Journal of Cleaner Production 373 (2022) 133834

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Analysis of environmental impacts and costs of a residential building over its entire life cycle to achieve nearly zero energy and low emission objectives

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A R T I C L E I N F O

Handling Editor: Mingzhou Jin

*Keywords:*
Environmental impacts
Costs
Residential building
Near-zero energy
LCA

A B S T R A C T

Nowadays, European Union (EU) requests that all its members encourage Net-zero energy and emission in the buildings by 2050. There are multiple studies within the EU related to this field, but few of them are associated with environmental cost assessment and reduction. What can be the new strategies allowing to reduce ecological impact costs at the scale of the building? In response to this question, this research has been carried out, with, the main objective, to evaluate, analyse, and propose some scenarios allowing to design of residential buildings with nearly zero energy, low emission, and low cost throughout the world. The strategies detailed in this research can be applied and adapted in all the regions of the world. A life cycle assessment (LCA) of a typical building is carried out using the Pleiades software database comprising a Dynamic Thermal Simulation calculation engine (STD) making it possible to simulate the thermal in order to describe the energy behaviours of a building and its equipment. Four life cycle phases (construction, use, renovation, and end of life) of buildings have been assessed. The results showed that the use of a dual-service air-to-water heat pump enables a considerable reduction in greenhouse gas (GHG) emissions and, on average, the indicators decrease by around 9%. It was concluded that the use of heat pumps makes it possible to reduce the cost of 9 environmental impacts between 8.7% and 13.1% compared to the initial cost, over a period of 80 yr.

## 1. Introduction

The beginning of the 1970s marked a turning point in the awareness of the importance of protecting the environment both nationally and internationally. Indeed, several salient facts have made it possible to question the model of society that had prevailed since the end of the Second World War. Following a great awareness of environmental issues, several large non-governmental organizations for the protection of nature have been created (Greenpeace and World Wildlife Fund (WWF), United Nations Environment Program (UN)).

At COP24 in Poland in December 2018, the UN highlighted that the building sector alone emits 39% of total energy-related $CO_2$ emissions (Trabelsi, 2018). Therefore, the UN recommends a new design with low-emission (Global warming 2013; Glineur et al., 2014). In Belgium, an energy performance certificate (EPC) is issued indicating the building's theoretical energy consumption and the general improvement measures that can be made. It is thus possible to objectively compare the energy performance of different buildings (Glineur et al., 2014). Moreover, the regulation of the new building sector in the region analysed in this study follows a logical sequence of similar official acts such as the United Nations Framework Convention. In 2013, the regional decree of November 28, 2013, aimed to transpose the latest European directive relating to the performance of buildings (Wallonia 2018; Wallonia 2019). In this sense, the principle of the building energy performance (BEP) calculation method consists of calculating the energy

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https://doi.org/10.1016/j.jclepro.2022.133834
Received 7 March 2022; Received in revised form 11 August 2022; Accepted 23 August 2022
Available online 3 September 2022
0959-6526/

**Nomenclatures**

| | |
|---|---|
| CMV | Controlled mechanical ventilation |
| EPS | expanded polystyrene |
| EU | European Union |
| GHG | Greenhouse Gas |
| GMM | Global method monetize |
| LCA | Life Cycle Assessment |
| Net ZEB | Net Zero Energy Building |
| Q-ZEN | Quasi-zero-energy standard |
| STD | Dynamic Thermal Simulation |
| UNEP | United Nations Environment Program |
| WWF | World Wildlife Fund |

consumption of a building for heating, domestic hot water, auxiliaries and possible cooling, as part of a standardized use.

In the particular case of Belgium, according to a study carried out in 2017, and based on more than 365,000 building energy performance certificates, the majority of Belgian housing had poor energy performance with more than 30% classified as G label (primary energy≥510 kWh/m$^2$.yr), 15% F label (425 <primary energy<510 kWh/m$^2$.yr) and 15% E label (340 kWh/m$^2$.yr < Ep)(SPW, 2017) and, what is more, other indicators make it possible to assess certain energy characteristics of the building (Wallonia energy 2017b). Over time, the BEP requirements set by the order of the Walloon government of Belgium on May 15, 2014 and its annexes have been strengthened and extended to new buildings. Since January 1, 2019, public authorities have recommended reaching the Quasi-zero-energy standard (Q-ZEN). From 2021, all new residential buildings in Wallonia will also have to meet the Q-ZEN standard.

During the 2010s, the operational phase of a standard building represented between 60 and 90% of environmental loads total, mainly due to heating and air conditioning (Buyle et al.2013). In 2012, a study conducted by B. Rossi, A-F. Marique and S. Reiter compared the LCA of an existent residential building with two construction systems and a metal frame house located in three different European countries: Belgium, Portugal and Sweden. Although the climate in these three countries differs, the operational phase was found to be the most harmful period of the life cycle in all three cases. This study also showed the strong influence of the country's energy mix vis-à-vis equivalent $CO_2$ emissions related to the operational phase. The heating and cooling systems usually used in the three countries were also of great importance (Rossi, 2012; Rossi, 2012).

As a result of increasing demands on energy performance, the energy efficiency of buildings is increasing. Consequently, other aspects of the life cycle such as the choice of materials, construction, end-of-life measures or even water consumption become important in the environmental balance (Wallonie Energie SPW, 2017a). Huberman and Pearlmutter (2008) performed an energy assessment of the life cycle of a residential building in Israel with a lifespan of 50 years. They come to the conclusion that, when the energy consumption of the operational phase decreases, the relative share of embodied energy increases, sometimes exceeding the operational phase in terms of environmental impacts. Blengini and T. Di Carlo (2010) studied a low-energy house in Italy with a lifespan of 70 years and whose energy consumption is ten times less than a standard reference house. Despite such a reduction in energy consumption, the environmental impact is reduced by only a factor of 2.1. So, like Huberman and Pearlmutter (2008), they observe that when a home's energy consumption is reduced, the other phases of the life cycle become more important. Unlike the majority of studies where the operational phase is dominant, the impacts of the production phase of this study exceed those of the operational phase. Thus, the choice of materials and method of construction are crucial (Blengini et Carlos 2010). (Citherlet, 2007) had already mentioned that it seemed relevant to pay close attention to the life cycle phases of construction and demolition when the annual energy consumption is less than 150 MJ/m$^2$. The potential for recycling was studied in Switzerland by (Thormark, 2002, 2006) (Blengini, 2009). considered the demolition of an apartment in Italy with a lifespan of 40 years. These two studies showed the advantages of reuse over recycling. The reuse of constructive elements during renovation or deconstruction depends on the ease with which constructive elements can be recovered without damage. The method of the assembly during construction is decisive. Nevertheless, (Thormark and Blengini, 20002) have reservations about the feasibility of large-scale reuse.

(Erlandsson and Levin, 2005) focus on the advantages of renovating an existing home in Switzerland in 2005. They conclude that, generally, renovation is a solution that is respectful of the environment but urban regulations are a limitation which often do not allow all optimal measurements. In Belgium, the proportion of renovation increased by more than 30% between 1995 and 2010 (Bouwvergunningen 2010). Aware of the strong demographic growth expected in the coming years in the cities (Kameni et al. 2019), compared the results obtained during the LCA of a sustainable neighbourhood with those obtained during the LCA of an old district, both located in Belgium. Thus, they could assess the impact of this new concentration on the environment. It was found that $CO_2$ emissions were up to 36.6% higher in an older neighbourhood than in a sustainable neighbourhood. Overall, they indicated that the renovation of residential buildings is very important. In both neighbourhoods, it can be mitigated on average up to 30% of environmental impacts. In addition, good public space planning plays an important role in reducing eutrophication by up to 15% in both neighbourhoods. Another frequent finding revealed by almost all researchers is the minor importance of material transport during the construction phase due to construction materials are often produced locally. In this sense, according to a study carried out in 1997 in Switzerland (Adalberth, 1997), states that the impacts associated with the transport of materials are 1% of the total environmental load, or even less, and (OrtizBruno, 2009) draw the same conclusion, in Spain. Despite this, transportation of building materials is a problem of concern when all materials are transported a long distance. For instance, in a study carried out by (Chen, 2001) in 2001 based on two office buildings in China, the contribution of material transport was 7% of the environmental load as a consequence of massive importation of building materials.

In the context of low-energy homes, much research has been done comparing the results obtained with renewable materials (wood) and with non-renewable materials (masonry, concrete, steel) (Orosa and García-Bustelo, 2012; Nematchoua et al., 2015. Most research attributes better results to wooden structures; the latter being easy to handle and neutral, even negative, in $CO_2$. Only the research of (Marceau, 2006) led to opposite conclusions, bringing a preference for concrete structures.

Over the past ten years, Nearly Zero Energy Building has experienced an increasing development in industrialized countries. In fact, since 2019, all new public buildings in the European Union must comply with the European directive for buildings with almost zero energy consumption. In Belgium, the "PassivScholen" project comprising the construction of more than 30 educational buildings complying with the Belgian PassivHaus standard and near zero energy building targets was promoted in 2012 by the government to build new near zero energy schools. Piderit et al. (2019) reviewed the design measures and technical requirements necessary to achieve Nearly ZEB energy performance goals in schools in Chile. New standards were required in this country based on the new climatic conditions. In his book published in 2018 (Attia, 2016), examines the nearly/Net ZEB concept in detail to establish a roadmap for the analysis and implementation of Nearly ZEB projects. He points to 3 major challenges to be overcome in designing a robust Nearly ZEB building: the performance gap between the design assumptions and the building's actual energy consumption; sick building syndrome; for designers faced with various choices, to make informed design decisions.

In the literature, there are several LCA of building studies, however, until now, no study simultaneously assessed the impact of transport, renewable energies, heat pump, and insulation thickness on environmental impacts produced in the residential building sector. Therefore, the main purpose of this research is to evaluate, analyse, and propose some scenarios allowing to design the of buildings with Nearly Zero-energy, low $CO_2$ and cost throughout the world.

This research is made up of several parts: (1) first, the introduction which allowed us to present the motivations of this work and a review of the literature; (2) second, we will present the LCA method in more detail, study the application of this method on the scale of construction and realize the state of the art on this topic. In addition, we will present the Global method monetize (GMM) updated in 2017 (Nocker, 2018), which is based on the methodologies developed previously by Debacker et al. (2012); (3) third, we will describe the reference building studied and the different case studies that will be considered during the LCA. An environmental cost analysis will also be carried out. The different results will be presented, discussed and compared to the findings of the state of the art; (4) fourth, we will analyse the LCA results of the different scenarios and compare them to the results of the case study to quantify the impact of study time, insulation level, etc. Thus, it will be possible for us to identify certain design parameters that will have to be treated as a priority to reach the Nearly ZEB standard. We will end with a conclusion summarizing the main results of this work and the research perspectives.

## 2. Methods

In current practice, LCAs are performed according to EN 15978. The relationships between the different phases of the LCA process are given in reference (EN 15978).

### 2.1. Description and modelling

#### 2.1.1. Building site

The building studied is located in the Sustainable district of Sart-Tilman, geographically located to the south of Liege city in Belgium. This district can be certified as an eco-district since it meets the requirements of the sustainable district benchmark. For more than 50% of the dwellings to reach the passive standard, the following technical elements have been taken into account: the layout and orientation of the buildings, the joint ownership of more than 50% of the buildings and efficient insulation. In addition, this district includes many plots, cycle and pedestrian paths, landscaped natural ponds and large green areas favouring a healthy quality of life and where the relationship with nature predominates. On the site, a separate network for wastewater and rainwater has been set up and each house and apartment building has a rainwater collection tank. The “valleys” (natural, shallow ditches) and the plantations present on the site make it possible to collect rainwater and safeguard certain biodiversity by attracting amphibians and insects.

