Ambient Heat Source Availability for Low-Ex Heating of Multi-Family Buildings

Stefan Hess[1], Raphael Vollmer[1], Jeannette Wapler[2], Martin Kleinstück[2]
Constanze Bongs[2], Hans-Martin Henning[1,2]

[1] Albert-Ludwigs-Universität Freiburg, Freiburg (Germany)

[2] Fraunhofer-Institute for Solar Energy Systems, Freiburg (Germany)

Abstract

Heat pumps (HP) for space heating and domestic hot water are well-established and considered to be a decisive technology for carbon emission reduction. However, in existing multi-family homes (MFH) their market share is still very low. In this work, the sufficient availability of the heat sources ambient air, ground probe and ground collector is assessed for one common MFH type in three different urban contexts. The heat demand of a reference building is calculated for the refurbishment state EnEV 2016 and for more ambitious refurbishment. The building is placed in the urban space types row house, perimeter block and city development. For each, the average open space around the building is estimated. Two bivalent air-source and ground-source HP system variants with gas backup boiler are designed. The necessary ambient heat extraction rates are simulated and the necessary size/distance of the heat source is calculated by using the design methods of TA Lärm, VDI 4640, Geo Hand and SIA 384/6. Finally, the resulting source demands are compared to the available space.

The results show that typical row house developments have sufficient open space for either bivalent air-source or ground probe HP systems; it is also the only investigated urban space type suitable for ground collectors. In perimeter blocks, air-source HPs and ground probes are usually possible. The open space in city developments is often too small for the investigated HP system types. Here, air-source HPs may be possible if additional acoustic enclosures are installed. For HPs in city developments, combinations with photovoltaic-thermal or solar thermal collectors, multi-source systems, or cold district heat networks should be further investigated.

Keywords: LowEx-Bestand, heat pump, multi-family building, building renovation, carbon emissions

1. Heat Pumps for Multi-Family Houses

In Germany, 54 % of all flats are situated in multi-family houses (MFH), i.e. in buildings with three or more flats. This represents a share of 41 % of the overall residential living area (Bürger et al. 2016, p. 121). The focus of this study is on MFHs, because related to living area they have a smaller plot size than single-family homes and consequently a more restricted heat source availability for HPs. A study on monovalent HP systems (i.e. systems without another heat generator) by Vollmer et al. (2018) concluded that the space around MFHs is in many urban contexts not sufficient. The study presented here investigates the heat source sufficiency for the more realistic case of bivalent HP systems (i.e. systems with additional boiler or heating element).

In 2016, space heating for MFHs in Germany was mainly provided by central heating systems (57 %), district heating (19 %) or apartment block heating (6 %), so the share of central heating types is already at 82 %. In these systems, the main heat generators are gas boilers (67 %) and oil boilers (26 %). Other technologies like cogeneration plants or wood/biomass boilers only have small shares. Heat pumps are only in 1 % of the German MFH building stock the main heat generator (all values calculated from Cischinsky and Diefenbach 2018, p. 82). The shares of single-story and single-room heating decrease, since in new MFHs the systems are almost exclusively central ones and after building renovation some decentralized systems are changed to central ones. It is estimated that hot water is in 92 % of all MFHs provided centrally by the same heat generator as space heating. In 8 % provision is separate and decentralized, e.g. by electric boilers (Forthuber and Hartner 2017).

The market share of HPs in Germany strongly increased over the last years, reaching 40 % at newly built single and double family houses in 2017 and 18 % at newly build multi-family homes (Destatis 2018). At renovation of existing heating systems, HPs have a still small, but growing share of 5.5 % (Bundesverband Wärmepumpe (BWP) e.V. 2018, p. 17).

doi:10.18086/swc.2019.10.01 Available at http://proceedings.ises.org

2. Reference Building, System Variants and Urban Space Structures

This study is performed for one specific reference building, selected based on its relevance for renovation of the German MFH building stock. Ebert (2018, p. 57 ff.) proposed four characteristic MFH building age classes (BAK), which have been aggregated based on literature data from Loga et al. (2015) und IWU (2012). Aim of the aggregation is to summarize similar construction periods, since it is expected that the refurbishment potentials only significantly differ between clearly distinguishable periods. The MFH in LowEx-BAK I were constructed before 1957 and show very little standardization. In LowEx-BAK II (1958-1978), building construction was already unified to a large extent, but with no energy saving requirements. LowEx-BAK III (1979-1994) has been constructed according to the Thermal Insulation Regulations (Ger.: Wärmeschutzverordnungen), LowEx-BAK IV (1995-2009) after 2002 with Energy Saving Regulations (Ger.: Energieeinsparverordnungen EnEV). In both regulations, the permitted heating demand regularly decreased over time.

For the potential impact of certain energetic refurbishments, both the frequency of a building type, but also its current energetic state (i.e. heating demand) are relevant. Under both aspects, the buildings of LowEx-BAK I and II are of particular interest for this study. However, for about 35 % of the German residential building stock monument and ensemble protection laws apply. This can result in more individual and cost-intensive refurbishment measures, e.g. for building wall insulation. It is assumed that the majority of the protected buildings were constructed before 1958 (Ebert 2018, p. 57). It is therefore concluded that LowEx-BAK II has the best cost/savings relation and thus the highest relevance for energetic refurbishment and subsequently heating system modernization. Accordingly, a MFH from this BAK was chosen as a reference for this study.

2.1. Reference Building

The dimensions and energy-related parameters for a typical medium-sized apartment building of LowEx-BAK II were derived from data of Loga et al. (2015) and IWU (2012). Figure 1 shows the reference building defined.

