TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology

DIPLOMARBEIT

Life cycle design of a single family house in Poland – comparative study

unter der Leitung von

Univ.-Prof. Dipl.-Ing. Dr. Techn. Ardeshir Mahdavi

E 259-3 Abteilung für Bauphysik und Bauökologie

Institut für Architekturwissenschaften

eingereicht an der

Technischen Universität Wien

Fakultät für Architektur und Raumplanung

von

Szymon Zwoniarkiewicz

1428438

Wien, October 2017

KURZFASSUNG

Die aktuelle Marktsituation in Polen wird von einem fachspezifischen Informationsmangel beeinflusst welcher bewirkt, dass Neubauten meistens auf konventionelle Weise gebaut werden. Andererseits werden Niedrigenergiebauten und energieeffiziente Systeme öffentlich stark gefördert. Ziel dieser Masterthesis war es ökologische, wirtschaftliche und energiespezifische Aspekte solcher Konstruktionen über die gesamte Gebäudelebenszyklusdauer zu analysieren.

Fünf Szenarien wurden in Bezug auf Leistung und Kosten über eine 50 Jahre lange Lebenszyklusdauer analysiert und verglichen. Zu den Szenarien gehören typische Bauten von Einfamilienhäusern in Polen, d.h. Kalksandsteinziegel mit Mineralwolle isoliert, Keramikziegel isoliert mit EPS und Porenbetonziegel. Das Stampflehmhaus mit Holzfasern isoliert wurde als Repräsentant von Konstruktionen mit niedrigem Verbrauch von grauer Energie analysiert. Zwei Arten von Gebäudeausstattungen wurden simuliert, d.h. ein konventionelles System bestehend aus Gaskessel sowie ein modernes System bestehend aus mechanischer Belüftung, Photovoltaik, solarthermisch unterstützter Fußbodenheizung und Warmwasser. Einer der Forschungsschwerpunkte war eine dynamische Energiesimulation, welche zur Analyse des operativen Energieverbrauchs der unterschiedlichen Szenarien beiträgt.

Die Energiesimulation verdeutlicht wie erwartet, dass das Szenario mit der high-end energieeffizienter Gebäudeausstattung den kleinsten Energiebedarf hat. Dennoch zeigt der Vergleich der Primärenergie-Indikatoren aufgrund des besonderen elektrischen Energieportfolios in Polen fast keinen Unterschied zwischen den Szenarien. In Abhängigkeit von der Umweltverträglichkeitskategorie (GWP, ODP, AP, POCP, ADPF) wurde jedes Szenario unterschiedlich positioniert.

Als Ergebnis konnte kein klarer Gewinner der Lebenszyklusanalyse gewählt werden. In Bezug auf die Kosten, die als Nettogegenwartswert repräsentiert wurden, führte das Szenario welches mit Keramikziegel gebaut und mit konventionellem Energiesystem ausgestattet wurde, während das energieeffiziente Hochleistungsgebäude und jene Konstruktion mit niedrigem Verbrauch von grauer Energie schlechter abschnitten.

Schlüsselwörter

LCA, LCC, Energy Simulation, Low-energy housing, Poland

ABSTRACT

Current situation on the market in Poland and lack of proper information causes that the most popular new built houses are still conventional ones. On the other hand, low energy and low embodied energy objects are highly promoted. The goal of this thesis was to investigate environmental, economic and energy performance aspects of these constructions during their life cycle.

Five scenarios were analysed and compared in regard of Life Cycle Assessment and Life Cycle Cost over 50 years of service life. The scenarios include typical constructions of single family houses in Poland, i.e. sand-lime brick insulated with mineral wool, ceramic brick insulated with EPS and aerated concrete brick. Rammed earth house insulated with wood fibre was analysed as a representative of low-embodied energy constructions. Two types of building services were investigated, i.e. conventional system including a condensing gas boiler, as well as advanced system consisting of mechanical ventilation, photovoltaic panels, solar thermal assisted underfloor radiant heating and DHW supported with an electric coil. One of the focuses of the research has been also dynamic energy simulation contributing to analysis of the impact of the operational energy use in every scenario.

Energy simulation showed as expected that Scenario containing high performance building services has the smallest energy demand. Nevertheless, due to particular electrical energy mix in Poland, comparison of the primary energy demand shows very small difference among the scenarios. Depending on environmental impact category (GWP, ODP, AP, POCP, ADPF) every scenario was positioned differently. As a result a clear leader in whole Life Cycle Assessment has not been chosen. Concerning cost represented as a Net Present Value, a scenario built with ceramic brick and equipped with conventional energy system performed the best, while high performance building and low-embodied energy building the worst.

Keywords

LCA, LCC, Energy Simulation, Low-energy housing, Poland

LIST OF ABBREVIATIONS

Abbreviation	**Explanation**
ach	Air change rate
ADPF	Abiotic Resource Depletion Potential of fossil fuels
AP	Acidification Potential
BEM	Building Energy Modelling
BIM	Building Information Modelling
BoQ	Bill of Quantities
CO_2	Carbon Dioxide
CFC11	Trichlorofluoromethane
EPD	Environmental Product Declaration
EPS	Expanded polystyrene
EU	European Union
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
NPV	Net Present Value
n_{50}	Air changes at a differential pressure of 50 Pa
ODP	Ozone Depletion Potential
PEF	Primary Energy Conversion Factor
POCP	Photochemical Ozone Creation Potential
PV	Photovoltaic
RES	Renewable Energy Source
S1	Scenario 1: Sand lime brick insulated with mineral wool
S2	Scenario 2: Sand lime brick insulated with mineral wool, PV, Solar thermal assisted underfloor radiant heating and DHW supported with an electric coil, mechanical ventilation

S3	Scenario 3: Brick insulated with EPS, gas boiler, natural ventilation
S4	Scenario 4: Aerated concrete, gas boiler, natural ventilation
S5	Scenario 5: Rammed earth insulated with wood fibre, gas boiler, natural ventilation
SO_2	Sulphur Dioxide

CONTENTS

1 INTRODUCTION

1.1 Overview

The concept of Life Cycle Design is to analyse cost and environmental impact of a designed building during its whole life cycle. Such holistic concept allows optimization of materials or building services in order to select the most environmentally friendly and/or cost efficient combination within service life of a building. Currently, the main indicator influencing choice of building components in Poland is their initial investment cost. Impact on energy demand, maintenance or disposal cost are usually omitted or roughly estimated. Moreover, environmental impact in any form is a concept which is barely known among Polish construction professionals.

This thesis investigates environmental impact and cost during life cycle of a single family house constructed in four combinations of materials and two combinations of building services resulting in five scenarios as follows:

Table 1 Overview of investigated scenarios

Scenario	Characteristic of materials	Characteristic of building services
S1	Sand lime brick insulated with mineral wool	PV, Solar thermal assisted underfloor radiant heating and DHW supported with an electric coil, mechanical ventilation
S2	Sand lime brick insulated with mineral wool	Gas boiler, natural ventilation
S3	Brick insulated with EPS	Gas boiler, natural ventilation
S4	Aerated concrete	Gas boiler, natural ventilation
S5	Rammed earth insulated with wood fibre	Gas boiler, natural ventilation

Chapter 2 presents methodology used in the research. It describes all assumptions made in Life Cycle Assessment and Life Cycle Costing. Furthermore, it defines approach and parameters used in in the whole building energy simulation, as well as the weather data.

Chapter 3 depicts results of all Scenarios during 50 years of service life of a building. LCA results are subject of normalisation which defines significance of chosen environmental impact categories. Additionally, sensitivity analysis is performed in order to investigate impact of duration of service life of a building on final result. 30 and 80 years of service life are taken into consideration.

Chapter 4 presents conclusion of the whole research study in view of the defined hypothesis. It shows the most favourable of investigated Scenarios in view of Life Cycle Assessment and Life Cycle Cost.

1.2 Motivation

All over the Europe low-energy housing is promoted as a mean of energy conservation. However, the most popular houses in Poland are still conventional ones. It is a result of a belief that a cost of a low-energy house is higher than conventional one and its pay-off period is unreasonably long. In terms of low-energy housing, due to its expansive marketing and lobbying by manufacturers of mechanical equipment, the most popular are ones in passive standard. Low-energy (without heat recovery system or ground heat exchanger) or low-embodied energy houses, both constructed using passive solar techniques are rather rare. Lack of clear and objective comparative estimation of energy demand, ecological and economic impact of mentioned housing types during whole life cycle results in popularity of a conventional type of construction, rarely related to local microclimate, orientation or other local factors.

The outcome of performed research may lead to more conscious decisions about new housing constructions in Poland by private customers as well as construction developers. Information gap about performance of mentioned buildings types will be filled. Life cycle assessment, life cycle cost and energy performance analyses based on dynamic simulation are the concepts, which need to be emerged into Polish market, which is currently dominated by much less precise steady-state certifications, investment cost factors and materials considered as energy saving, but only during operation phase of the life cycle of the building.

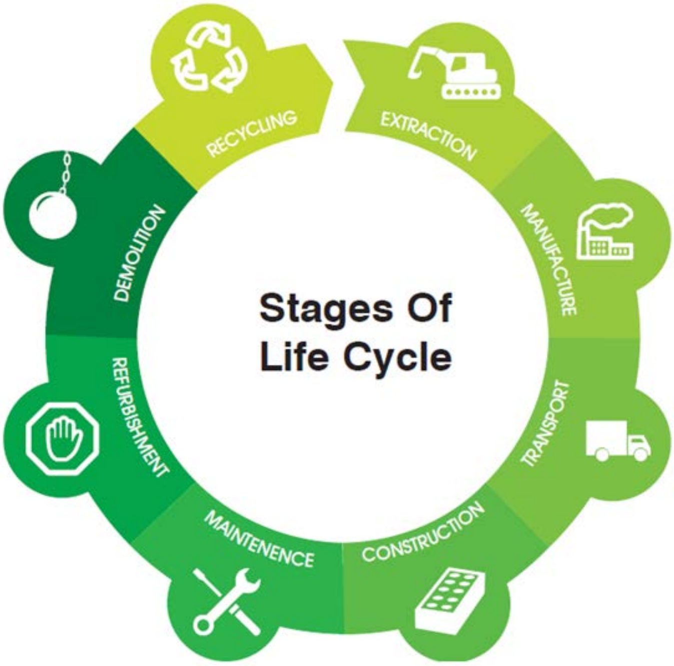

Figure 1 Stages of life cycle of a building

1.3 Background

1.3.1 Sustainable development

The definition of the term sustainable development was described in October 1987 in the Brundtland Report "*Our Common Future*". The document, released by World Commission on Environment and Development (WCED) led by Norwegian Prime Minister Gro Harlem Brundtland states: *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987, p. 54).* There exist several models of sustainable development (Figure 2), but all of them base on three dimensions: economic, social and environmental, which form *"[…] interdependent and mutually reinforcing pillars" (United Nations General Assembly 2005, p. 12).*

Figure 2 Models of three dimensions of sustainable development

The meaning and scope of these components was described as follows: *“Environmental. Reduction of local and global pollution (among them, emissions of greenhouse gases), lower exploitation of the natural resources in the territory and maintenance of the resilience (ability to adapt to change), integrity and stability of the ecosystem.*

Economic. Increase of regional per capita income, improvement in the standard of living of the local population, reduction of energy dependence and increase in the diversification of energy supply.

Social. […] the achievement of peace and social cohesion, stability, social participation, respect for cultural identity and institutional development. Reducing unemployment and improving the quality of jobs (more permanent jobs), increasing regional cohesion and reducing poverty levels are key actions at local level to achieve social sustainability” (Jaramillo-Nieves & del Río 2010, p. 787).

In the end of the XX century the notion of sustainability became so significant that some of its principles where included in Polish Constitution: *„The Republic of Poland [...] shall ensure the protection of the natural environment pursuant to the principles of sustainable development” (Constitution of Republic of Poland 1997, Art. 5).* However, it is likely to observe that in reality the regulation is not always followed. Economic interest is often much more important than environmental (Figure 3).

Figure 3 The three pillars of sustainable development, from left to right, the theory, the reality and the change needed to better balance the model (Source: Voices & Earth 2008)

1.3.2 Energy sector in Poland

According to Eurostat (2016), Poland is a country with one of the highest gross inland energy consumption within EU. Main source of the energy are solid fuels like bituminous coal or lignite (Figure 4). Polish energy dependency in 2014 was 28.6%, what places this country in one of the most energy independent countries in EU. Nevertheless, Poland is one of the biggest producers and exporters of the bituminous coal, what distort whole classification. Statistics show that production of this source has been decreasing for last decade. Hence, in order to keep relatively low level of energy dependency, other sources will need to enhance their role in the energy production.

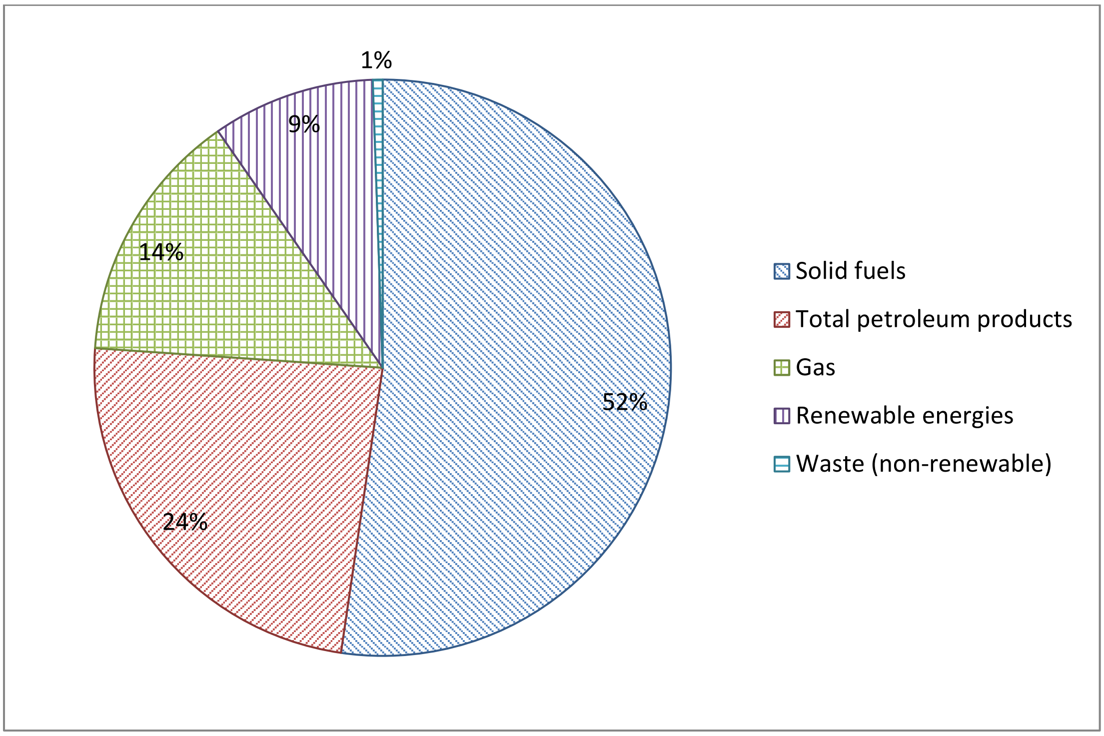

Figure 4 Gross inland energy consumption by fuel type in 2014 (Source: Eurostat 2016)

In order to fulfil the ecological goals of EU, but also to become less dependent on imported energy Polish government enacted a resolution containing fundamental goals of Polish Energy Strategy until year 2030:

- Improvement of energy efficiency;
- Improvement of safety regarding fuels and energy supply;
- Diversification of the structure of electricity production by implementation of nuclear energy;
- Development of acquisition of energy from renewable resources;
- Development of competitive fuel and energy markets;
- Reduction of the environmental impact of the energy sector (Polish Ministry of Economy 2009).

Figure 5 shows that the final energy consumption is the biggest in the residential sector (excluding production and transportation of the construction materials). Therefore this master's thesis will give a set of information, which might be valuable in achieving the first of the mentioned goals.

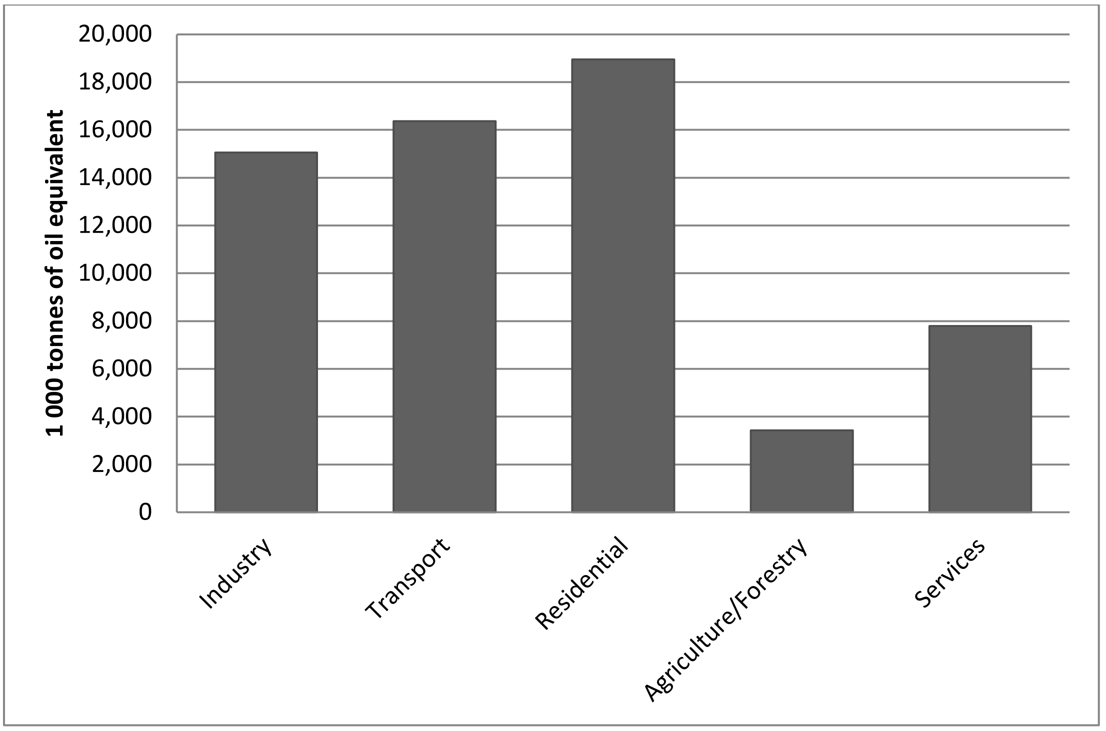

Figure 5 Final energy consumption by sector in 2014 (Source: Eurostat 2016)

Share of renewable energy in gross final energy consumption in 2014 according to Eurostat data is 11.4%. The goal set by Polish authorities to be achieved in 2030 is 15%. Majority of current clean energy production comes from biomass and renewable wastes plants (89%) and wind turbines (8%). Thanks to favourable wind conditions, especially in the northern part of the country, the latter source has a potential for further development (International Renewable Energy Agency 2015). Nevertheless, turbulent airflow triggered by the obstructions like trees or houses affects the efficiency of the wind turbines. There are suggestions regarding minimum distance and height of such installations, which in case of house microturbines set in rural environment might be hard to achieve or in case of urban one even impossible.

