Renobel - Technical Report

Renobel is a model designed to calculate the profitability of energy renovation investments using data from the 2023 Woonsurvey[1], a large-scale housing survey carried out across Flanders, in Belgium. The profitability of investments in Renobel is computed using households' actual energy consumption, under the assumption that their chosen indoor temperature would remain unchanged after renovation. In general, theoretical energy consumption tends to significantly overestimate actual consumption. To address this, we use the theoretical energy consumption before and after the potential renovation to calculate the expected reduction in energy needs, and we apply this same rate of reduction to the observed energy consumption. This technical report presents the structure of the data and how we impute missing values (NA's and omitted variables) (see section 1), the methodology and the assumptions used to construct the theoretical energy consumption of each dwelling (see section 2) and to estimate the costs of energy renovations (see section 3). Assumptions are highlighted in blue.

1 Woonsurvey

Woonsurvey is a particularly rich source of microdata for our analysis, as it provides detailed information on household socio-demographic characteristics, dwelling attributes relevant for computing theoretical energy consumption, and actual energy bills. In this section, we explain how we clean the data, how we derive the dwellings' energy performance (U-values), how we impute missing information such as envelope surfaces and solar panel areas, and how we compute the quantity of energy effectively consumed based on the reported energy bills.

1.1 Data cleaning

The Woonsurvey 2023 sample contains roughly 4400 dwellings, but Renobel requires *observed* energy consumption from household energy bills to calibrate baseline energy use. In practice, this implies that households with missing or unusable bill information cannot be retained, which

[1] Data have been made available by Agentschap Wonen in Vlaanderen and collected by Steunpunt Wonen.

is the main source of attrition. Indeed, missing values are very frequent in the bill-derived consumption variables: 1592 observations have missing electricity consumption, and among the 1491 remaining households with positive electricity bills, 58 have missing spending on fossil fuels while reporting having a fossil heating system. Ultimately, only half the original sample has exploitable energy expenditures.

For households with usable bills, we compute the ratio of observed to theoretical consumption (based on the EPC-style model). The ratio distribution is highly dispersed, with extreme low values (close to zero) and high values above 2. Such extremes can arise from misreporting, very atypical heating patterns (second residency), partial-year bills, etc. Since this ratio directly scales the energy-savings estimates, extreme values can exert disproportionate influence on renovation profitability and policy impacts.

To limit sensitivity to these extremes, we remove the bottom 5% and top 5% of the ratio distribution using weighted quantiles. In the reported run, the weighted 5th and 95th percentiles are 0.10 and 1.40, respectively, leaving 1154 observations after trimming. This trimming is a pragmatic robustness choice: it reduces leverage from likely erroneous or non-comparable observations, at the expense of discarding genuine extreme behaviours if they exist.

Lastly, we drop observations with missing income (29) or other key socio-demographic variables (16) as we need them for our distributional analysis. We end up with 1109 observations.

1.2 The U-Values

The U-value measures how effectively a building component insulates: the lower the U-value, the better the insulation. The Woonsurvey provides information on the year of construction and on the insulation level of each component (bad, intermediate, good). For the windows we have four levels of information concerning the insulation of the glass (triple glazing, high-efficiency double glazing, other double glazing and single glass). We construct U-values based on Gendebien et al. (2014), who distinguish five main construction periods and two insulation levels (bad, good). Since the Woonsurvey reports an additional insulation level (intermediate), we assume that its U-value corresponds to the average of the bad and good scenarios. For buildings constructed since 1990, we adjust the "bad" insulation scenario from Gendebien et al. (2014) to comply with the maximum U-values imposed by the Flemish Region (Vlaamse Overheid, 1991, 2018). For windows we do not differentiate between years of construction as the type of glazing does not depend on its year of installation.

Table 1 presents the U-values associated with each insulation quality level (bad, intermediate, good) for the different components of the building envelope, as a function of the dwelling's year of construction.

Table 1: U-Values

YOC*	Wall			Windows				Roof			Floor		
	Bad	Int.	Good	VB†	Bad	Int.	Good	Bad	Int.	Good	Bad	Int.	Good
< 1945	2.25	1.42	0.59	5	4	3	2	4.15	2.3	0.44	3.38	2	0.77
1945–69	1.56	1	0.53	5	4	3	2	3.33	1.9	0.43	3.38	2	0.77
1970–89	0.98	0.71	0.44	5	4	3	2	0.77	0.5	0.30	1.14	0.8	0.43
1990–2010	0.60	0.5	0.40	5	4	3	2	0.60	0.45	0.30	0.60	0.5	0.40
> 2010	0.24	0.24	0.24	2	2	2	2	0.24	0.24	0.24	0.24	0.24	0.24

* YOC: Year of Construction

† VB: Very bad

Source: Own calculations based on Gendebien et al. (2014) and Flemish regional norms (Vlaamse Overheid, 1991).

