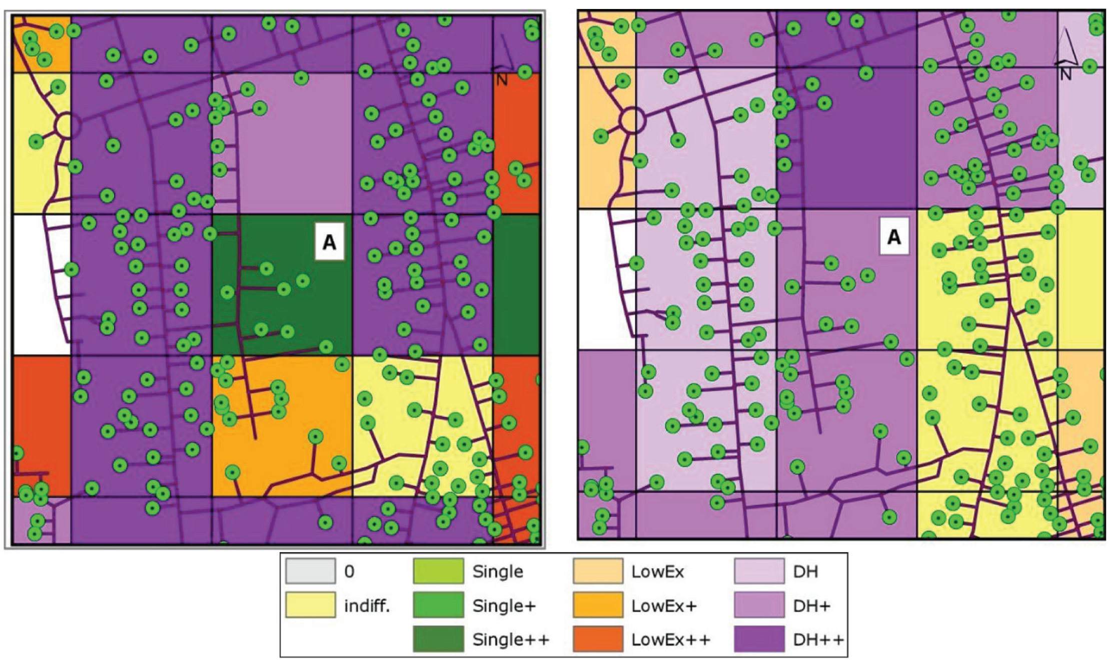

Figure 6: Comparing the effect of focal analysis (left: non focal, right: focal, unscaled)

So, this is a good starting point to illustrate the change of suitability areas by following the scenario paths (-40%/-60%) in a close up of Bramsche (Figure 9).

After a largely parallel development, the big differences in 2050 are noticeable.

4.2. Spatial compactness

The change of area shares over time within suitability areas in the given scenarios is a first step to describe the spatial effect and is shown in Figure 10.

The normalized Landscape Shape Index (nLSI) provides a simple measure of class aggregation or clumpiness. nLSI is equal to 0, when the landscape consists of a single square or is a maximally compact (i.e., almost square) patch of the corresponding type; nLSI increases as the patch type becomes increasingly disaggregated and is 1 when the patch type is maximally disaggregated. The effect of the focal and non-focal analysis (Figure 6) can be described by the nLSI indicator very well (Figure 11).

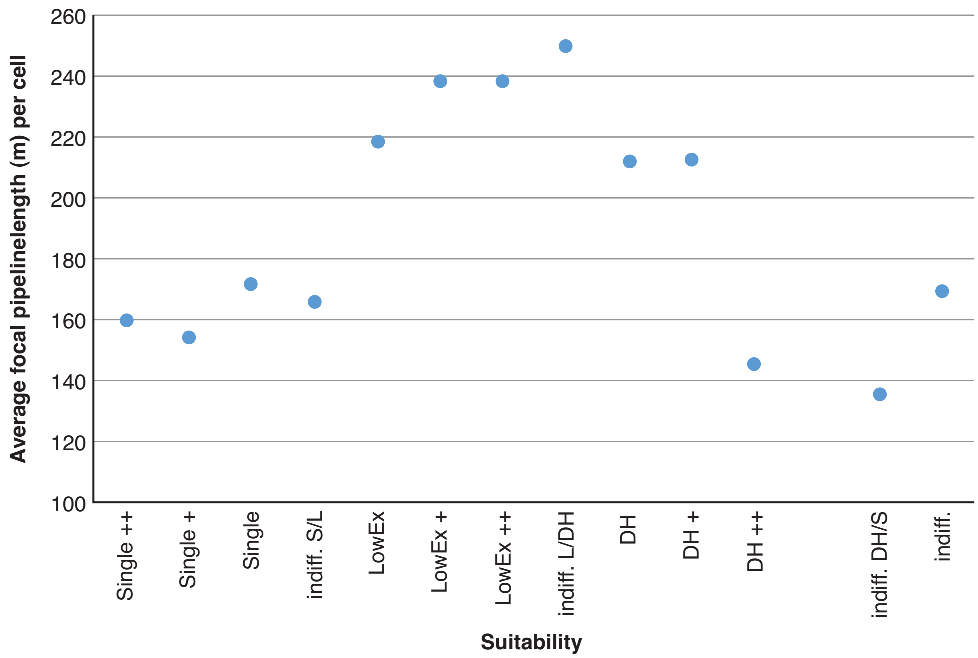

Figure 7: Distribution of the modelled pipeline length (status quo)

