Spatiotemporal building stock modeling for residential decarbonization in the Netherlands

Yang, X.

Chapter 7 Appendix

7.1 Supporting information to Chapter 2

7.1.1 Building classification and identification

Table S7.1.1 Dutch building classification and naming system used in this article.

Construction period	Single-family house	Mid-terraced house	End-terraced house	Apartment building	Multi-family house
<=1964	SFH1	Mid_TH1	End_TH1	AB1	MFH1
1965-1974	SFH2	Mid_TH2	End_TH2	AB2	MFH2
1975-1991	SFH3	Mid_TH3	End_TH3	AB3	MFH3
1992-2005	SFH4	Mid_TH4	End_TH4	AB4	MFH4
2006-2014	SFH5	Mid_TH5	End_TH5	AB5	MFH5
>=2015	SFH6	Mid_TH6	End_TH6	AB6	MFH6

Table S7.1.2 Criteria for identifying the building types.

Building type	Number of shared walls	Number of registered addresses	Building footprint area	Gross floor area	Number of Stories
Single-family House	0	<=2	<250	<400	-
Mid-Terraced House	2	<=3	<200	<400	<=4
End-Terraced House	1	<=3	<200	<400	<=4
Apartment Building	0	>3	none	>1000	-
Multi-family House	else				

These criteria in **Table S7.1.2** are based on experience and field visits. The trial-and-error experience in data processing is also taken into account to determine these values. For example, some garages are merged with the main buildings in BAG and this makes the buildings have larger ground floor areas. Therefore, we set larger

gross floor areas for the criteria of single-family houses and terraced houses.

Table S7.1.3 Distribution of building types and ages (the number of buildings).

Period	Single-family house	Mid-terraced house	End-terraced house	Apartment building	Multi-family house	Total
<=1964	347	9417	3185	40	3026	16015
1965-1974	18	1156	394	34	150	1752
1975-1991	54	5576	1886	72	528	8116
1992-2005	17	1050	305	65	94	1531
2006-2014	13	854	264	29	86	1246
>=2015	11	209	94	6	50	370
All periods	460	18262	6128	246	3934	29030

Table S7.1.4 Distribution of building types and ages (the conditioned area of buildings).

Period	Single-family house	Mid-terraced house	End-terraced house	Apartment building	Multi-family house	Total
<=1964	65945	1387770	523841	312404	1303743	3593702
1965-1974	3831	163253	61644	303699	211630	744057
1975-1991	12561	839554	310542	266627	351527	1780812
1992-2005	4623	177264	57180	315307	187989	742362
2006-2014	2534	150358	48808	248657	145331	595688
>=2015	1662	21026	11206	71977	17760	123631
All periods	91155	2739225	1013221	1518671	2217980	7580252

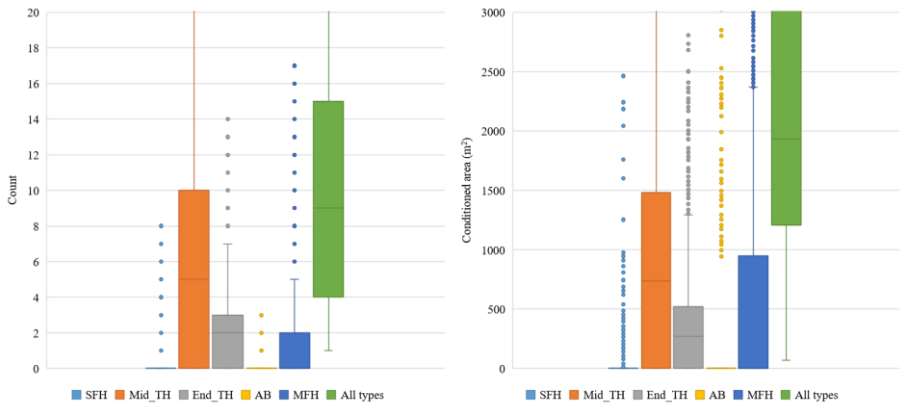

Figure S7.1.1 Distribution of dwellings per postcode. The left is for the number of dwellings per type and the right is the conditioned area of dwellings per postcode.

Not all the buildings that share walls are terraced houses. This is obvious in the city center of Leiden, where buildings are densely distributed and share walls with

adjoined buildings. Therefore, in this study, the difference between the apartment building and the multi-family house is assumed that apartment buildings have larger sizes and do not share walls with other buildings. Compared with the single-family house, the multi-family house is smaller, but compared with apartment buildings, it has shared walls. In this way, all the dwellings that do not belong to the former four building types are categorized as the multi-family house.

Based on buildings' postcodes, Google Map is applied to validate the results of building category identification for some sample buildings. We find that it fitted very well in most cases.

7.1.2 Geometries of windows and doors

Table S7.1.5 Geometry information of windows and doors in TABULA.

Building type	window-to-façade ratio	door-to-façade-ratio	TABULA door area (m^2)
SFH1	0.17	-	2.90
Mid_TH1	0.30	-	2.50
End_TH1	0.19	-	2.50
AB1	0.29	0.03	-
MFH1	0.25	0.03	-
SFH2	0.23	-	1.90
Mid_TH2	0.39	-	1.60
End_TH2	0.22	-	1.60
AB2	0.43	0.04	-
MFH2	0.34	0.04	-
SFH3	0.21	-	1.90
Mid_TH3	0.32	-	1.80
End_TH3	0.18	-	1.80
AB3	0.22	0.04	-
MFH3	0.25	0.04	-
SFH4	0.21	-	4.00
Mid_TH4	0.30	-	2.30
End_TH4	0.18	-	2.30
AB4	0.32	0.04	-
MFH4	0.27	0.04	-
SFH5	0.18	-	2.40
Mid_TH5	0.39	-	2.40
End_TH5	0.21	-	2.40
AB5	0.36	0.05	-
MFH5	0.50	0.03	-
SFH6	0.18	-	2.40
Mid_TH6	0.39	-	2.40

End_TH6	0.21	-	2.40
AB6	0.35	0.05	-
MFH6	0.50	0.03	-

7.1.3 Relative deviations

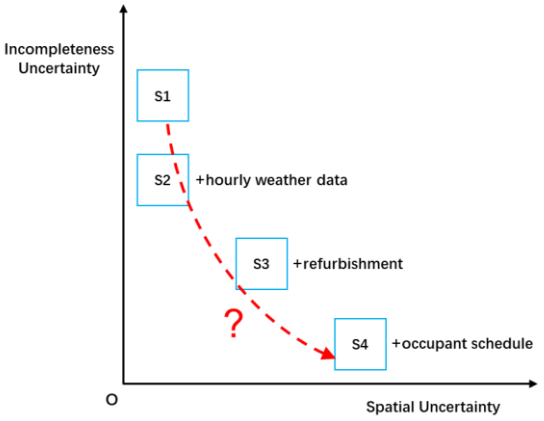

Figure S7.1.2 The evolution of models and the corresponding included factors.

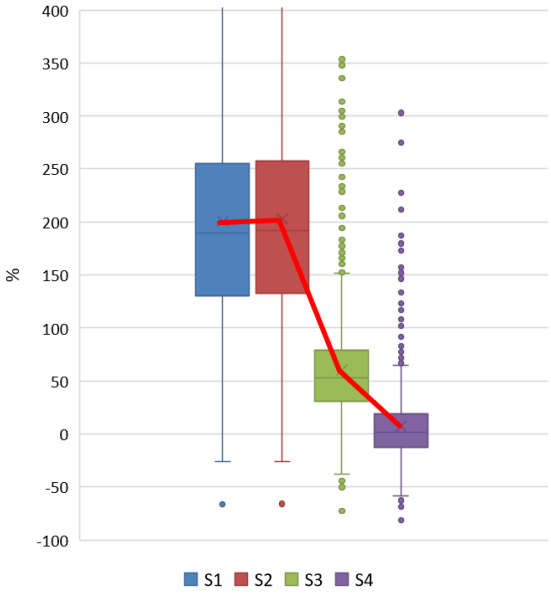

Figure S7.1.3 Relative deviations at postcode level and building stock level. The box plots show the relative deviations at the postcode level while the red line shows the relative deviations at the building stock level for Leiden.

7.1.4 Calculation method

7.1.4.1 Space heating

S1 uses the seasonal calculation method, the calculation step of which is a fixed heating season, and S2-4 use the hourly calculation method, the calculation step of which is one hour. The building energy demand for space heating (Q_{nd}) at the building level is calculated by subtracting the heat gains from heat transfer loss. Heat transfer loss is due to thermal transmission through the building envelope (Q_{tr}) and the heat flow by ventilation (Q_{ve}). The heat gains consist of the internal heat gains (Q_{int}, e.g. occupant metabolism, appliance, and lighting) and the solar radiation entering through windows (Q_{sol}). The calculation method is as follows:

$$Q_{nd} = \sum_{t=1}^{m}(Q_{tr,t} + Q_{ve,t}) - \eta_{gn}(Q_{int,t} + Q_{sol,t}) \qquad (1)$$

where nd denotes need; t denotes the time step (heating season for S1 and hour for S2-4); m denotes the total number of time steps (1 for S1, 5088 for S2-3 and 2968 for S4). η_{gn} is the dimensionless gain utilization factor for the heat gains (see section **7.1.4.3**).

The heat transfer loss by transmission through the envelope is determined as follows:

$$Q_{tr,t} = \begin{cases} \sum_{i=1}^{n} b_i A_i U_i (T_{int,t} - T_{ext,t}) & if\ T_{int,t} > T_{ext,t} \\ 0 & if\ T_{int,t} \le T_{ext,t} \end{cases} \qquad (2)$$

where A_i is the area of element i of the building envelope (roof, window, door, wall and ground floor); U_i is the thermal transmittance (U-value) of element i. T_{int} is the room temperature and T_{ext} is the temperature of the external environment. b_i is the adjustment factor, and in this study, its value for the ground floor is 0.5 while its value for other envelope elements is 1.

The heat transfer loss by ventilation is determined as follows:

$$Q_{ve,t} = \begin{cases} \rho_a c_a A_{con} * 2.5m * (n_{ve,use} + n_{ve,infiltration}) \times (T_{int,t} - T_{ext,t}) & if\ T_{int,t} > T_{ext,t} \\ 0 & if\ T_{int,t} \le T_{ext,t} \end{cases} \qquad (3)$$

where $\rho_a c_a$ is the heat capacity of air per volume and its value is 1200 $\mathrm{J/(m^3 \cdot K)}$. $2.5m$ is the ventilation reference room height from TABULA. $n_{ve,use}$ is the air change rate by use and $n_{ve,infiltration}$ is the airflow rate by infiltration.

The internal heat gains are determined as follows:

$$Q_{int,t} = tq_{int}A_{con} \qquad (4)$$

where q_{int} is the average thermal output of internal heat sources.

In this study, only the solar gain from windows is considered. As the orientation of each building is unknown, we attribute all heat gains from the solar radiation to the east and west. The solar heat gains are determined as follows:

$$Q_{sol,t} = I_{sol}(F_{east} + F_{west})A_{window}F_{sh}(1 - F_F)F_W g_{gl} \qquad (5)$$

where I_{sol} is the global solar radiation falling onto a horizontal surface. $F_{east}(0.69)$

and F_{west} (0.68) are the factors converting the horizontal solar radiation to the windows in the east and west orientation of buildings and they are calculated based on seasonal values from TABULA. F_{sh} is the shading reduction factor for movable shading provisions and its value is 0.6. F_F is the frame fraction of the windows and its value is 0.3. F_W is the correction factor for non-scattering glazing and its value is 0.9. g_{gl} is the total solar energy transmittance.

The annual building energy need for space heating of the four models is converted to energy consumption for space heating by considering the heating system efficiency following the TABULA calculation method.[176] The annual energy consumption for space heating (q_h) is formulated in eq 6:

$$q_h = [Q_{nd}/A_{con} + q_{d.h} + q_{s,h} - \eta_{h,gn}(q_{w,h} + \eta_{ve,rec}Q_{ve})]e_{g,h}A_{con} \qquad (6)$$

herein, h denotes space heating, and g denotes heat generator. $q_{d,h}$ is the effective heat loss of the space heating distribution system and $q_{s,h}$ is the effective heat loss of the space heating system storage. $q_{w,h}$ is the recoverable heat loss of the DHW system. $\eta_{ve,rec}$ is the efficiency of ventilation heat recovery. $e_{g,h}$ is the heat generation expenditure factor of the heat generator. Q_{ve} is the annual heat transfer by ventilation calculated based on the seasonal method. $\eta_{h,gn}$ is the dimensionless gain utilization factor (see section **7.1.4.3**) of ventilation heat recovery and recoverable heat loss of the DHW system.

7.1.4.2 Domestic hot water

The energy consumption for DHW (q_w) is calculated as follows:

$$q_w = (q_{nd,w} + q_{d,w} + q_{s,w})e_{g,w}A_{con} \qquad (7)$$

where w denotes water. $q_{nd,w}$ is the annual energy need per conditioned floor area for DHW, $q_{d,w}$ is the heat loss of the DHW distribution system and $q_{s,w}$ is the heat loss of the DHW storage. $e_{g,w}$ is the heat generation expenditure factor of the DHW heat generator.

7.1.4.3 Gain utilization factor

In this study, the gain utilization factor (η) is used for calculating both the energy need and delivered energy for space heating. η is the function of the heat-balance ratio (γ_H). γ_H is determined as follows:

$$\gamma_H = \frac{(Q_{int,t}+Q_{sol,t})}{(Q_{tr,t}+Q_{ve,t})} \qquad (8)$$

where for S1 and the calculation of delivered energy, the time step t is one season; for S2-4 the time step t is one hour.