1.3 Areas of the envelope's components

The surfaces of the envelope's components are not provided in Woonsurvey, except for the ground floor area (A_{floor}). We make the following assumptions regarding the components' surfaces. The roof surface (A_{roof}) is assumed to equal the ground floor area for flats and is multiplied by $\sqrt{2}$ for houses to account for 45° inclined roofs:

$$A_{roof} = \begin{cases} 1.44 \times A_{\text{floor}} & \text{if house} \\ A_{\text{floor}} & \text{if flat} \end{cases}$$

The vertical surface (A_{vert}), which serves as the basis for wall and window areas (A_{wall} and A_{win} respectively), is estimated by assuming a rectangular building with a floor-to-floor height of 3 meters and a ground footprint twice as long as it is wide. Here, n_{floor} denotes the number of floors of the dwelling, so that the vertical surface is calculated as:

$$A_{\text{vert}} = 9 \times n_{\text{floor}} \times \sqrt{2 \times A_{\text{floor}}}$$

The surface of shared walls ($A_{\text{wall,ter}}$), is modeled using a terraced correction coefficient C_{ter}, which represents the fraction of vertical surface in contact with adjacent dwellings. Its values depend on the housing type: Studio/Room: 5/6, Flat: 2/3, Terraced house: 2/3, Semi-detached house: 1/3, and Detached house: 0.

$$A_{\text{walls,ter}} = A_{\text{vert}} \times C_{\text{ter}}$$

Windows are assumed to cover 30% of the exposed vertical surface, excluding shared walls, while external walls are assumed to cover the remaining 70%:

$$\begin{cases} A_{\text{win}} = A_{\text{vert}} \cdot (1 - C_{\text{ter}}) \cdot 0.3 \\ A_{\text{walls,ext}} = A_{\text{vert}} \cdot (1 - C_{\text{ter}}) \cdot 0.7 \end{cases}$$

1.4 Photovoltaic and solar thermal panels

Woonsurvey reports whether a dwelling is equipped with photovoltaic panels; however, the total panel surface area is missing. We assume that $A_{\text{PV}} = \frac{A_{\text{roof}}}{6}$ if photovoltaic panels are present [2]. We further assume that dwellings with solar thermal panels have installed 1 m^2 capacity per inhabitant, according to InfoZonneboiler.be (2025b).

1.5 Energy Consumption

Woonsurvey contains information about energy bills and the type of heating system, but not the quantities of fuel consumed. We therefore divide the bill by the estimated prices to compute the quantities, which are needed in the analysis to compute the future energy bills. Energy prices are 2017–2018 averages as we do not know the exact timing of the billing period. Gas and electricity come from the Belgian regulator's semiannual residential reports (CREG, 2018); heating oil is computed from the average end-user price per liter reported by the FPS Economy, converted using the net calorific value (PCI) of $\approx$ 10 kWh/L; wood fuels (logs) and pellets follow Valbiom market reports (2008–2021).

[2] This corresponds to a mean A_{PV} of 27 m^2, in line with evidence from Energuide (2026).

Table 2: Residential energy price assumptions (2017–2018 averages, €/MWh)

Energy carrier	**Price (€/MWh)**	**Source**
Natural gas	56.9	CREG semiannual basket, 01/2017–06/2018
Electricity	259	CREG semiannual basket, 01/2017–06/2018
Heating oil	65.2	FPS Economy
Firewood (logs)	44	Valbiom price synthesis
Pellets	52	Valbiom price synthesis

Missing heat price values are imputed by the sample mean of available heat price. We assume that dwellings using gas or fuel oil are equipped with a single boiler providing both space heating and domestic hot water. In all other cases, we assume that domestic hot water is produced by a dedicated electric boiler.

2 Theoretical Energy consumption

The theoretical energy consumption of buildings in Europe is determined within the framework of the *Energy Performance of Buildings Directive* (EPBD), which requires that national calculation methods rely on the European framework standard ISO 52000-1 (International Organization for Standardization, 2017). This directive has been transposed by each member state – and, in Belgium, by each region. Our analysis relies on the Flemish methodolgy (Vlaamse Overheid, 2022). This section presents the methodology, together with the additional resources used to compute the theoretical energy consumption. The elements shown in blue indicate the supplementary assumptions or parameter values that we may use for simplicity.

The EPC score is expressed in kWh/m^2.year and is defined as the theoretical primary energy consumption ($E_{th,primary}$) divided by the heated surface of the dwelling in square meter (A) times the conversion factor 3.6 to convert MJ in kWh. A is computed as $A_{floor}(1+0.7(n_{floor}-1))$ (Cellar and attic are excluded from the area).

$$EPC_{score} = \frac{E_{th,primary}}{3.6 \cdot A} \tag{2.0.1}$$

where the theoretical primary energy consumption is the sum of the theoretical energy consumption from electricity ($E_{th,elec)}$) penalized by a factor 2,5[3] and the theoretical energy consumption from other fossil fuels ($E_{th,other}$).

$$E_{th,primary} = 2.5 \times E_{th,elec} + E_{th,fossil} \tag{2.0.2}$$

where the theoretical energy consumption from electricity ($E_{th,elec}$) is the sum of the energy needed for electric heating (E_{heat}, Section 2.1), for electric domestic hot water heating (E_{DHW}, Section 2.2), for auxiliary equipment (E_{aux}, Section 2.3) and cooling (E_{cool}), from which we substract the energy produced by photovoltaic panels (E_{PV}, Section 2.4):

$$E_{th,elec} = E_{heat,elec} + E_{DHW,elec} + E_{aux} + E_{cool} - E_{PV} \tag{2.0.3}$$

The theoretical energy consumption from fossil fuels ($E_{th,fossil}$) is the sum of the fossil energy needed for heating (E_{heat}, Section 2.1), fossil energy for domestic hot water (E_{DHW}, Section 2.2):

$$E_{th,fossil} = E_{heat,fossil} + E_{DHW,fossil} \tag{2.0.4}$$

The Renobel model does not include space cooling (E_{cool}), as we do not have any information about potential cooling installations in Woonsurvey. According to Eurostat estimates for 2023 (Eurostat, 2025), space cooling accounts for only 0.6% of residential energy consumption in EU households.

