The Cost of Sustainability in the Construction Sector

The Case of Family Houses in Belgium

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Working Paper 2023-068

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The cost of sustainability in the construction sector – the case of family houses in Belgium

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September 2023

Abstract.
What is the return to investment in sustainable materials for houses? This research question is addressed through Life Cycle Assessments and Life Cycle Cost analyses of two reference houses and their "sustainable" alternatives in Belgium. The most striking results are that (1) the operational stage accounts for about 65% of the total impact of a house; (2) a 1 € investment in sustainable materials induces a drop of 1 to 1.3 KgCO2eq; (3) this impact fluctuates across elements, with higher returns for widows (-3 to -6 KgCO2eq) and for external walls (-6 KgCO2eq) and the lowest for ground floor (-0.3 KgCO2eq).

Keywords: Life Cycle Assessment (LCA), Life Cycle Cost (LCC), single family house, sustainability, carbon footprint

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1 Introduction

In Belgium, the housing market accounts for a significant share of the overall emission of greenhouse gases. For instance, in 2020 the residential sector was accountable for 14% of the total 106.8Mt of CO2eq emitted, only considering the emissions related to space heating. The residential sector is the third biggest impactor after the industry and the transport sectors. And this does not even consider the embodied emissions of the houses.[3]

About 83% of the Belgian housing market is represented by single family houses fractioned in detached (33%), attached (27%), and semi attached (24%) houses. Apartments represent the remaining 17% of the market (SPW, 2020). Although single-family houses are losing ground in the proportion of authorized constructions, they represent half of new residential buildings.[4]

Measuring the drivers of a typical house's environmental footprint is therefore an essential step forward in tackling carbon emissions in Belgium. If the literature is burgeoning for several countries, very few studies actually measure the full environmental footprint of Belgium family houses. Furthermore, understanding the drivers of a house' footprint constitute only one aspect of the decision process, be it at the private or policy level of decision making. The other dimension that matters is the cost and financial consequences of these drivers. And one can hardly disagree with the fact that very little evidence is available so far in the literature.

This paper precisely aims at filling this gap, by providing up-to-date overall assessment of family houses environmental footprint, the impact of their sustainable 'version' and the cost of these alternative materials. The methodology used to measure the environmental impact is the cradle-to-grave Life Cycle Assessment (LCA) framework that measures the Global Warming Potential (GWP). It is run on two different types of houses to assess the robustness of the results.

The paper is structured as follows. The next section presents the state of the art of the literature aiming at measuring the environment footprint of houses, with their construction and their use or operational components. Section 3 explains the methodology, system boundaries and working hypotheses. The results are presented in Section 4 and Section 5 provides concluding remarks, policy implications and methodological limits.

2 State of the art

Real estate life cycle assessments have been performed for more than two decades, and the literature is quite large, with more than 5 thousand contributions (cf. Table 1). However, heterogeneous LCA methodologies are observed across countries, and very few perform a life cycle cost analysis.

[3]National Inventory Report, 2022
[4]Etat de l'environnement Wallon, 2019.

Table 1 : Overview of literature density

Research key words (Title-Abs-Key)	# of publications
life PRE/ cycle PRE/ assessment AND building	5.091
life PRE/ cycle PRE/ assessment AND house	839
life PRE/ cycle PRE/ assessment AND life PRE/ cycle PRE/ cost AND house	65

Source : Scopus and own computation.

A select literature review is presented in appendix Table A. 1. It covers 10 scientific articles published between 2001 and 2022 from several EU countries. Studies generally distinguish between the embodied impact (construction stage) and operational impact (use of the house during its lifetime). Some of the reviewed studies integrate the End-Of-Life stage, or waste management. There are very few estimates available for the Belgian housing sector, so far. Most existing studies focus on a specific country and very few provide multi country comparisons. Five main observations can be drawn from Table A. 1.

First, although the LCA methodology provides a standardized analytical framework, the building sector is so complex to cope with that cross study and international comparisons must be performed with a high degree of caution, even within a given analysis. Methodological simplifications must be made on system boundaries, data sources, or granularity of information. The estimated carbon footprint is sensitive to working hypotheses and to the depth of the analysis. This methodological heterogeneity is witnessed by the various LCA tools used by authors, as clearly illustrated in Table A. 1. The most frequently used software and database are Simapro and EcoInvent.

Second, most studies distinguish between the embodied impact (house construction, from cradle to grave), and the operational impact (including energy consumption). Sometimes, the End of Life stages is computed. The outcome of the 10 studies listed in Table A1 is displayed in Figure 1. The share of the embodied impact in the total impact fluctuates between 6 and 80% across countries. This variable depends most often on the type of materials used and on the system boundaries. The operational energy use (usage stage) is the most sensitive measure, as countries operate different energy mix. Nevertheless, most studies converge towards the conclusion that the operational phase has the most important environmental impact, fluctuating between 70% and 80%[5] of house's total GWP impact. Nevertheless, the operational impact seems to be decreasing as a share of total impact with time (Rock et al. (2020), Rosa et al. (2012)). The construction phase accounts for 20 to 30%, including end-of-life stages.

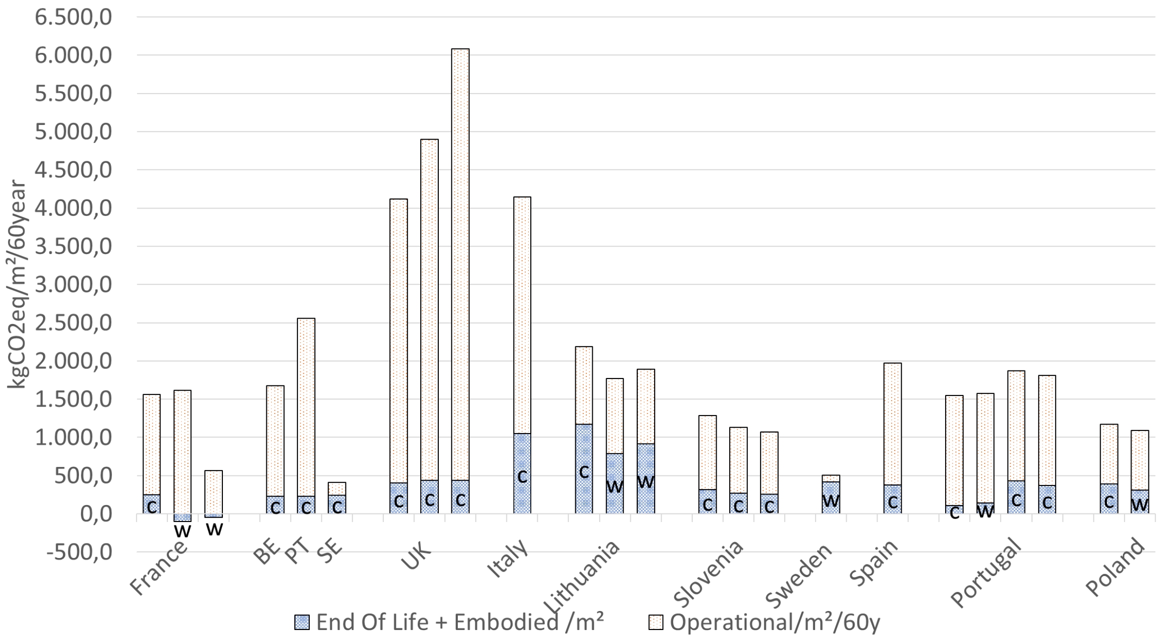
Third, there are some extreme cases where the operational impact – and hence the total impact – is particularly low, like in Sweden (cf. Rossi et al. ,2012 and Petrovic et al. ,2019). This is due to the availability of district heating systems serving several houses, being particularly effective for local communities. The embodied impact is also reduced thanks to wooden structures used in houses. Ideally, the centralized heating system should be integrate in these studies.

[5] In some cases, such as the study conducted by Peuportier (2001) the Embodied phase accounts for negative values. Therefore pushing the operational phase at more than a 100% impact proportion.

Fourth, the carbon footprint of the end-of-life stage (EOL) is sometimes integrated in the embodied impact. When data is accessible in the literature its impact is displayed as an independent impact. Though for some studies no distinction between Embodied and EOL is made, potentially overestimating the Embodied phase (Peuportier, 2001.) There appears to be no clear rule of thumb for the EOL results as it ranges from -4% to up to 24% of the total impact when it is computed. This stage is quite complex to measure, and depends heavily on the methodology, the materials used and the scope of the study.

Fifth, few studies provide both economic and environmental assessment of houses impact based on LCA and LCC.

Figure 1 : Comparison of Embodied and Operational impact per square meter in select literature. [kgCO2eq/m²*60year].



Note : All parameters have been normalized for an homogeneous 60 years lifespan per square meter. The EOL stage is included in the embodied charts. Studies are order according to publication year. Source: own computations based on reference papers available in Table A. 1 Where "c" and "w" respectively indicate the concrete and wooden frame for each of the case.

In a nutshell, most of the existing literature, despite being embedded with heterogeneous methodologies, scope, and data sources, reaches the conclusion that the operational use of a house generates a substantially higher carbon footprint than its construction or end of life phase. Very few studies integrate alternative construction material, and even less the cost component of these alternatives. The present analyses aim to bridge these gaps, by performing a systematic comparison of different types of new houses, and more sustainable materials to build them.

3 Methodology

The Life Cycle Assessment (LCA) methodology used in this paper is detailed in the ISO standards 14044 (ISO 14044) and relies on the Belgian online tool TOTEM to quantify CO2 emissions[6] and assess the Global Warming Impact (GWP) of the selected houses. The tool uses the EcoInvent data base with adapted generic data to Belgian context such as energy mix and waste treatment. For certain materials the tool also contains data about Belgian materials specific to the national context. This feature is highly valuable for this study as it provides more accurate evaluation of the environmental impact of the construction in Belgium. The fact that TOTEM relies on Belgium-specific data for transportation and building led our choice for this software.[7]

The total GWP impact on the environment is split in two categories: 1) Embodied carbon impact and 2) Operational energy use. Embodied Carbon impact is the sum of emissions associated to all the materials used to build the house. It is computed with a cradle to grave approach and therefore considers all stages described in the system boundaries (cfr Figure 4) (i.e. from extraction of raw materials to waste management). In other words, it is the total impact without the energy use of the house (Operational energy use). The End Of Life (EOL) is also computed and is integrated in the Embodied phase. Operational Energy Use impact is the impact in terms of CO2 emissions linked to the heating of the house. It comes from operational use in heating from gas energy[8] to cover surface heat losses and ventilation heat losses.

3.1 Scope and functional units

The analysis intends to develop a cradle to grave life cycle assessment of 2 reference houses and their sustainable alternatives alongside with their life cycle cost. Providing both assessments will enable to generate a price of CO2 abated and give a ranking of relative performance, on average, and for each element or material.

The reference houses are called "House 1" and "House 2". The first one is a full detached house with four external walls, and the second one is attached, between two other houses, hence with only two external walls. For each reference house, an alternative one – the sustainable house - has been built with different materials and elements. The alternative more sustainable houses are called "House 1.2" and "House 2.2", respectively. Both houses' designs were chosen on a Belgian construction catalogue and were described for the LCA tool with the close cooperation of an architect to ensure the reliability in construction method and materials used.[9]

House 1 and its sustainable alternative (House 1.2) are fully detached 4 walls houses which can be considered as modern houses with a 293m² (square meter) habitable surface, a flat roof and one floor. It has 4 bedrooms, of which 1 can be considered as an office, 1 kitchen, 1 living room, 2 bathrooms and toilets, a garage for 2 cars and 2 terrasses. It has a total of 630m³ (cubic meter) heated volume. The shape is provided on Figure 2. House 1.2 is built using a wooden frame house in opposition to masonry frame of House 1.

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[6] LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave). (ISO 14040, 2006).

[7] https://www.totem-building.be/pages/about.xhtml#3.0

[8] SPF Economie, 2022

[9] Maison Compere (2021). Consulted June 3 2021. https://www.maisonscompere.be (MC13,MC464)

Figure 2 : Layout of House 1

Source: Maison compere 2021 (MC464)

Both attached Houses 2 and House 2.2 have the same shape and design displayed in Figure 3 . It has 3 bedrooms, 1 kitchen, 1 living room, 1 toilet and a bathroom. Both houses therefore respect the same 112m² (square meter) of habitable surface and a total 290 m³ (cubic meter) heated volume. They have an under-roof space.

