DIPLOMARBEIT

Integrierte ökologische und ökonomische Bilanzierung der Wärme- und Warmwasserversorgungsysteme in einem Wohnhaus aus Lebenszyklusperspektive

Integrated environmental and economic assessment of heat and warm water supply systems in a residential building from a life cycle Perspective

von

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Objectives

The aim of this Final Thesis is to generate a base of environmental and economic criteria to support the decision on a specific combined thermal energy supply system.
Via the method of Life Cycle Assessment (LCA), the differences between each type of system will be evaluated from an environmental perspective, followed by the economic assessment through the method of Life Cycle Costing (LCC).
With the GaBi software for Life Cycle Engineering, an assessment of the current status of a residential building will be modeled, followed by different scenarios of mixed energy provision. To work with GaBi, the available professional database of components and materials will be used for the modeling of the case study, in order to evaluate the environmental impacts of different heating systems. This will be complemented through the LCC study of each system. To conclude, environmental and economic results will be integrated and analyzed through suggestions on results presentation.

Systematic approach

This study analyses the theoretical background of the methods of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) as well as their applications in the building industry and the integration of both methods.
The method of LCA is applied to the different proposed scenarios of heat and warm water supply systems. The GaBi 5 software for Life Cycle Engineering is used for the LCA modeling.
This study starts with the description of the functional unit and the system boundaries, the detailed description of each system and the data collection of these systems applied in the specific residential building. After developing the Life cycle Inventory, the impacts are calculated and analyzed in the Life Cycle Impact Assessment.
In a next step the economic assessment of each system is done through the method of LCC.
The results of both methods are integrated in order to extract conclusions on both economic and environmental aspects.
This study is part of the 7th Framework Program of the European Commission, namely the CILECCTA project.

Kurzfassung

Die Diplomarbeit „Integrierte ökologische und ökonomische Bilanzierung der Wärme- und Warmwasserversorgungsysteme in einem Wohnhaus aus der Lebenszyklusperspektive“, analysiert die Umwelt- und Wirtschaftsleistung von vier Szenarien der Wärme- und Warmwasserversorgungsysteme mit Hilfe der Durchführung einer Ökobilanz (Life Cycle Assessment) und einer Lebenszykluskostenrechnung (Life Cycle Costing).

Die Studie, die ganz speziell das Wohnhaus der Angestellten des Robinson Club Cala Serena in Mallorca, Spanien untersucht, erfolgt im Rahmen des CILECCTA Projekts, welches ökologische und ökonomische Bewertungen verbindet, um ein Instrument zur Lebenskostenanalyse (Life Cycle Cost Analysis) zu entwickeln.

Die Grenzen der Ökobilanz und der Lebenszykluskostenrechnung umfassen die Abschnitte Herstellung, Nutzung und End-of-Life über einen Zeitraum von 40 Jahren.
Die funktionelle Einheit ist der thermische Energiebedarf des Gebäudes in einem Jahr, der 100.000 kWh entspricht. Die untersuchten Szenarien sind eine Biomassenheizungsanlage (Szenario 1, Ist-Zustand des Gebäudes), eine Solaranlage mit Gas-Brennwertkessel (Szenario 2), eine Wärmepumpe im Szenario 3 mit Biomasseanlage und Szenario 4 mit Solaranlage.

Technische Daten und Kostendaten des aktuellen Zustands des Gebäudes werden durch die Robinson Club GmbH [63] zur Verfügung gestellt. Mit den verfügbaren Daten wurden Abmessungen und technische Voraussetzungen der installierten Geräte für die drei anderen Szenarien berechnet.
Für die Umweltauswirkungen der vier Szenarien wurde eine Ökobilanz durchgeführt und mit Hilfe der Software GaBi 5 modelliert. Die ökologischen Datensätze der Bauteile in den Lebenszyklusphasen wurden aus der Ökobau.dat-Datenbank [7] zusammengestellt.
Die ökonomische Betrachtung wird mithilfe einer Lebenszykluskostenrechnung durchgeführt. Die Kosten werden in Installation, Betrieb und Abbau unterteilt und während der Studiendauer angewendet. Kostenangaben wurden bei Herstellern, Zulieferern und aus technischen Katalogen gesammelt.

Die Ergebnisse aus der Sachbilanz wurden nach der jeweiligen Umweltauswirkung kategorisiert und zugeordnet. Ausgewählt wurden sechs verschiedene Wirkungskategorien, zwei Energieindikatoren und ein Wirtschaftsindikator.

Auf die Auswertung der Sachbilanzergebnisse ist der starke Einfluss der Betriebsphase der Geräte angezeigt. Szenario 2 verursacht die größten Umweltauswirkungen aufgrund der Verbrennung von Erdgas.
Die Verbrennung von Pellets und die Anforderung von Strom wirkt sich stark auf die Kosten aus. Daher ist Szenario 3 am teuersten.
Diese Ergebnisse werden auf der Fallstudie unterzogen. Die Energieeffizienz des Gebäudes wird nicht auf die Auswahl und Dimensionierung der Bauteile berücksichtigt. Die Betriebsphase einer Heizungsanlage ist mit der Brennstoff-Quelle verbunden, die der Primärenergiebedarf durch einen Primärenergiefaktor beeinflusst, und auch von der Fallstudie abhängt.

Bei der integrierten Bewertung werden die verschiedenen Wirkungen, die in dieser Studie analysiert wurden, in einer Lebenszykluskostenanalyse vereinigt. Dafür werden zwei Methoden vorgeschlagen:
Bei der ersten Variante werden die Ergebnisse der Umweltwirkungskategorien durch Normierung und Gewichtung in einen einzelnen Wirkungsfaktor zusammengefasst und mit den Gesamtkosten in einer zweidimensionalen Grafik verglichen, dem sogenannten Eco-Portfolio.
Bei Variante zwei wird ein Ranking entwickelt. Die Ergebnisse dieses Rankings werden als Entscheidungskriterium eingeführt.

Die vorgeschlagenen Methoden der Ergebnisdarstellung bieten eine Grundlage für weitere Anwendungen im Bereich der LCCA und das CILECCTA Tool.

Abstract

This Diploma thesis, under the title “Integrated environmental and economic assessment of heat and warm water supply systems in a residential building from a Life Cycle Perspective”, analyses the environmental and economic performance of four scenarios of heat and warm water supply systems through the conduction of a Life Cycle Assessment and a Life Cycle Costing.

The study is carried out within the specific case of the employee’s house of the Mediterranean resort Robinson Club Cala Serena; located in Mallorca, Spain, in the context of the CILECCTA project, which aims to create a tool for Life Cycle Cost Analysis (LCCA), bringing together LCA and LCC.

LCA and LCC system boundaries include production, use and end-of-life stage of the heating systems in a study period of 40 years. Scenarios studied are a biomass heating system (scenario 1, current status of the building), solar thermal heating system combined with a natural gas condensing boiler (scenario 2), water-water heat pump combined with a biomass heating system (scenario 3) and with a solar thermal heating system (scenario 4).

Technical and economic data related to the current status of the building is provided by Robinson Club GmbH [68]. With the data available, dimensions and technical requirements of the devices installed in the other three scenarios are calculated.
The LCA is carried out through the modeling of the scenarios with the software GaBi 5 [63]. Environmental profiles of the components in the life cycle stages are compiled in the professional Ökobau.dat database [7].
Cost performance is conducted through an LCC. Costs are divided into installation, operation and dismantling and applied over the study period. Data is compiled among manufacturers, suppliers and technical catalogs.

Inventory data is classified and assigned to six the environmental categories, two energy indicators, and one economic indicator.
The evaluation of the environmental impacts shows the strong influence of the operation stage of the devices. Scenario 2 has the highest environmental impact share due to the combustion of natural gas. Scenario 3 results to be the most expensive, because of the steady requirement of pellets and electricity.

These results are subjected to the case study. The energy efficiency of the building is not considered on the selection and dimensioning of the components. The operation stage of a heating system is strongly related to the fuel source, which influences on the primary energy demand through a primary energy factor which also depends on the case study.

On the integrated assessment the two impact dimensions analyzed in this study, environmental and economic, are brought up together in a Life Cycle Cost Analysis through two suggested alternatives.

In the first alternative, results of the environmental impact categories are gathered through normalization and weighting criteria in an environmental impact factor and compared directly to the total cost in a two-dimensional graph, a so-called eco-portfolio.

In the second alternative, a decision-making criteria is established, based on the creation of a ranking.

These suggested methods of result presentation offer a first basis for further research about LCCA, which becomes a next step in sustainability assessments and which will be strongly improved by the CILECCTA tool.

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Abbreviations and symbols directory

ADP	Abiotic Depletion Potential
AP	Acidification Potential
CILECCTA	Construction Industry Life Cycle Cost Analysis
CO_2	Carbon Dioxide
CFC´s	Chlorofluorocarbons
DIN	Deutsche Institut für Normung
E	Electricity (kWe)
EP	Eutrophication Potential
GaBi	Ganzheitliche Bilanzierung (Integrated Assessment)
GBP	Gross domestic product
GWP	Global Warming Potential
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
Hd	Heat demand (kWh)
HHV	Higher Heating Value
ISO	International Organization for Standardization
kWh	Kilowatt hour
kW	Kilowatt
kWe	Kilowatt electricity
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCCA	Life Cycle Costing Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
NPV	Net Present Value
NOx	Nitrogen Oxide
ODP	Ozone Depletion Potential
P	Power (kW)
PE ren	Primary Energy demand from renewable resources
PE non-ren	Primary Energy demand from non-renewable resources
POCP	Photochemical Smog
PP	Polypropylene
VOC´s	Volatile Organic Compounds

1 Introduction

In the late 90´s, the building industry grew fast in most European countries. For more than ten years, the property market started to suffer abnormal price rises encouraged by speculation and excess of credit from the banks.

The construction, use and demolition of buildings provide on average 5 to 10 % of employment at the national level and normally generate 5 to 15 % of the GDP [70].

The situation in Spain exceeded the averages as far as the employment in the construction sector rose from 9,4 % in 1995 to 14 % in 2007 and the GDP from 6, 9 % to 11 % respectively [35].

The importance of this sector is not only limited to the increase of the production or the employment creation, but also means the expansion of many industry areas involved as suppliers [35]. For example, more than 50 % of all materials extracted from earth are transformed into construction materials and products [30].

Although being a positive contribution to a nation´s economy, the construction, use and demolition of buildings may also have serious negative impacts, in particular on the environment. Buildings account for the 40 % of the energy consumption in Europe [28], 44 % of the total material use [1] and produce about 35 % of all greenhouse emissions [30]. They are responsible for a large share of water use and waste generation. About 30 % of the energy used on their production, installation, use and management is induced on the environment [53].

Due to the current increase in social and political concern about environmental protection and the increasing research into new manufacturing technologies and new materials looking for sustainability, the sector is being transformed in order to address environmental and social issues [70].

Consequently, Life Cycle Assessment and Life Cycle Costing methods have become tools which are used to support the decision making regarding to environmental and cost issues.

In response to these demands, the European Commission, under the 7th Framework Program, supports the development of a suite of software under the name of CILECCTA (Construction Industry Life Cycle Cost Analysis) which will be a step forward on the application of both LCC and LCA methods. It will be capable of integrated Life Cycle Cost Analysis (LCCA), compatible with codified Price Banks (PBs) and Life Cycle Inventory Results (LCIRs) databases [9].

Among the members of the project, Universität Stuttgart, Chair for Building Physics, together with the German group TUI AG, will be in charge of the development of protocols for the implementation of CILECCTA software, and will evaluate the qualitative and quantitative performance criteria for the CILECCTA project. This study will be conducted on one of the TUI´s Mediterranean hotels, Robinson Club Cala Serena (Robinson Club GmbH) in Mallorca, Spain.

This demonstration model carried out under the framework of CILECCTA will be an assessment of different scenarios of mixed thermal energy provision within the specific case of the employee’s house of the Mediterranean resort Robinson Club Cala Serena.

Warm water accounts about the 65 % of the total domestic energy consumption in Spain (20 % for domestic hot water). However, only 1 % of the Spanish homes have solar energy collectors installed and only 6,7 % use wood as energy source, whereas 40,5 % use Natural gas and 100 % use electrical power in greater or lesser extent [42], [51]. Energy from biomass plays currently a minor role on the heat supply.

Nevertheless, these technologies have observed particularly high growth rates in Europe in recent years due to the significantly increasing prices of fossil fuels, the increasing research in renewable energy technologies and the political measures to promote the installation of renewable energy devices as, for instance, biomass or solar energy systems.

The combination of biomass and solar collectors as new energies sources with the most common natural gas boilers and heating pumps is a practical example of different combinations of energy supply possibilities. The scenarios under assessment have been chosen by taking different sources of renewable energy as the main point, using the technical boundaries of the building under assessment.

2 Background

2.1 The method of Life Cycle Assessment

According to the standard DIN EN ISO 14044:2006, an LCA is the “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system through its life cycle” [16][15].

Thus, an LCA is a tool to track all significant environmental aspects and potential impacts, by a standardized procedure and through each phase of the product system. This approach has been named cradle-to-grave. It starts with the extraction of resources and followed by the production of materials, the parts and the product itself, the use of the product and its maintenance and ending by the final disposal, recycling or reuse. The steps of an LCA are defined in DIN EN ISO 14040 and DIN EN ISO 14044. With an iterative nature, it is divided into the goal and scope definition, inventory analysis, impact assessment and the evaluation and interpretation of results (see Figure 2-1).

LCA applications can be classified into external or internal. Internal applications involve decisions regarding to the improvement of the environmental performance of a product, for instance, the materials used; or to the detection of problems in one of the phases of its life cycle. External applications are aimed to assess in strategic measures around a product system such as identifying opportunities to enhance the environment, identifying business opportunities, marketing strategies or political measures.

Among the main internal applications of LCA, the goal of the LCA developed in this study is to compare several systems, which specify the implementation of the LCA, always under the application of the ISO standards [15] [40][56].

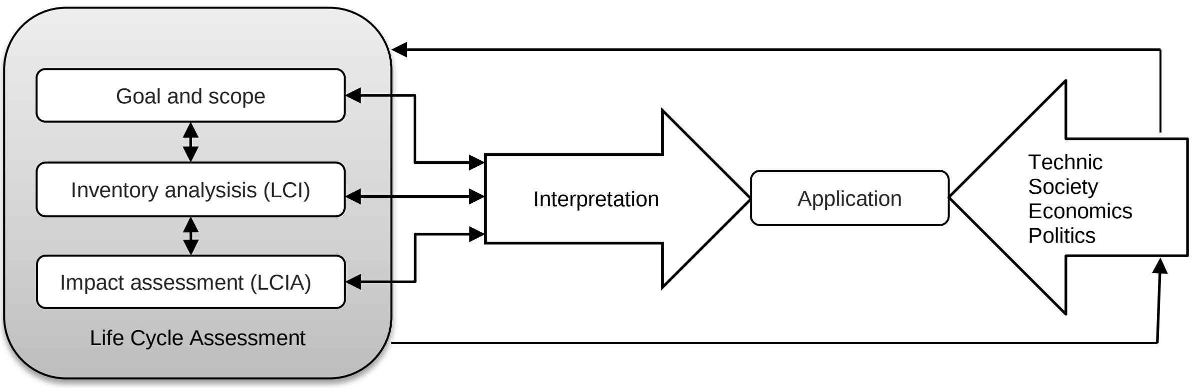

Figure 2-1: Steps and boundaries of an LCA [42]

2.2 The method of Life Cycle Costing

Life Cycle Costing is a technique to estimate the total costs occurring during the life cycle of a product, namely the total cost of ownership (TCO). It allows comparative cost assessments to be made over a specific period of time, taking into account relevant economic factors both in terms of initial capital costs and future operational costs [29].

From the perspective of a company, the classic product life cycle is based on the route of a system within the market over time, namely the market life cycle. The scope of this analysis can be either a single product or a group of products, and it is focused on the sales volume. The cycle is divided in five phases (see Figure 2-2). It starts on the introduction of the product in the market, going on the growth period which means the raise of sales due to the newness of the product and its expansion in the market (maturity), and finally the decline, ending in an exit of the product from the market [43].

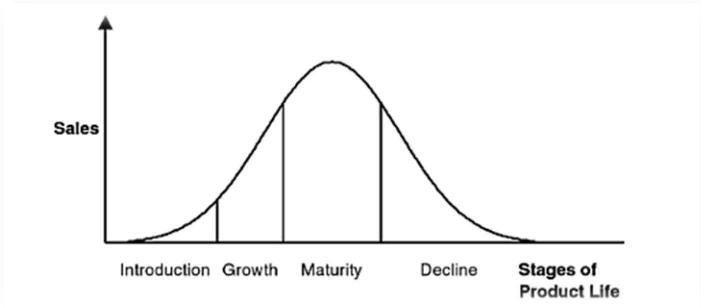

Figure 2-2: Market Life cycle [24]

Besides, the product LCC focuses on the costs of each stage of the product life cycle, being able to identify saving and benefits in the whole cradle-to-grave (including acquisition of materials, production, operation, maintenance, replacement and disposal), (see Figure 2-3). It allows comparisons of cost among different investment scenarios, designs and specifications.

Nevertheless, the application of LCC is still limited. The ISO/DIS 15686-5 gives guidelines for performing LCC analyses of buildings and constructed assets, but it is still a draft. Different sources of information are required in LCC and thus, the analysis process becomes complicated [13].

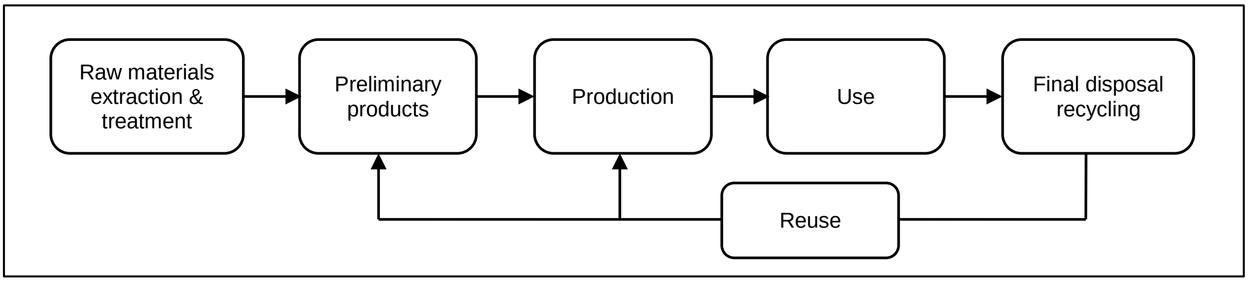

Figure 2-3: Product life cycle [40]

The approach is the calculation of the costs of each stage of the value chain, which goes from the production costs of preliminary products to the final product, use costs and disposal discounts, etc. The classic life cycle of a product in the market becomes, hence, part of the product LCC as gate-to-gate analysis. It calculates the total cost of each component involved on the life cycle of the product under study.

2.3 Life Cycle thinking in the building industry

Thinking from a life cycle perspective allows the application of improvement measures in a product in any point of its life cycle so that they don´t involve a negative impact in any other stages [31].
Buildings form complex and dynamic structures, since they have longer lifetimes as most other products and they can change in design and function during their lifespan. Hence, the application of LCA in constructions has become a specific area in LCA practice [1].
Conducting LCA presented also many problems, such as lack of adequate data for the building, lack of a working methodology and management of the data or the importance of the energy in the use stage. This and other factors ended in the creation of sustainability evaluation schemes, such as the “Deutschen Gütesiegels für Nachhaltiges Bauen (DGNB)”, from July 2007, which was the first international certification system that integrated together environmental and life cycle costing assessments for buildings [53].
Moreover, international norms have been developed. Examples are the ISO 21931-1 “Sustainability in building construction-Framework for methods of assessment for environmental performance of construction works” [52] and the equivalent European prEN 15978 of “Sustainability of construction works - Assessment of the environmental performance of buildings” [65].

Regarding to LCC, the European norm EN15459 [25], Energy performance of buildings-Economic evaluation procedure for energy systems in buildings, November 2007, provides a guide to calculate the feasibility of energy conservation options in buildings and compare different options of energy supply in buildings.
The assessment of a building can be done from two different points of view:
The starting-point of the study can be either the reduction of some significant environmental aspect of the whole building (top down) or the improvement or selection of a component or material of the building (bottom up). This study is a bottom up analysis, since some specific components of the building (i.e. heating and warm water) are going to be studied regarding LCA and LCC in order to find the less pollutant and feasible option for the whole building [1].

2.4 Life Cycle Cost Analysis

Now that sustainability has become a significant factor in decision making, the growing number of LCA and LCC studies shows the necessity of bringing both tools together. Comparing alternatives, the choice will not only be based on the less pollutant option, but also on the most economical over the long term [34].
Even so, both LCC and LCA present two main points that must be clearly defined in order to obtain reasonable and believable results: The scope and the comparable units.
Hence, to develop an LCCA methodology which integrates both costs and environmental impacts of systems and allows their comparison, certain requirements must be met. The following table shows the differences between the scope definition of LCC and LCA:

Table 2-1: Stages included in an LCC and in an LCA [34]

	Planning and design	**Production**	**Transports**	**Construction**	**Use Phase**	**Deconstr. and Disp.**	**Discounting**
LCC (costs)	Included	Included on the final production cost	Included on the production cost	Included	Included	Included	Possible
LCA (environment)	insignificant	upstream Itemized	Itemized	Included (manpower excluded)	Included	Included	Not possible

To integrate both assessments in an LCCA, the study period has to be defined and be equal for both and the scopes equally demarcated. Although the costs can be relevant, environmental impacts in planning and design phase are irrelevant in LCA, so the scope of the LCCA will include the environmental impacts on this stage optionally, depending on the availability of the data. In an LCC, the costs of production are summarized on the material prices. On the contrary, in an LCA, production impacts are itemized in raw materials extraction, process of the preliminary products, transport, etc. Therefore, the scope of the LCC has to be modified in order to distinguish the costs of each flow in this phase. Manpower involved on the life cycle is, of course, considered in an LCC, but not in the LCA as their waste production or emissions are usually excluded [64]. Use and maintenance scope does not present any difference between the two assessments. Deconstruction and EoL are included in both approaches.

Discounting is applied for economic factors, but not in LCA.

Once the scope and the boundaries are fixed and the LCCA is conducted, the results are expressed in environmental and economic units. In order to analyze the obtained values and do the comparison, it is necessary to find a suitable tool which permits their combination, for example, an environmental LCC portfolio [43] or eco-portfolio [34] (see Figure 2-4).

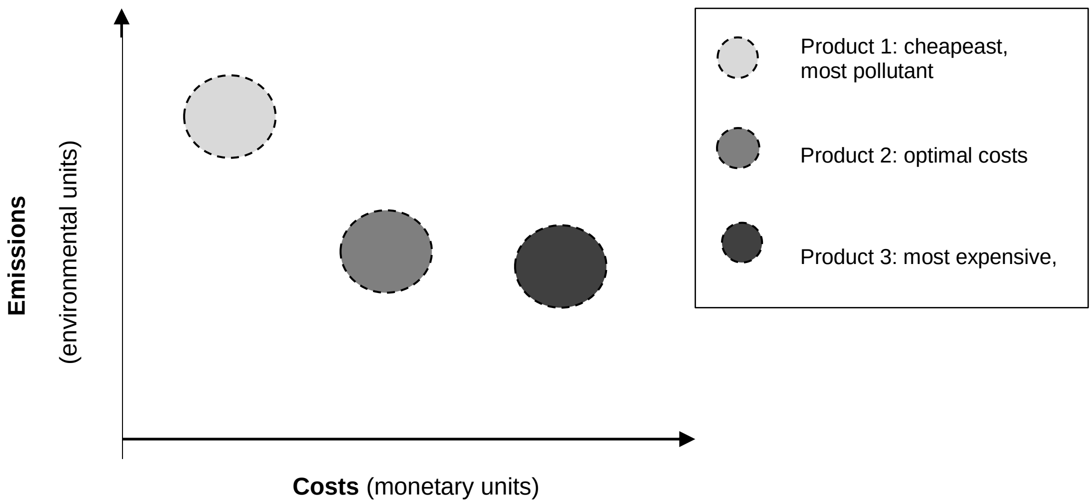

Figure 2-4: Example of an eco-portfolio [43] [34]

3 Description of the Heating systems

In this chapter, the heating systems studied are described in order to derive background information required to conduct both LCC and LCA.
As a starting point the current status of the building under study, a biomass heating system is described.
For the scenarios, a solar thermal heating system and a water-water heat pump are selected. As a support system a natural gas condensing boiler is chosen, which although it is a fossil fuel boiler, it is characterized by its high efficiency.
These four different devices are combined into four different scenarios, which are modeled and evaluated through LCA and LCC methodologies.