2.1 Heating

The energy consumption for heating is the ratio between the energy need for heating ($E_{heat,need}$, Section 2.1.1), and the efficiency of the heating system (η_{heat}, Section 2.1.2).

$$E_{heat} = \frac{E_{heat,need}}{\eta_{heat}} \tag{2.1.1}$$

2.1.1 Heating need

The yearly energy need for heating is the summation over the twelve months of the difference between monthly energy losses ($E_{loss,m}$) and heat gains ($E_{int,m} + E_{sol,m}$) for which a correction

[3] Electricity is multiplied by 2.5 because producing and delivering 1 unit of electricity typically requires about 2.5 units of primary energy due to generation and grid losses.

factor is applied (ϕ_m). If the heating need is negative in any month, it is set to zero.

$$E_{\text{heat,need}} = \sum_{m=1}^{12} E_{\text{loss},m} - \phi_m(E_{\text{int},m} + E_{\text{sol},m}). \tag{2.1.2}$$

2.1.1.1 Energy Losses. Monthly energy losses, denoted $E_{\text{loss},m}$, represent the amount of heat that a dwelling must compensate through its heating system to maintain a comfortable indoor temperature. These losses arise from three main sources. The first component, $E_{\text{loss,tr}}$, captures transmission losses through the building envelope, including walls, windows, the roof, and the floor; these losses depend on the thermal properties (U-values) and surface areas of each component. The second component, $E_{\text{loss,air}}$, reflects heat losses due to air exchange, combining both uncontrolled infiltration and controlled mechanical ventilation. The third component, $E_{\text{loss,tb}}$, corresponds to thermal bridge losses, which occur at junctions where insulation is reduced or interrupted. The total heat loss of the dwelling is therefore computed by summing the transmission, air-exchange, and thermal-bridge loss coefficients, and by converting these instantaneous heat-loss rates into monthly energy losses through multiplication by the indoor–outdoor temperature difference and the monthly duration (D_m, see Table 9). The indoor temperature T_{int} is conventionally fixed at 18°C, while the monthly outdoor temperatures in Flanders ($T_{e,m}$) are retrieved from Table 9.

$$E_{\text{loss},m} = (E_{\text{loss,tr}} + E_{\text{loss,air}} + E_{\text{loss,tb}}) \times (T_{\text{int}} - T_{e,m}) \times D_m.$$

Transmission heat losses. Transmission heat losses are calculated as the sum over all components of the product of each component's U-value (U) (see Table 1) , its surface area (A), and an exposure correction factor (b). $b = 2/3$ for houses' ground floors in contact with a basement and $1/3$ for flats' ground floors and roofs.

$$E_{\text{loss,tr}} = U_{win} \times A_{win} + U_{roof} \times A_{roof} \times b_{roof} + U_{wall} \times A_{walls,ext} + U_{floor} \times A_{floor} \times b_{floor} \tag{2.1.3}$$

Air exchange losses. Air exchange losses are computed based on the total air renewal rate, which includes either infiltration losses for old, non-renovated buildings, or ventilation losses for renovated or new buildings. The formula for air exchange heat loss is

$$E_{\text{loss,ae}} = 0.34 \times Q_{\text{air,age}}, \tag{2.1.4}$$

where 0.34 is the volumetric heat capacity of air and $Q_{\text{air,age}}$ is the total air flow rate, which is computed differently for buildings constructed before 2010 and after 2010.

For buildings constructed before 2010, only infiltration is considered. In this case, the total air flow is calculated as :

$$Q_{\text{air,old}} = \left(\frac{2}{50}\right)^{0.66} \times q_{50} \times A, \tag{2.1.5}$$

where $\left(\frac{2}{50}\right)^{0.66}$ is a conversion factor from 50 Pa to natural pressure (approximately 2 Pa). We assume the standard exponent of 0.66 for Belgian dwellings, following Gendebien et al. (2014). The parameter q_{50} denotes the air leakage rate at 50 Pa ((in $\text{m}^3/\text{h}/\text{m}^2$). In the absence of surveyed leakage measurements, we follow Gendebien et al. (2014) and use the values they report, depending on the year of construction and dwelling type. These are summarized in Table 3.

Table 3: Infiltration rate at 50 Pa per time period and type of dwelling

YOC	**Initial walls**				**Insulated walls**
	Apt.	Terraced	Semi	Free	if ins=good
<1971	14.9	14.9	18	18	6
1971–1990	14.1	14.1	16.3	17.1	6
1991–2007	10	10	12	12	6
2008–2010	6	6	6.3	6.1	6

YOC: Year of Construction. Apt. = Apartment, Semi = Semi-detached house, Free = Freestanding house.
Source: Gendebien et al. (2014).

For dwellings constructed after 2010, mechanical ventilation is considered instead of infiltration. The corresponding net airflow is:

$$Q_{\text{air,new}} = 0,6 \times (1 - \kappa) \times V, \tag{2.1.6}$$

where the air change rate is set to $0,6$ is the air change rate (Gendebien et al., 2014). The internal volume V is computed as $3A$, assuming an average storey height of 3 m. Since we only consider new or renovated dwellings in this case, we follow Gendebien et al. (2014) and assume a heat-recovery efficiency of $\kappa = 0.8$ (80%) for all buildings equipped with mechanical ventilation.