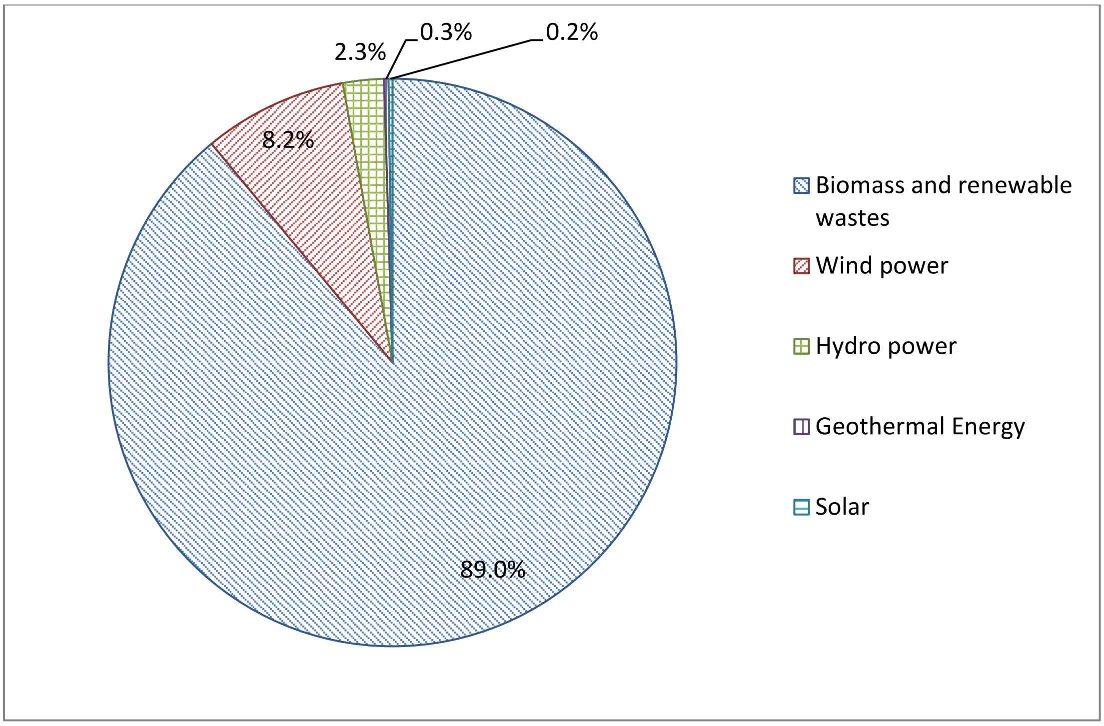

Figure 6 Primary production of energy from renewable resources in 2014 (Source: Eurostat 2016)

The primary energy conversion factor (PEF) of electrical energy after a report of (Molenbroek et al. 2011) is 3. PEF of natural gas is assumed to be 1.24 after Anke Esser & Frank Sensfuss (2016). The referenced document does not provide information on PEF in Poland. Hence one for Czech Republic was selected.

Every phase, starting with extraction of fossil fuels, through energy generation and ending with energy supply to a consumer has particular impact on environment. Due to domination of solid fossil fuels in Polish energy mix its environmental impact is noticeably higher in comparison to Western countries like Germany relying on more ecological energy sources (Table 2).

Table 2 Comparison of environmental impact of electrical energy mix per kWh) in Poland and Germany (Source: Ökobaudat.de 2015; Lelek et al. 2016)

	GWP [kg CO_2 equiv.]	ODP [kg CFC11 equiv.]	POCP [kg Ethene equiv.]	AP [kg SO_2 equiv.]	ADPF [MJ]
Poland	0.6215	2.7E-09	1.9E-05	0.0065	7.3453
Germany	0.5345	3.6E-11	6.1E-05	0.0008	5.455

1.3.3 Typology of residential housing in Poland

Detached single family houses are major type of housing across the country. The observation was confirmed by Atanasiu (2012) in his report for The Buildings Performance Institute Europe and presented on Figure 7.

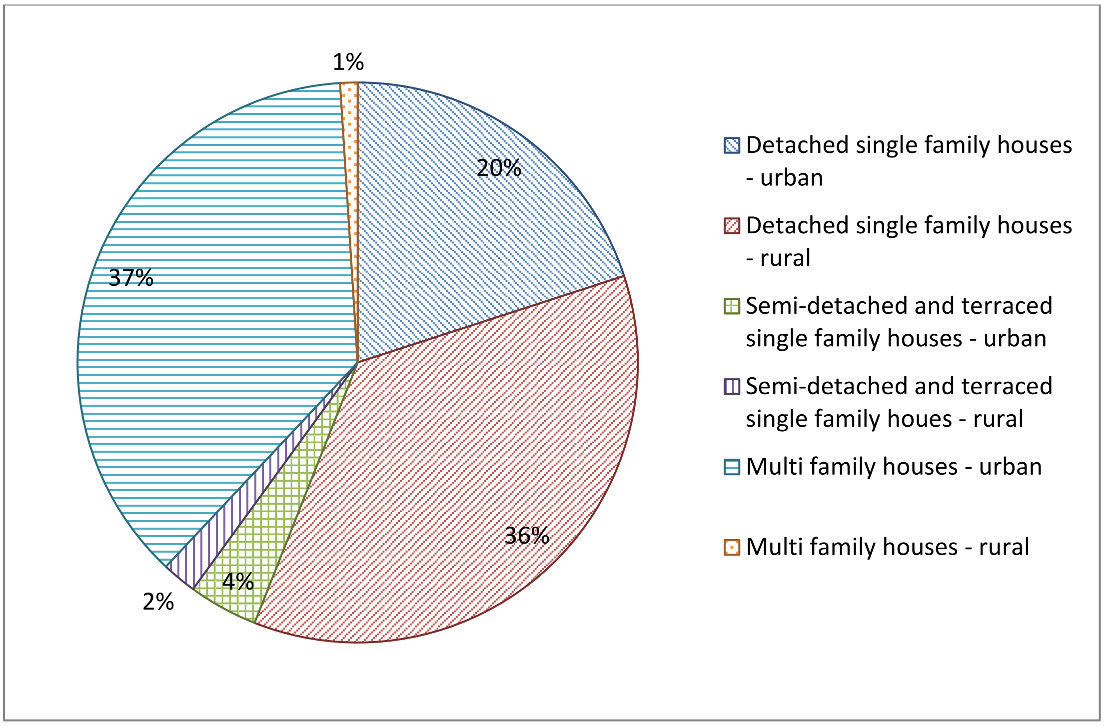

Figure 7 Distribution of residential floor area by building type (Source: Atanasiu et al. 2012)

In his research feasibility of implementation of nearly Zero Energy Buildings (nZEB) in polish environment was investigated. As a reference house he used detached, two floors building of an area of 183.5 m^2. In another study performed for project 'EPISCOPE' a two floors house with heating area of 172 m^2 was defined as a typical one (National Energy Conservation Agency 2011).

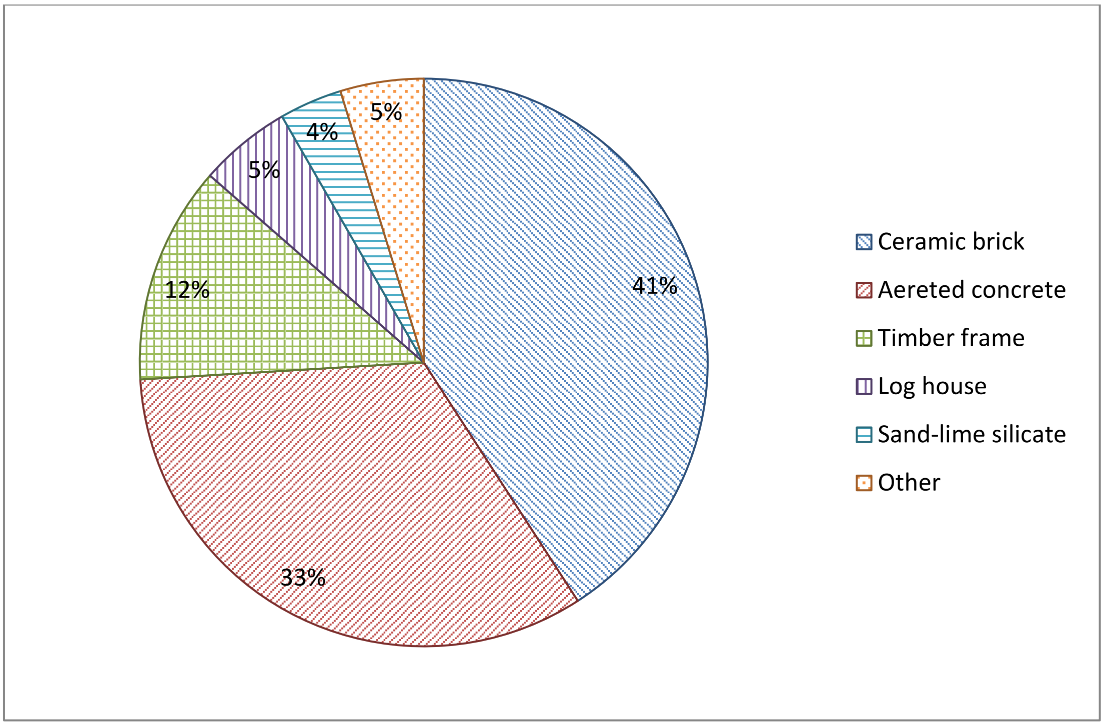

Figure 8 The most popular single family housing materials in Poland (Source: Oferteo.pl 2014)

Polish attitude towards housing materials is rather conservative. The market of new-built houses is dominated by heavy constructions, which components consist usually of diverse kinds of masonry. According to a survey, more than 77% of new houses are built of ceramic brick, aerated concrete brick or sand-lime silicate (Figure 8).

Current regulation in Poland limits the airtightness n50 of a building to 1.0 ach (in case of energy saving houses NF40. Conventional houses with natural ventilation must stay below 3.0 ach according (K.A.P.E. 2012). Nevertheless there is no obligation of performance of relevant measurement proving compliance of the new construction with the regulations.

1.3.4 Life-cycle design

During last century technology and materials used in the construction have become more advanced, but in the same moment, their production has been more energy demanding. Along with development of the national economies we observed changes in proportions of used types of materials. A few decades ago share of natural materials was definitely bigger than it is now. Concrete, masonry, insulation based on plastics and others took over the market due to their price, accessibility and possibilities they give. Nevertheless, together with some advantages we receive higher rate of negative environmental impact. On the other hand, if we take into consideration contemporary materials, it may happen, that price of a product will be misleading. A cheaper product might have bigger ecological footprint than more expensive one. Furthermore, costs and activities required for maintenance during whole life cycle of a building can turn up-side-down initial financial and ecological assessment of the products. Hence, this thesis focuses on analysis during life cycle of a building.

Assessment of ecological impact – Life Cycle Assessment

The Life Cycle Assessment (LCA) reports and assesses all inputs (for example: energy, raw material, water and others), outputs (emissions, product, co-product, waste and others) and environmental consequences of a product (goods and services) during all phases of its life, including production, transportation, operation, disposal and others. Any social or economic aspects are excluded. Main purpose is to give exhaustive information and opportunity of benchmarking of the products or buildings in range of an environmental footprint. It allows to choose components according to the scientific environmental characteristics (ISO14040 2009; ISO14044 2006).

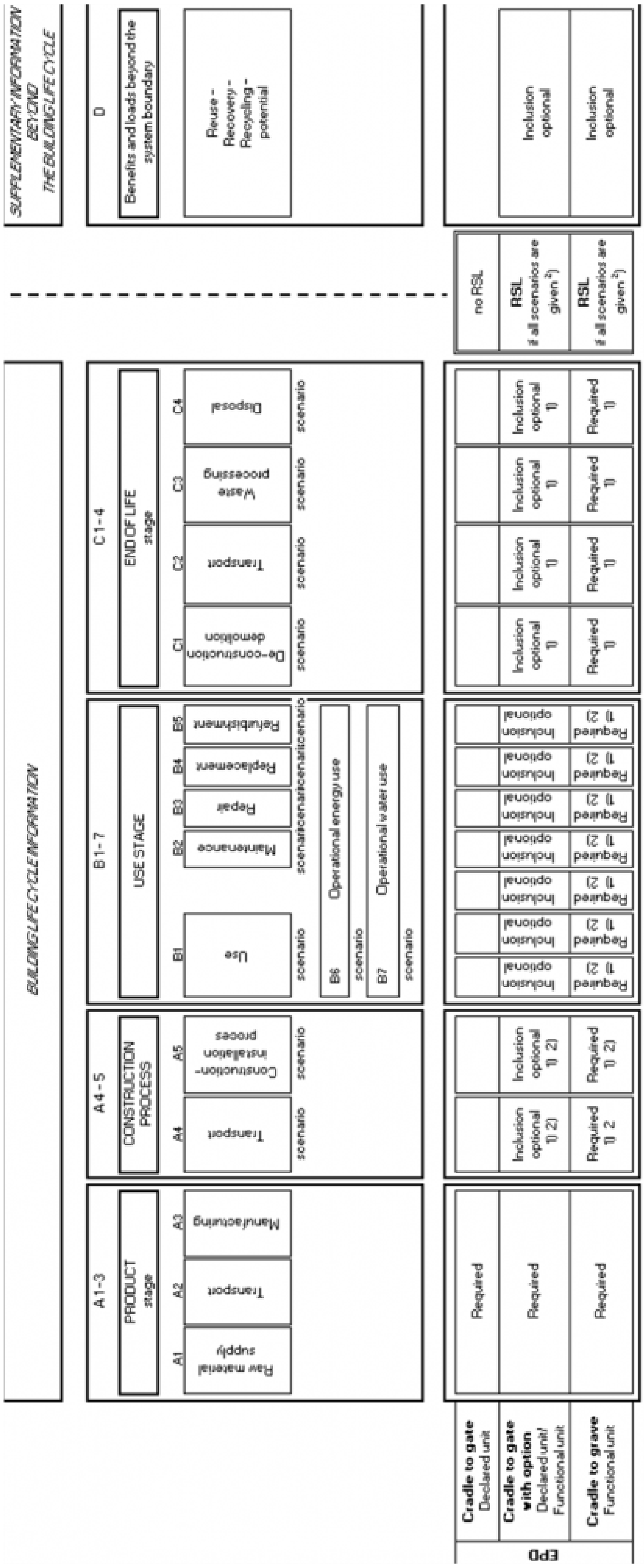

Figure 9 Definition of life cycle stages according to EN15804 2012

Assessment of economic impact – Life Cycle Cost

The Life Cycle Cost (LCC) is a tool serving for evaluation of costs of a product (goods and services) during all stages of its life including production, transportation, operation, disposal and others. The main purpose of the study is to support decisions regarding various investment scenarios, design optimization, components, etc. and assess their financial benefits (Islam et al. 2015). Ideally, LCC should be performed during planning phase, giving the biggest saving potential during life cycle (Figure 10). "*Up to 80 % of the operation, maintenance and replacement costs of a building can be influenced in the first 20 % of the design process*" (ISO 2009, p. 12). The final result should include such parameters like change of costs of energy, products and services, but discounted to current value of the money (ISO 2009). The relevant definitions are explained in chapter 2.5.

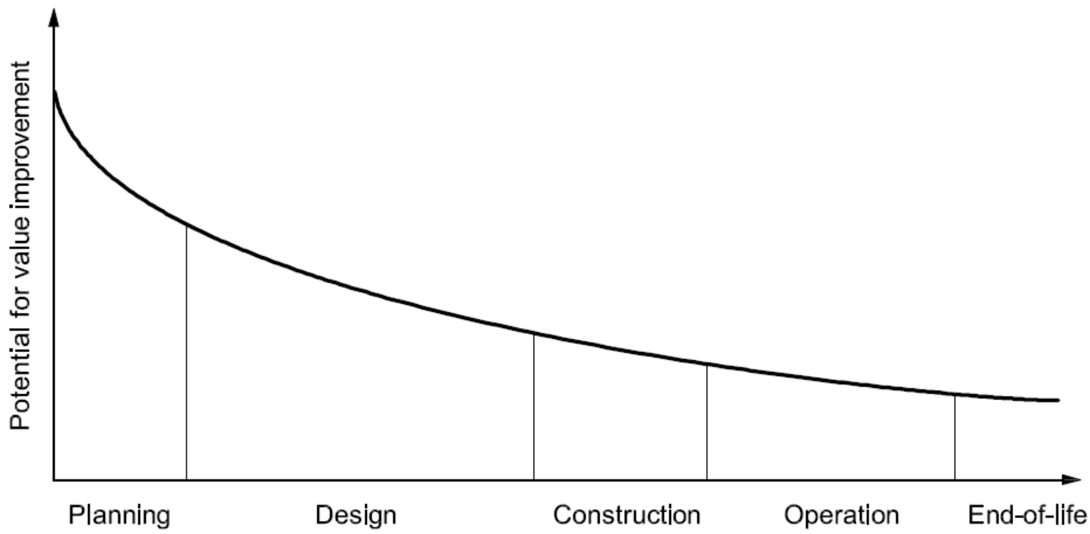

Figure 10 Scope to influence LCC savings over time (Source: ISO 2009)

Literature review

There is no complete comparative research concerning all aspects or cases published. Nonetheless, several studies investigate some of proposed in this research features.