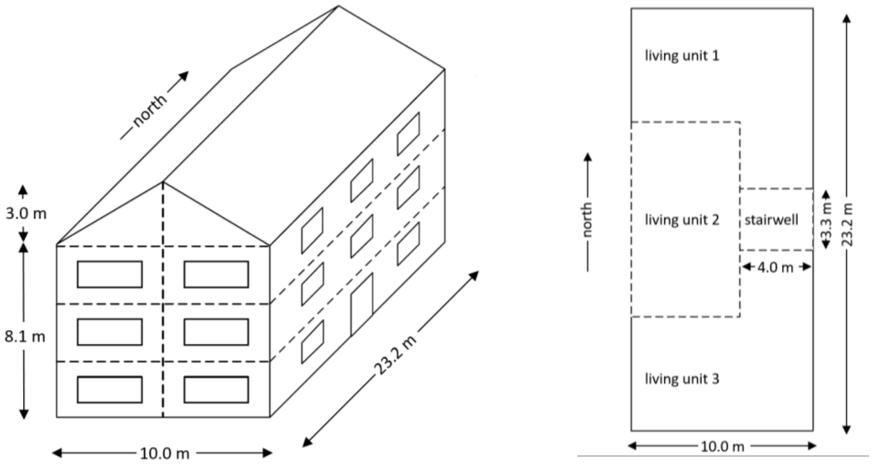

Figure 1: Typical medium-sized MFH built between 1958 and 1978 (LowEx-BAK II)

The building covers a base area of 232 m². The conditioned living area of 581 m² is distributed over three floors and three apartments per floor; the attic is not developed. Statistically, the available living area per person in Germany is currently about 45 m^2, averaged for all building types (Ebert 2018, p. 27). Thus, a number of 13 residents is assumed (e.g. five single person flats and four flats with two persons).

For this generic building, the annual heat demand and heating load was calculated for three different refurbishment states: State 0 is the state of construction[1], state 1 is the fully refurbished building according to the current requirements of the German Energy Saving Regulations (EnEV 2014/2016) and state 2 is an ambitious refurbishment, achieving a thermal loss reduction similar to the passive house standard[2]. Table 1 gives the parameters used to characterize the different refurbishment states of the reference building.

---

[1] energetic state as constructed, except for the windows, which are assumed to have been exchanged once

[2] no ventilation heat recovery assumed

Table 1: U-values of building components and other building parameters of the refurbishment states

Building element / parameter	Unit	No refurbishment **State 0**	Conventional refurbishment **State 1**	Ambitious refurbishment **State 2**
window	W/(m²*K)	3.25	1.30	0.70
window (g-value)	[-]	0.75	0.75	0.47
outer wall	W/(m²*K)	1.13	0.23	0.13
pitched roof	W/(m²*K)	0.55	0.19	0.16
top floor ceiling	W/(m²*K)	0.60	0.19	0.13
lowest floor ceiling	W/(m²*K)	1.33	0.30	0.20
thermal bridging factor	W/(m²*K)	0.10	0.10	0.05
infiltration rate	1/h	0.20	0.10	0.05
hygienic ventilation rate	1/h	0.40	0.40	0.40
internal loads	W/m²	3.00	3.00	3.00

2.2. Heating System

A central heating system with two variants for the main heat generator was simulated: An ambient-air-to-water heat pump and alternatively a brine-to-water heat pump. The backup heater is always a condensing gas boiler. The heat transfer system for space heating is radiators. For the initial state of the unrefurbished building it is assumed that the heating circuit design flow and return flow temperatures were 70 °C / 55 °C, but that the radiators are now overdimensioned by 15 % compared to the standard design heating load at ambient temperature of -14 °C. This is because the windows were assumed to have been already replaced once, but also due to higher safety factors used at the time when the original heating systems were designed. Thus, reduced design heating circuit temperatures of 62 °C / 52 ° C were used to simulate the heating demand in state 0. For the conventionally refurbished building (state 1) and the ambitiously refurbished building (state 2), the design temperatures 45 °C / 38 °C were used (Wapler et al. 2018, p. 10). For all stages, adapted heating curves were used. Domestic hot water (DHW) is prepared via a central fresh water station with storage and circulation line. The target temperature of this storage is 64 °C.

Two bivalence design temperatures for sizing the heat pump were considered, namely -5 °C and +2 °C. The HP heating power was selected in a way that it could cover the space heating and DHW load at the bivalence temperature. The system is operated bivalent-parallel, i.e. the HP is always running if the operation conditions allow (maximum output temperature of 62 °C). Independently of the ambient air temperature, the backup provides all additional heating power, i.e. assisting the heating below the bivalence temperature, covering dynamic peak loads in the system, but also for fully charging the DHW storage until the target temperature of 64 °C.

2.3 Urban Space Structures

After identifying an exemplary, relevant MFH building type as a reference for the study, the next step was the assessment of how much free space is statistically available around this building to provide ambient heat for air source or ground source HPs. Therefore, the building had to be analyzed in the context of the urban space types (ST) in which it would be typically found. According to Roth (1980), urban space can be categorized in nine different types, of which a selection is listed in Table 2. To identify the most relevant urban space structures for the reference building, the characteristics of the predominant buildings in each ST were compared to the characteristics of the reference building. These include the type of building stock (detached house, row house, MFH, etc.), the number of full storeys, the surface to volume ratio, the site occupancy index (German: Grundflächenzahl GRZ), the floor-space index (Ger.: Geschossflächenzahl GFZ), the period of building construction and the conditioned (i.e. heated) floor area.

The analysis of all space types of Roth (1980) showed that ST 4, 6 and 7 have the largest agreement with the reference building. Consequently, the free space availability in these three urban areas was calculated using the data of the reference building shown in Figure 1 and for comparison also in Table 2. The number of storeys, the heated floor area and the cubage of the reference building fit the three listed urban space types. The buildings in ST 6 were constructed earlier than LowEx-BAK II, but in the case that a MFH in ST 6 has already been partly refurbished and the resulting heat demand is similar to that of the reference building, this is also an interesting ST-type. ST 6 is also regarded relevant because of the high number of buildings in LowEx-BAK I.

Table 2: Urban space types according to Roth (1980, pp. 99–103) with parameters of the reference building from LowEx-BAK II (with A/V = surface to volume ratio (cubage), GRZ = site occupancy index, GFZ = floor-space index, BAK = building age class, A = conditioned floor area per building)

Code	Type	Storeys	A/V	GRZ	GFZ	BAK	A
ST 4	Row house development (medium density)	3 - 5	0.35 - 0.45	0.15 - 0.20	0.40 - 0.80	before 1915: 0 % 1915-1948: 0 % after 1948: 100 %	340 - 660 m²
ST 6	Perimeter block development	3 - 4	0.30 - 0.40	0.30 - 0.40	0.50 - 1.50	before 1915: 60 % 1915-1948: 40 % after 1948: 0 %	330 - 670 m²
ST 7	City develop-ment (based on ST 6)	4 - 6	0.20 - 0.30	0.50 - 0.70	1.00 - 3.00	before 1915: 50 % 1915-1948: 0 % after 1948: 50 %	530 - 1070 m²
Refer-ence	Medium-sized MFH (1958 – 1978)	3	0.48	-	-	before 1915: 0 % 1915-1948: 0 % after 1948: 100 %	581 m²