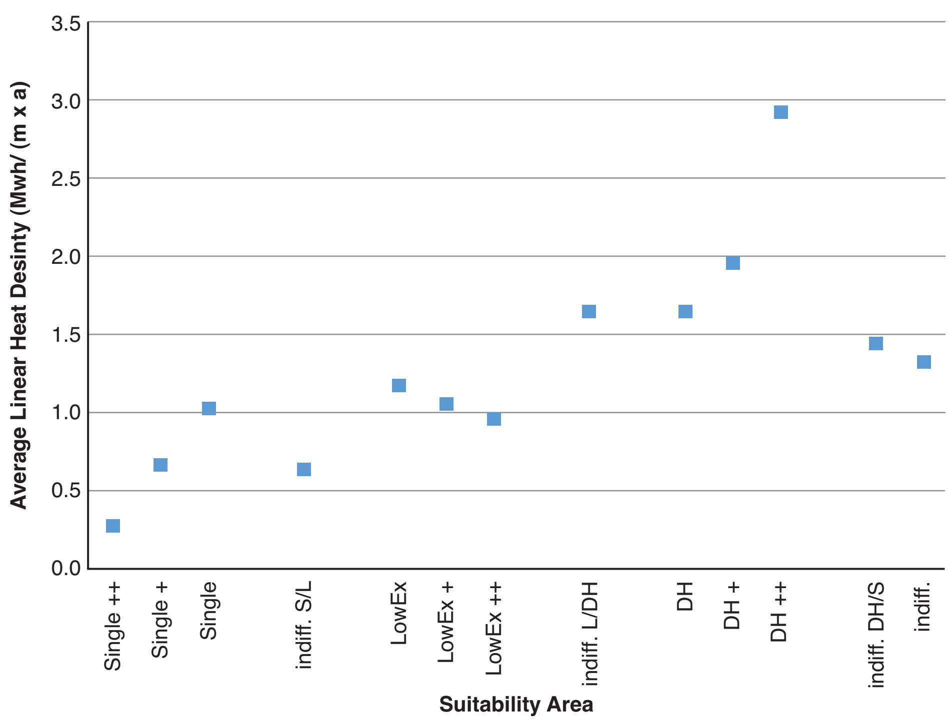

Figure 8: Distribution of average linear heat density (status quo)

The focal analysis leads to more compact shapes of suitability areas. But, on the other hand, new categories of indifferences are added.

Next, the nLSI is used to investigate the effect on the scenario driven suitability areas. The result illustrates that the −60% – scenario (2050A) has a focus on single supply and LowEx systems, but with a large share of indifferent zones between both. The −40%-scenario (2050B) has a focus on LowEx. On closer inspection, the shares in both scenarios are similar, but switched. In

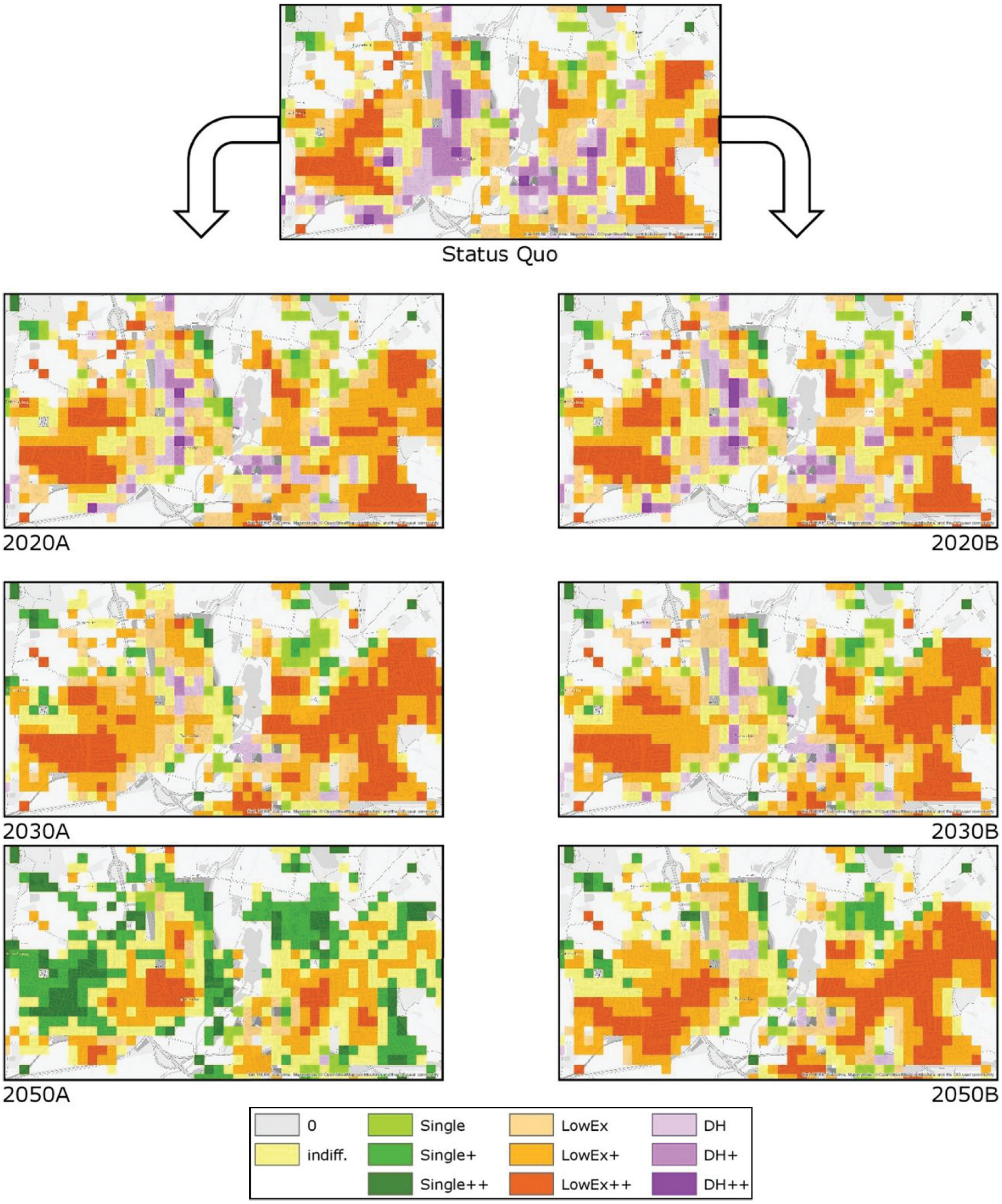

Figure 9: Scenario paths of suitability areas, close-up of Bramsche (unscaled)

2050B the LowEx-areas are more compact than in 2050A (see Figure 12).

4.3. Integration of seasonal power generation

Given the predicted competition for renewable power, the required power should be generated as locally as possible. For the heat supply this means that building-related power generation should be taken into account, in this case, PV power generation on roofs. The potential power generation from exploiting all suitable roofs helps to cover the power demand for coupling systems like heat pumps or direct electrical boosting, regarding the distinction between winter and summer.