η is calculated as follows:

$$\eta = \begin{cases} \frac{1-\gamma_H^{a_H}}{1-\gamma_H^{a_H+1}} & if\ \gamma_H > 0\ and\ \gamma_H \neq 1 \\ \frac{a_H}{a_H+1} & if\ \gamma_H = 1 \\ \frac{1}{\gamma_H} & if\ \gamma_H < 0 \end{cases} \quad (9)$$

where a_H is a dimensionless numerical parameter depending on the time constant and it is determined as follows:

$$a_H = a_{H,0} + \frac{\tau}{\tau_{H,0}} \quad (10)$$

where $a_{H,0}$ is a dimensionless reference numerical parameter and $\tau_{H,0}$ a reference time constant. Their values (from EN ISO 13790) are shown as follows:

Table S7.1.6 Values of $a_{H,0}$ and $\tau_{H,0}$.

Calculation method	$a_{H,0}$	$\tau_{H,0}$
Seasonal method of energy demand for space heating (S1)	0.8	30
Hourly method of energy demand for space heating (S2-4)	1	15
Calculation of delivered energy	0.8	30

τ is the time constant of the building and it is calculated as follows:

$$\tau = \frac{C_m A_C}{H_{tr}+H_{ve}} \quad (11)$$

where C_m is the internal heat capacity per conditioned floor area and in this study its value is 45 $\mathrm{Wh/(m^2K)}$. H_{tr} is the heat transfer coefficient by transmission and calculated as follows:

$$H_{tr} = \sum_{i=1}^{n} b_i A_i U_i \quad (12)$$

H_{ve} is the heat transfer coefficient by ventilation and calculated as follows:

$$H_{ve} = \rho_a c_a \left(q_{ve,use} + q_{ve,infiltration}\right) \quad (13)$$

7.2 Supporting information to Chapter 3

7.2.1 Building stock characterization

Figure S7.2.1 shows the process of characterizing the existing building stock. The characterization and initialization are based on the method by Yang et al. [27]. The main data sources used are:

(1) The BAG [172] dataset (GIS data) mainly contains building footprints, construction years, functions, and registered addresses, which is used to derive buildings' geometries (e.g. conditioned floor area and envelope element areas) and building types (single-family house, end-terraced house, mid-terraced house, apartment building, and multi-family house). According to BAG, the total number of residential buildings is 5,092,999 in 2015.

(2) TABULA [68] (Typology Approach for Building Stock Energy Assessment) mainly includes the archetypes of the Dutch residential buildings (differentiated by construction periods and building types), and their envelope geometries, thermal properties of different insulation standards, ventilation and heating systems. These parameters are mapped to BAG buildings according to the types and construction periods of BAG buildings.

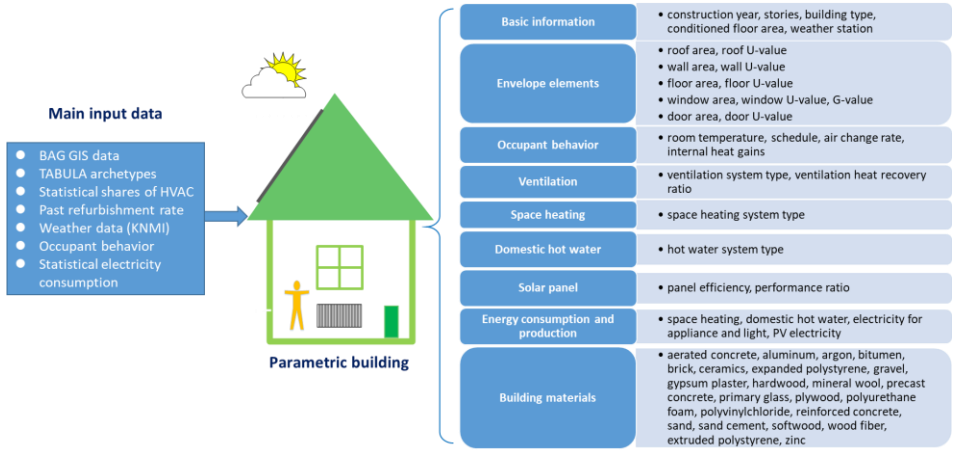

Figure S7.2.1 Building stock characterization and initialization.

(3) KNMI [173] (Royal Dutch Meteorological Institute) holds the weather records (this study uses the averaged data of 2001-2019) of different stations, which can be used to describe the outdoor environment of buildings. It also includes the longitude and latitude of each weather station, which enables the spatialization of weather records (see **Figure S7.2.4**). Individual buildings are linked to the nearest weather stations by the "Spatial Join" tool of ArcGIS 10.6. For new buildings, the weather data are mapped to new buildings by postcode to estimate the potential PV electricity generation. The postcodes of new buildings are randomly sampled from the postcodes of buildings demolished in the same year.

(4) Occupants are assumed to set the room temperature as 20 °C and heat the rooms from 7:00 pm to 7:00 am (+1 day, 12 h) [27,180].

(5) The statistical past envelope renovation rates for envelope elements (roof, external wall, window, and ground floor) [174], and the distributions of ventilation and heating systems [174] are applied to initialize the current building stock.

(6) The material intensities of different building types (see 7.2.4) are from a Dutch study [205].

(7) CBS[182] (Central Bureau of Statistics) contains the statistical electricity consumption reported at the postcode level, which is used to derive the residential electricity consumption intensities (kWh/m^2).

The past renovation rates [27] of envelope elements are applied to initialize the

current physical properties. The data in **Table S7.2.2** is adapted from diffusion rates in literature [174] to initialize the space heating and hot water systems. The heat supply type "other" is used to represent the space heating and hot water systems of which we lack the details on types and shares. The diffusion rates of ventilation systems are shown in **Table S7.2.3**. The Dutch rooftop PV installation rate [70] is 4.4% in 2017 and it is used as the rate of 2015.

Table S7.2.1 Building classification and naming system.

Construction period	Single-family house	Mid-terraced house	End-terraced house	Apartment building	Multi-family house
<=1964	SFH1	Mid_TH1	End_TH1	AB1	MFH1
1965-1974	SFH2	Mid_TH2	End_TH2	AB2	MFH2
1975-1991	SFH3	Mid_TH3	End_TH3	AB3	MFH3
1992-2005	SFH4	Mid_TH4	End_TH4	AB4	MFH4
2006-2014	SFH5	Mid_TH5	End_TH5	AB5	MFH5
>=2015 (CNEW)	SFH6	Mid_TH6	End_TH6	AB6	MFH6
>=2015 (nZEB)	SFH7	Mid_TH7	End_TH7	AB7	MFH7

Table S7.2.2 The distribution of space heating systems and domestic hot water systems.

Space heating type	Domestic hot water	Proportion
Natural gas boiler	common boiler for heating and DHW	86%
Heat networks	other	7%
Other		7%

Table S7.2.3 The distribution of ventilation systems.

Ventilation type	Percentage
Natural ventilation	67%
Exhaust air ventilation	30%
Balanced ventilation	3%

In this study, the conditioned floor area [176] is used to quantify the floor area stock and flows. To validate the derived floor area based on BAG data against the statistical useful floor area, the conversion factors [327] in **Table S7.2.4** are applied. The statistical (CBS) useful floor area of the Netherlands is on average 65 m^2 per capita [232]. The derived useful floor area after conversion in this study is 69 m^2 per capita (population 16901000 in 2015). The useful floor area per capita is a bit larger than the statistical value, but they are very similar. Part of the reason for overestimation

is that some building footprints include the garage or utility rooms. The distribution of construction year and building type is shown in **Figure S7.2.2** and **Figure S7.2.3**.

Table S7.2.4 Floor area conversion.

Building type	Conditioned floor area (m^2)	Conversion factor	Useful floor area (m^2)
SFH	164106085.98	0.75	123079564.49
Mid_TH	320859889.16	0.79	253479312.44
End_TH	281788682.41	0.79	222613059.10
AB	211019372.95	0.90	189917435.66
MFH	428275389.30	0.90	385447850.37
Total	1406049419.80	-	1174537222.05
Floor area per capita	83.19	-	69.49

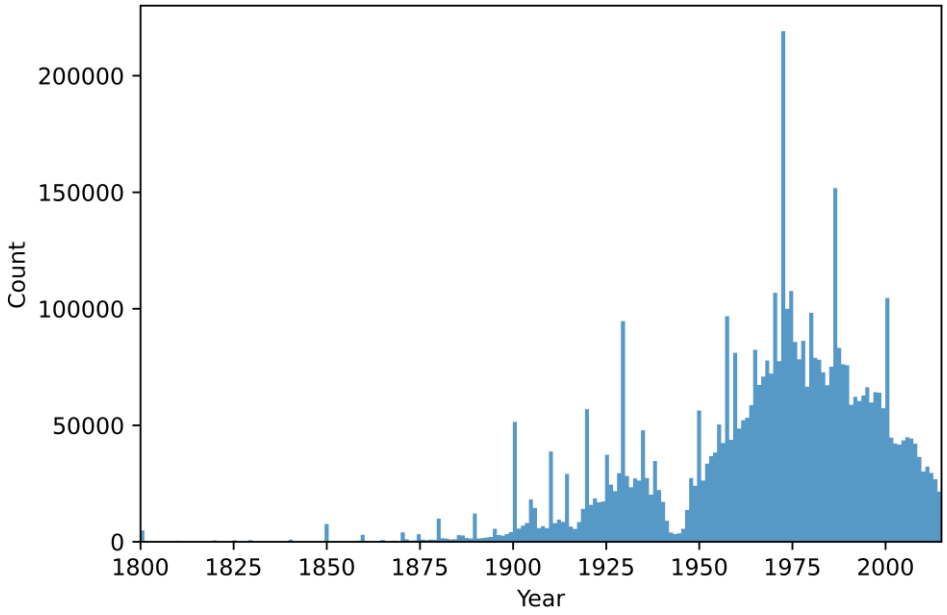

Figure S7.2.2 The distribution of construction year of Dutch residential buildings. Only the buildings built between 1800 and 2015 are shown.

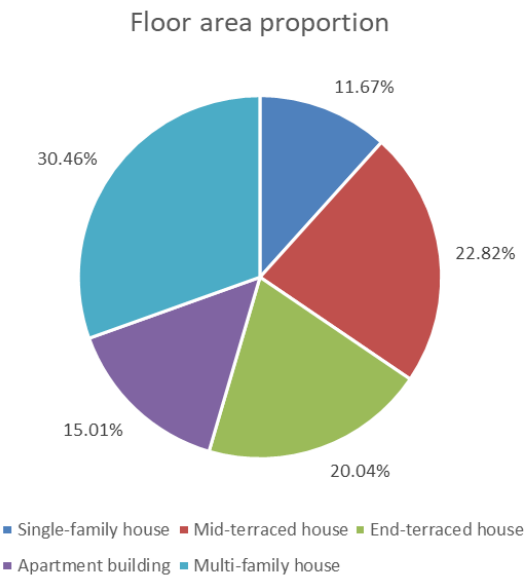

Figure S7.2.3 The proportion of building types by conditioned floor area. It is derived from BAG (GIS data of buildings) based on the method by Yang et al. [27].

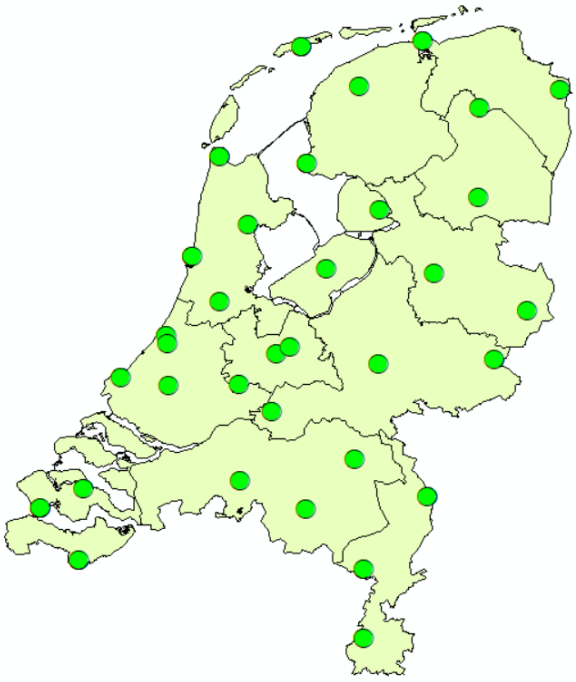

Figure S7.2.4 The map of weather stations. The green points are the weather stations included in this study.

7.2.2 Dutch population

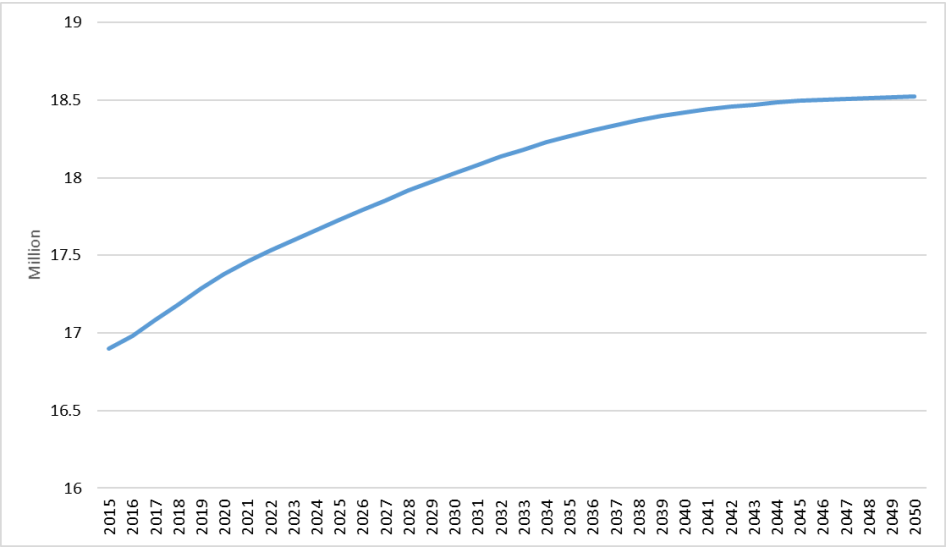

Figure S7.2.5 Population trend of the Netherlands [221].

