

Supplement A Building Retrofit Model

The building retrofit model consists of the following model components, described in section A1-A5:

- Thermal building model – calculation of the building heat load (A1)
- Thermal building model – domestic hot water generation and additional heat losses and wins (A2)
- Solar thermal model (A3)
- Building surface model – calculation of specific building surface investment expenditures and heat transmission coefficients (A4)
- Preprocessing procedure for the calculation of the building individual investment expenditures for the heating system (A5)

Supplement A.1 Thermal Building Model - Calculation of the Building Heat Load

We base our calculation on DIN EN 12831 [73] and model the whole building in a single-zone: The design relevant load for the heating systems S_j^{BE} has to consider transmission and ventilation losses. Radiation losses and wins, internal wins, wins and losses of the hot water distribution system S_j^S and the generation of domestic hot water S_j^{DHW} are neglected. As a result S_j^{BE} is dependent on the transmission heat loss H_j as well as the outdoor ϑ^{out} and indoor ϑ^{in} temperature, which are set in design case ΔT^{nom} to -12°C for the outdoor, respectively 20°C for the indoor temperature.

$$S_j^{BE} = H_j \cdot (\vartheta^{out} - \vartheta^{in}) = H_j \cdot \Delta T^{nom} \quad (S1)$$

Whereas H_j itself is a function of the transmission H_j^T and the ventilation heat losses H_j^V . In our model a building surface renovation measure influences the heat transmission coefficient U_j^T . Ventilation heat losses which are function of infiltration and window ventilation losses and heat transmission losses from thermal bridges ΔU_j^{TB} remaining at a stable level.

$$H_j = H_j^T + H_j^V = (U_j^T + \Delta U_j^{TB}) \cdot A_j^E + H_j^V \quad (S2)$$

The heat transmission coefficient is represented by an area weighted average value U_j^T (for the whole surface area, see Supplement A.4) which can be influenced by adding an additional insulation on the building surface represented by the equivalent insulation thickness d^D based on [74].

$$U_j^T(d^D) = \frac{1}{\frac{1}{U_j^0} + \frac{D^D[m]}{0,04}} \quad (S3)$$

As a result, the heat load for the design of the heating system is formulated to:

$$S_j^{BE} = \left(\left(\frac{1}{\frac{1}{U_j^0} + \frac{D^D[m]}{0,04}} + \Delta U_j^{TB} \right) \cdot A_j^E + H_j^V \right) \cdot \Delta T^{nom} \quad (S4)$$

Supplement A.2 Thermal Building Model - Domestic Hot Water Generation and Additional Heat Losses and Wins

The building specific equivalent heat load for the domestic hot water generation S_j^{DHW} is based on specific values according to [62]: $20 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ for SFH and TH; $22.4 \text{ kWh}/(\text{m}^2 \cdot \text{a})$ for MFH.

The additional heat wins and losses of a building are summed up in the equivalent heat load S_j^S , which is a building individual parameter, independent from renovation measures, and includes following components:

- Wins through the solar heat load and the internal heat sources, modelled according to [62].
- Wins and losses through the hot water distribution pipes interpolated, according to [95] for a DHW distribution within the thermal envelope with circulation, dependent on the reference floor area of the building.

We calculate the heat loads S_j^S and S_j^{DHW} via a multiplication of the specific yearly energy consumptions with the reference floor area of the building and a division with the yearly usage hours T_j^N .

Supplement A.3 Solar Thermal Model

The solar thermal plant is able to cover a certain share of the yearly energy demand of the domestic hot water generation, see Table S1. We model it according to [62, 76].

Table S1. Parameters of the available solar thermal plants.

#	Share in hot water generation	F_s^{STERed} [-]	$C_s^{STEvvar}$ [$\frac{\text{€}}{\text{m}^2}$]	C_s^{STEFix} [€]	M_s^{STE} [-]
0	20%	0.8	366.59	3094	0.015
1	40%	0.6			
2	60%	0.4			
3	80%	0.2			
4	Full	0			
Sources		[62]	[76]	[76]	[76]

In the paper we describe the size of the solar thermal system with $S_{s,j}^{STE}$, which is a function of the of the DHW reduction factor F_s^{STERed} (Describes the share of the reduction of the annual hot water energy demand to be generated.). The plant size is determined by the binary decision variable $b_{s,j}^{STE}$:

$$S_{s,j}^{STE} = S_j^{DHW} \cdot F_s^{STERed} \cdot b_{s,j}^{STE} \quad (S5)$$

The investment expenditures depend on the installed collector surface area A^{STE} and divided into fix C_s^{STEFix} and variable $C_s^{STEvvar}$ expenditures. The individual collector surface area is determined by the reduction variable F_s^{STERed} and the annual average solar yield of the collector STE^{yield} in kWh/(m²·a) and the yearly usage hours T_j^N in h/a as follows:

$$\forall j \in J, s: A^{STE} = F_s^{STERed} \cdot \left(\frac{S_j^{DHW} \cdot T_j^N}{STE^{yield}} \right) \cdot b_{s,j}^{STE} \quad (S6)$$