Thermal bridging losses. Thermal bridging losses are computed as

$$E_{\text{loss,tb}} = \left(A_{\text{floor}} + A_{\text{vert}} + A_{\text{roof}}\right) \times U_{\text{sup}},$$

where U_{sup} is an additional U-value representing the contribution of linear thermal bridges. Following Gendebien et al. (2014), we use the U_{sup} values they provide for different dwelling configurations.

The envelope area used in this calculation is the sum of the floor, vertical wall, and roof areas, an approximation that treats thermal bridges as proportional to the overall envelope surface rather than relying on detailed junction-by-junction lengths. The corresponding U_{sup} values are reported in Table 4.

Table 4: Supplementary U-values (W/(m^2 K))

YOC	**Insulation Walls**	**Apartment**	**Terraced**	**Semi**	**Free**
<1970	Bad	/	/	/	/
<1970	Inter./Good	0.15	0.10	0.08	0.07
1971–2009	All	0.15	0.10	0.08	0.07
>2010	Good	0.04	0.02	0.01	0.005

Source: Own hypotheses based on Gendebien et al. (2014)

2.1.1.2 Internal gains. Internal gains, such as body heating, electric appliances and lighting contribute to heating. Monthly internal gains are computed by multiplying a fixed base load of 220 W, supplemented by a volume-dependent component of 0.67 W per cubic metre of the internal volume ($V = 3 \cdot A_{floor} \cdot n_{floor}$), by the monthly duration D_m (see Table 9):

$$E_{int,m} = (220 + 0,67 \cdot V)D_m \tag{2.1.7}$$

2.1.1.3 Solar gains. Solar gains represent the monthly heat contribution from incident solar radiation transmitted through the glazed surfaces of the dwelling. They are computed by multiplying a reduction factor of 0.513 (accounting for incidence-angle correction, dirt and shading) by the glazed area (A_{win}), the monthly solar irradiance for an angle of 90° ($I_{so,m}$, see table 11), and the solar factor at normal incidence of the selected glazing type (g_{win}, see Table 10). We assume that all the windows are vertical to the ground and that no solar protection is installed. Furthermore, as we don't know the orientation of the dwelling, we take the average of the different orientations for $I_{so,m}$.

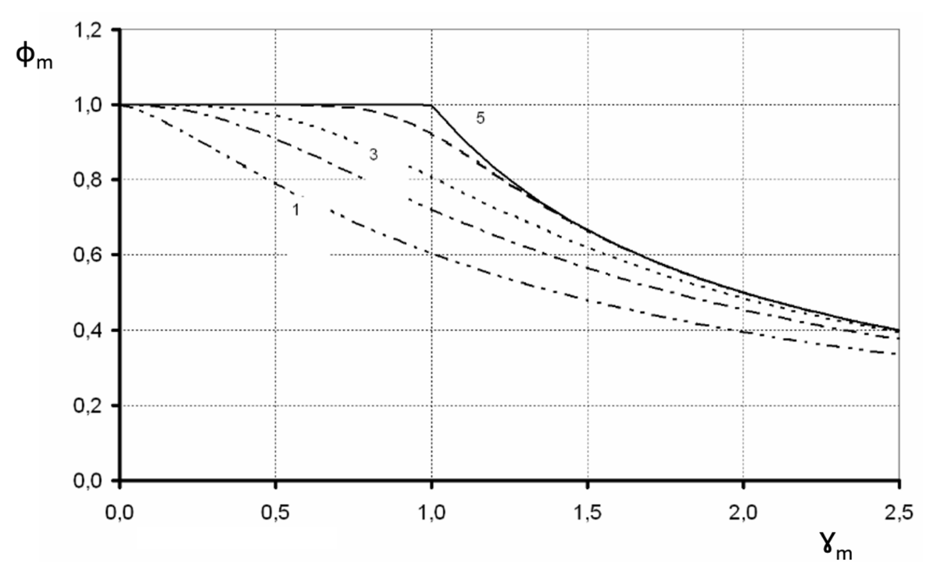
$$E_{\text{sol},m} = 0.513\, A_{win}\, I_{so,m}\, g_{win} \tag{2.1.8}$$

2.1.1.4 Correction factor. The monthly correction factor (ϕ_m) represents the fraction of internal and solar heat gains that can actually be used to offset heating needs. Because gains do not always coincide with periods of heat demand, only part of them is effectively useful. The factor therefore adjusts the raw gains based on the monthly balance between heat losses and gains (γ_m), ensuring that only the usable share contributes to reducing heating energy needs.

$$\gamma_m = \frac{E_{\text{int},m} + E_{\text{sol},m}}{E_{\text{loss},m}}, \tag{2.1.9}$$

The correction factor ϕ_m is then a function of this ratio, for which we retrieve the relationship from ISO 13790 (International Organization for Standardization, 2008), as shown in Figure 1. As Woonsurvey does not provide information about the thermal inertia of the building, we take the average value represented by curve 3 on Figure 1.

Figure 1: Relationship between the gain–loss ratio γ_m and the correction factor ϕ_m.