7.2.3 Electricity intensities

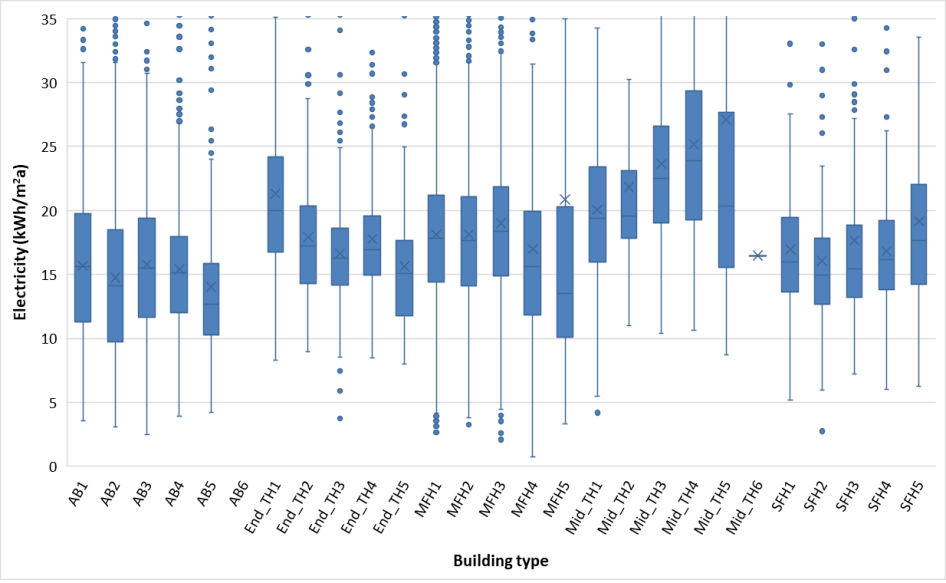

Figure S7.2.6 Distribution of electricity intensity (annual electricity consumption per conditioned floor area), derived based on the method of Yang et al. [27].

7.2.4 Building materials

Table S7.2.5 Building material densities [211].

Label	Material type	Density (kg/m^3)
AC	main material	750
Al	main material	2700
Ar	insulation material	1.66
Bi	main material	2400
Br	main material	1700
Ce	main material	2000
EPS	insulation material	27.5
Gr	main material	2240
GY	main material	1120
HW	main material	750
MW	insulation material	140
PC	main material	2200
PG	insulation material	2500
Pl	main material	540
PUR	insulation material	45
PVC	main material	1380
RC	main material	2300
Sa	main material	2240
SC	main material	2200
SW	main material	560
WF	main material	750
XPS	insulation material	37.5
Zn	main material	7000

Table S7.2.6 The matching relationship between building types of this study and literature building types [211].

Building types of this study	Literature building type
SFH1	standard single-family house
Mid_TH1	standard mid-terraced house
End_TH1	standard mid-terraced house
AB1	standard apartment
MFH1	standard apartment
SFH2	standard single-family house
Mid_TH2	standard mid-terraced house
End_TH2	standard mid-terraced house
AB2	standard apartment

MFH2	standard apartment
SFH3	standard single-family house
Mid_TH3	standard mid-terraced house
End_TH3	standard mid-terraced house
AB3	standard apartment
MFH3	standard apartment
SFH4	standard single-family house
Mid_TH4	standard mid-terraced house
End_TH4	standard mid-terraced house
AB4	standard apartment
MFH4	standard apartment
SFH5	standard single-family house
Mid_TH5	standard mid-terraced house
End_TH5	standard mid-terraced house
AB5	standard apartment
MFH5	standard apartment
SFH6	new single-family house
Mid_TH6	new mid-terraced house
End_TH6	new mid-terraced house
AB6	new apartment
MFH6	new apartment
SFH7	advanced new single-family house
Mid_TH7	advanced new mid-terraced house
End_TH7	advanced new mid-terraced house
AB7	advanced new apartment
MFH7	advanced new apartment

Table S7.2.7 Material intensities for existing residential buildings (kg/m^2) [211].

Building type	SFH1-5	Mid_TH1-5	End_TH1-5	AB1-5	MFH1-5
AC	0.00	0.00	0.00	0.00	0.00
Al	0.00	0.00	0.00	0.00	0.00
Ar	0.00	0.00	0.00	0.00	0.00
Bi	2.50	2.50	2.50	4.79	4.79
Br	96.42	48.91	48.91	55.65	55.65
Ce	5.63	5.66	5.66	4.69	4.69
EPS	0.00	0.00	0.00	0.00	0.00
Gr	6.30	6.34	6.34	12.62	12.62
GY	45.27	45.24	45.24	43.89	43.89
HW	0.00	0.00	0.00	0.00	0.00
MW	0.00	0.00	0.00	0.00	0.00

PC	844.82	725.37	725.37	550.89	550.89
PG	5.34	1.86	1.86	1.76	1.76
Pl	13.75	13.97	13.97	5.26	5.26
PUR	0.00	0.00	0.00	0.00	0.00
PVC	0.04	0.04	0.04	0.02	0.02
RC	255.76	533.10	533.10	330.88	330.88
Sa	571.90	571.95	571.95	571.68	571.68
SC	135.55	135.60	135.60	106.36	106.36
SW	53.00	52.30	52.30	1.12	1.12
WF	0.00	0.00	0.00	0.00	0.00
XPS	0.00	0.00	0.00	0.00	0.00
Zn	1.09	14.09	14.09	0.00	0.00

Table S7.2.8 Material intensities for new buildings [211].

Material labels	SFH 6	Mid_TH6	End_TH6	AB6	MFH6	SFH 7	Mid_TH7	End_TH7	AB7	MFH7
AC	30.3	30.32	30.32	24.5	24.5	30.3	30.32	30.32	24.5	24.5
Al	3.58	5.15	5.15	6.61	6.61	2.15	2.92	2.92	3.44	3.44
Ar	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Bi	2.44	2.44	2.44	4.70	4.70	2.44	2.44	2.44	4.70	4.70
Br	96.4	48.94	48.94	55.4	55.4	18.3	9.29	9.29	10.4	10.4
Ce	5.66	5.59	5.59	4.70	4.70	5.66	5.59	5.59	4.70	4.70
EPS	1.12	1.12	1.12	0.12	0.12	0.62	0.62	0.62	0.16	0.16
Gr	6.34	6.41	6.41	12.5	12.5	6.34	6.41	6.41	12.5	12.5
GY	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HW	8.50	7.87	7.87	7.86	7.86	8.50	7.87	7.87	7.86	7.86
MW	28.4	25.13	25.13	6.39	6.39	31.3	15.92	15.92	18.0	18.0
PC	810.	702.19	702.19	750.	750.	685.	638.85	638.85	678.	678.
PG	5.86	2.07	2.07	1.96	1.96	5.86	2.07	2.07	1.96	1.96
Pl	14.6	14.96	14.96	6.13	6.13	14.6	11.84	11.84	6.13	6.13
PUR	0.00	0.00	0.00	1.35	1.35	5.70	6.42	6.42	1.43	1.43
PVC	0.04	0.04	0.04	0.01	0.01	0.04	0.04	0.04	0.01	0.01
RC	255.	532.97	532.97	284.	284.	255.	532.97	532.97	284.	284.
Sa	571.	571.74	571.74	571.	571.	571.	587.11	587.11	571.	571.
SC	135.	135.49	135.49	105.	105.	135.	135.49	135.49	105.	105.
SW	51.4	51.39	51.39	0.00	0.00	51.4	51.39	51.39	0.00	0.00
WF	0.00	0.00	0.00	0.00	0.00	8.50	4.34	4.34	4.92	4.92
XPS	0.00	0.00	0.00	0.00	0.00	2.30	2.30	2.30	0.25	0.25
Zn	1.24	14.24	14.24	0.69	0.69	1.24	14.24	14.24	0.69	0.69

Table S7.2.9 Insulation materials. HR++ glass contains 2 plates (2×0.5cm thick) and 2 cm argon [211]. HR+++ glass is assumed to contain 3 plates (3×0.5cm thick) and 2cm argon [209,211]. The typical U-values of glasses are from TABULA and Milieu Centraal [68,209].

Insulation standards	Element	Material	Thermal conductivity (k, W/mK)	U-value	G-value [210,3	Density (kg/m^3)
conventional	roof	mineral	0.037	-	-	140
	window	HR++	-	1.8	0.7	-
	wall	mineral	0.037	-	-	140
	door	-	-	-	-	-
	Ground	PUR	0.025	-	-	45
advanced	roof	PUR	0.025	-	-	45
	window	HR+++	-	1.0	0.6	-
	wall	mineral	0.037	-	-	140
	door	PUR	0.025	-	-	45
	Ground	mineral	0.037	-	-	140

7.2.5 Environmental impact factors of materials and energies

Table S7.2.10 GHG emissions factors (SSP2 [216]) of building materials from ecoinvent 3.6 (kg CO_2 eq/kg).

Materials	Product	Activity	Location	2015-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
AC	Autoclaved aerated concrete block	market for autoclaved aerated concrete block	CH	0.43	0.43	0.42	0.41	0.41	0.40	0.40
Al	Aluminium, wrought alloy	market for aluminium, wrought alloy	GLO	11.07	10.99	10.93	10.87	10.77	10.72	10.71
Ar	Argon, liquid	market for argon, liquid	RER	2.18	1.99	1.77	1.62	1.44	1.32	1.24
Bi	Bitumen seal	market for bitumen seal	GLO	1.11	1.10	1.10	1.09	1.09	1.09	1.09
Br	Clay brick	market for clay brick	GLO	0.30	0.30	0.30	0.30	0.30	0.30	0.30

Ce	Ceramic tile	market for ceramic tile	GLO	0.73	0.71	0.70	0.69	0.69	0.69	0.69
EPS	Polystyrene foam slab, 10% recycled	polystyrene foam slab production, 10% recycled	CH	3.94	3.90	3.86	3.83	3.79	3.77	3.76
Gr	Gravel, crushed	market for gravel, crushed	CH	0.01	0.01	0.01	0.01	0.01	0.01	0.01
GY	Gypsum plasterboard	market for gypsum plasterboard	GLO	0.34	0.34	0.33	0.33	0.33	0.32	0.33
HW	Sawnwood, beam, hardwood, dried (u=10%), planed	market for sawnwood, beam, hardwood, dried (u=10%), planed	GLO	-2.14	-2.14	-2.15	-2.15	-2.15	-2.15	-2.15
MW	Glass wool mat	market for glass wool mat	GLO	2.27	2.18	2.11	2.06	2.03	2.03	2.04
PC	Concrete, sole plate and foundation	market for concrete, sole plate and foundation	CH	0.15	0.14	0.14	0.14	0.14	0.14	0.14
PG	Glazing, double, U<1.1 W/m2K	market for glazing, double, U<1.1 W/m2K	GLO	1.41	1.40	1.38	1.38	1.37	1.37	1.37
Pl	Plywood, for indoor use	market for plywood, for indoor use	RER	-3.12	-3.15	-3.19	-3.22	-3.24	-3.26	-3.27
PUR	Polyurethane, flexible foam	market for polyurethane, flexible foam	RER	5.45	5.44	5.43	5.42	5.41	5.41	5.40

PVC	Polyvinylchloride, suspension polymerised	market for polyvinylchloride, suspension polymerised	GLO	2.25	2.20	2.16	2.13	2.11	2.11	2.12
RC	Fibre-reinforced concrete	market for fibre-reinforced concrete, steel	BR	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Sa	Sand	market for sand	CH	0.01	0.01	0.01	0.01	0.01	0.01	0.01
SC	Cement mortar	market for cement mortar	CH	0.24	0.24	0.23	0.23	0.23	0.22	0.22
SW	Shavings, softwood, loose, measured as dry mass	planing, board, softwood, u=10%	CH	-0.87	-0.88	-0.88	-0.88	-0.89	-0.89	-0.89
WF	Fibreboard, soft, latex bonded	market for fibreboard, soft, latex bonded	GLO	0.31	0.30	0.30	0.29	0.29	0.29	0.29
XPS	Polystyrene, extruded	market for polystyrene, extruded	GLO	9.49	9.45	9.41	9.39	9.37	9.37	9.37
Zn	Zinc	market for zinc	GLO	3.19	3.08	2.93	2.85	2.76	2.73	2.72

Table S7.2.11 GHG emissions factors (SSP2 450 [216]) of building materials from ecoinvent 3.6 (kg CO_2 eq/kg).