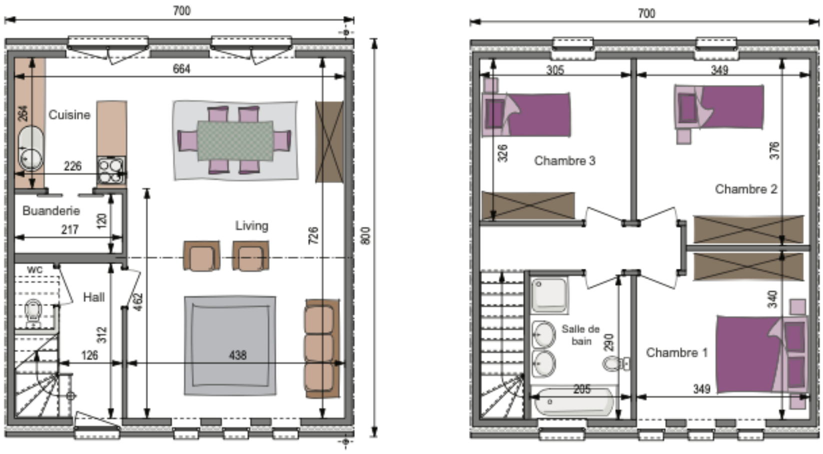
The operational energy use to compensate heat transmissions through surfaces and ventilation of the houses is computed in [KgCO2eq] and [kWh/Year]. Both measures are used to respectively compute the LCA and the LCC. The yearly energy consumption is assumed to remain constant throughout the whole lifespan of the houses (60 years).

As the analysis is performed on new houses located in Belgium, the energy source considered for heating is gas. As Ben-Alon et al. (2021) show, climate dependency plays a big role in the final evaluations of LCAs. Therefore, this research considers the Belgian climate to be tempered and to remain constant throughout the full lifetime of houses. Additionally, since Belgian climate does not suffer from harsh summers, no air-cooling system is considered in either the LCA or the LCC. Finally, no solar panels or specific ventilation systems is considered.

For easier comparability between houses, some results are provided as impact per square meter for each dwelling (e.g., [kgCO2eq/m²],[€/m²]). For such computations the surface used as denominator is the total habitable surfaces described above. (House 1 and 1.1 : 293m² ; House 2 and 2.2 : 112m²).

Figure 3 : Layout of House 2

Source: Maison compere 2021 (MC13.)



3.2 Service life

The service life of all houses is assumed to be 60 years, and the residual values at end of life are expected to be 0€. Impacts of component and elements with lower lifespan are considered multiple times according to their respective lifespan in the LCA and LCC. The detailed lifespan of each element as well as their respective replacement timelines can be found in appendix Table A. 2 and the details are presented in the Appendix (Table A. 3, to Table A. 6).

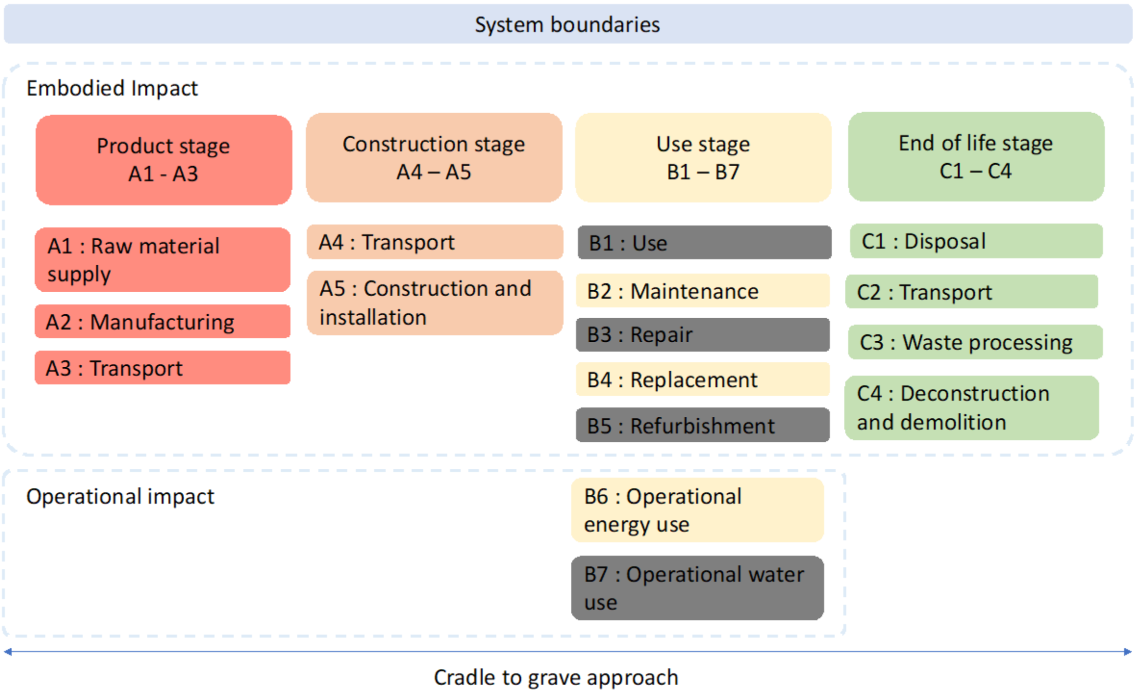
3.3 System Boundaries

The system boundary used in the study is based on the European standards EN 15978:2011, and is illustrated in Figure 4. End of life (EOL) of houses is considered to secure a comprehensive cradle to grave analysis. However, because of lack of data, no reusing nor recycling of materials has been considered in the analysis. The EOL is included in the Embodied impact (as in Gervasio and Dimova, 2018).

The operational energy use (B6) is computed using the degree-day method for heat losses through external surfaces transmission.[10] The default energy source used is natural gas.

[10] The operational energy impact linked to heat losses has been computed only for the structure exposed to the exterior and based on their intrinsic insulating values (U-Values, i.e. external walls, windows, floor on ground and roof). The internal features were therefore not considered in the operationnal use simulation, but they do have an impact in the embodied and the EOL stages. In addition to heat transfert through surfaces, ventilation and air infiltrations cause heat losses and are computed in all houses by the software. Calculations are based on transfering heat surfaces and heated volume as well as on fixed parameters such as buildings airthighness, ventilation air flow, ventilation and standard heat transfer performances (OVAM, 2021). As houses designs have not been altered the ventilation is assumed to remain constant among reference and alternative houses ensuring a comparison on heat transfers on surfaces only.

Figure 4 : System boundaries



Source: OVAM, SPW, Bruxelles Environnement. (2020). Environmental Profile of Building elements. Note: Each stage of the system boundary has a specific colour : Product stage (Red), Construction Stage (Orange), Use Stage (Yellow) and End of life (Green). Grey areas designate the LCA processes that are not included in the analysis.

As shown on Figure 4, all cradle-to-grave modules are assessed in the LCA, except for modules B1, B3, B5 and B7, mainly because of a lack of available data. According to Energy Efficient Buildings Initiative guide project[11], failing to integrate those modules does not affect substantially the consistency of the analysis. B1 and B7 are outside the scope of the study and B5 is recommended only for buildings with a lifespan that is above 100 years. Even though the modules B3 should ideally be integrated most studies do not consider it because of the lack of data (Soust-Verdaguer et al.,2016).

It is important to bear in mind that this empirical investigation is based on the envelope of houses and that some parameters are beyond the scope of this study such as: heating ventilation and air conditioning (HVAC) performances and prices, inhabitant behaviours, or the available Belgian energy mix for electricity and energy. Similarly, parameters that do not have direct influence on the LCA, but rather on quality of life within the house (habitability and comfort of houses, design or aesthetic), are not included.

The life cycle inventory has been build using specific and generic data. Specific data come from Belgian Environmental Product Declarations and generic data comes from the Ecoinvent 3.6 data base.[12] Generic data are adapted to the Belgian context when necessary and possible

[11] Eeb Guide project https://www.eebguide.eu/eebblog/?page_id=704ct
[12] Ecoinvent data base website : https://www.ecoinvent.org/home.html

(i.e., transport when impactful, western European transformation processes, Belgian energy mix, …).

3.4 Life cycle impact assessment

Table 2 : Proportion of each impact indicators in the total aggregated impact

Impact indicators	Units	Aggregating ratios	Environmental score %			
			House 1	Alternative house 1.2	House 2	Alternative house 2.2
GWP	kg CO2 eq.	0.026 mPt/kg CO2 eq	39.00	41.00	40.00	42.00
Ozone depletion	kg CFC 11 eq.	1176 mPt/kg CFC11 eq	0.27	0.28	0.27	0.27
Acidification	mol H+ eq.	1.1 mPt/mol H+ eq	4.00	3.90	4.20	4.10
Eutrophication			3.10	3.10	3.20	3.30
Aquatic eutrophication - fresh water	kg P eq.	17 mPt/kg P eq	0.31	0.31	0.31	0.31
Aquatic eutrophication - marine	kg N eq.	1.5 mPt/kg N eq	1.10	1.10	1.20	1.20
Land eutrophication	mol N eq.	0.21 mPt/mol N eq	1.70	1.70	1.80	1.80
Photochemical ozone creation	kg NMVOC eq.	1.2 mPt/kg NMVOC eq	3.30	3.20	3.30	3.40
Abiotique ressources depletion			28.00	30.00	28.00	30.00
Abiotique ressources depletion - minerals and metals	kg Sb eq.	1186 mPt/kg Sb eq	1.70	1.60	1.80	1.80
Abiotique ressources depletion fossil fuels	MJ, net calorific value	0.001 mPt/MJ	26.00	28.00	26.00	28.00
water resource depletion	m3 world eq. deprived	0.007 mPt/m3 depriv.	1.70	1.50	1.50	1.30
Fine particules	Disease incidence	2E+05 mPt/disease inc.	11.00	6.20	9.80	6.10
Ionasing radiations - human health	kBq U235 eq.	0.012 mPt/kBq U-235 eq	0.42	0.46	0.42	0.45
Ecotoxicity - water	CTUe	5E-04 mPt/CTUe	5.60	5.10	5.20	4.90
Human toxicity			2.50	2.20	2.00	2.10
Human toxicity, carcinogenic effects	CTUh	1E+06 mPt/CTUh	1.40	1.30	1.20	1.30
Human toxicity, non carcinogenic effects	CTUh	80114 mPt/CTUh	1.10	0.88	0.86	0.81
Land use and soil quality	dimensionless	1E-04 mPt/Pt	0.57	3.10	1.40	2.70
Total			**100**	**100**	**100**	**100**

Source: TOTEM's results and own calculations. Note: every indicator is displayed in a different colour for easier interpretation. Guide for abbreviations: Global Warming Potential (GWP), Milli-points (mPt), Carbon Dioxide equivalent (CO2 eq.), Trichlorofluoromethane equivalent (CFC11 eq.), Mole of H+ equivalent (Mol H+ eq.), Phosphorus equivalent (P eq.), Nitrogen equivalent (N eq.), Mole of Nitrogen Equivalent (Mol N eq.), Non-methane volatile organic compounds equivalent (NMVOC eq.), Antimony equivalent (Sb eq.), Uranium 235 Becquerel equivalent (Bq U235 eq.), ecotoxicity Comparative Toxic Units (CTUe), human Comparative Toxicity Units (CTUh).

The four houses are first assessed using the 12 LCA indicators recommended by EN 15804 and their contributions to total impact are displayed in Table 2, for each house. All indicators are computed with their respective units to provide an extensive and coherent understanding of the overall impact of a house on the environment. Each impact score is then normalized and aggregated in a single unit, being milli-points [mPt] using fixed aggregating ratios (displayed on the table). This aggregation provides a total impact score in milli-points [mPt] which ultimately enables a comparison of all indicators. As showed on Table 2, the Global Warming Potential (GWP) is by far the highest contributor to total environmental impact with a contribution to total aggregated impact of 39% to 42%. This very high ratio led us to decide that the analysis developed in the present analysis will focus essentially on the GWP indicator to provide a deep and extensive understanding of the carbon impact of the chosen Belgian houses. Results will therefore be expressed in [kgCO2eq].