The annual average solar yield is a function of the annual total global radiation, which depicts 1191 kWh/(m²·a) for Bamberg in 2019 [82] and the average efficiency of an entire solar thermal energy plant, which is assumed to be 50% [83]. This results in a value of 595.25 kWh/(m²·a) for STE^{yield} .

Supplement A.4 Building Surface Model – Calculation of Specific Building Surface Investment Expenditures and Heat Transmission Coefficients

Within the optimization we model the investment expenditure for the whole building surface based on a fixed C_j^{BEfix} and the variable C_j^{BEvar} component. In a preprocessing procedure these values are calculated building individually based on the areas of the surface parts p , see Table S2.

Table S2. Specific investment expenditures per building part based on [75].

Parameter	Unit	Roof	Facade	Floor	Window	Door
$C_{j,p}^{\text{BEfix}}$	$\left[\frac{\text{€}}{\text{m}^2} \right]$	151.01	96.882	54.25	476.84	1433
$C_{j,p}^{\text{BEvar}}$	$\left[\frac{\text{€}}{\text{m}^2 \cdot \text{cm}} \right]$	2.7738	2.8102	1.547	0	0

Each building consists of five different parts (roof, facade, floor, window and door), whereby each part have several sub-parts, which results in a total of \mathcal{P} different parts, with Q^p different sub-parts (roof 1, roof 2, facade 1, facade 2, ...). First, the surface areas of the individual sub-parts are added up to obtain the surface areas $A_{j,p}^{\text{EP}}$ of the building parts:

$$\forall j \in \mathcal{J}, p: A_{j,p}^{\text{EP}} = \sum_{q \in Q_j^p} A_{q,j}^{\text{ESP}} \quad (\text{S7})$$

Second, the complete envelope surface area A_j^{E} of the building is calculated by adding up the surface areas of the individual building parts:

$$\forall j \in \mathcal{J}: A_j^{\text{E}} = \sum_{p \in \mathcal{P}_j} A_{j,p}^{\text{EP}} \quad (\text{S8})$$

Third, the weighted average value for each of the fix and variable expenditure is calculated for each building:

$$\forall j \in \mathcal{J}: C_j^{\text{BEfix}} = \sum_{p \in \mathcal{P}} \left(C_{j,p}^{\text{BEfix}} \cdot \frac{A_{j,p}^{\text{EP}}}{A_j^{\text{E}}} \right) \quad (\text{S9})$$

$$\forall j \in \mathcal{J}: C_j^{\text{BEvar}} = \sum_{p \in \mathcal{P}} \left(C_{j,p}^{\text{BEvar}} \cdot \frac{A_{j,p}^{\text{EP}}}{A_j^{\text{E}}} \right) \quad (\text{S10})$$

We consider the heat transmission coefficients of each part or sub-part of the building surface $U_{j,p}^{\text{ESP}}$ [61, 62], and calculate a value for the whole building surface area:

$$\forall j \in \mathcal{J}: U_j^{\text{D}} = \sum_{p \in \mathcal{P}} \left(\frac{A_{j,p}^{\text{ESP}}}{A_j^{\text{E}}} \cdot U_{j,p}^{\text{ESP}} \right) \quad (\text{S11})$$

Supplement A.5 Preprocessing Procedure for the Calculation of the Building Individual Investment Expenditures for the Heating System

In addition to the investment expenditures for the heating system, there are also expenses for the conversion of the technical building equipment, like a chimney renovation or installation of an oil tank. We call these additional expenditures cost drivers. We determine and calculate them individually for each possible new system type (AWHP, GWHP, GCB, OCB, PB, EDH, and STE) for a renewal of the heating system of each building in the preprocessing of the MILP based on the

individual initial technical equipment status. We consider each of the following additional parts of the technical equipment in our investment expenditures (For an overview of the cost drivers see Table S3, for the available heating systems Table S4 and for the available solar thermal power plants Table S1).