3.1 Biomass heating system

In general terms, a biomass boiler facility is considered in the field of renewable or green energy. It uses renewable materials as fuel, usually wood pellets or wood Chips.
The stored fuel is transported to a burner where the air is combusted. Then, the air is used to heat water which, in turn, drives the boiler. The combustion gases are expelled through a chimney, and the ashes to disposal equipment. The hot water is transported to the destination through Pipes. Biomass boilers have a high wear resistance, long life and between 75 % and 90 % energy efficiency [47].
Their characteristics are described in the following paragraphs.

3.1.1 Components

<u>Fuel</u>
For a domestic biomass heating system; wood pellets or wood chips are the proper fuel. Their physical, environmental and energetic characteristics and requirements have been documented and standardized by different organizations from different countries. Wood pellets with the DINplus [20] mark meet the requirements of the European Standard DIN EN 14961-2 [18][69].

Wood pellets are small cylinders of compressed sawdust that come from wood chips and dry sawdust. These cylinders are formed without any additives, through high pressure using a matrix with low humidity conditions of the wood, since the lignin of the wood works as a natural agglomerating agent [41]. Wood chips are mostly straight.

They are processed in a sawmill. They typically come from wood or branches that cannot be used for higher-value products [41].
Although during the production and transport processes of pellets are released several pollutants, pellets have a neutral balance of CO_2 in their combustion, since the amount of CO_2 emissions due to combustion is the same as the CO_2 absorbed by the tree during its growth. This contributes to the reduction of greenhouse gases and acid rain [44].
The table below (Table 3-1) shows the main differences between the two main sources, according to DINplus certification [20].

Table 3-1: Main properties of Wood Chips and Wood pellets

	LHV	Moisture	Ashes	Density
Pellet	17,5-19,5 MJ/kg	<12 %	<1,5 %	650 kg/m³
Wood Chip	6,6-13,9 MJ/kg	20-55 %	1-2 %	250 kg/m³

It is observed that, in terms of combustion efficiency, it is better to use Pellets instead of Wood Chips, since 1m³ of pellets burn as much as 4m³ of wood chip.

Fuel Storage facility

Depending on the amount of pellet, it can be chosen among bunkers or silos. The ideal storage system will depend on the building preconditions and the costumer desires [57]. The advantages of the silo versus a bunker are, among others, that they are prefabricated, whereas bunkers must be constructed. They have more moisture protection and produce less dust while the storage. Moreover, they are not subjected to local regulations for housing construction [57].

Bunkers or below-ground silos have to comply with several requirements: They need to obey local fire-protection regulations, they need sloped floor to help pellets to sly continuously towards the conveyor system, the door should be designed in order to prevent electrostatic charge and the room dry, insulated and sealed against dust to maintain the optimal conditions of the pellet [57]. In the building under study a bunker is chosen, since all the heat demand is provided by a biomass heating system and a continuous and regular pellet supply over the year is required. It consists of a chamber inside the wall in the heating room, made of reinforced concrete.

Combustion appliance

Wood pellet boilers are automatic combustion devices, the pellets are directly transformed to heat and ashes as outputs without any intermediate step that requires handwork. The following Figure 3-1shows its parts, explained below.

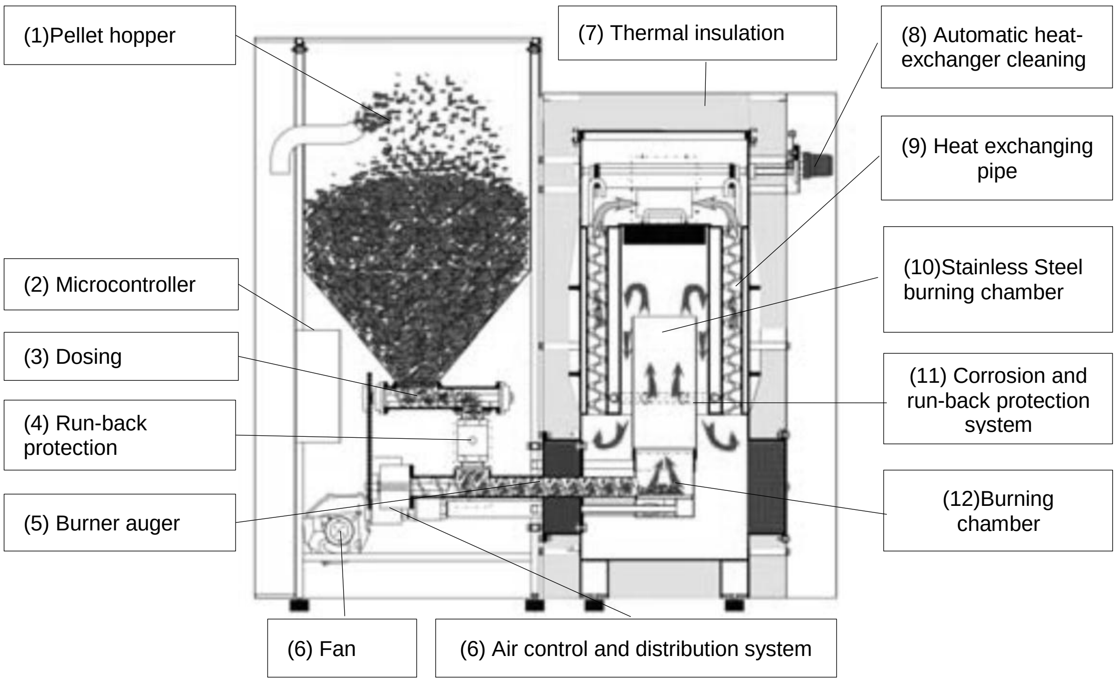

Figure 3-1: Example of a biomass heating device [33]

Through the feed pipe, the fuel comes into the pellet hopper (1).

With the microcontroller (2) the desired output is decided, so that the necessary pellets are put into the combustion chamber throw the dosing, which can be even a screw conveyor or an induced draft fan (3).

The security valve (4)(11) avoids the entry of excel fuel as well as stops the installation if there is any problem in another chamber, such as burning of the fuel before the burning chamber. The fan (6) handles the continuously cooling of the circuit and removes the air.

The combustion process consists of three phases: The drying phase, the pyrolysis and the final combustion. During the drying, the remaining water of the pellets is released and evaporated. Then the primary combustion takes places with deficient air supply, namely pyrolysis (12). Finally, the secondary combustion takes place with excess air (10). In the steady-state, both combustions take place at the same time.

Combustion air supply is either natural or forced. Air supply is controlled by a thermostat (Lambda probe) in response to energy demand, adjusting the combustion to the used fuel (2).
Combustors have grates made of cast iron or refractory which support the fire bed. They have holes that allow the under-fire air to be blown up through the fire bed.
Once the combustion is finished, the hot gas moves to the heat exchanger (9), a tube in which turbulences are made in order to promote a good exchange with the water.
A regular cleaner is designed to avoid the ash inlay on the walls of the chamber. Usually the cleaner consists on swinging the grate [59].
Exhaust gases pass through a short flue to an insulated steel chamber, where can be recovered**.** An electric pump moves the heated water through insulated pipes to the load [59].

Exhaust gas system

Combustion gases must be evacuated from the system. It is important to design the chimney to ensure that the gas is thrown out the boiler in one of three ways: natural, induced draft or forced draft. In a natural draft system, warm air moving out of the stack creates negative pressure in the stack which moves the gas up the stack. An induced draft system uses a big blower located up the stack which sucks the exhaust gases out of the boiler and forces them up. The draft of this fan is regulated in relation of the combustion air. Forced-draft fans create a positive pressure on the burning chamber, forcing the combustion gases through the heat exchanger and up the stack [59]. This last case corresponds to the current biomass boiler installed in the building under study.
Stacks are usually constructed of steel or stainless steel and are insulated to avoid the condensation of the water vapor contained on the gases inside them. The height and dimensions of the chimney must adjust to local building [59]. Dimensions of the exhaust tube are specified DIN 18160-1:2006 [19].

3.1.2 Environmental considerations

In spite of being favorable for the environment, the combustion of biomass pellets emits different gases, that must be taken into account and that are legally restricted. The concentration of those gases depends on the used wood and its characteristics, as well as on the combustion device and combustion efficiency [44].
The flue gases from the combustion of biomass are composed primarily of CO_2 which is neutral cycle, and steam. The presence of nitrogen compounds, sulfur or chlorine is

very low. However, the presence of particles or dust is significant, in spite of being easy controllable controlling the combustion. There is small risk of emitting CO due to bad combustions [44].
In the Annex 1 are listed the permitted atmospheric emission limits of Spain according to Spanish laws, where is placed the building under study [66][67][23].

3.2 Solar Heating System

The premise of solar heating systems is to take advantage of sunlight energy in order to transform it into heat. They are also called Active Solar systems. Active Solar Heating Systems are classified in systems of low, medium and high temperature [27].
To produce Domestic heated water and space heating in a building, a Low temperature system is used, which can be distinguished between open or closed loop systems.
The difference between them is the use of a heat exchanger between the fluid warmed by the solar collectors and the domestic water (see Figure 3-2).
The solar collector surface absorbs the sun rays which warm the solar liquid or transport medium that circulates through the primary circuit. The heated fluid is transported through pipes to the hot water store, where the heat is exchanged with the cold domestic or heating water which flows through a secondary circuit. The cooled liquid is thereafter pumped back to the solar collector, and the warmed water rises up the storage tank, ready to use (see Figure 3-2) [38] [61] [55].

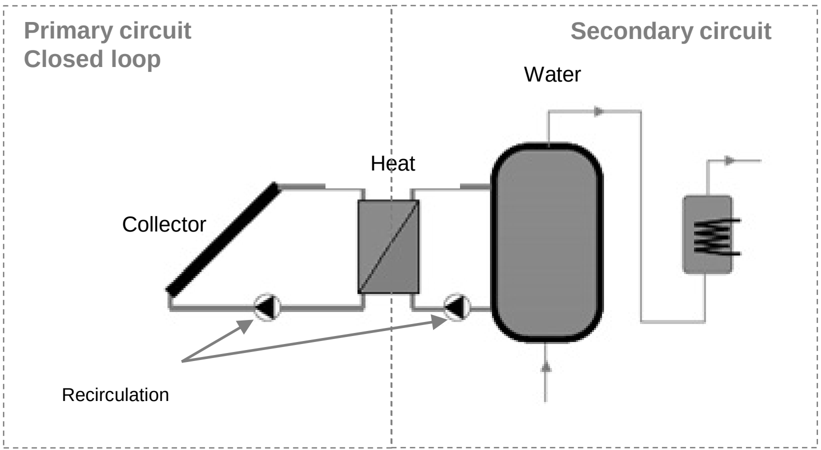

Figure 3-2: Process diagram of a closed-loop solar water heating system.

3.2.1 Components

<u>Glazed flat-plate collectors</u>

Solar collectors are heat exchangers between solar radiation and a working fluid [27]. There are many different types and designs of solar collectors, depending on the application. For domestic water heating and space heating, the most common are the glazed flat-plate collectors and the vacuum flat-plate collectors [38]. However, in this study glazed flat-plate collectors, which present a better relation price-efficiency, are installed.

Its operation is based on the principle of the Greenhouse effect [27]. Solar radiation enters the collector through the transparent cover above the glass and reaches the absorber, thus heating the working fluid that flows through the pipes [73].

As shown in Figure 3-3, several losses occur on the operation of the collectors. They are distinguished between optical and thermal losses. Optical losses take place by reflection of the radiation on the glass transparent cover and on the paint coat of the absorber [73]. They grow with increasing angles of the incident sunlight [38].

Most glass-layers have an absorption rate of approximately 92 % and a reflection around 8 % of the radiation [38].

Thermal losses are mainly caused by convection. The circulating air between the absorber and the cover transports the absorbed heat to the glazing. After heat conduction through the cover there is again convective loss because of the air that flows around the collector [73].

There can be also infrared radiation from the absorber to the cover, and thermal losses on the insulation of the backside [73].

The efficiency of a collector is defined as the ratio of usable thermal power to the irradiated solar energy flux, considering all the different losses, and it is around the 15 % [38].

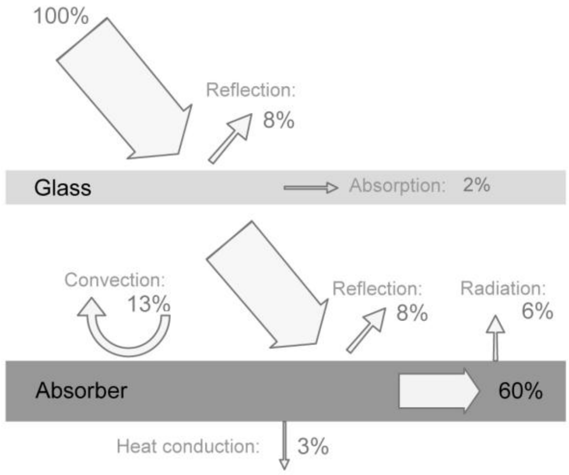

Figure 3-3: Operating principle of a glazed flat-plate collector [73]

<u>Working fluids</u>

The antifreeze solutions used as working fluids must obey the current legislation, in this case the Spanish UNE-EN 12976-2. [71] [48].

It is important to prevent possible damages of the antifreeze due to high temperatures and to assure the homogeneity of the mixture of the antifreeze, the water and the corrosion protectors [48].

<u>Buffer tank</u>

Solar thermal facilities require unconditional a storage tank, because the solar radiation is not controllable. In chapter 3.5 the tanks used in this study are explained.

To properly size a tank connected to a solar installation, it is important to consider not only the water demand but also the solar collector area.

3.2.2 Environmental considerations

Solar energy is a free and inexhaustible energy source, more environmentally friendly than conventional energy. These facilities do not harm air or soil quality. They also do not cause noise or affect to the hydrology.

They also contribute to the reduction of the CO_2 emissions as they replace fuels.

The hardest impact relies on the production of the components required due to the complexity of materials and processes.

3.3 Heat pump

Heat pump systems are identified as reverse cycle refrigeration systems, because they can provide heating and cooling. If the operation of a refrigerator is reversed, it is obtained a heat pump. The operating principle is to extract heat from a low-temperature source and release it to a higher-temperature source. Heat pumps are classified according to the heat source and the thermodynamic cycle they use. In this study the system installed is a water-to-water heat pump with a vapor-compression cycle driven by an electrical compressor in order to connect it to an underfloor heating system [22].

To measure the heat pump efficiency is commonly used the Coefficient of Performance (COP), which is the ratio of the heat delivered and the electrical energy supplied to the compressor. This efficiency is related to the gradient of temperature, which is the difference between the low-temperature and the higher-temperature source. Electrical compression heat pumps have usually a COP range between 2.5 and 5.0. The typical COP for a water-to-water heat pump with floor heating distribution system is 4.0, with a heat-source temperature of 5°C and heating temperature between 30-35 °C; which means that it delivers 4 times more thermal energy than the electricity required [50].

3.3.1 Water-to-water heat pump

In these types of heat pumps, water for both heat source and heat-releasing is used.

They are also called ground-source or geothermal heat pumps, as they obtain the water from the ground relying on the fact that the underground temperature has a low variation over time. The underground systems are connected to the heating system, and are classified generally as opened or closed systems. In closed systems the heat exchangers are located in the underground, and a heat medium flows within them, transporting heat from the ground to the heat pump in a closed circuit.

In opened systems the heat source is the ground water, and it is brought directly to the heat pump [62].

Since this case study takes place in Illes Balears, which has groundwater available, can properly work with an open system (see Figure 3-4).

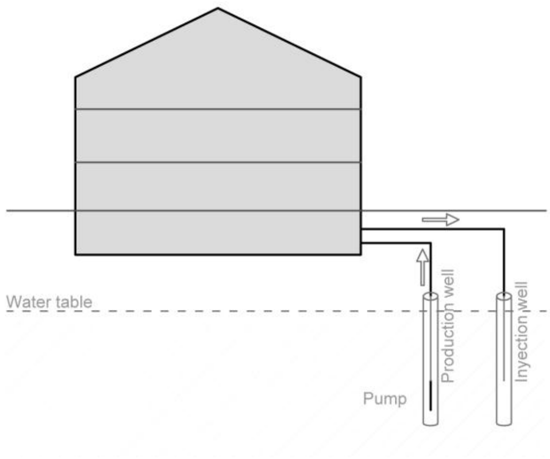

Figure 3-4: water-to-water heating pump with Open-loop underground system [62]

3.3.2 Vapor-compression cycle

The most common operating mechanism in a heating pump is the vapor-compression cycle, shown in Figure 3-5. It is formed by four main components: two heat exchangers, namely the evaporator and the condenser, the mechanical compressor and the expansion valve. These components are connected in a closed circuit, through which circulates the working fluid. The system operates thanks to an electrical motor that drives the compressor [50].

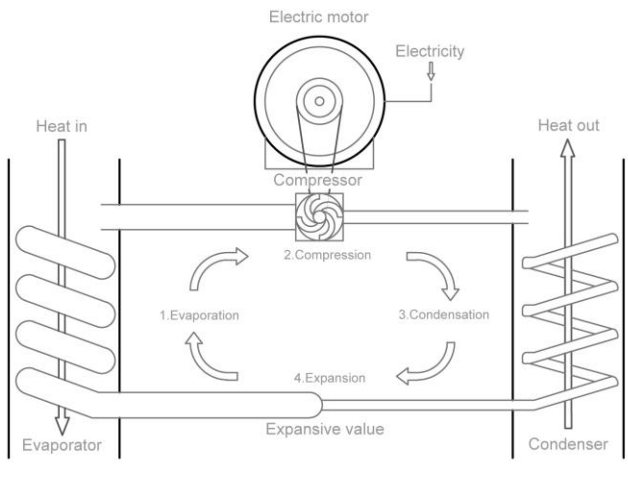

Figure 3-5: Heating pump vapor-compression cycle [50]

Underground water, which has higher temperature with higher temperature than the working fluid, is pumped into the evaporator causing the first heat flow from the water to the working liquid, and the liquid evaporates. This vapor is compressed thanks to an electric motor, and its pressure and temperature increases. As the compressed vapor enters the condenser, it releases the useful heat to the water which will be transported to heat load point. To close the circuit, the high pressure working fluid is expanded to the evaporator conditions. [50]

Working fluids

Traditionally, the most common working fluids for heat pumps have been the Chlorofluorocarbons (CFCs), but they are prohibited due to their high Ozone Depletion Potential (ODP) and Global Warming Potential (GWP). The alternative of the hydrochlorofluorocarbons (HCFCs) working fluids was neither successful. Although their environmental damage is lower than the CFCs, it is also significant. Therefore, the European Union has adopted an accelerated phase-out schedule for these substances [50].

The solution then lies on the chlorine-free hydrofluorocarbons (HFCs), which do not contribute to the ODP, although they do to the GWP. The most known is the R-134a.

Other options are the blends or mixtures made of HFC and hydrocarbons (e.g. propane); and natural working fluids, which would be the less environmental harmful option, such as water or CO_2, but that are not yet as efficient as the named above [50].

3.3.3 Underfloor heating

In this study, the water heated by the heat pump will be circulated throughout the building with an underfloor heating installation.

The basic principle of this method consists of circulating medium-temperature water through a closed piping circuit located under the floor of the rooms to be heated. The floor structure is heated and, in turn, the floor surface becomes the heat emitter and transfers heat upwards to warm the room or space by convection and radiation. With a thermal insulation coating the heat transfer downwards is avoided [72], [54].

Constructions of underfloor heating are distinguished in wet and dry systems.

In the wet system, the pipes are placed in the floor screed before it dries, above the concrete floor. Therefore, this type of construction is recommended for new construction buildings, since it is necessary to build or rebuild the complete surface.

The construction assumed in this study is the dry system, where a prefabricated structure is installed above the screed. This structure consists of a rigid foam board with grooves where the heating pipes are placed (see Figure 3-6).

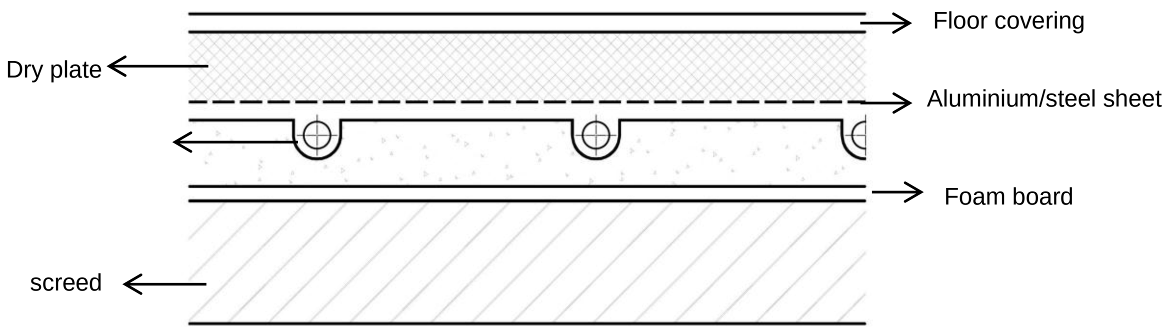

Figure 3-6: Transversal section of underfloor heating installation [54]

Between the screed floor, usually made of concrete, and the foam board it is important to glue an insulation coat of Polyurethane or Polystyrene, to avoid the heat transfer under wards. It insulates thermally and acoustically the installation and works as support and guide of the tube.

To improve the heat distribution, aluminum or steel sheets are laid above the heat pipes.

The dry plates are glued to guarantee a fast heat transmission without bringing additional moisture into the building.

Floor coverings are made from natural or artificial stone, tile or brick material. Carpets on stone floors act as a brake heat, which increases the storage capacity of the floor design and produce a very uniform temperature distribution in the floor surface. The pipes can be laid in two ways, in serpentine or in spiral (See Figure 3-7).

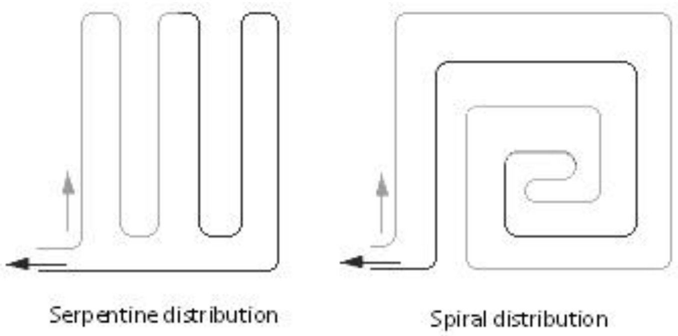

Figure 3-7: Distributions of the heating pipe coil for underfloor heating

In the serpentine installation occur certain temperature differences at the floor surface. The temperature distribution is better when the forward and return pipes are laid side by side in opposite arrangement, as in the spiral installation. It is also possible to mix both forms, called double serpentine.
In the border areas of the windows it is recommended to reduce the spacing between pipes in order to achieve the necessary heat output.
The endpoints of the pipe coils are all connected in a distribution box, usually in the stokehold or in a cabinet. Since it is a closed circuit, the endpoints have to be distinguished in inlet and outlet collectors.
There will be as many pairs of collectors as circuits for the heated rooms installed.

For underfloor heating the pipe materials have been mainly limited to three, namely polybutylene, cross-linked polyethylene (PEX) and polypropylene (PP). These are resistant to corrosion or attack from cement floor screeds, suitable for the water temperatures involved, and commercial available in long coils that can be laid without any intermediate pipe joints within the floor screed. They can also be bent to a reasonable bending radius of 200 mm.
In this study PEX pipes have been chosen [54] [72].
Underfloor heating is classified as low-temperature heating, so it is particularly suitable for systems that use solar thermal energy and heat pumps.

3.3.4 Environmental considerations

Geothermal heat pumps provide a new and clean way of heating buildings, as they use renewable sources as fuel. This technology is based on the fact that the underground has a relatively constant temperature, warmer than the air in winter and cooler than the air in summer.
The application of ground-source heat pumps is increasing because of their potential to reduce primary energy consumption and, in turn, reduce emissions of greenhouse gases. However, it is essential to control the quantity and quality of the underground water to protect the pump on its operation. Environmental impacts rely, thus, on the electricity required to power the pumps and on the potential of environmental damage that has the working fuel [50].

3.4 Natural Gas Boiler

There are different types of fossil fuel boilers, depending on the method of operation, the fuel, the efficiency or the energy consumption: Standard boilers, low temperature boilers or condensing boilers [49]. Actual state-of-the-art show condensing boilers to be the most efficient. Moreover, since they consume less fuel, they release less Carbon Dioxide in the exhaust gases. For this reason this boiler is selected for this study [49].