3.5 Composition

Both reference houses are designed with the most frequently used elements on Belgian housing market. The objective of this paper is to stick as close as possible to the typical house construction and the LCA analysis has been performed ex post. A detailed composition of all houses can be found in annexes (cfr Table A. 3, to Table A. 6 in the appendix). About House 2, the external walls are in clay bricks and no wooden structure has been used for the sustainable alternative. Since shared walls of attached House 2 and 2.2 cannot be constructed in wood, by law, shared walls remain the same in both houses.

3.6 Variation on elements

During the construction process of both alternative houses the choice of alternative materials composing each element was based on the total aggregated score [mPt] (see Table 2). Each material was systematically replaced by an alternative similar material available on the platform providing the lowest possible aggregated score to the whole element. This means that all impact indicators displayed in Table 2 were considered to choose alternative construction materials and elements. This method ensured that best elements were picked selected based on total environmental impact therefore ensuring that no arbitrage of indicators was made (i.e., lower GWP impact but heavier CFC impact). Building on this method, the work ultimately focuses on the analysis of GWP to give an overall understanding of the CO2 emissions.

The major changes in the envelope and the total variations induced using sustainable materials in alternative houses, as compared to the reference ones, have been computed for the two designs. The proportions have been assessed by comparing the reference of material, keeping the value of 1 if material references are the same and 0 otherwise. Then the surfaces of each element have been used as a weighting factor. In a nutshell, there is a 42% similarity rate regarding elements and materials between reference House 1 and House 1.2. The similarity comes mainly from foundations and interiors features such as doors which remain constant between reference and alternative dwellings.

Regarding House 2, attached between two other houses, the degree of similarity is 68% with its alternative sustainable one. The higher similarity rate comes mainly from Belgian regulatory constraints regarding attached walls and the use of a similar roofs. In Alternative House 2.2, attached walls had to be kept in masonry inducing a higher similarity rate with reference House2. Also, as the roof used in reference House2 is the most performant roof available on the software, the one used in alternative House 2.2 is the same as its reference one. Since both house designs and shapes are very different from each other (window/wall ratio, walls and floor surfaces ratio, conduction heat surfaces ratio, …) comparison of House 1 and House 2 or House 1.2 with House 2.2 should be made with caution.

3.7 Life Cycle Cost analysis

The LCC follows the methodology mostly used in the literature (Hasan et al. (2008), Allacker (2010), Lechon et al. (2021)). It is characterized by Equation 1. The total ownership cost (TOC) of a house is composed of the sum of the construction costs (COC, Equation 2), discounted operational costs (OPC, Equation 3), and discounted maintenance costs (MAC, Equation 4). Because of a lack of data for the Belgian construction system, the End Of Life costs are not included in the analysis.[13] To remain consistent with the end of life treatment without

[13] Petrović et al., (2021) show that End of Life costs are negligible in the LCC.

recycling and reuse of materials, the residual value of a house is assumed to be of 0€ after 60 years. HVAC system costs are also excluded from computations (see: Table 4) because of their high volatility in prices and performances (Pernetti et al., 2021) and lack of available data. Finally, prices include work of assembly and VAT is excluded from all cost's computations.

Equation 1 : Total Ownership Costs

$$TOC = COC + PV(MAC) + PV(OPC)$$

Note : TOC : "total ownership cost", COC : "Cost of construction", PV(MAC) : Present Value of Maintenance Costs PV(OPC) : "Present Value of Operational Costs over the 60 years lifespan"

Equation 2 : Construction costs

$$COC = \sum_{i=1}^{n} P_i * S_i$$

Note : P_i: "Price of specific material per square meter", S_i: "Surface of the specific material". The price of material includes work of assembly. VAT is excluded.

Equation 3 : Present Value of Maintenance Costs

$$PV(MAC) = \sum_{i=1}^{k} \frac{P_i * S_i}{(1+q)^{t_i}}$$

Note : P_i: "Price of each specific material which needs to be replaced during the lifespan of the house", S_i: "The surface of the specific material", q : "discount rate fixed at 3%", t_i: "number of years after which the specific material needs to be replaced". K is a lower number than n as all elements do not need to be replaced during the lifetime of the house. The price of material includes work of assembly. VAT is excluded.

Equation 4 : Present value of the operational costs

$$PV(OPC) = \sum_{t=1}^{60} \frac{kWh_a * (EP * g)}{(1+r)^{t}}$$

Note : kWh_a: "Annual consumption of energy of the concerned house (which is assumed constant throughout the years for each house)", EP : "Energy price considered fixed at 0.14312€/kWh", g : "growth factor simulating inflation for energy prices fixed at 0.5%", r : "discount rate fixed at 4%", t : "year of each yearly consumption"

The prices used in the life cycle cost analysis for the construction phase is in € and are based on the "Bordereau des prix unitaires" of 2017 (UPA, 2017). A correction to get prices of 2022 was used with the Abex index[14] at a 18% inflation from 2017 to 2022. The Bordereaux provides upper and lower prices for each materials including work for assembly and VAT excluded. For the current simulations, the average price of each material was used in the simulations. All prices are directly converted in the reference surface unit of each material.

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

(i.e., square meter in most cases). When prices are delivered per cubic meters, the thickness of the material is used to convert the price per square meter.[15]

When the price of a specific material cannot be found in the Bordereau, pricing is made with materials that resemble the specific one available on the Bordereau. (e.g. wooden frame with cork for windows).[16] If similar materials were not available in the bordereau (e.g. expanded cork used for alternative sustainable insulation), then an average price is computed, based on online search.[17]

Future maintenances costs are discounted at present value. The discount rate is set at 3% based on the existing literature (e.g., Islam et al., 2015; Hasan et al., 2008; Allacker, 2010). Replacement costs are assumed to be equal to their respective construction costs at time t0 and are actualized with their respective time factors.

Regarding gas prices, for the LCC the discount rate is chosen at 4% and initial price is picked at 0.14312€/kWh[18] VAT excluded. A growth rate of 0.5% is added to the energy price to simulate a light inflation, see Table 3.

Table 3 : Details of energy costs

Energy consumption per house	**Energy consumption/y [kWh]**	**Price of kWh [€/ kWh]**	**Energy cost [€]**	**Discount rate**	**Growth Factor**	**Total DCF (60y) [€]**
Maison 1 kWh	16410.90	0.14312	2348.73	4.0%	0.5%	61143.20
Maison 1.2 kWh	16550.20	0.14312	2368.66	4.0%	0.5%	61662.20
Maison 2 kWh	6236.85	0.14312	892.62	4.0%	0.5%	23237.06
Maison 2.2 kWh	6079.19	0.14312	870.05	4.0%	0.5%	22649.65

Note : The energy price per kWh is chosen accordingly to reported Belgian price of February 2022 when the study was performed. Source : https://callmepower.be/fr/energie/guides/tarifs/gaz.

As reference houses are chosen on a Belgian website[19], it is possible to compare the independent aggregate price from the data obtained in the Bordereau and the official catalogue price of reference houses. Table 4 compares the catalogue prices of reference houses and the independent computation of this study based on the prices provided by the Bordereaux (UPA, 2017) actualised for 2022. As HVAC and electricity systems prices are not included in the research, a 15.2% discount has been integrated on catalogue prices to ensure comparability among both values (UPA, 2017).

[15] For instance, for concrete block, the Bordereau price ranges from 350€/m³ to 441,36€/m³, hence a concrete block with 19cm of thickness would have a price of 75.2€/m².

[16] For instance, no data could be found for the price estimations in the Bordereau concerning alternative windows frames made of wood and cork. Though, in the Bordereau on average wooden frames are less expensive that good aluminum frames but cork would increase the total price of such frames. Therefore, it is assumed that the wooden frames would have the same price as the reference windows.

[17] For instance, the average price of the cork used in ground floor is set at 58€/m². 30% of material price was added to simulate work of assembly, providing a total of 75€/m².

[18] new ref : Engie : https://callmepower.be/fr/energie/guides/tarifs/gaz

[19] https://www.maisonscompere.be (House reference codes : (MC13,MC464)

Table 4 shows that both reference houses are somewhat overestimated in the present simulations, compared to their catalogue prices. The rather low disparities in the final prices, mostly in House 2, can be explained by two phenomena. First, a high raw material price incertitude combined to an extraordinary high inflation rates happening in the constructing sector in the Covid crisis. Second, a possible mismatch between the prices suggested by the sellers and the actual value of materials at the time the study was conducted. It is likely that those rates are not highly representative of the economic values of the period hence should be interpreted with care.

Table 4 : Price comparison of reference houses (2022)

	House 1	House 2
Surface [m2]	293	112
Catalogue price [€/m2]	1200€	1069€
Catalogue price excluding HVAC and Electric Instalation (-15.2%) [€/m2]	1018€	907€
Independent estimated price of the study based on Boredereau [€/m2]	1101€	1116€
Over/under estimation of final price for houses	**+8.2%**	**+23.1%**

Source: Maison compere (2022), Bordereaux des prix unitaires 2017 and own calculations.
Note : As stated by Bordereaux des prix unitaires 2017, the price of the electric and HVAC system accounts for 15.2% of a house's price.

4 Results and discussion

4.1 Outcome of the LCA

The LCA results presented in Table 5 and displayed in Figure 5 are compatible with the literature survey. Similar observations can be drawn about the higher impact linked to the operational phase compared to the embodied impact. The operational stage represents at least 59% of the total traditional house impact. The proportion even grows for the alternatives sustainable houses, because the operational phases has been very lightly affected by the use of alternative materials, hence increasing in proportion. This is explained by the fact that for coherence and comparison purposes the thickness of alternative materials is kept identical to reference materials. It is clear that for some elements the difference of performance is wide but when considering full houses the overall operational impact remains stable.

These results are aligned with the observation from the literature about the high operational impact, for all types of houses. The embodied impact has however a higher proportion than in the literature, thus potentially indicating that the houses are already well insulated and hence have a reduced operational impact. About the EOL, this study is also aligned with the literature about references houses. However, it provides rather high proportion of end-of-life stage impact for the sustainable alternative houses. The results for the sustainable houses are close to those presented in a small number of investigations, suggesting that the EOL should not be neglected in LCAs.

The main driver of impact reduction is the embodied carbon, reduced by up to 37% in alternative houses 1. As displayed on Table 5, the parameters for two types of houses indicate that sustainable materials have similar operational performances on average but have a significantly lower embodied impact than synthetic materials. In other words, alternative materials have a positive contribution towards the reduction of CO_2 emissions linked to the housing market, mainly on the embodied phase.

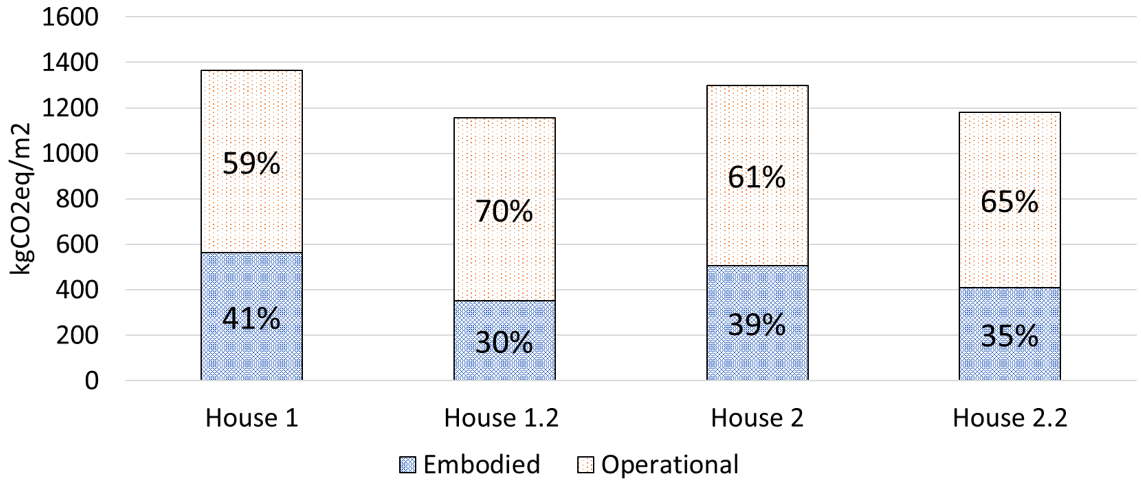
Even though results are comparable, the ratio of operational energy use of houses on total GWP impact for reference houses (about 60%) is lower than in previous studies, witnessing an increasing energy efficiency of recent buildings. (Cuellar-Franca and Azapagic. 2012)

Table 5 : Overview of LCA and LCC results per square meter per year [kgCO2eq/m²Y] [€/m²Y]

	Embodied impact [kgCO2eq/m²Y]	**Operational impact [kgCO2eq/m²Y]**	**Total impact [kgCO2eq/m²Y]**	**Embodied costs [€/m²Y]**	**Operational costs [€/m²Y]**	**Total costs [€/m²Y]**
House 1	9.37	13.35	22.72	23.15 €	3.48 €	26.63 €
House 1.2	5.87	13.38	19.26	25.94 €	3.51 €	29.45 €
House 2	8.44	13.20	21.64	23.54 €	3.46 €	26.99 €
House 2.2	6.81	12.87	19.68	25.48 €	3.37 €	28.85 €

Source : own computations.