Depending on the initial building status, the respective cost drivers are determined, calculated and added to the fixed investment expenditures of the heating system C_{ℓ}^{BESfix} . The resulting fixed expenditures for the corresponding heating system $C_{\ell,j}^{\text{BESfix}}$ depend on the heating system type and the individual building. The same procedure is used for the solar thermal system: Depending on the system-dependent fixed investment expenditures C_s^{TEfix} , the building-specific parameter $C_{s,j}^{\text{TEfix}}$ is calculated. The maintenance costs M_{ℓ}^{BES} refer to the investment expenditures of the heating system C_{ℓ}^{BESfix} . We consider the following cost drivers:

- Chimney Renovation and Exploitation of Heat Source: Only necessary if the new building energy system type differs from the current built-in one and needed for the system.
- Installation: Always necessary expenditure for a building energy system replacement.
- Gas Grid Connection: Only necessary when the building has no connection to the gas grid infrastructure but wants to install a GCB.
- Fuel Storage: Both functions were derived from the results of a study from the BDEW [78]. Only necessary if the new building energy system type is not equal to the current system and needs a fuel storage. This is based on the assumption that an adequately dimensioned fuel storage is already available if the new and current system type are equal: The new building energy system has always a higher efficiency, which results in a lower energy demand for heating and thus also a decrease of the necessary amount of fuel.
- Deconstruction: Only necessary if the current building energy system is an OCB and the new one after a replacement differs from an OCB.
- Domestic Hot Water Tank: Every replacement of the building energy system also includes a replacement of the domestic hot water tank as a renewal measurement. The required volume $V_{j,\ell,s}^{\text{DHW}}$ [litre] is modelled according to DIN V 4701-10, with a dependence on the reference floor area of the building [95]. Each system type uses an indirectly heated storage tank, an additional buffer storage is used by heat pumps and solar thermal plants:

$$\forall j \in J: V_{j,\ell,s}^{\text{DHW}} = \begin{cases} 6 \left[\frac{\text{litre}}{\text{m}^2} \right] \cdot \text{RFA}_j^{0.7} [\text{m}^2] + 4 \left[\frac{\text{litre}}{\text{m}^2} \right] \cdot \text{RFA}_j^{0.7} [\text{m}^2], & \text{for AWHP and GWHP} \\ 6 \left[\frac{\text{litre}}{\text{m}^2} \right] \cdot \text{RFA}_j^{0.7} [\text{m}^2], & \text{for GCB, OCB, PB and EDH} \\ 2 \left[\frac{\text{litre}}{\text{m}^2} \right] \cdot \text{RFA}_j^{0.9} [\text{m}^2], & \text{for STE} \end{cases} \quad (\text{S12})$$

- Refurbishment of Heating Surfaces & Pipe System: The heating surfaces and the pipe system of the building are renewed, if the system temperature of the new building energy system differs from the current system temperature. If the new system temperature is equal to the current, no renewal is necessary and thus no additional expenditures are due here. The expenditures of this measure depend on the building energy system type and the target new system temperature, expressed by the variable C_{ℓ}^{BHS} (See Table S4, the corresponding values of this variable were also derived from [78]). With a decreasing target temperature, the expenses for this measure increase (independent of the initial heating circuit temperature). At system temperatures of 90°C/70°C, 70°C/55°C and 55°C/45°C, according to DIN V 4701-12, radiators are usually installed and at 35°C/28°C underfloor heating is usually installed [109].

Table S3. Considered cost drivers for the heating system.

Cost Driver	System Type							Source
	AWHP	GWHP	GCB	OCB	PB	EDH	STE	
Chimney Renovation	/	/	900€	900€	900€	/	/	[37]
Exploitation of Heat Source	1000€	7000€	/	/	/	/	/	[77]
Installation	500€	500€	700€	600€	600€	300€	300€	[77, 78]
Gas Grid Connection	/	/	$RFA_j [m^2]$ $\cdot 163.09 \left[\frac{\text{€}}{m^4} \right]$ $\cdot RFA_j^{-0.49} [m^2]$	/	/	/	/	[75]
Fuel Storage	/	/	/	$RFA_j [m^2]$ $\cdot 16.53 \left[\frac{\text{€}}{m^2} \right]$	$RFA_j [m^2]$ $\cdot 16.70 \left[\frac{\text{€}}{m^2} \right]$	/	/	[78]
Deconstruction	/	/	/	700€	/	/	/	[37]
Domestic Hot Water Tank	$1.12 \left[\frac{\text{€}}{\text{litre}} \right] \cdot V_{j,k,s}^{DHW} [\text{litre}] + 806.46 [\text{€}]$							[76]
Refurbishment of Heating Surfaces & Pipe System	$RFA_j [m^2] \cdot C_k^{BHS} \left[\frac{\text{€}}{m^2} \right]$					/		[78]

Table S4. Available building heating systems.