Condensing boilers, according to DIN 4702-7 [21], are boilers that recover the waste heat of the flue gases to heat the water entering the boiler. The water vapor produced during combustion contains energy in form of latent heat that is released by condensation [54]. The condensed water from the flue gases is accumulated as long as the boiler is working [5].

Condensing boilers are based on the use of the higher heating value (HHV) of the fuel.

The higher heating value is the quantity of heat released on the combustion considering that the water contained on the fuel condenses completely. On the contrary, the lower heating value (LHV) considers that the water contained on the fuel remains as vapor [5].

To compare different types of heat sources, it is now common practice to relate the efficiency of condensing boilers to the LHV instead of to the HHV.

This principle allows condensing boilers to achieve efficiencies over 100 %. Natural Gas boilers can achieve efficiencies around the 107 % [5].

It is important that the return temperature of the water from the heating system is lower than the dew point of the flue gases, so that the condensation occurs.

The energy savings depend on the type of fuel. For fuel oil the HHV is 6 % greater than the LHV, whereas in natural gas the difference is of 11 %. About between 50 to 80 % of the heat contained in the condensate can be recovered [5][60].

The content of water vapor that can be condensed depends on several factors: The flue gas temperature, the air content on the gases and the relative humidity of the combustion air. These factors determine the quantity of hydrogen contained, which is for the Natural Gas almost twice as for the fuel oil [5]. For this reason, today most of the condensing boilers use Natural Gas as fuel [5].

The optimal efficiency of Natural Gas boilers depends on the return temperature of the water from the heating system, because it determines the amount of water condensed and the final temperature of the exhaust gases [25].

The optimal efficiency is therefore not at full load, but at 30 to 60 %, namely at exhaust temperatures between 0°C and 10°C and accordingly low return temperatures. The condensation of the flue gases from Natural Gas begins at 56°C (dew point), with efficiency around 90 % [25].

The combustion of fossil fuels has an acidity character which involves the risk of corrosion of the device, so the boiler has to be built with suitable materials to prevent corrosion. Moreover, fuel oil contains a significant content of sulfur that has to be removed before condensing [8].

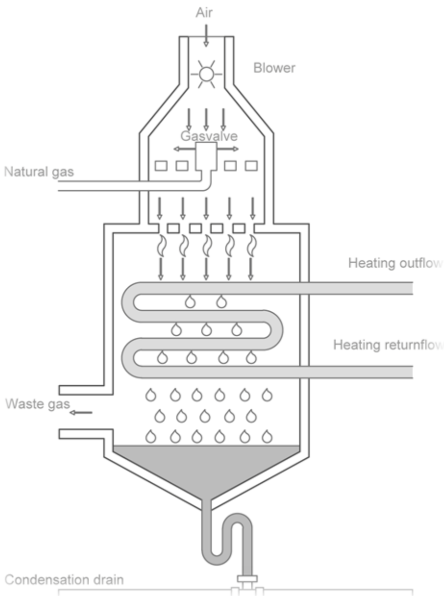

Figure 3-8: Condensing boiler operation [8].

The nowadays boilers with condensation in them consist of an integrated device, with the boiler, the burner; the heat exchanger and the moisture-resistant chimney (See Figure 3-8).

Since the condensation takes place in the same boiler, the devices have to be protected against corrosion. Therefore the exhaust gases tube, the burning chamber and the heat exchanger are usually made of stainless steel. Moreover, the heat-exchanger chamber has smooth surface in order to drain the condensed water easily. Therefore, it is necessary to have a drainage device and a collector for the condensate [5].

In this study, a Natural Gas boiler with the heat exchanger included is used. A gas storage tank is not included, so the fuel is directly supplied by pipes.

3.4.1 Exhaust gas system

Once the condensation is done, the exhaust gases have to be expelled through a chimney. In a condensing boiler, the expulsion requires the help of a fan which produces an

overpressure inside the tube, because the temperature of the gases is too low, so there is not enough pressure to push them out [5].
Although part of the water vapor contained in the flue gases is liquefied, there is still moisture. Therefore the exhaust tube must be enough close to avoid condensation inside, since the gases are cooled to approximately 40°C.
Due to the acidic character of the exhaust gases, chimneys are made of stainless steel (selected for the study), glass, plastic or aluminum [25].
Dimensions of the exhaust tube are specified in DIN 18160-1:2006 [19].

3.4.2 Environmental considerations

Boilers which work with fossil fuels are characterized by the emission of CO_2, which is an important contributor to the greenhouse effect. These carbon dioxide emissions can be reduced by using less fuel and improving the efficiency of the boiler [25].
That is why condensing boilers are nowadays the most favorable with the environment, as they emit 35 % less than conventional boilers [8] thanks to the condensation of the flue gases which involves removing sensible heat [25].
Since the combustion of fossil fuels has an acidic character, the condensed water presents an acidic PH-Value, which in case of Natural Gas is between 3,5 and 5,5. If the nominal output of the boiler is above 50 kW, the condensed water produced has to be neutralized before its disposal [5].
In the Annex 1 are listed the permitted atmospheric emission limits of Spain according to Spanish laws, where is placed the building under study [66][67][23].

3.5 Water Storage Tanks

Heat exchangers are the transport medium for the heat generated by the different heating appliances. This heat is transferred to water stored in a tank which will be afterwards used in the house.
Storage tanks are classified according to their use in two types: Domestic hot water tanks and buffer tanks.
Domestic hot water tanks store the water required for human consumption, like drinking, washing or cooking. They are distinguished in monovalent and bivalent storage tanks depending on whether they contain one or two heat exchangers. Bivalent tanks are mostly used in houses with a solar thermal system, since the water is heated both by solar energy and a support boiler.

Buffer storage tanks are filled with no drinkable water for the heating system of the house. As the water for heating flows in a closed circuit, the buffer tank is usually dimensioned to supply water on peak demands.
Both domestic and buffer storage tanks are made of either steel or stainless steel. It is important that they are coated against corrosion.
Since the technical and design characteristics of the two tanks are similar in terms of cost and environmental impact, in this study is assumed that the storage tanks are not distinguished by the use of them and are considered all buffer storage tanks (See Figure 3-9) [6].

Figure 3-9: Buffer storage tank [6]

3.6 Distribution system

In this study heat is transported as warm water. Water is transported by circulation pumps through pipes to its destination. According to the current status of the building under study, the pipes to transport both domestic water and heating water are made of Polypropylene (type PP-R (80)). Therefore, the pipes chosen for this study are made of PP.
This material can withstand high temperatures, so it is suitable to domestic and heating water supply. It is also characterized by being friendly to the environment, non-polluting and recyclable [1].
As explained in chapter 4.3.1, distribution pipelines are the same for all the scenarios, so they do not play a significant role when comparing scenarios.

3.7 Load points

Heat for space heating is released through radiators and through underfloor heating (see chapter 4.3.2). Besides, the piping structure is assembled as a two-line system for the input of warm water to the load points and the output of cooled water. In both cases heat is spread by convection and radiation.

Domestic water outlets are not taken into account in this study as they remain the same for all the scenarios, since they depend on the characteristics of the building instead of on the heating system.

4 Goal and scope of the LCA and LCC

The following points are developed according to the standards DIN EN ISO 14040 [15] and DIN EN ISO 14044 [16][15].

The goal of this study is the approach of a methodology of an integrated environmental and economic assessment, as part of the CILECCTA project. Hence, it is addressed to experts on LCC and LCA in the construction sector.
The purpose is to compare both environmental impacts and costs of different domestic warm water and heating systems in a residential building, in order to find the most environmental friendly and in turn, the most economically feasible, based on the concept known as eco-efficiency.
The study takes place in the specific case of the employee´s house of the Robinson Club Cala Serena in Mallorca, Spain.

The study period is 40 years. The scope covers the heating installation of the house, not including the building. Therefore, the processes analyzed are the extraction of raw materials necessary to the production of the system components, the production of the components, transport of energy and fuel required the heating process and the dismantling or replacement processes as well as End of Life of the components.

4.1 Scenarios under study

The base scenario is the current heating system in the Employee´s house of the Robinson Club Cala Serena.
In a next step, different facilities are combined, taking into account Biomass, water and solar as renewable energy sources.

The systems which are modeled are the following:

1. Biomass heating system (current status)
2. Solar heating system and Natural Gas Condensing Boiler
3. Biomass heating system and heat pump with underfloor heating.
4. Solar heating system and heat pump with underfloor heating.

4.2 Functional Unit

In this study the functional unit is defined as the required amount of thermal energy in order to satisfy the house necessities in a specific period of time.
The annual consumption of heat and hot water in the Employee´s house of the Robinson Club Cala Serena is of 100.000 kWh of thermal energy. Therefore, the Functional Unit is the provision of 100.000 kWh of thermal energy per year.
The study period is of 40 years. Therefore, an extended functional unit is defined, which corresponds to the total thermal energy demand in 40 years, 4.000.000 kWh of heat.
This means that the input and output data of the LCA and the LCC is always related to provide 400.000.000 kWh of thermal energy in forty year, so that the environmental impacts and the costs resulting can be compared for each system.

4.3 System boundaries

The entire life cycle of each facility is considered within the timeframe of the study, so both costs and environmental impacts are calculated for 40 years.
The components inside the system limits are only and exclusively those necessary for the installation of the heating systems defined and the provision of the heating demand. This means that the construction and characteristics of the building are not taken into account. Heat recovery systems and auxiliary heating suppliers such as district heating or auxiliary boilers are not considered. The influence of external conditions on the dimension of the heating systems and their characteristics is not taken into account.
Emissions and costs of replacement of the components of every system that occur during the timeframe of the study are considered in the use-phase as maintenance processes. End-of-life processes for replaced components will be analyzed

4.3.1 Inputs and Outputs of the systems

The Figure 4-1 shows the elementary flows considered for the modeling of the scenarios. All the intermediate processes that occur between the inputs and the outputs defined are analyzed. They are described in detail in chapter 4.4.2.

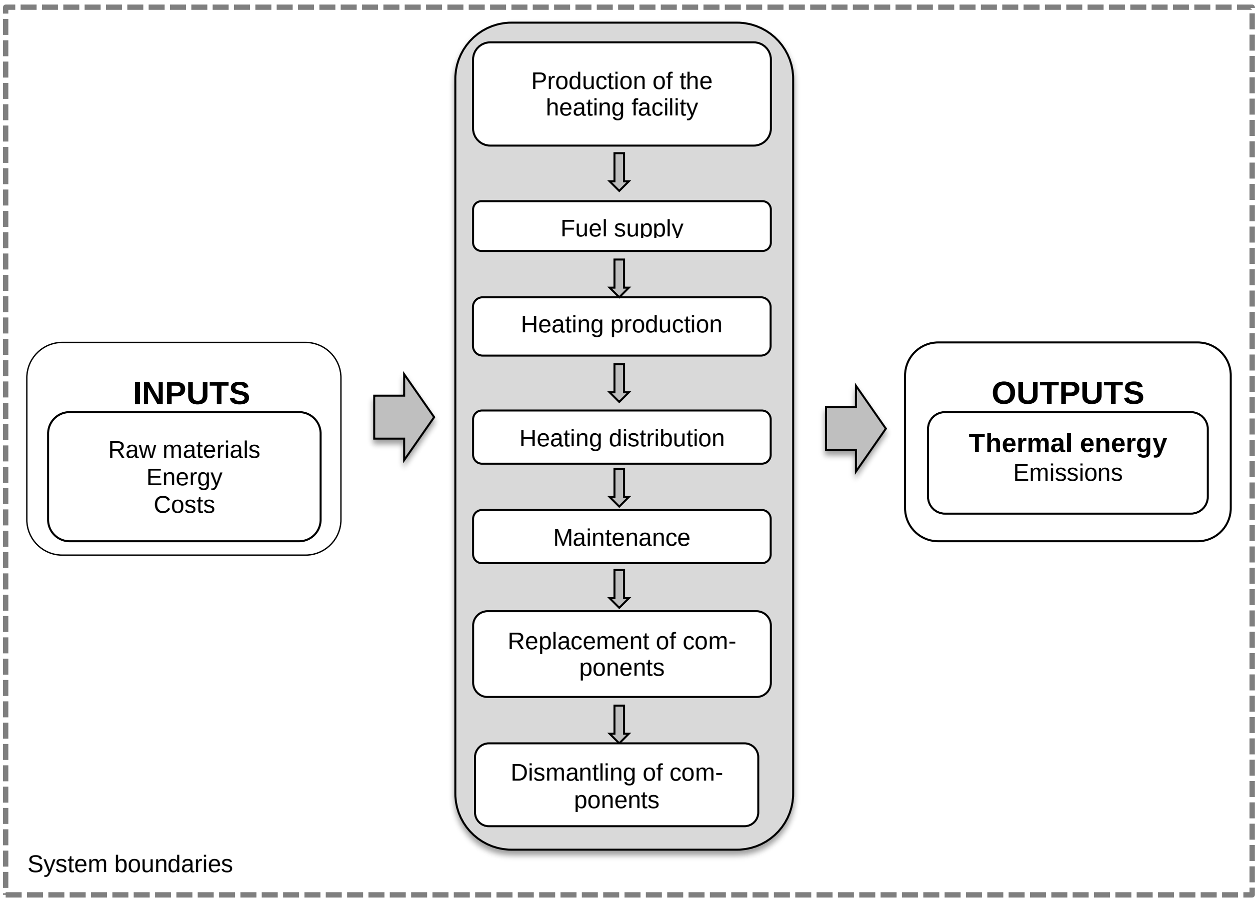

Figure 4-1: System boundaries, inputs and outputs of the system

Inputs are the consumption of raw materials needed to build each scenario and the different energy sources required in all the processes involved in the life cycle.

Energy sources are distinguished in primary regenerative energy, primary non regenerative energy and other fuels.

Other inputs include the fuel required to the operation of each device, which are pellets, solar energy, natural gas and water, as well as fuel oil and electricity needed in several stages.

Input costs include costs of the components and systems in the production stage, costs of operation and maintenance and costs of replaced components and costs of dismantling.

As outputs are evaluated atmospheric emissions and the thermal energy produced as main product.

4.3.2 Cut-off-criteria and assumptions

The goal of this study is the comparison of different scenarios, which consist of heating system installation. When comparing alternatives, only particular components of the scenarios are considered.

Since the heat demand is a constant value and external conditions are the same for each scenario, the water flow remains constant during the study and it is therefore not considered. Water distribution systems require a pipeline installation which remains the same (see Figure 4-2), not depending on the heat devices. Although it will be analyzed for each system separately, it does not play a role on the comparison. No energetic losses are considered. This involves pressure drop of the pipeline and heat losses that occur during the operation of the scenarios in any point of the installation.

Resulting sub products of the scenarios are not considered. This includes waste water, ashes from the combustion processes or paint residues.

For the dimensioning of the energy sources and water distribution components, the energetic model of the building is not considered. This involves geographic conditions, climatological conditions and energy efficiency of the building materials. Components selected and their characteristics are specific for the case study of the employee´s house of Robinson Club Cala Serena hotel.

Inputs and Outputs that contribute less than 1% to mass, energy and costs are neglected in this study, as their influence on the result of the study is marginal.

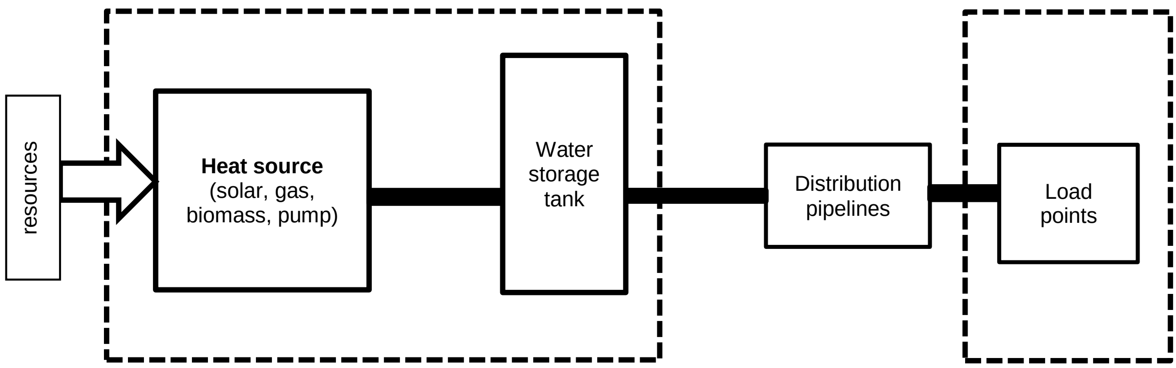

Figure 4-2: General diagram of the scenarios.

4.4 Impact dimensions

4.4.1 Environmental indicators

The resulting flows of the Life Cycle Inventory are translated into their contribution to significant impact categories for the Life Cycle Assessment. The environmental impact categories selected are stated in the following Table 4-1 and described in detail in Annex 2. Each category is expressed in a reference unit.

Table 4-1: Impact categories

Impact category	Direction	Category indicator	Reference Unit
Abiotic Depletion potential	Input	ADP	Kg Antimony (Sb)-equivalents
Global Warming Potential (100 years)	Output	GWP	Kg CO_2-equivalents
Acidification	Output	AP	Kg SO_2-equivalents
Photochemical smog	Output	POCP	Kg Ethen C_2H4-equivalents
Eutrophication	Output	EP	kg Phosphat (PO_4)-equivalents
Stratospheric Ozone Depletion	Output	ODP	Kg R-11-equivalents

In addition to the environmental emissions harmful to the environment, it is also studied the quantity of primary energy demand required during the life cycle of the systems, coming from renewable or non-renewable resources. Quantities are referred to Net calorific Value and represented in Mega joules.

Primary energy demand from renewable sources	Input	PED ren	MJ
Primary energy demand from non-renewable sources	Input	PED non-ren	MJ

4.4.2 Economic indicators

Costs involved on each scenario belong to different points in time within the 40 years of the study. For example, the water storage tank has a lifespan of 20 years, which means that the cost of replacement will be applied on year 20.

This cost does not have the same monetary value on year 20 than on year 0 or year of the study. Therefore Net Present Value (NPV) is a suitable method for using the time value of money to evaluate long-term projects, because it translates costs from a future point of time to the present. NPV is defined as the sum of the present values of the individual cash flows of a system, which are the difference between the incomes and outcome, and represents the worth of the investment, including an interest rate which discounts the future cash flows to the present value. It is calculated by applying the following formula:

$$NPV=\sum_{t=0}^{40}\frac{R_t}{(1+i)^t}$$

Where R_t corresponds to the cash flow in the year t and i is the interest rate.

In this study, cash flows correspond to the costs of installing, operating and replacing components of each scenario. The applied interest rate in this study is 6%

4.5 Data sources and data Quality

The development of the project meets the requirements of DIN EN ISO 14040 and DIN EN ISO 14044. Background of the study regarding to LCA, LCC and LCCA methodologies is documented on the corresponding ISO norms and specific literature research and official websites.

Theoretical background of the study regarding to the description of the heating systems is documented on literature from year 2000 until now.

Technical data collected on the Life Cycle Inventory of the current status of the building under study is provided by Robinson Club Cala Serena [68], including the building energy requirements and the characteristics and dimensions of the device and distribution components.

For the rest of the scenarios, dimensions of the heating devices are calculated, and dimensions for the rest of components come from technical literature research on the last three years, 2009 till currently.

Required processes involved in the scenarios are available through the Ökobau.dat database available in GaBi 5 software, created in accordance with the ISO standards.
For all scenarios, data of components characteristics such as material quantities for their manufacturing, energy required for their operation, Life Cycle emissions and waste generation is available in Ökobau.dat database collected by PE-International[63] and developed according to ISO standards [63].
Geographic conditions considered, like for the calculation of solar irradiation, correspond to hotel´s location in Mallorca, Spain.
Operation costs of electricity and Natural gas correspond to current Spanish rates.
Costs of the components of the heating system currently installed are provided by Robinson Club Cala Serena [68] and from a benchmarking among real suppliers in the Spanish Market.
Dismantling costs are checked in the German's Bau-Kosten-Index book [12].

4.6 Critical review considerations

A critical review is not required for this study, as it is used internally to validate results created with the CILECCTA tool.

5 Life Cycle Inventory

Once the goal and scope of LCA and LCC is clearly defined, the next step is the data collection.

The inventory analysis gathers the inputs and outputs of the scenarios, which are validated and scaled to relate them to the functional unit. Therefore, in this chapter all the data required either as input or as output of the system boundaries in order to model the scenarios in the GaBi 5 Software is collected [63].

For this study, the steps in the data collection are the identification of required heat in the building, the calculation of the dimensions of the devices to install and their material quantities, the energy required to produce heat in the operation stage and its cost and the material quantities for the recycling and disposal of the infrastructures.

Only heat suppliers, heat distribution and release infrastructures are assessed. Systems are all installed in the same building, whose characteristics are considered as constant in the study. Therefore the building is not assessed.

Data of the processes involved on the scenarios modeled, including components characteristics and lifespan, come from the Ökobau.dat database [7] available in GaBi 5 Software [63] and created in accordance with the ISO standards. Data about the dimension and costs of the components of the current status of the building is provided from Robinson Club Cala Serena [68]; costs related to the other scenarios come from a literature and internet research in the Spanish Market and in technical documentation. (See paragraph 4.5).

Data collection is determined by the goal and scope of the LCA and the LCC, detailed in chapter 4.

5.1 Model with Life Cycle Engineering software GaBi 5

The GaBi 5 Software is a tool for conducting Life Cycle Assessments by creating life cycle modeling and balances [63]. GaBi enables to model in a comprehensive and simple way all processes and flows involved in the life cycle of a system or process chain, distinguishing its inputs and outputs on the stages of production, use and end-of-life so that they can be processed separately from each other.

It also offers the user a wide repertoire of databases which contains life cycle inventory data obtained by long-term research by LBP, University of Stuttgart and PE International, such as the professional database Ökobau.dat 2011, which is used in this study.

Ökobau.dat 2011 database is a compilation of datasets standardized in the ISO 14044 [16] containing all information related to a construction product (material properties,

emissions inventory, etc.). Datasets are separated in the production, use and disposal of the product. Components required for the modeling of a central heating system of a building are also included in Ökobau.dat database.
GaBi 5 is a modular system. Plans, processes and flows form modular units. As a result, the GaBi system has a clear and transparent structure [63].

5.2 Model structure and assumptions

5.2.1 Structure of the scenarios

Scenarios are equally structured in order to find a comprehensive way of evaluation of both environmental and economic impacts.
All the components required for a heating system are grouped into single units which work as inputs to the thermal energy demand of the house.
Data collected and information required for the scenarios is classified in the following:

Energy sources: Information related to the operation stage of devices that supply heat in each scenario. Fuel characteristics, electricity required and other operating conditions are included in this process as inputs, and thermal energy provided as output.

Infrastructure: Processes involved on the manufacturing of the devices and their disposal. This includes as inputs the material properties and quantities and the energy required to their manufacturing. As output the recycling potential and the quantity of generated waste at the end of life is included.

Distribution of domestic heated water: Components required for the distribution of DHW. This includes data related to the pipeline, water storage systems and circulating pumps as inputs and their recycling potential and disposal as outputs.
All the information related to these components corresponds to the current status of Cala Serena Employee´s house. As the heating demand and the quantity of water remains constant, this set of components is used identically for all the scenarios.

Distribution of space heating water: Components required for the distribution of water for space heating. This includes the manufacturing and disposal characteristics of the pipeline and the water storage, the manufacturing and use stage of the circulating pumps and the manufacturing and disposal of the heat-release devices, which varies depending on the scenario.

5.2.2 Components lifespan

In chapter 3 (Description of the Heating systems) all the components involved in each scenario according to the heating system are listed and explained.
As the timeframe of the study is of 40 years, these components might be replaced according to their lifespan.
The following figure shows the different lifespans and the point in time when components should be replaced, so it can be observed how many pieces of each component are required. The study period ends after year 40, so there are components that do not deplete their lifespan. However, at year 40 the dismantling of all components takes place.