Materials	Product	Activity	Location	2015-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
AC	Autoclaved aerated	market for autoclaved aerated	CH	0.43	0.42	0.41	0.38	0.36	0.36	0.36

	concrete block	concrete block								
Al	Aluminium, wrought alloy	market for aluminium, wrought alloy	GLO	11.04	10.91	10.81	10.65	10.45	10.33	10.25
Ar	Argon, liquid	market for argon, liquid	RER	2.05	1.76	1.37	0.71	0.23	0.05	0.03
Bi	Bitumen seal	market for bitumen seal	GLO	1.10	1.08	1.07	1.04	1.01	1.00	1.00
Br	Clay brick	market for clay brick	GLO	0.30	0.30	0.29	0.28	0.27	0.27	0.27
Ce	Ceramic tile	market for ceramic tile	GLO	0.70	0.67	0.63	0.57	0.51	0.49	0.48
EPS	Polystyrene foam slab, 10% recycled	polystyrene foam slab production, 10% recycled	CH	3.92	3.87	3.79	3.66	3.56	3.53	3.52
Gr	Gravel, crushed	market for gravel, crushed	CH	0.01	0.01	0.01	0.01	0.01	0.01	0.01
GY	Gypsum plasterboard	market for gypsum plasterboard	GLO	0.33	0.32	0.30	0.28	0.25	0.25	0.24
HW	Sawnwood, beam, hardwood, dried (u=10%), planed	market for sawnwood, beam, hardwood, dried (u=10%), planed	GLO	-2.14	-2.15	-2.16	-2.18	-2.19	-2.20	-2.20
MW	Glass wool mat	market for glass wool mat	GLO	2.15	1.92	1.70	1.36	1.03	0.91	0.85
PC	Concrete, sole plate and	market for concrete, sole plate	CH	0.15	0.14	0.14	0.13	0.13	0.13	0.13

	foundation	and foundation								
PG	Glazing, double, U<1.1 W/m2K	market for glazing, double, U<1.1 W/m2K	GLO	1.40	1.36	1.33	1.28	1.23	1.21	1.21
Pl	Plywood, for indoor use	market for plywood, for indoor use	RER	-3.14	-3.20	-3.26	-3.38	-3.46	-3.49	-3.50
PUR	Polyurethane, flexible foam	market for polyurethane, flexible foam	RER	5.44	5.42	5.40	5.37	5.34	5.33	5.33
PVC	Polyvinylchloride, suspension polymerised	market for polyvinylchloride, suspension polymerised	GLO	2.19	2.06	1.94	1.75	1.56	1.49	1.46
RC	Fibre-reinforced concrete	market for fibre-reinforced concrete, steel	BR	0.18	0.17	0.17	0.17	0.17	0.17	0.17
Sa	Sand	market for sand	CH	0.01	0.01	0.01	0.01	0.00	0.00	0.00
SC	Cement mortar	market for cement mortar	CH	0.24	0.23	0.23	0.21	0.20	0.20	0.20
SW	Shavings, softwood, loose, measured as dry mass	planing, board, softwood, u=10%	CH	-0.88	-0.88	-0.89	-0.90	-0.90	-0.91	-0.91
WF	Fibreboard, soft, latex bonded	market for fibreboard, soft, latex bonded	GLO	0.30	0.28	0.26	0.24	0.21	0.20	0.19

XPS	Polystyrene, extruded	market for polystyrene, extruded	GLO	9.44	9.33	9.23	9.06	8.90	8.84	8.82
Zn	Zinc	market for zinc	GLO	3.01	2.74	2.37	1.75	1.25	1.09	1.04

Table S7.2.12 GHG emissions factors (SSP2 [216]) of energy supply from ecoinvent 3.6 (kg CO_2 eq/kWh). The GHG emission factors of heat networks and hybrid heat pumps are weighted average factors of sub-energy sources [156]. Green gas is produced by drying and purifying biogas to the same quality as natural gas [329,330]. In the Netherlands, biogas will be mainly produced from animal manure (e.g. cattle and chicken) and the treatment of biowaste (e.g. fruit and vegetables) [331]. And their shares are similar (assumed as 50% for each) [331].

Energy supply	Product	Activity	Location	2015-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
Natural gas boiler	Heat, central or small-scale, natural gas	Heat production, natural gas, at boiler condensing modulating <100kW	Europe without Switzerland	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Heat network	Heat	70%: geothermal (GHG emission factor is from Verhagen et al.[74])	NL	0.09	0.09	0.09	0.09	0.09	0.09	0.09
		15%: heat and power co-generation, biogas, gas engine (biogas inputs adapted with shares of production methods of the Netherlands)	NL	0.23	0.23	0.23	0.23	0.23	0.23	0.23
		10%: heat and power co-generation, wood chips, 6667 kW,	NL	0.01	0.01	0.01	0.01	0.01	0.01	0.01

		state-of-the-art 2014								
		5%: heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	NL	0	0	0	0	0	0	0
		Weighted average factors	-	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Electric heat pump	Heat, air-water heat pump 10kW	Market for floor heating from air-water heat pump	Europe without Switzerland	0.26	0.24	0.22	0.20	0.18	0.17	0.16
Hybrid heat pump (heat pump +biogas boiler)	Heat	65%[214]: market for floor heating from air-water heat pump	Europe without Switzerland	0.26	0.24	0.22	0.20	0.18	0.17	0.16
		35%[214]: heat production from green gas boiler (adapted from natural gas boiler by replacing natural gas with green gas; 1 m^3 of biogas equals to 0.63 m^3 of natural gas[331])	NL	0.37	0.37	0.37	0.37	0.36	0.36	0.36
		Weighted average factors	-	0.30	0.29	0.27	0.26	0.25	0.24	0.23
Solar water heater	Heat, central or small-scale, other than natural gas	Operation, solar collector system, Cu flat plate collector, multiple dwelling, for hot water	CH	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Grid electricity	Electricity, low voltage	Market for electricity, low voltage	NL	0.66	0.59	0.52	0.47	0.42	0.38	0.37
PV electricity	Electricity, low voltage	Electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	NL	0.08	0.08	0.08	0.07	0.07	0.07	0.07

Table S7.2.13 GHG emissions factors (SSP2 450 [216]) of energy supply from ecoinvent 3.6 (kg CO_2 eq/kWh). The GHG emission factors of heat networks and hybrid heat pumps are weighted average factors of sub-energy sources [156]. Green gas is produced by drying and purifying biogas to the same quality as natural gas [329,330]. In the Netherlands, biogas will be mainly produced from animal manure (e.g. cattle and chicken) and the treatment of biowaste (e.g. fruit and vegetables) [331]. And their shares are similar (assumed as 50% for each) [331].

Energy supply	Product	Activity	Location	2015-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
Natural gas boiler	Heat, central or small-scale, natural gas	Heat production, natural gas, at boiler condensing modulating <100kW	Europe without Switzerland	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Heat network	Heat	70%: geothermal (GHG emission factor is from Verhagen et al.[74])	NL	0.09	0.09	0.09	0.09	0.09	0.09	0.09
		15%: heat and power co-generation, biogas, gas engine (biogas inputs adapted with shares of production methods of the Netherlands)	NL	0.23	0.23	0.23	0.23	0.22	0.22	0.22

		10%: heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014	NL	0.01	0.01	0.01	0.01	0.01	0.01	0.01
		5%: heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas	NL	0	0	0	0	0	0	0
		Weighted average factors	-	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Electric heat pump	Heat, air-water heat pump 10kW	Market for floor heating from air-water heat pump	Europe without Switzerland	0.25	0.22	0.18	0.11	0.05	0.03	0.03
Hybrid heat pump (heat pump +biogas boiler)	Heat	65%[214]: market for floor heating from air-water heat pump	Europe without Switzerland	0.25	0.22	0.18	0.11	0.05	0.03	0.03
		35%[214]: heat production from green gas boiler (adapted from natural gas boiler by replacing natural gas with green gas; 1 m³ of biogas equals to 0.63 m³ of natural gas[331])	NL	0.37	0.37	0.36	0.36	0.36	0.35	0.35
		Weighted average factors	-	0.29	0.27	0.24	0.19	0.16	0.15	0.14
Solar water heater	Heat, central or small-	Operation, solar collector system, Cu flat	CH	0.01	0.01	0.01	0.01	0.01	0.01	0.01

	scale, other than natural gas	plate collector, multiple dwelling, for hot water								
Grid electricity	Electricity, low voltage	Market for electricity, low voltage	NL	0.63	0.54	0.44	0.22	0.06	0.00	-0.01
PV electricity	Electricity, low voltage	Electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	NL	0.08	0.07	0.06	0.05	0.04	0.04	0.04

7.3 Supporting information to Chapter 4

7.3.1 Map of population per city

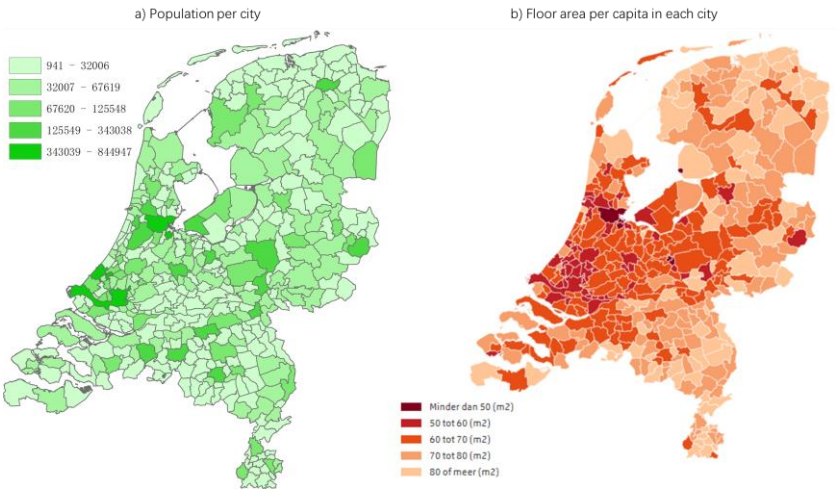

Figure S7.3.1 Population and floor area per city [232,332].

7.3.2 Material composition

Table S7.3.1 Material intensities [147] of existing buildings (kg/m^2). Apartment buildings are divided into low and high (more than 5 floors) apartment buildings [44]. SFH: single-family house. TH: terraced house. AB: apartment building.

Building type	SFH	TH	AB_low	AB_high
Al	6.05	6.05	6.05	6.05
Ar	0.00	0.00	0.00	0.00

Bi	0.00	0.00	0.00	0.00
CB	635.29	124.10	310.28	245.78
Ce	5.17	21.29	5.17	5.17
Co	0.00	0.00	0.00	0.00
CI	4.90	4.90	4.90	4.90
Cr	974.12	353.20	883.09	699.53
EPS	0.00	0.00	0.00	0.00
Gl	0.00	0.00	0.00	0.00
Gr	0.00	0.00	0.00	0.00
Gy	0.00	10.26	10.96	6.70
HW	0.00	0.00	0.00	0.00
MW	0.00	0.00	0.00	0.00
Pl	0.00	7.65	0.00	5.11
PUR	0.00	0.00	0.00	0.00
Pw	0.00	0.00	0.00	0.00
RC	0.00	0.00	0.00	0.00
Sa	0.00	0.00	0.00	0.00
SC	0.00	0.00	0.00	0.00
St	36.52	14.80	33.34	26.92
SW	246.70	69.27	49.10	61.09
WF	0.00	0.00	0.00	0.00
XPS	0.00	0.00	0.00	0.00
Zn	0.00	0.00	0.00	0.00

Table S7.3.2 Material intensities [211] of new buildings (kg/m^2). SFH: single-family house. TH: terraced house. AB: apartment building. MFH: multi-family house.

Building type	SFH 6	Mid_TH6	End_TH6	AB6	MFH6	SFH 7	Mid_TH7	End_TH7	AB7	MFH7
Al	3.58	5.15	5.15	6.61	6.61	2.15	2.92	2.92	3.44	3.44
Ar	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Bi	2.44	2.44	2.44	4.70	4.70	2.44	2.44	2.44	4.70	4.70
CB	96.43	48.94	48.94	55.44	55.44	18.35	9.29	9.29	10.49	10.49
Ce	5.66	5.59	5.59	4.70	4.70	5.66	5.59	5.59	4.70	4.70
Co	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	810.69	702.19	702.19	750.20	750.20	685.89	638.85	638.85	678.46	678.46
EPS	1.12	1.12	1.12	0.12	0.12	0.62	0.62	0.62	0.16	0.16
Gl	5.86	2.07	2.07	1.96	1.96	5.86	2.07	2.07	1.96	1.96
Gr	6.34	6.41	6.41	12.5	12.5	6.34	6.41	6.41	12.5	12.5

				0	0				0	0
Gy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HW	8.50	7.87	7.87	7.86	7.86	8.50	7.87	7.87	7.86	7.86
MW	28.47	25.13	25.13	6.39	6.39	31.38	15.92	15.92	18.03	18.03
Pl	0.04	0.04	0.04	0.01	0.01	0.04	0.04	0.04	0.01	0.01
PUR	0.00	0.00	0.00	1.35	1.35	5.70	6.42	6.42	1.43	1.43
Pw	14.60	14.96	14.96	6.13	6.13	14.60	11.84	11.84	6.13	6.13
RC	255.75	532.97	532.97	284.48	284.48	255.75	532.97	532.97	284.48	284.48
Sa	571.89	571.74	571.74	571.89	571.89	571.89	587.11	587.11	571.89	571.89
SC	135.60	135.49	135.49	105.79	105.79	135.60	135.49	135.49	105.79	105.79
St	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SW	51.42	51.39	51.39	0.00	0.00	51.42	51.39	51.39	0.00	0.00
WF	0.00	0.00	0.00	0.00	0.00	8.50	4.34	4.34	4.92	4.92
XPS	0.00	0.00	0.00	0.00	0.00	2.30	2.30	2.30	0.25	0.25
Zn	1.24	14.24	14.24	0.69	0.69	1.24	14.24	14.24	0.69	0.69

Table S7.3.3 Insulation materials. HR++ glass contains 2 plates (2×0.5cm thick) and 2cm argon [211]. HR+++ glass is assumed to contain 3 plates (3×0.5cm thick) and 2cm argon [209,211]. The typical U-values of glasses are from TABULA and Milieu Centraal [68,209].

Insulation standards	Element	Material	Thermal conductivity (k, W/mK)	U-value	Density (kg/m^3)
conventional	Roof	mineral wool	0.037	-	140
	Window	HR++ glass	-	1.8	-
	Wall	mineral wool	0.037	-	140
	Door	-	-	-	-
	Ground floor	PUR	0.025	-	45
advanced	Roof	PUR	0.025	-	45
	Glass	HR+++ glass	-	1.0	-
	Wall	mineral wool	0.037	-	140
	Door	PUR	0.025	-	45
	Ground floor	mineral wool	0.037	-	140

7.3.3 Outflow collection and recycling

Table S7.3.4 EOL collection rate and recycled content potential of material outflows [44]. Considering that [44] only includes the EOL processing of 11 kinds of main materials (italicized), the EOL collection rates and recycled content potential of other materials are assumed as zero.