#	Type	Sys. Temp. [°C]	$E_k^{BES} [-]$	Only for the heating		$F_k^P [-]$	$M_k^{BES} [-]$	$C_k^{BHS} \left[\frac{\text{€}}{m^2} \right]$
				$C_k^{BESvar} \left[\frac{\text{€}}{\text{kW}} \right]$	$C_k^{BESfix} [\text{€}]$			
0	AWHP	90/70	0.39	588.07	7460.60	1.8	0.025	38.62
1	AWHP	70/55	0.32	588.07	7460.60	1.8	0.025	46.48
2	AWHP	55/45	0.29	588.07	7460.60	1.8	0.025	52.37
3	AWHP	35/28	0.25	588.07	7460.60	1.8	0.025	60.22
4	GWHP	90/70	0.36	318.58	16373.00	1.8	0.025	38.62
5	GWHP	70/55	0.30	318.58	16373.00	1.8	0.025	46.48
6	GWHP	55/45	0.26	318.58	16373.00	1.8	0.025	52.37
7	GWHP	35/28	0.23	318.58	16373.00	1.8	0.025	60.22
8	GCB	90/70	1.14	61.17	4794.00	1.1	0.030	46.84
9	GCB	70/55	1.13	61.17	4794.00	1.1	0.030	47.47
10	GCB	55/45	1.08	61.17	4794.00	1.1	0.030	49.83
11	GCB	35/28	1.01	61.17	4794.00	1.1	0.030	53.05
12	OCB	90/70	1.14	151.88	5436.40	1.1	0.030	46.84
13	OCB	70/55	1.13	151.88	5436.40	1.1	0.030	47.47
14	OCB	55/45	1.09	151.88	5436.40	1.1	0.030	49.20
15	OCB	35/28	1.04	151.88	5436.40	1.1	0.030	51.57
16	PB	90/70	1.28	177.14	16469.00	0.2	0.060	46.45
17	PB	70/55	1.25	177.14	16469.00	0.2	0.060	47.47
18	PB	55/45	1.18	177.14	16469.00	0.2	0.060	50.30
19	PB	35/28	1.10	177.14	16469.00	0.2	0.060	54.24
20	EDH	/	1.05	167.68	295.30	1.8	/	0.00
Sources		[109]	[95, 106, 107]	[76]	[76]	[76]	[76]	[78]