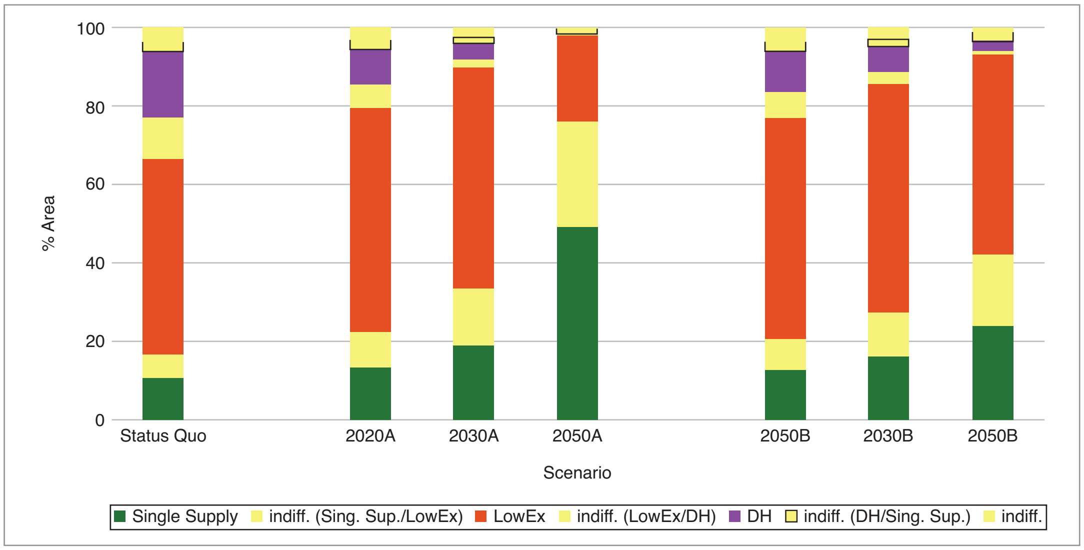

Figure 10: Area shares of suitability areas in two scenarios

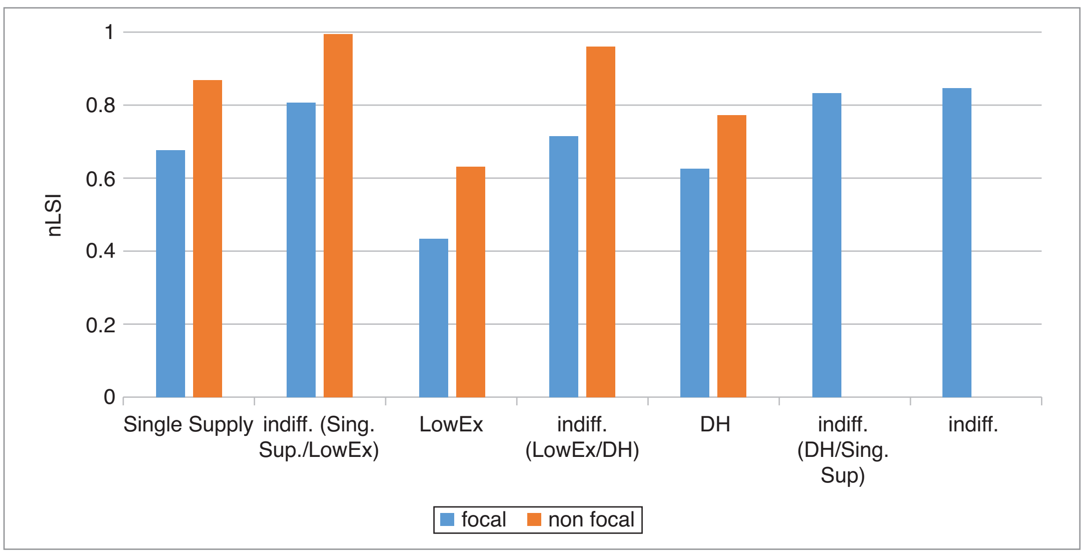

Figure 11: Comparing the nLSI for each supply option (status quo) – focal / non focal

In summer, direct electrical boosting is considered with an efficiency factor of 0.9.

The rough balance check of potential generation and demand shows that the DHW demand could easily be covered, whether with heat pumps (see COP in Table 5) or direct electrical boosting. The gap between the potential and current coverage by PV units is obvious, so there is a great need for further expansion of PV on roofs.

In winter, the situation is different. In addition to DHW, space heating must be supplied.

Depending on the heat supply option, DHW can be prepared either together with the space heating system by heat pumps (Single Supply, LowEx), or directly (LowEx, cDH), or separately (heat pump, electrical boosting). Assuming the heat demand in Single Supply areas will be covered by geothermal heat pumps, the COP of the heat pump is around 3.8 [61] and in LowEx systems the heat pumps can run with a COP of around 5 up to 6 [62, 63].

Table 5 shows that even in the 2050 scenarios the power demand cannot be covered by PV on roofs.

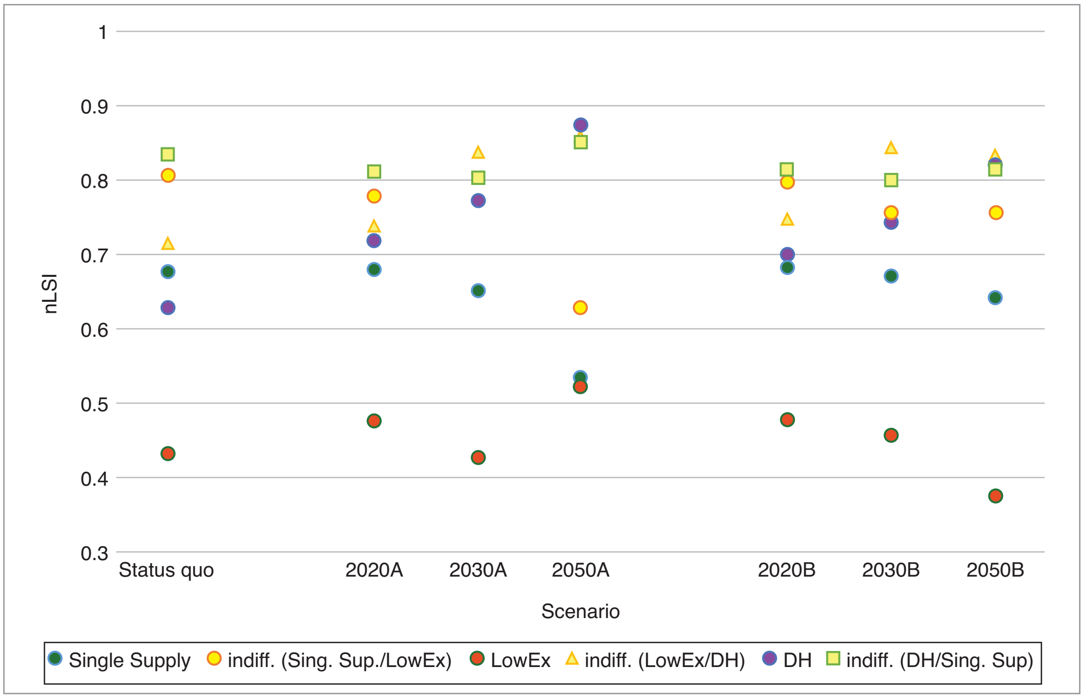

Figure 12: Scenario-related nLSI of suitability areas

Table 4: Accounted integration of solar power (summer)