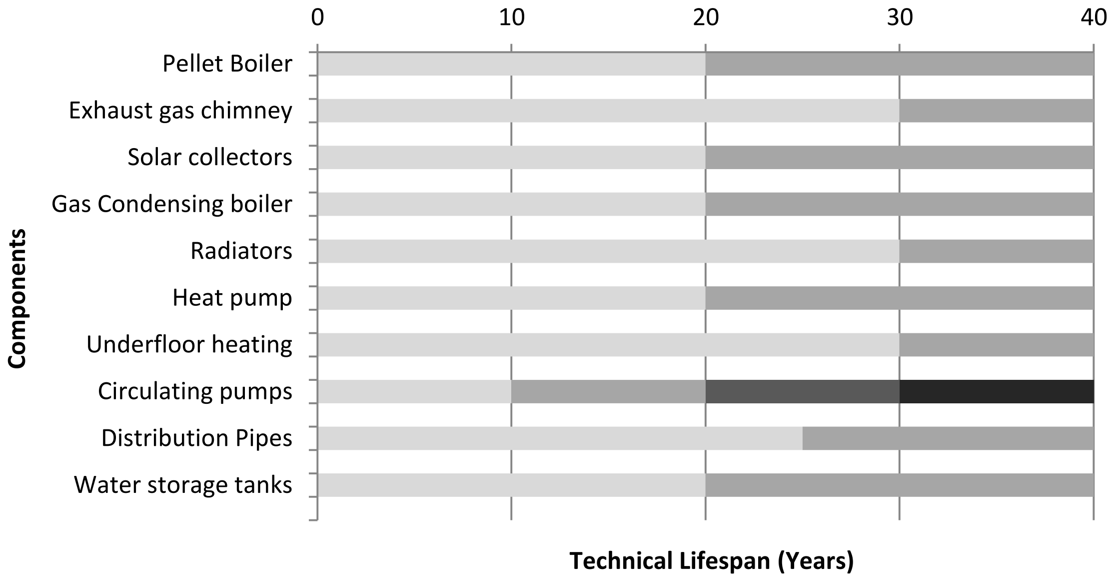

Figure 5-1: Required units and technical lifespan of each component

5.2.3 Energetic data

The functional unit of the study is the thermal energy demand of Cala Serena employee's house, which is 100.000 kWh /year, of which 65.000 kWh/year are used for space heating and 35.000 kWh/year are used for domestic warm water. This functional unit is extended to the 40 years of study period.
These three flows are parameterized in the GaBi 5 software so that the scenarios can be dimensioned according to their values. These parameters are the following:

TED.Total_thermal_energy: Global parameter. It corresponds to the total energy demand of the house in 40 years, which sums up 4.000.000 KWh. As a global parameter it can be implemented and adapted simultaneously in all scenarios.

cons_DHW: Local parameter. It corresponds to the portion of heated water consumed for heating. As a local parameter, it can have different values for each scenario.

cons_HW: Local parameter. It corresponds to the portion of heated water used for domestic warm water. This parameter is linked to the previous ones by being the difference between the total energy demand and the consumption of domestic heated water.

Annex 3 contains the full list of parameters applied for the combination of the thermal energy in the four scenarios.

Regarding to energy resources information, electricity and fuel data have to be considered.
Natural gas and electricity prices correspond to Spanish rates, whereas pellets cost is provided by Robinson Club Cala Serena [68] (see Annex 5).
To obtain the electricity required, it is necessary to know the time of operation of the devices. Therefore, after a literature research, an assumption has been adopted.
Domestic heated water is supplied 365 days per year during 10 hours per day.
In the case of heating, it is required 8 months per year during 24 hours per day.

5.2.4 Domestic heated water distribution

Equipment for the storage, distribution and load of the heated water are already installed in the building of Cala Serena employee's house.
Annual average of heat for domestic water, building characteristics and external environmental conditions are the same for all scenarios, which means that gradient temperature and pressure conditions are the same in all cases. If the distribution system does not change, water flow is also held constant.
Therefore, losses of pressure drop or heat that occur during the operation of the devices are considered irrelevant.
In consequence, distribution components do not have an influence on the comparison of the scenarios. However, they are analyzed in order to observe their environmental and cost impact within each scenario.

All technical and economic data concerning to the water distribution system is provided by Robinson Club Cala Serena [68].

According to the technical data of the building, pipeline installed in the building for the distribution of DHW is made of Polypropylene (PP), with a total length of 364 m and split in pipelines with dimensions of diameter and thickness.

To obtain the total quantity of material required for the total pipeline in kg, the different standard pipe sizes are known, so their weight is calculated with the tabulated values available in Ökobau.dat database. (see Annex 4).

Technical lifespan of the pipeline is 25 years, so both technical and economic data is scaled double for the 40 years of the study.

Once the water is heated, it is stored in two buffer tanks with 750 l capacity each. According to the Ökobau.dat datasheet one buffer tank of this capacity weighs 140 kg, with a lifespan of 20 years.

To transport the heated water from the storage to the load points, two circulating pumps of 250W each are used. One of them operates as return pump. According to Ökobau.dat datasheet of these pumps, their weight is 5 kg each, with a lifespan of 10 years.

Investment costs of the pipeline and the buffer tank are provided by Robinson Club Cala Serena [68], whereas circulating pump costs are obtained from the manufacturer DAB pumpen Deutschland GmbH [11] (see Annex 5), which is the supplier of the pumps in Robinson Club Cala Serena [68].

Information related to the manufacturing of the devices, materials, transport of materials and processes involved is included in Ökobau.dat datasheets.

Table 5-1: DHW distribution – Production

	Input	**Component**	**Output flow**		**Number of units**[1]	**Investment Cost (1 unit)**
			Units	**Value (1 unit)**		
Production	Distribution DHW	Pipes[2]	Mass	71,8 kg	2	11.057 €
		Buffer storage (stainless steel)	Mass	140 kg	4	4.104 €
		Circulating pumps 250 W	Mass	5 kg	8	384 €

Pipes and buffer storage tanks do neither consume nor release any type of energy or resource during the operation stage. Circulating pumps are measured on hours of oper-

[1] Components required during the Study period.
[2] One unit is equivalent to the total 365 meters installed in the building in a period of lifespan.

ation, which are, in the case of DHW, 10 h/day 365 days/year. They require 1,5 W electricity per 1 kW rated power of the boiler. Since the pumps are connected in series, the electricity required for their operation is calculated with the equation (5-1) as follows:

$$E=H_d*1,5 \tag{5-1}$$

$$E=35*1,5=52,5\ kW_e/year$$

Cost of electricity corresponds to Spanish rates (See Annex 5).

Table 5-2: DHW Distribution – Operation

	Input	Component	Output flow		Number of units	Operating Costs[3]
			Units	Value		
Operation	Distribution DHW	Circulating pumps 250 W	Time	3650 h/year	8	7,47 €/year

End-of-life stage corresponds to the dismantling of the infrastructure. Costs of dismantling of pipes and buffer tanks are detailed in Annex 5. Dismantling costs of the circulating pumps are included in the costs of dismantling of the storage tanks.
Data of the dismantling, transport and waste generation of the components is included in Ökobau.dat database.

Table 5-3: DHW distribution – End-of-Life

	Output	Component	Input flow		Number of units	Dismantling costs (1 unit)
			Units	Value (1 unit)		
EoL	Distribution DHW	Pipes	Mass	71,7 kg	2	364 €
		Buffer storage (stainless steel)	Mass	140 kg	4	220 €
		Circulating pumps 250 W	Mass	5 kg	8	

The following Figure 5-2 shows the structure of the distribution system modeled in GaBi 5. Components are dimensioned for the 40 years of study. Circulating pumps life cycle is grouped in one set, including their production, use and end-of-life data.

[3] Cost of total electricity required by all the pumps in one year

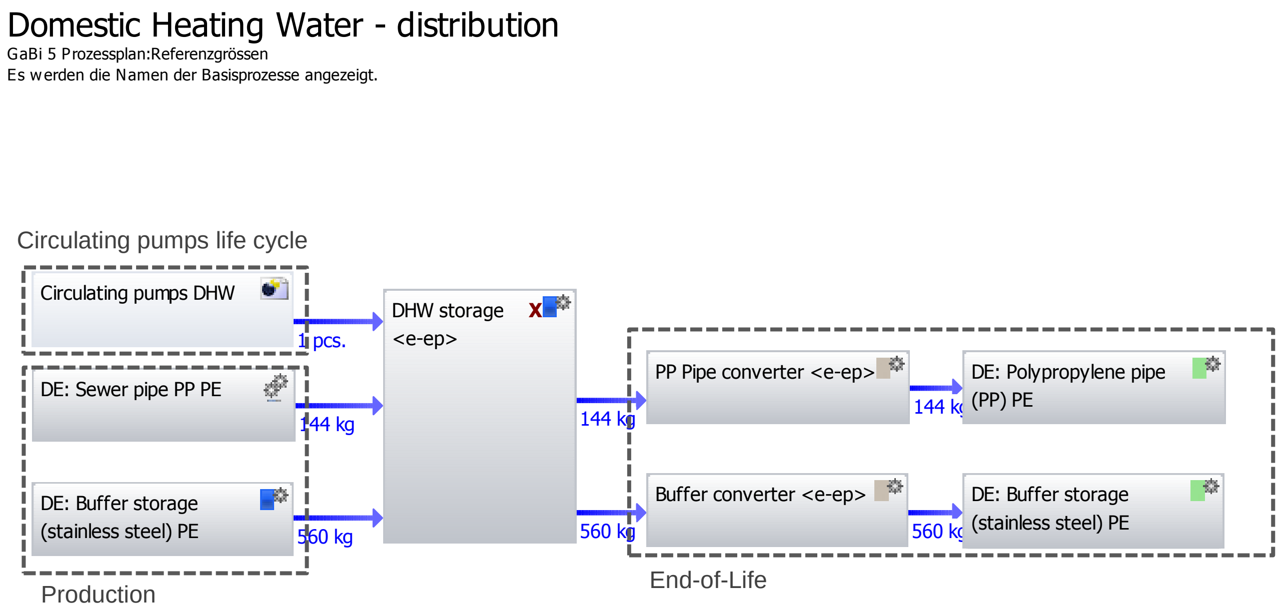

Figure 5-2: Domestic Heated Water distribution – Structure n GaBi 5

5.2.5 Heating distribution

To heat the building two different forms of heat release have been selected.
In scenario 1, biomass heating system and scenario 2, solar heating system combined with a natural gas boiler, heating is released through radiators.
In Scenarios 3 and 4, which combine a heat pump with a biomass boiler and a solar heating system respectively, heat is released through underfloor heating.
As in the DHW distribution, annual average heating demand remains constant, and building characteristics as well as external environmental conditions do not change for the different scenarios. Therefore, losses that occur during the operation are considered irrelevant.

5.2.5.1 Heating by radiators

In the case of heating by radiators, warm water is stored in a buffer tank to achieve the steady state in the cycle, and pumped through pipes to the load points.
According to buildings´ technical data, pipeline for heating water installed in Cala Serena is made of polypropylene (PP), with a total length of 480 meters. To obtain the quantity of material required, the different pipe dimensions installed in Cala Serena are

known, and its corresponding properties are obtained from Ökobau.dat standard tabulated values available (see Annex 4). Pipeline costs of installation are provided by Robinson Club Cala Serena [68].

Material data, properties data and costs of the pipeline is scaled 2 times, as their lifespan is of 25 years.

Heating water is stored in a 1650 l capacity buffer tank made of steel. Its weight is interpolated with the values tabulated on the Ökobau.dat datasheet, resulting in a weigh of 219,2 kg/unit**.** Investment costs are provided by Robinson Club Cala Serena [68]. One circulating pump of 750 W is installed to pump water from the storage to the load points. According to its Ökobau.dat datasheet, one pump weighs 25 kg, with a technical lifespan of 10 years. Costs are provided by Robinson Club Cala Serena [68].

According to the information available from Robinson Club Cala Serena, 35 radiators are installed. Developed calculations to obtain the total weight of radiators required are attached in Annex 4.

Table 5-4: Heating distribution with radiators – Production

	Input	Component	Output flow		Number of units	Investment cost (1 unit)
			Units	Value (1 unit)		
Production	Heating distribution (radiators)	Pipes[4]	Mass	118,6 kg	2	9.611 €
		Buffer storage	Mass	219,2 kg	2	1.093 €
		Circulating pumps 750 W	Mass	25 kg	4	2.678 €
		Radiators[5]	Mass	455 kg	2	7.853 €

Pipes and buffer storage tanks do not neither consume nor release any type of energy or resource during the operation stage. Circulating pumps are measured on hours of operation, which are, in the case of Heating, 8 months/year and 24 hours/day.

Circulating pumps are connected in series. They require 1,5 W electricity per 1 kW rated power of the boiler. Applying this ratio with the equation (5-1), electricity required results:

$$E=H_d*1,5 \qquad (5\text{-}1)$$

$$E=65000*1,5*10^{-3}=97,5\ kWe/year$$

[4] One unit is equivalent to the total 480 meters installed in the building in a period of lifespan (25 years).
[5] One unit corresponds to the 35 radiators installed in the house in a period of lifespan (30 years).

Cost of electricity corresponds to Spanish rates (see Annex 5).

Table 5-5: Heating distribution with radiators - Operation

	Input	Component	Output flow		Number of units	Operating Costs[6]
			Units	Value		
Operation	Heating distribution (radiators)	Circulating pumps 750 W	Time	2880 h/year	4	13,88 €/year

End-of-life stage corresponds to the dismantling of the infrastructure. Costs of dismantling of pipes, buffer tanks and radiators are detailed in Annex 5. Dismantling costs of the circulating pumps are included in the costs of dismantling of the storage tanks.

Table 5-6: Heating distribution with radiators – End-of-Life

	Output	Component	Input flow		Number of units	Dismantling costs (1 unit)
			Units	Value (1 unit)		
EoL	Heating distribution (radiators)	Pipes[4]	Mass	118,56 kg	2	2.880 €
		Buffer storage	Mass	219,2 kg	2	220 €
		Circulating pump 750 W	Mass	25 kg	4	
		Radiators[5]	Mass	455 kg	2	1.155 €

The following Figure 5-3 shows the heat distribution and release through radiators modeled in GaBi 5. Circulating pumps are grouped in one set including data of their production, operation and end- of-life.

[6] Cost of total electricity required by all the pumps in one year

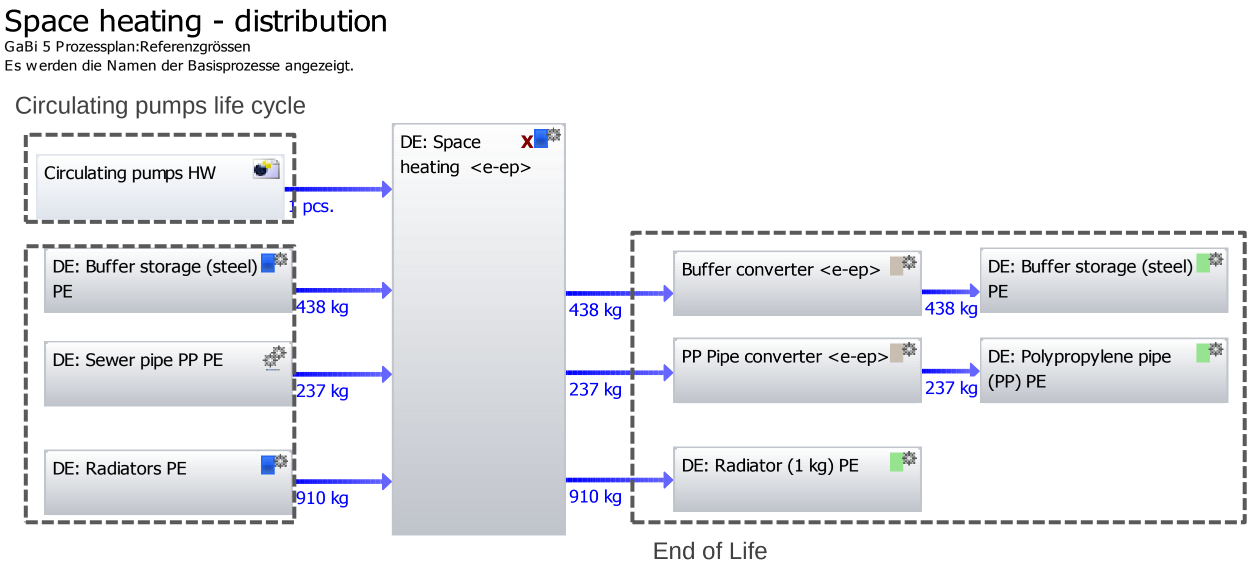

Figure 5-3: Heating distribution with radiators

5.2.5.2 Underfloor heating

Heated water is pumped through the pipes (made of PEX in this case) that form the underfloor heating surface. The circulating pump selected is the same as in case of heating by radiators.

Cala Serena´s employee’s house has a total floor surface of 600 m². In order to obtain the heated surface, it is applied a factor between 75-80 % to the total surface. Hence, it is selected a ratio of 0,77. Investment costs are obtained from an internet research of several installers of these devices.

Table 5-7: Underfloor heating – Production

	Input	Component	Output flow		Number of units	Investment cost (1 unit)
			Units	Value (1 unit)		
Production	Heating distribution (underfloor heating)	Underfloor heating surface[7]	Area	462 m²	2	16.170 €
		Circulating pumps 750W	Mass	25 kg	4	2.678 €

[7] One unit corresponds to the total underfloor heating surface in a period of lifespan (30 years)

Pipes and buffer storage tanks do neither consume nor release any type of energy or resource during the operation stage. Circulating pumps are measured on hours of operation, which are, in the case of heating, 8 months/year and 24 hours/day. Electricity required for their operation is included on the data sheet. Cost of electricity corresponds to Spanish rates (see Annex 5).

Table 5-8: Underfloor heating – Operation

<table>
<tr><th rowspan="2"></th><th rowspan="2">Input</th><th rowspan="2">Component</th><th colspan="2">Output flow</th><th rowspan="2">Number of units</th><th rowspan="2">Operating Costs[8]</th></tr>
<tr><th>Units</th><th>Value</th></tr>
<tr><td>Operation</td><td>Heating distribution (underfloor heating)</td><td>Circulating pumps 750 W</td><td>Time</td><td>2880 h/year</td><td>4</td><td>13,88 €/year</td></tr>
</table>

End-of-life stage corresponds to the dismantling of the infrastructure. Due to missing data, dismantling costs of underfloor heating and circulating pumps have been calculated as 20 % of the investment costs. To calculate the weight of the underfloor heating, after an internet research it has been selected the technical data available of the installer Cliber, model Panel Acoustic, cod.1054045 [10], with a value of 1,43 kg/m².

Table 5-9: Underfloor heating – End-of-Life

<table>
<tr><th rowspan="2"></th><th rowspan="2">Output</th><th rowspan="2">Component</th><th colspan="2">Input flow</th><th rowspan="2">Number of units</th><th rowspan="2">Dismantling Costs (1 unit)</th></tr>
<tr><th>Unit</th><th>Value (1 unit)</th></tr>
<tr><td rowspan="2">EoL</td><td rowspan="2">Heating distribution (underfloor heating)</td><td>Underfloor heating surface[7]</td><td>Mass</td><td>660,66 kg</td><td>2</td><td rowspan="2">3.770 €</td></tr>
<tr><td>Circulating pumps 750 W</td><td>Mass</td><td>25 kg</td><td>4</td></tr>
</table>

The following figure shows the underfloor heating structure modeled in GaBi 5. Distance between pipes varies according to the location. Near areas with more heat losses like windows or doors, and in sanitary areas, a distance between pipes of 100 mm is applied. For the rest of the building distance between pipes is of 200 mm. Circulating pumps are grouped in one set including data of their production, operation and end- of-life.

[8] Cost of total electricity required by all the pumps in one year

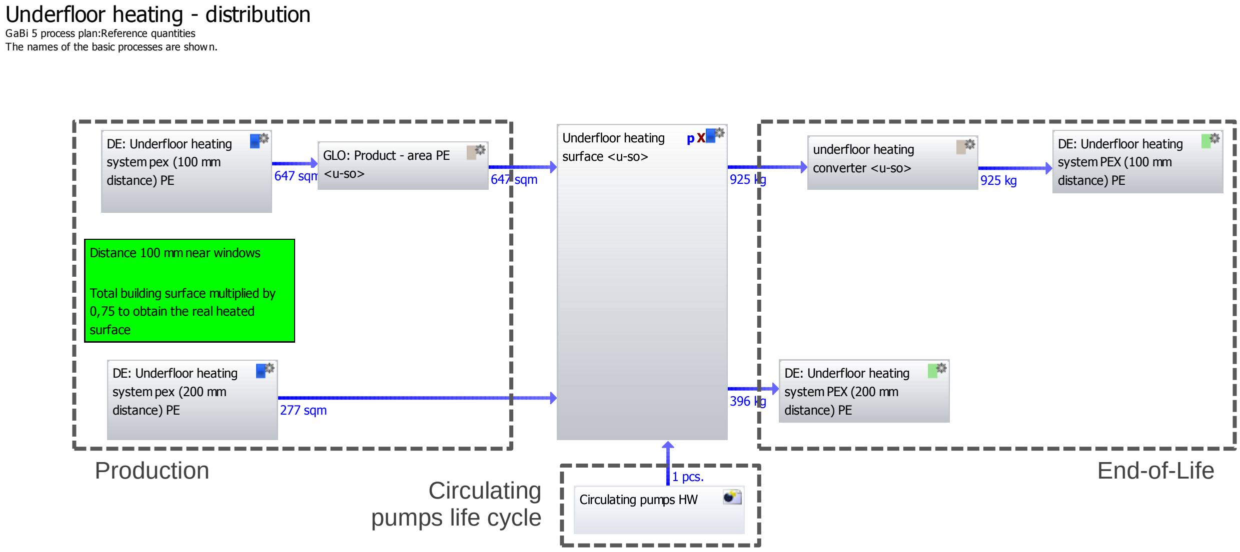

Figure 5-4: Underfloor heating: Structure in GaBi 5

5.3 Scenario 1: Biomass system

Data collected for the biomass system corresponds to the current heating system installed in Cala Serena employee's house.

The infrastructure required for the Biomass system includes the pellet boiler housing and components manufacturing, an exhaust gas chimney and a pellet silo:

Table 5-10: Infrastructure of the Biomass boiler – Production

	Input	Component	Output Flow		Number of units	Investment Costs (1 unit)
			Units	Value (1 unit)		
Production	Infrastructure (Biomass boiler)	Pellet boiler 20-120 kW	Mass	833 kg	2	22.695 €
		Exhaust gas chimney	Mass	2,6 kg	2	
		Pellet silo	Mass	3427,2 kg	1	2.100 €
		Grant			2	-14.829 €

Pellet boiler and exhaust gas chimney weight correspond to data of the Ökobau.dat database. The pellet silo is made of concrete, type C20/25, with a density of 2.400 kg/m³, which is reinforced with steel, assumed 2 % of the total weight. Dimensions are 2x1,5x2 m. Walls have 0,1 m of thickness.

Materials, processes and transport required for the manufacturing of the components are included in the Ökobau.dat datasheets.
Costs are based on information from Robinson Club Cala Serena [68] and a market analysis, detailed in Annex 5.
As seen in Table 5-10 of chapter 5.2.2, the chimney has a longer lifespan than the boiler. However, boiler and chimney are installed as a single piece, so the chimney will be replaced before finishing its lifetime**.**
As biomass is classified as renewable energy source, the Spanish government provides grants to the installation of these devices. The value of the Grant is in this case of 14.829 € [68], applied to the whole installation cost.

All the heating demand is produced by a pellet boiler with 120 kW power. 65 % of heat is used for heating water and the remaining 35 % for domestic heated water, according to Cala Serena´s employee´s house heat consumption:

Table 5-11: Biomass Boiler – Operation

	Input	Component	Elementary flow		Operatings Costs
			Units	Value	
Operation	Energy source (Pellets)	Pellet boiler 20-120 kW	Thermal energy	100.000 kWh/year	5.600 €/year

Data about boiler´s efficiency and electricity required for the operation of the device, as well environmental profile are included in the Ökobau.dat dataset of the process. Operating costs correspond to pellets cost of Robinson Club Cala Serena [68]. The pellet consumption is 1800 kg/year [68] (See Annex 5).
End-of-life stage takes place when components are replaced. Recycling potential, waste generation and transport of the infrastructure are quantified in Ökobau.dat dataset. Costs of dismantling are detailed in Annex 5.

Table 5-12: Biomass boiler – End-of-Life

	Output	Component	Input Flow		Number of units	Dismantling costs (1 unit)
			Units	Value (1 unit)		
EoL	Infrastructure (Biomass boiler)	Pellet boiler	Mass	833 kg	2	2.800 €/unit
		Exhaust gas chimney	Mass	2,56 kg	2	
		Pellet silo	Mass	3.360 kg	1	480 €/unit

The following Figure 5-5 shows the base plan of the scenario 1 modeled in GaBi based on the data collected. The evaluation of environmental impacts is conducted based on this model.