Figure 5 : Proportion of total Embodied and Operational impact per square meter [kgCO2eq/m²] [%]



Source: TOTEM's results and own calculations. Note : the results are displayed for 1 square meter for 60 years lifetime.

The amount of carbon abated is not evenly split among elements and is heterogeneous across the two houses. Figure 6 displays the repartition of abated carbon by elements having an impact on the variation of total GWP impact for both embodied (construction) and operational (use) phases. The elements with the greatest impact are those in which concrete or metals structures are replaced by wooden structures (i.e. external walls, roof for House 1.2, windows in both house type).

Interestingly – and counter intuitively - the operational impact of some elements (i.e. floor on ground and the roof for House 1.2) increases from the traditional to the more sustainable alternative. In these cases, the alternative insulation material has lower intrinsic performances and therefore induces a higher demand for heating.[20] However, the total GWP systematically decreases (for the two houses), thanks to a much lower footprint of the embodied phase. It would also be possible to decrease the total impact further by increasing the insulation thickness using the identified alternative material. This would lead to a reduction of operational required energy and would contribute to the lower total impact. However, a thicker insulation would obviously imply a greater cost of CO2 emissions in the embodied phase.

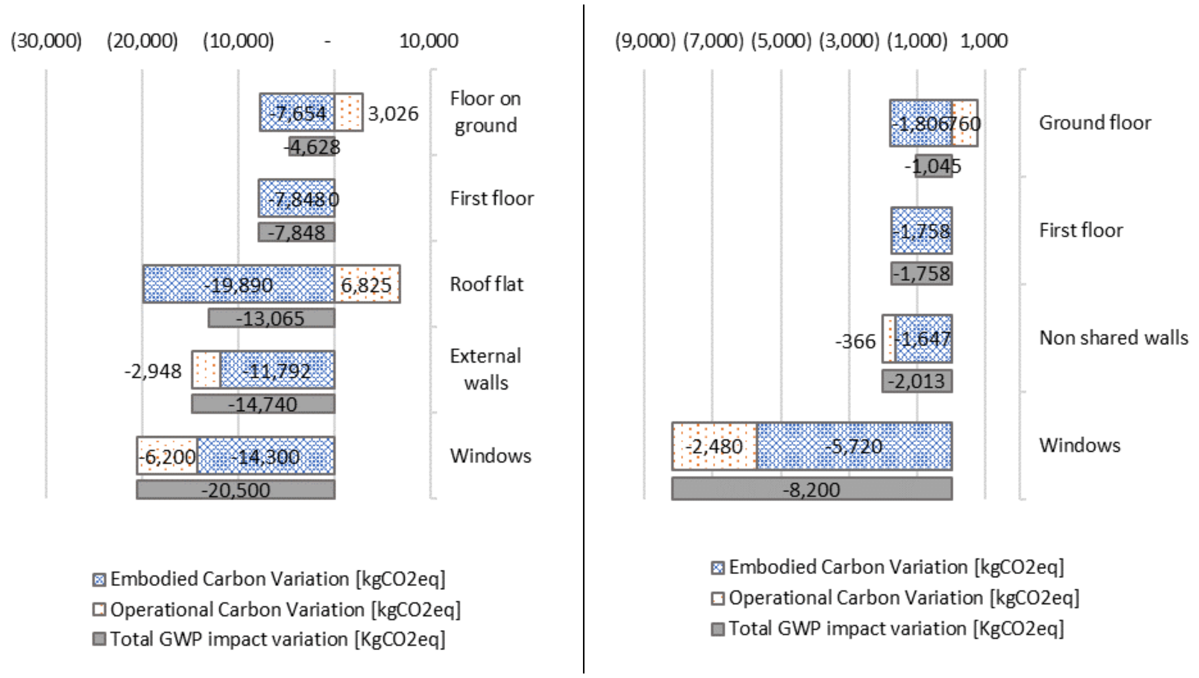
For House 1, switching to sustainable materials induces a total reduction of -61.484kgCO2 for embodied, and a small increase in operational use (+703kgCO2eq). Windows have the greatest impact, about one third of total reductions.

The elements having the greatest impact are the windows being built in wood and cork, cork has very interesting properties with a lesser impact both in embodied and operational phases. As displayed on Figure 6 the external walls of alternative House 1.2 also play an important role in the decrease of the embodied and operational carbon impact.

The alternative House 2.2 has been built with the same roof as its reference house. Indeed, in this case the reference roof has very good performances and no better alternative could be designed, as opposed to the case of House 1. This suggests that reference roofs for attached houses should not anymore be on the focus for the decrease of GWP impact. Nevertheless, a higher insulation of such roofs with the identified alternative materials will still decrease the operational impact at a relatively low embodied carbon impact increase.

[20] As shown in Figure 6, in the case of House 1 transformed to House 1.2, the floor on ground and Roof Flat both have a higher operational impact. This is explained by the fact that the material used for the insulation of the two elements (expended cork and rock wool + cellulose wadding respectively) has a lower insulation efficiency. As the thickness of the material is the same for the reference material and the sustainable alternative, the elements have a lower insulation property requiring a higher operational energy heating.

Figure 6 : Embodied and operational carbon abated by elements from traditional to sustainable houses (House 1 left, House 2 right) [kgCO2eq]

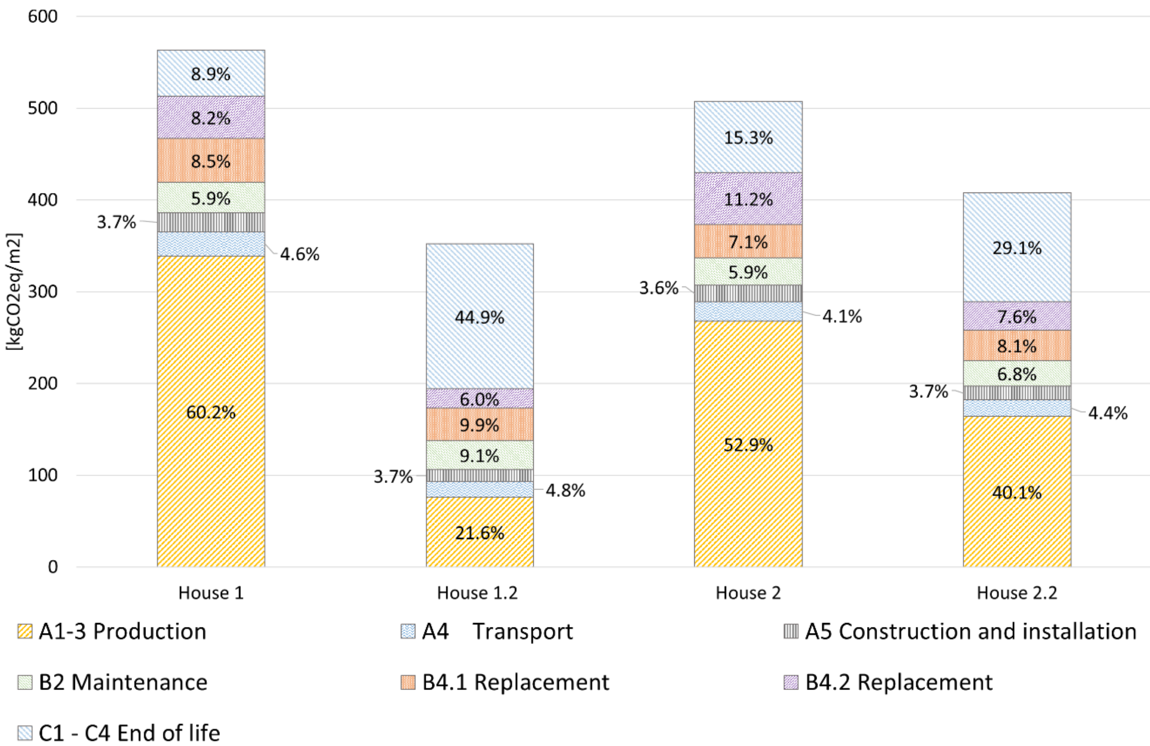


Source: TOTEM's results and own calculations.

4.2 Embodied carbon by system boundary stages

Figure 7 shows the impact of each LCA stage contributing to the embodied phase. Regarding reference Houses 1 and 2 the production stage is the main contributor to the embodied impact. As reference houses 1 and 2 are mainly composed of concrete structures and synthetic materials, the production stage is the main contributor of impact among all stages and aggregated End Of Life stage (C1-4) for both reference House 1 and reference House 2 are relatively low.

Figure 7 : Embodied carbon impact of each system boundary stage at house level. [kgCO2eq/m²]



*Note: Modules B1, B3, B5, B7 from Figure 4**Erreur ! Source du renvoi introuvable.** are not represented in the figure since they have not been assessed by the platform (seeFigure 4). Module B6 is not represented on the figure. Source: TOTEM's results and own calculations.*

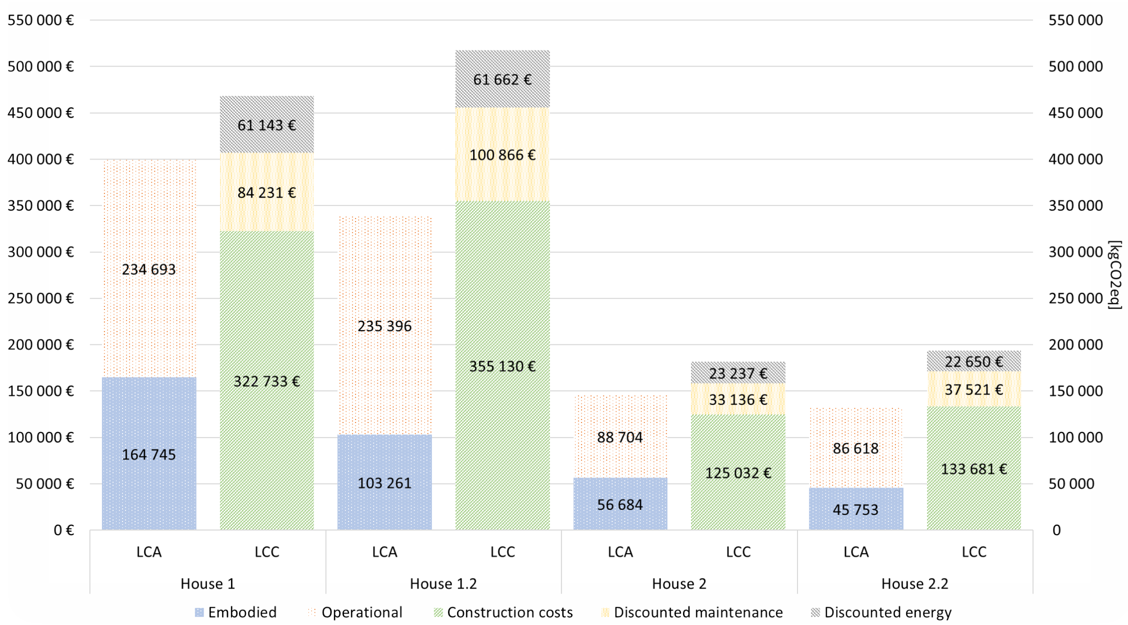
Interestingly, EOL impact is greater for the sustainable houses compared to their traditional versions, whereas other stages remain stable. In the two cases the strong increase in the End Of Life stage (overly represented by the Waste Elimination Stage; C4) is a consequence of the replacement of concrete by wooden materials. Nevertheless, the magnitude of the impact switch from production to EOL is not even for both house types. The difference between the two sustainable structures is explained by the unequal proportion of wood used in both dwellings. Indeed, House 1.2 being fully built with wooden structure shows a drastic switch from stage A1-3 to C1-4 while House 2.2 containing fewer possible wooden materials in the structure implies a lower switch among the stages.