	Option	Pot. solar power (kWh)	DHW demand (kWh)	Share pot. solar power to DHW with boosting	Share current solar power to DHW with boosting
Status Quo					
	cDH	20,512,889	4,954,034	373%	33%
	LowEx	58,229,070	12,317,525	425%	48%
	Single	6,244,106	1,295,095	434%	67%
2050A					
	cDH	1,194,999	235,734	456%	29%
	LowEx	31,743,296	7,319,651	390%	31%
	Single	41,804,136	9,204,918	409%	44%
2050B					
	cDH	3,675,736	748,038	442%	32%
	LowEx	70,456,589	15,852,872	400%	33%
	Single	15,298,741	3,284,310	419%	48%

To cover the demand, further energy sources are needed. The so-called “Wind Power Equivalence “(based on chapter 3.5) for power generation requirements in winter is convenient for the purposes of gaining a first impression:

- Status Quo → 26.5 wind plants
- 2050 A → 4.2 wind plants
- 2050 B → 12.8 wind plants

The power required can be generated by other technologies, like CHP based on renewable gas or biomass, of course, but the numbers illustrate that only the heating sector will make use of large quantities of renewable power.

However, the question arises whether large, grid related heat pumps should take over the heat supply especially in LowEx areas [28, p. 152], in contrast to the Single Supply areas with building related heat pumps.

4.4. Integration of industrial excess heat

The integration of industrial excess heat into grid related supply systems is a complex technical challenge. Initial spatial matchmaking provides guidance for the next planning steps.

The following figure shows spatial matchmaking based on the example of three companies in Bramsche.

Table 5: Accounted integration of solar power (winter)

	Option	Pot. solar power (kWh)	DHW + space heating demand (kWh)	Share pot. solar power	Share current solar power	Solar Energy/ heat pump (COP 5)	Solar Energy/ heat pump (COP 3.8)
Status Quo							
	cDH	12,500,034	263,719,051	5%	0.4%		
	LowEx	35,256,539	524,530,543	7%	0.8%	34 %	
	Single	3,782,472	54,286,250	7%	1.1%		26%
2050A							
	cDH	733,185	5,748,766	13%	0.8%		
	LowEx	19,219,707	146,537,877	13%	1.0%	66%	
	Single	25,377,557	156,653,221	16%	1.7%		62%
2050B							
	cDH	2,242,452	26,854,872	8%	0.6%		
	LowEx	42,684,717	436,732,345	10%	0.8%	49%	
	Single	9,316,718	83,995,061	11%	1.3%		42%

Table 6: Estimation of the usable excess heat and the search radius

Company	Exhaust gas temperature (°C)	Excess heat (kW)	Operating time (fixed), h/a	Potential energy quantity (MWh / a)	Usable excess heat (kW)	Search radius(m)	
						Target system LowEx	Target system cDH
A	240–280	800	6750	5400	70	700	282
B	850	600	6750	4000	75	750	302
C	320–435	530	6750	3500	50	500	201

Due to data protection issues, the company names and exact locations are not mentioned. After consultation with the PinA-project and in contrast to [59, p. 33], the usable excess heat of company B is set to 75 kW, due to the local constructional conditions. Regardless of the individual values, the focus is on spatial integration. The results differ too [60], because the County of Osnabrück updated the heat demand data in the meantime.

The spatial algorithm discards isolate raster cells, so the cell with a suitability in cDH 2050A is not taken into account. The following table shows the share of the heat demand coverage within each target system.

In view of the fact that the systems could also be operated in a coupled way, the following table represents a combined coverage rate.

5. Discussion

The approach presented in this article provides an overview of the possible heat supply options und suitability areas within a municipality. The starting point is the heat demand data. The better the modelling of the heat demand the more reliable the result is. The grid-based and focal analysis allows single errors to be smoothed, but systematic errors will, of course, lead to other suitability areas (see results of [60]).

5.1. Suitability areas

The calculation of the linear heat density using only the modelled pipelines of each grid is not topologically correct for district heating systems. The intention of this approach is to provide a first sketch that has to be refined at the subsequent detailed planning level.

The spatial conceptualization and scale of analysis is a compromise: Neither a purely geostatistical analysis nor a strict technical directive is helpful. The chosen resolution of 100 × 100 m gives both an overview and a suitable size to detect and depict peculiarities, wide areas and coupling zones. The cells with an indifferent suitability are of particular interest (see Figure 14). They are spatially explicit coupling and transition zones between two different suitability areas. LowEx and cDH areas can be coupled in these zones by means of a meshed network: coupled in winter, and de-coupled in summer, for instance.

The approach has its limits at the borders and edges of the settlements, as does every grid-based