Hegger et al. (2012) developed energetic urban space types (EST) which are very similar to the ST of Roth (1980). But for the EST, no BAK is given and only median values are available for the number of storeys, A/V-ratio, GRZ and GFZ. Additionally, the values for GRZ and GFZ are slightly higher, since sealed areas like access roads and paths were not considered for plot size (Ebert 2018, p. 16 f.). Therefore and to have the opportunity to investigate the minimum and maximum range of open space area within a ST as source for heat pumps, for the current study the values of Roth (1980) were used. Figure 2 to Figure 4 show typical examples of row-house, perimeter block and city development according to Hegger et al. (2012), which are comparable to ST 4, ST 6 and ST 7 of Roth (1980). On the left hand side, the bird view settlement structure is shown in 2D, on the right hand side a 3D model of the urban space type. Clear differences in building density and arrangement of the buildings are visible. All three urban spaces consist of 100 % MFHs (Ebert 2018, p. 16 f.).

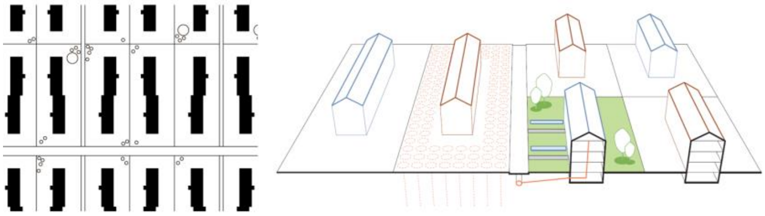

Figure 2: **Row house development**, characterized as EST 3 in UrbanReNet (Hegger et al. 2012, pp. 460–462). The structure corresponds to **ST 4** in Roth (1980).

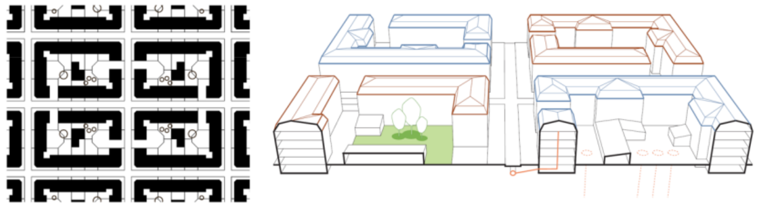

Figure 3: **Perimeter block development**, characterized as EST 5 in UrbanReNet (Hegger et al. 2012, pp. 472–474). The structure corresponds to **ST 6** in Roth (1980).

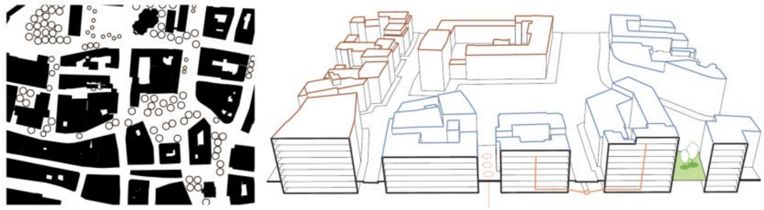

Figure 4: **City development**, characterized as EST 8 in UrbanReNet (Hegger et al. 2012, pp. 490–492). The structure corresponds to **ST 7** in Roth (1980).

The open space area A_{open} on a property with the overall plot area A_{tot} can be calculated for all three STs based on the known building footprint area A_{build} of the reference building and the site occupancy index GRZ given in Table 2 as follows:

$$A_{open} = A_{tot} - A_{build} = \frac{A_{build}}{GRZ} - A_{build} = A_{build}\left(\frac{1}{GRZ} - 1\right) \quad (1)$$

For the base area of 232 m² and the range of values for GRZ in Table 2 the following minimum and maximum available open space areas around the reference building result:

Table 3: Estimated property plot-sizes and open space areas of the reference building placed in ST 4, 6 und 7

	Unit	ST 4		ST 6		ST 7	
		min.	max.	min.	max.	min.	max.
Plot size	m²	1160	1545	580	775	330	465
Open space	m²	930	1315	350	540	100	230

3. System Simulation Results

For the reference building in its different refurbishment states, the space heating demands were determined in TRNSYS and exported as a demand time series. The simulations were done for a constant indoor air temperature of 20 °C (DIN V 18599-12:2017-04) with a typical meteorological year (TMY) file of Potsdam, which represents average German climate conditions. The domestic hot water demand profile of the occupants was modelled in the software SynPro (Fischer et al. 2016), showing a DHW energy demand of 510 kWh per person and year. Table 4 gives the simulation results for heating and DHW demand.

Table 4: Simulation results for the reference building in Potsdam, Germany

	Unit	No refurbishment **State 0**	Conventional refurbishment **State 1**	Ambitious refurbishment **State 2**
Specific heating demand	kWh/(m²*a)	169	63	48
Heating demand	MWh/a	100	35	26
DHW demand	MWh/a	7	7	7
Mean DHW power demand (incl. all losses)	kW	3	3	3
Standard heating load at -14 °C	kW	51	23	16

The final energy demands (electrical energy or natural gas) of the considered heating system variants were determined for states 0 to 2 in Python with a simplified dynamic calculation approach in a calculation time step of 5 min. Heat output and coefficient of performance (COP) of the HPs are represented mathematically as characteristic performance curves[3] depending on the source and sink temperatures[4]. Thus, the COP should be seen as an upper benchmark, neglecting dynamic effects. For reference conditions of source temperature 0 °C (brine) and 2 °C (air) combined with 35 °C sink temperature, the COP of the used air-water HP is 3.4 and the COP of the brine-water HP is 4.6. The thermal storages for DHW and heating are simulated in 10 layers within Dymola Modelica, using a Functional Mock-up Interface (FMI) for coupling with Python. For the brine temperature, an outdoor temperature-dependent annual cycle was used. Further information on the simulations is given in (Wapler et al. 2018).

Table 5 to Table 7 show the simulated variants with their most characteristic design parameters and simulation results. The determined HP cover shares relate to the overall demand (space heating plus DHW). They decrease from state 0 to 2 because the share of DHW (higher temperature level) increases. The SPH highly depends on the space heating flow and return flow temperatures.

