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Potential-estimation of thermal micro-grids in urban areas based on heat load and building clustering

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Potential-estimation of thermal micro-grids in urban areas based on heat load and building clustering

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Abstract. As a result of climate change, fossil heating systems must be replaced with renewable systems. The question arises whether it makes sense for each building to have its own new heating system or whether a thermal micro-grid is possible. In this paper a model is presented which allows to aggregate buildings into thermal micro-grid clusters. All gas-heated residential buildings of Basel (Switzerland) are marked via geo-data. The heat demand of each building is determined depending on the year of construction and is then converted into the heat load. Each building then is grouped into thermal micro-grids according to a given grid load limit. The thermal micro-grids generated in this way are marked in color, so that the potential of any given city district can be easily and quickly identified. If the grid load limit is increased, the number of possible micro-grids increases, also.

1. Introduction

Switzerland used a total of 55.2 TWh for space heat and domestic hot water (DHW) in 2021, corresponding to around 80 % of the energy consumption in Swiss households [1]. Fossil heating systems account for 62 % of the heating energy in buildings and 51 % of DHW generation. This corresponds to 33.4 TWh per year and causes 7.4 million t/a CO_2-emissions. With the "Energy Strategy 2050+" Switzerland commits to becoming climate neutral by 2050. One building stone to reach this goal is to replace fossil-based heating systems in existing buildings with heating systems based on renewable energy e.g. heat pumps. As gas grids will be shut down, buildings previously supplied with gas will have to change their energy source. If the gas grid is not replaced by district heating, the heat must be generated at the buildings locally. As a result, each building will need an own heating system. Since larger heating systems are usually more resource-efficient and economical than individual smaller ones, it makes sense to combine adjacent buildings into a thermal micro-grid, e.g., semi-detached houses are supplied by one heating system.

The model for the clustering of buildings into feasible thermal micro-grids is developed as an example for the canton of Basel-Stadt, Switzerland. Only adjacent residential buildings that currently have gas as energy source are considered.

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2. Methodology

2.1. Heating demand and heat load

For the replacement of a heating system the design heat load must be known. This can be derived from the heating demand. In [2] the final energy consumption for heating and domestic hot water for the canton of Basel-Stadt is examined and presented depending on the year of construction. To derive the heating demand, a few assumptions must be made:

- Conversion between useful and final energy is done with an assumed utilization rate of $\eta = 0.9$ both for space heat and DHW
- Based on [3] it is determined that buildings with a construction year before 1880 have a heating consumption of 72 kWh/(m^2 y)
- For the domestic hot water demand, the average value is taken from SIA 380/1:2016 [4], using the average of the standard values for single-family and multi-family houses (18 kWh/(m^2 y))
- The average heat load for domestic hot water heating 2.5 W/m^2 is the mean value between single-family and multi-family houses according to the guideline values from [5].

The average final energy consumption depending on the year of construction for heating and domestic hot water is calculated according [2]. Subsequently, the domestic hot water demand is subtracted from the final energy consumption at the final energy level. Thus, the heating consumption is known. This is converted from final energy to useful energy using η given above. With this calculated heating consumption, the specific heating load can be calculated with the help of SIA 384/1:2022 (using the 90 % characteristic curve). The conversion of demand to load according to SIA 384/1:2022 takes the additional heat load for domestic hot water into account. The total heat load can then be assigned to each building depending on the year of construction (figure 1). This is the basis for the aggregation of buildings into thermal micro-grid clusters depending on a given micro-grid capacity.