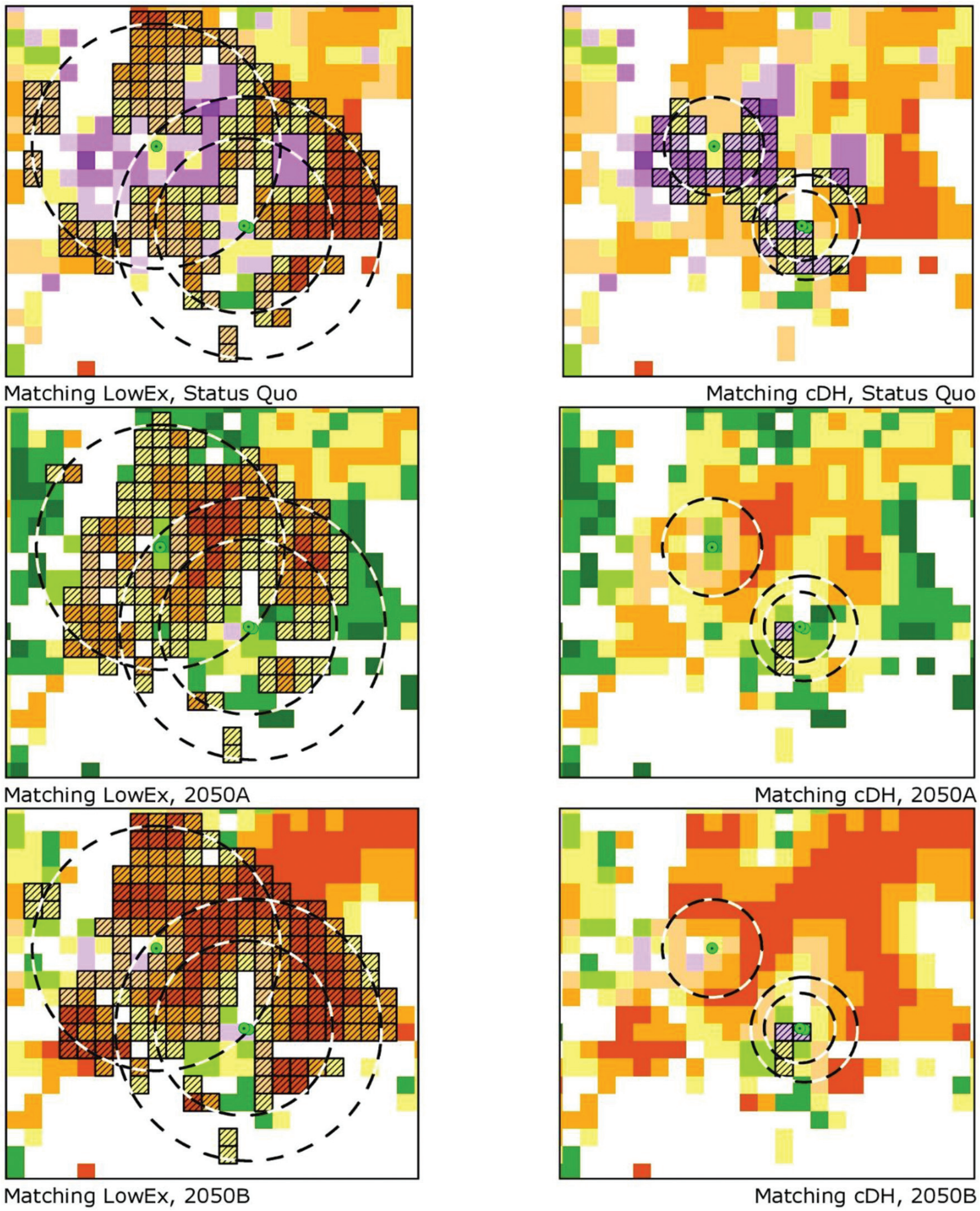

Figure 13: Search radius for industrial excess heat and matching with the target supply system (unscaled)

approach [53]. The border effect is shown in Figure 14. This effect has to be taken into account at the detailed planning level.

Each cell represents a preference of suitability. This means that each cell also includes a degree of suitability for another heat supply option. Local decisions at the detailed planning level could use and activate these hidden suitabilities. Definition of the heat supply options by fuzzy membership gives a snapshot of the technological development. This means the range of

Table 7: Share of the heat demand covered by industrial excess heat within each target system

	Status Quo		2050A		2050B	
Company	**Coverage rate LowEx**	**Coverage rate cDH**	**Coverage rate LowEx**	**Coverage rate cDH**	**Coverage rate LowEx**	**Coverage rate cDH**
A	16.2%	43.1%	27.1%	—	17.7%	—
B	12.2%	49.8%	23.6%	356.3%	13.5%	348.1%
C	22.5%	89.5%	37.2%	311.8%	23.4%	304.6%
A/B/C	25.6%	65.3%	50.0%	668.2%	30.2%	652.8%

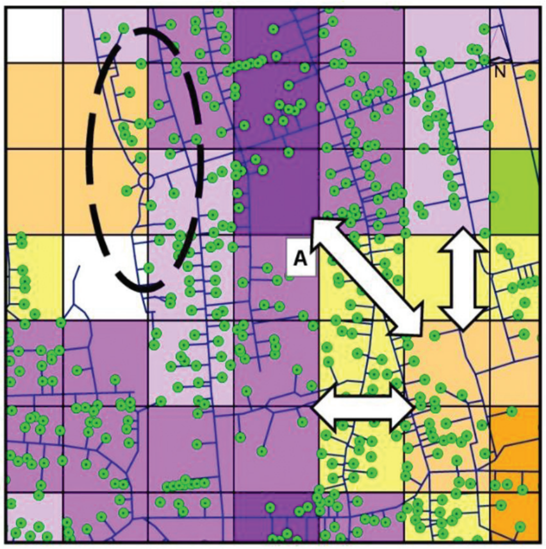

Figure 14: Border effect (dashed line) and indifferent cells as coupling zones (arrows, unscaled close-up)

each heat supply option should be monitored and updated according to the experience gained with 4th generation district heating systems.

Recent technological developments and the traditional view on district heating are in an area of tension. To meet the hygiene requirements, especially the legionella issue, it is necessary to be on the safe side. Health should not be put at risk merely in the name of efficiency. The potential damage could be higher than the savings. Not least, because popular acceptance would be jeopardized.

The preparation of DHW is a very important issue for the overall efficiency of grid-related heat supply:

- The use of DHW from heat pumps is important in areas in which grid-related supply is, in all probability, unsuitable, both now and in the near future (2030; Single Supply Areas).
- Electrical boosting of DHW, filtering systems, or a combination with limited storage could be suitable for areas where LowEx systems will last a long time, despite heat demand reduction measures.
- In cDH – areas the DHW should be prepared directly by the district heating system. Filtering systems or a combination with limited storage can provide DHW in summer mode with reduced supply temperature.

Finally, for the robustness of the system, the implementation should be as simple as possible [21].

To decarbonize the heat sector the temperature level must be lowered as a matter of urgency, but the technical solutions should be compatible with a transition process that will take decades. As pointed out in [17], 2030 is a very important milestone towards reaching the 2050 goals

Based on Figure 9, changes to suitability areas in space and time are, exemplarily, illustrated in Figure 15.

The suitability area A indicates LowEx and B indicates DH (status quo). With the help of the scenarios it is possible to show the potential development of the suitability status in the areas. The area A turns to single supply and B turns to LowEx in Scenario 2050A. In 2050B both areas indicate LowEx, additionally with some DH cells in area B.

The scenarios are based on the overall reduction targets (minimum: -40% / maximum:

-60% by 2050) required to achieve the climate protection goals. These numbers are important guard rails. More specific data about the retrofitting status and potential of each building allows the scenarios to be fine-tuned to the actual local situation. From today's position, it is questionable whether the minimum target of -40% can be reached by 2050.