Material label	Material name	EOL collection rate (%)	Recycled content potential (%)
Al	*Aluminum*	*95*	*50*
Ar	Argon	0	0
Bi	*Bitumen*	*50*	*50*
CB	*Clay brick*	*95*	*50*
Ce	*Ceramic*	*95*	*80*
Co	Copper	0	0
CI	*Cast iron*	*95*	*96*
Cr	*Concrete*	*85*	*50*
EPS	Expanded polystyrene	0	0
Gl	*Glass*	*95*	*91*
Gr	Gravel	0	0
Gy	*Gypsum*	*95*	*40*
HW	*Hardwood*	*95*	*90*
MW	Mineral wool	0	0
Pl	Plastic	0	0
PUR	Polyurethane foam	0	0
Pw	Plywood	0	0
RC	reinforced concrete	0	0
Sa	Sand	0	0
SC	Sand cement	0	0
St	*Steel*	*95*	*85*
SW	*Softwood*	*95*	*90*
WF	Wood fiber	0	0
XPS	Extruded polystyrene	0	0
Zn	Zinc	0	0

7.3.4 Environmental impact factors of materials, transportation, and landfill

Table S7.3.5 GHG emissions factors (SSP2) [142,216] of building material production from ecoinvent 3.6 (kg CO_2 eq/kg) [138].

Materials	Product	Activity	Location	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049	2050

Al	aluminium, wrought alloy	market for aluminium, wrought alloy	GLO	11.1708	11.0726	10.9905	10.9299	10.8688	10.7739	10.7226	10.7092
Ar	argon, liquid	market for argon, liquid	RoW	2.1136	2.0157	1.8903	1.7881	1.7290	1.6830	1.6788	1.6938
Bi	bitumen adhesive compound, hot	market for bitumen adhesive compound, hot	GLO	0.5125	0.5114	0.5090	0.5069	0.5056	0.5045	0.5043	0.5045
CB	clay brick	market for clay brick	GLO	0.3054	0.3041	0.3019	0.3000	0.2988	0.2979	0.2976	0.2978
Ce	ceramic tile	market for ceramic tile	GLO	0.7372	0.7252	0.7100	0.6981	0.6911	0.6857	0.6857	0.6882
Co	copper	market for copper	GLO	4.1972	4.1027	4.0054	3.9332	3.8907	3.8575	3.8601	3.8794
CI	cast iron	market for cast iron	GLO	1.7268	1.7104	1.6888	1.6710	1.6606	1.6526	1.6519	1.6547
Cr	concrete, normal	market for concrete, normal	CH	0.0737	0.0743	0.0733	0.0720	0.0711	0.0702	0.0696	0.0693
EPS	polystyrene, expandable	market for polystyrene, expandable	GLO	3.6422	3.6418	3.6412	3.6406	3.6403	3.6400	3.6400	3.6401

Gl	flat glass, coated	market for flat glass, coated	RoW	1.1517	1.1423	1.1335	1.1269	1.1234	1.1213	1.1223	1.1244
Gr	gravel, crushed	market for gravel, crushed	CH	0.0088	0.0090	0.0087	0.0083	0.0080	0.0078	0.0076	0.0075
Gy	gypsum, mineral	gypsum quarry operation	CH	0.0026	0.0027	0.0026	0.0025	0.0025	0.0024	0.0024	0.0024
HW	sawn wood, hardwood, raw	sawing, hardwood	CH	-2.1050	-2.1040	-2.1057	-2.1078	-2.1092	-2.1107	-2.1116	-2.1122
MW	glass wool mat	market for glass wool mat	GLO	2.3360	2.2667	2.1758	2.1053	2.0630	2.0302	2.0286	2.0413
Pl	extrusion, plastic pipes	market for extrusion, plastic pipes	GLO	0.3488	0.3390	0.3189	0.3009	0.2899	0.2797	0.2761	0.2761
PUR	polyurethane, flexible foam	market for polyurethane, flexible foam	RER	5.4463	5.4495	5.4394	5.4282	5.4206	5.4118	5.4061	5.4028
Pw	plywood, for indoor use	market for plywood, for indoor use	RER	-3.1333	-3.1204	-3.1531	-3.1899	-3.2151	-3.2442	-3.2631	-3.2743

RC	fibre-reinforced concrete	market for fibre-reinforced concrete, steel	BR	0.1738	0.1736	0.1736	0.1735	0.1732	0.1731	0.1733	0.1734
Sa	sand	gravel and sand quarry operation	CH	0.0037	0.0039	0.0037	0.0035	0.0033	0.0031	0.0031	0.0030
SC	cement mortar	market for cement mortar	CH	0.2401	0.2424	0.2384	0.2336	0.2304	0.2268	0.2248	0.2235
St	wire drawing, steel	market for wire drawing, steel	GLO	0.3117	0.3049	0.2992	0.2952	0.2932	0.2922	0.2933	0.2950
SW	sawn wood, softwood, raw	sawing, softwood	CH	-1.4715	-1.4705	-1.4721	-1.4741	-1.4754	-1.4768	-1.4776	-1.4781
WF	fibreboard, soft	fibreboard production, soft, from wet & dry processes	Europe without Switzerland	-0.0821	-0.0807	-0.0867	-0.0935	-0.0983	-0.1045	-0.1087	-0.1113
XPS	polystyrene, extruded	market for polystyrene, extruded	GLO	9.5244	9.4950	9.4501	9.4121	9.3897	9.3708	9.3668	9.3701

Zn	zinc	market for zinc	GLO	3.1601	3.1950	3.0817	2.9311	2.8472	2.7568	2.7267	2.7197

Table S7.3.6 GHG emissions factors (SSP2 450) [142,216] of building material production from ecoinvent 3.6 (kg CO_2 eq/kg) [138].

Materials	Product	Activity	Location	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049	2050
Al	aluminium, wrought alloy	market for aluminium, wrought alloy	GLO	11.1667	11.0403	10.9137	10.8074	10.6457	10.4540	10.3293	10.2472
Ar	argon, liquid	market for argon, liquid	RoW	2.0820	1.8549	1.5417	1.2476	0.7770	0.3092	0.1337	0.0731
Bi	bitumen adhesive compound, hot	market for bitumen adhesive compound, hot	GLO	0.5119	0.5084	0.5029	0.4973	0.4885	0.4802	0.4769	0.4754
CB	clay brick	market for clay brick	GLO	0.3049	0.3014	0.2961	0.2909	0.2826	0.2747	0.2717	0.2706
Ce	ceramic tile	market for ceramic tile	GLO	0.7333	0.7047	0.6652	0.6269	0.5679	0.5106	0.4893	0.4794
Co	copper	market for copper	GLO	4.1720	3.9733	3.7175	3.4744	3.1055	2.7341	2.5898	2.5228
CI	cast iron	market for cast iron	GLO	1.7212	1.6818	1.6266	1.5741	1.4909	1.4091	1.3786	1.3668
Cr	concrete, normal	market for concrete, normal	CH	0.0734	0.0737	0.0723	0.0702	0.0666	0.0638	0.0628	0.0627
EPS	polystyrene,	market for polystyre	GLO	3.6420	3.6409	3.6392	3.6376	3.6350	3.6325	3.6316	3.6311

	expandable	ne, expandable									
Gl	flat glass, coated	market for flat glass, coated	RoW	1.1494	1.1296	1.1055	1.0838	1.0498	1.0143	1.0009	0.9956
Gr	gravel, crushed	market for gravel, crushed	CH	0.0087	0.0088	0.0084	0.0077	0.0066	0.0058	0.0055	0.0055
Gy	gypsum, mineral	gypsum quarry operation	CH	0.0026	0.0026	0.0026	0.0024	0.0022	0.0021	0.0020	0.0020
HW	sawnwood, hardwood, raw	sawing, hardwood	CH	-2.1054	-2.1050	-2.1074	-2.1108	-2.1167	-2.1213	-2.1230	-2.1232
MW	glass wool mat	market for glass wool mat	GLO	2.3139	2.1527	1.9243	1.7032	1.3646	1.0343	0.9115	0.8547
Pl	extrusion, plastic pipes	market for extrusion, plastic pipes	GLO	0.3437	0.3161	0.2702	0.2246	0.1503	0.0809	0.0549	0.0469
PUR	polyurethane, flexible foam	market for polyurethane, flexible foam	RER	5.4438	5.4419	5.4249	5.4042	5.3687	5.3417	5.3316	5.3299
Pw	plywood, for indoor use	market for plywood, for indoor use	RER	-3.1413	-3.1435	-3.1962	-3.2625	-3.3766	-3.4624	-3.4944	-3.4989
RC	fibre-reinforced concrete	market for fibre-reinforced concrete, steel	BR	0.1736	0.1723	0.1710	0.1698	0.1678	0.1660	0.1657	0.1655

Sa	sand	gravel and sand quarry operation	CH	0.0037	0.0038	0.0035	0.0032	0.0025	0.0021	0.0019	0.0019
SC	cement mortar	market for cement mortar	CH	0.2392	0.2401	0.2345	0.2266	0.2127	0.2021	0.1981	0.1977
St	wire drawing, steel	market for wire drawing, steel	GLO	0.3103	0.2963	0.2802	0.2660	0.2439	0.2202	0.2113	0.2077
SW	sawnwood, softwood, raw	sawing, softwood	CH	-1.4719	-1.4715	-1.4737	-1.4769	-1.4824	-1.4866	-1.4883	-1.4884
WF	fibreboard, soft	fibreboard production, soft, from wet & dry processes	Europe without Switzerland	-0.0837	-0.0859	-0.0968	-0.1096	-0.1319	-0.1485	-0.1544	-0.1556
XPS	polystyrene, extruded	market for polystyrene, extruded	GLO	9.5131	9.4398	9.3316	9.2277	9.0604	8.8983	8.8375	8.8170
Zn	zinc	market for zinc	GLO	3.1193	3.0114	2.7432	2.3736	1.7496	1.2504	1.0924	1.0431

Table S7.3.7 GHG emissions factors (SSP2) [142,216] of recycled building materials. The materials are from ecoinvent 3.6 (kg CO_2 eq/kg) [138]. The factors of the other recycled materials are assumed as zero.

Materials	Product	Activity	Location	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049	2050
Al	aluminium scrap, post-consumer, prepared for melting	aluminium scrap, post-consumer, prepared for melting, Recycled	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

		Content cut-off									
Ar	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Bi	waste bitumen sheet	market for waste bitumen sheet	CH	-2.3591	-2.3587	-2.3580	-2.3573	-2.3569	-2.3565	-2.3563	-2.3563
CB	waste brick	treatment of waste brick, recycling	CH	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033
Ce	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Co	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CI	iron scrap, sorted, pressed	iron scrap, sorted, pressed, Recycled Content cut-off	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cr	waste concrete, not reinforced	treatment of waste concrete, not reinforced, recycling	Europe without Switzerland	-0.0040	-0.0040	-0.0040	-0.0040	-0.0040	-0.0040	-0.0040	-0.0040
EPS	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gl	glass cullet, sorted	glass cullet, sorted, Recycled Content cut-off	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gr	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Gy	waste gypsum plasterboard	treatment of waste gypsum plasterboard, recycling	CH	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033
HW	waste wood, post-consumer	waste wood, post-consumer, Recycled Content cut-off	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
MW	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pl	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PUR	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pw	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
RC	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sa	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SC	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
St	waste reinforcement steel	treatment of waste reinforcement steel, recycling	CH	-0.0574	-0.0573	-0.0572	-0.0571	-0.0571	-0.0570	-0.0570	-0.0570
SW	waste wood, post-consumer	waste wood, post-consumer, Recycled	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

		Content cut-off									
WF	-	-	-	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000
XPS	-	-	-	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000
Zn	-	-	-	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000

Table S7.3.8 GHG emissions factors (SSP2 450) [142,216] of recycled building materials. The materials are from ecoinvent 3.6 (kg CO_2 eq/kg) [138]. The factors of the other recycled materials are assumed as zero.

Materials	Product	Activity	Location	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049	2050
Al	aluminium scrap, post-consumer, prepared for melting	aluminium scrap, post-consumer, prepared for melting, Recycled Content cut-off	GLO	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000
Ar	-	-	-	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000
Bi	waste bitumen sheet	market for waste bitumen sheet	CH	-2.3 589	-2.3 579	-2.3 562	-2.3 544	-2.3 516	-2.3 490	-2.3 480	-2.3 477
CB	waste brick	treatment of waste brick, recycling	CH	-0.0 033	-0.0 033	-0.0 033	-0.0 033	-0.0 032	-0.0 032	-0.0 032	-0.0 032
Ce	-	-	-	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000
Co	-	-	-	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000	0.0 000

CI	iron scrap, sorted, pressed	iron scrap, sorted, pressed, Recycled Content cut-off	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cr	waste concrete, not reinforced	treatment of waste concrete, not reinforced, recycling	Europe without Switzerland	-0.0040	-0.0040	-0.0040	-0.0040	-0.0039	-0.0039	-0.0039	-0.0039
EPS	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gl	glass cullet, sorted	glass cullet, sorted, Recycled Content cut-off	GLO	-2.3589	-2.3579	-2.3562	-2.3544	-2.3516	-2.3490	-2.3480	-2.3477
Gr	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gy	waste gypsum plasterboard	treatment of waste gypsum plasterboard, recycling	CH	-0.0033	-0.0033	-0.0033	-0.0033	-0.0032	-0.0032	-0.0032	-0.0032
HW	waste wood, post-consumer	waste wood, post-consumer, Recycled Content cut-off	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
MW	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pl	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PUR	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Pw	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
RC	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sa	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SC	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
St	waste reinforcement steel	treatment of waste reinforcement steel, recycling	CH	-0.0573	-0.0572	-0.0569	-0.0567	-0.0563	-0.0560	-0.0558	-0.0558
SW	waste wood, post-consumer	waste wood, post-consumer, Recycled Content cut-off	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WF	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
XPS	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Zn	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table S7.3.9 GHG emissions factors (SSP2) [142,216] of transportation from ecoinvent 3.6 (kg CO_2 eq/(kg·km)) [138].

Materials	Product	Activity	Location	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049	2050
Truck transpor	transport, freight, lorry	transport, freight, lorry 16-32 metric	RER	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002

tation (SSP2)	16-32 metric ton, EURO6	ton, EURO6									
Ship transportation (SSP2)	transport, freight, sea, container ship	market for transport, freight, sea, container ship	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Truck transportation (SSP2 450)	transport, freight, lorry 16-32 metric ton, EURO6	transport, freight, lorry 16-32 metric ton, EURO6	RER	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Ship transportation (SSP2 450)	transport, freight, sea, container ship	market for transport, freight, sea, container ship	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table S7.3.10 GHG emissions factors of landfill from ecoinvent 3.6 (kg CO_2 eq/kg) [138,142].