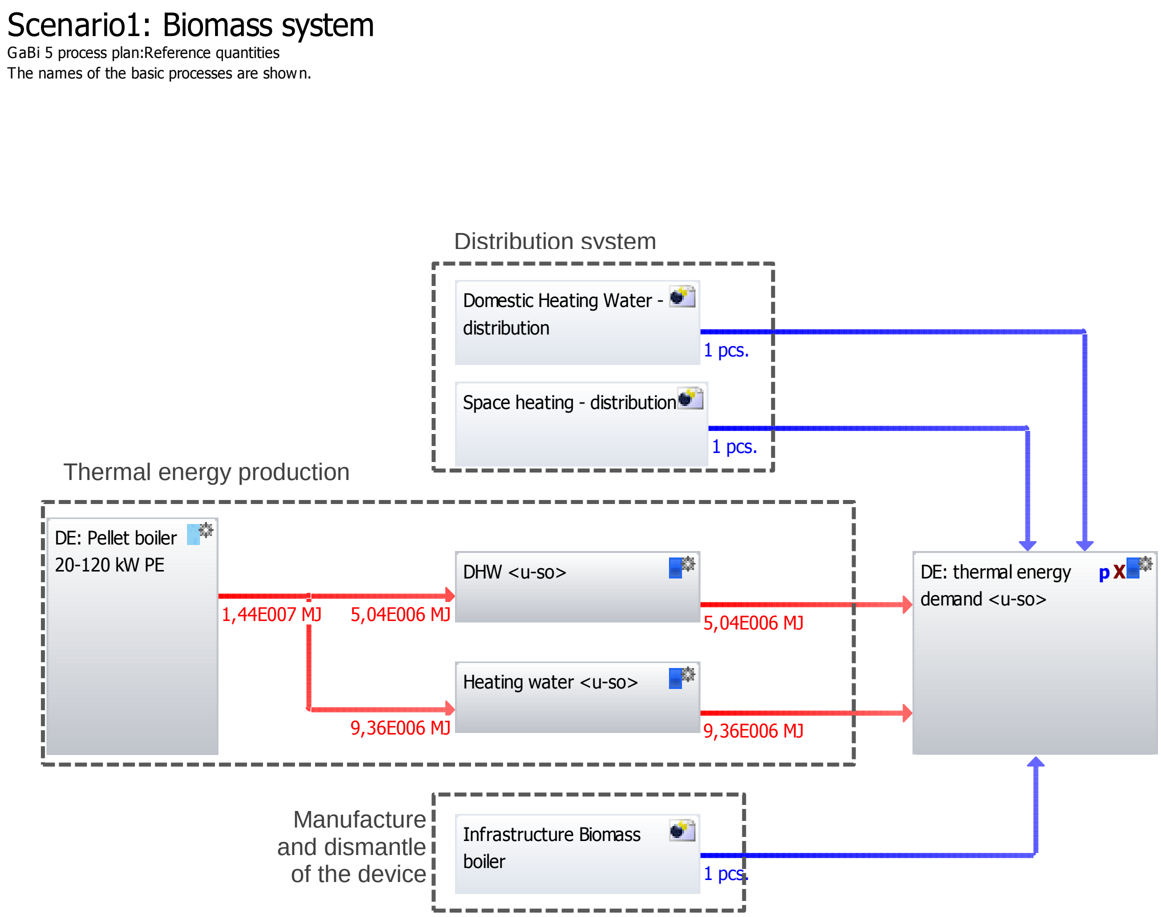

Figure 5-5: Scenario 1: Structure in GaBi 5

The flow illustrated in red lines corresponds to the thermal energy demand of 40 years. Infrastructure of biomass boiler, components for domestic heated water distribution and components for heating water distribution are respectively grouped constituting a single set of pieces.

Distribution of DHW and of heating is explained in detail paragraph 5.2.4.

5.4 Scenario 2: Solar heating system and natural gas condensing boiler

To integrate a solar thermal system in the central heating system of a house it is necessary to choose a support heating system to cover part of demand, because of the low efficiency of collectors, the lack of a constant energy source and the high investment costs of the installation.

Gas condensing boiler becomes, hence, a good and common solution to supply the rest of the demand, thanks to its high combustion efficiency and economic advantages compared a solar collector device.

To design a combined central heating system with a solar thermal device it is dimensioned providing that the area of solar collectors installed covers around the 60 % of the domestic heated water demand and the 20 % of the total warm water (heating and DHW) [45]. This share is applied based on the assumptions explained in paragraph 4.3.2. Depending on the case study the dimensioning of the components can vary around these values.

To calculate the required power of the boiler, the timeframe in which the devices will operate must be determined. As explained in chapter 5.2.3, DHW is supplied 365 days per year during 10 hours a day, and heating is required 8 months per year during 24 hour a day. With this assumption, the power of the boiler is calculated through the equation (5-2):

$$H_d = \frac{SHW}{t1} + \frac{DHWb}{t2} \tag{5-2}$$

Hd: Heat demand of the condensing boiler (KW)

SHW: Space heating water (KWh)

t1: hours per year of space heating (h)

t2: hours per year of Domestic heated water (h)

DHWb: Fraction of Domestic heated water produced by the boiler (KWh)

$$H_d = \frac{65000}{8*30*24} + \frac{35000*0,4}{365*10} = 15$$

Data of Gas condensing boilers available in Ökobau.dat database correspond to boilers efficiency of 105 % at 30 % load. For security measures and to assure the capacity of the boiler, it is dimensioned to cover the heat demand operating at 30 % load:

$$P=\frac{15}{0,3}=50\ \text{kW}$$

Selected boiler has, thus, power between 20-120 kW.

To calculate the required collectors total surface are taken into account the geographic conditions of the building. Developed calculation is attached in Annex 4.

Table 5-13: Solar collectors and Gas boiler - Production

	Input	Component	Output flow		Number of units	Investment Costs (1 unit)
			Units	Value (1 unit)		
Production	Infrastructure (Solar collectors)	Glazed flat-plate solar collectors[9]	Area	111 m²	2	36.364 €
		Grant			2	-20.175 €
	Infrastructure (Gas boiler)	Natural gas condensing boiler 20-120 kW	Mass	283 kg	2	18.163 €
		Exhaust gas chimney		2,56 kg		

Type of materials and quantities required to the manufacturing of a gas boiler with 20-120 kW power, 1 m² of solar collector, as well as transport or other processes involved and the environmental profiles are included in the Ökobau.dat dataset.
Manufacture costs of the gas condensing boiler and solar collectors are detailed in Annex 5. As in scenario 1, gas boiler manufacture cost includes the exhaust gas systems.

As solar energy is classified as renewable energy source, Illes Balear´s government provides grants to the installation of these devices. The value of the Grant is 37 % of the total installation cost (considering auxiliary devices) [39].
Operation costs are limited to fuel costs, which are null for the solar irradiation cost. Natural gas fuel costs correspond to Spanish rates (see Annex 5).

[9] One unit corresponds to the total surface installed in the building a period of lifespan.

Table 5-14: Solar collectors and gas boiler - Operation

	Input	Component	Elementary flow		Operating Costs
			Units	Value	
Operation	Energy source (Solar irradiation)	Glazed flat-plate solar collectors	Thermal energy	21.000 kWh/year	0 €/year
	Energy source (Natural gas)	Natural gas condensing boiler 20-120 kW	Thermal energy	79.000 kWh/year	4.329€/year

Data related to waste generation, recycling potential and transport is included in Ökobau.dat dataset. Solar collectors weigh 18 kg/m² [33]. Due to missing data, dismantling costs are assumed to be 20 % of the investment costs. Boiler dismantling costs are detailed in Annex 5.

Table 5-15: Solar collectors and gas boiler – End-of-Life

	Output	Component	Input flow		Number of units	Dismantling Cost (1 unit)
			Units	Value (1 unit)		
EoL	Infrastructure (Solar collectors)	Glazed flat-plate solar collectors	Mass	1.997 kg	2	7.273 €/unit
	Infrastructure (Gas boiler)	Natural gas condensing boiler 20-120 kW	Mass	283 kg	2	1.400 €/unit
		Exhaust gas chimney		2,56 kg		

Figure 5-6 shows the structure of the scenario 2 modeled in GaBi 5, with the combined thermal energy production. Systems are scaled to the heating demand of 40 years.

Distribution system is explained in detail in paragraph 5.2.4. Environmental analysis is conducted based on this model. Processes involved in the manufacturing and the dismantling of the devices are grouped into one set of pieces for each device.

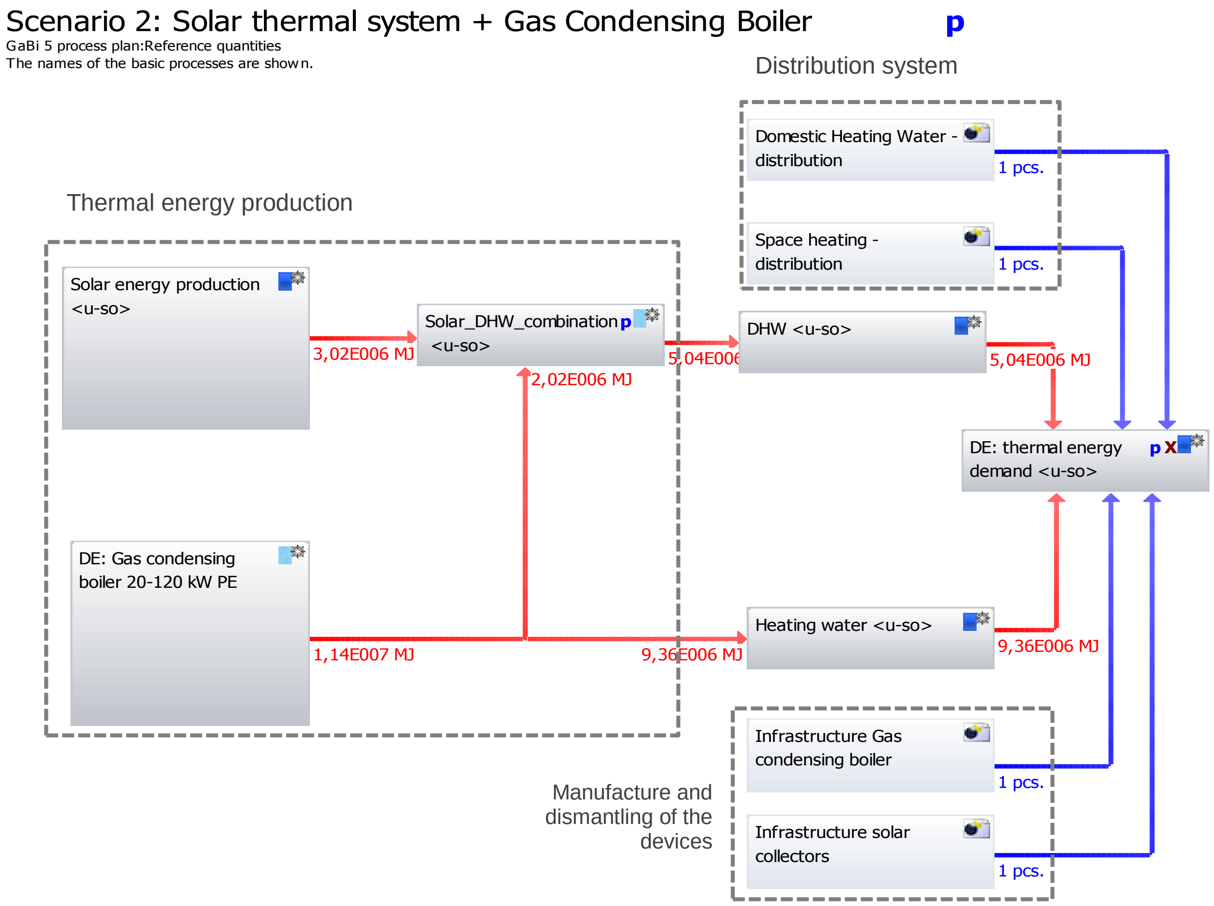

Figure 5-6: Scenario 2: Structure in GaBi 5

5.5 Scenario 3: Biomass system and heat pump with underfloor heating

Underfloor heating is classified as low-temperature heating, as it operates with a water flow temperature of 60ºC or less, because higher temperatures could damage the floor structure [72]. Therefore, the heating source selected is a water-water heat pump with a COP of 3.8, brine temperature of 10ºC and flow temperature of 50ºC, which is also a low-temperature heating system. The acronym COP refers to the Coefficient of Performance, which is the ratio of the heat delivered and the electrical energy supplied to the compressor, as explained in paragraph 3.3.1.

Domestic heating water is supplied by a biomass system.

This share is applied based on the assumptions explained in paragraph 434.3.2. Depending on the case study the dimensioning of the components can vary around these values.

The basis plan of the scenario modeled in GaBi 5 is shown in Figure 5-7. It is observed the separation between domestic heated water and heating systems. DHW is explained in detail in paragraph 5.2.4. Underfloor heating for heating distribution is explained in paragraph 5.2.5.2.

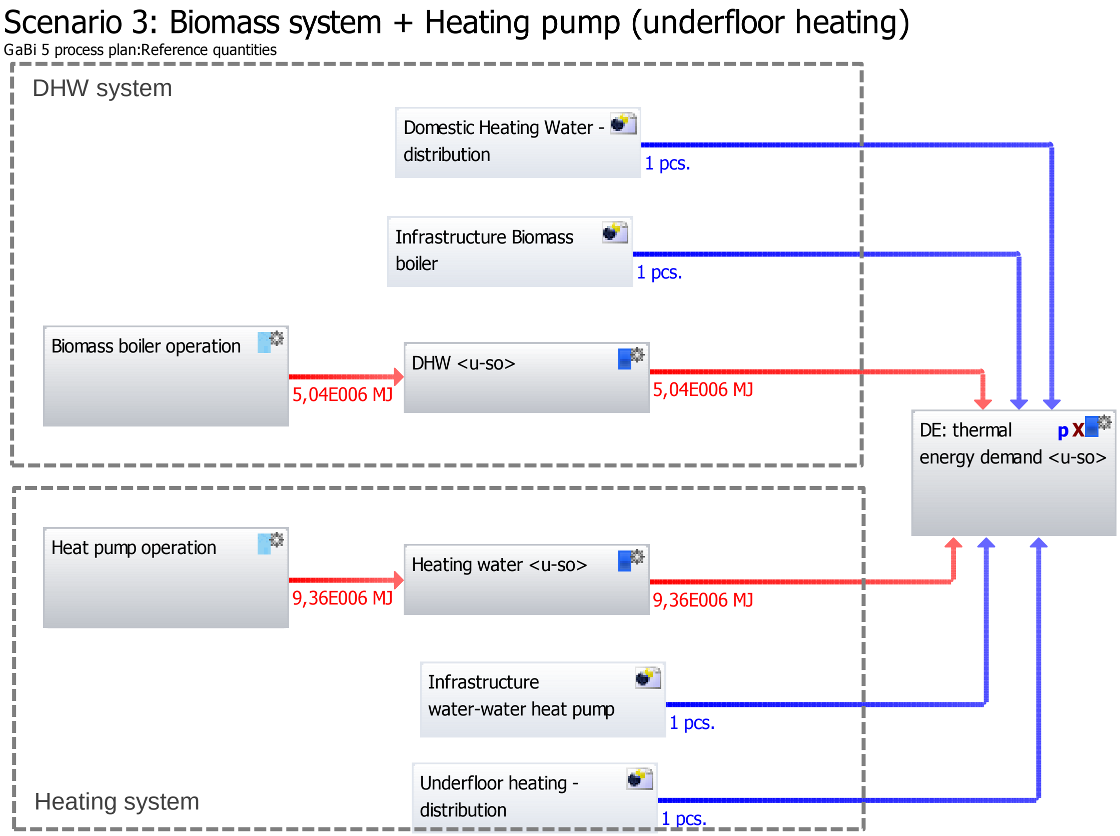

Figure 5-7: Scenario 3: Structure in GaBi 5

The biomass system is the same as the one installed in scenario 1, as it is the current device installed in the building under study.

To calculate the power of the heat pump, it is followed the same procedure as in the previous-dimensioned natural gas boiler, applying the equation (5-3):

$$H_d = \frac{SHW}{t} \qquad (5\text{-}3)$$

Hd: Heat demand of the heat pump (KW)

SHW: Space heating water (KWh)

t: hours per year of space heating (h)

Considering that heating is required 8 months per year during 24 hours per day:

$$H_d = \frac{65000}{8*30*24} = 11.28 \text{ kW}$$

For security measures the pump is oversized double:

$$P = 11.28*2 = 22.57 \text{ kW}$$

Among the devices available, the heat pump selected is an electrical water-water heat pump for 70KW heating. Weight of the pump is included in the Ökobau.dat dataset, as well as quantity of the materials and processes involved in its manufacturing.

Table 5-16: Biomass boiler and heat pump – Production

	Input	**Component**	**Output Flow**		**Number of units**	**Investment Costs (1 unit)**
			Units	**Value (1 unit)**		
Production	Infrastructure (Biomass boiler)	Pellet boiler 20-120KW	Mass	833 kg	2	22.695 €
		Exhaust gas chimney	Mass	2,6 kg	2	
		Pellet silo	Mass	3427,2 kg	1	2.100 €
		Grant			2	-14.829 €
	Infrastructure (Heat pump)	Elecrical heat pump water-water 70 kW	Mass	1410,9 kg	2	6.500 €

As in scenario 1, a Grant is provided for the installation of a Biomass boiler, in this case of 14.829 € [68], applied to the whole installation cost. Costs of production are detailed in Annex 5.

On the operation stage, refrigerant for the compressor of the heat pump is included in the Ökobau.dat dataset, as well as the electricity required for the compressor. Pellets supply, boilers' efficiency and electricity for the device is also included in Ökobau.dat.
Cost of pellets is provided by Robinson Club Cala Serena [68], electricity costs correspond to Spanish electricity rates (see Annex 5). .
The electricity (E) required by the heat pump is obtained with the efficiency of the pump, COP: 3.8, applying the equation (5-6):

$$E = \frac{H_d \text{ (KWh)}}{\text{COP}} \tag{5-4}$$

$$E=\frac{79.000}{3,8}=20.789,5\ \text{kWhe}$$

Table 5-17: Biomass boiler and heat pump – Operation

	Input	Component	Elementary flow		Operating Costs
			Units	Value	
Operation	Energy source (pellets)	Pellet boiler 20-120 kW	Thermal energy	35.000 kWh/year	4.030 €/year
	Energy source (elecricity)	Electrical heat pump water-water 70 kW	Thermal energy	65.000 kWh/year	2.959 €/year

End-of-life data of the biomass boiler is the same as in scenario 1. Due to missing data, dismantling costs of the heat pump are assumed to be the 20 % of the investment costs.

Table 5-18: Biomass boiler and heat pump – End-of-Life

	Output	Component	Input Flow		Number of units	Dismantling costs (1 unit)
			Units	Value (1 unit)		
EoL	Infrastructure (Biomass boiler)	Pellet boiler	Mass	833 kg	2	2.800 €
		Exhaust gas chimney	Mass	2,6 kg	2	
		Pellet silo	Mass	3427,2 kg	1	480 €
	Infrastructure (Heat pump)	Elecrical heat pump water-water 70 kW	Mass	1411 kg	2	1.300 €

Heated water for heating is stored in a tank and released through underfloor heating. Data required for the distribution system is detailed in paragraph 5.2.4, as well as Domestic heated water distribution system.

5.6 Scenario 4: Solar collectors and heat pump with underfloor heating

In this scenario, in contrast to scenario 2, a solar heating system is supported by a water-water heat pump, with the same combination of sources. 60 % of the DHW is supplied by the solar collectors, and the rest 40 % as well as heating is supplied by the heat pump. Heating is released through an underfloor heating system.
This share is applied based on the assumptions explained in paragraph 434.3.2. Depending on the case study the dimensioning of the components can vary around these values.

The figure bellow shows the model in Gabi 5 of scenario 4, through which the Life Cycle Assessment is conducted. In this case, it is observed the combination of solar and heat pump heat for the thermal energy production.

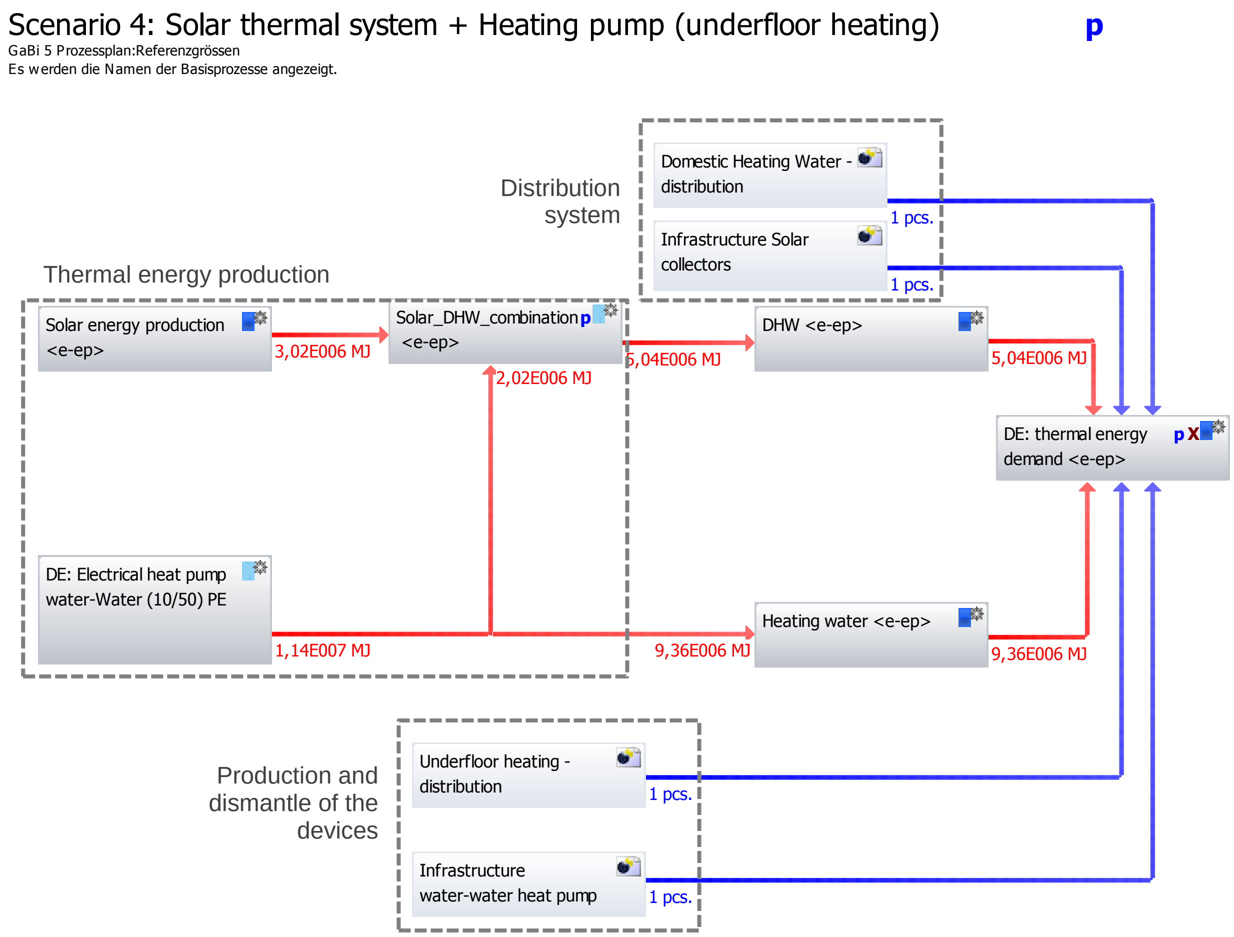

Figure 5-8: Scenario 4: Structure in GaBi 5

For the infrastructure of the solar collectors it is required to calculate the Solar collectors' surface, which is developed in Annex 4.

To dimension the heat pump, the same calculation procedure as in scenario 2 and 3 is developed, with the equation (5-5):

$$H_d = \frac{SHW}{t1} + \frac{DHWb}{t2} \qquad (5\text{-}5)$$

Hd: Heat demand of the condensing boiler (KW)
SHW: Space heating water (KWh)
t1: hours per year of space heating (h)
t2: hours per year of Domestic heated water (h)
DHWb: Fraction of Domestic heated water produced by the boiler (KWh)

$$H_d = \frac{65000}{8*30*24} + \frac{35000*0,4}{365*10} = 15\ kW$$

,
Applying a safety factor of 2:

$$P = 15*2 = 30\ kW$$

Heat pump selected is, thus, an electrical water-water heat pump for 70 kW heating, same case as in scenario 3.