Under the premise that the reduction targets are set, a system being implemented today must be able to take into account future development. So, a DH system in area B should be convertible to a LowEx system. Whether stricter reduction goals in area A are achievable, can only be said 1.) with a closer technical investigation and 2.) with a political statement of intent to achieve these stricter goal.

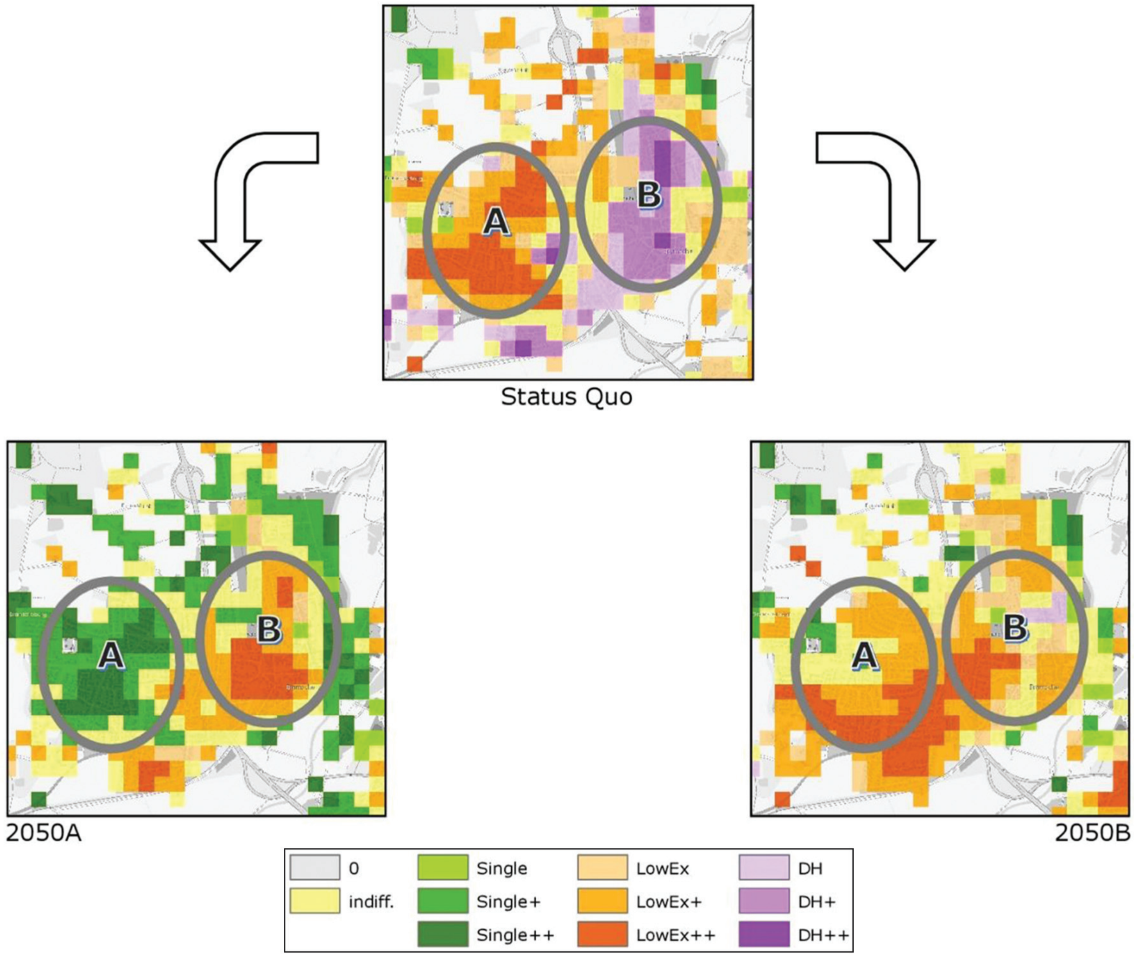

Figure 15: Scenario paths of suitability areas, spatiotemporal assessment (unscaled)

The approach can be understood as an entry to a dynamic and cyclical process.

5.2. Spatial compactness

The effect of the focal analysis step on the compactness of the suitability areas is shown in Figure 11 and proved. As far as the scenarios are concerned, scenario B leads to more compact areas. From the perspective of municipalities, scenario B provides more coherent and – from the point of view of urban planning – more convenient planning areas. Besides showing compactness, Figure 10 enables a first estimation to be made of area shares for target systems and related technical solutions.

5.3. Integration of seasonal power generation

As an example, the seasonal production of solar power on roofs and first accounting are presented. In summer, the DHW demand can easily be covered by the potential solar power, whether with electrical boosting or with heat pumps in all supply options. But the additional use of heat pumps in DH is not recommended. In winter, both space heating and DHW have to be supplied. The potential solar power production combined with heat pumps is not able to cover the power demand. As a result, external power has to be produced. The "Wind Power Equivalence" delivers a number which is easy to communicateand which illustrates the need in terms of the number of wind turbines.

The question of the shares of solar power and solar thermal energy should be clarified at the subsequent, more technical planning level. With regard to a possible extensive electrification of other application fields such as mobility the cost impact on the grid must be taken into account, but only proportionally. Rather it can be said that in some suitability areas heating will not be a cost driver for the power grid, especially in DH systems and, depending on the implementation, also in some LowEx systems.

The relationship between the efforts in the reduction of heat demand and the need of further wind turbines can fuel the political debate towards reduction and more solar energy.

5.4. Integration of industrial excess heat

The integration of industrial excess heat is a very interesting point and, as can be seen in Table 8, the overall coverage is moderate but stable according to the scenarios. However, it should be noted that the estimation of the useable excess heat is very approximate and it only allows search radii to be found. From a municipal point of view, it should be emphasized that this approach delivers an overview of potential sources and their spatial impact for subsequent planning. In a way it is spatially indexed check list for the communication between municipality and technical planners.

Table 8: Combined share of the heat demand covered by industrial excess heat within each target system

Company	Status Quo Coverage rate LowEx/cDH	2050A Coverage rate LowEx/cDH	2050B Coverage rate LowEx/cDH
A/B/C	20.1%	27.9%	29.5%

In addition, it should be noted that companies can change locations or change their production dramatically. The use of industrial excess heat can, therefore, not be a trigger for the choice of a particular heat supply option, but merely a supplement. The basic decision on the future heat supply system should not, therefore, be made dependent on the sources of excess heat, but lead to a sustainable and viable system even if these sources fail. Spatial matchmaking is a simple way to combine supply and demand, and provides a good basis for further planning.