Materials	Product	Activity	Location	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049	2050
Landfill (SSP2)	inert waste	treatment of inert waste, sanitary landfill	Europe without Switzerland	-0.0103	-0.0102	-0.0101	-0.0100	-0.0100	-0.0100	-0.0099	-0.0100
Landfill (SSP2 450)	inert waste	treatment of inert waste, sanitary landfill	Europe without Switzerland	-0.0103	-0.0101	-0.0098	-0.0096	-0.0092	-0.0088	-0.0087	-0.0086

7.3.5 Sensitivity analysis for concrete

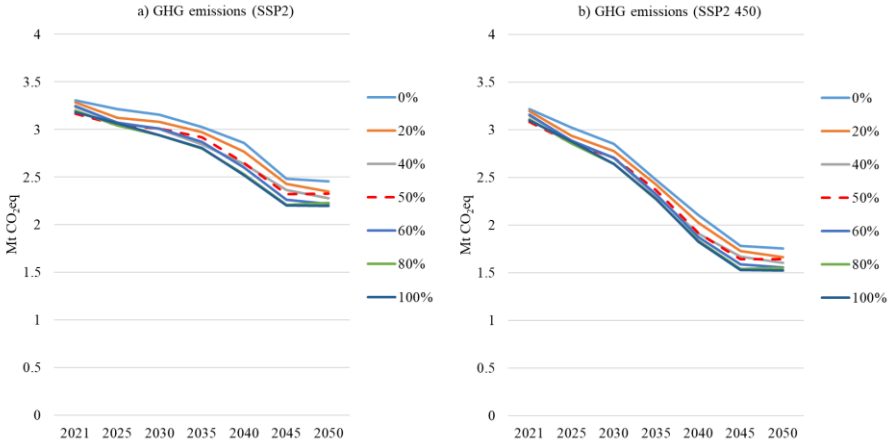

Figure S7.3.2 Sensitivity analysis for the recycled content potential of concrete. The recycled content potential for the red dash line is 50%, which is used in this study.

7.4 Supporting information to Chapter 5

7.4.1 Individual building characterization

Table S7.4.1 Building classification based on TABULA[68].

Construction period	Single-family house	Mid-terraced house	End-terraced house	Apartment building	Multi-family house	Apartment building (wood)
<=1964	SFH1	Mid_TH1	End_TH1	AB1	MFH1	-
1965-1974	SFH2	Mid_TH2	End_TH2	AB2	MFH2	-
1975-1991	SFH3	Mid_TH3	End_TH3	AB3	MFH3	-
1992-2005	SFH4	Mid_TH4	End_TH4	AB4	MFH4	-
2006-2014	SFH5	Mid_TH5	End_TH5	AB5	MFH5	-
>=2015 (conventional new)	SFH6	Mid_TH6	End_TH6	AB6	MFH6	AB6_wood
>=2015 (nZEB new)	SFH7	Mid_TH7	End_TH7	AB7	MFH7	AB7_wood

Table S7.4.2 Attributes of individual buildings.

Information type	Parameters
Basic information	ID number

	construction yeat	
	expected demolition year	
	stories	
	building type	
	conditioned floor area	
Location	postcode	
	neighborhood code	
	weather station code	
	available heat sources	
Envelope	roof	surface area
		U-value
		construction year
		retirement year
	external wall	surface area
		U-value
		construction year
		retirement year
	ground floor	surface area
		U-value
		construction year
		retirement year
	glazing	surface area
		U-value
		G-value
		construction year
		retirement year
	door	surface area
		U-value
		construction year
		retirement year
Technical system	space heating system	type
		recoverable heat loss of the heat distribution system per m²
		recoverable heat loss of the storage per m²
		annual effective heat loss of the space heating distribution system per m²
		annual effective heat loss of the heating system storage per m²
		installation year
		retirement year

	domestic hot water system	type
		annual energy need for domestic hot water per m²
		annual heat loss of the DHW distribution system per m²
		annual heat loss of the DHW storage per m²
		installation year
		retirement year
	ventilation system	type
		the efficiency of ventilation heat recovery
		installation year
		retirement year
	solar panel	type
		efficiency
		installation year
		retirement year
Occupant behavior	room temperature	
	time of presence	
Material composition (see **Table S7.4.3**)	material stock every year	
	material outflow every year	
	material inflow every year	
Energy	space heating	
	hot water	
	electricity for appliances and lighting	
	electricity generation	
Environmental impact	material-related emissions	
	space heating	
	hot water	
	electricity for appliances and lighting	
	electricity generation	

Table S7.4.3 The example table for recording material stock and flows.

Year	Material_1 stock	Material_2 stock	⋯	Material_1 outflow	Material_2 outflow	⋯	Material_1 inflow	Material_2 inflow	⋯
2015									
2016									
2017									
…									

2049									
2050									

Table S7.4.4 Building materials [280].

Label	Name	Label	Name
Al	Aluminum	MW	Mineral wool
Ar	Argon	Pl	Plastic
Bi	Bitumen	PUR	Polyurethane foam
CB	Clay brick	Pw	Plywood
Ce	Ceramic	RC	reinforced concrete
Co	Copper	Sa	Sand
CI	Cast iron	SC	Sand cement
Cr	Concrete	St	Steel
EPS	Expanded polystyrene	SW	Softwood
Gl	Glass	WF	Wood fiber
Gr	Gravel	XPS	Extruded polystyrene
Gy	Gypsum	Zn	Zinc
HW	Hardwood	-	-

Table S7.4.5 Material intensities of new buildings (kg/m^2). The material intensities of wood apartment buildings are from [211,281].

Building type	SFH6	Mid_TH6	End_TH6	AB6	MFH6	AB6_wood	SFH7	Mid_TH7	End_TH7	AB7	MFH7	AB7_wood
Al	3.58	5.15	5.15	6.61	6.61	0.10	2.15	2.92	2.92	3.44	3.44	0.10
Ar	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Bi	2.44	2.44	2.44	4.70	4.70	0.00	2.44	2.44	2.44	4.70	4.70	0.00
CB	96.43	48.94	48.94	55.44	55.44	0.00	18.35	9.29	9.29	10.49	10.49	0.00
Ce	5.66	5.59	5.59	4.70	4.70	0.00	5.66	5.59	5.59	4.70	4.70	0.00
Co	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Cr	810.69	702.19	702.19	750.20	750.20	454.20	685.89	638.85	638.85	678.46	678.46	454.20
EPS	1.12	1.12	1.12	0.12	0.12	0.00	0.62	0.62	0.62	0.16	0.16	0.20
Gl	5.86	2.07	2.07	1.96	1.96	3.80	5.86	2.07	2.07	1.96	1.96	3.80
Gr	6.34	6.41	6.41	12.50	12.50	92.70	6.34	6.41	6.41	12.50	12.50	92.70
Gy	0.00	0.00	0.00	0.00	0.00	51.40	0.00	0.00	0.00	0.00	0.00	51.40
HW	8.50	7.87	7.87	7.86	7.86	15.70	8.50	7.87	7.87	7.86	7.86	15.70
MW	28.47	25.13	25.13	6.39	6.39	11.30	31.38	15.92	15.92	18.03	18.03	18.00
Pl	0.04	0.04	0.04	0.01	0.01	1.10	0.04	0.04	0.04	0.01	0.01	1.10
PUR	0.00	0.00	0.00	1.35	1.35	0.00	5.70	6.42	6.42	1.43	1.43	1.40
Pw	14.60	14.96	14.96	6.13	6.13	79.80	14.60	11.84	11.84	6.13	6.13	79.80
RC	255.75	532.97	532.97	284.48	284.48	0.00	255.75	532.97	532.97	284.48	284.48	0.00
Sa	571.89	571.74	571.74	571.89	571.89	0.00	571.89	587.11	587.11	571.89	571.89	0.00
SC	135.60	135.49	135.49	105.79	105.79	94.80	135.60	135.49	135.49	105.79	105.79	94.80
St	0.00	0.00	0.00	0.00	0.00	43.90	0.00	0.00	0.00	0.00	0.00	43.90
SW	51.42	51.39	51.39	0.00	0.00	73.10	51.42	51.39	51.39	0.00	0.00	73.10
WF	0.00	0.00	0.00	0.00	0.00	0.00	8.50	4.34	4.34	4.92	4.92	0.00
XPS	0.00	0.00	0.00	0.00	0.00	0.00	2.30	2.30	2.30	0.25	0.25	0.20
Zn	1.24	14.24	14.24	0.69	0.69	0.00	1.24	14.24	14.24	0.69	0.69	0.00

Table S7.4.6 Material intensities[211] of existing buildings (kg/m^2). Apartment buildings are further divided into low and high (more than 5 floors) apartment buildings [44].

Building type	SFH1-5	Mid_TH1-5	End_TH1-5	MFH1-5	AB1-5 (low)	AB1-5 (high)
Al	6.10	6.10	6.10	6.10	6.10	6.10
Ar	0.00	0.00	0.00	0.00	0.00	0.00
Bi	0.00	0.00	0.00	0.00	0.00	0.00
CB	635.30	124.10	124.10	310.30	310.30	245.80
Ce	5.20	21.30	21.30	5.20	5.20	5.20
Co	0.00	0.00	0.00	0.00	0.00	0.00
CI	4.90	4.90	4.90	4.90	4.90	4.90
Cr	974.10	353.20	353.20	883.10	883.10	699.50
EPS	0.00	0.00	0.00	0.00	0.00	0.00

Gl	0.00	0.00	0.00	0.00	0.00	0.00
Gr	0.00	0.00	0.00	0.00	0.00	0.00
Gy	0.00	10.30	10.30	11.00	11.00	6.70
HW	0.00	0.00	0.00	0.00	0.00	0.00
MW	0.00	0.00	0.00	0.00	0.00	0.00
Pl	0.00	7.70	7.70	0.00	0.00	5.10
PUR	0.00	0.00	0.00	0.00	0.00	0.00
Pw	0.00	0.00	0.00	0.00	0.00	0.00
RC	0.00	0.00	0.00	0.00	0.00	0.00
Sa	0.00	0.00	0.00	0.00	0.00	0.00
SC	0.00	0.00	0.00	0.00	0.00	0.00
St	36.50	14.80	14.80	33.30	33.30	26.90
SW	246.70	69.30	69.30	49.10	49.10	61.10
WF	0.00	0.00	0.00	0.00	0.00	0.00
XPS	0.00	0.00	0.00	0.00	0.00	0.00
Zn	0.00	0.00	0.00	0.00	0.00	0.00

7.4.2 Leiden population

Table S7.4.7 The population forecast of Leiden [283].

Year	Population	Year	Population
2015	121562	2033	140500
2016	122561	2034	141200
2017	123661	2035	141900
2018	124306	2036	142500
2019	124899	2037	143100
2020	125900	2038	143800
2021	127000	2039	144500
2022	128200	2040	145200
2023	129600	2041	145700
2024	131000	2042	146300
2025	132600	2043	146900
2026	134100	2044	147600
2027	135100	2045	148200
2028	136100	2046	148700
2029	137000	2047	149200
2030	138000	2048	149900
2031	138900	2049	150400
2032	139700	2050	151000

7.4.3 Neighborhood-oriented heat transition in Leiden

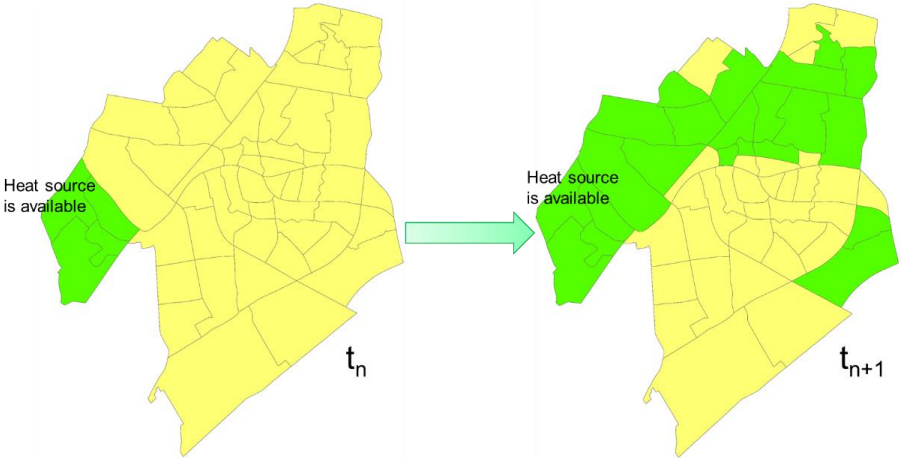

Figure S7.4.1 The schematic diagram for heat source availability per neighborhood in space and time. The neighborhoods in green are the neighborhoods where the corresponding heat source is available.

Table S7.4.8 Heat source map of Leiden [185,229]. HT is short for the high temperature.