Source: International Organization for Standardization (2008)

2.1.2 Efficiency of the heating system

The Efficiency (η_{heat}) of the heating system represents the number of kWh of useful heating obtained from 1 kWh of energy. This is represented in Table 5 for the different heating systems. The explanation for the efficiency factors of heat pumps is provided in Appendix 4. We consider that the heating systems have been installed after 2005.

Table 5: Heating systems and associated efficiencies

Heating system	η_{heat}
Fuel oil (standard boiler)	0,81
Fuel oil (condensing boiler)	0,92
Natural gas (standard boiler)	0,75
Natural gas (condensing boiler)	0,92
Pellets (standard)	0,84
Pellets (condensing)	0,91
Wood (standard)	0,69
Wood (condensing)	0,81
Heat pump (dwelling built after 2010)	4,2
Heat pump (good insulation)	3,4
Heat pump (medium insulation)	2,9

Source: Own estimations based on Vlaamse Overheid (2022) and Appendix 4.

2.2 Domestic Hot Water

The energy consumption for domestic hot water (E_{DHW}) represents the energy used for household purposes (kitchen and bathroom). It is computed as the sum of the monthly domestic hot water energy use,

$$E_{\text{DHW}} = \sum_{m=1}^{12} E_{\text{DHW},m} \tag{2.2.1}$$

where the monthly domestic hot water energy is the sum of the energy need for domestic hot water ($E_{\text{DHW,need},m}$, see 2.2.1) and the storage losses ($E_{storage,m}$, see 2.2.2) from which we retire the gains from the solar thermal panels ($E_{so,m}$, see 2.2.3). This is then divided by the efficiency of the domestic hot water system (η_{DHW}, see 2.2.4). Whenever the calculated monthly domestic hot water energy is negative, it is set to 0.

$$E_{\text{DHW,m}} = \frac{E_{\text{DHW,need,m}} + E_{storage,m} - E_{so,m}}{\eta_{\text{DHW}}} \tag{2.2.2}$$

2.2.1 Need of domestic hot water

The need for domestic hot water is computed as the sum of the domestic hot water need for the kitchen and for the bathrooms, divided by the distribution efficiency (η_{pipes}) :

$$E_{\text{DHW,need},m} = \frac{E_{\text{DHW,kitchen},m} + E_{\text{DHW,bathroom},m}}{\eta_{\text{pipes}}} \tag{2.2.3}$$

Where we assume that the distribution efficiency is based on the insulation of the pipes, which we retrieve from Woonsurvey (Bad=0.16; Intermediate=0.28; Good=0.39). Domestic hot water need for the kitchen and the bathroom are computed separately. The constants 16 and 64 represent the normative monthly hot-water needs for a reference dwelling of volume $V = 192$ m^3 for kitchen use and bathroom use respectively. The coefficients 0.055 and 0.22 are linear adjustment factors that increase hot-water consumption with dwelling volume above 192 m^3, reflecting the regulatory assumption that larger dwellings typically host more occupants and therefore require proportionally more kitchen and bathroom hot water. The minimal value for V is set to 192. D_m represents the monthly duration, exposed in Table 9:

$$E_{\text{DHW,kitchen},m} = (16 + 0.055\,(V - 192))\,D_m \tag{2.2.4}$$

$$E_{\text{DHW,bathroom},m} = (64 + 0.22\,(V - 192))\,D_m \tag{2.2.5}$$

2.2.2 Losses from storage

Storage losses from the hot-water storage tank refer to the amount of energy that is lost from the domestic hot-water buffer because the stored water gradually cools down over time. Even when no hot water is being drawn, the tank continuously loses heat to the surrounding environment through its walls, insulation and fittings.

$$E_{\text{storage},m} = \frac{q_{\text{tank}} \cdot V_{\text{tank}}}{12} \tag{2.2.6}$$

Where q_{tank} is the annual storage loss per unit volume and V_{tank} is the volume of the tank. We assume that its value depends on the insulation of the pipes (Bad=23.4 ; Intermediate=17 ; Good=11.9). We also assume that the volume of the tank is 100 L if A<100; 150 L if 100<A<200 and 200 L if A>200.

2.2.3 Contribution from solar thermal panels

Solar thermal panels can cover part of the domestic hot-water demand by converting incident solar radiation into heat and transferring it to the storage tank; this contribution is computed as the product of a fixed efficiency factor of 0.5, the monthly solar irradiance ($I_{so,m}$, see Table 12) for a 35° inclination and for which we take the average of the different orientations, and the collector surface area A_{so}, such that:

$$E_{\mathrm{so},m} = 0,5A_{\mathrm{so}}\, I_{so,m} \tag{2.2.7}$$

2.2.4 Efficiency of the domestic hot water system

The Efficiency (η_{DHW}) of the domestic hot water system represents the number of kWh of useful water heating obtained from 1 kWh of energy. As Woonsurvey does not provide information on the domestic hot water system, households using electricity, solid fuels, or a shared gas system as heating system are assumed to rely on an additional electric boiler for domestic hot water. Heat-pump households are assumed to use the heat pump for both heating and domestic hot water. For dwellings heated with oil or gas, we also assume that the same system serves both uses.

Table 6: Generation efficiency for domestic hot water

Energy carrier	$\eta_{\mathbf{DHW}}$
Gas	0.765
Fuel oil	0.800
Wood / pellets	0.760
Electric boiler	1.00
Heat pump (electricity)	1.40

Source: Own estimations based on Vlaamse Overheid (2022).