In the “project” tab, we entered the geographical location of the Arola residence. As a reminder, it is located in Sart-Tilman where the seismic activity is very low, at an altitude of 237 m and whose geographical coordinates of latitude and longitude are respectively: N

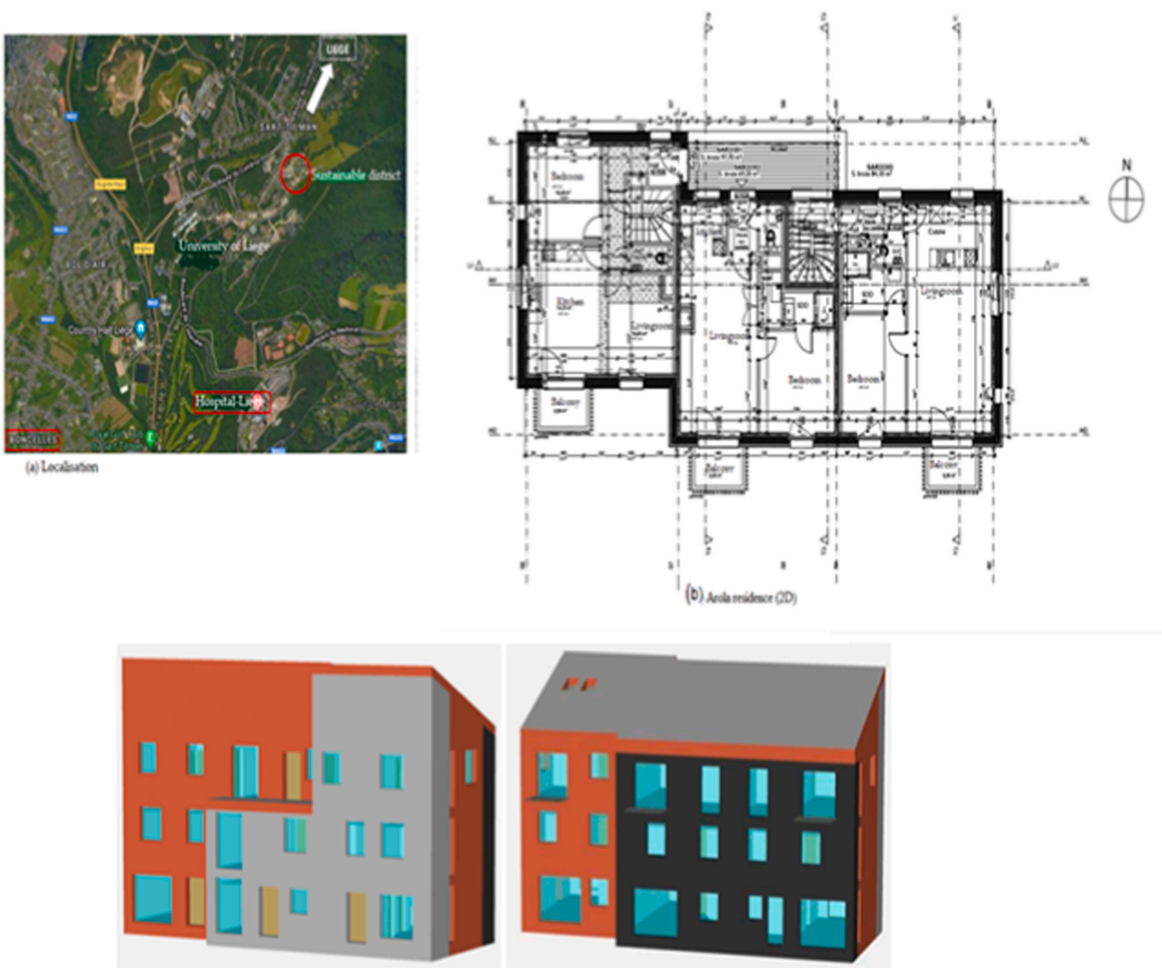



**Fig. 1.** Global view of the Sart-Tilman eco-district (a) and study residence (c) (Dozin, 2015).

50°35 ’20″ and E 5°34 ’18". The residence has 4 apartments for 4 people and 2 apartments for 2 people, there are 20 occupants in the residence. Its living area is 468 m$^2$. This building is called the Arola residence (building D4 in Fig. 1). It is a three-story apartment building consisting of three duplex apartments with three bedrooms, one duplex apartment with one bedroom, and two apartments with one bedroom. Fig. 1. Global view of the Sart-Tilman eco-district (a & b) and study residence (c).

**Goal and scope:** We want to reach a nearly zero energy building target. To achieve this goal, we applied several scenarios which allow reducing the different environmental impacts generated by this building. Even if in some cases, the influence of some of these scenarios was known, we wished to quantify precisely the environmental impacts and compare their importance with that of the other studied parameters. For this, we conducted the environmental analysis of a new building and we varied the different scenarios to quantify their impacts. Thus, we were able to provide recommendations regarding nearly zero energy building in the countries having almost similar climates. The scope is described in Fig. 2.

#### 2.1.2. Building modelling

(a) Construction data: In Pleiades Modeller, we entered the default composition of the walls, doors and windows, the default surface finishes and the default thermal bridges. These are the compositions, surface finishes and bridges most often encountered in our building. When a wall or joinery is not composed in the same way as the one encoded by default or if it is not of the same dimension as the one encoded by default, we can modify it later.

(b) Default composition of the walls: In Pleiades Library, the compositions and properties of walls, floors and roofs often encountered are encoded. In order to get as close as possible to the reality of the building studied, we can compose our own wall, floor or roof using materials or elements already encoded in the library or by creating new materials or elements. In this work, we modelled the walls as they actually are. The components of all the walls are given in Table 1 with their thicknesses (e), their surface masses (ρ*e), their thermal conductivities (λ) and their thermal resistances (R).

(c) Default composition of doors and windows: The insulating interior doors are in wood, the exterior frames are in PVC, and low-emission double glazing with argon gas (neutral and heavy gas), generally used in buildings with low energy consumption, has been placed.

### 2.2. Meteorological data

The most used meteorological station in Belgium is Uccle and the data concerning this station are not included in Pleiades so we have to introduce them ourselves. To do this, Pleiades’ STD COMFIE module integrates the Meteocalc utility which allows us to create or import our own weather data. From the Energy-Plus website, we get the weather data for Uccle and it is converted to TRY format to be used in Pleiades. The data imported are given every day of the year, hour by hour, and are as follows: temperatures, global and horizontal diffuse radiation (calculation of heating needs), direct radiation (solar thermal calculation), relative humidity, the cold water temperature (domestic hot water calculation), the wind speed and its direction (aeraulic calculation).

### 2.3. 3.D modelling

From the plans provided by the project architect, the walls, floors, slabs, roofs, openings and solar masks were modelled. At first, we only model the Arola residence as shown in Fig. 1 and the vegetation and buildings around this residence will be added in the final solution to take into account their influence.

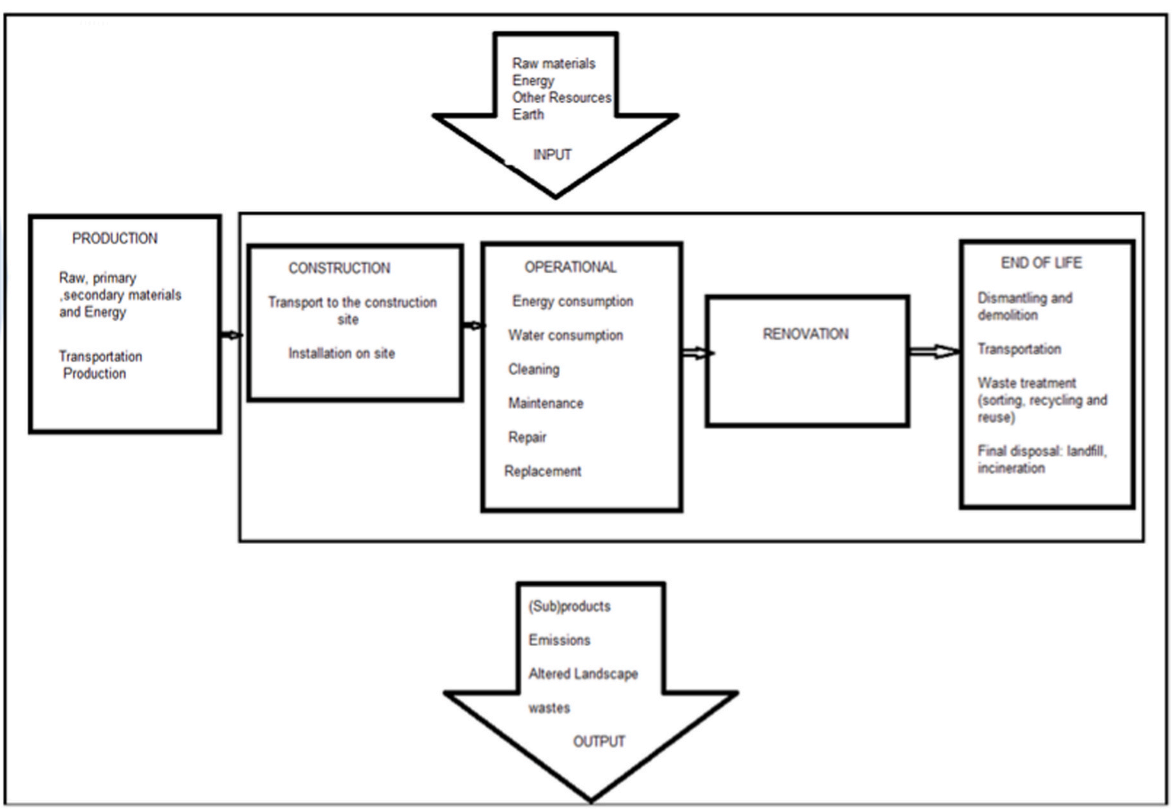



**Fig. 2.** Summary of the different phases of the life cycle of the building studied.

### 2.4. Dynamic thermal analysis

#### 2.4.1. Dynamic thermal simulation-comfie

For the dynamic thermal simulation, first, detailed zoning of the building was carried out. Assigning to each room a specific function allowed us to be more precise about the temperatures requested for each room, for example. Indeed, because the needs and activities are not the same in all rooms of a home, the temperature must be adapted.

(i) Heating instructions
- In the kitchen, dining room, and living room, the recommended indoor temperature is 19 °C when these rooms are occupied. When they are unoccupied, we will lower the temperature to 16 °C.
- In bedrooms, a night of deep and restful sleep is favoured by a temperature between 16 and 17 °C. Thus, during the night, a temperature of 18 °C was defined and when the chamber is not in use, the temperature was dropped to 15 °C.
- The bathrooms and showers require a slightly higher temperature than other rooms, so a temperature of 20 °C when used was selected.

(ii) Power dissipation instructions and lighting equipment

The Pleiades software considers 80 Watts per occupant, which corresponds only to metabolic heat. The other inputs (lighting, devices, etc.) must be entered in the dissipated power and lighting scenarios.

According to the Th-BCE(2012) calculation method developed by the Scientific and Technical Centre for Building, the heat power released by all the "furniture" equipment (household appliances, computers, washing, etc.) of individual or adjoining houses and collective housing is equal to 5.7 W/m$^2$ during the period of occupation and 1.1 W/m$^2$ during the period of sleep. The conventional lighting power is taken equal to 1.4 W/m$^2$ in the case of single or semi-detached houses and collective dwellings.

(iii) Occupancy instructions

Regarding the Th-BCE 2012 method, in this study, the number of occupants per m$^2$ varies between 0 and 0.022 depending on the absence or the average presence of 50% of the different members of the same dwelling. When they are all present, the occupancy rate is 0.044 occupants per m$^2$, or 20 occupants of the living area of the residence which is 468 m$^2$.

#### 2.4.2. Ventilation

Controlled mechanical ventilation, known as CMV, double flow is used and was made up of the following elements: (a) two separate duct networks, each with its own fan. The first breathes new air into the living-dining room and into the bedrooms. The second expels stale air from utility rooms, i.e. the kitchen, bathrooms and showers, and the laundry room. (b) a heat exchanger that recovers heat from the extracted air to transfer it to the incoming air. It was decided to bypass it during the months of June, July and August, that is, between the 23rd and the 35th week of the year. The efficiency of the heat exchanger was 90%. (c) An air inlet for fresh air and an air outlet for stale air.

In this research work, a ventilation system offered by the company Aldes was selected to determine the ventilation rates in the various rooms of the residence. These respect the ventilation rates to be satisfied in a residential building in accordance with the NBN D50-001 standard. Finally, the ventilation requirements only apply to rooms within the protected space so, in each room, the ventilation flow is calculated based on a standard flow rate of 3.6 m$^3$/h per m$^2$ of the floor.

#### 2.4.3. Airtightness

In Wallonia (Belgium), there are no recommendations concerning the overall airtightness of a building. The Brussels-Capital region, for its part, requires airtightness of less than 0.6 vol per hour for any new construction from 2018. In our case, since the eco-district includes low-consumption buildings or even passive buildings, we impose an air infiltration rate of 0.25 vol per hour in each area of the Arola residence, with the exception of the entrance halls and stairwells where the air infiltration rates are 1 vol per hour.

#### 2.4.4. Heating

The generation of hot water for the heating and domestic hot water systems is provided by three standard condensing gas boilers with a PCI efficiency of 92.38% and an estimated lifespan of 20 years (CTE 2020). Today, the residence could be equipped with a new condensing boiler whose PCI efficiency would exceed 100%, and could even reach 110%. The fact that the efficiency reaches 110% on PCI results from the condensation of the water vapour of the fumes, the energy of which is not taken into account in the measurement of the PCI. The same yield, calculated on PCS, cannot exceed 100%. Finally, the heat emitter consists of hot water radiators.

### 2.5. Monetization of the GMM method

The GMM project (Wallonia 2017) consists of developing a method and tools for evaluating the impact of materials adapted to the context of the countries of the European Union of construction. The GMM method has been developed in line with European standards for the assessment of the environmental impacts of buildings. Thus, the results concerning the environmental impacts of an element or a building are proposed through a monetized score. In Table 2, this score is presented individually by environmental impact (Wallonia 2017b). For example, if we had to pay for our GHG emissions following construction in Belgium, by applying the polluter pays principle, Table 2, tells us that we would have to pay 50 € per ton $CO_2$ emitted, in Belgium. This price is not the same for all the countries. The recommended value of 180 €2016/t CO2 eq in Germany is close to the value of 173.5 €2016/tCO2 determined in the 5th Assessment Report of the IPCC(Astrid Matthey,2019).

The main functional unit applied in this research is the area (m$^2$) of living space.