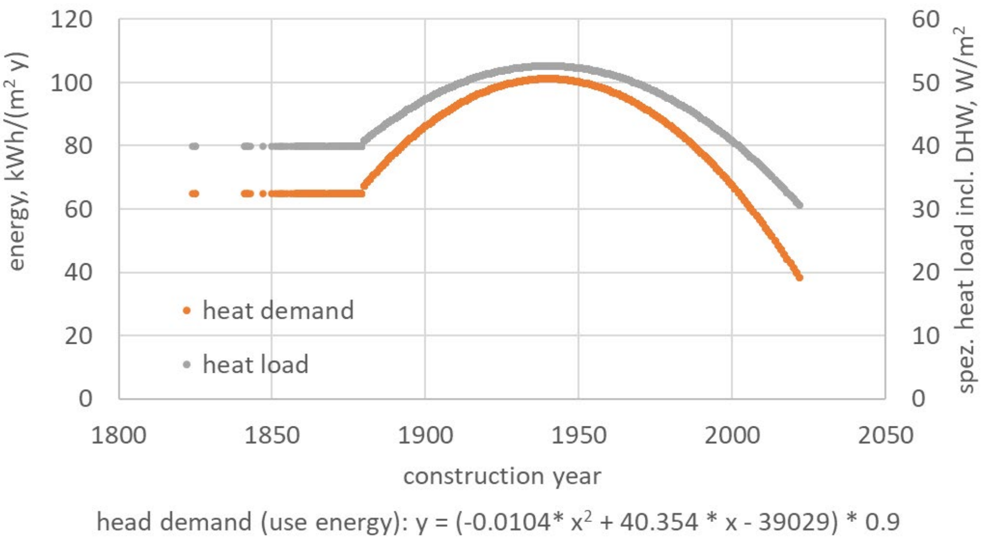

Figure 1. Heat demand and heat load depending on the year of construction.

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2.2. Building aggregation

Based on the estimated heat load for each building the method for generating potential micro-grids applied is a Delaunay triangulation of city blocks based on the building centroid points. City blocks are chosen as regions in which to generate the micro-grids, as the distance between buildings across streets are likely larger and linking buildings is likely more expensive given existing infrastructure underneath streets. Using the Delaunay triangulation the method derives the minimum spanning tree (MST) [6] based on the Euclidean distance between buildings. The weights of the edges of attached houses are decreased significantly to favour the link between attached houses in the MST (figure 2). The algorithm then starts at an end node of the MST and traverses it to form micro-grids along the branches of the MST. The traversal of the MST considers the following three constraints for clustering buildings to form a micro-grid:

- the network should not exceed a maximum heat load or
- a maximum distance between buildings and
- adjacent buildings should be of the same type, that is residential buildings with gas supply.

During the traversal, the algorithm checks each building against the constraints. If any of the constraints are met, the building is disregarded. Thus, the building clusters are formed as shown in figure 2.

Figure 2. Generation of micro-grids with a maximum heat load of 100 kW for two city blocks, a) inner city block b) suburban city block.

Different suitable upper heat load limits (30 – 100 kW) for the micro-grids are considered for the canton Basel-Stadt in Switzerland. Only residential buildings that are currently heated with gas are considered (figure 2, buildings in green and white).

3. Results and analysis

Figure 3 shows the maximum heat load for each multi-family terraced house in a building block (a) and the results for thermal micro-grids with different maximum heat load limits (b-c). Adjacent buildings with the same color are grouped into a micro-grid. The colored buildings are valid candidates but cannot be included due to load or distance limit restrictions. Buildings with gray color are excluded because they are not residential buildings with gas supply. The number of micro-grids increases when the maximum heat load limit increases. The number of single buildings which cannot join a micro-grid vs. the number of buildings in thermal micro-grids are shown in figure 4 a for load limits of 30- 100 kW. The total heat load gives figure 4 b.

The overview map of canton Basel-Stadt shows the potential total heat load summed up for each city block (figure 5). For reference the existing district heating regions are shown. Buildings with gas supply situated in district heating regions have the option to change to district heating.