2.3 Auxiliary energy

Auxiliary energy refers to the electricity required to operate the technical components that ensure the proper functioning of the heating and ventilation systems, independently of the energy used to generate heat itself. It includes (i) the electricity consumed by the central-heating circulation pump that distributes heat throughout the dwelling, and (ii) the electricity used by ventilation fans to ensure air exchange and indoor air quality.

$$E_{aux} = E_{pump} + E_{ventilation} \tag{2.3.1}$$

2.3.1 Energy for the circulation pump

It is computed as the product of a conventional coefficient 0.7, the heated volume V, and a conversion factor 3.6 converting kWh into MJ:

$$E_{pump} = 0,7 \cdot 3,6 \cdot V \tag{2.3.2}$$

2.3.2 Energy for the ventilation fans

Ventilation energy is calculated on a monthly basis as a function of the month-duration factor D_m (see Table 9, the heated volume V, and the specific fan power of the ventilation system, denoted by 0.235. The annual ventilation energy demand is obtained by summing the monthly values over the twelve months of the year:

$$E_{ventilation} = \sum_{m=1}^{12} (D_m \cdot 0.235 \cdot V) \tag{2.3.3}$$

2.4 Photovoltaic panels

Photovoltaic (PV) panels reduce the theoretical electricity consumption of a dwelling by the production they generate. The yearly photovoltaic electricity production E_{PV} is computed as the sum of the monthly productions:

$$E_{\text{PV}} = \sum_{m=1}^{12} E_{\text{PV},m} \tag{2.4.1}$$

where 0,7 is a reduction factor, $I_{so,m}$ is the solar irradiance at an angle of 35 degree (see Table 12) for which we take the average of the different orientations, A_{PV} is the surface of the photovoltaic panels (see section 1.4) and O_{PV} is the PV panel output per square meter, set at 125.

$$E_{\text{PV},m} = \frac{0,7 \cdot I_{so,m} \cdot A_{PV} \cdot O_{PV}}{1000} \tag{2.4.2}$$

3 Renovation Costs

The total renovation cost ($Cost$) is defined as the sum of the individual costs associated with each upgraded building component towards the category "good" from the Woonsurvey. These include the cost of insulating walls ($Cost_{wall}$), floors ($Cost_{floor}$), and roofs ($Cost_{roof}$), the cost of replacing or upgrading windows ($Cost_{win}$) (see Section 3.1), as well as the cost of installing a heat pump ($Cost_{hp}$) and photovoltaic/thermal panels ($Cost_{pa}$) (see Sections 3.2 and 3.3):

$$Cost = Cost_{wall} + Cost_{floor} + Cost_{roof} + Cost_{win} + Cost_{hp} + Cost_{pa}. \tag{3.0.1}$$

3.1 Components of the envelope

We follow the methodology developed in Ryckewaert et al. (2019) for the cost of walls, floors, roofs, and windows, which is itself based on the Woonsurvey dataset. Costs are independently computed for each component of the renovation. The cost of renovation of component x is given by a share α_x of the total rebuilding cost, which is given by the product of the price per square meter (see Table 13 and the surface of the building, times a correction factor of City $= 1,07$ for dwellings located in cities and equal to 1 otherwise, and a correction factor ($f_{int} = 0,5$) if the component is at the intermediate insulation level, and equal to 1 otherwise. The values of the parameters α are obtained from Ryckewaert et al. (2019): $\alpha_{wall} = 5\%; \alpha_{win} = 10\%; \alpha_{floor} = 8\%$ and $\alpha_{roof} = 9\%$. An adaptation of the surface from Woonsurvey is necessary as Ryckewaert et al. (2019) based their measure of the surface on the VMSW calculations, which defines the surface differently. As such: $A_{new} = A \times 2/3 \times 1.58$. The cost is uprated to reflect increases in construction prices through time. We follow the ABEX index.[4]

$$Cost_x = \alpha_x \times Price_{sqm} \times A_{new} \times f_{int} \times City \times Index \tag{3.1.1}$$

3.2 Heat Pump

To determine heat pump installation costs, we first estimate the required power P, as the system size is a key cost driver. We restrict heat pump installation to dwellings requiring less than 20 kW, as units above 20kW remain relatively uncommon for the residential sector (Joint Research Centre, 2023). Following Energie (2000), the total required power is defined as the sum of the power needed for space heating (P_{hs}) and the power needed to produce domestic hot water (P_{DHW}).

$$P = P_{hs} + P_{DHW}, \tag{3.2.1}$$

[4] https://www.abex.be/fr/indice-abex/

The heating component P_{hs} is the product of the heat losses, the design temperature difference (ΔT) set to 25 K (18°C indoors and -7°C outdoors), and f_s is a safety coefficient (set to 1.2) used to ensure the heating system can meet peak demand:

$$P_{hs} = E_{loss} \times \Delta T \times f_s. \tag{3.2.2}$$

The domestic hot water component P_{DHW} is assumed to be 750 W for dwellings with 2–4 occupants and 1 kW for those with up to 6 occupants, reflecting typical hot water production requirements. According to Protopadaki et al. (2023), the installation cost of heat pumps can be computed as :

$$Cost_{hp} = 4275 + 290P \tag{3.2.3}$$

where P is in kW

3.3 Photovoltaic and solar thermal panels

3.3.1 Photovoltaic panels

The installation of photovoltaic panels is restricted to households living in houses and is limited to a maximum area of one quarter of the roof surface. The average installation cost in 2022 is set at €1,100 per kilowatt-peak (kWp) (Protopadaki et al., 2023), and, according to Ecoconso (2025), one kilowatt-peak corresponds to an area of about 5 m^2. The resulting cost is therefore estimated at €240/m^2.