---

[3] The performance curves of the differently sized brine-water heat pumps and the ambient air-water heat pumps are based on manufacturer data sheets (Dimplex 2012, Stiebel-Eltron 2019).

[4] Source side: inlet temperature; sink side: mean temperature between inlet and outlet

Table 5: Ground source and air source HP system simulation parameters and results
for **state 0,** the **unrefurbished reference building.**

		Unit	**Air**		**Ground probes**	
System / refurbishment code			**A-5_0**	**A+2_0**	**E-5_0**	**E+2_0**
Bivalence design temperature		°C	- 5	+ 2	- 5	+ 2
HP type (nominal heating power)	A/W-HP	kW	51	28	-	-
	B/W-HP	kW	-	-	37	24
Backup (nominal heating power)	Gas boiler	kW	22	36	18	31
Demand share covered by HP		%	96.3	86.3	96.4	88.8
Seasonal performance factor (SPF)		-	2.5	2.6	3.5	3.6

Table 6: Ground source and air source HP system simulation parameters and results
for **state 1,** the building **refurbished conventionally according to EnEV 2014/2016.**

		Unit	**Air**		**Ground probes**	
System / refurbishment code			**A-5_1**	**A+2_1**	**E-5_1**	**E+2_1**
Bivalence design temperature		°C	- 5	+ 2	- 5	+ 2
HP type (nominal heating power)	A/W-HP	kW	23	12	-	-
	B/W-HP	kW	-	-	16	10
Backup (nominal heating power)	Gas boiler	kW	12	19	9	15
Demand share covered by HP		%	91.7	83.2	91.9	86.3
Seasonal performance factor (SPF)		-	3.2	3.3	4.3	4.4

Table 7: Ground source and air source HP system simulation parameters and results
for **state 2,** the building **with ambitious refurbishment**.

		Unit	**Air**		**Ground probes**	
System / refurbishment code			**A-5_2**	**A+2_2**	**E-5_2**	**E+2_2**
Bivalence design temperature		°C	- 5	+ 2	- 5	+ 2
HP type (nominal heating power)	A/W-HP	kW	17	9	-	-
	B/W-HP	kW	-	-	12	8
Backup (nominal heating power)	Gas boiler	kW	9	13	6	11
Demand share covered by HP		%	89.5	80.1	89.6	82.8
Seasonal performance factor (SPF)		-	3.1	3.2	4.2	4.3

Based on the parameters given above and using the monthly heat extracted from the ground probes, the sufficient availability of ambient heat sources air and ground is assessed for the reference building using the determined open space areas within the selected three urban space types. For this, the necessary heat extraction power for ground probe and ground collectors were assumed to be identical.

4. Heat Source Availability

An estimation of representative min. and max. plot-sizes around the MFHs in the different urban spaces is shown in Table 3 above. Using additionally plot shapes from real urban contexts, for the reference building the available area for drilling bore holes or burying ground collectors as well as distances to neighboring houses, which are relevant for noise protection of air source heat pumps, can be determined.

4.1 Heat Source Ambient Air

With a share of more than 70 % of newly installed HP systems, ambient air is currently the dominant source for HPs in Germany (BWP 2019). This is mainly due to the low investment costs and easy accessibility of the source. The main disadvantage of outdoor air HPs is, in addition to their lower SPF than ground source HPs (cp. Table 5 to Table 7), the problem of noise. In Germany it is necessary to comply with the limits of the TA Lärm for the perceived sound pressure level L_{Aeq}, which is 35 dB (A) for purely residential areas between 22:00 and 06:00 (Bundesministerium der Justiz und für Verbraucherschutz 1974). Decisive are the distance r between sound receiver and the source, the place of installation (directivity factor Q for sound propagation) as well as the sound power level L_{WAeq} emitted by the HP. The directivity factor Q can have the numerical value of two for a free placement on the property (radiation into the half space), the value of four when installed on a wall (radiation into the quarter space) or the value eight when set up in a corner (radiation into the eighth-room).

The perceived sound pressure L_{Aeq} can be calculated using the following formula:

$$L_{Aeq} = L_{WAeg} + 10 * \log\left(\frac{Q}{4 * \pi * r^2}\right) \qquad (2)$$

As indicated by above equation, the sound propagation is simplified to a hemispherical form. In reality, however, the propagation is more cuboid-shaped, because the suction- and outlet sides of the air unit have higher emission levels than its sides. This should be taken into account when placing the unit (Dimplex 2018). The experienced noise exposure in the heated building itself is less relevant for self-used property, but certainly to be considered for a property rented out. In these cases, the air unit should be placed in the minimum distance r to the own wall, as it is calculated for directivity factor Q = 2. To allow for this factor to be used, the distance to the next wall must be at least 3 m (Dimplex 2018). In addition, a distance of the heat pump to the boundary of the neighbouring property of another 3 m must be maintained (Berlinghoff et al. 2017).

Figure 5 shows typical plots sizes in ST 4, 6 and 7 taken from real building development plans. While the basic structure of the urban space types is clearly recognizable, the individual characteristics of each building are also visible. Highest uniformity is found for ST 4 row development. In contrast, ST 6 and 7 have often grown historically and therefore their property geometry and available open space show higher variations (cp. Table 3). Thus, the uncertainties of the HP source availability assessment are higher for these two urban space types.

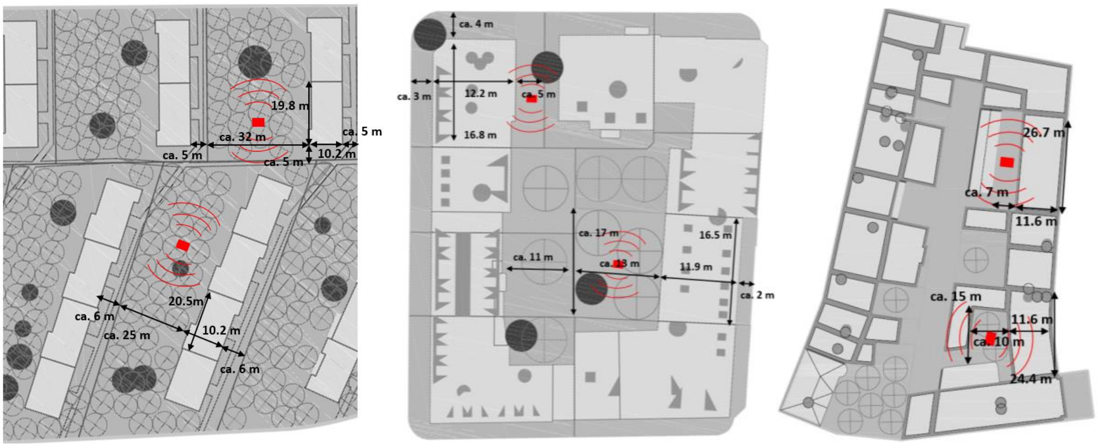

Figure 5: Typical plot sizes of ST 4 (Frankfurt am Main), ST 6 (Frankfurt am Main) and ST 7 (city center Essen) with potential ground probes (grey crossed circles) and trees (black circles) from Hegger et al. (2012, p. 425, 431, 434). Additionally, for the current study the property- and building dimensions as well as potential HP air units (red) are indicated.