Neighborhood code	Neighborhood name	Current heat source
BU05460000	Pieterswijk	Natural gas
BU05460001	Academiewijk	Natural gas
BU05460002	Levendaal-West	Natural gas
BU05460003	Levendaal-Oost	Natural gas
BU05460100	De Camp	Natural gas
BU05460101	Marewijk	Natural gas
BU05460102	Pancras-West	Natural gas
BU05460103	Pancras-Oost	Natural gas
BU05460104	d'Oude Morsch	Natural gas
BU05460105	Noordvest	Natural gas
BU05460106	Havenwijk-Noord	Natural gas
BU05460107	Havenwijk-Zuid	Natural gas
BU05460108	Molenbuurt	Natural gas
BU05460109	De Waard	Natural gas
BU05460200	Stationskwartier	Natural gas
BU05460300	Groenoord	Natural gas
BU05460301	Noorderkwartier	Natural gas

BU05460302	De Kooi	Natural gas
BU05460400	Meerburg	Natural gas
BU05460401	Rijndijkbuurt	Natural gas
BU05460402	Professorenwijk-Oost	Natural gas
BU05460403	Burgemeesterswijk	Natural gas
BU05460404	Professorenwijk-West	Natural gas
BU05460405	Tuinstadwijk	Natural gas
BU05460406	Cronestein	Natural gas
BU05460407	Klein Cronestein	Natural gas
BU05460408	Roomburg	Natural gas
BU05460409	Waardeiland	Natural gas
BU05460500	Vreewijk	Natural gas
BU05460501	Haagweg-Noord	Natural gas
BU05460502	Gasthuiswijk	Natural gas
BU05460503	Fortuinwijk-Noord	Natural gas
BU05460504	Boshuizen	Natural gas
BU05460505	Oostvliet	Natural gas
BU05460506	Haagweg-Zuid	Natural gas
BU05460507	Fortuinwijk-Zuid	Natural gas
BU05460600	Transvaalbuurt	Natural gas
BU05460601	Lage Mors	Natural gas
BU05460602	Hoge Mors	Natural gas
BU05460700	Pesthuiswijk	Natural gas
BU05460701	Houtkwartier	Natural gas
BU05460702	Raadsherenbuurt	Natural gas
BU05460703	Vogelwijk	Natural gas
BU05460704	Leeuwenhoek	Natural gas
BU05460800	Slaaghwijk	Natural gas
BU05460801	Zijlwijk-Zuid	Natural gas
BU05460802	Zijlwijk-Noord	Natural gas
BU05460803	Merenwijk-Centrum	Natural gas
BU05460804	Leedewijk-Zuid	Natural gas
BU05460805	Leedewijk-Noord	Natural gas

BU05460900	Schenkwijk	Heat networks (HT)
BU05460901	Kloosterhof	Heat networks (HT)
BU05460902	Dobbewijk-Noord	Heat networks (HT)
BU05460903	Dobbewijk-Zuid	Heat networks (HT)

7.4.4 Renovation options

Table S7.4.9 U-values (W/m^2 K) of different thermal standards from TABULA for buildings in the Netherlands[68].

Building type	Conventional standard					nZEN standard				
	roof	wall	floor	window	door	roof	wall	floor	window	door
SFH1	0.24	0.24	0.25	1.8	3.5	0.15	0.18	0.18	1	1.4
Mid_TH1	0.25	0.25	0.26	1.8	3.5	0.15	0.18	0.18	1	1.4
End_TH1	0.25	0.25	0.26	1.8	3.5	0.15	0.18	0.18	1	1.4
AB1	0.24	0.24	0.23	1.8	3.5	0.15	0.18	0.17	1	1.4
MFH1	0.24	0.24	0.25	1.8	3.5	0.15	0.18	0.18	1	1.4
SFH2	0.22	0.24	0.25	1.8	3.5	0.14	0.18	0.18	1	1.4
Mid_TH2	0.22	0.24	0.25	1.8	3.5	0.14	0.18	0.18	1	1.4
End_TH2	0.22	0.24	0.25	1.8	3.5	0.14	0.18	0.18	1	1.4
AB2	0.22	0.24	0.24	1.8	3.5	0.14	0.18	0.17	1	1.4
MFH2	0.22	0.24	0.25	1.8	3.5	0.14	0.18	0.18	1	1.4
SFH3	0.2	0.2	0.2	1.8	3.5	0.13	0.13	0.15	1	1.4
Mid_TH3	0.2	0.2	0.23	1.8	3.5	0.13	0.15	0.17	1	1.4
End_TH3	0.2	0.2	0.23	1.8	3.5	0.13	0.15	0.17	1	1.4
AB3	0.2	0.2	0.19	1.8	3.5	0.13	0.15	0.15	1	1.4
MFH3	0.2	0.2	0.23	1.8	3.5	0.13	0.15	0.17	1	1.4
SFH4	0.16	0.16	0.16	1.8	3.5	0.11	0.13	0.13	1	1.4
Mid_TH4	0.16	0.16	0.16	1.8	3.5	0.11	0.13	0.13	1	1.4
End_TH4	0.16	0.16	0.16	1.8	3.5	0.11	0.13	0.13	1	1.4
AB4	0.16	0.16	0.15	1.8	2	0.11	0.13	0.12	1	1.4
MFH4	0.16	0.16	0.16	1.8	3.5	0.11	0.13	0.13	1	1.4
SFH5	0.13	0.14	0.14	1.8	1.65	0.1	0.11	0.11	1	1.4
Mid_TH5	0.13	0.14	0.14	1.8	1.65	0.1	0.11	0.11	1	1.4
End_TH5	0.13	0.14	0.14	1.8	1.65	0.1	0.11	0.11	1	1.4
AB5	0.13	0.14	0.13	1.8	1.65	0.1	0.11	0.11	1	1.4
MFH5	0.13	0.14	0.14	1.8	1.65	0.1	0.11	0.11	1	1.4
SFH6	0.16	0.21	0.27	1.8	1.65	0.08	0.1	0.11	1	1.4
Mid_TH6	0.16	0.21	0.27	1.8	1.65	0.08	0.1	0.11	1	1.4

End_TH6	0.16	0.21	0.27	1.8	1.65	0.08	0.1	0.11	1	1.4
AB6	0.16	0.21	0.25	1.8	1.65	0.08	0.1	0.11	1	1.4
AB6_wood	0.16	0.21	0.25	1.8	1.65	0.08	0.1	0.11	1	1.4
MFH6	0.16	0.21	0.27	1.8	1.65	0.08	0.1	0.11	1	1.4
SFH7	0.08	0.1	0.11	1	1.4	0.08	0.1	0.11	1	1.4
Mid_TH7	0.08	0.1	0.11	1	1.4	0.08	0.1	0.11	1	1.4
End_TH7	0.08	0.1	0.11	1	1.4	0.08	0.1	0.11	1	1.4
AB7	0.08	0.1	0.11	1	1.4	0.08	0.1	0.11	1	1.4
AB7_wood	0.08	0.1	0.11	1	1.4	0.08	0.1	0.11	1	1.4
MFH7	0.08	0.1	0.11	1	1.4	0.08	0.1	0.11	1	1.4

Table S7.4.10 Insulation measures. HR++ glass contains 2 plates (2×0.5cm thick) and 2cm argon[211]. HR+++ glass is assumed to contain 3 plates (3×0.5cm thick) and 2cm argon[209,211]. The typical U-values of glasses are from TABULA and Milieu Centraal[68,209].

Insulation standards	Element	Material	Thermal conductivity (k, W/mK)	U-value	Density (kg/m^3)	Lifetime (years) [278]
conventional	Roof	mineral	0.037	-	140	30
	Window	HR++ glass	-	1.8	-	30
	Wall	mineral	0.037	-	140	40
	Door	-	-	-	-	30
	Ground	PUR	0.025	-	45	40
nZEB	Roof	PUR	0.025	-	45	30
	Glass	HR+++	-	1.0	-	30
	Wall	mineral	0.037	-	140	40
	Door	PUR	0.025	-	45	30
	Ground	mineral	0.037	-	140	40

Table S7.4.11 Ventilation systems [68].

Type	Heat recovery fraction	Electricity intensity (kWh/m^2a)	Lifetime (years) [333]
Natural ventilation	0	0	20
Exhaust air ventilation	0	2.4	20
Balanced ventilation	0.95	4.2	20

Table S7.4.12 Space heating system types [68,74].

Type	Lifetime (years)
Natural gas boiler	20 [334]
Heat networks (high temperature)	15 [74]

Heat networks (low temperature)	15 [74]
Electric heat pump	15 [74]

Table S7.4.13 Domestic hot water systems [68].

Type	Lifetime (years)
Natural gas boiler	20 [334]
Heat networks (high temperature)	15 [74]
Solar water heater	20 [335]
Electric water heater	15 [336]

Table S7.4.14 Solar panel [212].

Type	Panel efficiency	Performance ratio	lifetime
Modern crystalline Silicon panels	0.17	0.85	25 [337]

Table S7.4.15 Future renovation combinations [68,74,248].

Insulation standards	Ventilation systems	Space heating systems	Domestic hot water system	Solar panel
Conventional	Exhaust air ventilation	Natural gas boiler	· Solar water heater (the first choice if applicable) · Natural gas boiler	Modern crystalline Silicon panels
	Exhaust air ventilation	Heat networks (high temperature)	· Solar water heater (the first choice if applicable) · Heat networks (high temperature)	
nZEB	Balanced ventilation	Heat networks (low temperature). It is the first choice for multi-family houses and apartment buildings.	· Solar water heater (the first choice if applicable) · Electric water heater	
	Balanced ventilation	Electric heat pump. It is the first choice for single-family houses and terraced houses.	· Solar water heater (the first choice if applicable) · Electric water heater	

7.4.5 Environmental impact factors

Table S7.4.16 GHG emissions factors (SSP2-base) [142,216] of primary material production from ecoinvent 3.6 (kg CO_2 eq/kg) [138,280].

Materials	Product	Activity	Location	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049	2050
Al	aluminium, wrought alloy	market for aluminium, wrought alloy	GLO	11.1708	11.0726	10.9905	10.9299	10.8688	10.7739	10.7226	10.7092
Ar	argon, liquid	market for argon, liquid	RoW	2.1136	2.0157	1.8903	1.7881	1.7290	1.6830	1.6788	1.6938
Bi	bitumen adhesive compound, hot	market for bitumen adhesive compound, hot	GLO	0.5125	0.5114	0.5090	0.5069	0.5056	0.5045	0.5043	0.5045
CB	clay brick	market for clay brick	GLO	0.3054	0.3041	0.3019	0.3000	0.2988	0.2979	0.2976	0.2978
Ce	ceramic tile	market for ceramic tile	GLO	0.7372	0.7252	0.7100	0.6981	0.6911	0.6857	0.6857	0.6882
Co	copper	market for copper	GLO	4.1972	4.1027	4.0054	3.9332	3.8907	3.8575	3.8601	3.8794
CI	cast iron	market for cast iron	GLO	1.7268	1.7104	1.6888	1.6710	1.6606	1.6526	1.6519	1.6547
Cr	concrete, normal	market for concrete, normal	CH	0.0737	0.0743	0.0733	0.0720	0.0711	0.0702	0.0696	0.0693
EPS	polystyrene, expandable	market for polystyrene, expandable	GLO	3.6422	3.6418	3.6412	3.6406	3.6403	3.6400	3.6400	3.6401

Gl	flat glass, coated	market for flat glass, coated	RoW	1.1517	1.1423	1.1335	1.1269	1.1234	1.1213	1.1223	1.1244
Gr	gravel, crushed	market for gravel, crushed	CH	0.0088	0.0090	0.0087	0.0083	0.0080	0.0078	0.0076	0.0075
Gy	gypsum, mineral	gypsum quarry operation	CH	0.0026	0.0027	0.0026	0.0025	0.0025	0.0024	0.0024	0.0024
HW	sawnwood, hardwood, raw	sawing, hardwood	CH	-2.1050	-2.1040	-2.1057	-2.1078	-2.1092	-2.1107	-2.1116	-2.1122
MW	glass wool mat	market for glass wool mat	GLO	2.3360	2.2667	2.1758	2.1053	2.0630	2.0302	2.0286	2.0413
Pl	extrusion, plastic pipes	market for extrusion, plastic pipes	GLO	0.3488	0.3390	0.3189	0.3009	0.2899	0.2797	0.2761	0.2761
PUR	polyurethane, flexible foam	market for polyurethane, flexible foam	RER	5.4463	5.4495	5.4394	5.4282	5.4206	5.4118	5.4061	5.4028
Pw	plywood, for indoor use	market for plywood, for indoor use	RER	-3.1333	-3.1204	-3.1531	-3.1899	-3.2151	-3.2442	-3.2631	-3.2743
RC	fibre-reinforced concrete	market for fibre-reinforced concrete, steel	BR	0.1738	0.1736	0.1736	0.1735	0.1732	0.1731	0.1733	0.1734
Sa	sand	gravel and sand quarry	CH	0.0037	0.0039	0.0037	0.0035	0.0033	0.0031	0.0031	0.0030

		operation								
SC	cement mortar	market for cement mortar	CH	0.2401	0.2424	0.2384	0.2336	0.2304	0.2268	0.2248	0.2235
St	wire drawing, steel	market for wire drawing, steel	GLO	0.3117	0.3049	0.2992	0.2952	0.2932	0.2922	0.2933	0.2950
SW	sawnwood, softwood, raw	sawing, softwood	CH	-1.4715	-1.4705	-1.4721	-1.4741	-1.4754	-1.4768	-1.4776	-1.4781
WF	fibreboard, soft	fibreboard production, soft, from wet & dry processes	Europe without Switzerland	-0.0821	-0.0807	-0.0867	-0.0935	-0.0983	-0.1045	-0.1087	-0.1113
XPS	polystyrene, extruded	market for polystyrene, extruded	GLO	9.5244	9.4950	9.4501	9.4121	9.3897	9.3708	9.3668	9.3701
Zn	zinc	market for zinc	GLO	3.1601	3.1950	3.0817	2.9311	2.8472	2.7568	2.7267	2.7197

Table S7.4.17 GHG emissions factors (SSP2-2.6) [142,216] of primary material production from ecoinvent 3.6 (kg CO_2 eq/kg) [138,280].