3.3.2 Solar thermal panels

According to InfoZonneboiler.be (2025b), households typically install around 1 m^2 of solar thermal collector area per person. The installation cost amounts to approximately €1,200 per square meter, excluding VAT (InfoZonneboiler.be, 2025a).

4 Additional information for heat pumps

The efficiency of the heat pump, expressed through its Seasonal Coefficient of Performance (SCOP), depends on the heat pump's Coefficient of Performance (COP). To avoid relying on a default COP value, we aim for greater precision by computing it explicitly. The COP represents the efficiency of the heat pump for a certain supply temperature and a certain exterior temperature. But, as exterior temperatures change during the year (and thus also the supply temperatures), it is the Seasonal coefficient of performance (SCOP) that represents the weighted average efficiency of the heat pump during a year.

A first important assumption is that we consider ground heating for buildings built after 2010. As ground heating allows for a lower heating temperature for the same heating comfort, it is also paired with a higher SCOP that we estimate at 4.2 (Daikin, 2025).

In order to compute the SCOP for the buildings built before 2010, we need to make hypotheses about the following parameters:

- The size of the emitters (radiators). This is a very important point as larger emitters allow for a lower heating temperature and lead to a higher SCOP (better efficiency). We consider that the size of the radiators in houses built before 2010 is aligned with the heating need (supply temperature) for the most extreme conditions (-7°C).

- The COP of air-water heat pumps: We use the formula from Terry and Galvin (2023) which retrieves the COP from the supply temperature and the exterior temperature for air-water heat pumps. We consider four different COP, for temperature points 2°C; 7°C; 12°C and 17°C. These temperature points correspond to specific supply temperatures (see below).

$$COP = 0.4 \times \frac{273 + T_{supply}}{\max(T_{supply} - T_{ext},\ 15)}$$

- The maximal supply temperature of the heat pump (for an exterior temperature of -7°) is determined by the insulation of the building. We follow Vandevelde et al. (2023) who performed an analysis for Flanders on this. They associated the insulation of the building with the required temperature needed to heat the building in the coldest conditions. We compute an average U-value of the building in order to assign it a letter from a to f (see Table 7), and thus a supply temperature. The average U-values are computed for each building, depending on the surfaces of its component.

Table 7: U-values and corresponding Maximal Supply temperature

	a	**b**	**c**	**d**	**e**	**f**
Windows	1.5	2.5	3.0	3.5	3.6	5.0
Roof	0.24	0.4	0.8	1.2	1.3	1.9
Walls	0.24	0.6	0.6	1.4	1.9	2.2
Floor	0.24	0.4	1.5	2.1	2.7	2.8
Average U-value	<0.49	0.5-0.91	0.92-1.26	1.27-1.89	1.9-2.24	>2.25
$\boldsymbol{T_{\max}}$	**65°**	**65°**	**75°**	**75°**	**90°**	**90°**

Note: Average U-values are computed assuming an envelope composed of 20% windows, 15% floor, 20% roof and 45% walls.

Source: Own calculations based on Vandevelde et al. (2023).

- Supply temperature is derived from the weather-compensated heating curve used by Terry and Galvin (2023):

$$T_{\text{supply}} = \begin{cases} T_{\max} & \text{if } T_{\text{ext}} \leq T_b, \\ T_{\max} + (T_{\min} - T_{\max})\dfrac{T_{\text{ext}} - T_b}{T_{\min\_ext} - T_b} & \text{if } T_b < T_{\text{ext}} < T_{\min\_ext}, \\ T_{\min} & \text{if } T_{\text{ext}} \geq T_{\min\_ext}. \end{cases}$$

  where:

  - T_{supply} : heating system supply temperature (°C),
  - T_{ext} : outdoor air temperature (°C) (see Table 8),
  - $T_{\max}$: maximum supply temperature (see Table 7),
  - $T_{\min}$: minimum supply temperature (set at 45°C),
  - T_b : Outdoor temperature associated with $T_{\max}$ (set at −7°C),
  - $T_{\min\_ext}$: outdoor temperature above which the supply temperature plateaus at $T_{\min}$ (set at 15°C).

- Exterior temperatures play an important role in the COP of heat pumps. Table 8 represents the percentage of time at these temperatures in Flanders. It is constructed based on official European data (Joint Research Centre, 2025) concerning the average temperature hour by hour during the whole year, since 20 years in Flanders. We only consider temperatures below 20 degrees as no heating is required beyond that level.

Table 8: Distribution of exterior temperatures in Flanders

Exterior temperature (in °C)	**Percentage**
0-5	21,5%
5-10	28%
10-15	27%
15-20	23%

Source: Joint Research Centre (2025)

For buildings built before 2010, we only consider two kinds of air-water heat pumps, which are the ones with maximal supply temparature of 75°C and 65°C. With the parameters defined above, we can compute the SCOP for those two heat pumps with the following formula with 4 bins (representing 0-5°C; 5-10°C; 10-15°C; 15-20°C):

$$SCOP = \sum_{j=1}^{4} \omega_j \times COP(T_j)$$

- ω_j: share of time spent in temperature bin j, with $\sum_j \omega_j = 1$
- $COP(T_j)$: coefficient of performance at representative temperature T_j
- T_j: representative outdoor air temperature for bin j (midpoint of the bin)

Eventually we get a SCOP of 2,9 and 3,4 for heat pumps with maximal supply temperature of 75°C and 65°C respectively.