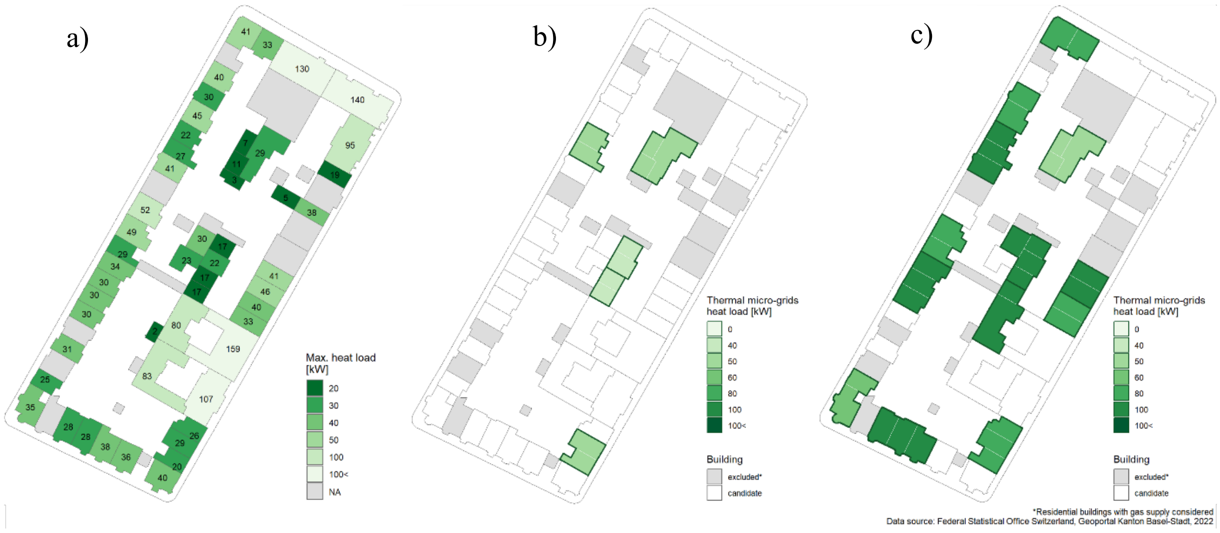

Figure 3. Building heat loads of multi-family terraced houses (a) and possible thermal micro-grids with heat load limits of 50 kW (b) and 100 kW (c).

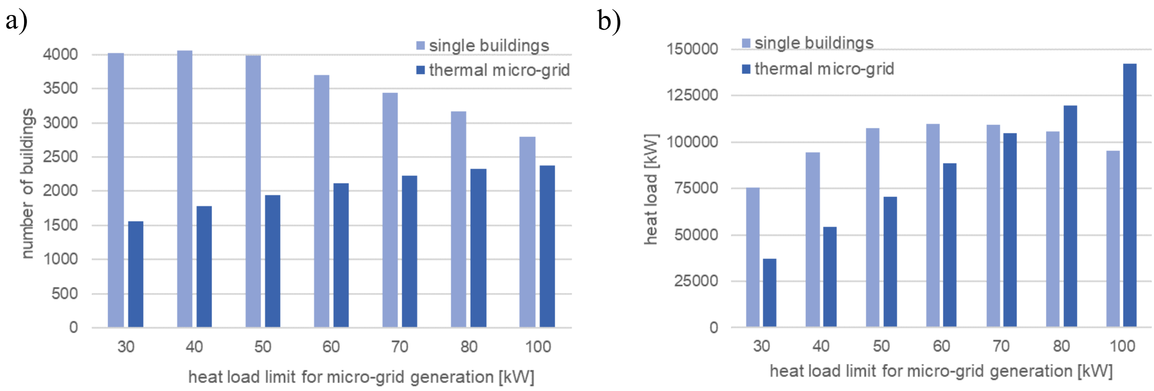

Figure 4. Canton Basel-Stadt a) number of buildings forming a micro-grid versus number of single buildings that cannot join a grid, b) total heat load of single buildings and thermal micro-grids.