The variation of the production and EOL stages is strongly affected by the Biogenic carbon computation delaying the carbon impact (Fouquet et al., 2015). With other words, when wooden structures are used to replace concrete; CO2 emission are temporarily stored in the structure and released at EOL. Interestingly, the combination of Production and EOL stages account consistently for 69%, 66%, 68% and 69% of the total embodied carbon, for House 1, House 1.2, House 2 and House 2.2 respectively. This observation does not contradict the fact that, overall, wooden structures are less impactful than concrete on a GWP point of view.

4.3 Life Cycle Cost analysis (LCC)

As illustrated in Figure 8, the total ownership costs (TOC) of Houses 1.2 and 2.2 are greater than their reference ones by 11% and 7%, respectively. This increase includes the construction costs, discounted maintenance costs and discounted energy cost over the full lifespan of houses. For both houses the main contributor to the overall increase is the cost of construction. It represents between 67% and 69% of the total cost of ownership, which is compatible with the literature results (see Lechon et al, 2021). Interestingly, for the two sustainable constructions, the maintenance costs increased. This is caused by the higher replacement rate of natural material compared to synthetics. As the operational phase remains stable the costs of heating is similar across reference and alternative houses.

Figure 8 : Total GWP impact [kgCO2eq] and ownership cost of houses [€]



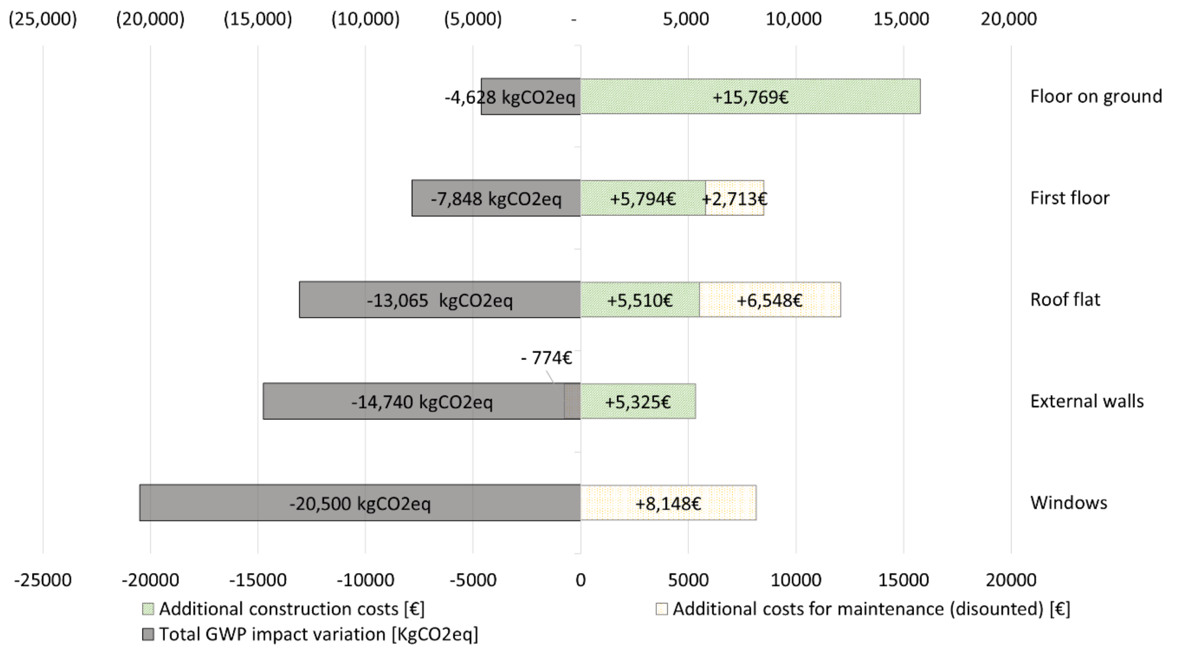
Note: Costs provided in the figure do not consider costs of HVAC equipment. Source: TOTEM's results, UPA 2017 and own calculations.

4.4 Construction and maintenance costs vs CO2 footprint

Considering aggregate construction costs only, houses 1.2 and 2.2 are respectively 10% and 7% more expensive than their references. This increase in cost for the construction process is not evenly split among all elements. Figure 9 and Figure 10 provide a detailed analysis of the variations in embodied and operational carbon footprint compared to costs for House 1.2 and House 2.2 respectively. In both cases the floors on ground have the biggest impact in the cost difference due to the expended cork used for the insulation, which is 2.5 times more expensive than the extruded polystyrene used in reference houses. The alternative roof flat of House 1.2 is 5 510€ more expensive to build and costs 6 548€ more to maintain than the reference roof from House 1, but it reduces the embodied and operational CO2eq impact of house 1.2 by 13 065kg.

In elements such as roof and external walls, the main reason for the overall cost increase is that wooden structures require a greater number of different materials that have on average the same price as reference elements. For House 1.2, the maintenance cost for walls is lower thanks to the lower cost of natural parging on wooden structure. The case of the roof also shows that more than half of additional costs come from maintenance. A wooden roof requires replacement of components such as wooden battens and plaster panels. For House 2.2, since no wooden structure has been used in external non-shared walls, the only variation in price come from the insolating clay bricks and clay-based paster used. It is important to keep in mind that shared walls are the same in both reference and alternative House 2.

Figure 9 : Embodied and Operational impact decrease [kgCO2eq] compared to Construction and Maintenance costs increase [€] per element from House 1 to 1.2.

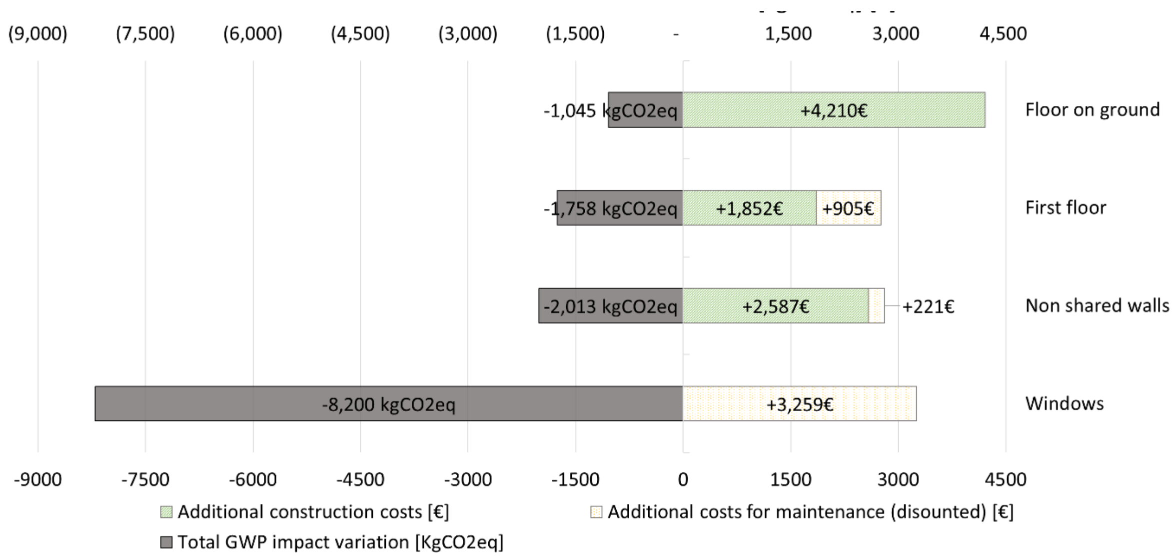


Note: The maintenance costs are discounted as detailed in methodology. (3% discount rate). Table A. 2 provides the full timeline for discount periods. Source: TOTEM's results, UPA 2017 and own calculations.

The first floor represents the last part of the total difference in prices. The main responsible of the difference are the plaster panels used instead of the cement on prestressed concrete in reference house. Next is the rockwool under the wood floor serving as an insulation of comfort and not playing any role in the energy efficiency of houses.

Although wood and aluminium window frames are expected to have the same price, maintenance costs linked to their lifespan are different. As wooden frames need to be replaced once during the building's lifespan, the windows have a greater impact in the LCC of alternative houses. Although being replaced once during the lifespan, windows have a major role in the decrease of alternative house's footprint and therefore are a key element to consider in both dwellings. The difference of impact is explained by the higher surface of windows in House 1 than House 2 (50m^2 and 20m^2, respectively).

Figure 10 : Embodied and Operational impact decrease [kgCO2eq] compared to Construction and Maintenance costs increase [€] per element from House 2 to 2.2



Note: The maintenance costs are discounted as detailed in methodology, with a 3% discount rate.Table A. 2 provides the full timeline for discount periods. Source: TOTEM's results, UPA 2017 and own calculations.

Figure 9 and Figure 10 display the additional costs of construction alongside the variation of maintenance costs per elements when implementing the sustainable materials. This means that maintenance costs linked to elements that did not vary are not represented on the figures (interior walls, doors, terrasses, shared walls, roof floor). Those elements still require maintenance costs but since they are the same in both reference and alternative houses they do not account for any difference and are therefore disregarded.

The alternative first floor of House 2.2 is 1 852 € more expensive to build and 905€ more to maintain than the reference first floor from House 2, but it reduces the embodied and operational CO2eq impact of house 2.2 by 1 758kg.

Maintenance costs increase for the two alternative houses (cf. Figure 8). More than half of total discounted maintenance cost come from paintings replacements.[21] The proportion of paintings maintenance in House 1 accounts for 66% of total maintenance costs. Same goes for House 1.2 (56%), House 2 (78%) and House 2.2 (65%). This over representation of painting costs comes from the fact that acrylic paint is assumed to be replaced every 10 years at actualized fixed costs.

The main reason for the overall price increase of non-painting maintenance - in the two sustainable houses - is related to the fact that wooden and cork window frames are to be replaced once in the lifespan of the alternative buildings, whereby aluminium frames do not. The rest of the variation is explained by the higher replacement rate of materials for wooden roof structure (wooden batters, plaster panel on wood).

[21] Figure 8 provides the full construction, maintenance and operational costs of all elements and includes paintings costs in maintenance total costs.

4.5 Cost per abated kgCO2: synthesis

Table 6 : Costs of 1kg of abated carbon from reference House 1 to alternative House 1.2

	Total GWP impact variation [KgCO2eq]	Total embodied variation costs [€]	Operational energy use cost variation discounted [€]	Cost of abated Embodied carbon [€/kgCO2eq]	Cost of abated Operational carbon [€/kgCO2eq]	Cost of total abated carbon [€/kgCO2eq]	Total CO2 abated/€ invested
Total	-60781	49032 €	519 €	-0.81	-0.01	-0.82	-1.23
Windows	-20500	8148 €	-4577 €	-0.40	0.22	-0.17	-5.74
External walls	-14740	4551 €	-2176 €	-0.31	0.15	-0.16	-6.21
Roof flat	-13065	12058 €	5039 €	-0.92	-0.39	-1.31	-0.76
First floor	-7848	8507 €	0 €	-1.08	0.00	-1.08	-0.92
Floor on ground	-4628	15769 €	2234 €	-3.41	-0.48	-3.89	-0.26

Note: This table provides all details on the variations of CO2 and costs between House 1 and House 1.2 during the 60 years lifetime for both Embodied and Operational phases. Elements are ranked according to the reduction of total environmental global warming impact. Total Embodied Costs are the sum of Construction and Maintenance Costs.

As total ownership costs and GWP impact have been provided for each element it is straightforward to compute their related cost per abated kg of CO2, hence identifying which element is the most efficient for each euro invested in the envelope, and vice versa. The results are presented in Table 6 for House 1 and Table 7 for House 2. Aggregate and element specific information are provided.

In alternative House 1.2 the external walls have the highest efficiency in term of Embodied abated CO2 per euro invested at 0.31€/kgCO2eq. Furthermore, as alternative external walls have better insulation property than the reference ones, the initial investment in alternative materials contributes to save CO2 emissions in the operational phase over the whole lifespan of the house and reduces the cumulated cost of heating. It can be considered as a return on investment and amounts to 0.15€ per KgCO2eq abated. Overall, after 60 years of use, alternative external walls reduced the total GWP impact by 14 740kg of CO2, costed an additional 4 551€ more to build and maintain and helped save 2 176€ in gas consumption at present value. Put it another way, for one EURO invested in external walls, the gains are of 6.21 kgCO2eq, the element with the highest level of carbon abated.