5 Additional tables

Table 9: Duration of months D_m (Ms) and average outdoor temperature $T_{e,m}$ (°C) in Flanders

Month	D_m	$T_{e,m}$
January	2.678	3.2
February	2.419	3.9
March	2.678	5.9
April	2.592	9.2
May	2.678	13.3
June	2.592	16.2
July	2.678	17.6
August	2.678	17.6
September	2.592	15.2
October	2.678	11.2
November	2.592	6.3
December	2.678	3.5

Source: Vlaamse Overheid (2022).

Table 10: Normal-incidence solar factor g for selected glazing types

Glazing type	g_{win}
Standard double glazing	0.77
High-performance double glazing	0.65
Triple glazing	0.70

Source: Own estimations based on Vlaamse Overheid (2022).

Table 11: Monthly solar irradiance $I_{so,m}$ (MJ/m^2) by orientation (at 90°) in Flanders

Month	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
Jan	25.4	26.9	45.3	85.1	108.0	85.1	45.3	26.9
Feb	42.1	46.4	78.7	128.5	158.7	128.5	78.7	46.4
Mar	79.6	95.6	146.6	204.0	233.7	204.0	146.6	95.6
Apr	117.0	151.7	214.0	260.6	272.2	260.6	214.0	151.7
May	169.0	218.6	285.0	315.0	306.9	315.0	285.0	218.6
Jun	183.5	232.6	291.9	308.8	292.9	308.8	291.9	232.6
Jul	178.5	225.5	285.2	307.9	296.6	307.9	285.2	225.5
Aug	146.2	190.2	258.7	300.4	303.5	300.4	258.7	190.2
Sep	98.0	126.2	194.3	259.0	286.7	259.0	194.3	126.2
Oct	61.4	71.4	121.1	188.4	227.6	188.4	121.1	71.4
Nov	30.4	32.8	58.1	106.1	134.5	106.1	58.1	32.8
Dec	19.7	20.7	34.8	68.7	87.7	68.7	34.8	20.7

Source: Vlaamse Overheid (2022).

Table 12: Monthly solar irradiance $I_{so,m}$ (MJ/m^2) by orientation (at 35°) in Flanders

	N	NO	O	ZO	Z	ZW	W	NW
Jan	48.8	50	67	92.4	104.8	92.4	67	50
Feb	81.7	87.9	118	152.3	169.3	152.3	118	87.9
Maa	154.9	178.5	224.9	267.8	287.8	267.8	224.9	178.5
Apr	244.4	282.1	336.7	376.7	391.8	376.7	336.7	282.1
Mei	375.7	403.1	457.5	490.6	499	490.6	457.5	403.1
Jun	409.9	428.1	475.2	499.3	503.2	499.3	475.2	428.1
Jul	394.7	415.4	463.2	489.8	495.4	489.8	463.2	415.4
Aug	318.2	353	411.5	450.8	463.8	450.8	411.5	353
Sep	192.7	236.2	298.1	349.7	372.5	349.7	298.1	236.2
Okt	119.8	134.3	180.4	228.5	251.8	228.5	180.4	134.3
Nov	58.9	61.2	84.6	116	131.5	116	84.6	61.2
Dec	38	38.6	51.3	72.6	82.9	72.6	51.3	38.6

Source: Vlaamse Overheid (2022).

Table 13: Correspondence between surface and price (in €/m²)

Surface	Price	Surface	Price	Surface	Price	Surface	Price
30	1600	61	1304	91	1091	121	949
31	1590	62	1295	92	1084	122	945
32	1579	63	1288	93	1079	123	942
33	1568	64	1279	94	1073	124	938
34	1557	65	1272	95	1068	125	936
35	1548	66	1263	96	1061	126	932
36	1537	67	1256	97	1056	127	929
37	1527	68	1247	98	1051	128	926
38	1516	69	1240	99	1046	129	923
39	1507	70	1232	100	1040	130	920
40	1496	71	1225	101	1035	131	918
41	1487	72	1217	102	1030	132	915
42	1476	73	1210	103	1025	133	912
43	1467	74	1202	104	1020	134	909
44	1457	75	1196	105	1016	135	908
45	1448	76	1188	106	1010	136	905
46	1437	77	1181	107	1006	137	903
47	1428	78	1174	108	1001	138	900
48	1419	79	1167	109	997	139	899
49	1410	80	1160	110	992	140	896
50	1400	81	1154	111	988	141	895
51	1391	82	1147	112	983	142	892
52	1382	83	1140	113	980	143	891
53	1373	84	1133	114	975	144	889
54	1364	85	1128	115	972	145	888
55	1356	86	1121	116	967	146	885
56	1346	87	1115	117	964	147	884
57	1338	88	1108	118	959	148	883
58	1329	89	1103	119	956	149	882
59	1321	90	1096	120	952	150	880
60	1312						

Source: Ryckewaert et al. (2019)

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