6. Conclusions

Of course, the approach will not automatically lead to decarbonization of the heat supply. The challenge of a carbon-free heat supply in winter in cities with a high density of settlements has not been solved. Renewable gas, biomass, heat storage in summer, wind plants etc. are necessary components which will have a deep impact on the urban and rural landscape.

The expected competition between the energy sources, domains (mobility, power, heating) and actors will take place at the local level. Funding authorities do not, yet, differentiate according to local settings, when subsidizing certain technologies. Local and regional differentiation of the potentials and possibilities helps to develop adapted focussing. The

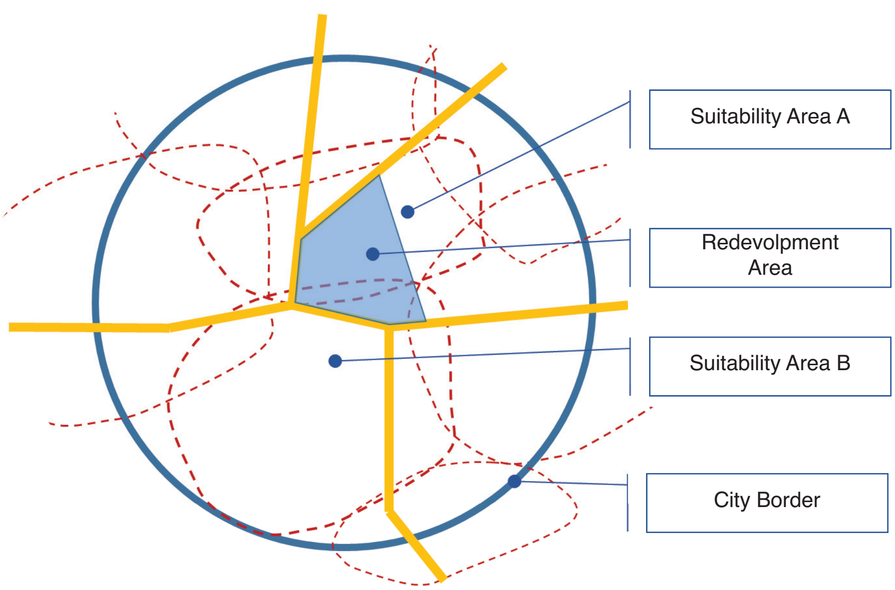

Figure 16: A “look over the project-fence” with suitability areas

high energy demand of an urban area can only be met with difficulty within the urban area itself. So, cooperation with suburban and rural regions is very important for the energy transition as, for example, large wind power plants and large solar thermal plants can only be built here. The energy transition can be organized as a win-win–process. To promote and encourage this a spatial component should be incorporated: Where a particular technology make a contribution in a local context, targeted funding should be provided. As a result, on the basis of suitability areas, locally appropriate funding for certain technologies can be used as an instrument to trigger the desired development. This would mean a fundamental change in current funding policy.

The approach also offers a spatial framework for integrated energy planning and allows a flexible response to local conditions, which can be refined at the subsequent planning level. Thus, the approach facilitates greater spatial concretization of energy planning [39, p. 233] and enables a "look over the project fence". To meet the needs of municipal planning culture, the concept of suitability areas could be used as a matrix for specific urban redevelopment areas. This would avoid small-scale optimizations that hinder larger-scale developments.

The implementation of the measures within the redevelopment area will have an impact on suitability areas, so a new cycle to determine suitability areas can be started.

Finally, it can be stated that:

- The district and the building are the operational level of the Heat Transition. However, for substantial discussions about a system decision, a broader perspective is needed (spatially and temporally). This requires a municipal energy-planning framework with a firm legal footing and appropriate instruments.
- The spatiotemporally driven detection of suitability areas offers
    - guardrails for subsequent detailed planning, and
    - an explicitly spatial long-term strategy
- The approach facilitates
    - dynamic data updating (heat demand, local reduction scenarios etc.), and
    - monitoring and controlling of measures.

To enable the transition process at a subsequent planning level a more economic view [64] and more technical refinements [65] are necessary. The "Where" and "What" questions can be now be narrowed down at a conceptual level, but the most important question is still open: Who will drive the process forward and how can the concept of long term energy planning actually be put into practice? The approach may help stakeholders to gain a spatial understanding of the challenges of the energy transition and the future tasks involved.

Acknowledgements

Thanks are due to Mr. Keiler for providing the wind plant data. Thanks are also due to the County of Osnabrück, the involved companies (Geoplex GmbH, ip syscon GmbH)/, and the "Kompetenzzentrum-Energie" at the University of Applied Sciences Osnabrück for the PiNA and solar data.

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9. Appendices

9.1. Appendix I

Pseudo code to calculate the linear heat line density:

```
  #   Preparing Data
Data: Heat demand points
  #   Process: Select Layer by Attribute (Demand > 0)
Data: OpenStreetMap Highways
  #   Process: Select analysis ("highway = 'construction'
      OR highway = 'living_street' OR highway =
      'primary' OR highway = 'proposed' OR highway =
      'residential' OR highway = 'secondary' OR
      highway = 'service' OR highway = 'tertiary'
      OR highway = 'tertiary_link' OR highway = 'track'
      OR highway = 'unclassified' OR highway =
      'pedestrian'")

  #   Connecting Heat demand Points with
      OpenstreetMap data
Data: Selected Heat demand Points + OpenStreetMap
      Highways
  #   Process: Generate Near Table ("LOCATION",
      "NO_ANGLE", "CLOSEST", "0", "PLANAR")
      from points to OSM
  #   Process: Generating Line from Near Table (XY in
      Line)
  #   Process: Buffer 1.5 meters (avoiding parallel
      structures)
  #   Process: Multipart in Singlepart of generated
      buffers
  #   Process: Create Centerlines of Buffers
  #   Process: Merge (selected OpenStreetMap data
      with centerlines)
      (Problem: There is still a gap between the point
      and the former centerlines due to the centerline
      and buffer processes)
  ##  Process: Generate Near Table ("LOCATION",
      "NO_ANGLE", "CLOSEST", "0", "PLANAR")
      from points to Centerlines
  #   Process: Generating Line from Near Table (XY in
      Line)
  #   Process: Merge (Near table lines with centerlines
      and OSM data)

  #   Calculating the linear heat density
  Data: 100 × 100 m polygon grid, total heat demand
per 100 × 100 m grid, derived linear structure (see above)
  #   Process: Intersect (polygon grid with linear
      structure)
  #   Process: Feature in Raster (length of linear
      structure, resolution 100 m)
  #   Process: Focal Statistics (focal rectangle of 3 × 3
      cells, mean of shape length)
  #   Process: Raster Algebra (Dividing total heat
      demand per 100 × 100 m grid by the focal shape
      length raster)
```