Windows have similar yield, or similar cost of CO2 abated with different embodied costs and operational returns. Adapting the roof would require a relatively high initial investment in alternative sustainable materials, with lower insulation outcome, actually implying higher costs of heating over the 60 years lifespan of building. The effectiveness rank of various elements is as follows: the most effective Euro invested is with external walls (-6.21 total CO2 abated), windows (-5.74), first floor (-0.92)[22], roof flat (-0.76) and finally the ground floor (-0.26). The average CO2 abated return for House 1 is of about -1.23 kg per Euro.

[22] To be noted that the first floor has no impact in the operational phase as it is inside the buildings and therefore does not contribute to heat losses.

Table 7 : Costs of 1kg of abated carbon from reference House 2 to alternative House 2.2

Cost linked to abated carbon	Total GWP impact variation [KgCO2eq]	Total embodied variation costs [€]	Operational energy use cost variation discounted [€]	Cost of abated Embodied carbon [€/kgCO2eq]	Cost of abated Operational carbon [€/kgCO2eq]	Cost of total abated carbon [€/kgCO2eq]	Total CO2 abated/€ invested
Total	-13017	13034 €	-587 €	-1.00	0.05	-0.96	-1.05
Windows	-8200	3259 €	-698 €	-0.40	0.09	-0.31	-3.20
Non shared walls	-2013	2808 €	-103 €	-1.39	0.05	-1.34	-0.74
First floor	-1758	2758 €	0 €	-1.57	0.00	-1.57	-0.64
Floor on ground	-1045	4210 €	214 €	-4.03	-0.20	-4.23	-0.24

Note: this table provides all details on the variations of CO2 and costs between House 2 and House 2.2 during the whole 60 years lifetime for both Embodied and Operational phases. Elements are ranked according to the reduction of total environmental global warming impact.

For House 2 the windows are by far the most performant element with the same price of abated CO2eq as for House 1 (0.4€/kgCO2eq). However, return linked to operational use is slightly lower due to intrinsic properties of reference House 2. Investment in more sustainable windows has the highest impact amongst all element, with more than 3 kgCO2 abated per EURO invested. The effectiveness rank of various elements is as follows: the most effective Euro invested is with windows (-3.20), non-shared walls (-0.74), first floor (-0.64), and finally the ground floor (-0.24). The aggregate CO2 abated return for House 2 is of about -1.05 Kg per Euro.

For the embodied phase (i.e., construction and discounted maintenance costs), each abated kilogram of CO2eq costs 0.82€ (0.96€) for alternative House 1 (House 2). Since alternative houses have lower operational performances when all elements are considered, the cost of operational energy use increases with the consumption of energy over the whole life time of the buildings, therefore increasing the cost of energy by 0.01€ by kilogram of CO2eq abated. Overall, the total cost of abated CO2 is 14.6% lower for sustainable House 1 than for sustainable House 2. The impact of an average Euro invested in attached houses (-1.05 KgCO2 abated per Euro) is lower than the equivalent impact for an investment in fully detached houses (1.23 KgCO2). An investment has greater impact (17% higher) on the reduction of CO2 if applied to detached houses rather than to attached houses.

On a purely financial basis, and in the frame of this study, it would be more interesting to invest in alternative sustainable elements such as windows and external walls rather than on ground floors and roofs as floors have a limited impact in the GWP impact variation and therefore have a highest cost per kgCO2eq abated.

5 Concluding remarks

The research objective of this paper was to evaluate the cost of reduced CO2 footprint in the Belgian family house sector. The contribution to the existing literature is twofold. First, it contributes to provide CO2 impact of the housing sector in Belgium, a country poorly covered in the current state of the art. Second, it provides a systematic assessment of the cost of being more sustainable, for aggregate houses in general and for their most important components in particular.

A first stage consisted in running a lifecycle analysis to assess the extent to which the use of more environmentally friendly construction materials and elements would reduce their CO_2 footprint, both for their construction and operational use. Two standard houses ("autonomous" four walls and "attached" two walls) were compared with their "sustainable" version (using more sustainable materials), in order to assess the cost of reducing their CO_2 footprint. The analysis is essentially empirical and provided – to the best of our knowledge – a first cradle to grave LCA of Belgian family houses, and a first assessment of their life cycle costs. The results can be summarized as follows.

First, about 60% of the total GWP impact of the reference houses comes from Operational Energy Use, a lower rate than in the literature surveyed in the paper. This might be the outcome of the better insulation of regular typical house over the past 10 years in Belgium. One must however keep in mind that the results are sensitive to the energy production mix and costs in Belgium. Indeed, the energy mix has a great impact on the LCA of houses, namely on the operational use stage. This should be accounted for by policymakers: securing alternative heating processes (than only gas or oil), international synergies and providing incentives to build more sustainable houses.

Although the operational phase is the main impactor phase in terms of LCA, the costs of energy represent only 11%-13% of the total ownership costs. Showing a disproportion between construction and energy at financial and environmental levels.

Overall, when all costs are considered (construction, operation, maintenance) the total ownership costs of "sustainable" houses is 7% to 11% higher than their reference ones. Interestingly, maintenance costs also increased in both alternative houses by 20% and 13%, induced by the required higher replacement rate of sustainable materials.

Second, each "sustainable" element has a different impact on budget (LCC) and environment (LCA). The best elements in terms of CO_2 abated per euro invested are the windows and external walls for House 1.2 and the windows for House 2.2. (-5.74kgCO2eq/€, -6.21 kgCO2eq/€ and -3.20 kgCO2eq/€, respectively). This study therefore shows that sustainable materials provide better insulation properties than their synthetic reference ones. The costs of 1kg of abated carbon was lower for fully detached houses than for attached ones with respectively a total price of 0.82€ per CO_2 abated for alternative House 1.2 and 0.96€ for alternative House 2.2.

To perform an unbiased scientific analysis this work focuses on the performances of materials in envelopes and therefore has excluded technical systems with high variability in performance and price such as HVAC and electric installations. As some studies have drawn conclusions about such systems these observations can easily be added to this work (Lechon et al. 2021).

6 Acknowledgment

The authors would like to extend their gratitude to Jean-Marc Douhard and Quattro Concept Architecture office for their help in the research. This research project was partly funded by the Solvay SA Chair of Innovation.

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8 Appendix

Table A. 1 Survey of the literature on family house carbon footprint

Authors and date	**Country, Software, and databases**	**Methodology and main characteristics**	**Results : proportion of Embodied, End-Of-Life and Operational impacts [%]**
Peuportier, BLP (2001) pas de numéro, juste nom et date entre ()	France -LCA software : EQUER -Data : Oekoinventar e	-LCA of 3 single family houses. Masonry, Wood-stone, Timber frame designed with different properties (i.e. Living area, insulation thickness, material used). -cradle to grave LCA. -80 years lifespan, -Multiple indicators used	Reference concrete structure: Embodied 16%, Operational 84% Observer: Embodied -6.6%, Operational 106.6% CNDB: Embodied -9.8%, Operational 109.8% (Where wooden structure help storing CO2 and reduce global impact and wastes but is not displayed.)
Rossi et al. (2011)	Belgium, Portugal and Sweden -Pleiades, Comfie and Equer -Data: Ecoinvent	-LCA of two structures: concrete and steel frame, in three different EU countries and their respective climates. (only concrete frame is considered here because of data access). -LCA stages : A1-A4, B6-B7. -50 years lifespan. -Indicators : GWP	Belgium: Embodied 13.8% , Operational 86.2% Portugal: Embodied 9%, Operational 91% Sweden: Embodied 59.4%, Operational 40.6%. The end of life is integrated in the Embodied impact. Also, cooling is included in the operational impact, hence the higher results for Portugal.
Cuéllar-Franca, R. Azapagic, A. (2011)	United Kingdom -Gabi V 4.3 -Data: EcoInvent 3.5 and Gabi V 4.3.	-LCA of three typical houses of the UK. Detached, semi-detached and terraced. -All stages cradle to grave LCA. -50 years lifespan. -Multiple indicators used.	Detached: Embodied 8.8%, EOL 1%, Operational 90.2% Semi-Detached: Embodied 8.1%, EOL 0.9%, Operational 91% Terraced: Embodied 6.4%, EOL 0.8%, Operational 92.8%. (The EOL phase includes some recycling assumptions. Specific observation : Habits of occupant represent a significant parameter in LCA.)
Asdrubalia,F. et al (2013)	Italy -Simapro 7.2 -Data : EcoInvent 3.5	-LCA of a detached single-family house. -All stages cradle to grave LCA. -60 years lifespan -Multiple indicators used.	Embodied : 23.3%, EOL 2%, Operational 74.7%. (The embodied carbon part of houses is growing due to the regulations aimed at reducing the operational carbon footprint of houses. Solution to decrease the energy use comes from the improvement of the materials and thickness of the envelope. Also, materials such as glass, aluminum steel and copper are assumed to be 100% recycled in the analysis.)
Motuziene, V., et al. (2016)	Lithuania -Simapro 7.2 -Data: IMPACT 2002+V2.10	-LCA of 3 a single-family house considering 3 different envelopes: Masonry, log and timber frame. -All stages cradle to grave LCA. -100 years lifespan. - Indicators: GWP, Primary Energy Demand (PED), Ozone Layer Depletion (OLD)	Masonry: Embodied 29.5%, EOL 24.1%, Operational 46.4% Log: Embodied 34.9%, EOL 9.6%, Operational 55.5% Timber frame: Embodied 33.9%, EOL 14.3%, Operational 51.8%. (The EOL includes dismantling and recycling stages . Wooden frames are less harmful to environment but come at higher costs.)
Leskovar,V et al. (2019)	Slovenia -Baubook eco2soft, 2017. Data : IBO	-Comparative LCA for three houses: Terraced, Semi-detached and Detached. -50 years Life span -Indicators: GWP, Air Pollution, Primary Energy Non Renewable Total	Detached house: Embodied 16.2%, EOL 8.2% Operational 75.6%. Semi-Detached house: Embodied 15.2%, EOL 8.8%; Operational 76% Terraced house: Embodied 14.9%; EOL 9.2%, Operational 75.9%.

		-Stages : A1-A3, B4, B6, C4	The results are displayed for 50 and 100 years. The adaptation ahs been made on the results of 50 years.
Petrovic,B.,et al. (2019)	Sweden -OneClick LCA -Data: EPDs	- LCA on sustainable mixed wooden and concrete structure house designed to be sustainable. -100 years lifespan -GWP and PE -All stages cradle to grave LCA.	Embodied 80.4%, EOL 1.8%, Operational 17.8% (As the water use (B7) of the house has been computed is has been counted in the operational use of the case study.)
Tavares . v et al (2021)	Portugal -Simapro V8.0 Data : EcoInvent V.3	-Compares pre-fabricated houses with lightweight steel frames (LSF) and wooden frame (WF) and two conventional structure with single (RC1) and double (RC2) concrete block layers. -50 years Lifespan -Indicators : Multiple indicators used. (AD, ADFF; GW, OD, PO, AC, EU, NRE) - Stages : All stages of cradle to cradle LCA.	LSF : Embodied 10.8%; EOL -3.3%; Operational 93.1% WF : Embodied 9.2%; EOL -0.4%; Operational 91.3% RC1 : Embodied 23.3%, EOL -0.2%; Operational 76.9% RC2 : Embodied 20.3%; EOL 0.1%; Operational 79.6%
Lechon, Y. et al. (2021)	Spain -Simapro V8 -Data: : EcoInvent 3.5	-LCA and LCC of a new building with different scenarios. All impact indicators are analysed. -All stages cradle to grave LCA. -50 years lifespan. -Multiple indicators used.	Embodied : 29.8%, EOL -0.53%, Operational 80.7%. (Insulations and forced ventilation are environmentally and slightly economically sustainable for Spanish houses. PV panels are the best option in term of LCA and LCC.)
Grygierek,K. and Ferdyn-Grygierek,J. (2022)	Poland - OpenStudio, EnergyPlus, and One Click LCA. -Data: form software.	-Comparative LCA 4 with 4 different structure compositions and insulation thickness for standard building in bricks (BSTP) and wood frames(WSTD) -25 years lifespan. -GWP, Acidification potential, Eutrophication, OLD, total use primary energy) Stages : A1-A4, B1-B5, B6	BSTD: Embodied 33.2%, Operational 66.8% WSTD: Embodied 28.5%; Operational 71.5%. (As the paper displayed different operational results depending on the boiler type, the ones hereby provided have been computed using the gas boiler to better fit into the review. Also, the operational results are expected to be the same for the BSTD and the WSTD). (No EOL is considered in the study).