### 2.6. Life cycle assessment

The Pleiades ACV software was employed to carry out the LCA and therefore assess the nine environmental impacts that we have decided to study in the case of the Arola residence. The LCA of this residence results from the chaining of data between three computer assessment tools: modeller, editor and results.

With Pleiades tool, it is easily to carry out a study of LCA at the scale of a neighbourhood, although, in this research, we concentrated on the case of residence building. Whereas other tools evaluated just some environmental impacts (i.e., One-click LCA), with Pleiades tool, we can study up to 12 of them.

Pleiades LCA uses a detailed methodology developed by the Centre for Energy Efficiency of Systems of Mines ParisTech. This methodology uses the Ecoinvent environmental database concerning the manufacture of materials and the various processes included in the system such as energy and water production and waste treatment. For this work, the Ecoinvent version 3 database was selected. This version includes international industrial life cycle inventory data on energy supply, resource extraction, materials supply, chemicals, metals, agriculture, waste management services, and transportation services.

(a) Parameters: It must be highlighted that a surplus of materials used on the site of 5% was considered, which corresponds to the amount of unused material, broken materials, and scraps. At the same time, the lifetimes by default of the various elements of the Arola residence were encoded to calculate the impacts of the renovation phase. In particular, it was set the service life of

**Table 1**
Composition of all the walls of the studied residence.

(d) Default thermal bridges: The desire to make more than 50% of the housing units in the district passive has, among other things, been respected, paying particular attention to reducing thermal bridges. Note that thermal bridges weigh all the more in the percentage of losses of the house that this one is well insulated. The better a house is insulated, the higher the percentage of losses due to thermal bridges (over 30%), but the overall losses are very low.

| | Element | Component | e (cm) | ρ*e (kg/m$^2$) | λ (W/m K) |
|---|---|---|---|---|---|
| Outdoor layers | Coated outdoor wall | Exterior coating | 1.50 | 26.00 | 1.15 |
| | | Expanded polystyrene | 32.00 | 8.00 | 0.03 |
| | | Limestone silico block | 15.0 | 270.0 | 0.13 |
| | | ceiling | 1.30 | 11.00 | 0.32 |
| | Barded outdoor wall | Cement fibre cladding | 2.00 | 36.00 | 0.95 |
| | | Air blade | 1.20 | 0.00 | 0.08 |
| | | Polyurethane | 24.00 | 7.00 | 0.02 |
| | | Limestone silico block | 15.00 | 27.00 | 0.14 |
| | | Ceiling | 1.30 | 11.00 | 0.32 |
| Indoor layers | Bearing wall | Ceiling | 1.30 | 11.00 | 0.32 |
| | | Limestone silico block | 15.00 | 270.00 | 0.13 |
| | | Expanded polystyrene | 4.00 | 1.00 | 0.03 |
| | | Limestone silico block | 15.00 | 270.00 | 0.13 |
| | | Ceiling | 1.30 | 11.00 | 0.32 |
| | Partition | Gypsum plaster | 1.00 | 12.00 | 0.42 |
| | | Rockwool | 8.00 | 2.00 | 0.04 |
| | | Gypsum plaster | 1.00 | 12.00 | 0.42 |
| Low Floor | Ground floor | Reinforced concrete slab | 25.00 | 588.00 | 2.30 |
| | | Polyurethane | 25.0 | 8.00 | 0.025 |
| | | Acoustic insulation | 1.00 | 12.00 | 0.36 |
| | | Screed + coating | 8.00 | 144.00 | 0.70 |
| Intermediate floor | Floors | Ceiling | 1.30 | 11.00 | 0.32 |
| | | Concrete Hourdis | 18.00 | 234.00 | 1.28 |
| | | Cellular concrete | 8.00 | 48.00 | 0.22 |
| | | Polyurethane | 1.00 | 0.00 | 0.025 |
| | | Screed + coating | 8.00 | 144.00 | 0.70 |
| Roof | roof | PVC cover | 1.00 | 12.00 | 0.14 |
| | | Expanded polystyrene | 4.00 | 1.00 | 0.03 |
| | | Mineral wool | 18.00 | 5.00 | 0.039 |
| | | Finishing plates | 2.00 | 0.33 | 0.03 |

**Table 2**
Monetary indicators of certain environmental impacts.

| Environmental impacts | Monetary indicators |
|---|---|
| Greenhouse gas (€/kg$CO_2$ eq.) | 0.05 |
| Acidification (€/kg $SO_2$ eq.) | 1.01 |
| Primary Energy Demand (€/GJ) | 0 |
| Waste water (€/m$^3$) | 0.079 |
| Depletion abiotic resource (€/kg antimony eq.) | 1.56 |
| Eutrophication (€/kg $PO_4$ eq.) | 40 |
| Photochemical ozone product (€/kg ethylene eq.) | 3.3 |
| Biodiversity damage (€/PDF m$^2$ yr.) | 0.46 |
| Health damage (€/DALYS) | 54.698 |

coatings at 10 years, 20 years for specific equipment, and 30 years for doors and glazing. Structural and insulating materials have an assumed lifespan equal to that of the building, i.e. 80 years. Finally, the transport distances were set at 100 km between the production site and the site and at 50 km between the site and the landfill (Wille, 2013).

(b) Project associations: From the Ecoinvent version 3 environmental database, life cycle inventories energy, materials, waste treatment, traffic, agricultural products and processes, electronics, machining of metals and ventilation of buildings was obtained. For each of the elements used, it can be encoded: (i) the typical life of the item in question. This lifetime will be specified when it is different from the default lifetime. (ii) the entry of the environmental basis that we wish to associate with each phase of the life of this material. The associations offered are the software's default associations.

### 2.6.1. *Energy*

To determine as accurately as possible, the impact of electricity consumption, the electricity production mix in Belgium in the software was entered as 49% nuclear energy, 27% natural gas, 19% renewable energy and 5% coal (Nguyen, 2020). The energy consumption related to heating and domestic hot water systems is calculated using the needs of the STD.

### 2.6.2. *Water*

Not knowing the exact behaviour of the occupants of the residence studied, the average water consumption in Wallonia (Belgium) was considered. At the end of 2019, the total consumption of mains water, all activities combined (agriculture, industries, households), relative to the number of inhabitants in Wallonia, was 119 L per day and inhabitant. The cold-water consumption represents 60% of this amount or 71.4 L per day and inhabitant. Finally, the domestic hot water consumption represents the remaining 40%, or 47.6 L per day per inhabitant 5CE2020).

### 2.6.3. *Waste*

Each year, in the Walloon Region, nearly 2,000,000 tons of household waste (sorted or not) and similar are collected, i.e. 550 kilos per inhabitant and year, or 1500 g per inhabitant and day. Note that to this waste are added 3500 kilos per year of so-called hidden waste. This is industrial waste caused by the manufacture of consumer goods Wallonia 2020). Household waste is a waste produced by households in the course of their usual activities. They understand: (i) Sorted waste such as cardboard paper, glass, PMC packaging, green waste, bulky items, etc. They represent 71% of total household waste and are mainly oriented towards recovery, recycling or energy production channels. The 90% glass, 75% paper and 40% plastic are sorted. (ii) Raw or residual household waste: this is another unsorted waste. They represent 29% of household waste and are most often directed to an incineration sector.

In Belgium, 40% of the 1500 g of household waste day labourers per person are sent to incineration with a yield of 85%. The average waste transport distances are as follows.

(Nematchoua and Reiter, 2019): (a) From demolition to sorting centre or collection point: 30 km; (b) from the collection point or sorting centre to the landfill: 50 km; (c) from the collection point or sorting centre to the incinerator: 100 km.

### 2.6.4. *Transport*

In the initial scenario, we do not consider the transport of occupants. The latter will be considered during a variation of the initial scenario in order to become aware of its impact.

### 2.6.5. *Scenarios*

To reach the nearly zero energy targets in residential buildings, we applied several scenarios as detailed in this section.

Scenario 1, Occupant's mobility: In order to determine the environmental impact of the occupants' daily trips, it must be specified the type of site where the residence is located as well as the residents' mobility behaviours regarding home-work and home-business trips.

90% of workers in the city studied drive to work (Nematchoua et al., 2015c). They travel an average of 25 km to reach their workplace. Assuming that the residence of 20 occupants is made up of 14 workers, 4 children and 2 elderly people, we can consider that 90% of the 14 workers will make the daily commute by car, and 63% of the occupants of the residence. As the daily home-school trip by car is not considered in the Pleiades tool, we will admit that 70% of occupants make the daily home-work/school trip. This 25 km journey is made 5 times a week for 47 weeks a year, or 235 days a year (Wille, 2013). It is important to note that the Belgian average use of a car as a means of transport to work represents 71% and, in particular, in the Wallonia region, this average is around 89%.

The average Belgian household visits food stores twice a week and the average distance to the supermarket is 3 km. However, many Belgians do not necessarily go to the nearest supermarket. In the Pleiades tool, the home-business trip is considered to be made once a week for 47 weeks a year. Considering a home-store distance of 5 km, carried out twice a week by each of the 6 apartments in the residence, the distance of the weekly home-store trip per occupant is 3 km. In Belgium, only 5% of workers take the bus or the train. In Liège, more often opt for the bus as a mode of public transport is the distance between the residence and the bus stop of 500 m away. In consequence, this journey is made on foot or by bike.

Scenario 2, Joinery choice scenario: In the initial scenario, the joinery used is that of a low-energy building. We will compare from a thermal point of view and from an environmental point of view the use of very insulating wooden interior doors and triple glazing with argon gas with the choices of joinery in the initial scenario. All the characteristics are given in Table 3.

Scenario 3, Variation of the insulation thickness on the facades**:** In this variant, we will modify the thicknesses and the nature of the insulators in the facades. The thicknesses and the nature of the insulation in the initial scenario are the actual thickness and nature of the residence, i.e. 24 cm of Polyurethane in the cladding exterior walls and 32 cm of expanded polystyrene in the exterior coated walls. Although the thicknesses of these two materials are different, the insulation performance of clad exterior walls and coated exterior walls are similar. Indeed, using the calculation tool available online on the Recticel Insulation website, we first calculated the U value. This indicates the amount of heat that passes through a surface on 1 s of 1 $m^2$ when there is a temperature difference of 1 °C between indoors and outdoors.

The airtightness values as well as the thermal bridges are shown in Table 4 for the different insulation variants that were tested.

Scenario 4, Variation of the insulation thickness on the roof: In this section, it will remain on the assumption that the unfinished attic could become it. Therefore, the roof is insulated correctly from the start and the ground will not be insulated. At the same time, double glazing was employed in order to measure only the impact of the nature of the insulation on the roof. Finally, in order to meet current environmental challenges, we replaced PIR and rock wool with wood fibre panels and wood wool. To respect the assumption that the attic would all be convertible, it was not planned to have a thickness of wool greater than the thickness of the current insulation, i.e. 42 cm (24 cm of PIR and 18 cm of rock wool). We will thus compare the impacts of the insulated residence on the roof as in the initial scenario and those of the insulated residence with 21 cm of wood fibre panels and 21 cm of wood wool, i.e. a total insulation thickness of 42 cm in both cases.

**Table 4**
Values of n50 and for the different insulation variants tested in the walls.

| Glazing | Initial | Variant 1 | Variant 2 | Variant 3 | Variant 4 |
|---|---|---|---|---|---|
| | double | double | double | triple | triple |
| Cladding wall insulation: Polyurethane (PUR) (cm) | 24 | 15 | 20 | 20 | 25 |
| Insulation coated walls: Expanded polystyrene (EPS) (cm) | 32 | 20 | 25 | 25 | 30 |
| n50: Hall and stairs (vol./h) | 1.00 | 2.00 | 1.50 | 1.50 | 1.00 |
| n50: Elsewhere (vol./h) | 0.25 | 1.00 | 0.50 | 0.50 | 0.25 |
| Support and threshold ($W/m^2K$) | 0.15 | 0.37 | 0.37 | 0.15 | 0.15 |
| Outside angle ($W/m^2K$) | 0.08 | 0.15 | 0.10 | 0.08 | 0.08 |
| Low floor ($W/m^2K$) | 0.20 | 0.28 | 0.24 | 0.20 | 0.20 |

Scenario 5, Renewable energy (photovoltaic panel)**:** In the initial scenario, the total electricity used for lighting and to power household appliances came exclusively from the Belgian electricity grid. In this variant, we install mono-crystalline panels on the part of the roof that does not include a skylight, i.e. over 102 $m^2$. This equates to approximately 2/3 of the total roof area. The roof is sloped 20° and faces south, which is something ideal for a photovoltaic installation and a superimposed installation on the roof was selected. Thus, the assembly does not require any subtraction of a sealing element; the photovoltaic panels are affixed directly above the roof with an air gap below through brackets. What is more, the air gap provides good ventilation at the rear of the modules, which mitigates performance losses due to heat. Finally, the chosen photovoltaic panels have a peak power of 142.8 $W/m^2$ (Nematchoua et al., 2021).