Supplement B DNO Model

Supplement B.1 Architecture of the Gas and Electricity Network Operator Model

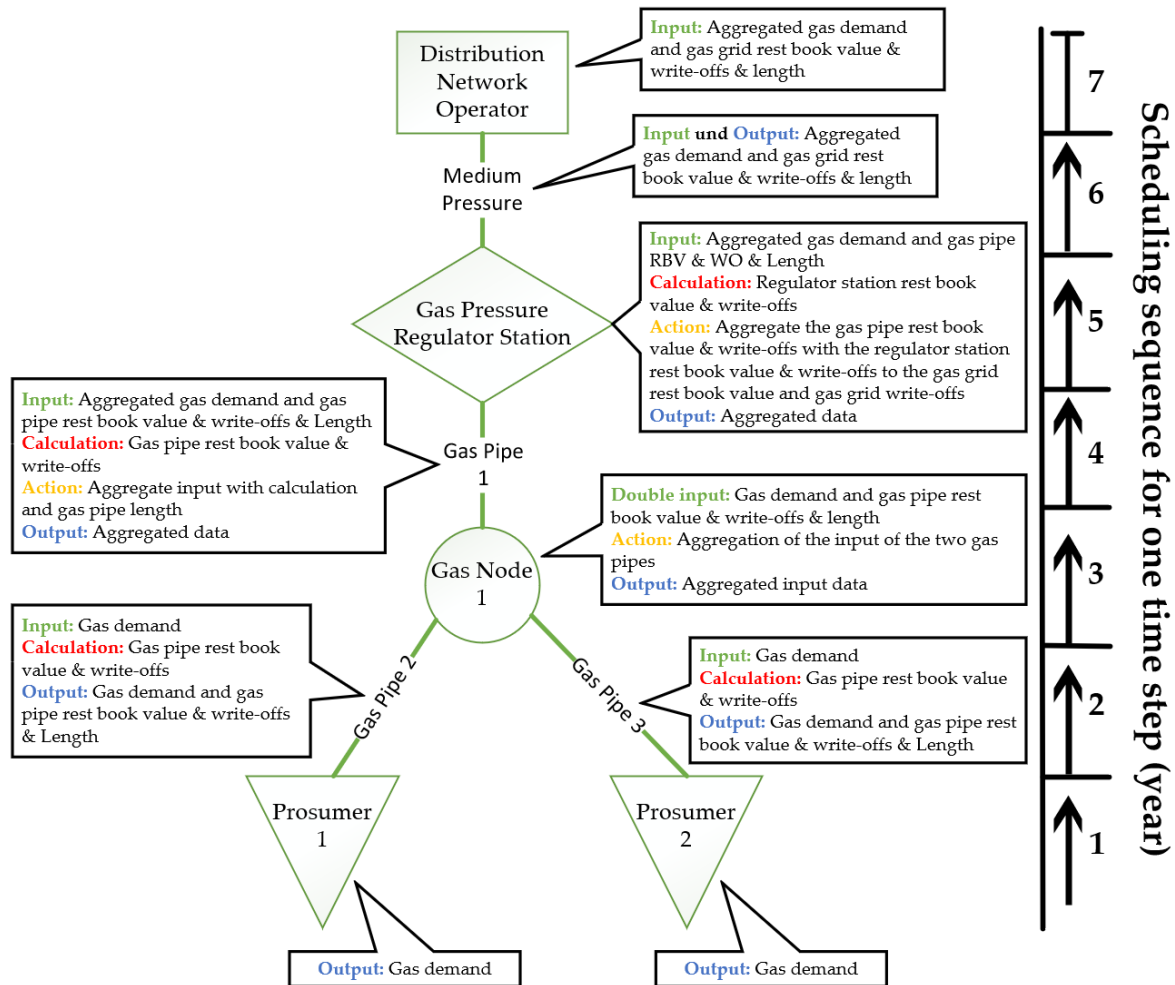


Figure S1. Scheme of data proration in regard to the energy demand and economic parameters implemented for natural gas and electricity grid (The procedure is shown for the gas grid. Analogous procedure in electricity grid.)

Data propagation between agents is a regular process that is performed once by all agents except the DNO during each time step of the simulation. The order of the data propagation is defined by the hierarchical arrangement of the agents in the form of a tree structure, which represents a radial grid structure. The arrangement in a predefined structure (depending on the given electricity and gas grids) and based on the MAS description of [91]. Implicitly it determines how directly the agents can interact with each other. The agents need a direct connection between the them, or if they are in a relationship with each other [91].

Over an entire MAS time step, the data propagation results in a data transfer through the complete tree structure, involving all agents, beginning with the leaf nodes, the prosumers, and ending with the root node, the DNO. The propagated attributes are: Energy demand (electricity or gas) of the prosumers, and length, rest book value (RBV), and depreciations (or write-offs - WO) of the lines/pipes. Figure S1 shows this process exemplary for the gas grid. The process of scheduling begins with the two prosumers agents with their gas demand, which is propagated to the respective gas pipe agent. Both pipe agents determine the RBV, WO and length of their subtree and transmit them to the subsequent gas node agent, where they are aggregated together and given to the next pipe until the medium pressure agent is reached. The medium pressure agent sends the data finally

to the DNO, which uses them afterwards to calculate the GC. During the runtime of the MAS, this process takes place separately for the electricity and the gas grid once in each time step.

Supplement B.2 Grid Measures of the Gas and Electricity DNO

The DNO agent has the ability to perform the following grid measures, applied at the end of each time step: Closure, reactivation, construction, and reinforcement (only applied for the electricity grid; not necessary for the gas grid, as the demand decreases)

- **Closure:** If there is no more gas consumption via a gas pipe agent, it reports this to the DNO, which then closes the corresponding pipe.
- **Reactivation:** If a gas pipe agent that is closed registers a gas consumption again, it will notify the DNO. The DNO reactivates the pipe.
- **Construction:** If a BO switches to a gas-based system, but is not connected to the grid, the BO notifies the DNO. The DNO creates a new pipe with an initialization of the following parameters: Agent ID (current highest ID, incremented by 1), type (standard pipe type for this: “50 PE 100 SDR 11”), length (Euclidean distance between the corresponding BO and the nearest gas node), age (0) and adjacent agents (ID of the BO and ID of the nearest gas node – the pipe agent connects these two). Afterwards, the pipe determines its initial status, which is considered in the following MAS time step.
- **Reinforcement in electricity grid:** If violations of the technical limits of assets are detected by the DNO within the load flow calculation ($I/I^{\text{Max}} = 100\%$ for all assets (branches); $U/U^{\text{N}} \pm 10\%$ for all nodes corresponding to DIN EN 50160) the corresponding asset will be reinforced starting from the point of violation (voltage violation: line next to node of violation; current ratio: branch of violation; measures: diameter extension of a line or parallel line or new asset).

Supplement C Case studies

Supplement C.1 Building, heating system and solar thermal parameters

Table S5. Heat transmission coefficients of the energy efficiency constraint for each building part [100].