Table A. 2 Timeline of maintenance costs occurrences

	10–20 years	20–30	30–40	40–50	50–60
House 1	• Paint (external walls, interior walls, first floor, flat roof, terrasse) (P10)	(P10)	• Doors (Interior, exterior, garage) • Windows • Roofing • (P10)	• Parging (exterior) walls and terrasse • Plastering (interior) • (P10)	(P10)
House 1.2	• Paint (external walls, interior walls, first floor, flat roof, terrasse)	(P10)	• Doors (Interior, exterior, garage) • Wooden batter (Walls, first floor, roof) • Plaster panels (first floor, roof) • Windows • Roofing • (P10)	• Parging on wood (external walls) • Plastering (interior walls terrasse) • Window frames • (P10)	(P10)
House 2	• Paint (shared and non shared walls, interior walls, first floor, roof floor) (P'10)	(P'10)	• Plaster panels (roof floor, • Wooden battern (roof floor • Windows • Interior + exterior doors • (P'10)	• Plastering (shared and non shared walls, first floor, non bearing walls) • (P'10)	(P'10)
House 2.2	• Paint (shared walls, interior walls, first floor, roof floor) (p''10)	(P''10)	• Wooden battern (walls, first floor, roof floor) • Plaster panels (first floor, roof floor) • Windows • Interior + exterior doors • (P''10)	• Clay based plaster (non shared walls) • Plastering (shared walls, non bearing walls) • Window frames • (P''10)	(P''10)

Table A. 3 Description of elements and materials used in House 1

Element	Material	Thickness [m]	Lifespan [years]	Prices [€/m²] (2022)	Ref Bordereau 2017	Embodied impact [kgCO2eq]	Energy use impact [kgCO2eq]	Total impact Embodied + Enregy [kgCO2eq]	Surfaces
House 1.1			>60 60	118%					293
Foundation reinforced concrete	Reinforced concrete on site	0.7	>60	106.3 €	12.01-3	159	0	159	32
Foundation walls		0.5906	>60	290.8 €		146	0	146	42
	Drain - Gravel	0.2	>60	50.8 €	17.02 1				
	HPDE drain	0.0006	>60	22.4 €	14.02-6				
	Cement mortar	0.01	>60	42.5 €	14.02 - 2				
	Concrete blocks	0.38	>60	175.1 €	14.01 2				
Foundation internal walls		0.21	>60	172.6 €		69	0	69	20
	Concrete blocks	0.19	>60	87.5 €	14.01 2				
	Cement mortar	0.02	>60	85.0 €	14.02 - 2				
External walls		0.315105	>60	277.1 €		94	125	219	268
	Traditionnal parging	0.007	40	153.6 €	45.02 - 2				
	EPS + mortar	0.16	40	0.0 €					
	Clay bricks non isolanting+ mortar	0.138	60	73.4 €	20.01 - 11				
	Plastering	0.01	40	23.6 €	50.02 + 50.01				
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
				0.0 €					
				0.0 €					

				0.0 €					
				0.0 €					
Interior bearing walls		0.148105	60	173.8 €		78	0	78	103
	Clay bricks non isolanting+ mortar	0.138	60	73.4 €	20.01 - 11				
	Plastering	0.01	40	47.2 €	50.02 + 50.01				
	Acrylic paint	0.000105	10	53.2 €	80.01 + 80.02				
Interior non bearing walls			>60	100.4 €		59	0	59	67
	Plaster blocks + gypsum + glue	0.1	>60	47.2 €	21.01 14				
	Acrylic paint	0.000105	10	53.2 €	80.01 + 80.02				
Floor on ground		1.0322	>60	271.1 €		210	135	345	178
	Excavation	0.48	>60	59.1 €	12.02 2				
	Levelling		>60	5.9 €					
	levelling compact sand	0.2	>60	20.1 €	10.07 7 + 10.07 4				
	HPDE drain	0.0002	>60	4.7 €	15.03 2				
	Reinforced concrete on site	0.15	>60	59.1 €	15.02 2				
	Extruded Polystyren (XPS) 33kg/m3	0.12	>60	35.4 €	52.04 1				
	Steel frame	0.002	>60	4.1 €	52.01				
	Cement screed	0.07	>60	23.6 €	52.06 1				
	Floor tiles + cement + glue	0.01	>60	59.1 €	53.01 14				
First floor floor			>60	256.3 €		154	0	154	109
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
	Plastering	0.012	40	28.3 €	50.02 + 50.01				
	Prestressed concrete	0.15	>60	79.1 €	28.02 1 + 28.02 5				
	Steel frame	0.002	>60	4.1 €	52.01				
	Cement screed	0.07	>60	23.6 €	52.06 1				
	Wood floor + glue + varnish	0.022	>60	94.5 €	53.04 11				
				0.0 €					
				0.0 €					
Interior doors			30	413.4 €	54.03 1	142	0	142	12
				0.0 €					
Garage doors	Aluminum frame		30	5,906.1 €		151	4126	4277	2
Exterior doors	Steel Frame - Wood aluminum pannels		30	1,181.2 €		442	1208	1650	1
Windows			>60	809.1 €		463	587	1050	50
	Aluminum Window frame		>60	531.6 €	40.01 - 02 - ...				
	Triple Glazing		30	159.5 €	41.01 2				
	Laminated Glass		30	118.1 €					
Roof flat			>60	314.2 €		161	74	235	195
	EPDM roofing + butyl glue + bitume	0.0042	30	76.8 €	35.03 2				
	PUR 30kg/m3	0.16	>60	49.0 €	34.01 14				
	Bitume glass	0.003	>60	17.7 €	34.02 2				
	Mortar	0.05	>60	36.6 €	33.02 2				
	Concrete	0.05	>60	5.9 €	28.02 5				
	Prestressed concrete	0.165	>60	73.2 €	28.02 2				
	Plastering	0.012	>60	28.3 €	50.02 + 50.01				
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
				0.0 €					
				0.0 €					
Terrasse			>60	329.6 €		141	0	141	27

	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02
	External plastering	0.012	40	56.7 €	
	Prestressed concrete	0.15	>60	79.1 €	28.02 1 + 28.02 5
	Steel frame	0.002	>60	4.1 €	52.01
	Cement screed	0.07	>60	23.6 €	52.06 1
	Polymer Bitume + glue	0.007	>60	80.3 €	35.03 1
	Floor tiles + cement + glue	0.01	>60	59.1 €	53.01 14

Note : Prices are indicated before the adjustments for 2022. Composition of elements highlighted in grey varied between reference house and alternative while green ones remained unchanged.

Table A. 4 : Desciprion of elements and materials of House 1.2

Element	Alternative material	Thickness [m]	Lifespan [years]	Prices [€/m²] (2022)	Ref Bordereau 2017	Embodied impact [kgCO2eq]	Energy use impact [kgCO2eq]	Total impact Embodied + Enregy [kgCO2eq]	Surfaces
House 1.2				118%					293
			60						
Foundation reinforced concrete	Reinforced concrete on site	0.7	>60	106.3 €	12.01-3	159	0	159	32
Foundation walls		0.5906	>60	290.8 €		146	0	146	42
	Drain - Gravel	0.2	>60	50.8 €	17.02 1				
	HPDE drain	0.0006	>60	22.4 €	14.02-6				
	Cement mortar	0.01	>60	42.5 €	14.02 - 2				
	Concrete blocks	0.38	>60	175.1 €	14.01 2				
Foundation internal walls			>60	172.6 €		69	0	69	20
	Concrete blocks	0.19	>60	87.5 €	14.01 2				
	Cement mortar	0.02	>60	85.0 €	14.02 - 2				
External walls			>60	297.0 €		50	114	164	268
	Parging on wooden structur	0.007	40	44.9 €	45.01 7				
	Wood fibre pannel insolated	0.018	>60	41.3 €	29.04				
	FJI 250 structure	0.36	>60	82.7 €	30.02 3				
	Cellulose wadding 45kg/m3	0.16	>60	16.4 €	22.02 2				
	OSB pannels	0.018	>60	35.4 €	29.04 15				
	sealing 50/50 PP/LDPE	0.00022	>60	0.0 €					
	Wooden batten	0.022	30	14.2 €	29.02 7				
	Plaster blocks + gypsum + glue	0.05	>60	35.4 €	estimation de 21.01 13				
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
Interior bearing walls			60	173.8 €		78	0	78	103
	Clay bricks non isolanting+ mortar	0.138	60	73.4 €	20.01 - 11				

	Plastering	0.01	40	47.2 €	50.02 + 50.01				
	Acrylic paint	0.000105	10	53.2 €	80.01 + 80.02				
Interior non bearing walls			>60	100.4 €		59	0	59	67
	Plaster blocks + gypsum + glue	0.1	>60	47.2 €	21.01 14				
	Acrylic paint	0.000105	10	53.2 €	80.01 + 80.02				
Floor on ground			>60	359.7 €		167	152	319	178
	Excavation	0.48	>60	59.1 €	12.02 2				
	Levelling	0	>60	5.9 €	0				
	levelling compact sand	0.2	>60	20.1 €	10.07 7 + 10.07 4				
	HPDE drain	0.0002	>60	4.7 €	15.03 2				
	Reinfored concrete on site	0.15	>60	59.1 €	15.02 2				
	Expensed cork 120kg/m3	0.12	>60	88.6 €					
	Steel frame	0.002	>60	4.1 €	52.01				
	Cement screed	0.07	>60	23.6 €	52.06 1				
	Wood floor + glue + varnish	0.022	>60	94.5 €	53.04 11				
First floor floor			>60	309.5 €		82	0	82	109
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
	Plaster pannels	0.0125	30	67.3 €	51.03 3				
	Wooden batten	0.022	30	14.2 €	29.02 7				
	Wooden Frame	0.225	>60	59.1 €	29.02 5				
	OSB pannels	0.018	>60	27.2 €	53.03 6				
	PP LDPE	0.003	>60	3.0 €	52.03 1				
	Rock wool 140kg/m3	0.03	>60	17.7 €					
	Wood floor + glue + varnish	0.022	>60	94.5 €	53.04 11				
Interior doors	0	0	30	413.4 €	54.03 1	142	0	142	12
				0.0 €					
Garage doors	Aluminum Frame		30	5,906.1 €	0	151	4126	4277	2
Exterior doors	Steel Frame - Wood aluminum pannels		30	1,181.2 €	0	442	1208	1650	1
Windows	0	0	>60	809.1 €		177	463	640	50
	Wood + cork frame		40	531.6 €					
	Triple Glazing	0	30	159.5 €					
	Laminated Glass	0	30	118.1 €					
Roof flat			>60	342.5 €		59	109	168	195
	EPDM roofing + butyl glue + bitume	0.0042	30	76.8 €	35.03 2				
	Rock wool 140kg/m3	0.06	>60	35.4 €	estimation				
	OSB pannels	0.018	>60	27.2 €	53.03 6				
	Wood profil	0.05	>60	23.6 €	estimation				
	FJI 350 structure	0.24	>60	59.1 €	29.02 5				

	Cellulose wadding 45kg/m3	0.11	>60	9.4 €	31.03				
	PP LDPE	0.003	>60	3.0 €	52.03 1				
	Wooden batten	0.022	30	14.2 €	29.02 7				
	Plaster pannels	0.0125	30	67.3 €	51.03 3				
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
Terrasse			>60	329.6 €		141	0	141	27
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
	External plastering	0.012	40	56.7 €	0				
	Prestressed concrete	0.15	>60	79.1 €	28.02 1 + 28.02 5				
	Steel frame	0.002	>60	4.1 €	52.01				
	Cement screed	0.07	>60	23.6 €	52.06 1				
	Polymer Bitume + glue	0.007	>60	80.3 €	35.03 1				
	Floor tiles + cement + glue	0.01	>60	59.1 €	53.01 14				

Note : Prices are indicated before the adjustments for 2022. Composition of elements highlighted in grey varied between reference house and alternative while green ones remained unchanged.