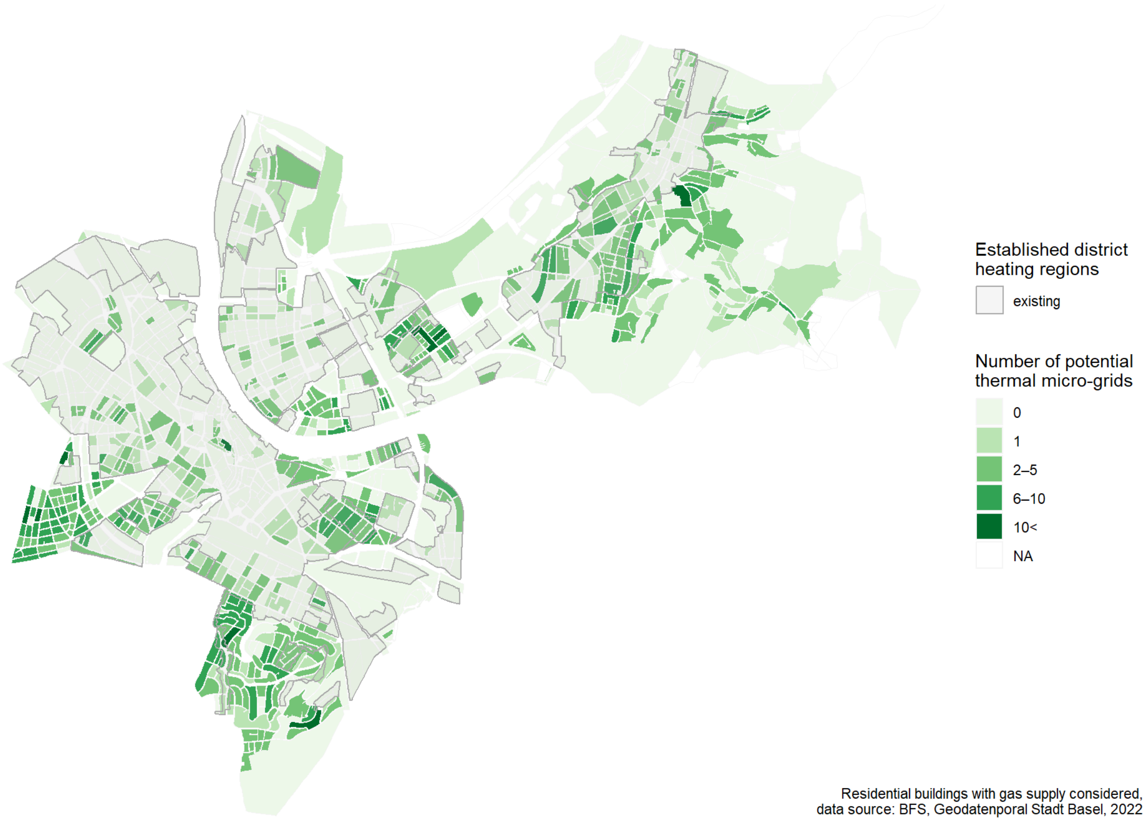

Figure 5. Number of potential thermal micro-grids with a heat load limit of 50 kW for each city block in canton Basel-Stadt. The existing district heating regions are mapped for reference.

As an example, the standard procedure for the replacement of the heating system in a single-family neighborhood is shown in figure 6 a. Each building is equipped with its own new heat pump with a design load of 5 kW each. Figure 6 b shows two possible 20 kW-micro-grids of four buildings each. As can be seen from table 1, the larger heat pump benefits from a smaller footprint and lower greenhouse gas emissions for the unit compared to four individual units. Additionally, there can be an advantage for brine water heat pumps as bore hole numbers and locations can be optimized. Since larger heat pumps have a higher sound power level, care must be taken to ensure high sound insulation.

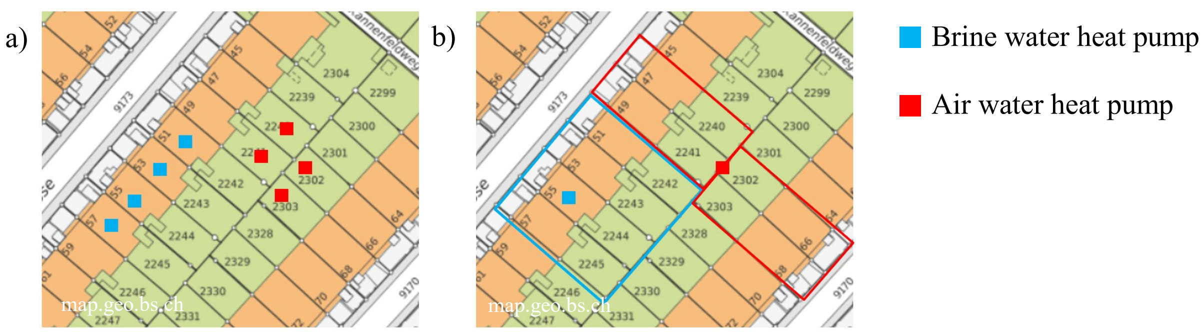

Figure 6. Standard heating replacement a) and thermal micro-grids b)

Table 1. Parameters for air/brine water heat pumps [7], [8]. Calculations of greenhouse gas emissions are based on [9].

parameter	5 kW	4 x 5 kW	20 kW	difference
Footprint, m^2	0.56/0.37	2.22/1.48	0.50/0.37	- 77/- 75 %
Unit weight, kg	98/ 139	392/576	177/205	- 55/- 64 %
GHG emissions, kg	1’500/2’200	6’000/8’800	2’700/3’100	- 55/- 65 %
Sound power level, dB(A)	58/43	64/---	73/47	+ 11/+ 4 dB(A)

4. Discussion and Conclusion

The project results are colored building-specific city or neighborhood maps of possible thermal micro-grids depending on heat load limits and building locations. The lower the heat load limit, the lower the number of buildings per micro-grid and the total number of necessary micro-grids increases. Terraced houses with low heat demand are found to be particularly suitable. The maps provide a quick overview of where new heating systems are necessary, the required heat load and which buildings can be usefully combined into micro-grids. The developed method is a great help for heating system transition. Also, it can be easily adapted for other towns or other building related issues.

When calculating the year-of-construction dependent heating demand, it is not considered whether and to which depth the buildings may have already been renovated. This can lead to wrong micro-grid aggregations. Also, it is important that the building stock data regarding heating systems and heat floor aera is up-to-date. Nevertheless, the developed method allows a good overview about the potential for thermal micro-grids.

Future work would involve taking renovation levels into account and analyzing the roll-out: how to inform building owners about the possibility and advantages of thermal micro-grids and how to support planning, financial and law topics.

Acknowledgments

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