EnEV Target U-Values					
Envelope Part	Roof	Facade	Floor	Window	Door
U-Value $\left[\frac{W}{m^2 \cdot K}\right]$	0.24	0.24	0.3	1.3	1.8

Table S6. Building properties of the used building types and corresponding energy efficiency constraint.

#	Building	Building Properties						EnEV energy efficiency targets	
		RFA_j [m ²]	T_j^N [h/a]	U_j^{TB} [$\frac{W}{m^2 \cdot K}$]	H_j^V [$\frac{W}{K}$]	S_j^S [kW]	S_j^{DHW} [kW]	S_j^T [kW]	Q_j^P [$\frac{kWh}{a}$]
0	SFH-A	218.90	1858	0.10	112	2.5993	2.3562	9.3978	17010
1	SFH-B	141.80	1961	0.10	72	1.6683	1.4464	7.4417	14157
2	SFH-C	302.50	2045	0.10	154	3.8462	2.9589	14.1402	27098
3	SFH-D	111.10	1952	0.10	57	1.3397	1.1384	6.4387	12175
4	SFH-E	121.20	1847	0.10	62	1.7023	1.3122	8.2765	14569
5	SFH-F	173.20	1953	0.10	88	2.4451	1.7733	10.3436	18893
6	SFH-G	215.60	2154	0.10	110	2.1000	2.0021	8.7497	18634
7	SFH-H	150.20	2134	0.10	77	1.9586	1.4078	8.5194	17004
8	SFH-I	121.90	2144	0.10	62	1.6646	1.1370	7.2747	14468
9	SFH-J	146.50	2219	0.05	62	1.6279	1.3202	6.7689	14340
10	SFH-K	186.80	2106	0.05	95	2.3007	1.7741	9.5518	19006
11	SFH-L	186.80	2275	0.05	95	1.9146	1.6421	9.5518	21112
12	TH-B	96.00	2011	0.10	49	1.1013	0.9546	4.7318	9222
13	TH-C	112.80	2096	0.10	58	1.3817	1.0764	4.8317	9487
14	TH-D	149.60	1969	0.10	76	2.7041	1.5194	8.0341	13488
15	TH-E	117.40	2069	0.10	60	1.0804	1.1349	4.1800	8761
16	TH-F	106.30	2070	0.10	54	1.3268	1.0269	4.9237	9572
17	TH-G	108.30	2073	0.10	55	1.2922	1.0448	5.3715	10623
18	TH-H	127.60	2176	0.10	65	1.2223	1.1726	5.0218	10821
19	TH-I	148.80	2225	0.10	76	1.4741	1.3375	5.7370	12461
20	TH-J	151.90	2266	0.05	65	1.8737	1.3404	6.7114	14002
21	TH-K	195.80	2193	0.05	100	1.6262	1.7859	7.9566	17797
22	TH-L	195.80	2362	0.05	100	1.4006	1.6576	7.9566	19404
23	MFH-A	677.50	2149	0.10	346	7.9214	7.0615	29.4552	61455
24	MFH-B	312.40	2244	0.10	159	3.4334	3.1184	11.6561	25449
25	MFH-C	385.00	2190	0.10	196	4.8051	3.9370	17.1947	35763
26	MFH-D	632.30	2080	0.10	322	7.3036	6.8104	28.2803	57789
27	MFH-E	3129.10	2237	0.10	1596	35.1692	31.3398	119.1096	257825
28	MFH-F	468.60	2225	0.10	239	5.2982	4.7171	20.1990	43654
29	MFH-G	654.00	2285	0.10	334	6.7897	6.4125	26.0069	58552
30	MFH-H	778.10	2324	0.10	397	9.8911	7.5008	34.3740	74320
31	MFH-I	834.90	2357	0.10	426	9.0101	7.9330	35.3354	80763
32	MFH-J	2190.10	2466	0.05	931	19.3170	19.8907	71.3245	177329
33	MFH-K	1305.00	2353	0.05	666	12.2683	12.4218	52.3202	123485
34	MFH-L	1305.00	2375	0.05	666	11.2076	12.3102	52.3202	52.32
Sources		[61, 62]						Derived from [100]	

Table S7. Initial building heating system types base on [95, 107, 109].