Scenario 6, Heat pump scenario**:** In this scenario, the three condensing boilers with heat pumps (PAC) will be replaced and will be used dual-service air-to-water heat pumps, that is to say, using the calories from the outside air to release them into the water which is then released into the heating installation. They are therefore used for heating and DHW. These heat pumps have an absorbed power of 5 kW, a coefficient of performance of 3.5, and a lifespan of 20 yr. This means that this heat pump produces 3.5 kWh of thermal energy for 1 kWh of electrical energy consumed. We configure each of the storage tanks as an integrated back-up water heater of the electric generator type. We are also adding extra-electric for heating which is triggered only if the heat pumps are not sufficient.

**Table 3**
Properties of the joinery of a passive building.

| | | Heat transfer coefficient $U_f$ ($W/m^2K$) | Overall heat transfer coefficients) $U_{w,vertical}$ ($W/m^2K$) | Overall heat transfer coefficients) $U_{w,horizontal}$ ($W/m^2K$) | Light transmission $T_l$ | Solar factor $S_w$ |
|---|---|---|---|---|---|---|
| Initial scenario | Insulating wooden interior doors | 1.00 | – | – | – | 0.040 |
| | Low-emissivity double-glazed door | 2.10 | 1.690 | 1.740 | 0.68 | 0.550 |
| New scenario | Very insulating door | 0.80 | – | – | – | 0.030 |
| | Triple low-emission glazing | 1.50 | 1.095 | 1.112 | 0.62 | 0.533 |

## 3. Results and discussion

The results of the dynamic thermal simulation are given in Pleiades Results. This will allow us to study the evolution of temperatures and the building's energy needs over a certain period of one year in our case, with a certain time step set at 30 min.

### 3.1. Case of the actual scenario

For a building, to be qualified as passive, one of the four conditions is that the net heating energy requirement is less than 15 kWh/m$^2$ per yr. If it is between 15 and 30 kWh/m$^2$, the building has very low energy consumption and if it is between 30 and 60 kWh/m$^2$, the building has low energy consumption. The net heating energy requirement is the energy required to maintain a comfortable indoor temperature in summer and winter. The 15 kWh/m$^2$ in question does not necessarily correspond to the energy that would actually be consumed in a year for heating. In fact, real consumption takes into account not only comfort but also the yields linked to technical installations and the occupants' way of life. For example, if the occupants of the residence go on vacation throughout the winter, the net heating energy requirements may be less than 15 kWh/m$^2$, but that does not mean that the residence has become passive. In the case of the Arola residence studied in this research, the net annual heating energy requirement is 22.13 kWh/m$^2$. This low requirement is explained by a much higher level of insulation than in new buildings: 32 cm of expanded polystyrene (EPS) in the exterior walls covered with plaster and 24 cm of polyurethane in the exterior walls covered with fibre-cement cladding.

The residence is therefore a very low consumption building but does not meet the passive standard. Through different scenarios, the first try was to reduce the heating needs and, secondly, to move towards a nearly-zero energy building (Nearly ZEB), also called energetically sufficient, that is to say, a building that annually produces as much as it consumes. The Sankey diagram makes it possible to represent schematically the energy balance of the residence and highlights the major transfers, contributions and losses. Thermal needs gross corresponds to the total amount of energy that must be supplied to the building to compensate for the thermal losses of the building depending on the heating scenario. These needs are compensated by the useful internal inputs (useful gains) and the energy provided by the heating system (net thermal needs) which, in the initial scenario, they amount to 24,571 kWh per yr. Note that the annual electricity consumption for devices located in the residence is 10,994 kWh.

By displaying the environmental indicators calculated for the different phases of the life of the house on the same graph, it would not be possible to compare them with each other because they do not have the same units. By normalizing the indicators in relation to the average values of impacts per inhabitant and per year it is, however, possible to represent them on a single scale allowing their comparison in a type of graphic called "eco-profile". Table 5 gives nine environmental impacts and different units.

The eco-profile of the initial scenario is shown in Fig. 3. It is obtained by dividing the results of column 1 of Table 5 by those of column 4. From this eco-profile, we can deduce that the Arola residence has a high contribution to the damage to human health, the cumulative demand for energy, the greenhouse effect and the water used. What is more, of the four phases in the life cycle of the residence, the use is the most important.

Fig. 3Eco-profile in a year of inhabitant - initial scenario.

In Fig. 4, it can be compared the reference values of the environmental indicators of 1997 (column 4 of Table 3) with those of the Arola residence (column 2 of Table 3) for which the town planning permit was issued in 2015. It was observed that all indicators are reduced by more than 80%. In consequence, the residence fully meets the European Commission's objective of reducing GHG emissions, namely a reduction of at least 40% between 1990 and 2030. Without studying in detail the other seven environmental impacts, it can be mentioned that the waste management sector occupies a very important place in many of the environmental impacts of the operational phase. It alone represents more than 40% of the following six impacts: acidification (71.1%), depletion of abiotic resources (42.8%), eutrophication (+45.9%), production of photochemical ozone (61.9%) damage to biodiversity (91.1%) and damage to health (68.8%).

**Table 5**
LCA results and reference values for the various indicators in years per capita and square meter.

| Environmental impacts | Residence results | | | IPCC/ITCAPS (1997) |
|---|---|---|---|---|
| | Per 20 inhabitants per 467.84 m$^2$ under 80 yr (column 1) | per inhabitant/ yr. (column 2) | Per m$^2$ of living space (column 3) | per inhabitant/yr. (column 4) |
| Greenhouse effect (100 yr) ($tCO_2$ eq.) | 1340.67 | 0.84 | 0.03 | 8.68 |
| Acidification (kg $SO_2$ eq.) | 5452.03 | 3.41 | 0.14 | 62.3 |
| Cumulative energy demand (GJ) | 45,567.33 | 28.48 | 1.21 | 175.54 |
| Water used (m$^3$) | 104,903.55 | 65.56 | 2.80 | 339 |
| Depletion of abiotic resources (kg Sb eq.) | 13,835.93 | 8.65 | 0.37 | |
| Eutrophication (kg $PO_{3-4}$–eq.) | 2722.73 | 1.70 | 0.07 | 38.1 |
| Photochemical ozone production (kg $C_2H_4$) | 321.92 | 0.20 | 0.008 | 19.7 |
| Damage to biodiversity (PDF m$^2$ yr.) | 79,754.96 | 49.85 | 2.130.00005 | 13,700 |
| Damage to health (DALYs) | 1.75 | 0.001 | | 0.0068 |

#### 3.1.1. Validation of results

In the literature, it is indicated that the operational phase of a standard building represents around of 50% of the total environmental loads (Sharma et al., 2011). With 86.28% of the total environmental loads found in this study(operational and construction phases), it was obtained a percentage nearby those given in the literature.

If we are more specifically interested in GHG emissions, the Architecture and Climate unit of the Catholic University of Louvain has established that a passive house (15 kWh/(m$^2$.yr)) with a lifespan of 50 years emits between 8.3 and 15.3 kilos $CO_2$ equivalent while a low-energy house (38 kWh/(m$^2$ yr.)) emits between 17.9 and 24.9 kilos $CO_2$ equivalent per year and m$^2$, depending on the materials chosen. During the operational phase of the building studied in this study, only heating was taken into consideration. In the initial scenario, the Arola residence is a very low energy house since the net heating energy requirement is 22.13 kWh/(m$^2$.yr). Adding up the GHG emissions during construction (145.93 tons of $CO_2$ equivalent), renovation (127.06 t) and end of life (5.69 t), and heating emissions during the operational phase (234.70 t), we arrive at 513.37 tons of $CO_2$ equivalent over 80 yrs and for 467.84 m$^2$, i.e. 13.52 kilos of $CO_2$eq. per yr. and m$^2$. Thus, this result is included in the ranges given in the literature (Nematchoua and Reiter, 2019b) so it can be concluded that these results are reliable.

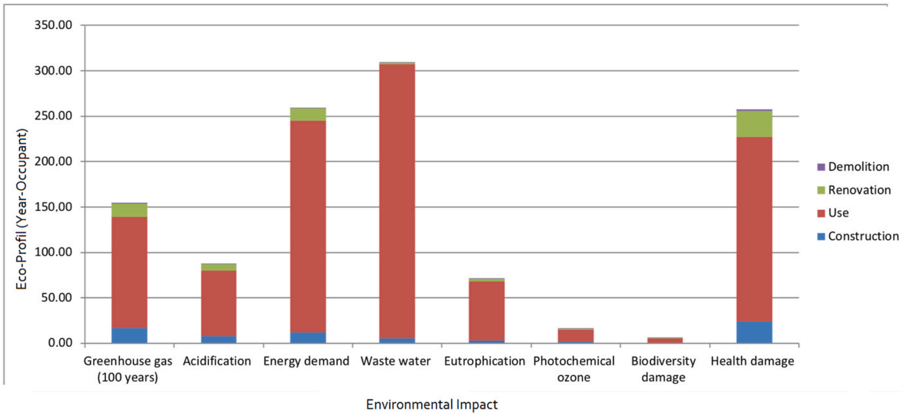



**Fig. 3.** Eco-profile in year of inhabitant - initial scenario.

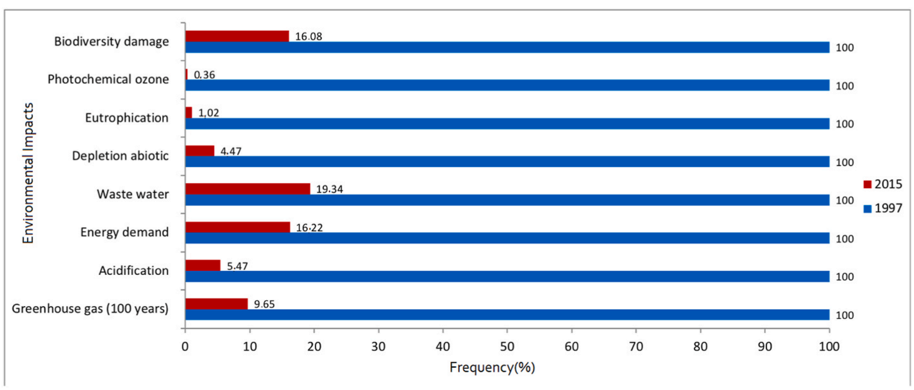



**Fig. 4.** Comparison of the reference values of the environmental indicators from 1997 to those of the Arola residence.

### *3.1.2. Monetization of the GMM method*

Table 6 shows the results obtained for the 9 environmental indicators during each of the four phases of the LCA in the case of the initial scenario. Then, we can determine the cost generated by each of the indicators during each phase by multiplying the result of the LCA by the cost recalled in Table 2. The total environmental cost comes to €249,166, when our analysis time is set at 80 yrs. With a cost of €217947.7, the usage phase, alone is responsible for 87.5% of the total cost. Construction; renovation; and end of life are responsible for 6.0; 6.2; and 0.3%, respectively, of the total cost. Eutrophication and GHG emissions together are responsible for 70.6% of the total environmental cost. Indeed, the cost related to eutrophication amounts to €108,909, corresponding to 43.7% of the total cost and the cost due to emissions of GES amounted to €67,034, corresponding to 26.9% of the total cost. These results agree with the observations made by (Nematchoua and Reiter, 2019) during the study carried out on a sustainable district located in Belgium.

Let's take a look at the environmental cost linked to GHG emissions during each phase. The operational phase is responsible for 79.2% of the environmental cost due to emissions. The construction and renovation of the house are responsible for 10.9% and 9.5% of the cost of total GHG emissions and the end of life phase is responsible for 0.4% of the environmental cost due to emissions. In the study conducted by (Sharma et al., 2011), It was found that the operational phase of the building produces more than 50% of GHG emissions, and is also considered to be one of the largest consumers of energy (over 80%). It is very important to explore other ways and alternative means, in order to build sustainable buildings more adapted to the new climate.

**Table 6**
Results of the GMM method in the case of the actual scenario for each of the 9 environmental indicators during the 4 phases of the life cycle.

| Parameters | Construction | | Operational | | Renovation | | End of life | |
|---|---|---|---|---|---|---|---|---|
| | Results | Cost (€) | Results | Cost (€) | Results | Cost (€) | Results | Cost (€) |
| Greenhouse effect (100 yr) ($tCO_2$ eq.) | 146.0 | 7296.4 | 1062.0 | 53100.2 | 127.1 | 6353.0 | 5.7 | 284.0 |
| Acidification (kg $SO_2$ eq | 471.7 | 476.4 | 4524.4 | 4569.6 | 415.1 | 419.2 | 41.0 | 41.4 |
| Cumulative energy demand (GJ) | 2110.1 | – | 40845.6 | – | 2469.7 | – | 142.0 | 0 |
| Water used ($m^3$) | 1726.6 | 136.4 | 102480.2 | 8095.9 | 590.9 | 46.7 | 105.9 | 8.4 |
| Depletion of abiotic resources (kg Sb eq.) | 851.0 | 1327.6 | 11939.2 | 18625.2 | 984.5 | 1535.9 | 61.2 | 95.4 |
| Eutrophication (kg $PO_3$ 4− eq.) | 103.0 | 4118.4 | 2492.2 | 99687.6 | 119.4 | 4777.0 | 8.2 | 326.3 |
| Photochemical ozone production (kg $C_2H_4$) | 35.2 | 116.2 | 258.6 | 853.5 | 26.9 | 88.7 | 1.2 | 4.0 |
| Damage to biodiversity (PDF.$m^2$.yr.) | 3135.8 | 1442.5 | 71608.3 | 32939.8 | 4901.9 | 2254.9 | 108.9 | 50.1 |
| Damage to health (DALYs) | 0.2 | 8.8 | 1.4 | 75.7 | 0.2 | 10.7 | 0.01 | 0.5 |
| Total cost | – | 14922.7 | – | 217947.7 | – | 15486.0 | – | 810.0 |

### 3.2. Case of Occupant's mobility scenario

So far, to carry out LCA in the initial scenario, it was considered a residence with a lifespan of 80 years and not considered the transport of occupants during the operational phase. In this section, we will study the influence on the results when we play on these two parameters.