The average estimated width of an open space in ST 4 is about 28 - 42 m for the reference building length of 23.2 m. For ST 6 and the same building length the open space width is 12 - 20 m, for ST 7 approx. 4 - 10 m (cp. Figure 5). Table 8 indicates the distance r determined for the directivity factor Q = 2 as a function of the sound power level of the HP. The assumed limit is a sound pressure of 35 dB (A). It can be concluded that for refurbished MFHs in ST 4 and 6, it will usually be possible to fulfil the noise protection requirements for air heat pumps. In contrast, in ST 7 this will in most cases not be possible without additional measures as e.g. acoustic enclosures or sound protection walls.

Table 8: Required distance of the heat pump air unit to building walls for half-space sound propagation (Q = 2) and max. sound pressure of 35 dB (A). Results are given for air HPs dimensioned according to the bivalence points -5 °C and +2 °C for the refurbishment states 1 and 2. Sufficient distance (i.e. feasibility) indicated by Yes [✓] and No [✕].

System code		**A-5_1**		**A+2_1**		**A-5_2**		**A+2_2**	
HP sound power level L_{WAeq} [dB(A)]		61		54		58		54	
Min. distance r [m]		8.0		3.6		5.7		3.6	
Distance to neighbouring buildings		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Urban space type (ST)	4	✓	✓	✓	✓	✓	✓	✓	✓
	6	✕	✓	✓	✓	✓	✓	✓	✓
	7	✕	✕	✕	✓	✕	✕	✕	✓

4.2 Heat Source Ground Probe

Three methods for the dimensioning of geothermal probes are used and compared in this work. These are the current German VDI-standard (VDI 4640 Blatt 2), the method GeoHand of Prof. Koenigsdorff (2011) and the Swiss standard (SIA 384/6). For the dimensioning of a ground heat source for a HP the characteristics of the ground itself are important, i.e. soil temperature, thermal conductivity and heat capacity. But also the maximum heat extraction rate, the number of full load hours and the arrangement of the probes are decisive factors.

Sizing according to VDI 4640

The VDI 4640 addresses the source dimensioning for small heat pump systems. For a valid probe design, the following constraints must be considered: The heating capacity of the HP must be below max. 30 kW. Max. 5 ground probes of between 50 m and 200 m depth with a distance of at least 6 m from each other can be installed in one system. Additionally, the annual full load hours must be within 1200 – 2400 h (VDI 4640 Blatt 2, p. 34). The calculation according to VDI 4640 is based on tabulated values. For this purpose, information on the geothermal conductivity, the full-load hours and the heat extraction rate of the HP are required. The extraction rate $\dot{Q}_Q$ can be calculated from heating capacity ($\dot{Q}_{WP}$) and coefficient of performance (COP):

$$\dot{Q}_Q = \dot{Q}_{WP} - P_{el} = \dot{Q}_{WP} * \left(1 - \frac{1}{COP}\right) \tag{3}$$

In practice, three different ranges of probe length exist in Germany, namely up to 100 m, between 100 m and 160 m and deeper than 160 m. Table 9 shows the results of the feasibility evaluation for the ground probe HP systems. Necessary number and lengths of the probes are calculated based on (VDI 4640 Blatt 2, p. 13, 34) and (Koenigsdorff 2011, p. 102).

Table 9: Evaluation of **open space sufficiency** for **ground probe** HP systems in ST 4, 6 and 7 for the two dimensioning bivalence points -5 °C and +2 °C and the refurbishment states 1 and 2. Sizing was done according to VDI 4640 Blatt 2, p. 113, Table B6. In the cases marked *, six probes would be necessary and sufficient space for them would be available, but the application range of **VDI 4640** allows a maximum of 5 probes only.

System code			**E-5_1**			**E+2_1**			**E-5_2**			**E+2_2**		
$\dot{Q}_{HP,extract}$ $[kW]$			12.3			7.7			9.1			6.1		
Ground thermal conductivity	Max. probe length [m]	ST	No. of probes length each (m)	Area		No. of probes length each (m)	Area		No. of probes length each (m)	Area		No. of probes length each (m)	Area	
				Min.	Max.		Min.	Max.		Min.	Max.		Min.	Max.
λ = 1.5 W/(mK)	≤ 100	4	-	*	*	4 (93)	✓	✓	5 (92)	✓	✓	3 (92)	✓	✓
		6		✗	*		✗	✓		✗	✓		✗	✓
		7		✗	✗		✗	✗		✗	✗		✗	✓
	≤ 160	4	4 (148)	✓	✓	2 (160)	✓	✓	3 (137)	✓	✓	2 (127)	✓	✓
		6		✗	✓		✓	✓		✗	✓		✓	✓
		7		✗	✗		✗	✓		✗	✓		✗	✓
λ = 2.5 W/(mK)	≤ 100	4	5 (87)	✓	✓	3 (82)	✓	✓	3 (97)	✓	✓	2 (91)	✓	✓
		6		✗	✓		✗	✓		✗	✓		✓	✓
		7		✗	✗		✗	✓		✗	✓		✗	✓
	≤ 160	4	3 (130)	✓	✓	2 (132)	✓	✓	2 (135)	✓	✓	2 (91)	✓	✓
		6		✗	✓		✓	✓		✓	✓		✓	✓
		7		✗	✓		✗	✓		✗	✓		✗	✓
λ = 3.5 W/(mK)	≤ 100	4	4 (84)	✓	✓	2 (94)	✓	✓	3 (79)	✓	✓	2 (74)	✓	✓
		6		✗	✓		✓	✓		✗	✓		✓	✓
		7		✗	✗		✗	✓		✗	✓		✗	✓
	≤ 160	4	2 (150)	✓	✓	2 (94)	✓	✓	2 (111)	✓	✓	1 (136)	✓	✓
		6		✓	✓		✓	✓		✓	✓		✓	✓
		7		✗	✓		✗	✓		✗	✓		✗	✓

In Germany, there is an obligation to notify authorities about bore holes deeper than 100 m (cp. Bundesberggesetz BBergG §127, Bundesministerium der Justiz und für Verbraucherschutz, 1980). This can prevent the installation of probes exceeding this length. The next depth limit is about 160 m, since this is the limit for the usually used standardized polyethylene probes with a nominal pressure of 16 bar (Stober and Bucher 2012, p. 68). With additional measures (material, drilling method, etc.), also probes deeper than160 m are possible.