Wang et al (2009) performed simulation based research on conceptualization of zero-energy house in UK and possible solutions necessary to implement. Life cycle design was not approached.

Citherlet & Defaux (2007) focused on three variants of a house in Switzerland, but only in terms of building certification and life cycle assessment. One of the crucial input factors – service life of the house was not described though. Hence, the results are incomparable with other studies.

Feist (1997) in his non-peered research focused on life cycle energy analyses of six types of houses in Germany. As expected, invented by him passive house performed the best during 80 years life cycle. Due to improvements on the market of construction products and systems, the study might be not up-to-date anymore.

Atanasiu et al. (2012) in his research investigates nearly-zero energy housing possibilities in Poland comparing diverse options of heating for a few variants of the single family house. He takes into consideration cost, energy demand and CO_2 emissions. However, study is focused on the systems, instead of passive solar design or specific properties of the materials. Moreover, environmental impact is limited to only one factor.

Audenaert et al. (2008) performed economic analysis of a passive, low-energy and conventional houses in Belgian market and environment conditions. It was pointed out that economic feasibility of passive house is highly dependent on source of the energy and resulting from it price and its annual growth. Taking into consideration the most common in Belgium gas heating a passive house becomes profitable in its life cycle only in case of doubtful energy price increase >10% annually. However, Badescu (2007) proved that application of ground source heat pump for house heating systems brings economically the best results.

Economic viability of passive houses was also investigated by Galvin (2014). He refers to big amount of studies presenting big discrepancy between measured and modelled values of energy demand of both conventional and passive houses ranging from 20% to 250% of their Energy Performance Ratings resulting obviously from various behavioural schemes of the occupants. Moreover, he questions the typical experts' assumptions regarding future fuel price increase and the discount rate suggesting that the latter is investor household based. According to the author, using a rule of thumb, a potential investor should believe that a passive house would out-perform a standard house by 50 kWh/m² per annum in order to pay back in less than 25 years.

Rammed earth is a very prolific construction material for hot and arid climates. Its use, performance and possible flaws with various position of insulation in cold climate of Canada were analysed by Fix and Richman (2009). Technical feasibility studies are the only ones they focused on, in contrary to Dong et al. (2015), who takes into consideration Life Cycle Cost as well. The research in which they investigate optimization of insulated cavity rammed earth walls is performed in three different climates of Australia. Nevertheless, the range of winter temperatures in the coldest one is much higher than in Poland.

Thiers & Peuportier (2012) and Citherlet & Defaux (2007) point out impact of national electricity generation mix on LCA results. In countries with developed nuclear or renewable electricity supply, electricity driven devices like heat pumps are put in favours due to lower environmental impact. In Poland major part in electricity generation play solid fuels, so other solutions in regard of building services might be applicable in this context.

2 METHOD

2.1 Overview

Due to the high cost, an experiment with use of built examples, followed by their long term measurements is unlikely to happen. Hence, simulation of a presented problem was chosen as a tool. Life cycle assessment (LCA) and Life cycle costing (LCC) based on publically available databases and results of dynamic energy simulation performed in EnergyPlus software were determined as a basic methodology. As every energy simulation engine, EnergyPlus is inaccurate. However, it allows to estimate and, what is more important, compare the results, which are considered to contain the same level of error. Obtained result will bring an answer with the enough accuracy for the target group of this research.

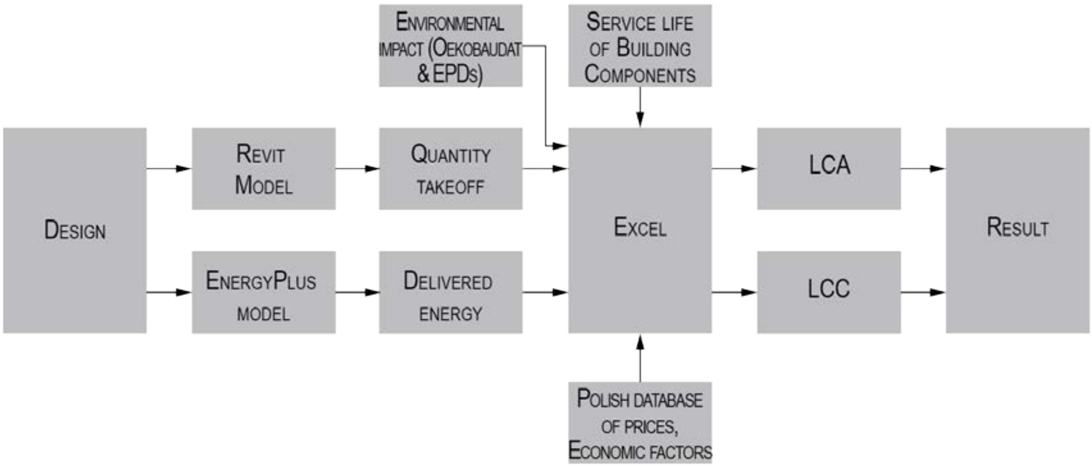

Figure 11 Flow chart of the research methodology

A simple, detached, low energy building has been chosen from a catalogue of one of the Polish construction companies (Figure 12). It is a compact house of 135 m^2 of floor area designed to be built of silicate (sand lime) bricks and insulated with rock wool, equipped with mechanical ventilation with heat exchanger, photovoltaic system and solar thermal collector assisted heating supported with electrical coil. The baseline scenario, hereafter called Scenario 1 is going to be compared with four other scenarios as described in Table 3.

Table 3 Overview of the properties of studied scenarios

Property	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Main feature	Sand-lime construction Advanced building services	Sand lime construction Conventional building services	Brick construction Conventional building services	Aerated concrete construction Conventional building services	Rammed earth construction Conventional building services
Area [m^2]			135		
Construction of the external walls	Gypsum plaster Sand lime brick Rock wool Silicate-silicone plaster		Sand-concrete plaster Hollow brick EPS Acrylic plaster	Sand-concrete plaster Aerated concrete Acrylic plaster	Clay plaster Rammed earth Wood fibre insulation Lime plaster
U-value of the external walls [W/(m^{2}K)]			0.15		
Construction of the ceiling*	Gypsum plaster Gypsum card plate Vapour Protection Rock wool		Sand-concrete plaster Gypsum card plate Vapour Protection Rock wool		Clay plaster Clay plate Wood fibre insulation
U-value of the ceiling [W/(m^{2}K)]			0.88		
Construction of the slab	Wooden floor Reinforced concrete slab XPS				Wooden floor Reinforced concrete slab Foam Glass
U-value of the slab [W/(m^{2}K)]			0.18		
Construction of the windows			4e-10-4-10-e4 Krypton 92%		
U-value of the windows [W/(m^{2}K)]			0.7		
g-value of the windows			0.62		
Airtightness n50 [ach]	0.6		1.7		

*ceiling is the part of thermal envelope

Property	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Main feature	Sand-lime construction Advanced building services	Sand lime construction Conventional building services	Brick construction Conventional building services	Aerated concrete construction Conventional building services	Rammed earth construction Conventional building services
Ventilation type	Mechanical	Natural			
Heating system and DHW system	1) Air heat recovery 2) Solar thermal assisted underfloor radiant heating and DHW	1) Gas boiler for heating and DHW 2) Conventional radiators			
Additional features	Solar thermal collector PV panels	n/a			

In all analysed scenarios a functional unit of components, namely U-value will be kept the same in order to compare LCA and LCC aspects. Scenario 2 – 4 will be adapted to conventional in Poland construction types considering air tightness, materials and heating system. Since cooling systems are not very common in Poland, they are not addressed in the research. The construction technologies, which will be verified are hollow brick insulated with EPS, aerated concrete and already mentioned insulated sand lime bricks. As a main material in the last scenario, low-embodied energy material will be used, i.e. insulated rammed earth. The heating system incorporated in Scenarios 2 – 4 is conventional one and it consists of a condensing gas boiler and conventional radiators. It is assumed that required amount of fresh air will be provided through natural ventilation

Figure 12 Reference house geometry used in the research (Source: Domyhybrydowe.pl 2017)

Next phase is devoted to comparative analyses which will help to find the best type of the housing in the selected location. The environmental and economic aspects are investigated taking into consideration different service life of the products resulting in their replacement during 30, 50 and 80 years of service life of the buildings. For assessment of environmental impact German database Ökobaudat is used. The quantities of the materials are derived from BIM models. Operational impact, namely energy load is simulated using dynamic energy simulation and local weather data. For LCC similar strategy is used. The difference is the ‘impact’, which in this case is money, with its changing value over the years. Hence, discount and growth rates are introduced and the result is presented in terms of Net Present Value.

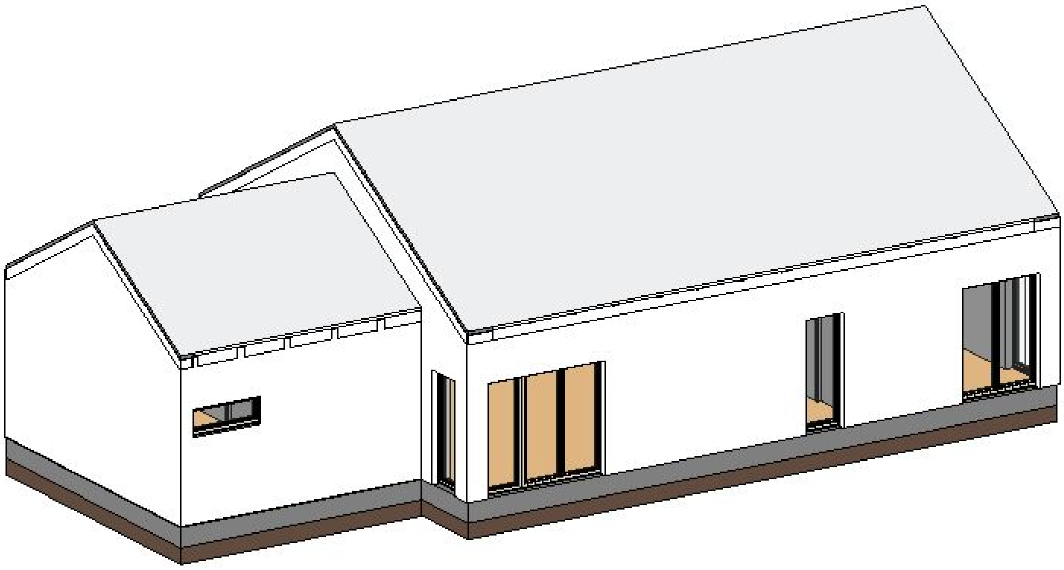

Figure 13 Geometry of the building as modelled in Autodesk Revit

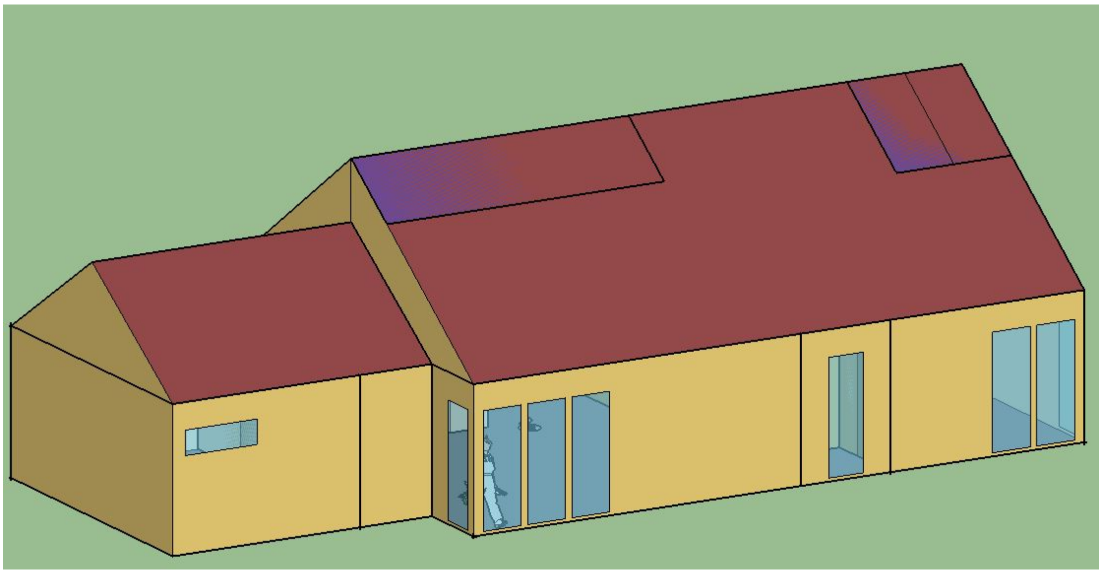

Figure 14 Geometry of the building as modelled for energy simulation in OpenStudio plugin for Google SketchUp

2.2 Hypothesis

It is assumed that the low-energy and low-embodied energy houses have smaller environmental impact and life cycle cost than conventional houses in Polish conditions concerning the climate and electrical energy mix. The major question is to what extent choice of the construction materials and heating strategy has impact on the final result of mentioned economic and environmental analyses.

2.3 Building Information Modelling for LCC and LCA

The first step is modelling of all cases in Building Information Modelling tool – Autodesk Revit. The modelling is based on the technical drawing provided on a website of a Polish construction company (Figure 15).

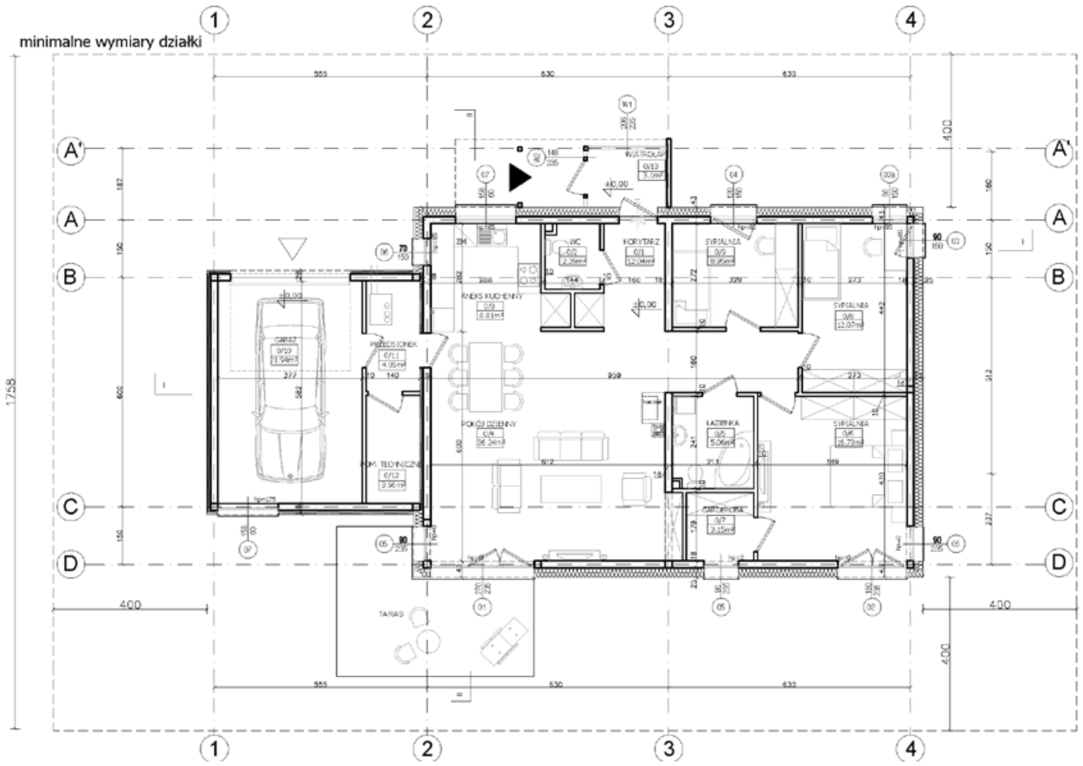

Figure 15 Plan of the house used in future research (Source: Domyhybrydowe.pl 2017)

Created three dimensional models serve as a base for bill of quantities of all constructions of the buildings. A sample of such BoQ can be seen in Table 4. Scope of the modelling excludes electrical installations, plumbing, ventilation ducts, heating installations, gutters, wall finishing (paint and ceramic tiles), window and door handles and other elements, which are irrelevant from future research point of view.

Table 4 Excerpt from Bill of Quantities of Scenario 1

Category	Material	Volume [m^3]	Area [m^2]	Density [kg/m^3]	Mass [kg]
Doors	Multiple	n/a	2.0	n/a	80.0
Ceiling	Gypsum Board Rigips Activ Air	1.7	139.4	1000.0	1740.0
Ceiling	Mineral wool ISOVER Multimax	15.6	108.8	12.5	195.1
Ceiling	Mineral wool ISOVER Supermata 20	24.3	130.8	12.5	303.4
Ceiling	Plastering internal	0.2	109.6	1800.0	396.0
Floors	Reinforced concrete slab	30.2	153.9	2400.0	72504.0
Floors	Wooden floor	3.1	151.5	675.0	2119.5
Floors	XPS	33.8	156.5	43.0	1452.5
Floors	Vapour Retarder	0.0	139.4	1500.0	15.3
Roofs	Steel sheeting Ruukki Emka Click	0.2	185.9	7800.0	1482.0
Roofs	Wind protection	0.0	184.3	930.0	22.1

2.4 Life Cycle Assessment (LCA)

2.4.1 Overview

Methodology of the Life cycle assessment consists of four phases: the goal and scope definition, the inventory analysis (LCI), the impact assessment (LCIA) and interpretation phase. In the first phase, it is necessary to define what is the reason and purpose of the study and intended audience, preparation of LCA for internal use and external use will look differently. Moreover, the scope of the study should be characterized. The most significant features are system boundaries (choice of the components of the study: inputs, outputs, processes), function and functional unit (quantified performance of a product to be used as a reference, proceeding analyses are related to this factor), LCIA methodology and types of impacts, type, quality and scope of data. Next step is the Life cycle inventory analysis (LCI), which includes an inventory analysis of all flows happening between environment and examined products. All necessary data corresponding to described goal should be collected and classified into groups defining the input of energy and materials, emissions to air, water and ground, products, co-products, waste and others. The calculation of gathered data needs to be performed afterwards, including its verification, relation to the unit process and to the functional unit. At the end, it is possible to refine system boundaries basing on sensitivity analyses (which allow us to define importance of data and possible exclusions or exchanges of unit processes). Third phase of the Life cycle assessment is the Life cycle impact assessment (LCIA) in which impact categories are selected (e.g. global warming, water depletion, acidification and others) and then defined. All results from previous phase (LCI) are assigned to suitable impact categories and characterized. Additionally, there may be performed optional elements: grouping, normalization, weighting and data quality analyses. Last phase of the LCA is interpretation of the inventory and an impact assessment combined together. It should deliver some conclusions, limitations and recommendations coherent to the goal and scope defined at the beginning. Interpretations should include also sensitivity check, which main point is assessment of reliability of the results under influence of uncertainties. An additional part of the LCA is reporting, which structure differs depending on intended audience (ISO14040 2009; ISO14044 2006).