Table 5-19: Solar collectors and heat pump – Production

	Input	**Component**	**Output flow**		**Number of units**	**Investment Cost (1 unit)**
			Units	**Value (1 unit)**		
Production	Infrastructure (Solar collectors)	Glazed flat-plate solar collectors[10]	Area	111 m²	2	36.364 €
		Grant		2	2	-20.175 €
	Infrastructure (Heat pump)	Elecrical heat pump water-water 70 kW	Mass	1410,91 kg	2	6.500 €

As in scenario 2, a Grant is provided for the installation of a solar thermal system, in this case of -20.175 €.
Operating costs are null for the solar system. The electricity (E) required is obtained with the efficiency of the pump, COP: 3.8, applying the equation (5-6)

[10] One unit is equivalent to the total area installed in the building in a period of lifespan.

$$E=\frac{H_d\ (KW)}{COP} \qquad (5\text{-}6)$$

$$E=\frac{79000}{3{,}8}=20789{,}5\ kWhe$$

Costs of electricity correspond to the Spanish rates (see Annex 5).

Table 5-20: Solar collectors and heat pump – Operation

	Input	Component	Elementary flow		Operating Costs
			Unit	Value	
Operation	Energy source (Solar irradiation)	Glazed flat-plate solar collectors	Thermal energy	21.000 kWh/year	0 €/year
	Energy source (electricity)	Electrical heat pump water-water 70 kW	Thermal energy	79.000 kWh/year	2.959 €/year

Due to missing data, dismantling costs of both heat pump and solar collectors are assumed to be 20 % of the investment costs.
Waste materials and quantities and recycling potential of the infrastructures are included in the Ökobau.dat dataset.

Table 5-21: Solar collectors and heat pump – End-of-Life

	Output	Component	Input flow		Number of units	Dismantling Cost
			Unit	Value		
EoL	Infrastructure (Solar collectors)	Glazed flat-plate solar collectors	Mass	1996,5 kg	2	7.273 €/unit
	Infrastructure (Heat pump)	Elecrical heat pump water-water 70 kW	Mass	1411 kg	2	1.300 €/unit

6 Analysis of the results

The third step of a Life Cycle Assessment is the impact assessment.
In an LCA, this process involves associating inventory data with a specific environmental impact categories and indicators [16]. This study aims to analyze together the environmental and cost influence on the four scenarios developed through the methods of LCA and LCC. Therefore, in the Life Cycle Inventory Analysis (LCIA) the significance of potential environmental and cost impacts is evaluated using the Life Cycle Inventory (LCI) results.
LCIA contains four main issues, the first three mandatory: categories definition, classification, characterization and evaluation of the LCIA results.
Impact categories, environmental and economic indicators and their reference units are defined in detail in paragraph 4.4.
In the classification step, LCI results are assigned to their corresponding impact category. Characterization stage consists on the calculation of category indicator equivalent values which, for the environmental impacts, are obtained through the GaBi 5 software for each scenario modeled, using the Ökobau.dat database.
For the costs impacts, the Net Present Value is chosen as category indicator, calculated by applying its formula (see paragraph 4.4) with a discount rate of 6 % to all costs detailed in the LCI in order to obtain the total cost of the scenarios under study over the 40 years.
Environmental and cost relevance of each component of the heating systems in the study period is assessed and interpreted at the evaluation.

6.1 Scenarios

Environmental and cost assessment is, in this chapter, carried out separately for each scenario.
To ensure the comprehensiveness of the results, these are grouped according to the structure of the scenarios described in paragraph 5.2.1, both for the economic and environmental assessment. Domestic heat water distribution and heating distribution results are attached in Annex 6 as additional information to the scenarios analysis.
The magnitudes of the categories are showing the relative value for each component of the scenario under study.
Stages of Production, use, and End-of-life of the components are distinguished on the representation of the results.

Results are referred to the functional unit scaled to the study period, 4.000.000 kWh of thermal energy demand in 40 years.

6.1.1 Scenario 1: Biomass heating system

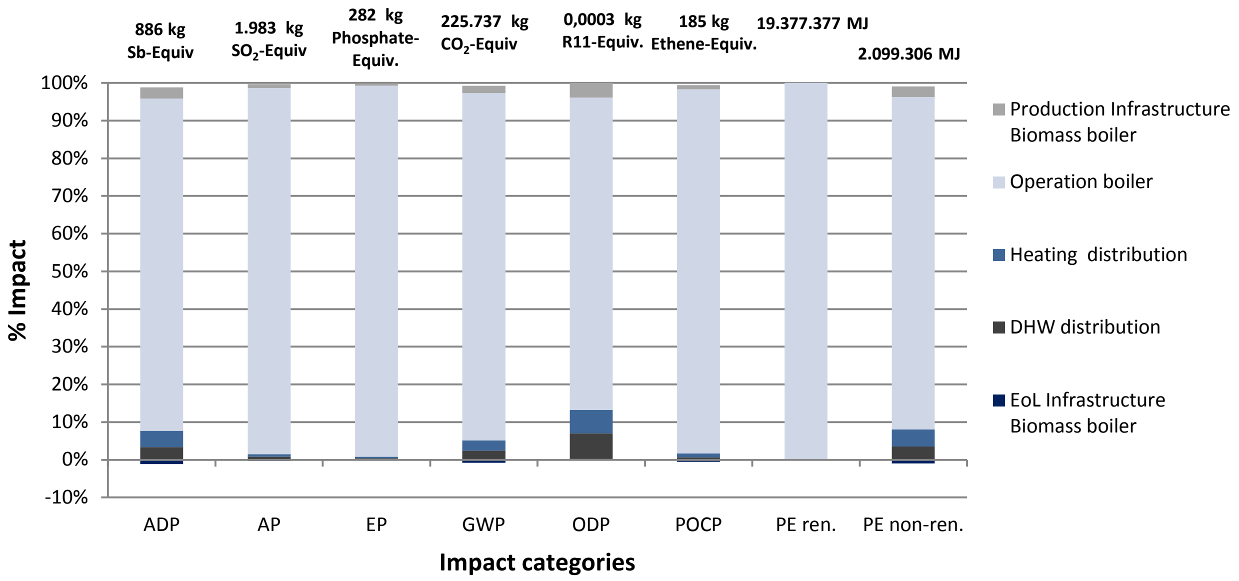

Figure 6-1: Scenario 1 environmental Impacts

As observed in the figure above, the most influential impact factor is the operation of the boiler, which represents more than 80 % of the total impact of the scenario in all categories. Thermal energy produced by a pellet boiler results from the combustion of wood pellets, which involves the release of air emissions, such as CO_2, SO_2 or NO_x, thus affecting considerably to the categories referred to air pollution.

Abiotic depletion and Eutrophication Potential are mostly affected by the operation of biomass boiler due to the requirement of wood as natural resource. Operation stage, due to the requirement of pellets and electricity necessary to the run the boiler, is also predominant on the consumption of primary energy from renewable and non-renewable, respectively.

Heating distribution shows a slight influence as it affects to the Abiotic Depletion Potential and primary energy consumption 4 % on average, mainly due to the production of the radiators and the circulating pumps required (see Annex 6).

Influence of the other groups of components is neglected as they contribute less than 4 % each to the total amounts. Recycling of the components of the devices result on benefits about 2 %.

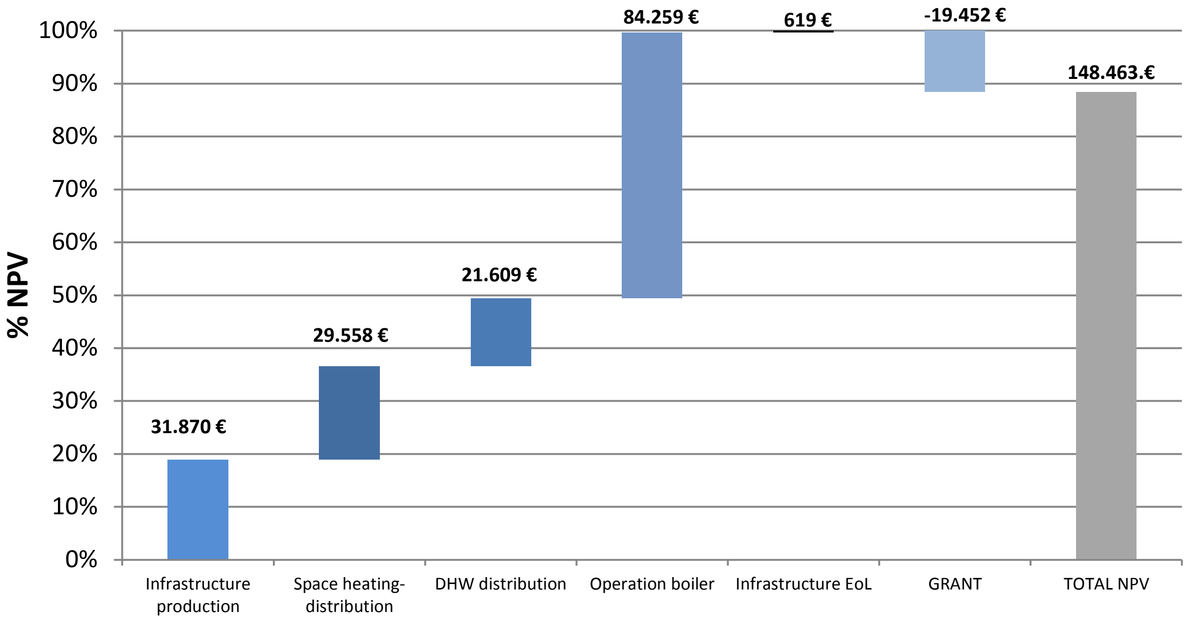

Figure 6-2: Costs distribution scenario 1

Net present value in 40 years of the scenario 1 is of 148.463 €.

As observed in the figure above, half of the total cost corresponds to the operation of the biomass boiler, due to the regular supply of pellets.

Infrastructure of the device must be installed twice, once at year 0 and again at year 20. This brings investment costs of installation up to 19 % of the total amount.

However, Spanish government provides grants to the installation of renewable energy source devices in houses. In this case, the discount applied twice to boiler installed reduces on 11 % the total cost of the heating system in 40 years.

DHW distribution system contributes on 13 % share, mainly due to the installation of the pipeline and the two buffer tanks (see Annex 6).

18 % share of total NPV corresponds to the heating distribution system, mostly because of the installation costs of Radiators, pipes and circulating pumps. Neither infrastructure nor distribution systems replacement and dismantling costs are significant on the total NPV, as they contribute less than 2 % each.

6.1.2 Scenario 2: Solar heating system and natural gas condensing boiler

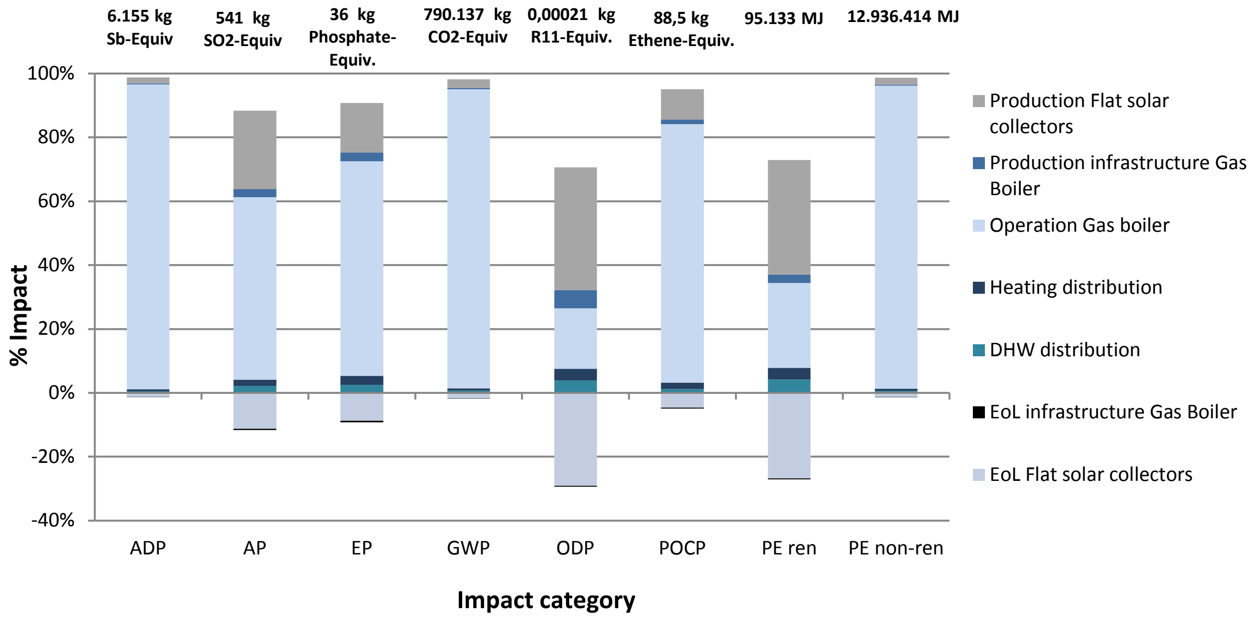

Figure 6-3: Scenario 2 Environmental Impacts

Combustion of natural gas during the 40 years that the heating system operates makes the use phase of the Gas condensing boiler the main influent impact source of this scenario in most of the impact categories. Although natural gas is the cleanest of all fossil fuels and a condensing boiler is high-efficient, the device is still based on combustion of a fossil fuel that releases many different air pollutants, such as CO_2, NO_X or VOC's.

Operation of the gas boiler is responsible of Abiotic Depletion Potential, Global Warming Potential and photochemical Smog in between 80-90 % share of the total amount in absolute values.

In order to reduce the environmental harm that produces a fossil fuel boiler, in this scenario the thermal energy production is combined with a solar heating system device. However, it is required a large quantity of material to manufacture 222 m² of solar collectors necessary to achieve the 60 % of the domestic heated water demand (3.992 kg). On this account, flat solar collectors' production contributes substantially on Acidification Potential (around 25 %), Eutrophication Potential (around 16 %), Ozone Depletion Potential (around 38 %) and Photochemical Smog (around 10 %). Primary energy demand from renewable resources corresponds on around 36 % share to the energy required for the production of materials required for the solar collectors.

In contrast, their impact is highly compensated due to their recycling potential, which reaches up to 30 % reduction on Ozone Depletion Potential, around 10 % on Acidification Potential and eutrophication, and provides an energetic benefit around 27 % on the primary energy demand.

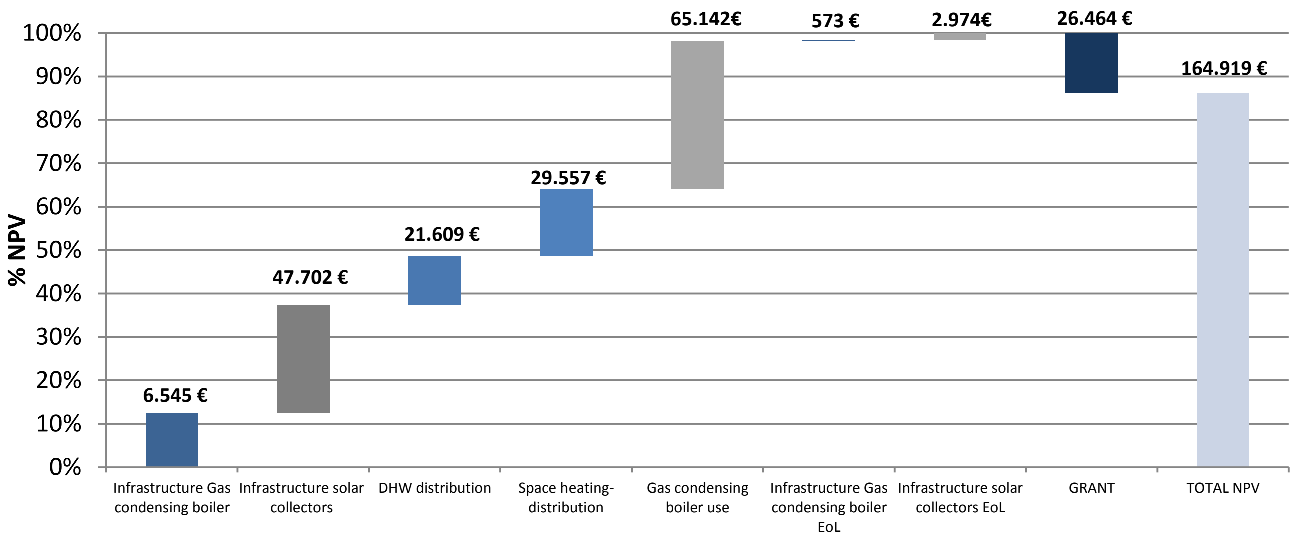

Figure 6-4: Costs distribution scenario 2

Total NPV of this scenario is of 164.919 €.

Flat solar collectors use sunlight as heating source, which is inexhaustible and free. Gas condensing boiler is thus the main responsible of the operation costs, which correspond to 34 % share of the total NPV.

One of the main disadvantages of installing a solar thermal heating system is the manufacture cost and consequently the whole installation price, which sums up to 25 % share in this scenario. However, to promote such facilities, government of the Balearic Islands, where Robinson Club Cala Serena is located, provides grants depending on the size and characteristics of the installation. In this case, the amount is of 37% of the whole installation costs. This discount reduces on 14 % the whole costs in 40 years.

DHW affects around 10 % the scenario NPV, mainly due to the installation of the pipeline and buffer tanks.

Investment costs of the components required for the Heating distribution system are the main influent factors to the total NPV of this group, which represents 15 % share to the total NPV.

Dismantling costs on the end-of-life stage of the whole infrastructure do not play a significant role, with less 2 % share.

6.1.3 Scenario 3: Biomass heating system and heat pump

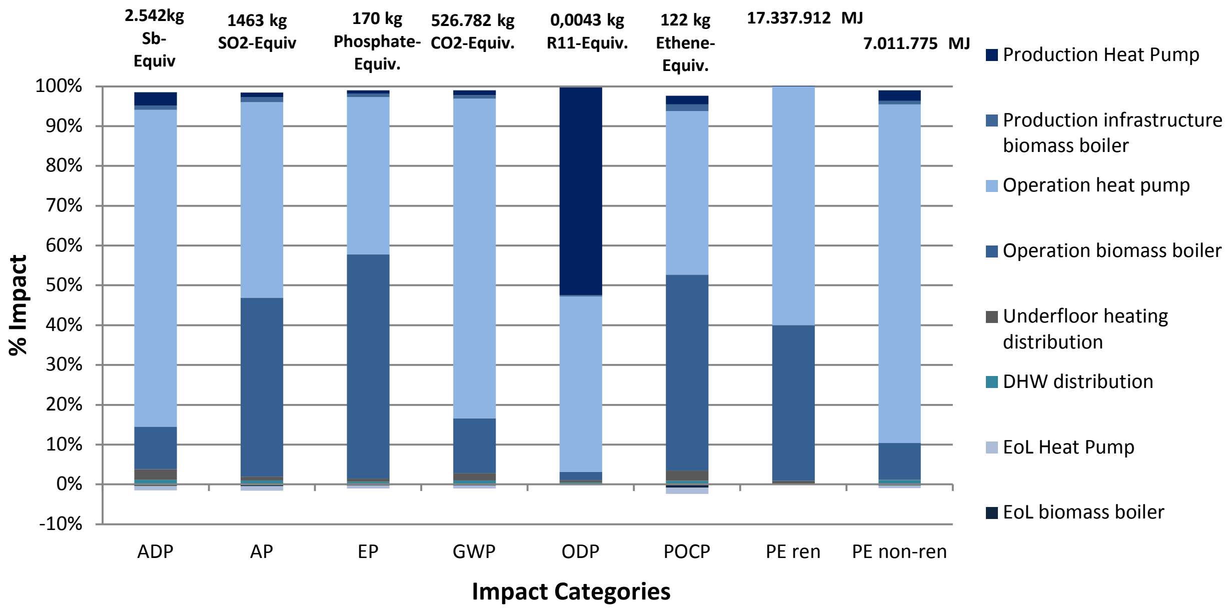

Figure 6-5: Scenario 3 environmental impacts

The two greatest influential groups in this scenario are the biomass boiler and heat pump use stage.

Water-Water heat pumps require electricity to power the geothermal probe and pumps which must be installed to pump the underground water. Moreover, vapor-compression cycle is also powered by electricity.

Therefore is primary energy demand mainly represented by the heat pump operation (60 % of renewable primary energy and around 85 % of non-renewable primary energy). Electricity and pellets required to operate the biomass boiler influence also on primary energy demand, 40 % share from renewable and 9 % from non-renewable sources.

Around 80 % share of Abiotic Depletion Potential and Global Warming Potential is also produced by the operation of the heat pump, whereas 10 % share is caused by the pellets combustion on the biomass device.

The two energy production sources of this scenario affect also Acidification Potential and Photochemical smog on between 45-50 % share. Biomass boiler operation predominates over Heat pump operation with 56 % versus 40 % share on the Eutrophication Potential.

Ozone Depletion Potential category breaks the trend of the scenario with 52 % share due to the manufacturing of the heat pump. Heat pump use stage is the other predominant factor with 44 % share. This is due to the use of hydrochlorofluorocarbons (HCFCs) as working fluid to the heat transmission inside the heat pump (0,00227 kg R11-eq for the production and 0,00192 kg R11-eq for the use of the heat pump).
Influence of the rest groups of components is neglected, since their contribution is below 2 % each.

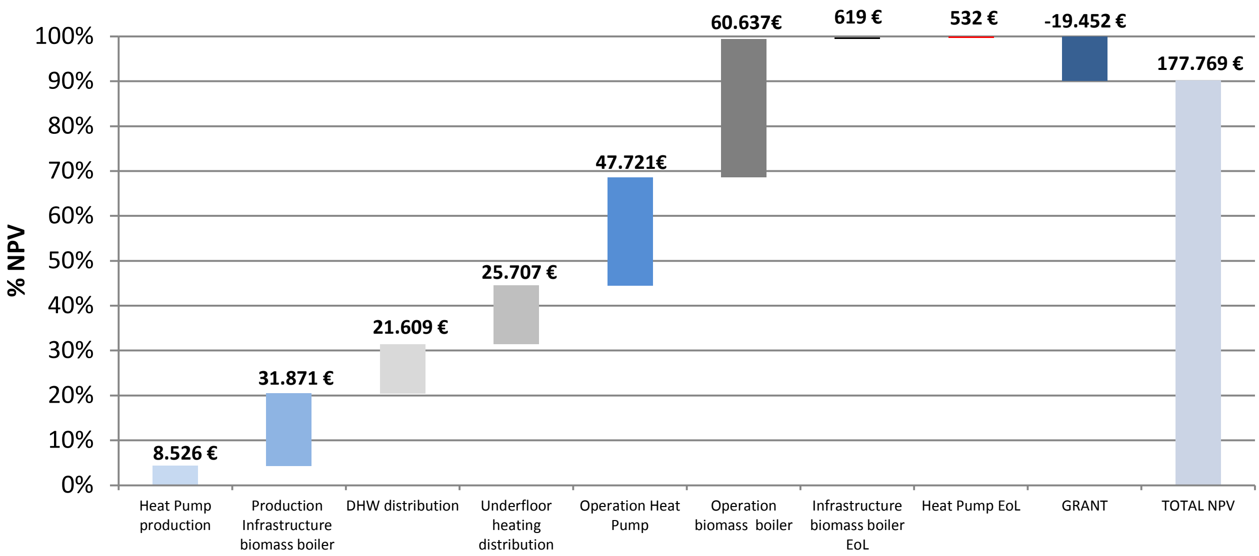

Figure 6-6: Costs distribution Scenario 3

Operation costs of the devices in this scenario are based on energetic costs. The figure above shows the difference between electricity rate to power the heat pump, which represents around 24 % share of the total NPV and pellets cost to run the biomass boiler, which increases up to around 31 % share.
Investment costs of the biomass system remains on 16 % share. Nevertheless, NPV of the scenario is reduced on a 10 % thanks to the grant applied to the price of the biomass heating system installation, which has a net value in 40 years of 19.452€.
DHW distribution system cost is around 11 % share mainly due to the cost of pipes and buffer tanks. Underfloor heating cost, assembled in panels, involves 13 % of the total NPV of the scenario. Around 4 % share corresponds to the installation of the heat pump.
Net Present Value of End-of-life costs for the infrastructure of both biomass boiler and heat pump are insignificant, as they account less than 2 % on the total NPV.