Table A. 5 : Description of elements and materials used in House 2

Element	Material	Thickness [m]	Lifespan [years]	Prices [€/m²] (2022)	Ref Bordereau 2017	Embodied impact [kgCO2eq]	Energy use impact [kgCO2eq]	Total impact Embodied + Enregy [kgCO2eq]	Surfaces
House 2				1,116.4 €				0	112
				0.0 €					
Foundation reinforced concrete	Reinforced concrete on site	0.7	>60	106.3 €		159	0	159	17
				0.0 €					
Foundation walls	0		>60	290.8 €		146	0	146	10
	Drain - Gravel	0.2	>60	50.8 €	17.02 1				
	HPDE drain	0.0006	>60	22.4 €	14.02-6				
	Cement mortar	0.01	>60	42.5 €	14.02 - 2				
	Concrete blocks	0.38	>60	175.1 €	14.01 2				
				0.0 €					
Foundation internal walls			>60	172.6 €		69	0	69	15
	Concrete blocks	0.19	>60	87.5 €	14.01 2				
	Cement mortar	0.02	>60	85.0 €	14.02 - 2				
				0.0 €					
Non shared external walls			>60	267.3 €		117	110	227	61
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
	Plastering	0.01	40	23.6 €	50.02 + 50.01				
	Concrete block (half heavy)	0.14	>60	60.4 €	20.01 1				

	Rock Wool 40kg/m3	0.15	>60	38.6 €	22.01 8-9				
	PVC clips		>60	0.0 €					
	Steel cavity ties		>60	0.0 €					
	Clay bricks + mortar	0.08	>60	118.1 €	23.01 6				
				0.0 €					
Shared external walls			>60	138.0 €		66	0	66	122
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
	Plastering	0.01 €	40	23.6 €	50.02 + 50.01				
	Clay blocks	0.14	>60	73.6 €	20.01 11				
	Rock Wool 40kg/m3	0.05	>60	14.2 €	22.01 8				
Floor on ground			>60	271.1 €		205	136	341	47.52
	Excavation	0.48	>60	59.1 €	12.02 2				
	Levelling	0	>60	5.9 €	0				
	levelling compact sand	0.2	>60	20.1 €	10.07 7 + 10.07 4				
	HPDE drain	0.0002	>60	4.7 €	15.03 2				
	Reinfored concrete on site	0.15	>60	59.1 €	15.02 2				
	Extruded Polystyren (XPS) 33kg/m3	0.12	>60	35.4 €	52.04 1				
	Steel frame	0.002	>60	4.1 €	52.01				
	Cement screed	0.07	>60	23.6 €	52.06 1				
	Floor tiles + cement + glue	0.01	>60	59.1 €	53.01 14				
First floor floor			>60	256.3 €		119	0	119	47.52
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
	Plastering	0.012	40	28.3 €	50.02 + 50.01				
	Prestressed concrete	0.15	>60	79.1 €	28.02 1 + 28.02 5				
	Steel frame	0.002	>60	4.1 €	52.01				
	Cement screed	0.07	>60	23.6 €	52.06 1				
	Wood floor + glue + varnish	0.022	>60	94.5 €	53.04 11				
				0.0 €					
				0.0 €					
Florr roof			>60	214.4 €		38	0	38	47.52
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
	Plaster pannels	0.0125	30	67.3 €	51.03 3				
	Wooden batten	0.022	30	14.2 €	29.02 7				
	Wooden Frame	0.225	>60	59.1 €	29.02 5				
	Glass wool	0.05	>60	27.8 €	31.01 6				
	Particul wood pannels	0.018	>60	19.5 €	22.04 8				
Roof			>60	220.9 €		42	77	119	75.6
	Purlins	0.026	>60	17.7 €	29.02 07				
	PP LDPE	0.003	>60	8.9 €	31.05 1				
	Wooden Frame FJI 350	0.24	>60	50.2 €	30.02 3				
	Rock Wool 40kg/m3	0.24	>60	44.9 €	31.01				

	Wood fibre Pannels	0.022	>60	28.3 €	30.04 5				
	Counter batten	0.02	>60	0.0 €					
	Purlins	0.026	>60	0.0 €					
	Glazed tiles clips	0.015	>60	70.9 €	32.01				
Windows			>60	809.1 €		463	587	1050	20
	Aluminum Window frame	0	>60	531.6 €	40.01 - 02 - ...				
	Triple Glazing	0	30	159.5 €	41.01 2				
	Laminated Glass	0	30	118.1 €	0				
Interior bearing walls			60	173.8 €		78	0	78	6.72
	Clay bricks non isolanting+ mortar	0.138	60	73.4 €	20.01 - 11				
	Plastering	0.01	40	47.2 €	50.02 + 50.01				
	Acrylic paint	0.000105	10	53.2 €	80.01 + 80.02				
Interior doors	0	0	30	413.4 €	54.03 1	142	0	142	7
				0.0 €					
Exterior doors	Steel Frame - Wood aluminum pannels	0	30	1,181.2 €	0	442	1208	1650	1
				0.0 €					
Interior non bearing walls			>60	100.4 €		59	0	59	70
	Plaster blocks + gypsum + glue	0.1	>60	47.2 €	21.01 14				
	Acrylic paint	0.000105	10	53.2 €	80.01 + 80.02				
Wood Beam	Glulam beam (m)	0.36	>60	99.5 €	29.03 2	14.52	0	14.52	21
				0.0 €					
Steel Beam	Steel Beam (m)		>60	419.3 €	27.01 1 27.02 1	52.95	0	52.95	5

Note : Prices are indicated before the adjustments for 2022. Composition of elements highlighted in grey varied between reference house and alternative while green ones remained unchanged.

Table A. 6 : Description of elements and materials used in House 2.2

Element	Alternative material	Thickness [m]	Lifespan [years]	Prices [€/m²] (2022)	Ref Bordereau 2017	Embodied impact [kgCO2eq]	Energy use impact [kgCO2eq]	Total impact Embodied + Enregy [kgCO2eq]	Surfaces
Alternative house 2.2				0.0 €				0	112
				0.0 €					0
Foundation reinforced concrete	Reinforced concrete on site	0.7	>60	106.3 €	12.01-3	159	0	159	17
				0.0 €					
Foundation walls	0		>60	290.8 €		146	0	146	10
	Drain - Gravel	0.2	>60	50.8 €	17.02 1				
	HPDE drain	0.0006	>60	22.4 €	14.02-6				
	Cement mortar	0.01	>60	42.5 €	14.02 - 2				
	Concrete blocks	0.38	>60	175.1 €	14.01 2				

				0.0 €					
Foundation internal walls			>60	172.6 €		69	0	69	15
	Concrete blocks	0.19	>60	87.5 €	14.01 2				
	Cement mortar	0.02	>60	85.0 €	14.02 - 2				
				0.0 €					
Non shared external walls			>60	309.7 €		90	104	194	61
	Acrylic paint	0.000105	10	26.6 €					
	Clay based plaster	0.02	40	35.4 €					
	Insolating clay bricks	0.138	>60	91.0 €	20.01 12				
	Rock Wool 40kg/m3	0.15	>60	38.6 €	22.01 8-9				
	PVC clips	0	>60	0.0 €					
	Steel cavity ties	0	>60	0.0 €					
	Clay bricks + mortar	0.08	>60	118.1 €	23.01 6				
				0.0 €					
Shared external walls			>60	138.0 €		66	0	66	122
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
	Plastering	0.01	40	23.6 €	50.02 + 50.01				
	Clay blocks	0.14	>60	73.6 €	20.01 11				
	Rock Wool 40kg/m3	0.05	>60	14.2 €	22.01 8				
Floor on ground			>60	359.7 €		167	152	319	47.52
	Excavation	0.48	>60	59.1 €	12.02 2				
	Levelling	0	>60	5.9 €	0				
	levelling compact sand	0.2	>60	20.1 €	10.07 7 + 10.07 4				
	HPDE drain	0.0002	>60	4.7 €	15.03 2				
	Reinfored concrete on site	0.15	>60	59.1 €	15.02 2				
	Expensed cork 120kg/m3	0.12	>60	88.6 €	0				
	Steel frame	0.002	>60	4.1 €	52.01				
	Cement screed	0.07	>60	23.6 €	52.06 1				
	Wood floor + glue + varnish	0.022	>60	94.5 €	53.04 11				
First floor floor			>60	295.3 €		82	0	82	47.52
	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
	Plaster pannels	0.0125	30	67.3 €	51.03 3				
	Wooden batten	0.022	30	0.0 €					
	Wooden Frame	0.225	>60	59.1 €	29.02 5				
	OSB pannels	0.018	>60	27.2 €	53.03 6				
	PP LDPE	0.003	>60	3.0 €	52.03 1				
	Rock wool 140kg/m3	0.03	>60	17.7 €	0				
	Wood floor + glue + varnish	0.022	>60	94.5 €	53.04 11				
Florr roof			>60	214.4 €		38	0	38	47.52

	Acrylic paint	0.000105	10	26.6 €	80.01 + 80.02				
	Plaster pannels	0.0125	30	67.3 €	51.03 3				
	Wooden batten	0.022	30	14.2 €	29.02 7				
	Wooden Frame	0.225	>60	59.1 €	29.02 5				
	Glass wool	0.05	>60	27.8 €	31.01 6				
	Particul wood pannels	0.018	>60	19.5 €	22.04 8				
Roof			>60	220.9 €		42	77	119	75.6
	Purlins	0.026	>60	17.7 €	29.02 07				
	PP LDPE	0.003	>60	8.9 €	31.05 1				
	Rock Wool 40kg/m3	0.24 €	>60	44.9 €	31.01				
	Wooden Frame FJI 350	0.24 €	>60	50.2 €	30.02 3				
	Wood fibre Pannels	0.02 €	>60	28.3 €	30.04 5				
	Counter batten	0.02 €	>60	0.0 €	0				
	Purlins	0.026	>60	0.0 €	0				
	Glazed tiles clips	0.015	>60	70.9 €	32.01				
Windows			30	809.1 €		177	463	640	20
	Wood + cork frame	0	40	531.6 €					
	Triple Glazing	0	30	159.5 €					
	Laminated Glass	0	30	118.1 €					
Interior bearing walls			60	173.8 €		78	0	78	6.72
	Clay bricks non isolanting+ mortar	0.138	60	73.4 €	20.01 - 11				
	Plastering	0.01	40	47.2 €	50.02 + 50.01				
	Acrylic paint	0.000105	10	53.2 €	80.01 + 80.02				
Interior doors	0	0	30	413.4 €	54.03 1	142	0	142	7
				0.0 €					
Exterior doors	Steel Frame - Wood aluminum pannels	0	30	1,181.2 €	0	442	1208	1650	1
				0.0 €					
Interior non bearing walls				100.4 €		59	0	59	70
	Plaster blocks + gypsum + glue	0.1	>60	47.2 €	21.01 14				
	Acrylic paint	0.000105	10	53.2 €	80.01 + 80.02				
Wood Beam	Glulam beam (m)	0.36	>60	99.5 €	29.03 2	14.52	0	14.52	21
				0.0 €					
Steel Beam	Steel Beam (m)	0	>60	419.3 €	27.01 1 27.02 1	52.95	0	52.95	5

Note : Prices are indicated before the adjustments for 2022. Composition of elements highlighted in grey varied between reference house and alternative while green ones remained unchanged.

Table A. 7 Decomposition of total ownership costs of houses

	House 1	House 1.2	variation	%	House 2	House 2.2	Variation	%
Lifespan [years]	60	60	0	0	60	60	0	0
Total Carbon Impact [kgCO2eq]	399,438	338,657	(60,781.0)	-15%	145,388	132,372	(13,016.7)	-9%
Embodied	164,745	103,261	(61,484.0)	-37%	56,684	45,753	(10,931.0)	-19%
Operational	234,693	235,396	703.0	0%	88,704	86,618	(2,085.7)	-2%
Construction cost [€]	322,733 €	355,130 €	32,397.7	10%	125,032 €	133,681 €	8,649.0	7%
Discounted maintenance cost [€]	84,231 €	100,866 €	16,634.5	20%	33,136 €	37,521 €	4,385.1	13%
Discounted Energy cost [€]	61,143 €	61,662 €	519 €	1%	23,237 €	22,650 €	-587 €	-3%
Total ownership cost [€]	468,107	517,658	49,551.1	11%	185,616	197,957	12,340.2	7%
%Construction costs	69%	69%			67%	68%		
%Maintenance costs	18%	19%			18%	19%		
%Energy costs	13%	12%			13%	11%		

Source: UPA 2017 and own calculations.

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