#	Type	Sys. Temp. [°C]	$E_{\#}^{BES}$ [-]	$\#$	Type	Sys. Temp. [°C]	$E_{\#}^{BES}$ [-]
0	AWHP	90/70	0.52	11	GCB	35/28	1.13
1	AWHP	70/55	0.43	12	OCB	90/70	1.24
2	AWHP	55/45	0.38	13	OCB	70/55	1.21
3	AWHP	35/28	0.33	14	OCB	55/45	1.18
4	GWHP	90/70	0.44	15	OCB	35/28	1.14
5	GWHP	70/55	0.36	16	PB	90/70	1.33
6	GWHP	55/45	0.32	17	PB	70/55	1.30
7	GWHP	35/28	0.28	18	PB	55/45	1.22
8	GCB	90/70	1.22	19	PB	35/28	1.13
9	GCB	70/55	1.20	20	EDH	/	1.12
10	GCB	55/45	1.17				

Table S8. Surface areas of building types [61, 62].

#	Envelope Surfaces [m ²]									
	Building	Roof 1	Roof 2	Facade 1	Facade 2	Floor 1	Floor 2	Window 1	Window 2	Door
0	SFH-A	134.20	0.00	169.80	0.00	85.50	0.00	28.80	0.00	2.00
1	SFH-B	83.10	0.00	194.00	0.00	45.60	32.70	22.30	0.00	2.00
2	SFH-C	214.00	0.00	235.30	0.00	144.90	0.00	52.40	0.00	2.00
3	SFH-D	125.40	0.00	117.80	0.00	62.00	17.90	18.40	0.00	2.00
4	SFH-E	168.90	0.00	141.20	8.70	115.80	0.00	27.10	0.00	2.10
5	SFH-F	183.10	0.00	177.60	0.00	78.30	74.00	34.20	0.00	2.00
6	SFH-G	100.80	0.00	159.40	0.00	83.40	0.00	27.00	0.00	2.00
7	SFH-H	123.20	0.00	211.30	0.00	75.30	0.00	29.70	0.00	2.00
8	SFH-I	115.50	0.00	126.60	0.00	84.30	0.00	32.50	0.00	2.00
9	SFH-J	85.90	0.00	188.90	0.00	79.80	0.00	28.30	0.00	2.00
10	SFH-K	131.90	0.00	227.60	0.00	107.80	0.00	42.00	0.00	2.60
11	SFH-L	131.90	0.00	227.60	0.00	107.80	0.00	42.00	0.00	2.60
12	TH-B	60.00	0.00	74.50	0.00	60.00	0.00	18.10	0.00	2.00
13	TH-C	50.40	0.00	64.10	0.00	50.40	0.00	21.50	0.00	2.00
14	TH-D	81.20	0.00	134.70	0.00	81.20	0.00	46.70	0.00	2.00
15	TH-E	46.20	0.00	40.40	0.00	46.20	0.00	13.50	0.00	2.00
16	TH-F	60.85	0.00	53.70	0.00	60.90	0.00	23.40	0.00	2.00
17	TH-G	97.60	0.00	54.10	0.00	73.00	0.00	20.20	0.00	2.00
18	TH-H	64.90	0.00	50.90	0.00	56.10	0.00	18.80	0.00	2.00
19	TH-I	77.40	0.00	45.20	13.90	51.90	0.00	22.40	0.00	2.50
20	TH-J	91.30	0.00	140.70	0.00	70.70	0.00	36.30	0.00	2.00
21	TH-K	75.70	0.00	137.80	69.20	67.80	0.00	25.50	2.60	2.70
22	TH-L	75.70	0.00	137.80	69.20	67.80	0.00	25.50	2.60	2.70
23	MFH-A	284.10	0.00	749.30	0.00	124.80	49.00	107.00	0.00	2.00
24	MFH-B	102.80	0.00	146.00	0.00	102.80	0.00	54.10	0.00	2.00
25	MFH-C	158.50	31.10	323.50	0.00	127.40	31.10	71.20	0.00	2.00
26	MFH-D	355.00	0.00	462.00	0.00	355.00	0.00	98.70	0.00	2.00
27	MFH-E	971.10	0.00	2039.00	0.00	971.10	0.00	507.50	0.00	2.00
28	MFH-F	216.70	0.00	336.00	0.00	216.70	0.00	81.30	0.00	2.00

29	MFH-G	248.30	0.00	447.10	0.00	248.30	0.00	99.40	0.00	2.00
30	MFH-H	249.40	0.00	774.80	0.00	249.40	0.00	161.00	0.00	2.00
31	MFH-I	283.70	0.00	695.80	0.00	283.70	0.00	162.80	0.00	2.00
32	MFH-J	580.00	0.00	1698.00	0.00	619.50	0.00	308.70	0.00	2.00
33	MFH-K	321.10	0.00	1193.20	0.00	321.10	0.00	243.60	0.00	47.90
34	MFH-L	321.10	0.00	1193.20	0.00	321.10	0.00	243.60	0.00	47.90

Table S9. U-Values of building types [61, 62].