#### 3.2.1. Impact of lifespan

On one hand, when the same study is conducted with a lifespan of the residence of 50 years, and not 80 years, the results of the nine impacts during the construction and end of life phases are unchanged. On the other hand, by annualizing the effects, it is obvious that the shares of these two phases are larger when analysing over 50 years. During use, the nine impacts are unchanged when expressed annually since the waste emissions and consumption in terms of heating, cold water, domestic hot water and electricity are considered to be identical every year. With the exception of damage to biodiversity and health, all annual impacts during renovation are less significant when analysed over 50 yr. When we add up the impacts over the four life cycle phases, we find that the totality of the impacts studied per year increases compared to the initial scenario. The water used is the least variable impact as it is mainly related to using.

#### 3.2.2. Impact of occupant mobility

When we consider transport, only the operational phase is increased because the transport of the occupants occurs during this phase; the other phases of the life cycle are unchanged. The share of use was initially 86.29%. In this variant, we see after implementing this scenario that it is 94.22%. In addition, the shares of the construction, renovation and end of life phases decrease, respectively, from 6.65, 6.69, and 0.37%

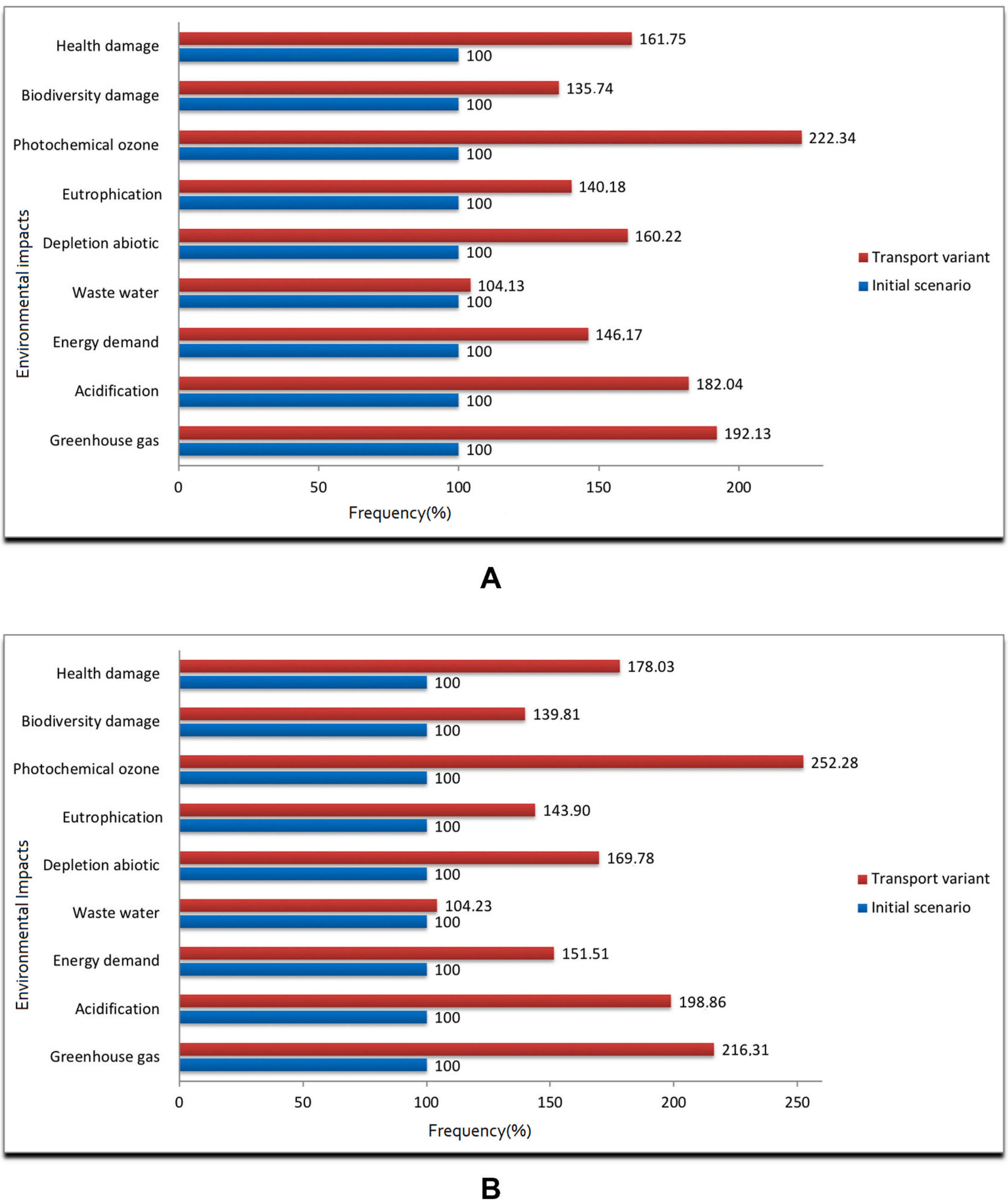



**Fig. 5.** (a) Comparison of the total environmental impacts of the initial scenario and the "transport" variant; (b) Comparison of the environmental impacts of the initial scenario and the "transport" variant during use.

to 2.65, 2.98, and 0.15%.

In Fig. 5a we see that almost all the indicators increase considerably between the initial scenario and this variant. The three indicators most affected by the consideration of transport are the production of photochemical ozone, the greenhouse effect and acidification. In particular, GHG emissions are increased by 92.13% compared to the initial scenario where 79.2% of the GHG emissions came from the operational phase. Considering the transport of occupants, 89.2% of total GHG emissions come from the operational phase. Within this phase, occupant transport alone is responsible for more than 50% of GHG emissions with 1235.2 tons of $CO_2$ equivalent emitted.

In addition, the evolution of the various indicators during the operational phase is given in Fig. 5b. The three environmental indicators showing the greatest increases are photochemical ozone production (+152.3%), GHG emissions (+116.3%) and acidification (+98.9%). Occupant transport alone accounts for more than a third of the following six impacts: greenhouse effect (53.8%), acidification (49.7%), cumulative energy demand (34.0%), depletion of abiotic resources (41.1%), production of photochemical ozone (60.4%) and damage to health (43.8%).

#### 3.2.3. Monetization of the GMM method

The total environmental cost of this variant amounts to €387,016, an increase of 55.3% over the total environmental cost of the initial scenario of €249,166. This cost increase is only for the transport of occupants during the operational phase. As in the study case, the most significant damage to the residence is due to eutrophication (39.4%) and the impacts of GHGs (33.2%). These results agree with the observations made by Nematchoua and Reiter (2019) during the study conducted on a sustainable neighbourhood located in Belgium.

### 3.3. Case of joinery choice scenario

By using highly insulating wooden doors and triple glazing on the four sides of the residence, the heating needs are 15.83 kWh instead of 22.13 kWh per $m^2$ and year in the initial situation, i.e. a gain of more than 6 kWh. With this unique modification, the Arola residence is almost passive as it approaches the upper limit of 15 kWh per $m^2$ and yr. Nematchoua et al., 2020, found after a study carried out in four regions located in a tropical climate that the application of highly insulating wooden allows energy consumption to be reduced by 8%–15%. This conclusion confirms the result found in this study.

#### 3.3.1. Life cycle assessment

On one hand, it is obvious that the nine environmental indicators are revised upwards during construction and renovation, mainly following the addition of additional glazing to the windows of all facades. On the other hand, all the indicators are revised downwards during use since this modification alone makes it possible to reduce the heating needs.

All environmental impacts are, all phases combined, reduced between 4.70% (greenhouse effect) and 0% (water used). The two environmental indicators that recorded the most significant reductions are the depletion of abiotic resources (3.8%) and the greenhouse effect (4.7%), with a reduction in emissions of 63 tons of $CO_2$ equivalent over the entire region of LCA of the residence.

#### 3.3.2. Monetization of the GMM method

It was observed that the environmental cost linked to construction and renovation increases by 1.09% and 2.02% respectively. In fact, as the nine environmental indicators are slightly revised upwards during these phases, the environmental cost also increases very slightly. During the operational phase which is the heaviest phase in the balance, the cost decreases by 2.19%. Therefore, the total environmental cost decreases by 1.72%, either a cost of €244,870 compared to €249,166 in the initial scenario.

Based on these results, we can conclude that installing highly insulating wooden doors and triple glazing is a good solution both from a thermal point of view and from an environmental point of view.

### 3.4. Case of insulation thickness scenario on the facades

#### 3.4.1. Impact of the insulation thickness on the exterior walls

As the insulation thicknesses of the Arola residence are greater than the Belgian average, the analysis will be focused on the impact of less insulation. However, we will not go below 15 cm of insulation since all homes in the eco-district must be low-energy or passive.

As the building's insulation initially planned was very efficient, it is normal that its airtightness was an important point in controlling air infiltration and exfiltration and certain energy losses.

In Fig. 6a, we compare the heating needs according to the insulation thickness put in the exterior walls of the residence. In the first variant, it was considered to have 15 cm of PUR or 20 cm of EPS in the exterior walls, as well as double glazing. The annual heating requirement is 64.59 kWh per $m^2$. Even if we multiply the solutions to reduce energy consumption, such a value does not allow us to go below 15 kWh per $m^2$. When we pass from 15 to 20 cm of PUR and 20–25 cm of EPS in the exterior walls, the heating needs decrease considerably from 64.59 to 38.05 kWh/($m^2$yr). By having triple glazing, always having 20 cm of PUR and 25 cm of EPS8.62 kWh/($m^2$yr) were saved, either annual heating needs of 29.43 kWh/$m^2$. Finally, with triple glazing, 25 cm of PUR, and 30 cm of EPS, the needs amount to 15.88 kWh/$m^2$. Continuing to increase the thickness of insulation in the exterior walls then seems to be unnecessary because we find that the energy gain to heat the residence is minimal, going from 15.88 to 15.44 kWh/($m^2$ year) when placing 30 cm of PUR, 35 cm of EPS, and triple glazing. Thus, beyond 25 cm of PUR and 30 cm of EPS, these efforts are not well rewarded.

The goal was to tend towards a Nearly-ZEB building by using in a useful and adapted way photovoltaic panels, ensuring a low airtightness and low thermal bridges etc., so we retain the variant 4. At this phase of this study, in the next section, it will be analysed if it is possible to obtain annual heating needs close to 15.88 kWh per $m^2$ by using other insulators than PUR and EPS in the exterior walls.

#### 3.4.2. Impact of the insulation nature

Insulation thickness scenario**:** Mineral wools such as glass wool and rock wool are recognized for, among other things, their good thermal performance and their low cost. However, they have a poor environmental record due to the large quantity of water required for their production. Synthetic insulators like EPS and PUR have a very poor carbon balance and emit pollutants (volatile organic compounds) into the surrounding air.

In Fig. 6b, it can be seen that PUR is the insulator with the smallest coefficient of thermal conductivity. Thus, on one hand, it is the one that transmits heat the least by conduction and insulates the best. In Fig. 6c, on the other hand, it can be observed that PUR is the insulator whose production generates the greatest greenhouse gas emissions. Wood fibre panels and wood wool constitute "carbon sinks", which are very effective in combating GHG emissions. To meet current environmental challenges, it will consider the use of wood wool to insulate the residence.

As shown in Fig. 6d, the heating needs are not significantly different when we put 25 cm of wood wool, 2 cm of wood panels and triple glazing. They are 17.24 kWh per $m^2$.

We will, therefore, compare the two following cases: (a) Wall insulation using 25 cm of PUR in the clad walls and 30 cm of EPS in the plastered walls; (b) insulation of the walls with two panels of wood fibre of 1 cm and 25 cm of wood wool.