6.1.4 Scenario 4: Solar heating system and Heat pump

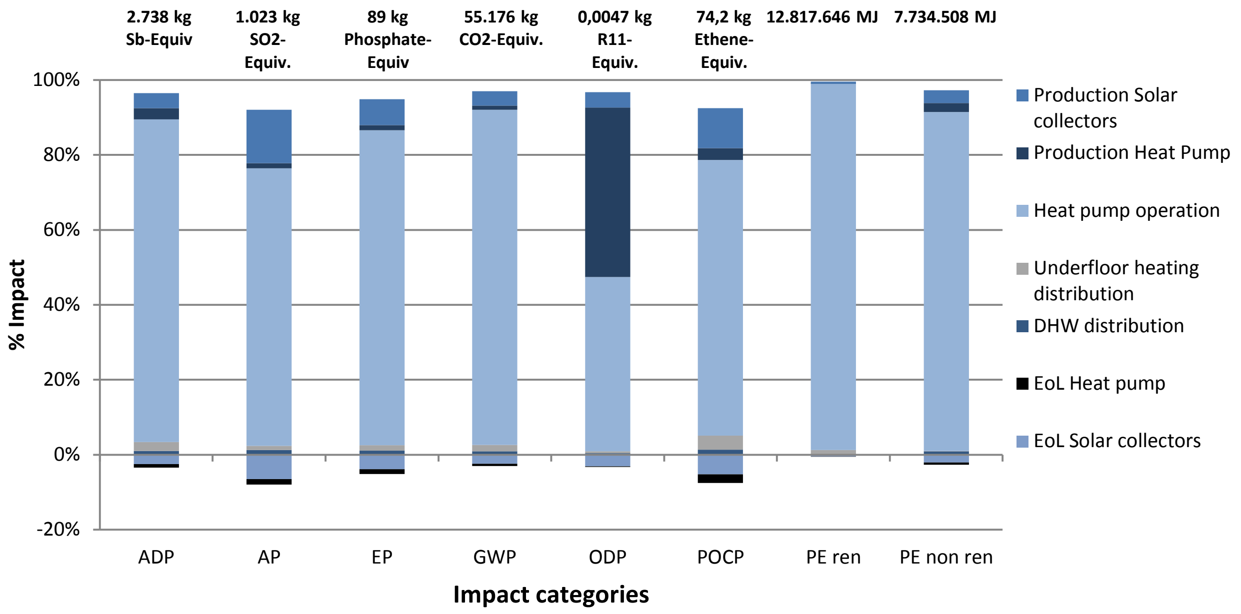

Figure 6-7: Scenario 4 environmental impacts

Scenario 4 combines a solar thermal heating installation which supplies 60 % of the DHW demand and with a water-water heat pump that supplies the rest of the DHW and heating, which is released through an underfloor heating system. As shown on the figure above, Heat pump operation is in this scenario the main contributor to most impact categories considered. Due to the high amount of electricity required, its influence remains around 80-90 % share in all categories except in ODP.

The use of hydrochlorofluorocarbons (HCFCs) as working fluid for the heat pump affects Ozone Depletion Potential. 45 % share corresponds to the manufacturing of the pump, whereas other 45 % is caused by its operation.

Production of solar collectors´ system contribute significantly to the categories of Acidification Potential (around 15 %), eutrophication (7 %) and photochemical smog (11 %), and their recycling confers benefits to these categories on 7 %, 4 % and 5 % share respectively.

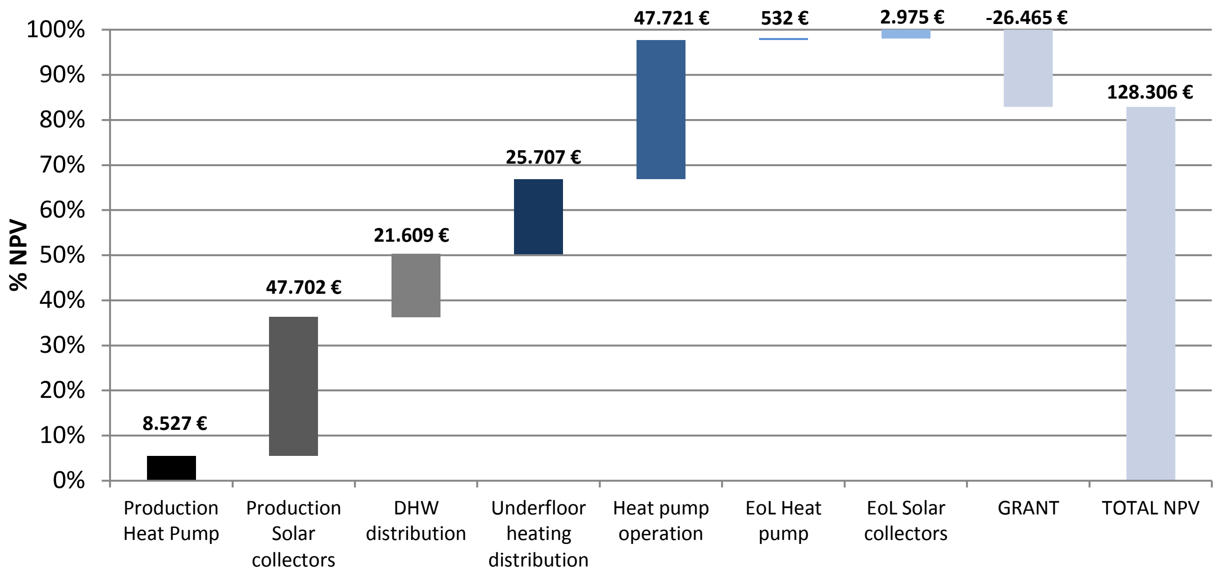

Figure 6-8: Costs distribution scenario 4

NPV calculated for this scenario sums up to 128.306€.

Production costs of the solar collectors together with electricity costs to run the heat pump constitute the most influential groups to the total NPV of the scenario, with 30 % share each.

The NPV of the grant provided by the government of the Balearic Islands regarding to solar thermal heating systems is of 26.465 €, which reduces the total NPV of this scenario on around 17%.

Underfloor heating investment costs are around 25.700€, which means 16 % share, whereas domestic heated water distribution system influences on 14 % share.

Production and installation of a heat pump system represents around 5,5 % of the total cost of the heating system.

End-of-life costs are negligible as they constitute less than 2 % of the NPV.

6.1.5 Comparison of the scenarios

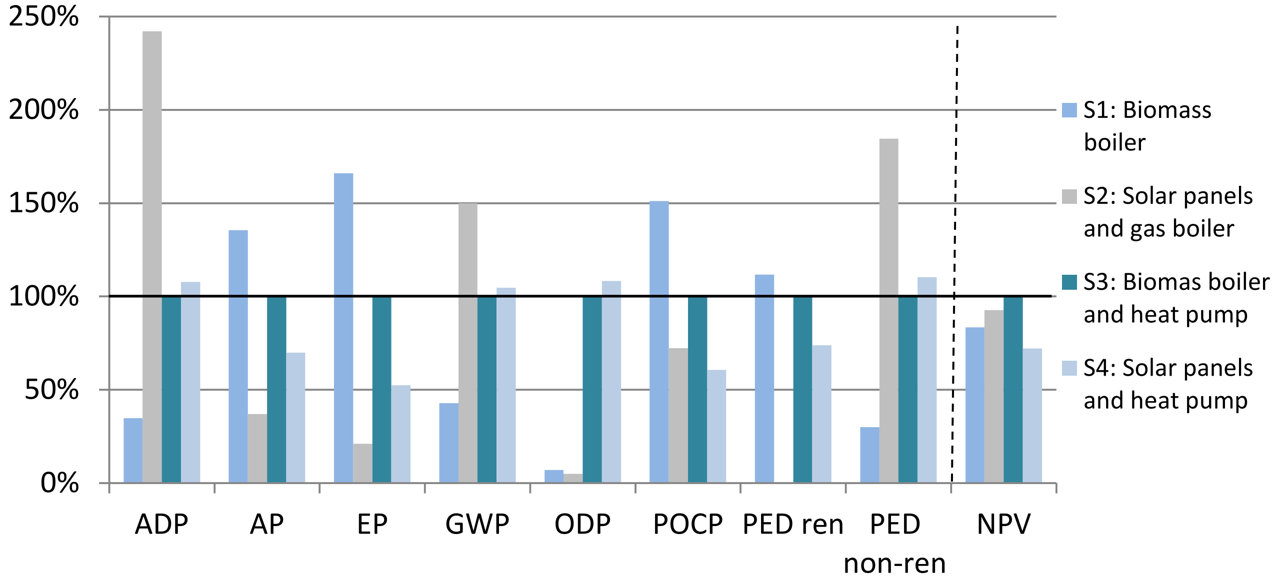

Figure 6-9: Comparison of the scenarios

In order to have an insight of the general differences between the four scenarios under analysis and compare them, the results obtained, both environmental and economic are referred to scenario 3, biomass heating system combined with a water-water heat pump.

The selection of the base scenario relies on the ratio values and therefore on the display of the results. However, base scenario can be chosen according to user priorities.

As observed in the figure, solar panels combined with a natural gas condensing boiler, namely scenario 2, is the one that shows major differences from scenario 3, being between 1,5 and 2,5 times higher Abiotic Depletion Potential, Global Warming Potential and Primary energy demand from non-renewable sources indicators, mainly due to the use of as natural gas as fossil fuel.

In contrast, Primary energy demand from renewable resources in scenario 2 is around 200 times lower than scenario 3 due to the use stage of the gas boiler, Ozone Depletion Potential around 20 times lower, as well as 5 times the Eutrophication Potential, primarily due to the use of HCFCs in the heat pump of the base scenario.

Acidification Potential and photochemical smog show values between around 3 and 1,5 times lower than the base scenario, respectively.

The use of a heat pump in the base scenario distinguishes scenario 3 from Scenario 1, which has only a Biomass boiler heating system, currently installed on the building studied.
The fact that in scenario 1 only one heating device is installed, explains that Abiotic Depletion Potential, Global Warming Potential and Primary energy demand from non-renewable sources are around 2,5 and 3,5 times lower values than in scenario 3.
However, in scenario 1 the biomass boiler is responsible of the production of all the heat demand, which makes Acidification and Eutrophication Potential, photochemical smog and primary energy demand from renewable sources around 1,1 and 1,6 higher than in scenario 3, which has less combustion products and requires less wood for the biomass boiler.

In scenario 4, a water-water heat pump is combined with solar panels which supply 21 % of the total heat demand, whereas the biomass boiler used in scenario 3 supplies the 35 % of total heat demand.
Photochemical smog, Acidification Potential, Eutrophication Potential and primary energy demand from renewable sources show a difference downward of between 1,3 and 2 times due to the use of solar energy in this case, instead of the wood pellets used in scenario 3 or base scenario.
Rest of the categories show a slightly rise from around 4 % to 10%.

Relating to costs, the highest Net Present Value for the 40 years of study corresponds to the scenario 3, biomass heating system combined with a water-water heat pump, with a total value of 177.769 €. Scenario 2 has a forecast NPV of 164.919 €, 7% lower than scenario 3, followed by scenario 1, with a NPV of 148.462 € and 20% lower than scenario 3. The lowest NPV corresponds to scenario 4, of 128.306 €.

6.2 Integrated Life Cycle Cost Analysis

Throughout the life cycle of a product system, LCA addresses the environmental aspects and potential environmental impacts, whereas LCC is used to evaluate the cost performance. Both allow comparison among different investment scenarios, designs and specifications.

In order to approach sustainable designs and respond to stakeholders demand, it is essential to come up to an integrated evaluation method which includes not only environmental, but also cost performances; so that users can base their decision on the combination of the most environmental friendly with the most economical feasible over long-term. This concept is currently known as eco-efficiency, which comprise product value and environmental input in a life cycle perspective, and can be analyzed bringing together both LCA and LCC methodologies in a Life Cycle Cost analysis (LCCA).

Nevertheless, there is still no defined methodology to apply LCCA. This year has been published the latest version of the draft of the norm DIN EN ISO 14045:2012 [17], a guide of eco-efficiency assessment of product systems, which introduces the requirements and guidelines to analyze together environmental aspects with product value indicators, but not specifically economic.

The integrated assessment intends to create results in two dimensions, economic and environmental. Therefore it is necessary to consider working with the many variables involved, which in this study are six environmental impact categories, two energy indicators and one economic indicator calculated for four different scenarios.

In this chapter are suggested two different ways to display and interpret the results.

6.2.1 Proposal for an integrated eco-portfolio

The results of the life cycle assessment and the life cycle cost are processed to obtain an eco-portfolio. Foremost, environmental impact results are transformed to one single environmental impact factor, so that it can be directly compared to the economic factor, in this study the NPV.

This brings out the problem that the different categories cannot be grouped together directly, so they have to be normalized calculating the magnitude of the category indicator result relative to reference information. In this case, the results obtained for each scenario in the six environmental categories considered (see Annex 7) are referred to the total amount of these categories in Europe, available in the GaBi 5 database [63]. (see Annex 8), so that index values for each environmental category and each scenario are obtained.

Once the results become dimensionless, indicator results are converted to a single value by weighting.
According to the ISO 14044 [16], weighting consists on converting and possibly aggregating indicator results across impact categories using numerical factors based on value choices.
These numerical factors are subjective, usually based on user priorities or in experts on the field. Still, it can be applied for eco-efficiency assessment [17].
In this study, a survey has been carried out on the University Stuttgart, Chair of Building physics, Life Cycle Engineering department, which includes 20 members' expertise on LCA. They were asked to weight the importance of each environmental category according to their knowledge and personal experience.
Members were to consider when assessing the following system boundaries:
The independence of the type of product, Europe as geographic boundary and pre-chains involved in the system spread around the world.
The table below shows the weighting factors resulting:

Table 6-1: Wieghting factors

Impact category	Weighting factor
ADP	19,9 %
AP	16,2 %
EP	16,5 %
GWP	22,1 %
ODP	10,6 %
POCP	14,9 %

These factors are a suggestion and only based on subjective criteria, so its value can vary according to users priorities.
Finally, index values obtained from the normalization are weighted, and the results obtained of each category are summed for each scenario, leading to an environmental impact factor. As the order of magnitude of the resulting values is of around 10^{-8}, they are multiplied by the factor 10^{+8} so that they become higher than 1 and, thus, more understandable.
The resulting environmental impact factor can be represented together with the economic factor, NPV, in a double dimension graph or eco-portfolio, shown in the figure below.

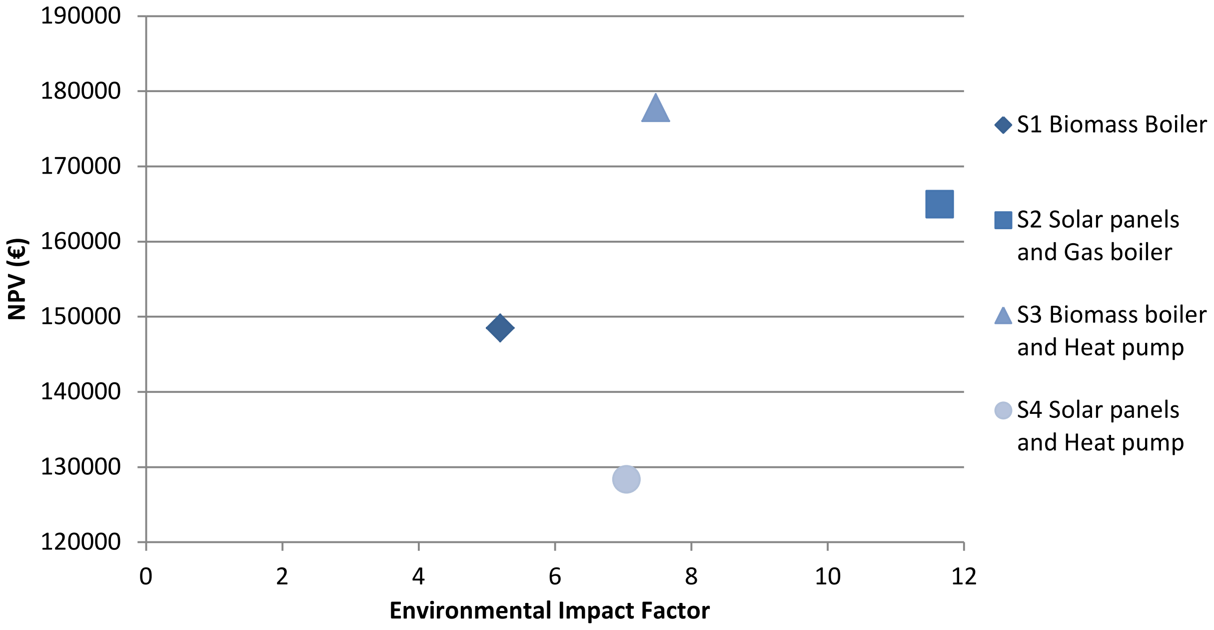

Figure 6-10: Integrated Eco-portfolio

It can be seen that, based on the assumptions, the most eco-efficient systems correspond to the current status of the study, a biomass heating system, with a normalized impact factor of 5,2 and a NPV of 148.463 €, and to Scenario 4, a solar thermal heating system combined with a heat pump. It has the lowest NPV, 128.306 €, but its impact factor rises to 7,05.

More remote are found scenarios 3 and 2. Biomass boiler combined with heat pump shows an average impact factor of 7,5, slightly higher to scenario 4, but its cost increases highly to 177.768 € . Scenario 2 costs are of 164.918 €, and its environmental impact factor is of 11,6.

Depending on users' preferences and the systems conditions, the most favorable alternative is scenario 1 or scenario 4, whereas the less eco-efficient is scenario 2 or scenario 3.

6.2.2 Proposal for a decision-making and evaluation criteria

The decision of the most eco-efficient alternative can also be made directly according to user priorities or by dismissing options. In this case an elaboration of a ranking is suggested.

On a first step, some impact category indicators are dismissed. In this study, three of them are selected among the 8 environmental category indicators considered according to the survey conducted among experts explained in the previous paragraph 6.2.1. These are Abiotic Depletion Potential, Eutrophication potential and Global Warming Potential. It is important to note that these selections are subjected to the opinion of those polled.

Afterwards, an eco-portfolio of these three categories is conducted:

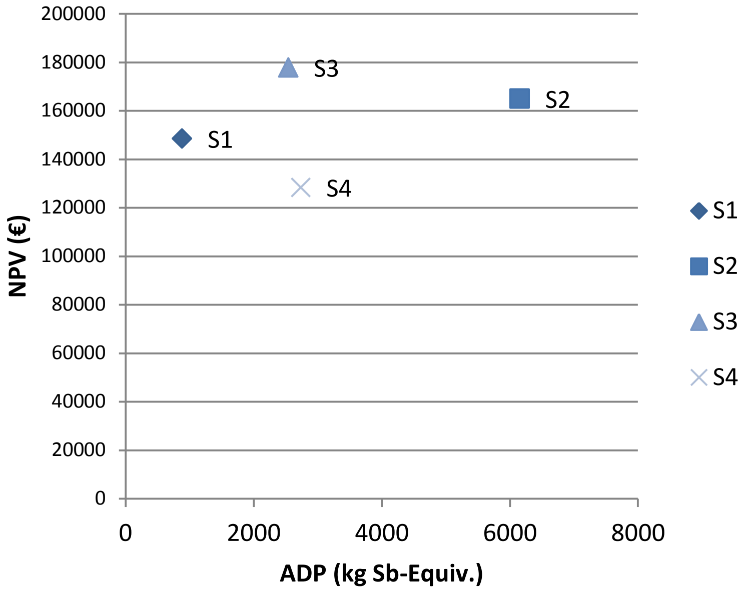

Figure 6-11: Eco-portfolio ADP vs. NPV

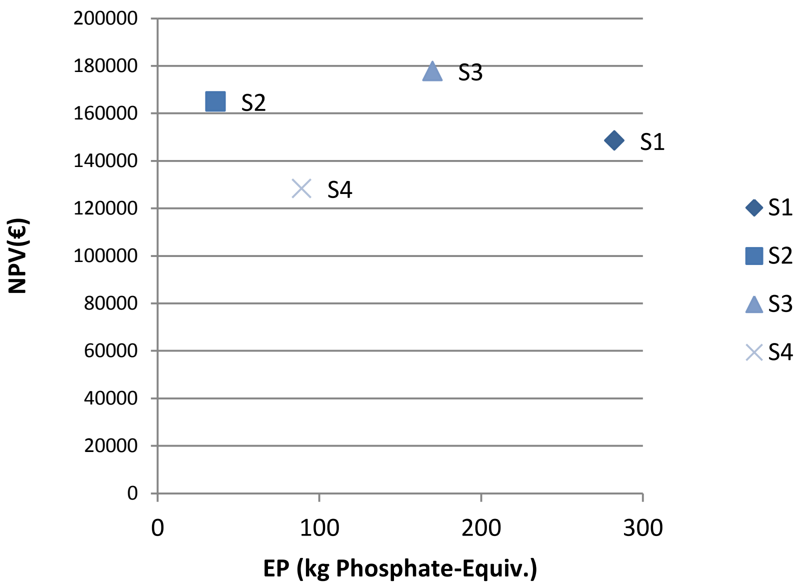

Figure 6-12: Eco-porfolio EP vs. NPV

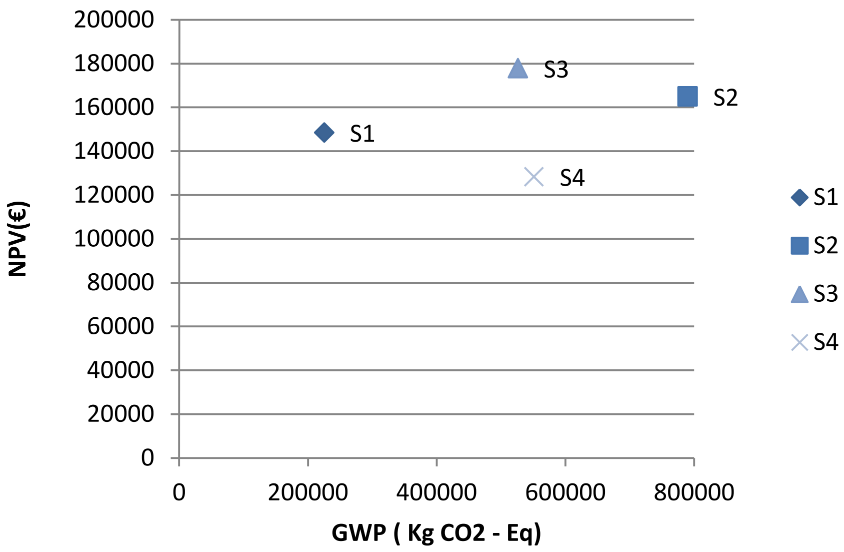

Figure 6-13: Eco-portfolio GWP vs. NPV

The figures above show the correspondence of the impact category amount selected to the total NPV of the four scenarios. According to the preferences of the user, best alternative can be identified. In this study it is considered the best alternative the one which less environmental impact and less cost. The higher this values, the less favorable is the alternative. Environmental and economic impacts are weighted equally, so the scenario closest to the origin corresponds to the most favorable alternative.
Under this premise is a ranking established. Each scenario gets a score depending on its efficiency. Figure 6-14 shows the ranking established.

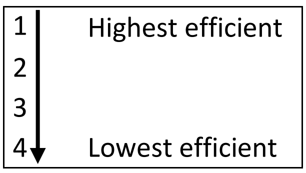

Figure 6-14: Efficiency Ranking

Table 6-2 shows resulting matrix with the score for each environmental category and each scenario.

Table 6-2: Results Matrix for the scenarios

	ADP	EP	GWP	TOTAL
S1	2	4	1	**7**
S2	4	2	4	**10**
S3	3	3	3	**9**
S4	1	1	2	**4**

As observed in the table above, and considering the assumptions, the alternative that best meets the necessities is scenario 4; solar thermal heating system combined with a heat pump. Scenario 1, current status of Cala Serena´s employee's house, takes the second position, because of its high contribution to Eutrophication Potential. Scenario 3, a biomass boiler combined with a heat pump, scores the third position in all impact categories. Finally, scenario 2, which has a Natural gas condensing boiler combined with solar panels, shows to be the most unfavorable.

Although the weighting criteria applied is the same in both examples, half the categories considered in the integrated eco-portfolio are rejected in the ranking method. Moreover, normalization applied to find the environmental impact factor on the integrated eco-portfolio transforms absolute values to index values, whose orders of magnitude depend on the reference value, which is not used on the ranking method.
It should be remembered that weighting factors are subjective and involved discussion among the stakeholders. Moreover, these results are specific for this case study. The energy concept of the building is not considered, and components are selected and dimensioned according to the specific case of Robinson Club Cala Serena Employee´s house.

6.3 Discussion of the results

On the analysis of the scenarios separately it is observed that, both for the environmental impacts and for cost distribution, the most influential factor in their life cycle is the operation stage of the heat devices. The constant requirement of fuel during the 40 years against the specific investments in a point of time bring the use stage to be around 80 % contributor of the total environmental impact of each category in all scenarios and around the 40-50% of the total Net Present Value of each scenario.
This means, that if the energy required to achieve the heat demand is reduced, increased or replaced, the amount of environmental impact and the total cost will be strongly affected.