For the resulting open space requirements, probe distances of 6 m to each other, of 5 m to the property boundary and 2 m to the heated building were taken into account. The results show that in ST 4 (row house development) there is both for the statistical minimum and maximum open space always enough area for installation of ground probes. In ST 6 (perimeter block development), the feasibility depends on the soil type, the design bivalence point of the system and on the considered drilling depth. In ST 7 (city development), probe drilling is not possible on small plot sizes because here the distance regulations cannot be fulfilled.

Dimensioning according to GeoHand

The simplified ground probe design method GeoHand^{light} is based on the models of Eskilson (1987) and was developed at the University Biberach (Koenigsdorff 2011, p. 209). The results are shown in Table 10.

Table 10: Evaluation of **open space sufficiency** for **ground probe** HP systems in ST 4, 6 and 7 for the two dimensioning bivalence points -5 °C and +2 °C and the refurbishment states 1 and 2 according to **GeoHand^{light}**

System code			**E-5_1**			**E+2_1**			**E-5_2**			**E+2_2**		
$\dot{Q}_{HP,extract}\ [kW]$			12.3			7.7			9.1			6.1		
$Q_{month,max}\ [kWh]$			6043			5600.2			4625.3			4245.0		
$Q_{year,tot}\ [kWh]$			33358.7			31560.9			25951.3			24209.0		
Ground thermal conductivity	Max. probe length [m]	ST	No. of probes length each (m)	Area		No. of probes length each (m)	Area		No. of probes length each (m)	Area		No. of probes length each (m)	Area	
				Min.	Max.		Min.	Max.		Min.	Max.		Min.	Max.
λ = 1.5 W/(mK)	≤ 100	4	7 (94)	✓	✓	6 (90)	✓	✓	5 (93)	✓	✓	4 (98)	✓	✓
		6		×	×		✓	✓		✓	✓		✓	✓
		7		×	×		×	×		×	×		×	✓
	≤ 160	4	4 (145)	✓	✓	3 (141)	✓	✓	3 (131)	✓	✓	3 (116)	✓	✓
		6		×	✓		×	✓		✓	✓		✓	✓
		7		×	×		×	×		×	✓		×	✓
λ = 2.5 W/(mK)	≤ 100	4	4 (98)	✓	✓	3 (92)	✓	✓	3 (89)	✓	✓	3 (79)	✓	✓
		6		✓	✓		✓	✓		✓	✓		✓	✓
		7		×	×		×	✓		×	✓		×	✓
	≤ 160	4	3 (123)	✓	✓	2 (128)	✓	✓	2 (125)	✓	✓	2 (110)	✓	✓
		6		✓	✓		✓	✓		✓	✓		✓	✓
		7		×	×		×	✓		×	✓		×	✓
λ = 3.5 W/(mK)	≤ 100	4	3 (98)	✓	✓	2 (100)	✓	✓	3 (71)	✓	✓	2 (88)	✓	✓
		6		✓	✓		✓	✓		✓	✓		✓	✓
		7		×	×		×	✓		×	✓		×	✓
	≤ 160	4	2 (135)	✓	✓	2 (100)	✓	✓	2 (100)	✓	✓	2 (88)	✓	✓
		6		✓	✓		✓	✓		✓	✓		✓	✓
		7		×	✓		×	✓		×	✓		×	✓

In GeoHand^{light}, the load profile of a probe is calculated by superposition of three components: annual base load $\dot{q}_{Q,year}$, amplitude of the periodic annual variation $\dot{q}_{Q,month}$ and the resulting peak load $\dot{q}_{Q,load}$. These load components are linked via the thermal resistances R_{year} (long-term stationary behavior), R_{month} (periodic annual variation), R_{load} (applied load) and R_b (borehole resistance) to the resulting thermal reactions of the ground (Koenigsdorff 2011, p. 212). The successive steps for calculating the geothermal load profile and the thermal resistances are described in detail in Koenigsdorff (2011). The probe distance is, in contrast to the VDI 4640, not a fixed parameter, but depends on the probe length. For the dimensioning, the smallest permitted distance was assumed, which is 5 % of the probe length. The length of the probes L_{EWS} can be calculated using the mean fluid temperature decrease ΔT_F^{min}[5]:

$$L_{EWS} = \frac{\dot{Q}_{year} * R_{year} + \dot{Q}_{month} * R_{month} + \dot{Q}_{load} * R_{load} + \dot{Q}_Q * R_b}{\Delta T_F^{min}} \tag{4}$$

Dimensioning according to SIA

SIA 384/6 is the Swiss pendant to the German VDI 4640. SIA in contrast to VDI only considers ground probes and no other forms like ground collectors, geothermal baskets, etc. The design methods are similar, but in SIA diagrams are used instead of tables like in VDI. The biggest difference is that SIA additionally takes the altitude with its associated soil temperature into account, which can be attributed to the Swiss geography. However, for the location Potsdam/Germany and the system cases given above, the results of SIA and VDI differ only marginally. They are therefore not shown here.

4.3 Heat Source Ground Collector

As for the design of ground probes, also the dimensioning of ground collectors in VDI 4640 is based on tabulated values. Since ground collectors are located closely beneath to the soil surface, their heat extraction rate is not only influenced by the soil type, but also by the the local climate. Accordingly, the soil characteristics[6] and the climatic zones[7] as subdivided according to DIN 4710 are taken into account, cp. Table A2 in (VDI 4640 Blatt 2, p. 91f). For geothermal collectors, the distance must be 1 m to buildings and property boarders, which reduces the usable open space, cp. (VDI 4640 Blatt 2, p. 22) and (VDI 4640 Blatt 1, p. 21). Roughly calculated, this results in an open space availability of between 785 - 1150 m² for the examples of ST 4, 230 – 400 m² for ST 6 and 40 – 170 m² for ST 7. From this, the feasibility of geothermal collectors was estimated. Table 11 shows that only ST 4 offers enough free ground space for ground collectors.