As shown in Fig. 7a, during construction, the nine environmental indicators are lower when we use insulation made of wood. The two most markedly reduced indicators are GHG emissions (−29.28%) and photochemical ozone production (−38.86%). The heating needs are greater when we have 25 cm of wood wool (17.24 kWh/($m^2$ yr.),

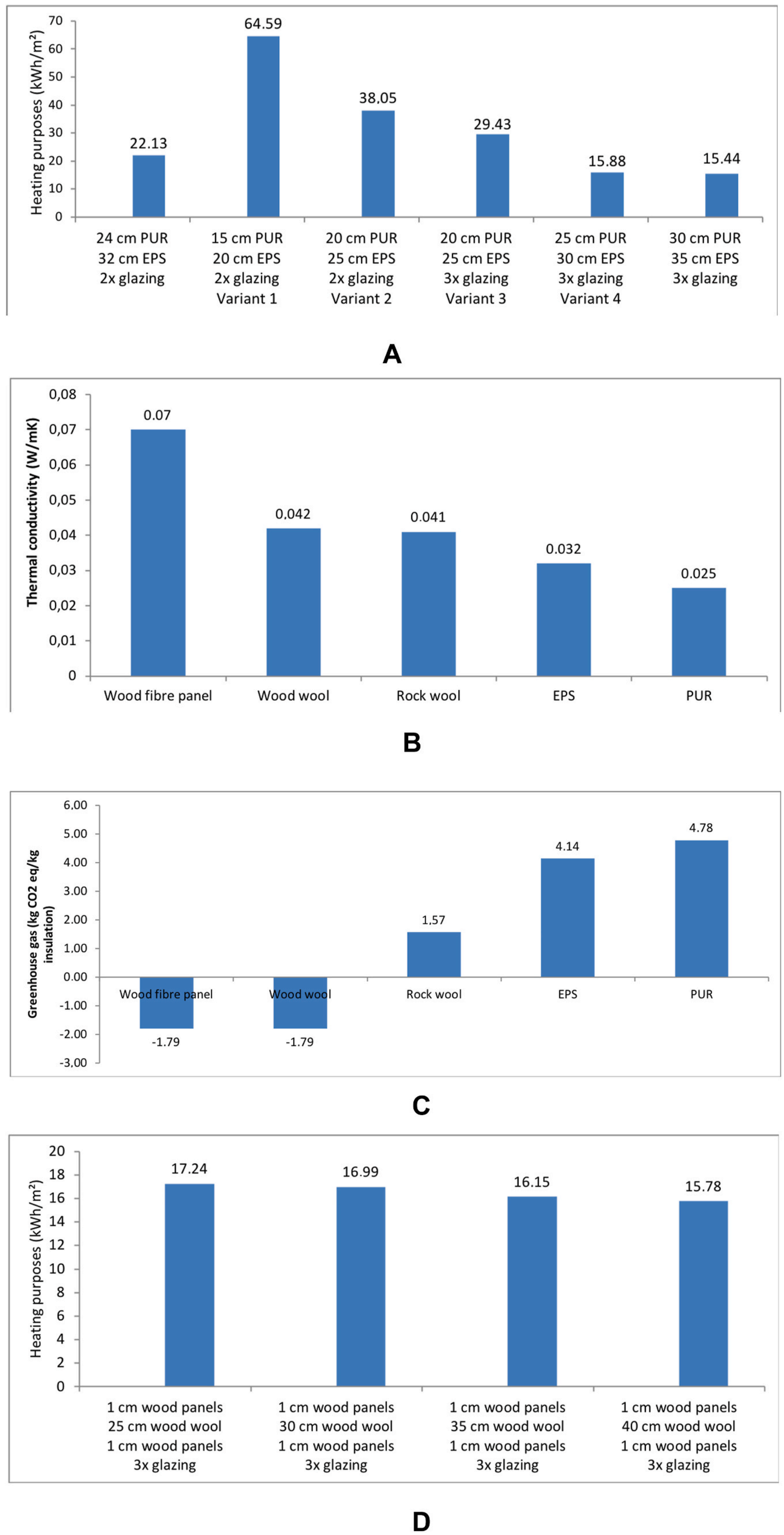
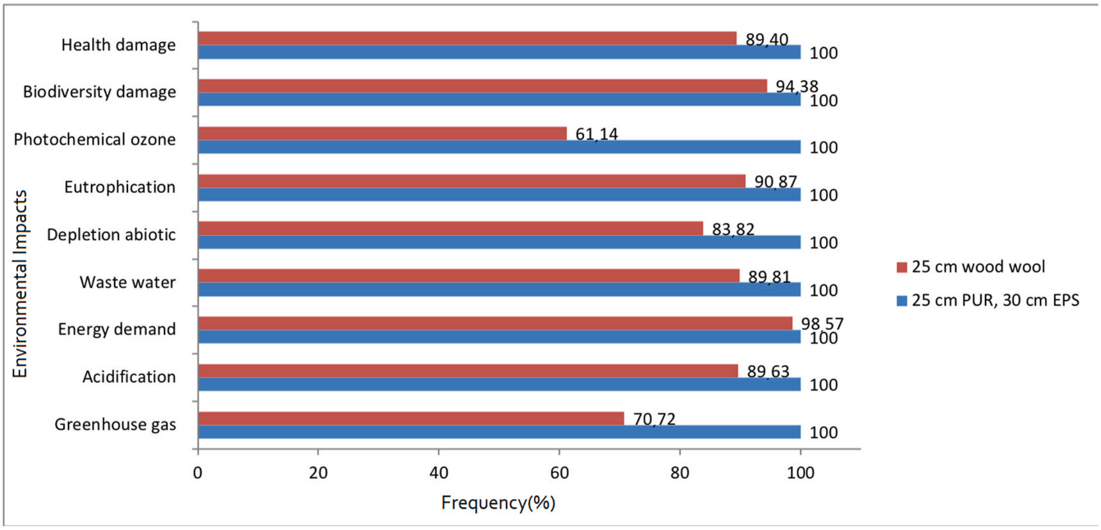
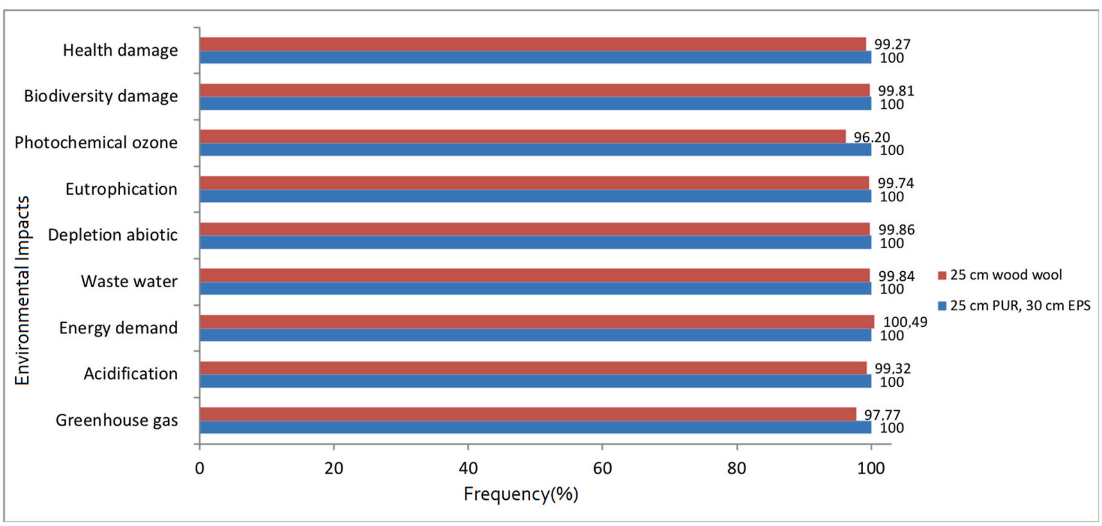



**Fig. 6.** (a) Comparison of heating needs as a function of the thickness of PUR placed in the exterior walls; (b and c) Coefficients of thermal conductivity and equivalent $CO_2$ emissions of several insulators; (d) Comparison of heating needs according to the thickness of the thickness of wood wool placed in the exterior walls.




A




B

**Fig. 7.** (a) Comparison of environmental impacts to construction: 25 cm of PUR or 30 cm of EPS and 25 cm of wood wool + 2 cm of wood fibre panels; (b) Comparison of total environmental impacts: 25 cm of PUR or 30 cm of EPS and 25 cm of wood wool + 2 cm of wood fibre panels.

compared to 15.88 kWh/(m$^2$ yr.) when 25 cm of PUR or 30 cm of EPS are placed, all environmental indicators are more important. In Fig. 7b, it can be observed that, over the entire life cycle of the residence, all environmental indicators are less when the walls are insulated with 25 cm of wood wool compared to the case in which the walls are insulated with 25 cm of PUR and 30 cm of EPS, except for the cumulative demand for energy.

### 3.4.3. *Monetization of the GMM method*

If, on one hand, we have 25 cm of PUR in the clad walls, 30 cm of EPS in the coated exterior walls and triple glazing, the environmental cost of construction increases by 0.96% compared to the initial scenario (24 cm of PUR, 32 cm EPS and double glazing). On the other hand, the annual heating needs are 15.88 kWh per m$^2$ in this variant against 22.13 kWh in the initial scenario, so the cost associated with use decreases by 2.17% and allows a reduction in the total cost of 1.71%, either a decrease of €4,270, as shown in Table 7.

It was observed that for the same thickness of PUR and wood wool, the total GHG emissions are lower in the case of wood wool. The high GHG emissions of PUR during the construction phase with respect to

**Table 7**
Comparison of the environmental costs of the initial scenario and of the “25 cm PUR or 30 cm EPS + triple glazing” and “25 cm wood wool + triple glazing” variant, during the different phases.

| Parameter | | Construction | Operational | Renovation | End of life | Total |
|---|---|---|---|---|---|---|
| Cost (10$^3$€) | Initial | 14.90 | 217.90 | 15.50 | 0.80 | 249.20 |
| | PUR + EPS | 15.10 | 213.20 | 15.80 | 0.80 | 244.90 |
| | | +0.96% | −2.17% | +2.05% | +0.12% | −1.71% |
| | Wool | 12.10 | 214.50 | 15.80 | 0.83 | 243.30 |
| | | −18.67% | −1.58% | +2.20% | +2.01% | −2.36% |

wood wool, which is a carbon sink, will generate a poorer construction result, a better result in use but a poorer global result. Therefore, if we are making walls with 25 cm of insulation, it is better to use wood wool from an environmental point of view. Whatever the variant, it will be possible to have an energy-sufficient residence, the heating needs are not significantly different. What is more, if the goal is to achieve the passive label, this 1.44 kWh per $m^2$ difference between annual heating needs becomes an obstacle and it will be easier to go below a requirement of 15 kWh per $m^2$ with PUR. The previous study carried out in other regions with almost the same climate found the insulation cost almost similar to this got in this research (Nematchoua et al., 2020).

### 3.5. Case of insulation thickness scenario on the roof

In this section, the thicknesses and the nature of the insulation in the sloping roof will be modified. In the initial scenario, we have 24 cm of PIR and 18 cm of rock wool.

#### 3.5.1. Impact of insulation nature

The annual heating needs in the initial case are 22.13 kWh per $m^2$. When 42 cm of wood fibre and wood wool panels are placed, the needs are 22.81 kWh per $m^2$ since these insulators have thermal conductivity coefficients higher than PIR and rock wool. In contrast, PIR and rock wool are less environmentally friendly. Consequently, when wool and wood fibre is used, eight environmental indicators, out of the nine studied, are lower during construction decreasing between 1.5 and 16% for GHG emissions. Only the cumulative demand for energy is greater, it increases by 1.1%. What is more, all the environmental indicators in use are very slightly revised upwards following slightly greater heating needs. Overall, insulation with more environmentally friendly insulation (−0.42%) is proving to be a better solution from an environmental point of view.

#### 3.5.2. Monetization of the GMM method

In Table 8 it can be observed that having 42 cm of wool and wood fibres instead of 24 cm of PIR and 18 cm of rock wool enables the environmental cost to be reduced by only 0.42%.

The results showed that, from a thermal point of view, 42 cm of PIR and rock wool generate less heating requirements than when the walls are insulated with 42 cm of plant-based insulation. These results are evident since the latter has higher thermal conductivity coefficients than PIR and rock wool. However, from an environmental point of view and over 80 years of analysis, having 42 cm of wood insulation is preferable. Consequently, it was concluded that the gains linked to the lower heating needs in the initial scenario are completely wiped out by an environmental cost of the construction much greater than wool and wood fibres. However, it is indicated that the solution with 42 cm of plant-based insulation on the roof is more environmentally friendly over the entire life cycle of the residence. In conclusion, preference is given to one or the other solution not according to the environmental cost, but according to the financial cost to the construction as well as the ease of having a certain type of insulation compared to another. Since these two aspects are not the ones that interest us in this research, will be kept the choice of insulation from the initial scenario: 24 cm of PIR and 18 cm of rock wool.

### 3.6. Case of renewable energy scenario

As shown in Fig. 8, the panels can produce 10,051 kWh per year, either 91.4% of the annual electricity consumption which amounts to 10,994 kWh. The excess electricity produced by photovoltaic panels during the months of April to August can also be used to recharge electric cars.

In this sense, by placing photovoltaic panels over the entire roof, and bypassing the two skylights, the area covered by the panels is 150 $m^2$. Such an installation allows an annual electricity production of 14,739 kWh which represents 134% of the annual electricity consumption of the 20 residents when no one uses an electric car. During the months of March to September, the panels provide most of the specific electricity requested, but are still connected to the Belgian network to supply electricity sometimes at night when the electricity intensity is low. The excess electricity is stored in the battery and used at night. Between October and February, the yield of electricity production from PV decreases, and we need more electricity from the Belgium grid.

If we consider that there are six electric vehicles in the residence, the annual electricity production of 14,739 kWh represents 55% of the specific annual electricity consumption of the 20 residents. The most important photovoltaic production, which takes place during the month of July, covers 97.6% of monthly consumption. Thus, it will be necessary to call on the Belgian grid throughout the year to supply electricity.