Materials	Product	Activity	Location	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049	2050
Al	aluminium, wrought alloy	market for aluminium, wrought alloy	GLO	11.1667	11.0403	10.9137	10.8074	10.6457	10.4540	10.3293	10.2472
Ar	argon, liquid	market for argon, liquid	RoW	2.0820	1.8549	1.5417	1.2476	0.7770	0.3092	0.1337	0.0731

Bi	bitumen adhesive compound, hot	market for bitumen adhesive compound, hot	GLO	0.5119	0.5084	0.5029	0.4973	0.4885	0.4802	0.4769	0.4754
CB	clay brick	market for clay brick	GLO	0.3049	0.3014	0.2961	0.2909	0.2826	0.2747	0.2717	0.2706
Ce	ceramic tile	market for ceramic tile	GLO	0.7333	0.7047	0.6652	0.6269	0.5679	0.5106	0.4893	0.4794
Co	copper	market for copper	GLO	4.1720	3.9733	3.7175	3.4744	3.1055	2.7341	2.5898	2.5228
CI	cast iron	market for cast iron	GLO	1.7212	1.6818	1.6266	1.5741	1.4909	1.4091	1.3786	1.3668
Cr	concrete, normal	market for concrete, normal	CH	0.0734	0.0737	0.0723	0.0702	0.0666	0.0638	0.0628	0.0627
EPS	polystyrene, expandable	market for polystyrene, expandable	GLO	3.6420	3.6409	3.6392	3.6376	3.6350	3.6325	3.6316	3.6311
Gl	flat glass, coated	market for flat glass, coated	RoW	1.1494	1.1296	1.1055	1.0838	1.0498	1.0143	1.0009	0.9956
Gr	gravel, crushed	market for gravel, crushed	CH	0.0087	0.0088	0.0084	0.0077	0.0066	0.0058	0.0055	0.0055
Gy	gypsum, mineral	gypsum quarry operation	CH	0.0026	0.0026	0.0026	0.0024	0.0022	0.0021	0.0020	0.0020
HW	sawnwood, hardwood, raw	sawing, hardwood	CH	-2.1054	-2.1050	-2.1074	-2.1108	-2.1167	-2.1213	-2.1230	-2.1232

MW	glass wool mat	market for glass wool mat	GLO	2.3139	2.1527	1.9243	1.7032	1.3646	1.0343	0.9115	0.8547
Pl	extrusion, plastic pipes	market for extrusion, plastic pipes	GLO	0.3437	0.3161	0.2702	0.2246	0.1503	0.0809	0.0549	0.0469
PUR	polyurethane, flexible foam	market for polyurethane, flexible foam	RER	5.4438	5.4419	5.4249	5.4042	5.3687	5.3417	5.3316	5.3299
Pw	plywood, for indoor use	market for plywood, for indoor use	RER	-3.1413	-3.1435	-3.1962	-3.2625	-3.3766	-3.4624	-3.4944	-3.4989
RC	fibre-reinforced concrete	market for fibre-reinforced concrete, steel	BR	0.1736	0.1723	0.1710	0.1698	0.1678	0.1660	0.1657	0.1655
Sa	sand	gravel and sand quarry operation	CH	0.0037	0.0038	0.0035	0.0032	0.0025	0.0021	0.0019	0.0019
SC	cement mortar	market for cement mortar	CH	0.2392	0.2401	0.2345	0.2266	0.2127	0.2021	0.1981	0.1977
St	wire drawing, steel	market for wire drawing, steel	GLO	0.3103	0.2963	0.2802	0.2660	0.2439	0.2202	0.2113	0.2077
SW	sawnwood, softwood, raw	sawing, softwood	CH	-1.4719	-1.4715	-1.4737	-1.4769	-1.4824	-1.4866	-1.4883	-1.4884

WF	fibreboard, soft	fibreboard production, soft, from wet & dry processes	Europe without Switzerland	-0.0837	-0.0859	-0.0968	-0.1096	-0.1319	-0.1485	-0.1544	-0.1556
XPS	polystyrene, extruded	market for polystyrene, extruded	GLO	9.5131	9.4398	9.3316	9.2277	9.0604	8.8983	8.8375	8.8170
Zn	zinc	market for zinc	GLO	3.1193	3.0114	2.7432	2.3736	1.7496	1.2504	1.0924	1.0431

Table S7.4.18 GHG emissions factors (SSP2-base) [142,216] of recycled building materials. The materials are from ecoinvent 3.6 (kg CO_2 eq/kg) [138]. The factors of the other recycled materials are assumed as zero [280].

Materials	Product	Activity	Location	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049	2050
Al	aluminium scrap, post-consumer, prepared for melting	aluminium scrap, post-consumer, prepared for melting, Recycled Content cut-off	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ar	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Bi	waste bitumen sheet	market for waste bitumen sheet	CH	-2.3591	-2.3587	-2.3580	-2.3573	-2.3569	-2.3565	-2.3563	-2.3563
CB	waste brick	treatment of waste brick, recycling	CH	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033	-0.0033

Ce	-	-	-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Co	-	-	-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
CI	iron scrap, sorted, pressed	iron scrap, sorted, pressed, Recycled Content cut-off	GLO	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Cr	waste concrete, not reinforced	treatment of waste concrete, not reinforced, recycling	Europe without Switzerland	-0.00040	-0.00040	-0.00040	-0.00040	-0.00040	-0.00040	-0.00040	-0.00040
EPS	-	-	-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Gl	glass cullet, sorted	glass cullet, sorted, Recycled Content cut-off	GLO	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Gr	-	-	-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Gy	waste gypsum plasterboard	treatment of waste gypsum plasterboard, recycling	CH	-0.00033	-0.00033	-0.00033	-0.00033	-0.00033	-0.00033	-0.00033	-0.00033
HW	waste wood, post-consumer	waste wood, post-consumer, Recycled Conte	GLO	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

		nt cut-off									
MW	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pl	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PUR	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pw	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
RC	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sa	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SC	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
St	waste reinforcement steel	treatment of waste reinforcement steel, recycling	CH	-0.0574	-0.0573	-0.0572	-0.0571	-0.0571	-0.0570	-0.0570	-0.0570
SW	waste wood, post-consumer	waste wood, post-consumer, Recycled Content cut-off	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
WF	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
XPS	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Zn	-	-	-	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00

Table S7.4.19 GHG emissions factors (SSP2-2.6) [142,216] of recycled building materials. The materials are from ecoinvent 3.6 (kg CO_2 eq/kg) [138]. The factors of the other recycled materials are assumed as zero [280].

Materials	Product	Activity	Location	2015 - 2019	2020 - 2024	2025 - 2029	2030 - 2034	2035 - 2039	2040 - 2044	2045 - 2049	2050
Al	aluminium scrap, post-consumer, prepared for melting	aluminium scrap, post-consumer, prepared for melting, Recycled Content cut-off	GLO	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00
Ar	-	-	-	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00
Bi	waste bitumen sheet	market for waste bitumen sheet	CH	-2.35 89	-2.35 79	-2.35 62	-2.35 44	-2.35 16	-2.34 90	-2.34 80	-2.34 77
CB	waste brick	treatment of waste brick, recycling	CH	-0.00 33	-0.00 33	-0.00 33	-0.00 33	-0.00 32	-0.00 32	-0.00 32	-0.00 32
Ce	-	-	-	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00
Co	-	-	-	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00
Cl	iron scrap, sorted, pressed	iron scrap, sorted, pressed, Recycled Content cut-off	GLO	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00	0.00 00

Cr	waste concrete, not reinforced	treatment of waste concrete, not reinforced, recycling	Europe without Switzerland	-0.0040	-0.0040	-0.0040	-0.0040	-0.0039	-0.0039	-0.0039	-0.0039
EPS	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gl	glass cullet, sorted	glass cullet, sorted, Recycled Content cut-off	GLO	-2.3589	-2.3579	-2.3562	-2.3544	-2.3516	-2.3490	-2.3480	-2.3477
Gr	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Gy	waste gypsum plasterboard	treatment of waste gypsum plasterboard, recycling	CH	-0.0033	-0.0033	-0.0033	-0.0033	-0.0032	-0.0032	-0.0032	-0.0032
HW	waste wood, post-consumer	waste wood, post-consumer, Recycled Content cut-off	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
MW	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Pl	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PUR	-	-	-	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Pw	-	-	-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
RC	-	-	-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Sa	-	-	-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
SC	-	-	-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
St	waste reinforcement steel	treatment of waste reinforcement steel, recycling	CH	-0.0573	-0.0572	-0.0569	-0.0567	-0.0563	-0.0560	-0.0558	-0.0558
SW	waste wood, post-consumer	waste wood, post-consumer, Recycled Content cut-off	GLO	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
WF	-	-	-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
XPS	-	-	-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Zn	-	-	-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table S7.4.20 GHG emissions factors [142,216] of transportation from ecoinvent 3.6 (kg CO_2 eq/(kg·km)) [138,280].

Transportation methods	Product	Activity	Location	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049	2050
Truck transportation	transport, freight, lorry	transport, freight, lorry 16-32 metric	RER	0.00002	0.00002	0.00002	0.00002	0.00002	0.00002	0.00002	0.00002

(SSP2-base)	16-32 metric ton, EURO6	ton, EURO6									
Ship transportation (SSP2-base)	transport, freight, sea, container ship	market for transport, freight, sea, container ship	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Truck transportation (SSP2-2.6)	transport, freight, lorry 16-32 metric ton, EURO6	transport, freight, lorry 16-32 metric ton, EURO6	RER	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
Ship transportation (SSP2-2.6)	transport, freight, sea, container ship	market for transport, freight, sea, container ship	GLO	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table S7.4.21 GHG emissions factors of landfill from ecoinvent 3.6 (kg CO_2 eq/kg) [138,142,280].

Materials	Product	Activity	Location	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049	2050
Landfill (SSP2-base)	inert waste	treatment of inert waste, sanitary landfill	Europe without Switzerland	-0.0103	-0.0102	-0.0101	-0.0100	-0.0100	-0.0100	-0.0099	-0.0100
Landfill (SSP2-2.6)	inert waste	treatment of inert waste, sanitary landfill	Europe without Switzerland	-0.0103	-0.0101	-0.0098	-0.0096	-0.0092	-0.0088	-0.0087	-0.0086

Table S7.4.22 GHG emissions factors (SSP2-base) of energy supply from ecoinvent 3.6 (kg CO_2 eq/kWh) [138,248].

Energy supply	Product	Activity	Location	2015-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
Natural gas boiler	Heat, central or small-scale, natural gas	Heat production, natural gas, at boiler condensing modulating <100kW	Europe without Switzerland	0.25	0.25	0.25	0.25	0.25	0.25	0.25

Heat network (LT)	Heat	Geothermal (GHG emission factor is from [74])	NL	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Heat network (HT)	heat, district or industrial, natural gas	heat and power co-generation, natural gas, conventional power plant, 100MW electrical	NL	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Electric heat pump	Heat, air-water heat pump 10kW	Market for floor heating from air-water heat pump	Europe without Switzerland	0.26	0.24	0.22	0.20	0.18	0.17	0.16
Solar water heater	Heat, central or small-scale, other than natural gas	Operation, solar collector system, Cu flat plate collector, multiple dwelling, for hot water	CH	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Grid electricity	Electricity, low voltage	Market for electricity, low voltage	NL	0.66	0.59	0.52	0.47	0.42	0.38	0.37
PV electricity	Electricity, low voltage	Electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted	NL	0.08	0.08	0.08	0.07	0.07	0.07	0.07

Table S7.4.23 GHG emissions factors (SSP2-2.6) of energy supply from ecoinvent 3.6 (kg CO_2 eq/kWh) [138,248].

Energy supply	Product	Activity	Location	2015-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
Natural gas boiler	Heat, central or small-scale, natural gas	Heat production, natural gas, at boiler condensing	Europe without Switzerland	0.25	0.25	0.25	0.25	0.25	0.25	0.25

		modulating <100kW								
Heat network (LT)	Heat	Geothermal (GHG emission factor is from [74])	NL	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Heat network (HT)	heat, district or industrial, natural gas	heat and power co-generation, natural gas, conventional power plant, 100MW electrical	NL	0.10	0.10	0.10	0.10	0.09	0.09	0.09
Electric heat pump	Heat, air-water heat pump 10kW	Market for floor heating from air-water heat pump	Europe without Switzerland	0.25	0.22	0.18	0.11	0.05	0.03	0.03
Solar water heater	Heat, central or small-scale, other than natural gas	Operation, solar collector system, Cu flat plate collector, multiple dwelling, for hot water	CH	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Grid electricity	Electricity, low voltage	Market for electricity, low voltage	NL	0.63	0.54	0.44	0.22	0.06	0.00	-0.01
PV electricity	Electricity, low voltage	Electricity production, photovoltaic,	NL	0.08	0.07	0.06	0.05	0.04	0.04	0.04

		3kWp slanted-roof installation, multi-Si, panel, mounted								

7.4.6 The effect of faster heat transition on GHG emissions

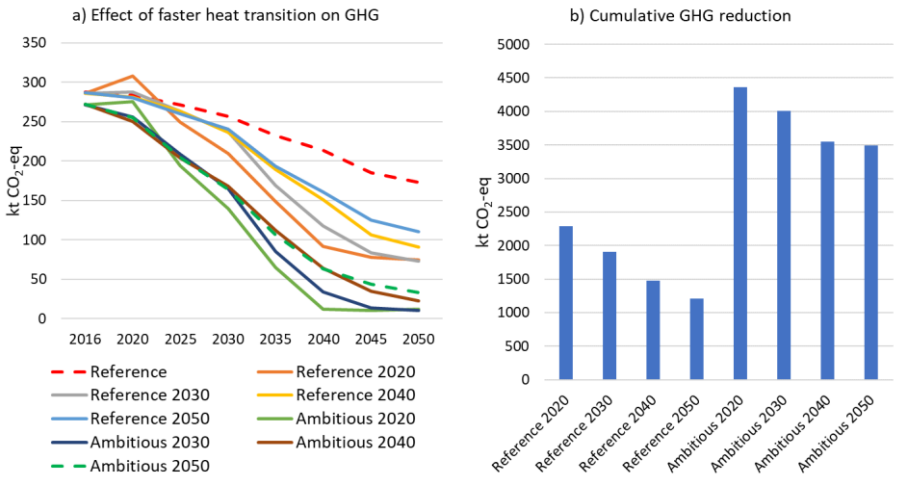

Figure S7.4.2 The effect of faster heat transition on reducing GHG emissions. The years are the earliest time when all the neighborhoods have implemented the natural-gas-free plan. It means that buildings will be installed with conventional heating systems, such as natural gas boilers if the natural-gas-free plan is not implemented. The dash lines are the default heat transition paces used in the study. The cumulative GHG emissions (2016-2050) are in comparison with the reference scenario.