#	Building Envelope U-Values $\left[\frac{W}{m^2 \cdot K}\right]$									
	Building	Roof 1	Roof 2	Facade 1	Facade 2	Floor 1	Floor 2	Window 1	Window 2	Door
0	SFH-A	2.60	0.00	2.00	0.00	2.90	0.00	2.80	0.00	3.00
1	SFH-B	1.30	0.00	1.70	0.00	0.88	1.20	2.80	0.00	3.00
2	SFH-C	1.40	0.00	1.70	0.00	0.77	0.00	2.80	0.00	3.00
3	SFH-D	1.40	0.00	1.40	0.00	0.78	1.01	2.80	0.00	3.00
4	SFH-E	0.80	0.00	1.20	0.80	1.08	0.00	2.80	0.00	3.00
5	SFH-F	0.50	0.00	1.00	0.00	0.77	1.00	2.80	0.00	3.00
6	SFH-G	0.50	0.00	0.80	0.00	0.65	0.00	4.30	0.00	3.00
7	SFH-H	0.40	0.00	0.50	0.00	0.51	0.00	3.20	0.00	3.00
8	SFH-I	0.35	0.00	0.30	0.00	0.40	0.00	1.90	0.00	2.00
9	SFH-J	0.25	0.00	0.30	0.00	0.28	0.00	1.40	0.00	2.00
10	SFH-K	0.20	0.00	0.28	0.00	0.35	0.00	1.30	0.00	1.80
11	SFH-L	0.15	0.00	0.17	0.00	0.17	0.00	1.10	0.00	1.30
12	TH-B	0.77	0.00	1.70	0.00	0.88	0.00	2.70	0.00	3.00
13	TH-C	0.65	0.00	1.70	0.00	0.77	0.00	2.80	0.00	3.00
14	TH-D	0.65	0.00	1.20	0.00	1.29	0.00	2.80	0.00	3.00
15	TH-E	0.51	0.00	1.20	0.00	1.08	0.00	2.80	0.00	3.00
16	TH-F	0.51	0.00	1.00	0.00	0.77	0.00	2.80	0.00	3.00
17	TH-G	0.50	0.00	0.80	0.00	0.65	0.00	2.80	0.00	3.00
18	TH-H	0.40	0.00	0.60	0.00	0.51	0.00	2.80	0.00	3.00
19	TH-I	0.35	0.00	0.60	0.60	0.45	0.00	1.60	0.00	2.00
20	TH-J	0.20	0.00	0.30	0.00	0.28	0.00	1.30	0.00	2.00
21	TH-K	0.20	0.00	0.28	0.28	0.35	0.00	1.30	1.30	1.80
22	TH-L	0.13	0.00	0.16	0.16	0.16	0.00	1.10	1.10	1.30
23	MFH-A	2.60	0.00	2.00	0.00	0.88	1.20	2.80	0.00	3.00
24	MFH-B	1.30	0.00	2.20	0.00	0.88	0.00	2.70	0.00	3.00
25	MFH-C	1.40	0.65	1.70	0.00	0.77	1.00	3.00	0.00	3.00
26	MFH-D	1.08	0.00	1.20	0.00	1.33	0.00	3.00	0.00	3.00
27	MFH-E	0.51	0.00	1.20	0.00	1.08	0.00	3.00	0.00	3.00
28	MFH-F	0.51	0.00	1.00	0.00	0.77	0.00	3.00	0.00	4.00
29	MFH-G	0.43	0.00	0.80	0.00	0.65	0.00	3.00	0.00	4.00
30	MFH-H	0.36	0.00	0.60	0.00	0.51	0.00	3.00	0.00	4.00
31	MFH-I	0.32	0.00	0.40	0.00	0.40	0.00	1.90	0.00	2.00
32	MFH-J	0.20	0.00	0.25	0.00	0.32	0.00	1.40	0.00	3.00
33	MFH-K	0.20	0.00	0.28	0.00	0.35	0.00	1.30	0.00	1.80
34	MFH-L	0.25	0.00	0.29	0.00	0.29	0.00	1.10	0.00	1.30

Table S10. Heating circuit temperatures for the corresponding building age classes and heating systems

Building age class		E	F	G	H	I	J	K	L
Heating system	AWHP	0	0	0	0	1	1	1	1
	GCB	1	1	1	1	1	1	1	1
	OCB	1	1	1	1	1	1	1	1
	PB	1	1	1	1	1	1	1	1
	EDH	1	1	1	1	1	1	0	0
Heating circuit temperature		90/70°C		70/55°C		55/45°C		35/28°C	

Table S12. Building age class of all buildings in the data set

Prosjekt	PROSJEKT	MED																																																																																																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	Prosjekt1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
2	Prosjekt2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100