#### 3.6.1. Life cycle assessment

In order to obtain an energetically sufficient building in terms of specific energy, 112 $m^2$ of panels must be available. This area allows the production of 11,026 kWh, or 100.3% of annual electricity consumption. Therefore, it will be performed an LCA based on this assumption. We note that the construction and renovation phases respectively contribute 8.49% and 10.01% of the total impacts while they contributed 6.65% and 6.69% in the initial scenario. These increases are solely due to the addition of 112 $m^2$ of photovoltaic panels whose lifespan has been set at 25 years. The weight of the operational phase decreases from 86.29% in the initial scenario to 81.10%.

When it is globally compared the nine environmental impacts of the initial scenario and this variant, as it is shown in Fig. 9, all the indicators show declining results, with the exception of damage to biodiversity. The three indicators recording the greatest variations are cumulative energy demand (−17.46%), GHG emissions (−9.80%) and depletion of abiotic resources (−8.40%).

#### 3.6.2. Monetization of the GMM method

In Table 9, the environmental cost of construction increases by more than 20% following the installation of photovoltaic panels which is an increase of 38.7% on the renovation. However, it decreases by 8.8% during the operational phase. Consequently, the overall price decreases by 4.06%, from €249,166 in the initial scenario to €239,051, from where an additional cost of €10,115.

### 3.7. Case of heat pump scenario

#### 3.7.1. Life cycle assessment

The production of three heat pumps and three DHW storage tanks instead of three gas condensing boilers in the initial scenario makes it possible to reduce four environmental indicators for construction:

**Table 8**
Comparison of the environmental costs of the initial scenario and of the "21 cm wood wool +21 cm wood fibre" variant with the attics fitted out during the different phases.

| | Construction | | Operational | | Renovation | | End of Life | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Initial | Fibre wool | Initial | Fibre wool | Initial | Fibre wool | Initial | Fibre wool | Initial | Fibre wool |
| Costs ($10^3$€) | 14.90 | 13.40 | 217.90 | 218.50 | 15.50 | 15.50 | 0.81 | 0.82 | 249.20 | 248.20 |
| | −10.48% | | +0.24% | | +0.00% | | 1.10% | | −0.42% | |

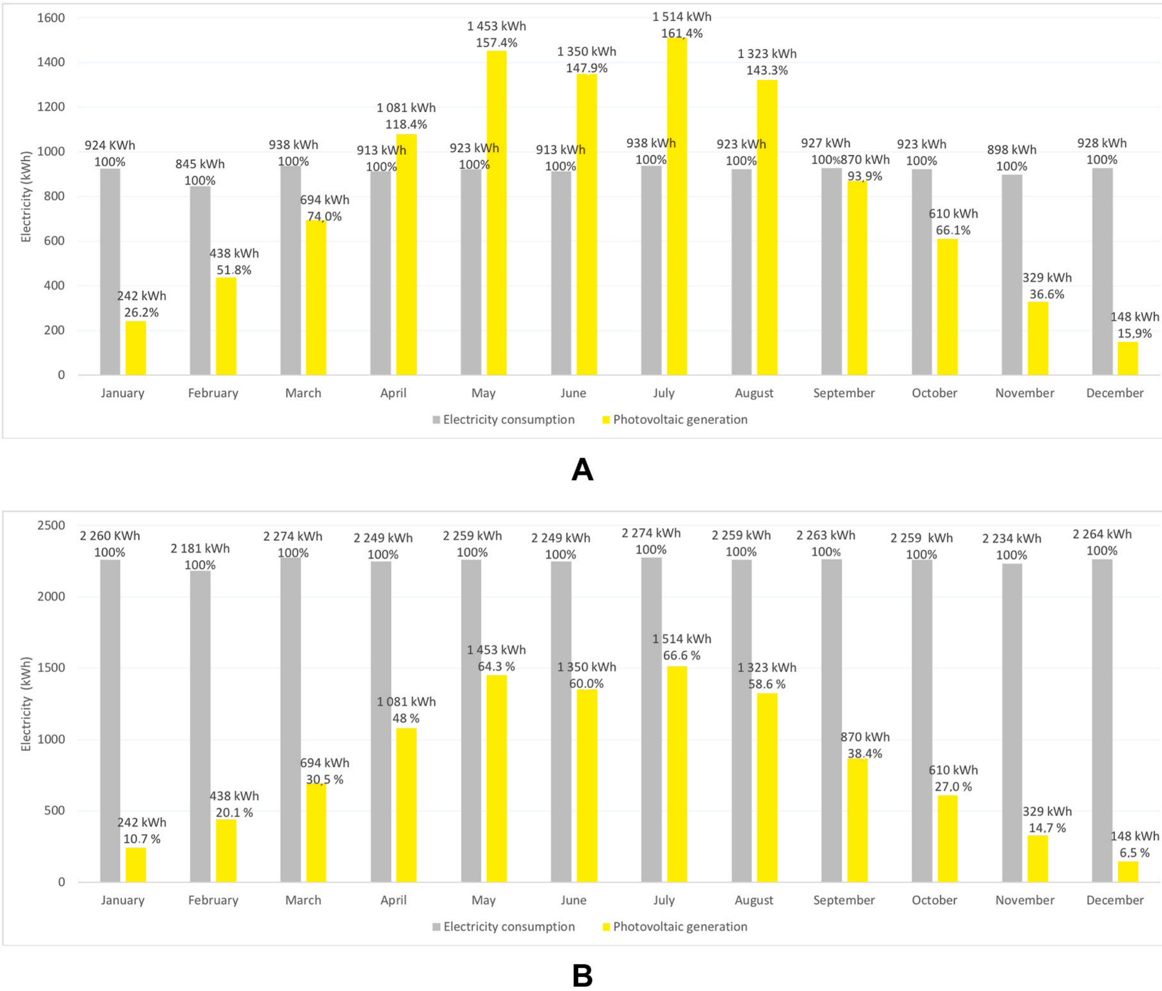



**Fig. 8.** (in high) Comparison between electricity consumption and photovoltaic production; (in low) and with use of electric cars, when 102 m$^2$ of panels are placed.

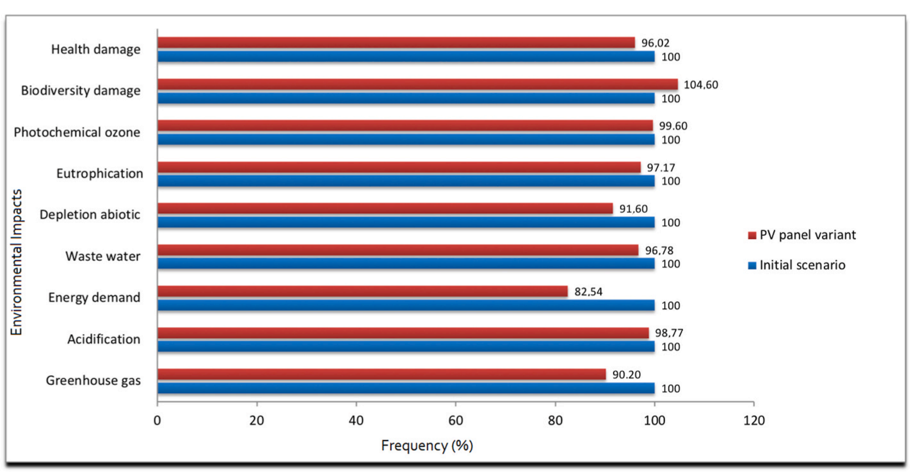



**Fig. 9.** Comparison of the environmental impacts of the initial scenario and the "PV" variant.

**Table 9**
Comparison of the environmental costs of the initial scenario and the "PV" variant during the different phases.

| | Construction | | Use | | Renovation | | End of Life | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Initial | PV | Initial | PV | Initial | PV | Initial | PV | Initial | PV |
| Costs (103€) | 14.9 | 17.9 | 217.9 | 198.8 | 15.5 | 21.5 | 0.8 | 0.8 | 249.2 | 239.1 |
| | +20.12% | | −8.77% | | +38.69% | | +0.12% | | −4.06% | |

cumulative energy demand (−1.10%), exhaustion of abiotic resources (−1.59%), photochemical ozone production (−0.51%) and damage to health (−8.75%). The other five indicators are increasing: greenhouse effect (+6.23%), acidification (+3.19%), water used (+0.31%), eutrophication (+23.89%) and damage to biodiversity (+19.09%). In this sense, Fig. 10a shows how each of the nine indicators varies. Except for the amount of water used and the damage to biodiversity which increases, the other seven indicators decrease, sometimes considerably. These reductions are only due to perceived reductions in terms of heating and DHW. The use of the CAP significantly reduces $CO_2$ emissions and cumulative energy demand. The evolution of the nine environmental indicators for heating and DHW during the operational phase is given in Fig. 10b. All the indicators are very strongly reduced except the damage to biodiversity, which increases by 21.64% for heating and by 21.63% for DHW, and water used, which increases considerably by 1100.72% (Fig. 10b).

#### 3.7.2. *Monetization of the GMM method*

The production of three heat pumps, three DHW storage tanks as well as three electrical back-ups (heating and water) inevitably generates an increase in the environmental cost of construction (+11.44%) and renovation (+32.90%). However, as seen in Fig. 10a, seven indicators decrease, sometimes considerably, during the operational phase. This is only the result of the reductions recorded for heating and DHW. Thus, the environmental cost to use is reduced by 13.11% compared to the initial scenario. Overall, the use of the three heat pumps reduces the environmental cost by 8.74% over 80 years.

### 3.8. *Case of optimal residency scenario*

In this scenario, it is combined all the scenarios already studied to have a more efficient residence. As a first step, the transport of the occupants will not be considered and panels are placed on almost the entire roof, approximately 145 $m^2$ that will provide 14,318 kWh, either 116.4% of the specific annual electricity consumption. Then, the transport of the occupants will be analysed while keeping photovoltaic panels on almost the entire roof and assuming that the panels will be used to meet specific electricity needs and allocating the excess electricity produced by the panels to electric vehicles.

#### 3.8.1. *Life cycle assessment*

Fig. 11 gives the percentage of variations of each of the impacts compared to the initial scenario (100%). The GHG emissions in the optimal solution represent 60.01% of the emissions in the initial

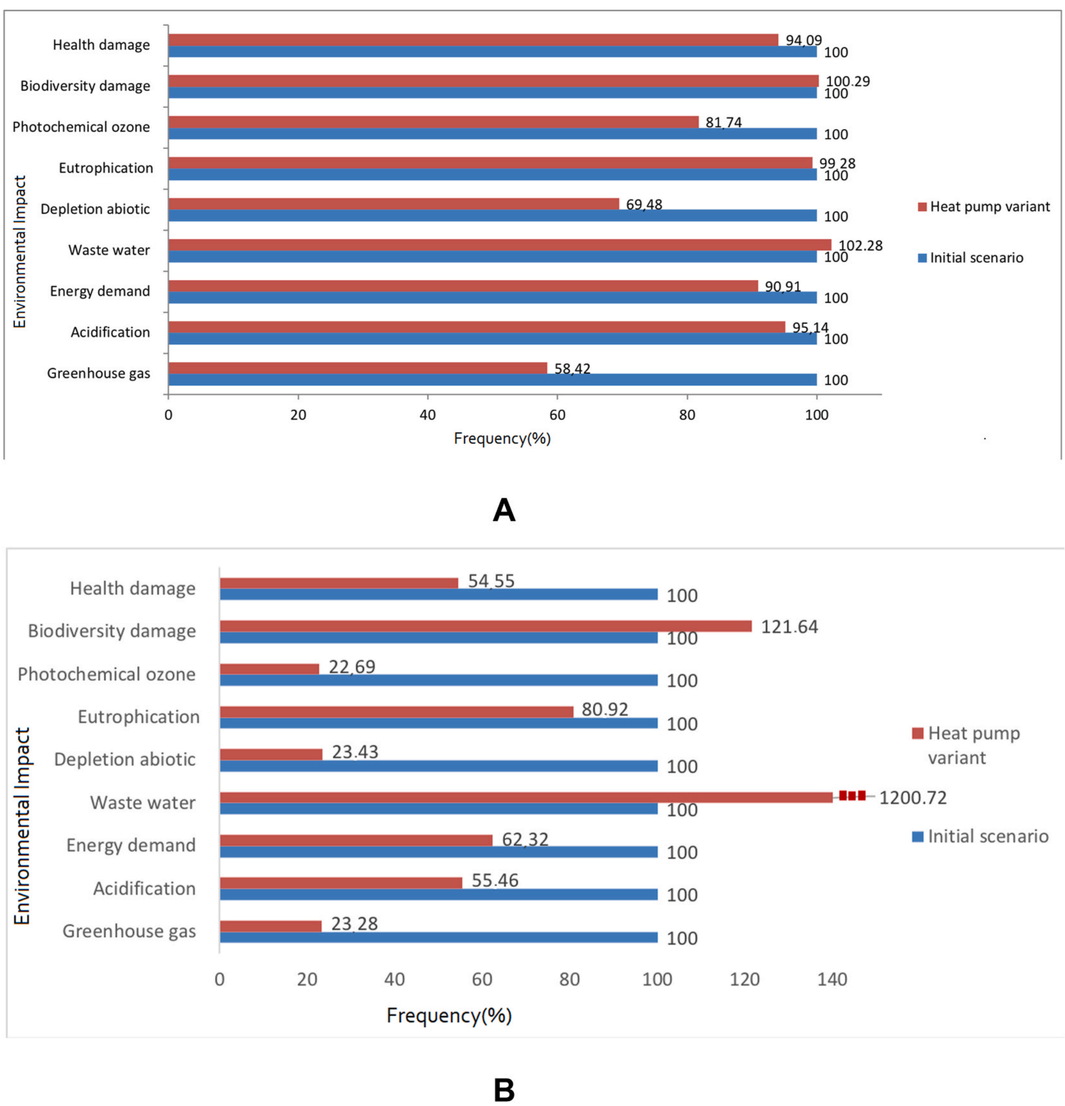



**Fig. 10.** (a) Comparison of the environmental impacts of the initial scenario and the "heat pump" variant during the use phase; (b) Comparison of the environmental impacts induced by heating during the phase of using the initial scenario and the "PAC" variant.