When comparing the scenarios, the heating system with a natural gas condensing boiler combined with a solar thermal heating system, namely scenario 2, shows the major differences with the other three scenarios modeled, mostly in the primary energy demand from non-renewable sources, in the Abiotic Depletion Potential and in the Global Warming Potential. These three indicators are strongly connected to the use of a fossil fuel to run the device.

Analyzing deeply, it is noted that in this scenario natural gas costs in the 40 years of study show to be the highest among all the other fuel costs involved in all scenarios, with the only exception of the scenario 1, where a biomass boiler is the only responsible of the heat supply. Costs of infrastructure of the solar collectors are also the highest compared to other infrastructure costs involved in the study.

The high quantity of material required for the production of solar panels and the complexness of the production turns them into high contributor to the environmental impacts of this scenario, although their impact is highly compensated with the recycling process of the panels, which provide a significant benefit that reaches until 30% of the total impact in some categories.

Although the operation stage of the scenarios is the determining factor on the impacts evaluation for all scenarios, these results are specific for the case study. The impacts resulting from the operation stage depend strongly on the characteristics of the energy source. The primary energy demand of any system is associated to a primary energy factor, which varies according to the type of fuel and its properties.

Consistent with the already said, in the integrated assessment scenario 2 shows to be the most unfavorable alternative in the two analyses proposed.

On the other side, scenarios 1 and 4 result the most favorable, with less impact factor and less NPV. The second alternative shows exchanged results, although at any rate they are far from scenarios 3 and 2.

The two methodologies suggested are subjected to user’s priorities. Depending on the weighting of the environmental factors or the ranking established, the decision of an alternative can vary. Besides, results can also depend on the weighting of environmental and economic factors, which is not applied in this study.

7 Summary and Outlook

Construction projects, which are very long lasting, require decisions on their design which have a long-term effect. The approach of sustainable construction designs is improved by Life Cycle Assessment and Life Cycle Costing studies, which will be integrated in a single evaluation tool in the CILECCTA project (funded by the EC 7th FP).

The goal of this study is to develop an integrated environmental and economic assessment of the life cycle of four combinations of heating and domestic heated water systems within the specific case of the employee’s house of the Mediterranean resort Robinson club Cala Serena; located in Mallorca, Spain; to use it as a reference model for the validation of the CILECCTA tool.

Following LCA methodology, the study is conducted according to the standards DIN EN ISO 14040 [15] and DIN EN ISO 14044 [16]. LCA and LCC boundaries include production, use and end-of life stages of the heating systems, namely a cradle-to-grave analysis.

The functional unit is the thermal energy demand of the house in one year, which is 100.000 kWh, including domestic heated water and heating. The study period is of 40 years. Therefore, this functional unit is extended to 4.000.000 kWh of thermal energy in 40 years. Thermal energy distribution corresponds to the current requirements of the house, 65% space heating and 35% domestic heated water.

As a starting point, the first scenario selected is the current status of the building, which has a Biomass heating system installed. Three more scenarios are chosen under the premise of considering sustainable alternatives. Solar thermal heating system combined with a natural gas condensing boiler, and a water-water heat pump combined with a biomass heating system and with a solar thermal heating system. The energy production mix for each scenario is specific for this case study. Depending on every case study conditions and assumptions the components selected, their dimensioning and their characteristics can vary. The energy concept of the building is not considered on the design of the scenarios.

With the cooperation of Robinson Club GmbH [68], technical and economic data related to the current status of the heating system of the building is provided.

With the data available, dimensions and technical requirements of the devices installed in the other three scenarios are calculated. Economic information related to the components is compiled among manufacturers, suppliers and technical catalogs.

LCA for environmental impacts is carried out through the modeling of the scenarios with the software GaBi 5 [63]. Environmental datasets of the components in the stages of production, use and end-of-life are compiled in the professional Ökobau.dat database [7], which includes material properties and emissions inventory for the components required. Scenarios are specified with the technical data collected and scaled linearly over the study period, over which most of the components are dismantled and replaced at least once.

Cost performance is conducted through a LCC. Costs are classified in installation, operation and dismantling and applied over the study period. The economic indicator selected is the Net Present Value, which enables to translate costs from a future point of time to the present applying an interest rate over time, in this case 6%.

Technology development is not considered in this study, since components replaced in the future during the study period are assumed to have the same characteristics that the ones in the present. Neither is considered the costs development. Energetic costs such as fuel or electricity remain constant every year, so do investment costs of installation when components are replaced. Current government of Spain provides grants to the biomass and solar thermal energy systems, which are also included in the study when these devices are installed. Future value of this amount is considered the same as the present value.

Once the data is collected in the Life Cycle Inventory, it is processed into the impact dimensions, which are six environmental categories (GWP, AP, ADP, POCP, ODP, EP), two energy indicators (PE ren and PE non-ren) and one economic indicator (NPV).

The evaluation of the results shows the strong influence of the operation stage of the devices, due to the continuous demand of fuel or electricity during the study period.

On the comparison of the four scenarios is observed that LCA results for scenario 2 show to be the highest, due to the combustion of natural gas. Scenario 3 results to be the most expensive, because of the steady requirement of pellets and electricity.

On the integrated assessment the impact dimensions analyzed in this study are brought up together in a Life Cycle Cost Analysis through two methodologies suggested.

On the first proposal, results of the environmental impact categories are gathered in an environmental impact factor, which can be directly compared to the NPV, in a double-dimension graph, namely eco-portfolio.

This impact factor is calculated first by normalizing the environmental impact quantities referring them to a reference value, in this case total amount of these categories in Europe. Index values obtained are weighted and summed resulting on the impact factor

On the second proposal, a decision-making criteria is established, based on the creation of a ranking. An individual eco-portfolio is made for three selected environmental impact categories. Results of the eco-portfolios are translated into a score system for each scenario.

In both methodologies, no difference is made on the importance of the environmental impact versus the cost, so the most eco-efficient alternative is the one with less cost and less impact factor.

There is no current standardized methodology for integrated LCCA methodologies. DIN EN ISO 14045 provides guidelines for the application of eco-efficiency, that enables to consider life cycle environmental impacts together with product value, but it is still a draft. Gathering environmental categories into one single impact factor depends still in subjective decisions. They are quantified in different units, and normalization reference values as well as weighting factors depend mostly in user priorities. However, these methodologies could be a start point to do a step forward on this field and find out how to approach objectivity.

Two key aspects of further development are identified, which will be hard improved by the CILECCTA tool: On the one hand, the invariability of the scenarios over time; on the other hand and also as a consequence of the foregoing, the deterministic nature of the study. Performing over long term in the future involves high level of uncertainty that offers a wide range of possibilities on the development not only of the economic market but also on environmental impact rates, as well as on science and technology. Political decisions and social trends are hardly predictable and affect directly to economic and environmental tendencies. Nevertheless, to apply current LCA and LCC methodologies in this study, precise data inputs are required, so that precise Life Cycle Inventory Results are obtained. CILECCTA takes account of future uncertainty, replacing a single prediction about the future with scenario modeling over a range of possible futures. With a repertoire of possible inputs, LCC and LCC results will work out as probability distributions, providing a more realistic basis for decision-making.

This study provides a reference model to support the development of the CILECCTA tool, which will allow conducting integrated LCCA by taking into account future uncertainties. Therefore, it is an important contribution to the field of sustainability assessment

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Affidavit

Affidavit

I hereby declare that I wrote this thesis on my own and without the use of any other than the cited sources and without any help except the participation of persons, companies and institutions mentioned in the acknowledgments.

Furthermore, I declare that the thesis has not yet been handed in neither in this nor in equal form at any other official commission.

Stuttgart, 06. July 2012

Amalia Sebastiá Puig

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Amalia Sebastiá Puig.

Annex 1

Permitted atmospheric emission limits in Spain [66][67][23]:

Component	Limit value	Concentration (µg/m3)	Max. Nr. of exceedances	Year of application
Dust (<10µg)	Annual average	40	35days/year	2005
	Daily average	50		
SO2	Daily average	125	3days/year	2005
	Hourly average	350	24hours/year	
	Alert level	500		
NO2	Annual average	40	18hours/year	2010
	Alert level	200		
CO	8hours average	10000		2005
NOX	Annual average	30		2001

Annex 2

Description of the impact categories [56]:

Impact category	Short description	Examples
Abiotic Depletion potential (ADP)	Extinction potential of nonliving natural resources, including energetic re-sources	Fuel Oil, coal…
Global Warming Potential (GWP) (100 years)	Air emissions which affect the heat balance of the atmosphere	CO2; CH_4
Acidification (AP)	Air emissions which cause rain water acidification	NOX; SO_2
Photochemical smog (POCP)	Air emissions which act as ozone re-flections to the ground	CHs
Eutrophication (EP)	Eutrophication (excess of nutrients) in waters and soils	P and N compounds
Stratospheric Ozone Depletion (ODP)	Air emissions, which contribute to the formation of tropospheric ozone	VOC

Annex 3

List of parameters

Parameter	Type	Formula	Value	Unit	Description
Thermal energy demand					
TED.Total_thermal_energy	Global, free		4000000	KWh	Energy demand in 40 years
cons_DHW	Local, Fixed	share_DH_water*total_heat_d		KWh	Consumption of Domestic heated water
cons_HW	Local, Fixed	share_heat_wate*total_heat_d		KWh	Consumption of space heating water
share_DH_water	Local, Fixed	1-share_heat_wate			[%] [0;1] share of DHW of total energy consumption
share_heat_wate	Local, Free		0,6		[%] [0;1] share of HW of total energy consumption
total_heat_d	Local, Fixed	TED.Total_thermal_energy	4000000	KWh	standard: 4 million in 40 years
Biomass system - infrastructure					
Concrete	Local, Fixed	1-steel	0,98	kg	[%] [0;1] kg concrete per kg silo
steel	Local, Free		0,02	kg	[%] [0;1] kg reinforced steel per kg silo
silo	Local, Fixed	steel+concrete		kg	1 kg pellets silo
Heat pump system - Underfloor heating-distribution					
underfloor	Local, Free		616	m²	Heated surface in 40 years
underfloor_100	Local, Free		0,7	m²	[%] [0;1] Surface ratio with 100 mm pipe bend radius
underfloor_200	Local, Fixed	1-underfloor_100			[%] [0;1] Surface ratio with 200 mm pipe bend radius
Area_100	Local, Fixed	underfloor_100*underfloor		m²	Surface with 100 mm pipe bend radius
Area_200	Local, Fixed	underfloor_200*underfloor		m²	Surface with 200 mm pipe bend radius
Weight_Area_100		Area_100*1,43		kg	1 m² underfloor heating=1,43kg
Weight_Area_200		Area_200*1,43		kg	
Scenario 2: Solar thermal system + Gas Condending boiler					
share_DHW	Local, Free		1	KWh	Demand of domestic heated water
Boiler_DHW_dema	Local, Fixed	TED.Total_thermal_energy*share_DHW*0,4		KWh	DHW supplied by the boiler (40 % demand)
solar_DHW_deman	Local, Fixed	TED.Total_thermal_energy*share_DHW*0,6		KWh	DHW supplied by the collectors (60 % demand)

Annex 4

Calculation of component dimensions

Solar collectors' surface

Geographic data from Mallorca and the calculation procedure are obtained from the technical specifications of low-temperature facilities developed by IDAE [48]:

I_h= 15 MJ/m²d	Daily horizontal irradiation, year average
L=39,6°	Latitude
N=49,6°	Inclination required: L+10°
K=0,86	Correction factor, worse case. (Tabulated)

Irradiation on sloped surface (N°):

$$I_o=\frac{I_h*K}{3,6}=\frac{15*0,86}{3,6}=3,46\ \frac{KWh}{m^2*d}$$

Estimated annual irradiation:

$$I_{tot}=Io*365=1262,3\ \frac{KWh}{m^2}$$

Solar thermal heating systems are design to cover around 60 % of the domestic heated water demand.
As detailed in chapter 3.2.1, efficiency of glazed flat-plate collectors is around 15 %

DHW=35000 kWh/year	Domestic heated water demand
SolarW= 21000 kWh/year	Heated water from solar collectors(coverture 60%)
η = 15 %	Collectors efficiency

Solar collectors' surface:

$$S=\frac{DHW}{I_{tot}}*\frac{1}{\eta}=\frac{21000}{1262,3*0,15}=110,9\ m^2$$

Radiators

Number of radiators installed: 35

Weight: 1,3 kg/column
Heat release (1 columns): 0,03 kW

Radiators are extended to 10 columns each:

Heat release: 0,03 kW/column * 10 columns = 0,3 kW/radiator
Weight:

m= 1,3*10 = 13 kg/radiator

Pipeline

Pipe dimensions are provided by Robinson Club Cala Serena. Weight is obtain from tabulated values available in Ökobau.dat datasheet.

Pipe dimensions		
DHW		
Øint x thickness	Length (m)	Weight (kg/m)
25 x 3,5	178	0,23
32 x 4,4	21	0,37
40 x 5,5	2	0,58
50 x 6,9	3	0,9
16 x 1,8	160	0,12
SHW		
20 x 2,8	260	0,15
25 x 3,5	66	0,23
32 x 4,4	34	0,37
40 x 5,5	10	0,58
50 x 6,9	10	0,9

Annex 5

Data collection costs.

Energetic Costs

Electricity [58]	0,152559 € /kWh	
Natural gas [37]	47,91 € /month	Fix rate
	0,049902 € /kW	Variable rate

Robinson Club Cala Serena [68]

Component	**Cost**	
Biomass boiler 20-120 kW	22.695 €	1 piece
Pellets cost	0,31 €	1 kg
Pipeline 365m PP	11.057 €	365m
Storage tanks DHW 750 l capacity	4.104 €	2 tanks
Buffer storage 1650l steel	1.093 €	1tank
Pipeline 480m PP	9611 €	480m
Radiators	7853,17 €	Installation
Circulating pump 750 W	2457 €	Installation

Manufacturers

Component	**Cost**		**Manufacturer**
Flat solar collectors	327,6 €	$1m^2$	Fagor [32]
Electrical Heat pump production 70KW	6.500 €	1 piece	Dimplex [14]
Circulation pumps 250W	384 €	1 piece	DAB pump performance [11]
Gas condensing boiler	18.163 €	1 piece	Baxiroca cathalog [3]
Underfloor heating panels	35 €	m^2	

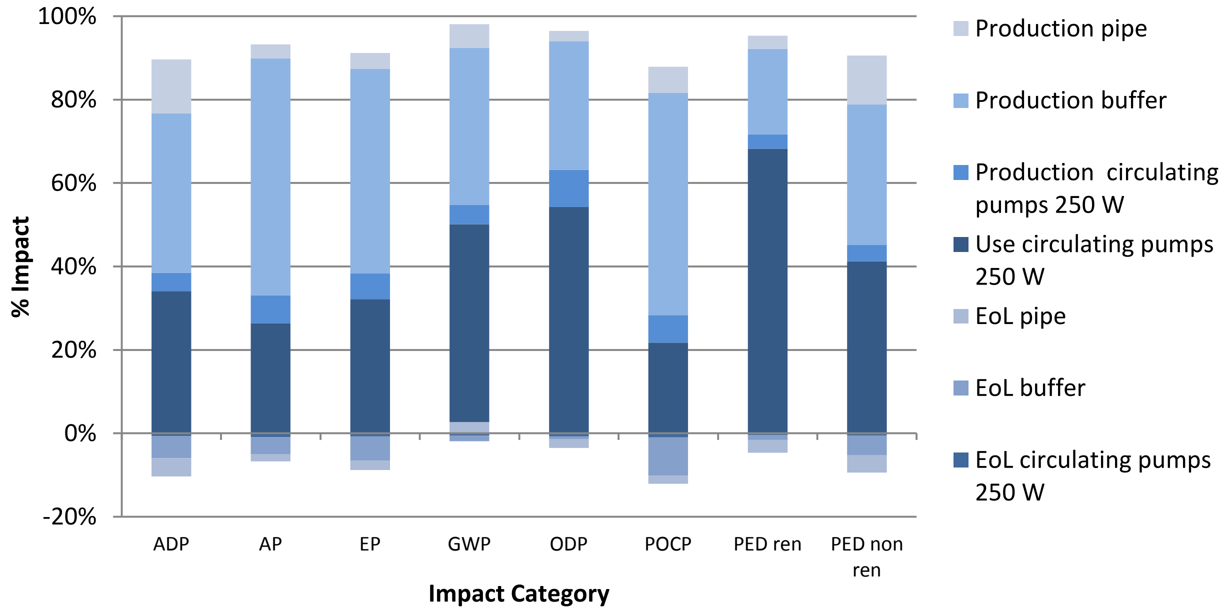
Dismantling costs [12]

Component	Cost	Manufacturer
Pellet silo	2100 €	1 Piece
Biomass Boiler	1.400 €	1 Piece
Gas condensing boiler	1400 €	1 Piece
Pipeline	6 €	1 m
Buffer storage tanks	220 €	1Piece
Radiators	33 €	1 Piece

Annex 6

Water distribution system results analysis

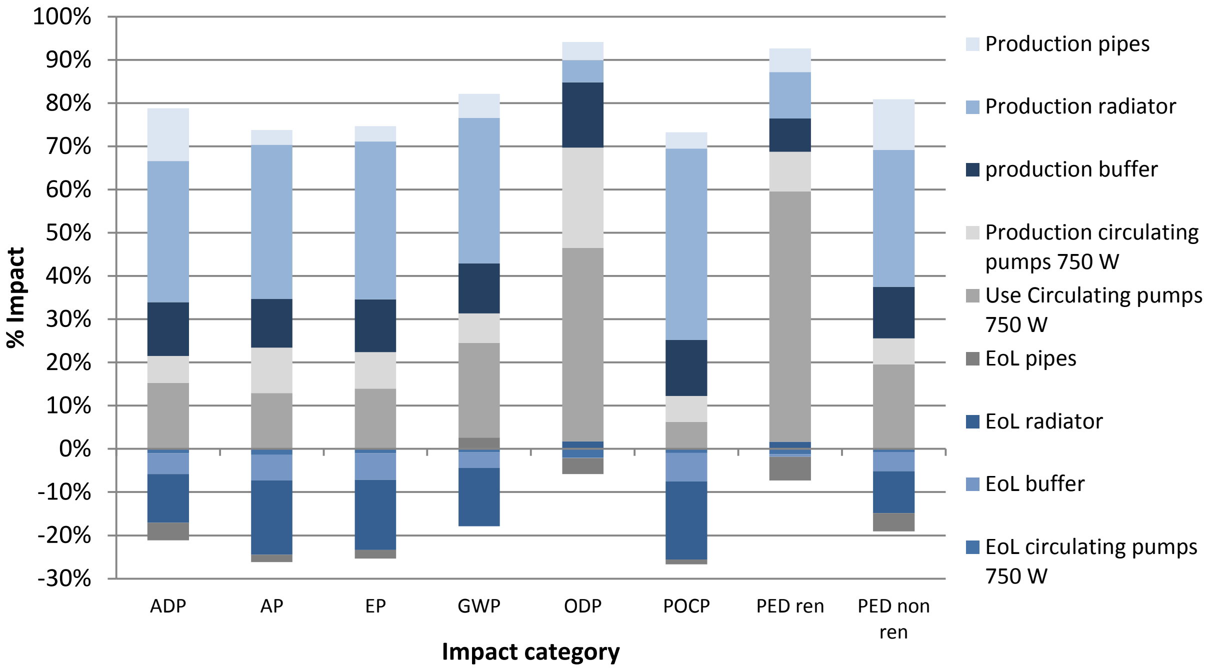
Domestic heated water distribution system – environmental impacts



Domestic heated water distribution system – Costs distribution

	Investment costs	Operation costs	EoL costs	Total
NPV (€)	20.587	121	901	21.609
%	95,27%	0,56%	4,17%	100%

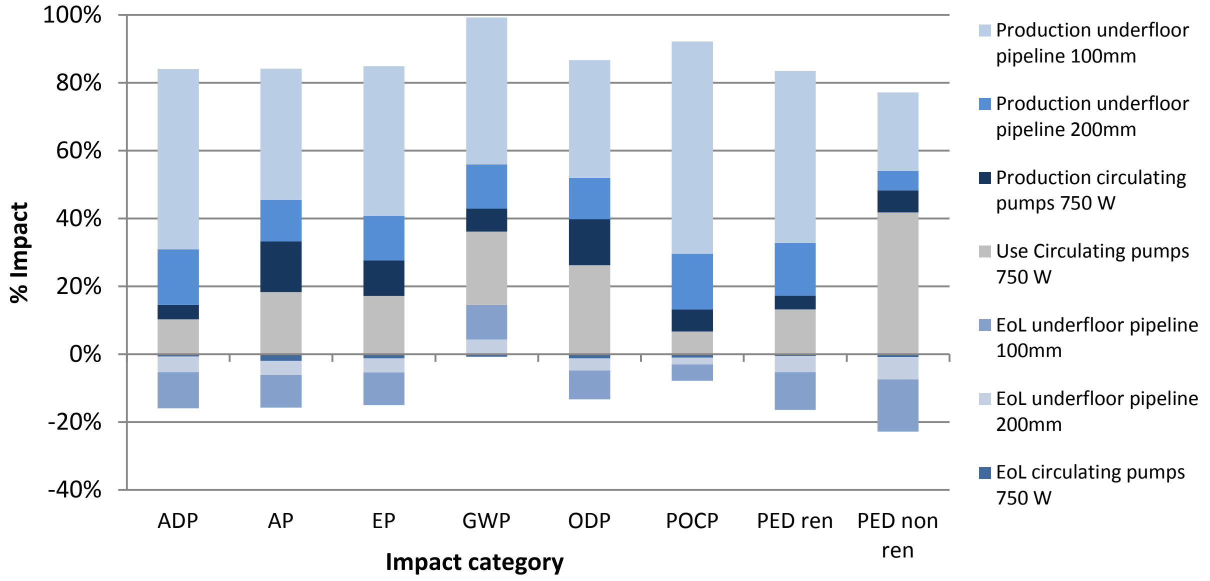
Space heating distribution system with radiators – environmental impacts



Space heating distribution system with radiators – Costs distribution

	Investment costs	Operation costs	EoL costs	Total
NPV (€)	27.979	224	1354	29.558
%	94,66%	0,76%	4,58%	100%

Space heating distribution system with underfloor heating – environmental impacts



Space heating distribution system with underfloor heating – Costs distribution

	Investment costs	Operation costs	EoL costs	Total
NPV (€)	24.460	224	1.023	25.707
%	95,15%	0,87%	3,98%	100%

Annex 7

Quantity of Environmental impact categories for the scenarios modeled

Quantity	S1 Biomass boiler	S2 Solar panels and Natural Gas boiler	S3 Biomass boiler and Heat Pump	S4 Solar pan-els and Heat pump
Abiotic Depletion (ADP) [kg Sb-Equiv.]	886	6.155	2.542	2.738
Acidification Potential (AP) [kg SO2-Equiv.]	1.983	542	1.463	1.023
Eutrophication Potential (EP) [kg Phosphate-Equiv.]	283	36	170	89
Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	225.738	790.137	526.783	551.765
Ozone Layer Depletion Potential (ODP) [kg R11-Equiv.]	0,00030	0,00022	0,00434	0,00471
Ozone Creation Potential (POCP) [kg Ethene-Equiv.]	185	89	122	74
PED ren (MJ)	19.377.377	95.134	17.337.913	12.817.646
PED non-ren (MJ)	2.099.307	12.936.414	7.011.775	7.734.508
NPV (€)	148.463	184.839	177.769	148.227

Annex 8

Quantity of Environmental impact categories in Europe

The following data is available in GaBi 5 Software [63], calculated through the method CML-2001- December 2007 for 25 countries in Europe. The equivalent value can represent an uncertain factor, which can be quantified based on the normal distribution with a standard deviation.

Quantity	Equivalences	Unit	Standard deviation	Factor
Abiotic Depletion (ADP elements)	16.900.000.000	kg Sb-Equiv.	0 %	5,92E-11
Acidification Potential (AP)	16.800.000.000	kg SO2-Equiv.	0 %	5,95E-11
Eutrophication Potential (EP)	18.500.000.000	kg Phosphate-Equiv.	0 %	5,41E-11
Global Warming Potential (GWP 100 years)	5.210.000.000.000	kg CO2-Equiv.	0 %	1,92E-13
Ozone Layer Depletion Potential (ODP, steady state)	7.700.000	kg R11-Equiv.	0 %	1,30E-07
Ozone Creation Potential (POCP)	2.660.000.000	kg Ethene-Equiv.	0 %	3,76E-10