Table 11: Evaluation of **open space sufficiency** for **ground collector** HP systems in ST 4, 6 and 7 for the two dimensioning bivalence points -5 °C and +2 °C and the refurbishment states 1 and 2 according to **VDI 4640**

System code			**E-5_1**			**E+2_1**			**E-5_2**			**E+2_2**		
$Q_{year,tot}$ $[kWh]$			33358.7			31560.9			25951.3			24209.0		
Soil type	Extraction energy [kWh/(m²a)]	ST	Coll. Area [m²]	Area		Coll. Area [m²]	Area		Coll. Area [m²]	Area		Coll. Area [m²]	Area	
				Min.	Max.		Min.	Max.		Min.	Max.		Min.	Max.
Sand	34	4	982	×	×	929	×	×	764	×	✓	713	×	✓
		6		×	×		×	×		×	×		×	×
		7		×	×		×	×		×	×		×	×
Clay	45	4	742	✓	✓	702	✓	✓	577	✓	✓	538	✓	✓
		6		×	×		×	×		×	×		×	×
		7		×	×		×	×		×	×		×	×
Slit	49	4	681	✓	✓	645	✓	✓	530	✓	✓	495	✓	✓
		6		×	×		×	×		×	×		×	×
		7		×	×		×	×		×	×		×	×
Sandy clay	54	4	618	✓	✓	585	✓	✓	481	✓	✓	449	✓	✓
		6		×	×		×	×		×	×		×	×
		7		×	×		×	×		×	×		×	×

---

[5] Max. permitted temperature difference between probe fluid and undisturbed ground. GeoHand builds upon the VDI 4640 in its 2001 version, which states that -17 K minus the half temperature spread of the HP should not be exceeded. With 4 K spread, a ΔT_F^{min} of 15 K results (Koenigsdorff 2011, p. 222).

[6] Water content and heat conductivity of the soil types sand, clay, slit and sandy clay

[7] In total 15 climatic zones are defined for Germany; Potsdam is located in zone 4

5. Summary and Conclusion

Table 12 gives a rough, qualitative summary of the results. Typical row house developments have sufficient space to install bivalent air-source and ground probe HP systems. Only there also ground collectors are possible. In perimeter blocks, air-source HPs are usually possible; ground probes often but highly depending on property dimensions, bivalence design point and soil type. The plots in city developments are usually too small for bivalent HP systems without additional measures, e.g. acoustic enclosures of air-source HPs.

Table 12: Heat source assessment for the three urban space structures and min. and max. free open spaces

Heat source		**Ambient air**	**Ground probes**		**Ground collector**
Method		TA-Lärm	VDI 4640 / SIA	GEO-Hand	VDI 4640
	Area	**ST 4 - Row house development**			
Heat source sufficient?	Min.	✓	✓	✓	×/✓
	Max.	✓	✓	✓	✓
		ST 6 - Perimeter block development			
	Min.	×/✓	×/✓	×/✓	×
	Max.	✓	✓	✓	×
		St 7 - City development			
	Min.	×	×	×	×
	Max.	×/✓	×/✓	×/✓	×

This study reveals that for row house developments, the system design bivalence points (-5 °C and +2 °C), i.e. the share of the overall demand covered by the HP, and also the refurbishment standard (EnEV 2014/2016 or more ambitious refurbishment) are to a large extent irrelevant for assessing the sufficiency of the open space to install a HP. These factors are only decisive for borderline cases, i.e. small area availability in perimeter blocks and for large plot sizes in city developments.

Acknowledgments

The authors thank Benjamin Köhler of Fraunhofer ISE and Bernd Ebert and Fritz Braeuer of KIT for development of the generic multi-family building. Felix Ohr of Fraunhofer ISE helped to setup of the system simulation model. This study is part of the research project network »LowEx-Bestand«, which analyses, develops and demonstrates solutions for the application of heat pumps in renovated MFHs in Germany (www.lowex-bestand.de). It was supported from the project »Smartes Quartier Karlsruhe Durlach«. Both projects are funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) according to a decision of the German Federal Parliament (grant agreements 03SBE0001A-C, 03ET1590C).

References

Berlinghoff, Ulf; Schnitzmeier, Dietmar; Löbrich, Sylivia (2017): Luftwärmepumpe muss Abstandsfläche von drei Metern zum Nachbargrundstück einhalten, updated on 3/4/2017, checked on 7/30/2019.

Bundesministerium der Justiz und für Verbraucherschutz (1974): Gesetz zum Schutz vor schädlichen Umwelteinwirkungen durch Luftverunreinigungen, Geräusche, Erschütterungen und ähnliche Vorgänge. TA Lärm. Available online at https://www.gesetze-im-internet.de/bimschg/BImSchG.pdf, checked on 5/17/2018.

Bundesministerium der Justiz und für Verbraucherschutz (1980): Bundesberggesetz. BBergG. Available online at http://www.gesetze-im-internet.de/bbergg/index.html#BJNR013100980BJNE012000315, checked on 8/1/2019.

Bundesverband Wärmepumpe (BWP) e.V. (Ed.) (2018): Branchenstudie 2018: Marktanalyse – Szenarien – Handlungsempfehlungen. Daten zum Wärmepumpenmarkt bis 2018 und Prognosen bis 2050. Available online at https://www.waermepumpe.de/verband/, checked on 7/30/2019.

Bürger, V.; Hesse, T.; Quack, D.; Palzer, A.; Köhler, B.; Herkel, S.; Engelmann, P. (2016): Klimaneutraler Gebäudebestand 2050. CLIMATE CHANGE 06/2016. Edited by Umweltbundesamt. Dessau-Roßlau (ISSN: 1862-4359). Available online at https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/climate_change_06_2016_klimaneutraler_gebaeudebestand_2050.pdf, checked on 7/30/2019.