2.4.2 Scope of the Life Cycle Assessment

The functional unit of the LCA performed in this master's thesis is a single family house occupied by a family of four over a fifty-year service life of the building. After analyses of available data the scope of the LCA was determined to include the LCA stages as marked below on Figure 16. Therefore, the final selection of LCA stages can be referred as cradle to gate with options including its construction (stages A1-A4), replacement (B4), operational energy use (B6), operational water use (B7), disposal (stages C2-C4). Benefits of reuse, recovery and recycle potential (stage D) are studied additionally as well.

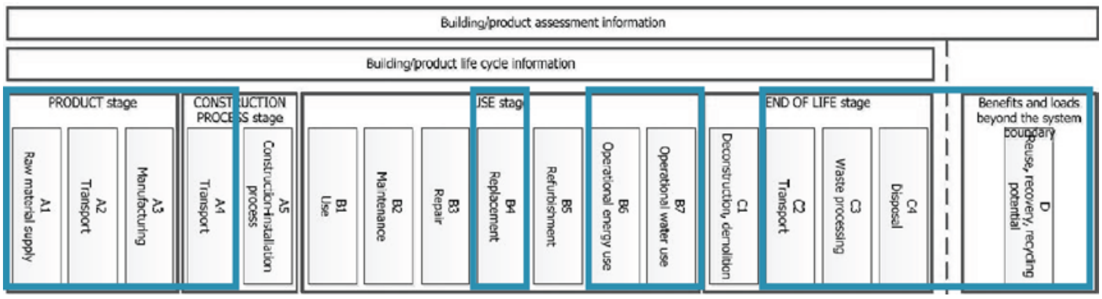

Figure 16 Scope of performed Life Cycle Assessment

As described in chapter 2.3, building components having minor impact on final results are excluded from the study. Moreover, avoided impact is the same in every scenario, due to exclusion of the same building components.

All building elements got assigned their hypothetical service life resulting in particular amount of their replacement during the lifetime of the buildings according to Association of the generally sworn and legally certified experts of Austria (2006) and can be found in Annex B.

2.4.3 Life Cycle Inventory (LCI)

The LCI phase was performed as described in chapter 2.3.

2.4.4 Life Cycle Impact Assessment (LCIA)

Due to influence of the age, origin and accuracy of the inventory data on precision of LCA studies (Szalay 2007) German database Ökobaudat has been chosen as a main source of environmental impact of relevant building elements. Ökobaudat database has been developed by German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety and is assumed to represent the Polish conditions the best.

As presented in Table 2 on page 7, the Polish electrical energy mix significantly varies from German one. Hence, the environmental impact values were excerpted from a study referring to the Polish electrical energy mix (Lelek et al. 2016) and used in this study. Nevertheless, the latter was assessed in regard of only five impact categories in contrary to seven provided in Ökobaudat, what shortened future choice of impact categories for whole research to following:

- Global Warming Potential [kg CO_2 equiv.],
- Ozone Depletion Potential [kg CFC11 equiv.],
- Tropospheric Ozone Creation Potential [kg Ethene equiv.],
- Acidification Potential [kg SO_2 equiv.],
- Abiotic Resource Depletion Potential of fossil fuels [MJ].

Following environmental indicators were excluded from data taken from Ökobaudat:

- Eutrophication Potential [kg PO_4 equiv.],
- Abiotic Resource Depletion Potential for elements [kg Sb. equiv.].

Transport related LCA stages (A4 and C2) are based on an assumption that goods are transported with a small truck over a distance of:

- 300 km in construction stage (A4),
- 15 km in disposal stage (C2).

The environmental impact of described transportation service after Ökobaudat.de is presented in Table 5.

Table 5 Environmental impact of transportation of 1000 kg of goods per km (Source: Ökobaudat.de 2015)

GWP [kg CO_2 equiv.]	ODP [kg CFC11 equiv.]	POCP [kg Ethene equiv.]	AP [kg SO_2 equiv.]	ADPF [MJ]
0.1466	2.8E-13	-0.0002	0.00057	1.991

2.4.5 Normalization

"Normalization is the calculation of the magnitude of the category indicator results relative to some reference information" (ISO14044 2006, p. 41). The absolute results of each environmental impact category of LCA calculations are normalized through division by a selected reference score resulting in their conversion to unitless values. Such representation of the environmental indicators helps to understand their relative impact. The reference scores used in this master's thesis were developed by Building Research Establishment and represents the environmental impact of one European citizen

Table 6 Normalization factors based on impact of Western European citizen (BRE 2008)

Category	Unit	Per Citizen
Global Warming Potential	[kg CO_2 equiv.]	12,300
Ozone Depletion Potential	[kg CFC 11 equiv.]	0.217
Tropospheric Ozone Creation Potential	[kg ethene equiv.]	21.5
Acidification Potential	[kg SO_2 equiv.]	71.2
Abiotic Resource Depletion Potential of fossil fuels	[MJ]	273,000

2.5 Life Cycle Costing

2.5.1 Overview

Methodology of LCC is comparable with the one of LCA, however the unit of the impact of a building is expressed in monetary value. Therefore LCC can be split into four phases as well:

- Goal and scope definition;
- Inventory analysis;
- Impact assessment;
- Interpretation phase.

2.5.2 Scope of the Life Cycle Costing

Similarly to assessment of the environmental impact, the functional unit of LCC is a single family house occupied by a family of four over a fifty-year service life of a building. Taking into consideration availability of the input data and their relevance particular life stages of a building are taken into consideration as presented on Figure 17 (marked blue).

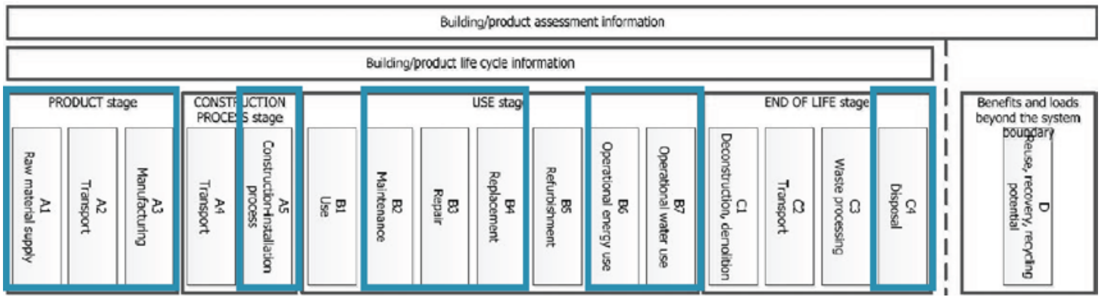

Figure 17 Scope of performed Life Cycle Costing

The building components which are taken into consideration in LCC study are the same as in LCA, i.e. components with minor impact on final results are excluded. Similarly, the same service life of each building component was assigned influencing the replacement occurrence during the life cycle.

Great impact on LCC calculation have economic parameters, affecting ratio of the growth of prizes or future value of the money. The LCC models are very sensitive to these variables and therefore the assumptions need to be done with caution. The LCC models used in this master's thesis contain following financial variables:

- Inflation rate;
- Discount rate;
- Growth rate of energy cost, water cost and construction costs.

Inflation rate

Inflation is a sustained increase of prices of goods and services, without corresponding increase in the value of money. When inflation rate is negative (decrease), it is called deflation. Assuming constant rate of change *i* over the *t* years, the future cost p_t can be expressed with following equation:

$$p_t = p_0(1 + i)^t \quad (1)$$

As a result, over the *t* years the purchasing power (*PP*) of *X* amount of money changes and can be expressed with following formula:

$$PP[X_t] = \frac{X_t}{(1+i)^t} \tag{2}$$

The inflation rate incorporated in the calculations is 1.8% after the forecast of Organisation for Economic Co-operation and Development for the year 2018 (OECD 2017).

Discount rate

Discount rate is a "*factor reflecting the time value of money that is used to convert cash flows occurring at different times to a common time" (ISO15686-5 2009, p. 4).* The discount rate affects Net Present Value of a cost occurring in the future by its discounting. The more time distant cost is, the bigger discount ratio. Through discounting the NPV is reduced and as result the importance of the future cost is diminished.

According to Kohler et al. (2010, p. 72) the discount rate could be assumed as one of the follows:

- *"The discount rate of a 10 year government bond;*
- *An average hypothetical discount rate for investments in real estate predominantly made by third parties;*
- *The relevant return on property;*
- *A discount rate appropriate to the particular risk (the higher risk, the higher discount rate);*
- *A discount rate based on a company's own defined or desired return on capital."*

The discount rate of 3.0% is assigned according to the first point. It is based on past trading and a forecast of tradingeconomics.com (2017).

Nevertheless, described discount rate is nominal, what means that it does not include future change of value of money known as inflation. The real discount rate (incl. inflation) can be calculated using following formula:

$$d' = \frac{1+d}{1+i} - 1 \tag{3}$$

where

i	average yearly inflation
d	nominal yearly discount rate
d'	real yearly discount rate

Growth rate

Historical patterns show that change of price of some goods or services not always go in line with inflation rate. Hence, another set of parameters which is taken into consideration in LCC calculation was determined, namely growth rate of:

- 0.5% for construction cost based on a trend of construction costs in Poland in last 10 years (Eurostat 2017a);
- 2.4% for electrical energy cost based on a trend of electrical energy costs in Poland in last 10 years (Eurostat 2017b);
- 2.4% for feed-in remuneration currently the feed-in tariff is equal to the electrical energy cost, therefore it is assumed that it will rise accordingly;
- 4.0% for gas cost based on a trend of gas costs in Poland in last 10 years (Eurostat 2017c);
- 3.0% for water cost based on a trend of water from municipal water supply cost on last 9 years (GUS 2017).

The growth rate is assumed to be constant over the years. The price over *t* periods is calculated using following equation:

$$p_t = p_0(1 + g)^t \tag{4}$$

where

p_0 Initial price

p_t price over t periods

g growth rate

2.5.3 Inventory analysis

The inventory analysis phase was performed as described in chapter 2.3.

2.5.4 Impact assessment

There are three main groups of costs which are assigned to every building throughout its life cycle and which have impact on NPV of each of them:

- Investment costs;
- Periodic costs;
- End of life costs.

All the prices used in the study exclude VAT.

Investment cost

All components derived from inventory analysis have assigned its investment cost consisting of labour cost and material cost. The prices come from a polish database (Wolters Kluwer 2016). Transportation costs, material losses resulting from construction processes, as well as cost of the land are excluded from the calculation.

Periodic costs

There are several groups of periodic costs which are taken into consideration. Some of them are related to everyday use of media like water or energy and appear in short intervals, e.g. monthly. Others result from maintenance of the building and ware-and-tear of its components. The assumptions concerning all of them are described below.

Energy and water cost

There are two types of energy investigated throughout all research scenarios, namely electrical energy obtained from the grid and thermal energy generated on-site using natural gas. The prices incorporated into the calculations are the prices of respective energy types for medium type households and they amount to 0.03917 €/kWh for natural gas and to 0.1332 €/kWh for electricity (Eurostat 2017b; Eurostat 2017c).

Similarly to introduced energy cost, water cost is based on average value for municipal water supply from year 2016 and it is equal 2.55 €/m³ (GUS 2017).

Cleaning

The cost of cleaning is excluded from LCC calculation.

Replacement and maintenance

All building components have assigned their service life according to Association of the generally sworn and legally certified experts of Austria (2006). As a result, the occurrence of replacement during service life of a building was determined.

The maintenance cost consists of the following parts and associated costs:

- Inspection and maintenance resulting in 0.5% of cost of a component per year;
- Regular repair cost resulting in 1.0% of cost of a component per year;
- Irregular repair cost resulting in 1.0% of cost of a component per year.

End of life cost

The last main group of cost includes end of life costs of building components, which appear both, after replacement of an element and at the end of service life of a whole building. The cost is simplified to landfill cost only. The adobe components of scenario 5 i.e. rammed earth walls, clay plasters, etc. are assumed to consist fully of the ingredients existing in the soil of the construction plot, therefore at their end of life they will be disposed on the spot resulting in no cost.

Feed-in remuneration

The Scenario 1 has installed photovoltaic installation, which besides on-site electricity use feeds in the grid as well. The Polish Act on Renewable Energy Sources (2016) states that 80% of electrical energy fed into the grid within preceding 365 days can be balanced with utilised one. Hence, the feed-in tariff used in the calculation is assumed to be the same as electricity price, but applied only to 80% of supplied energy.

2.5.5 Interpretation phase

The result of LCC calculation is presented as a Net Present Value (NPV), which is sum of all present values of all costs appearing during the life cycle of a building as described in previous chapter. The present value is the result of discounting future cash flows and it defines a value which *"should be allocated for future expenditure on an asset (ISO 2009 p. 25)."*

$$NPV = \sum_{n=1}^{p} \frac{C_n}{(1+d)^n} \tag{5}$$

where

C_n cost in year n;

d real discount rate per year;

n number of years between the base date and the occurrence of the cost;

p is the period of analysis.

The crucial for the calculation real discount rate is assumed as described in chapter 2.5.2.

2.6 Building Energy Modelling

Dynamic energy modelling is an approach which goal is to represent numerous physical phenomena occurring inside a building as close as possible to reality. Thanks to the complex and interdependent equations behind, the result is more reliable than simple stable state calculations lacking impact of one phenomenon on another. The simulations are performed using a calculation engine EnergyPlus, which is developed by an American governmental institution, namely Office of Energy Efficiency and Renewable Energy. "*EnergyPlus implements detailed building physics for air, moisture, and heat transfer including treating radiative and convective heat-transfer [...]; calculates lighting, [...] shading; supports flexible component-level configuration of HVAC [...]; simulates sub-hourly timesteps to handle fast system dynamics and control strategies."* (energy.gov 2017)

Hence, Building Energy Modelling is incorporated in the study in order to determine energy and water demand necessary for assessment of environmental and financial impact of the operational phase of a building life cycle.

2.6.1 Geometry and zoning

Geometry and zones of all scenarios are the same. Due to size of the house and simplicity of the model the thermal zones were assigned without any simplification, i.e. each room of the house is assigned as separate thermal zone.

2.6.2 Weather data

The weather data used for simulation represents average weather of the city of Poznan, Poland and it is based on measurements of nine reference years. The data includes information on dry and wet bulb temperature, direction and speed of wind, sky cover atmospheric pressure, and liquid precipitation. Solar radiation data in contrary to other information is not measured, but calculated based previously mentioned weather indicators and sun-earth geometry (ashrae.org 2017).

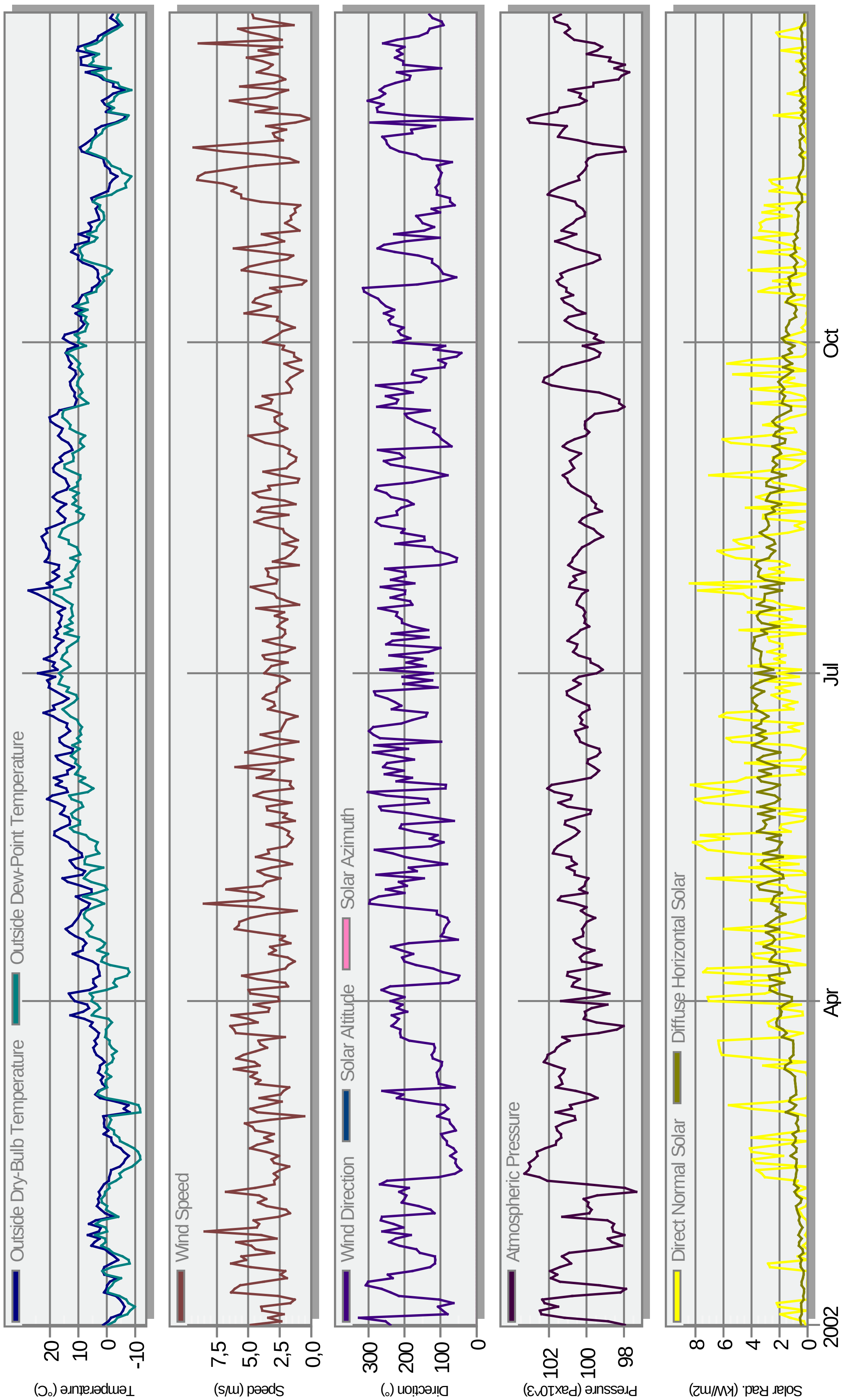

Figure 18 Weather data of Poznan, Poland: (Source: Energyplus.net 2017)

2.6.3 Input parameters

Thermal properties

Every investigated scenarios, even though build with different materials, incorporates U-value as a functional unit. Nevertheless, other indicators like density or specific heat capacity vary, what might result in small deviations of simulated energy demand due to the thermal mass effect. The properties of building components were modelled as described in Table 3 on page 16.