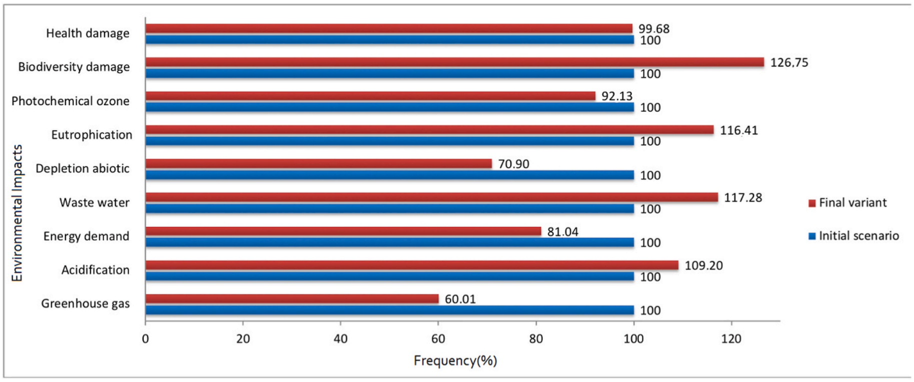



**Fig. 11.** Comparison of the total environmental impacts of the initial scenario and the optimal solution.

scenario, which was 1340.67 tons of $CO_2$ equivalent. During construction, seven indicators increase, four of which are quite significant: damage to biodiversity (+88.52%), eutrophication (+31.14%), cumulative energy demand (+25.56%) and acidification (+25.80%). Although the production of heat pumps and the production of photovoltaic panels increase the GHG emissions, the fact of having replaced PUR and EPS with wood wool in the exterior walls still makes it possible to reduce construction emissions by 1.15%.

During the operational phase, the most significant variation recorded concerns GHG emissions (−58.78%). Lower heating needs, as well as the use of heat pumps and panels, explain such a decrease. The cumulative demand for energy, the depletion of abiotic resources and the production of photochemical ozone also decrease (between −16 and −38% approximately).

When we take into account the transport of the 24 inhabitants, it is obvious that the share relative to use will increase: construction (4.23%), use (88.31%), renovation (6.24%) and end of life (0.21%). Indeed, from the months of April to September, photovoltaic production exceeds the consumption of electricity. A panel area of 127 $m^2$ would have been sufficient to cover the entire specific electricity consumption of the residence. The excess electricity is stored in the battery and used at night. However, the building remains connected to the Belgium grid which often provides electricity during the hours of low production or non-production of PV. Again, it was considered that some occupants will likely have electric cars in the near future and, therefore, excess production can be used to power electric cars with an estimated consumption of 7.32 kWh per day, or 219.6 kWh per month (30 days). Fig. 12 shows the monthly production of electricity by the panels (in yellow) and the specific electricity consumption (in grey). In April, 2 electric cars can be fully recharged without having to call on the Belgian network (in green in Fig. 12). This number increases to 4 electric cars during the months of May and June, 5 cars in July, 3 cars in August and only 1 vehicle in September.

### 3.8.2. Monetization of the GMM method

In this section, it is compared the initial total environmental cost to the cost of the optimal solution with 145 $m^2$ of photovoltaic panels. For construction and renovation, the cost increases by 18.15% and 83.53%, respectively, and it decreases by 8.80% with use. The environmental cost of the Arola residence over the four phases of its life cycle amounts to €245,621. Thus, by considerably reducing the heating needs of the residence, increasing its housing capacity and living area and by reducing its energy dependence, the environmental cost decreases by 1.42% compared to the initial cost.

In Table 10, the total environmental cost of the initial scenario and the optimal scenario is reported per inhabitant, per living $m^2$ and per inhabitant $m^2$. Since it increased the living area of the building, and therefore also its occupancy capacity, by partially fitting out the attic, the decrease of 1.42% is greater when the cost is expressed per inhabitant or $m^2$. When the environmental cost is given per capita, it is €12,458 in the initial scenario and €10,234 in the final solution, i.e. a decrease of 17.85%. It drops by 11.32% when expressed per $m^2$ and by 26.10% when expressed per inhabitant.

The environmental cost of construction increases by 18.15% compared to the initial scenario. This increase is mainly due to a very significant increase in the cost of equipment (heat pump and photovoltaic panels). The equipment initially occupied a share of less than 10% of the environmental cost. With the addition of panels and the replacement of boilers with heat pumps, the share of equipment increases to 40%. The cost of renovation increases by 83.53% when our analysis is made over 80 years, the equipment having a lifespan of between 20 and 25 yr. The share of equipment which was initially less than

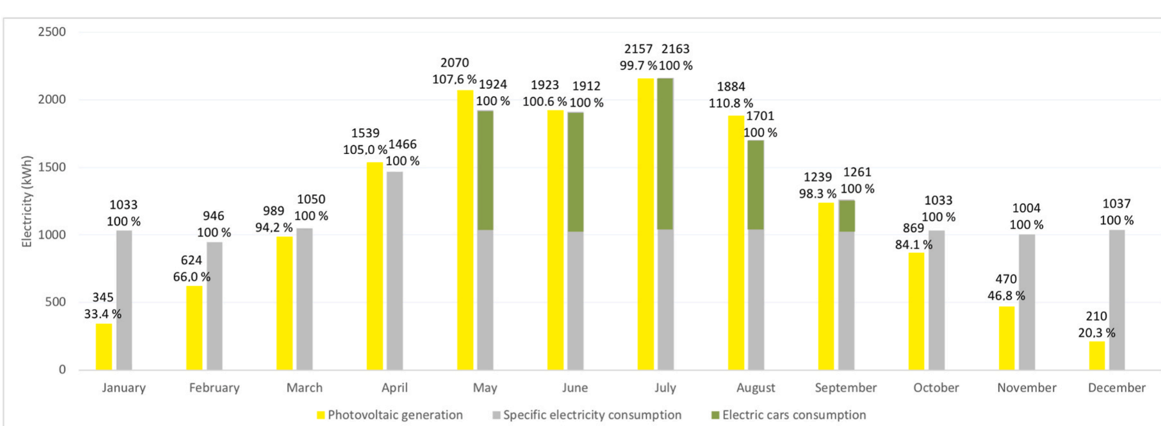



**Fig. 12.** Comparison between electricity consumption with the use of electric cars and monthly photovoltaic production when 145 $m^2$ of panels are placed.

**Table 10**
Comparison of the total environmental cost expressed per inhabitant, per m² and inhabitant.m² in the case of the initial scenario and the optimal solution.

| | Total environmental cost (€) | | | | | | |
|---|---|---|---|---|---|---|---|
| Initial | Optimal | Initial | Optimal | Initial | Optimal | Initial | Optimal |
| 20 occupants (468 m²) | 24 occupants (520 m²) | Per capita | | Per m² | | Per capita/m² | |
| 249166.3 | 245620.8 | 12458.3 | 10234.2 | 532.6 | 472.3 | 26.6 | 19.7 |
| −1.42% | | −17.85% | | −11.32% | | −26.10% | |

30% increased to almost 75%.

Table 11, it is summed up the conclusions drawn from the different variants. We benchmark 100% of the results of the initial scenario. For each of the variants, we indicate the variation in the results of the STD, the LCA (indicating the strongest decrease, the strongest increase and the average variation of 9 impacts) and the variation in the environmental cost.

Striving for the Nearly-ZEB standard makes it possible to strive for energy independence, without however being the solution for having the least environmental cost. In addition, financial cost constraints will have to be taken into consideration during construction as well as renovation.

We find that it is triple glazing that allows the greatest reduction in heating needs. On the other hand, it records the smallest decrease in the environment. If triple glazing is combined with insulation that is more respectful of the environment but whose thermal conductivity is greater, the reduction in heating needs is less while the environmental cost decreases more sharply. On the roof, the fact of fitting out the attic allows a 13% reduction in energy needs expressed per m², but the environmental cost increases since the occupancy capacity are greater. The use of a dual-service air-to-water heat pump enables a considerable reduction in GHG emissions. On average, the indicators decrease by around 9%.

## 4. Challenges and barriers

In any scientific research, there are always limitations, and future directions, in the case of this study:

(a) Maybe, it will have been better to focus on the concept of dynamic LCA by using projected weather data for the specific location of this studied building to conduct a dynamic thermal analysis and calculate corresponding operational impacts out of that. It is very important to carry out this case in future research. In addition, the results regarding the embodied emissions, operational energy, etc. should be published.

(b) Most of the results obtained in this study are expressed as a percentage, which makes comparison difficult with other studies in the field found in the literature. Perhaps, it would have been better to express all the results obtained in functional units (m² or per capita), to facilitate comparison with other research. We will do this in future research.

Despite these different limitations, it is interesting to note that the approach applied in this research allows us to have a global idea of the effect of several scenarios applied in this study on the different environmental impacts generated by a residential building.

Nevertheless, these results can already be the subject of a publication that could clarify or serve as a reference for future researchers in this field.

## 5. Conclusions

In this study, a life cycle assessment of a building as it exists considering four phases (construction phase, operational, renovation and end of life), with its energy needs and its impacts on the environment, was carried out. After this, various scenarios were considered. These were aimed at improving the energy performance of the residence, and for conducting this residence building toward nearly zero energy and low carbon through the use of renewable energies. It is analysed the impact of each scenario implemented on the LCA of this residence allowing us to imagine a residence, which we qualify as optimal, containing all the solutions combining a good balance between good energy performance, and an acceptable environmental footprint. Despite the fact that the existing building already has good energy performance, it was possible to improve them by installing triple glazing. Two other factors come into play: airtightness and the thickness of the insulation. In addition, buildings with unfinished attics, and therefore not heated, experience significant energy losses if no insulation is placed on the floor. Therefore, was proposed a solution to overcome this problem. In this sense, the existing building uses the Belgian electricity network for all of its energy needs. By placing photovoltaic panels, the building produces 68.5% of total electricity consumption, which is a great step forward in moving towards nearly-zero energy building. From an environmental point of view, it is recommended the installation of heat pumps because they reduce the total environmental cost, and especially the environmental cost to use. The most strongly reduced indicators are the greenhouse effect and depletion of abiotic resources. Photovoltaic panels also reduce the total environmental cost, but it is clear that there is a sharp increase in

**Table 11**
Global scenarios.

| Parameters | Energy analysis | Life cycle Assessment | | | Monetization of the MMG method |
|---|---|---|---|---|---|
| | Average | Minimum | maximum | Average | Average |
| Initial/Actual | 100% | | | | |
| Scenario 1: triple glazing | −38% | −4.7% (GHG) | +0% (Waste water) | −1.6% | −1.7% |
| Scenario 2: External walls 25 cm wood wool, 3x glazing | −22% | −6.8% (GHG) | −0.2% (Waste water) | −2.5% | −2.5% |
| Scenario 3: Roof 24 cm PIR, 18 cm rock wool Fully furnished attic (+4 people) | −13.3% | +10.4% (GHG) | +19.3% (Waste water) | +15.07% | +15.3% |
| Scenario 4: Photovoltaic panels (112 m²) | +0% | −17.5% (Energy) | +4.6% (Biodiversity) | −4.8% | −4.1% |
| Scenario 5: Heat pump | +0% | −41.6% (GHG) | +2.2% (Waste water) | −9.2% | −8.7% |
| Scenario 6: 50 years of Life cycle | +0% | −36.9% (Waste water) | −33.6% (Photochemical ozone) | −35.1% | −35.3% |
| Scenario7: Occupant's mobility | +0% | +4.1% (Waste water) | +122.3% (Photochemical ozone) | +60.5% | +55.3% |

environmental costs for construction and renovation. A residence with good energy performance and which tends towards nearly zero energy records the lowest environmental damage in terms of eutrophication, biodiversity damage and GHG emissions. Good water management and the development of residential buildings with multi-level are effective strategies to reduce environmental costs. Increasing the built density by adding a level through roof stacking, is ideal from an ecological point of view in almost all the countries of the world.

In a future study, it would be interesting to compare the financial cost of the residence as it is built with the cost of each of the scenarios considered. Thus, it was observed after how many years the supplements invested in construction and renovation, in the case of a Quasi-zero energy or even Net-zero energy building, will be covered by the gains made during the operational phase. This same comparison would be very interesting for a building with a passive label.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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