9.2. Appendix II

Overlay Codes

Overlay Code	Reclassification	Suitability
2021	0	No preference
2023	3	Single Supply
2024	2	Single Supply+
2025	1	Single Supply++
2041	0	No preference
2042	0	No preference
2043	3	Single Supply
2044	2	Single Supply+
2045	1	Single Supply++
2061	10	LowEx
2062	10	LowEx
2063	5	Indifferent: (Single Supply and LowEx)
2064	2	Single Supply+
2081	20	LowEx+
2082	20	LowEx+
2083	20	LowEx+
2101	30	LowEx++
2102	30	LowEx++
4022	500	Indifferent: Single Supply and District Heating
4023	3	Single Supply
4024	2	Single Supply+
4025	1	Single Supply++
4041	50	Indifferent: LowEx and District Heating
4042	1000	Indifferent: All options
4043	3	Single Supply
4044	2	Single Supply+
4061	10	LowEx
4062	10	LowEx
4063	5	Indifferent: (Single Supply and LowEx)
4081	20	LowEx+
4082	20	LowEx+
4101	30	LowEx++
6021	100	District Heating
6022	100	District Heating
6023	500	Indifferent: Single Supply and District Heating

Overlay Code	Reclassification	Suitability
6024	3	Single Supply
6041	100	District Heating
6042	100	District Heating
6043	500	Indifferent: Single Supply and District Heating
6061	50	Indifferent: LowEx and District Heating
6062	50	Indifferent: LowEx and District Heating
6081	20	LowEx+
8021	200	District Heating+
8022	200	District Heating+
8023	200	District Heating+
8041	200	District Heating+
8042	200	District Heating+
8061	200	District Heating+
10021	300	District Heating++
10022	300	District Heating++
10041	300	District Heating++

9.3. Appendix III

Solar power estimation for Bramsche/Wallenhorst (Lower Saxony), based on PVGIS-classic:

Nominal power of the PV system: 1.0 kW (crystalline silicon)

Estimated losses due to temperature and low irradiance: 7.9% (using local ambient temperature)

Estimated loss due to angular reflectance effects: 3.1%

Other losses (cables, inverter etc.): 10.0%

Combined PV system losses: 20.9%

Calculation of kWh/kWp, depending on the orientation:

Fixed system: inclination = 35°, orientation = −1° (optimum)

Month	E_d	E_m	H_d	H_m
Jan	0.83	25.7	0.95	29.4
Feb	1.77	49.5	2.05	57.4
Mar	2.16	66.9	2.58	79.9
Apr	3.28	98.4	4.09	123
May	3.83	119	4.88	151
Jun	3.51	105	4.55	136
Jul	3.63	112	4.72	146
Aug	3.41	106	4.39	136
Sep	2.61	78.3	3.27	98.2
Oct	1.89	58.4	2.28	70.7
Nov	1.09	32.6	1.27	38.1
Dec	0.6	18.5	0.68	21.1
Yearly average	2.39	72.5	2.98	90.6
Total for year		871		1090

Fixed system: inclination = 36°, orientation = 90°

Month	E_d	E_m	H_d	H_m
Jan	0.44	13.7	0.57	17.7
Feb	1.05	29.4	1.29	36.1
Mar	1.62	50.1	1.96	60.8
Apr	2.74	82.1	3.41	102
May	3.49	108	4.42	137
Jun	3.35	101	4.33	130
Jul	3.38	105	4.38	136
Aug	2.94	91	3.77	117
Sep	2	60	2.53	75.8
Oct	1.22	37.8	1.53	47.5
Nov	0.59	17.7	0.76	22.8
Dec	0.31	9.58	0.41	12.7
Yearly average	1.93	58.8	2.45	74.6
Total for year		705		895

Fixed system: inclination = 36°, orientation = −90° East

Month	E_d	E_m	H_d	H_m
Jan	0.44	13.6	0.57	17.5
Feb	1.06	29.5	1.29	36.1
Mar	1.62	50.4	1.96	60.8
Apr	2.75	82.6	3.41	102
May	3.51	109	4.42	137
Jun	3.37	101	4.32	130
Jul	3.4	105	4.37	136
Aug	2.95	91.5	3.77	117
Sep	2.01	60.2	2.52	75.7
Oct	1.22	37.9	1.53	47.4
Nov	0.59	17.6	0.76	22.7
Dec	0.31	9.47	0.41	12.6
Annual Average	1.94	59	2.45	74.5
Total		708		894

Fixed system: inclination = 35°, orientation = −45° South-East

Month	E_d	E_m	H_d	H_m
Jan	0.7	21.9	0.82	25.5
Feb	1.54	43.1	1.8	50.5
Mar	1.99	61.7	2.39	74
Apr	3.15	94.5	3.91	117
May	3.79	117	4.79	149
Jun	3.51	105	4.53	136
Jul	3.6	112	4.66	144
Aug	3.3	102	4.23	131
Sep	2.43	72.9	3.05	91.4
Oct	1.67	51.9	2.04	63.2
Nov	0.92	27.7	1.1	33
Dec	0.51	15.7	0.59	18.4
Annual Average	2.26	68.8	2.83	86.1
Total		826		1030

Fixed system: inclination = 35°, orientation = 45° South-West

Month	E_d	E_m	H_d	H_m
Jan	0.71	22	0.83	25.6
Feb	1.53	43	1.8	50.5
Mar	1.98	61.5	2.39	74
Apr	3.13	94	3.91	117
May	3.77	117	4.79	149
Jun	3.49	105	4.53	136
Jul	3.59	111	4.66	145
Aug	3.29	102	4.23	131
Sep	2.42	72.7	3.05	91.5
Oct	1.67	51.8	2.04	63.3
Nov	0.93	27.9	1.11	33.2
Dec	0.51	15.8	0.6	18.5
Annual Average	2.26	68.7	2.83	86.2
Total		824		1030

Aggregated generation (kWh/kWp)

	Pitched Roof			Flat Roof
Period\ Orientation	South	West/ East	South-West/ South-East	(overall average)
May-Sept.	520.30	465.85	508.30	498.15
Oct.-April	350.00	240.73	316.25	302.33