Air tightness

Important aspect of a building envelope is its airtightness. The assumed values presented in Table 3 represent airtightness under 50 Pa pressure difference. However, EnergyPlus does not provide possibility of such input. Therefore a methodology allowing conversion of airtightness n50 to one under normal pressure presented in a norm EN 12831:2003 is applied (Equation 6.

$$V_{inf,i} = 2 \times V_i \times n_{50} \times e_i \times \varepsilon_i \tag{6}$$

where

V_i	heated volume [m³];
n_{50}	air change rate per hour [h^{-1}] under 50 Pa pressure difference;
e_i	shielding coefficient;
ε_i	height correction factor.

The volume of each space was derived from BIM model, n_{50} air change rate per hour as in Table 3 on page 16 and coefficients e_i *and* ε_i from Table 7 and Table 8.

Table 7 Shielding coefficient (Source: PN-EN12831 2006)

	e		
Shielding class	**Heated space without exposed openings**	**Heated space with one exposed opening**	**Heated space with more than one exposed opening**
No shielding (buildings in windy areas, high rise buildings in city centres)	0	0.03	0.05
Moderate shielding (buildings in the country with trees or other buildings around them, suburbs)	0	0.02	0.03
Heavy shielding (average height buildings in city centres, buildings in forests)	0	0.01	0.02

Table 8 Height correction factor (Source: PN-EN12831 2006)

Height of heated space above ground-level (centre of room height to ground level)	Height correction factor ε
0-10 m	1.0
>10-30 m	1.2
>30 m	1.5

Internal gains and schedules

The occupancy schedules represent typical occupancy of a single family house for a family of four. During the weekday the house is empty between 10.00 and 19.00 while during weekends it is occupied 24 hours a day.

Furthermore following light and equipment density is incorporated in every scenario:

- 5.00 W/m² of indoor light density;
- 30.28 W/m² of kitchen equipment density;
- 4.30 W/m² of living room equipment density;
- 1.67 W/m² of bathroom equipment density;
- 1.61 W/m² of toilet equipment density.

Systems

Building systems are inherent elements of every building in Polish climate zone. In majority of cases they are limited to heating system powered by conventional energy sources like gas, pellets or coal. Necessary amount of fresh air is usually provided naturally. Nevertheless, promotion of other technologies (e.g. equipment acquiring energy from renewable sources, mechanical ventilation, heat pumps, etc.) is noticeable on the market. Therefore impact of two different systems is analysed within this master's thesis. In order to make all scenarios comparable the same properties of the systems are assumed i.e.

- no cooling is provided;
- heating temperature setpoint is 20°C;
- ventilation rate is modelled as 0.6 ach 24/7.

System 1 – advanced

System 1 is incorporated within Scenario 1 and it is equipped with advanced heating and energy generation systems containing following components (Figure 19 and Figure 20):

- Mechanical ventilation with air heat recovery of 90% effectiveness;
- 5.46 m² of solar thermal flat plate collectors;
- Solar assisted underfloor radiant heating;
- Solar assisted DHW;
- 8.85 m² of photovoltaic panels;
- Inverter of 96% efficiency;
- Electrical backup coil.

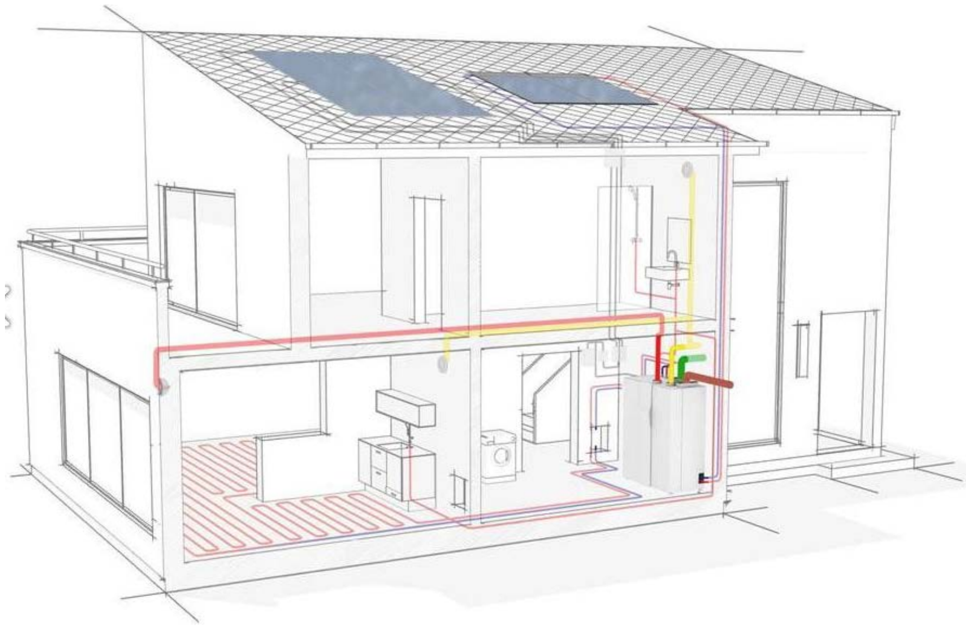

Figure 19 Schema of the advanced system incorporated in Scenario 1 (Stiebel Eltron 2017)

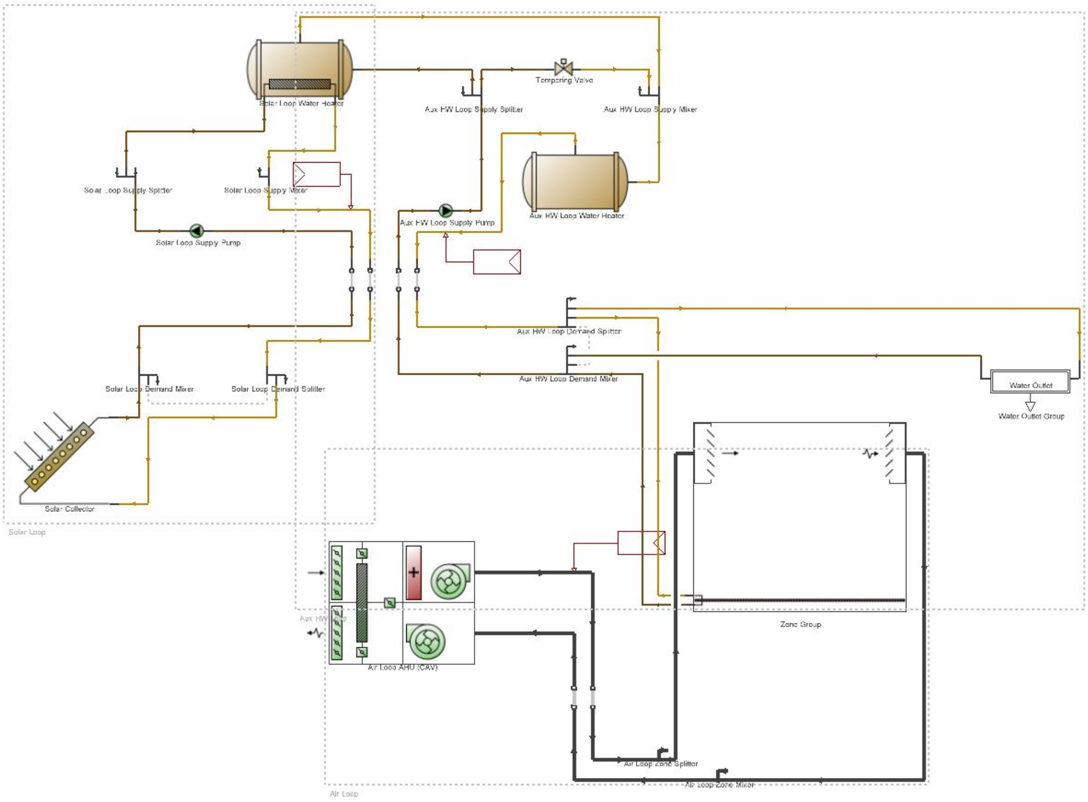

Figure 20 Schematic of the advanced system incorporated into Scenario 1

System 2 – simple

System 2 is incorporated within Scenarios 2 – 5 and it is equipped with simple heating system containing following components:

- Gas boiler of 89% efficiency;
- Conventional convectors.

The required volume of fresh air is provided naturally.

3 RESULTS AND DISCUSSION

3.1 Overview

The results of the energy simulation clearly show that energy demand of Scenarios 2 – 5 featuring conventional heating system, natural ventilation and no renewable energy sources is two times bigger than in case of Scenario 1 (Figure 21). The same figure shows that the building components not related directly to provision of the heat or DHW (i.e. light and equipment) have minor effect on total energy demand in all cases: respectively approx. 10% and 16% in Scenario 1 and 6% and 10% in Scenarios 2 – 5.

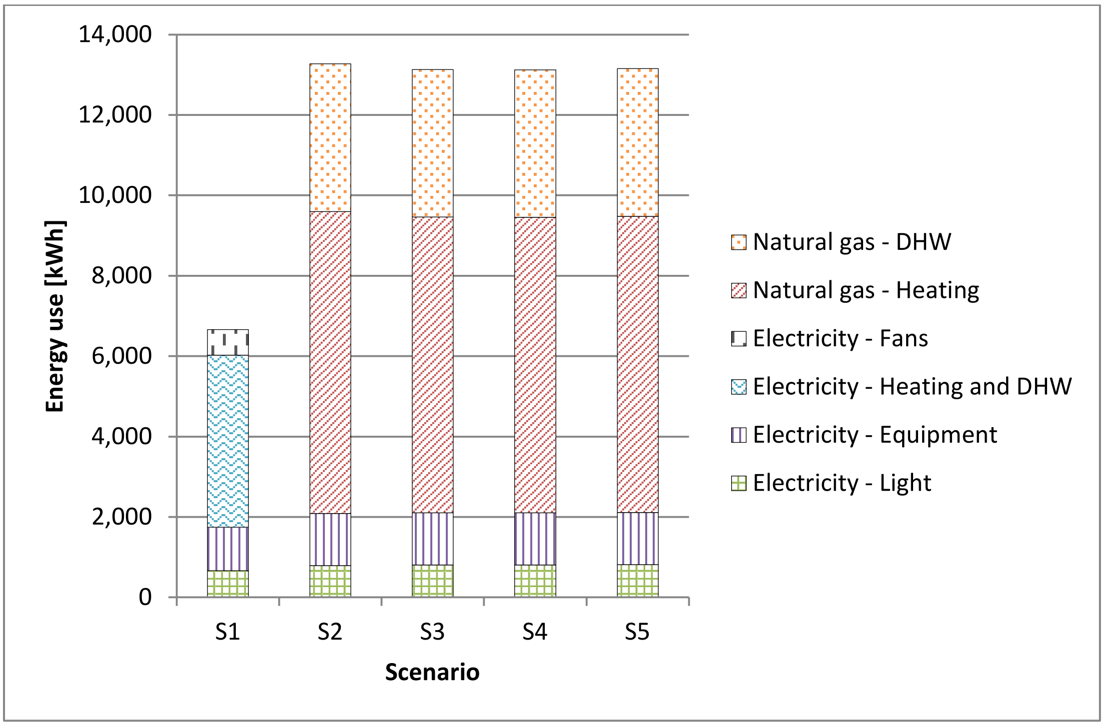

Figure 21 Site energy demand per year

Smaller heating and DHW energy demand of the Scenario 1 results on the one hand from smaller heat losses due to better airtightness and mechanical ventilation equipped with heat exchanger and on the other hand from incorporated equipment allowing use of solar energy (solar thermal flat collectors and photovoltaic installation). The contribution of on-site renewable energy to total energy use is presented on Figure 22. As described in chapter 2.5.4, according to Polish legislation 80% of surplus energy fed into the grid can be balanced with utilised one. Therefore this ratio was taken into account in the calculation of the RES coverage rate of total energy demand.

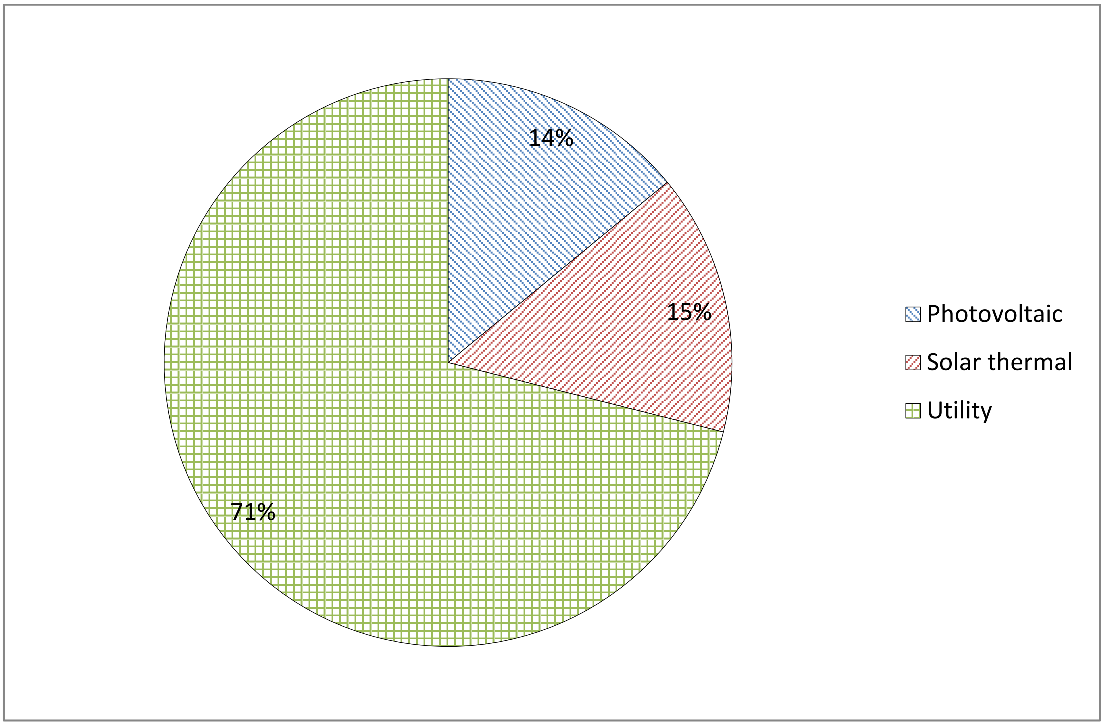

Figure 22 Coverage rate of energy in Scenario 1 by various energy sources

As described in chapter 1.3.2 the assumed primary energy conversion factor for electrical energy is 3 and for natural gas 1.12.

The building analysed in Scenario 1 is equipped with solar thermal collectors and photovoltaic panels. Nevertheless, remaining energy is provided from the grid in form of electrical energy. The PEF of electrical energy is nearly 2.5 times larger than PEF of gas source energy. As a result, the relative difference between all scenarios concerning primary energy demand becomes smaller than in case of site energy. Scenario 1 accounts to approx.19.5 MWh per annum, while Scenarios 2 to 5 to approx.. 20.9 MWh per annum.