BWP (2019): BWP Marktzahlen 2018. Nachhaltiges Wachstum mit Luft nach oben, deutliches Signal für die Politik. Available online at https://www.waermepumpe.de/presse/pressemitteilungen/details/bwp-marktzahlen-

2018-nachhaltiges-wachstum-mit-luft-nach-oben-deutliches-signal-fuer-die-politik/#content, updated on 1/25/2019, checked on 7/30/2019.

Cischinsky, H.; Diefenbach, N. (2018): Datenerhebung Wohngebäudebestand 2016 - Datenerhebung zu den energetischen Merkmalen und Modernisierungsraten im deutschen und hessischen Wohngebäudebestand. 1st ed. Edited by Institut Wohnen und Umwelt IWU. Darmstadt (ISBN: 978-3-941140-71-4). Available online at https://www.iwu.de/fileadmin/user_upload/dateien/energie/Endbericht_Datenerhebung_Wohngeb%C3%A4udebestand_2016.pdf, checked on 7/30/2019.

Destatis (2018): German Federal Statistical Office. Statistics for building Completion – New Buildings: Germany, years, building type, energy use, energy type. Table code 31121-0004. Sums for geothermal and ambient air heat pumps. Available online at https://www-genesis.destatis.de/genesis/online, updated on 7/30/2019.

Dimplex (2012): Projektierungshandbücher. Geräteinformationen. Available online at http://www.dimplex.de/fileadmin/dimplex/downloads/projektierungshandbuecher/de/496-geraeteinformationen-wp-08-2012.pdf, checked on 7/29/2019.

Dimplex (2018): Schallberechnung. Available online at http://www.dimplex.de/professional/online-planer/schallberechnung.html, checked on 7/30/2019.

DIN V 18599-12:2017-04: Energetische Bewertung von Gebäuden_- Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung_- Teil_12: Tabellenverfahren für Wohngebäude. DIN V 18599. Berlin.

Ebert, B. (2018): Systematische Analyse von Mehrfamilien-Bestandsgebäuden. Report on AP 1.1 of project LowEx-Bestand Analyse. Fachgebiet Bauphysik & Technischer Ausbau. Karlsruhe. Available online at https://www.lowex-bestand.de/wp-content/uploads/2018/08/Abschlussbericht-zu-AP-1.1-Systematische-Analyse-von-Mehrfamilien-Bestandsgeb%C3%A4uden.pdf.

EnEV 2014/2016: Zweite Verordnung zur Änderung der Enerieeinsparverordnung, revised 11/18/2013. In *Bundesgesetzblatt* (Teil I Nr. 67), pp. 3951–3990. Available online at https://enev-online.com/enev_2014_volltext/enev_2014_verkuendung_bundesgesetzblatt_21.11.2013_leseversion.pdf.

SIA 384/6, 2010: Erdwärmesonden. Schweizer Norm.

Eskilson, P. (1987): Thermal analysis of heat extraction boreholes. PhD Thesis. Lund. Available online at https://www.buildingphysics.com/download/Eskilson1987.pdf.

Fischer, David; Wolf, Tobias; Scherer, Johannes; Wille-Haussmann, Bernhard (2016): A stochastic bottom-up model for space heating and domestic hot water load profiles for German households. In *Energy and Buildings* 124, pp. 120–128. DOI: 10.1016/j.enbuild.2016.04.069.

Forthuber, S.; Hartner, M. (2017): Disaggregated heating system data for the building stock of Germany. Model-based forward projection of heating system data from 2008 using Invert/EE-Lab for year 2016. TU Vienna, Energy Economics Group (Unpublished data set).

Hegger, M.; Dettmar, J.; Martin, A. (2012): UrbanReNet. Schlußbericht. Edited by Technische Universität Darmstadt. Darmstadt.

IWU (2012): TABULA WebTool. Edited by Institut Wohnen und Umwelt. Available online at http://webtool.building-typology.eu/#bm, checked on 7/19/2019.

Koenigsdorff, R. (2011): Oberflächennahe Geothermie für Gebäude. Grundlagen und Anwendungen einer zukunftsfähigen Heizung und Kühlung. Stuttgart: Fraunhofer IRB Verlag.

Loga, T.; Stein, B.; Diefenbach, N.; Born, R. (2015): Deutsche Wohngebäudetypologie. Beispielhafte Maßnahmen zur Verbesserung der Energieeffizienz von typischen Wohngebäuden. Projekte Tabula & Episcope. zweite erweiterte Auflage. Edited by Institut für Wohnen und Umwelt. Darmstadt. Available online at http://www.building-typology.eu/downloads/public/docs/brochure/DE_TABULA_TypologyBrochure_IWU.pdf, checked on 7/30/2019.

Roth, Ueli (1980): Wechselwirkungen zwischen der Siedlungsstruktur und Wärmeversorgungssystemen. Forschungsprojekt BMBau RS II 4 - 70 41 02 - 77.10. With assistance of Fritz Häubi, Joachim Albrecht, Mathias Bischoff, Annemarie Deucher, Lucius Harder, Beatrice Langraf, Pape Giesela. Edited by Bundesminister für Raumordnung, Bauwesen und Städtebau. Bonn (Raumordnung, 06.044).

Stiebel-Eltron (2019): Planung und Installation. Wärmepumpen. Available online at https://www.stiebel-eltron.de/content/dam/ste/de/de/products/downloads/Planungsunterlagen/Planungshandbuch/Planungshandbuch_EE_Waermepumpen.pdf, checked on 7/29/2019.

Stober, Ingrid; Bucher, Kurt (2012): Geothermie. Heidelberg: Springer (Springer Geology). Available online at http://dx.doi.org/10.1007/978-3-642-24331-8.

VDI 4640 Blatt 2, 2019: Thermische Nutzung des Untergrunds.

VDI 4640 Blatt 1, 2010: Thermische Nutzung des Untergrunds.

Vollmer, R.; Hess, S.; Henning, H.-M. (2018): Quellen-Verfügbarkeit für Wärmepumpen-Systeme im deutschen Mehrfamilienhaus-Bestand. In *Tagungsband Solarthermie-Symposium, Kloster Banz, Bad Staffelstein*, pp. 622–638.

Wapler, J.; Hess, S.; Kleinstück, M.; Ohr, F.; Bongs, C. (2018): Wärmepumpen-Systeme im Mehrfamilienhaus-Bestand. In *44. DKV-Tagungsbericht, Deutschen Kälte- und Klimatagung 2018, Aachen.* (Band IV).