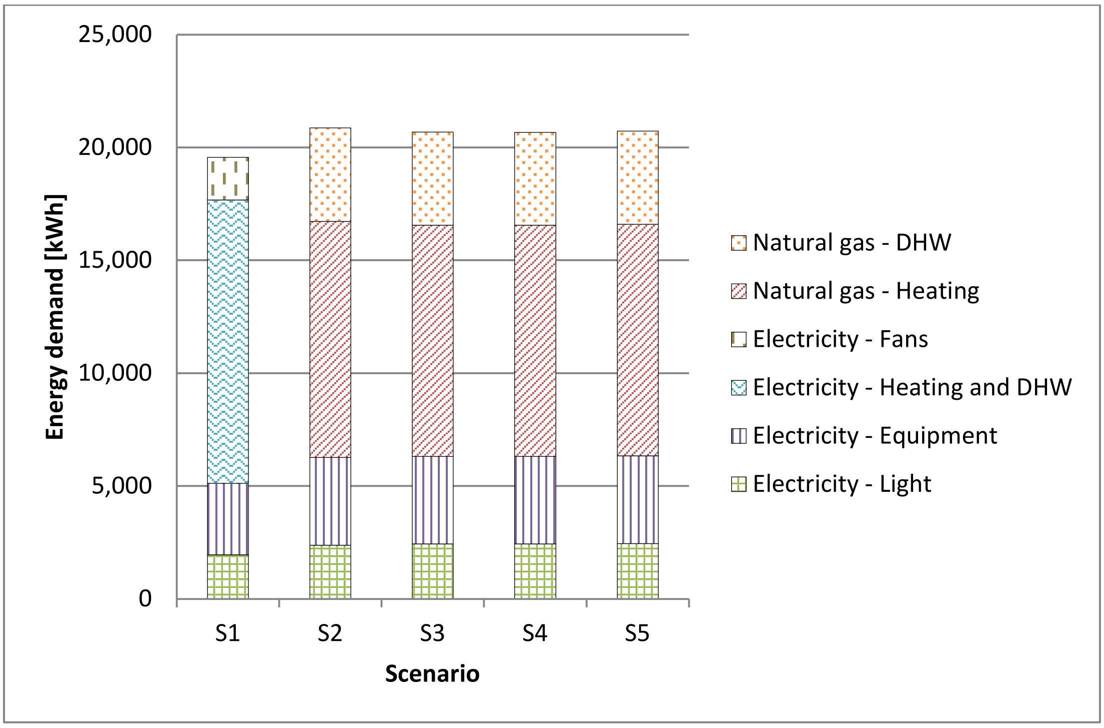

Figure 23 Primary energy demand per year

3.2 Life-Cycle Assessment

3.2.1 Global Warming Potential

The results of LCA show that Scenario 1 is the one having the lowest GWP, while Scenario 4 the highest. The difference between these two accounts to 15% (Figure 24). Moreover it can be observed that the operational stage i.e. replacement of building components and energy use have the biggest impact on GWP. Depending on the scenario, the latter accounts to between 76% and 80% of total GWP potential. Significant differences can be observed in the production stage. The lowest impact of the production stage can be seen in Scenario 5 with rammed earth and wood fibre insulation as main materials of walls constructions and amounts to approx. 20 t of CO_2 equiv. during 50 years of building life cycle. The second best scenario concerning this stage (Scenario 3 with brick wall build up) produces 55% more CO_2 equiv. during the same time. The worst scenario considering the production stage is Scenario 4. It is built with aerated concrete blocks and results in 128% bigger impact in GWP and the best one Scenario 5.

On the other hand, impact of disposal stage is the highest in Scenario 5 and the smallest in Scenario 4. The CO_2 equiv. produced during that stage in Scenario 5 is nearly 46% higher than in Scenario 4. Due to small impact of replacement of building components (2-6% of total impact) this stage can be assumed to be of rather minor relevance. Nevertheless, it is important to mention that highest impact during this stage is achieved by Scenario 1 (high performance building with advanced building services).

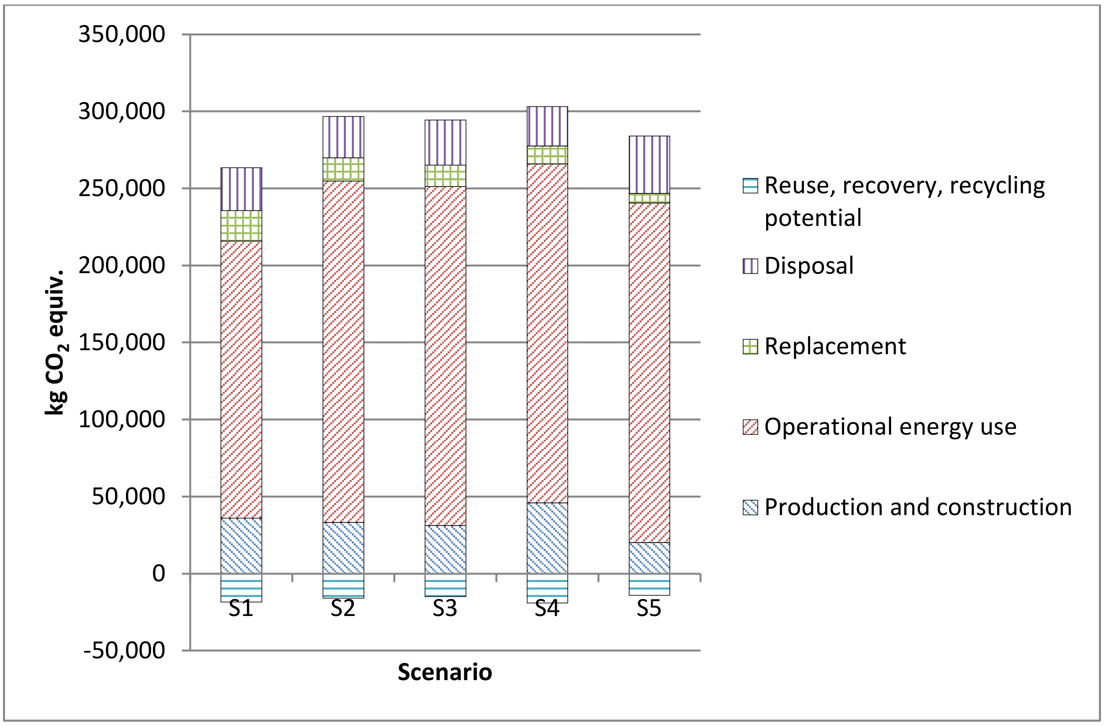

Figure 24 Global warming potential during different stages of the life cycle

3.2.2 Ozone Depletion Potential

Looking at absolute values the worst is Scenario 1 where only production phase has ODP as whole impact of Scenario 5. The result of the Scenario 1 is three times bigger than the result of Scenario 5. The increased value of ODP in regard of energy use results from electricity driven heating system, which due to Polish energy mix relying mainly on solid fuels (as described in chapter 1.3.2) is two times bigger than Scenarios incorporating a gas boiler.

The only difference between Scenario 1 and Scenario 2 besides airtightness is the system. Scenario 1 incorporating advanced building services can be directly translated into growth of impact of replacement stage. The difference between these two scenarios in regard of replacement stages reaches 85%.

Significance of energy use during the service life is much smaller than in GWP impact category amounts to 17% - 38%. On the other hand, impact of the production stage (37% - 73%) as well as reuse, recovery and recycling potential become more important. In fact, in some of the scenarios the latter exceeds total ODP. Effect of the disposal stage is negligible (1% - 3%). Depending on the scenarios replacement stage has small impact of approx. 2% reaching in 35% in Scenario 1.

Big reuse, recovery and recycling potential is a result of thermal utilisation of wooden roof construction.

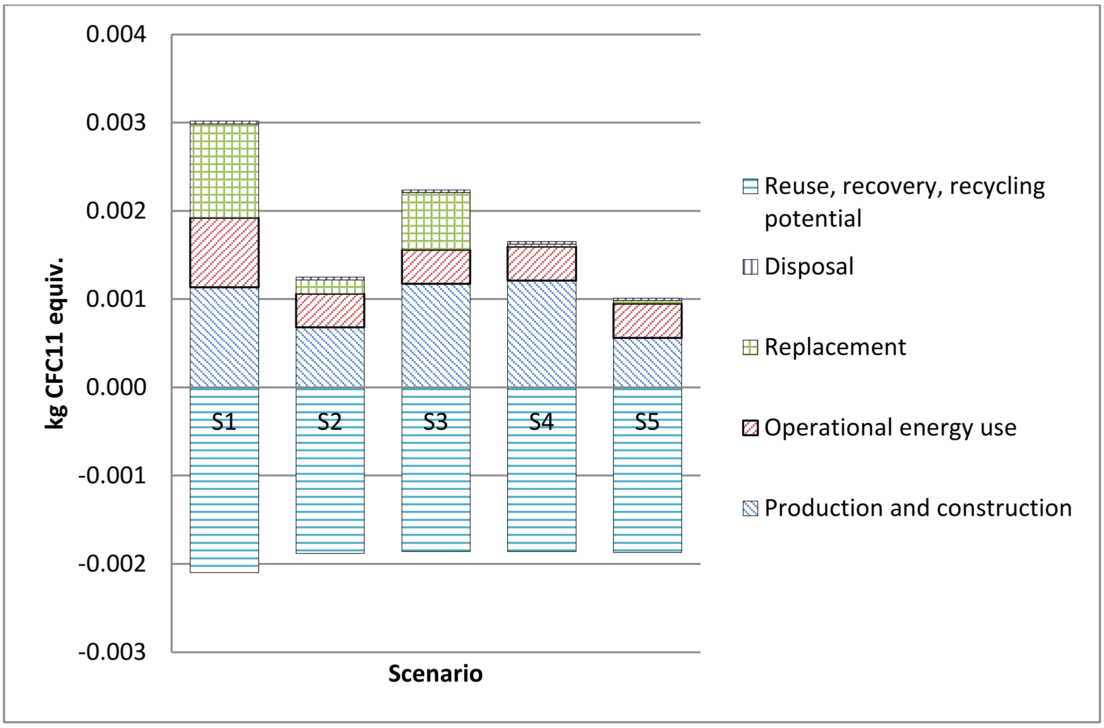

Figure 25 Ozone depletion potential during different stages of the life cycle

3.2.3 Photochemical Ozone Creation Potential

Similarly to ODP, the differences between all the scenarios are more vivid than in GWP (Figure 26). Clearly Scenario 5 built of rammed earth and wood fibre board has the smallest POCP impact, mainly because of reduction of POCP in production stage of the building. Scenario 4 – built of aerated concrete as an only case does not have insulated walls what influence reduction of POCP in production and replacement stage. Concerning operational energy use, it is visible that Scenarios 2 – 5, heated with gas boiler have more than three times bigger POCP impact than Scenario 1 which is heated with solar energy and supporter with electrical heating coil.

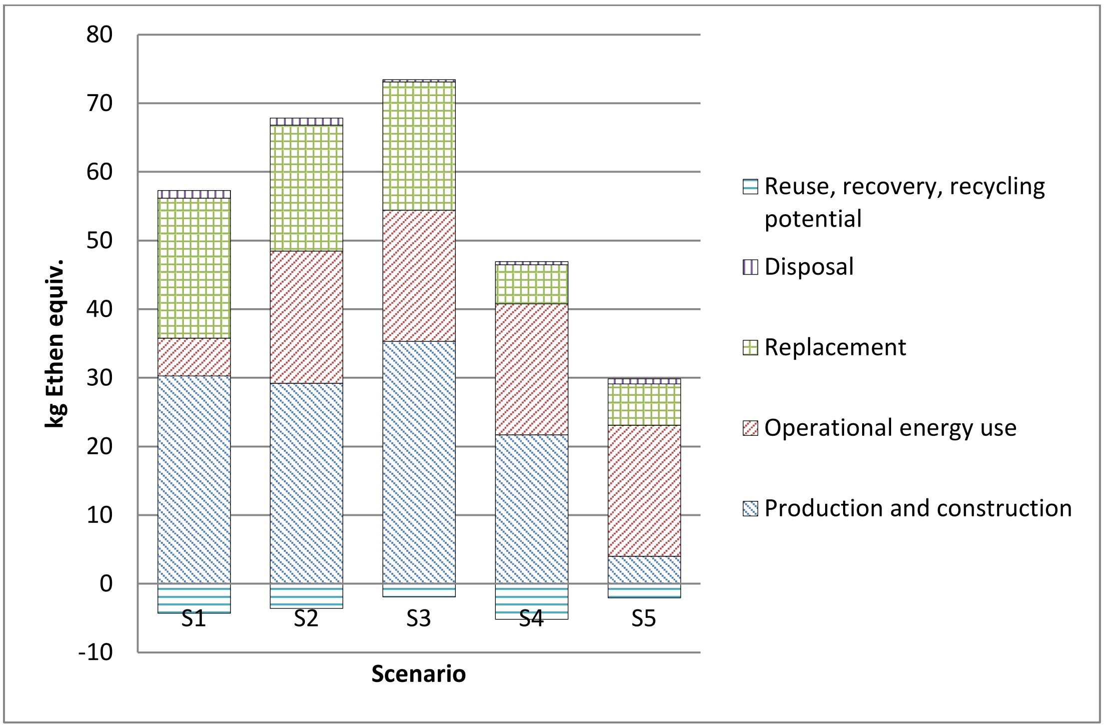

Figure 26 Photochemical ozone creation potential during different stages of the life cycle

3.2.4 Acidification Potential

As seen on Figure 27, the results of Scenarios 2 – 5 are 40% better than Scenario 1. The component having the biggest impact on Acidification Potential in all Scenarios is operational energy use. The differences between the Scenario 1 incorporating advanced, electrical building services and Scenarios 2 – 5 (with gas boiler) are substantial. In Scenarios 2 – 5 energy use contributes in 81% - 83%, while in Scenario 1 in 87%. Such difference results from particular electrical energy mix in Poland described in chapter 1.3.2, which clearly puts in favour natural gas. The acidification potential of the energy generated with natural gas is nearly 37 times smaller than of the Polish electrical energy mix (Ökobaudat.de 2015; Lelek et al. 2016). According to Lelek et al. (2016, p. 1) *„acid and CO_2 emissions increased significantly in 2012 as a result of higher consumption of brown coal as a fuel for energy production".* Impact of production stage amounts to 8% - 13%, replacement stage to 4.2% - 5.7% and disposal stage to 0.4%-1.2%.

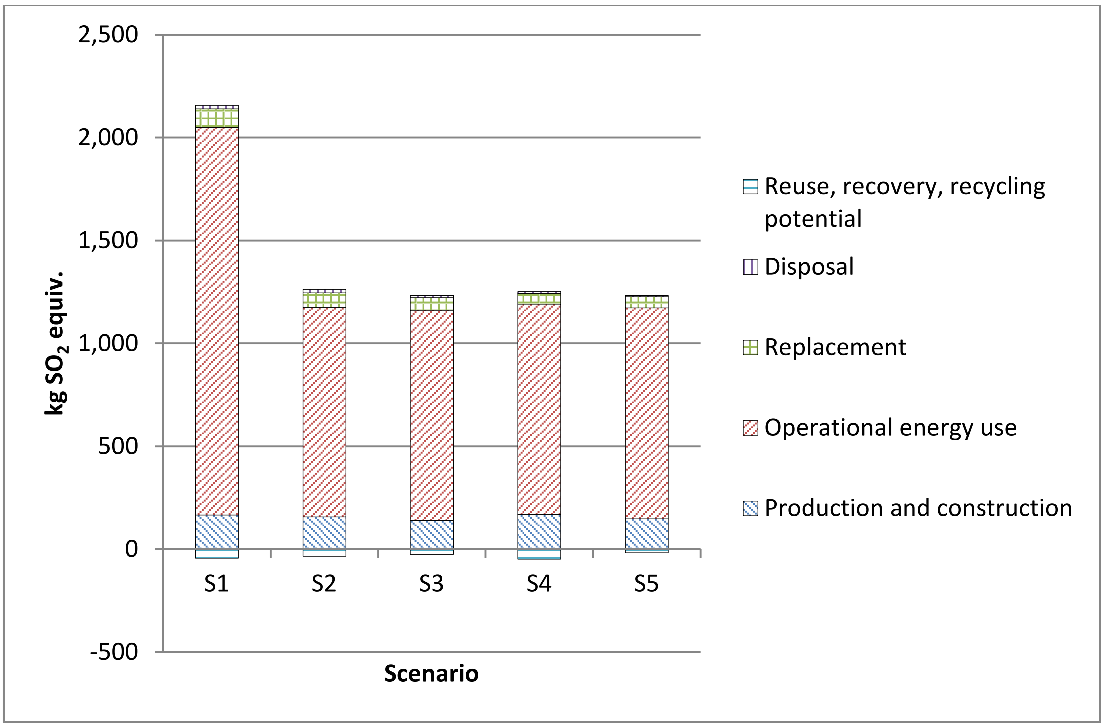

Figure 27 Acidification potential during different stages of the life cycle

3.2.5 Abiotic Depletion Potential for Fossil Resources

Scenario 2 built of sand lime brick and using conventional building services has the worst result in contrary to Scenario 1, which differs with the building services (and related to the types of the energy sources) and airtightness.

The biggest impact (reaching depending on the scenario between 68% and 81%) has again operational energy use stage. It is the smallest in Scenario 1 and differs from other scenarios due to the electricity as an only source of energy. The impact of the production stage is between 14% and 21%, replacement 4% - 9% and disposal 0.4% - 1.2%.

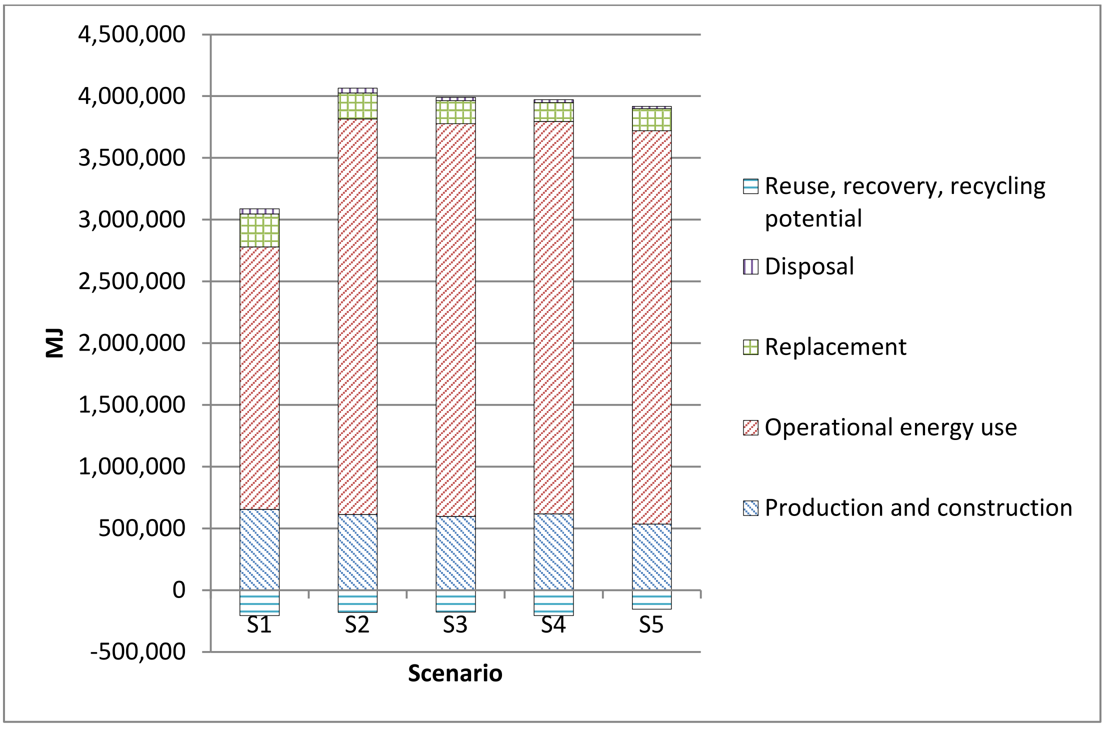

Figure 28 Abiotic depletion potential for fossil resources

3.2.6 Normalization

As described in the chapter 2.4.5 the results are divided by conversion factors. Such an action allows comparison of relative, unitless values, and as a result determination of significance of particular environmental impact categories. Figure 29 shows that the most important impact category is GWP. Nevertheless, both AP and ADPF should also be taken into consideration constituting approx. 72% of GWP. On the other hand, remaining ODP and POCP are of rather minor importance with approx. 0.05% and 14% respectively of impact in comparison to GWP. Hence, all previous considerations in chapters 3.2.1 - 3.2.5 should take in into consideration results of normalization process and interpret the results of LCA accordingly.

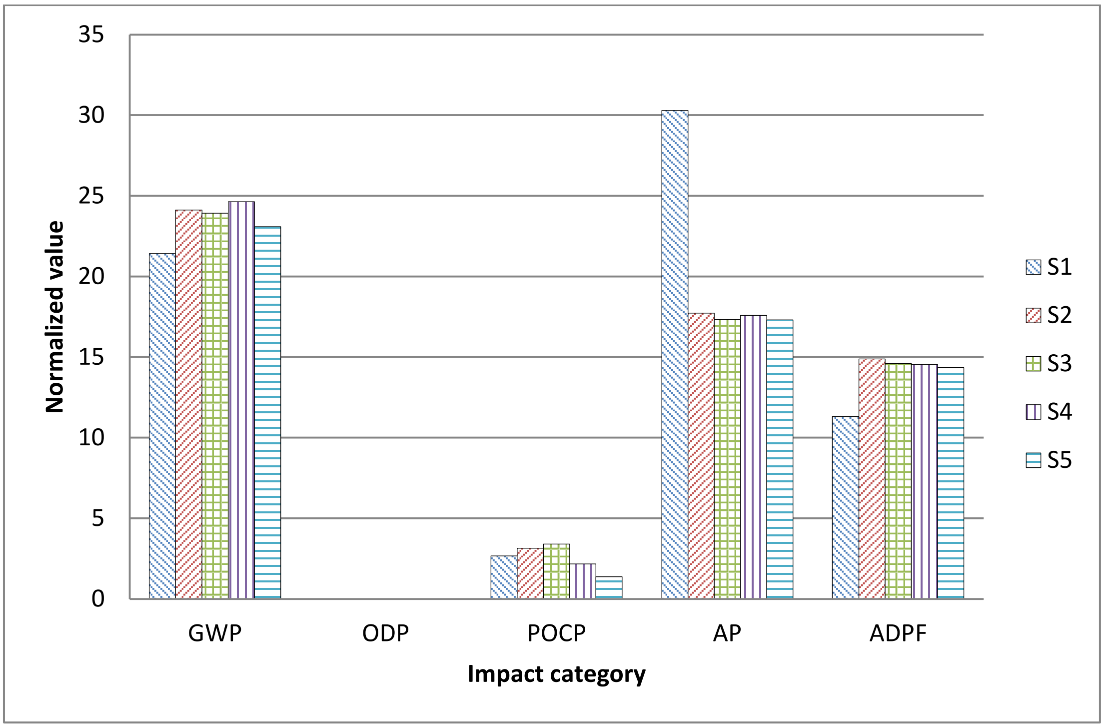

Figure 29 Normalized impact category results

3.3 Life Cycle Costing

Figure 30 presents cumulative cost of all Scenarios during service life of 50 years. Investment cost in the year 0 is the highest for Scenario 5 (a house built with rammed earth) and it amounts to nearly €89,000. Scenario 1 (sand lime brick house with advanced building services) is approx. 2% cheaper. Initial cost of remaining Scenarios 2 – 4 fluctuates between €70,300 and €74,300 what makes 16.2% to cheaper in the year 0 in comparison to Scenario 5. All of the Scenarios are exposed to rising costs of energy, water and other fixed costs resulting in exponential rise of the cumulative costs. Due to various energy sources in Scenario 1 (electricity) and

Scenarios 2 – 5 (electricity and gas) characterised by various prices as well as various growth rate the curves representing cumulative cost over the years are of different slope. Additionally, each of scenarios requires periodical replacement of some of their components which can be seen on the Figure 30 as "steps" appearing usually every 20 or 30 years. Due to expensive building services in Scenario 1 the "steps" are higher than in case of other scenarios. A breakdown of the cumulative nominal cost of each scenario can be found in Annex A.

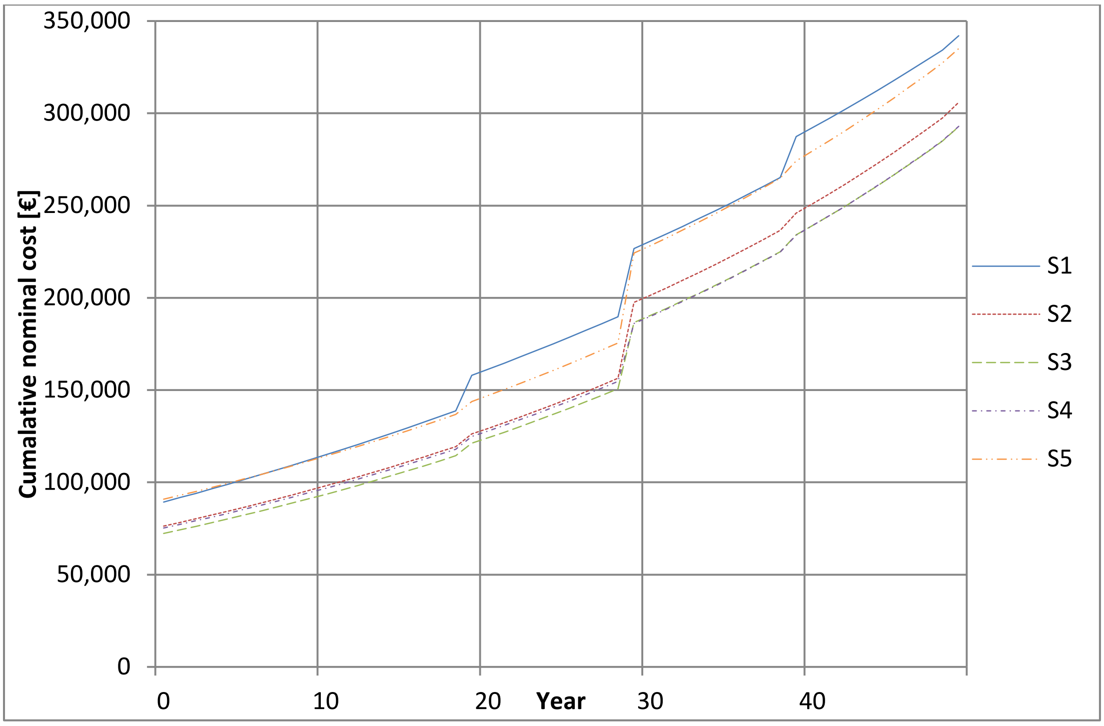

Figure 30 Cumulative nominal cost during life cycle

As described in chapter 2.5.5, all the costs are discounted to present value (Net Present Value) and presented in Figure 31. The lowest cost (NPV) during life cycle of 50 years has been assigned to Scenario 3 – house built of brick walls and amounts to €227,326. Scenario 4 (aerated concrete) is 0.5% more expensive – €228,417. The most expensive ones: Scenario 5 (rammed earth) and Scenario 1 (sand lime brick with advanced building services) are respectively 15.7% and 18.4% more expensive than Scenario 3.

The biggest impact on NPV of all Scenarios has initial investment which amounts to 31.0% - 33.7% of total NPV. Another big group of costs is related to replacement and maintenance of the building components (26.5% - 34.4%). Due to high cost of building services and as a result maintenance and replacement costs Scenario 1 is characterized with the highest relative and absolute cost in this group of costs among all Scenarios. Third group of significant costs are running costs of energy and water. In Scenario 1 these costs are the lowest (€88,404), while in Scenarios 2 – 5 approx. €94,000. Relative value varies between 32,9% and 41,3%. The lowest cost, namely deconstruction and disposal constitutes less than 1% of total NPV and therefore it is irrelevant.

Detailed cumulative cost analysis for every Scenario is presented in Appendix A on page 61.

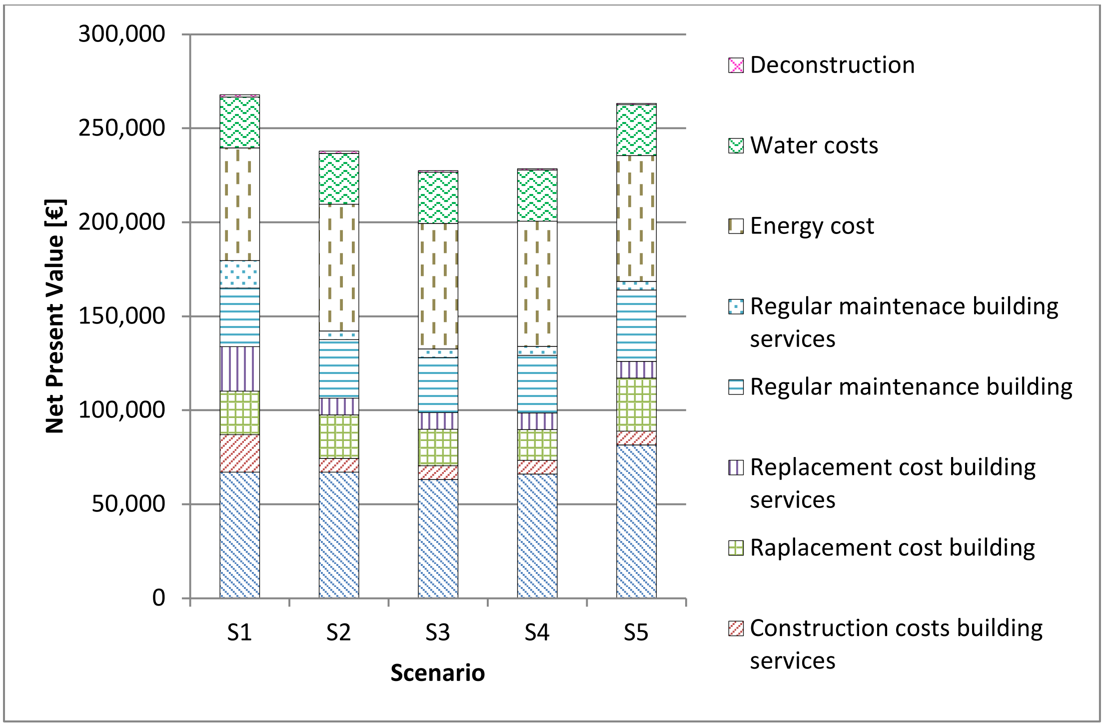

Figure 31 Net Present Value during life cycle

3.4 Sensitivity analysis

The main parameter which was analysed in order to verify its impact on final result was service life of the buildings. Initial analysis took into consideration life cycle of 50 years. Nevertheless, there is a chance that the duration of life of a building might be both, longer or shorter. As a result an operational stage of a building might gain or lose its significance due to e.g. change of amount of replacements. As a result two additional scenarios were analysed in regard of LCA and LCC and compared with baseline scenario of 50 years of service life:

- 30 years of service life of a building;
- 80 years of service life of a building.

3.4.1 LCA

Following conclusions of normalization from chapter 3.2.6, only Global Warming Potential, Acidification Potential and Abiotic depletion potential for fossil resources are taken into consideration in the sensitivity analysis.

In principle, significance of the operational stage of the building life cycle has risen. Nevertheless, the relative impact of each Scenario remained the same in all options of service life, i.e. the ranking of Scenarios has not changed in comparison to baseline (50 years of service life) with Scenario 5 having the lowest GWP and Scenario 1 the highest (Figure 32).

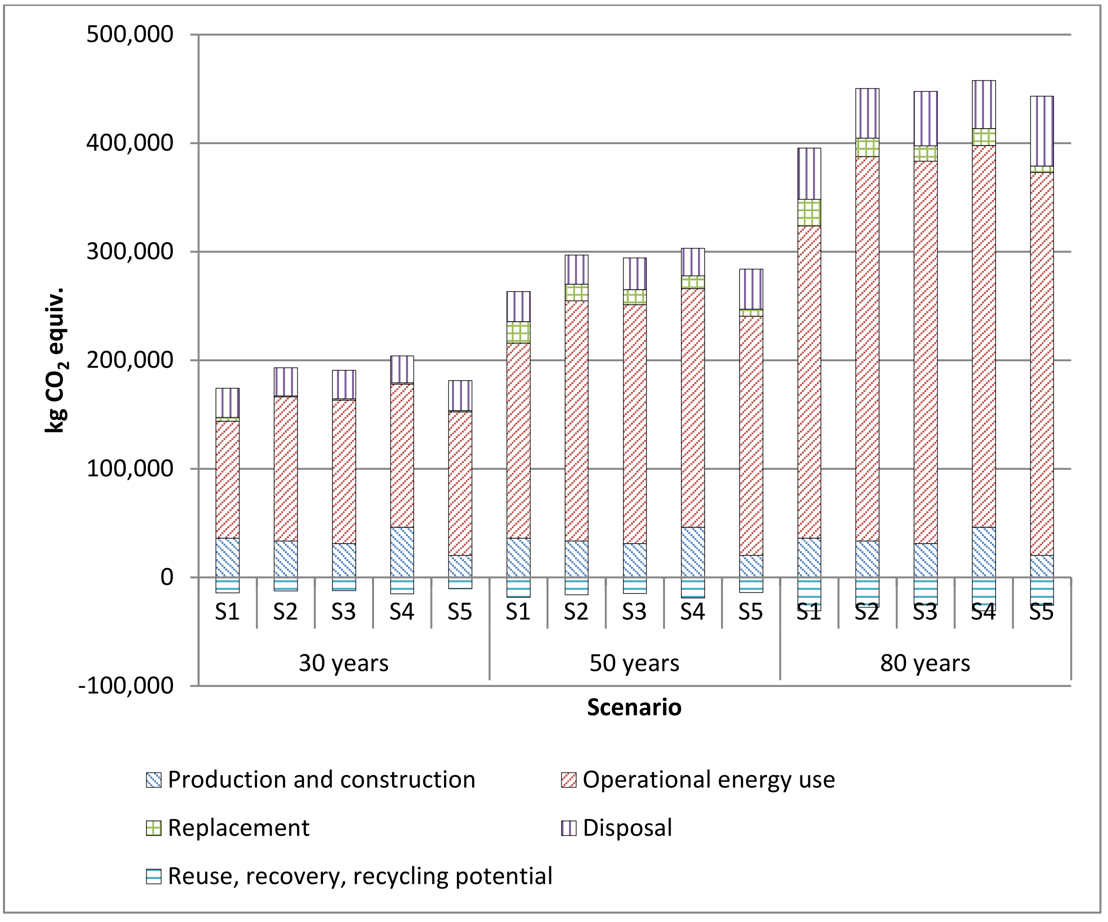

Figure 32 Impact of the building service life on GWP

Similar trend can be observed in regard of Acidification Potential (Figure 33). As in baseline, the biggest impact in this category has Scenario 1 (sand lime brick with advanced building services). Extension of the operational stage affect amount of supplied energy which in case of Scenario 1 is produced mainly from solid fuels. Remaining Scenarios present rather similar impact throughout all durations of service life.

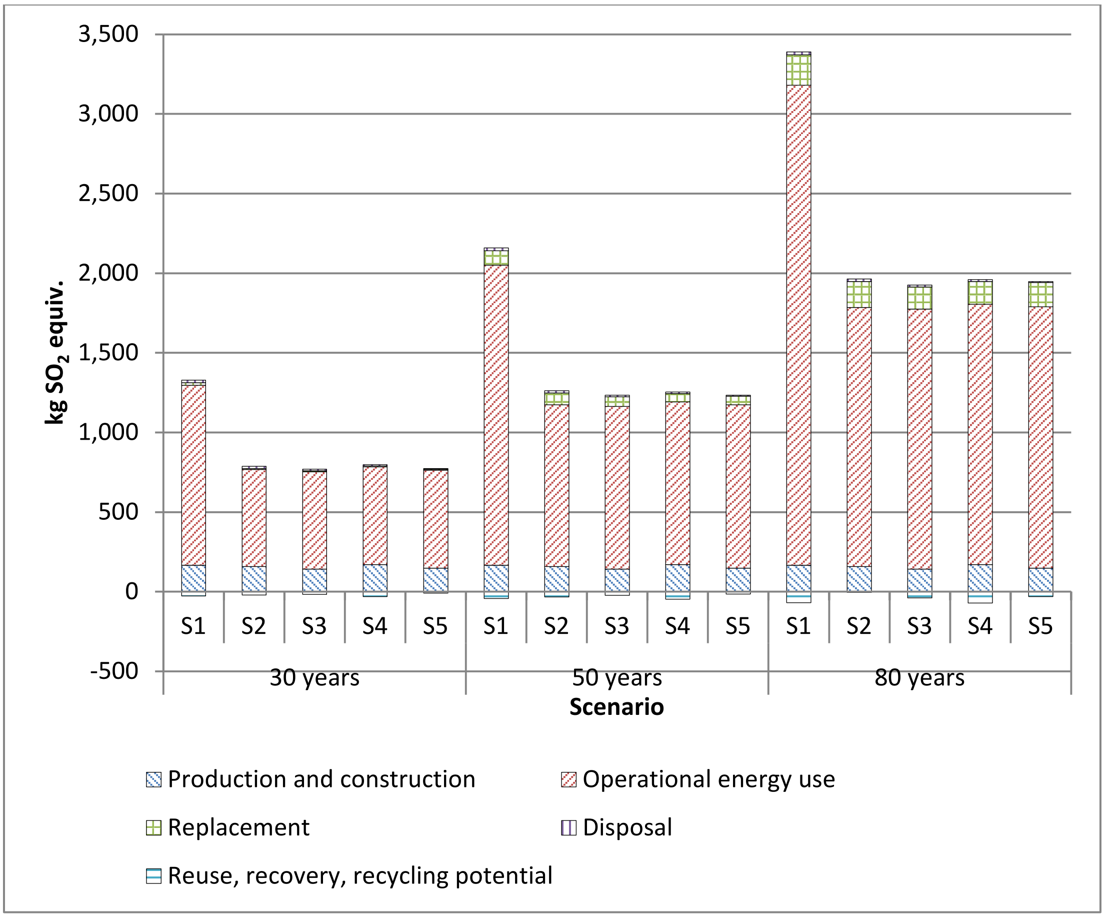

Figure 33 Impact of the building service life on AP

As seen on Figure 34 throughout all analysed durations of service life of a building the worst is Scenario 2 (sand lime brick), while the best Scenario 1 (sand lime brick with advanced building services). Ranking of remaining Scenarios 3 – 5 differs depending on analysed service life, hoverer the differences are limited up to 5.6% regardless the duration of service life.

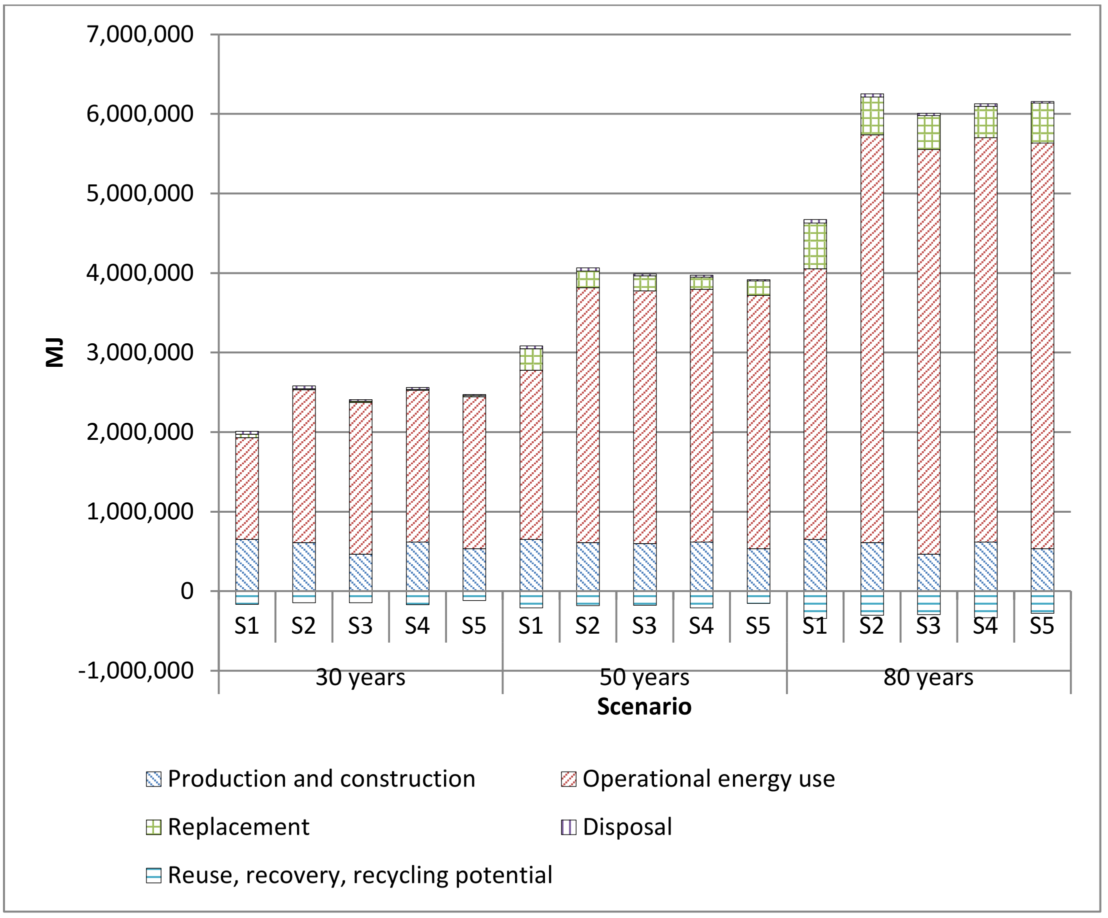

Figure 34 Impact of the building service life on ADPF

3.4.2 LCC

Analysing impact of service life of a building on LCC it can be easily determined that operational stage is the one having the greatest impact on final result (Figure 35). Taking into consideration 30 years of service life the ranking of Scenarios does not change. As in baseline scenario of fifty years of service life Scenario 3 (brick) results in the best score, while Scenario 1 (sand lime brick with advanced building services) the worst.

On the other hand, analysing 80 years of service life the ranking alters. Prolonged duration of operational stage results in higher running costs (energy, water), maintenance costs and more replacements of building components. As a result, Scenario 5 (rammed earth) has the highest Net Present Value over the period of 80 years of service life of a building, while Scenario 4 (aerated concrete) the lowest. The best within 30 and 50 years of service life Scenario 3 (brick) is 0.3% more expensive than Scenario 4.

80 years of service life of a building is also a time period which makes Scenario 1 (sand lime brick with advanced building services) worth considering. In this time frame Scenario 1 stops being the most expensive as considering 30 or 50 years of service life. This electricity powered Scenario becomes more competitive (3.8% more expensive than the cheapest Scenario 4) due to differences in gas and electricity price increase ratio (4% p.a. and 2.4% p.a. respectively). Consequently, total discounted energy price within 80 years of service life is the lowest in Scenario 1. Savings on energy nearly fully pay for increased costs associated with more advanced and thus more expensive building services (investment, replacement and regular maintenance).

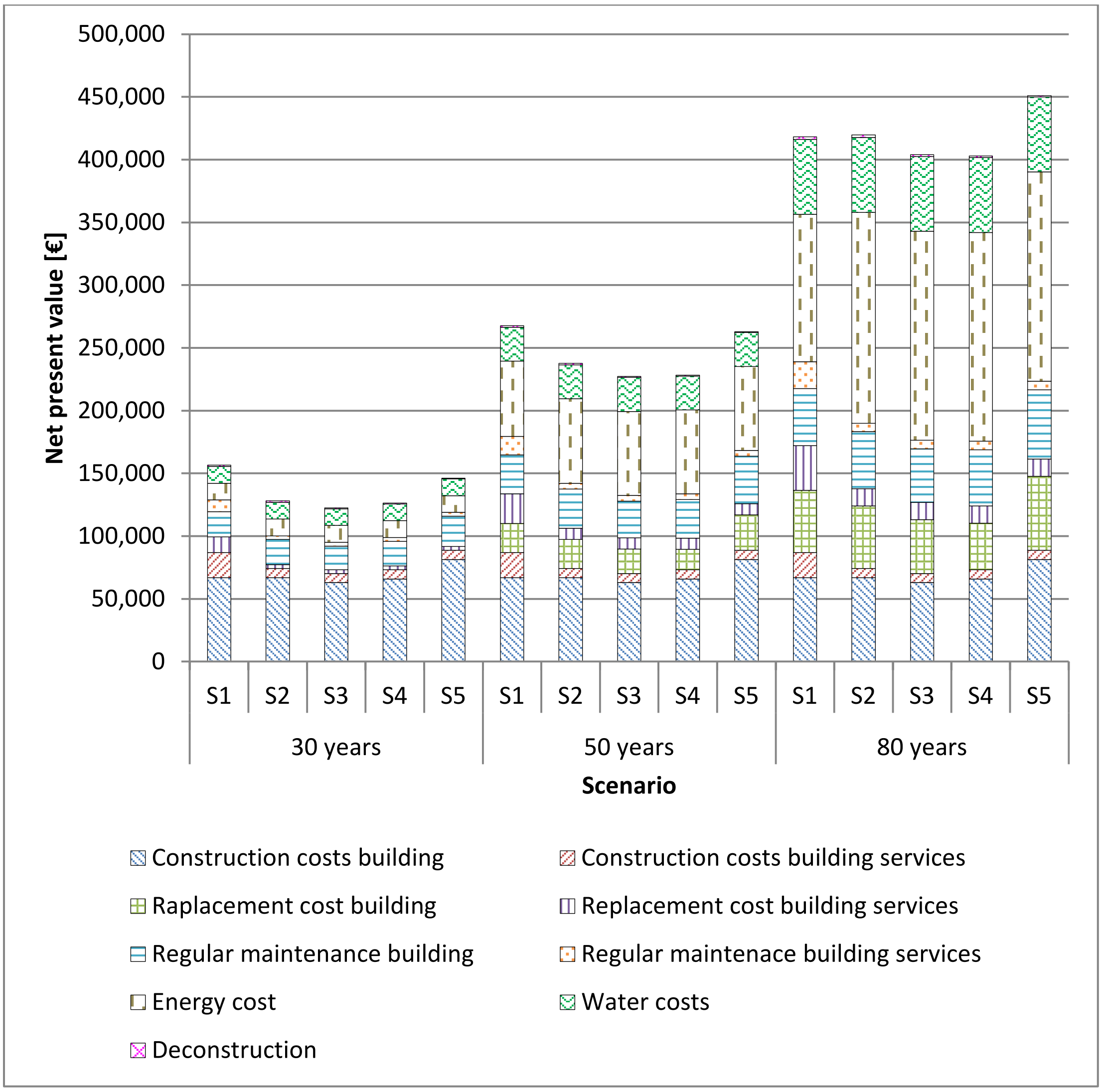

Figure 35 Impact of the building life on NPV

4 CONCLUSION

4.1 Conclusions

This work is an attempt of proving that low-energy and low-embodied energy houses have smaller environmental impact (LCA) and life cycle cost (LCC) than conventional houses in Polish conditions concerning the climate and electrical energy mix. The major question asked in this research work was as follows:

To what extent choice of the construction materials and heating strategy in single family house in Poland has impact on the results of LCA and LCC?

There are five scenarios analysed varying with main construction materials (sand lime brick, fired brick, aerated concrete, rammed earth) and building services (mechanically ventilated house with solar thermal supported heating with electrical coil and naturally ventilated house with conventional gas boiler). The service life of the building is assumed to be 50 years. Nevertheless sensitivity analysis taking into consideration 30 and 80 years has been performed as well. The results of LCA have been normalized in order to define impact categories with relevant environmental impact (GPW, AP, ADPF).

The hypothesis has not been proved. Depending on assessed performance indicator various Scenarios were in favour and can be break into following:

- Energy demand of Scenarios 2 – 5 featuring conventional heating system, natural ventilation and no renewable energy sources is two times bigger than in case of Scenario 1;
- Different PEF of natural gas and electrical energy result in nearly the same primary energy demand of all the Scenarios with Scenario 1 being better than the others by max. 7%;
- The results of LCA show that Scenario 1 is the one having the smallest GWP, while Scenario 4 the highest. Nevertheless, the difference between them is only 15%
- The energy type has the biggest impact on AP. As a result Scenario 1 is nearly two times worse than the others;
- Concerning ADPF Scenario 1 the best, while Scenario 2 the worst. Similarly to other impact categories operational energy use is the most relevant stage;

- Normalisation shows that ODP and POCP are not relevant for the final result of the research;
- The lowest Net Present Value over 50 years of service life of a building has Scenario 3 (brick build-up with conventional heating), while the highest Scenarios 1 and 5 (sand-lime brick with advanced systems and rammed earth with conventional heating respectively).

Research shows that the biggest impact on both LCA and LCC has operational stage of building life. Polish energy mix relying mostly on solid fuels has extremely negative influence on environmental impact of houses using electrical energy. It can be assumed that the same research performed in countries depending on cleaner energy mix would bring different results i.e. working more in favour of systems powered with electrical energy like Scenario 1. Furthermore, all building services require periodical maintenance and replacement. Nevertheless, advanced and thus expensive systems result in higher operational costs. Consequently, Scenario 1 equipped with such system does not present enough energy saving during 50 years of service life to pay back.

It is impossible though to foresee development of energy mix and of its environmental impact and price. Especially the latter depends strongly on political and economic situation in and between Poland and countries exporting gas. In case of significant changes in any of analysed aspects i.e. price or environmental impact results of this research may not be valid anymore.

4.2 Future research

The goal of this research was to analyse if nonconventional technologies of house construction will outrun typical ones in Polish conditions. A sample of both has been chosen. Nevertheless, selection and combination of construction materials is way bigger. Moreover, construction industry is constantly developing and as a result introduces new materials and building services. Hence, potential future research should take into consideration more extensive sample of products. Collaboration with IT sector is desirable in order to respond to enormous amount of products, their producers, all the thermal and environmental properties, as well as costs. Automatic acquisition of such data should be performed followed by generic optimization of acquired building products and services.

5 INDEX

5.1 List of Figures

5.2 List of Tables

5.3 List of Equations

6 LITERATURE

Act on Renewable Energy Sources, 2016. *Act of 22 June 2016 amending the Act on Renewable Energy Sources and some other acts [Ustawa dnia 22 czerwca 2016 r. o zmianie ustawy o odnawialnych źródłach energii oraz niektórych innych ustaw]*, Poland.

Anke Esser & Frank Sensfuss, 2016. *Evaluation of primary energy factor calculation options for electricity*, Karlsruhe. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/final_report_pef_eed.pdf [Accessed August 30, 2017].

ashrae.org, 2017. International Weather for Energy Calculations. Available at: https://www.ashrae.org/resources--publications/bookstore/international-weather-for-energy-calculations [Accessed August 3, 2017].

Association of the generally sworn and legally certified experts of Austria, 2006. *Service life of building and buidling services components [Nutzungsdauerkatalog baulicher Anlagen und Anlagenteile]* 3rd ed., Graz: Association of the generally sworn and legally certified experts of Austria.

Atanasiu, B. et al., 2012. *Implementing nearly Zero-Energy Buildings (nZEB) in Poland - Towards a definition and roadmap*, Brussels: Buildings Performance Institute Europe (BPIE).

Audenaert, A., De Cleyn, S.H. & Vankerckhove, B., 2008. Economic analysis of passive houses and low-energy houses compared with standard houses. *Energy Policy*, 36(1), pp.47–55.

Badescu, V., 2007. Economic aspects of using ground thermal energy for passive house heating. *Renewable Energy*, 32(6), pp.895–903.

BRE, 2008. *BRE Global Methodology for Environmental Profiles of Construction Products. SD6050*, Walford. Available at: http://www.greenbooklive.com/filelibrary/environmental_profiles/Methodology_for_Environmental_Profiles_2008_SD6050.pdf [Accessed August 1, 2017].

Citherlet, S. & Defaux, T., 2007. Energy and environmental comparison of three variants of a family house during its whole life span. *Building and Environment*, 42(2), pp.591–598.

Constitution of Republic of Poland, 1997. *Kancelaria Sejmu*, Poland.

Domyhybrydowe.pl, 2017. Ecological and hybrid houses [Domy ekologiczne i hybrydowe]. Available at: http://domyhybrydowe.pl/ [Accessed July 30, 2017].

Dong, X., Soebarto, V. & Griffith, M., 2015. Design optimization of insulated cavity rammed earth walls for houses in Australia. *Energy and Buildings*, 86, pp.852–863.

EN15804, 2012. *Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products EN 15804:2012+A1:2013*, Berlin: Deutsches Institut für Normung.

energy.gov, 2017. EnergyPlus. Available at: https://energy.gov/eere/buildings/downloads/energyplus-0 [Accessed August 3, 2017].

Energyplus.net, 2017. Weather Data by Location. Available at: https://energyplus.net/weather-location/europe_wmo_region_6/POL//POL_Poznan.123300_IMGW [Accessed August 3, 2017].

Eurostat, 2017a. Construction cost (or producer prices), new residential buildings. Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=sts_copi_a&lang=en [Accessed August 2, 2017].

Eurostat, 2017b. Electricity prices by type of user. Available at: http://ec.europa.eu/eurostat/tgm/table.do?tab=table&plugin=1&language=en&pcode=ten00117 [Accessed August 2, 2017].

Eurostat, 2016. Energy statistics. Available at: http://ec.europa.eu/eurostat [Accessed April 21, 2016].

Eurostat, 2017c. Gas prices by type of user. Available at: http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=ten00118&plugin=1 [Accessed August 2, 2017].

Feist, W., 1997. Life-Cycle Energy Analysis: Comparison of Low-Energy House, Passive house, Self-Sufficient House. *Passive House Institut*, p.13.

Fix, S. & Richman, R., 2009. *Viability of Rammed Earth Building construction in Cold Climates*, Toronto.

Galvin, R., 2014. Are passive houses economically viable? A reality-based, subjectivist approach to cost-benefit analyses. *Energy and Buildings*, 80, pp.149–157.

GUS, 2017. *Concise Statistical Yearbook of Poland 2008-2017*, Warsaw.

International Renewable Energy Agency, 2015. *Remap 2030: Renewable Energy Prospects for Poland*, Abu Dhabi. Available at: www.irena.org/remap.

Islam, H., Jollands, M. & Setunge, S., 2015. Life cycle assessment and life cycle cost implication of residential buildings—A review. *Renewable and Sustainable Energy Reviews*, 42, pp.129–140.

ISO14040, 2009. *Environmental management – Life cycle assessment – Principles and framework (ISO 14040:2006)*, Berlin: Deutsches Institut für Normung.

ISO14044, 2006. *Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006)*, Berlin: Deutsches Institut für Normung.

ISO15686-5, 2009. *Buildings and constructed assets — Service-life planning — Part 5: Life-cycle costing*, Geneva: International Organization for Standardization.

Jaramillo-Nieves, L. & del Río, P., 2010. Contribution of renewable energy sources to the sustainable development of islands: An overview of the literature and a research agenda. *Sustainability*, 2(3), pp.783–811.

K.A.P.E., 2012. *Energysaving houses. Manual of good practices [Domy energooszczędne. Podręcznik dobrych praktyk]*, Krajowa Agencja Poszanowania Energii.

Kohler, N. et al., 2010. *A life cycle approach to buildings*, Munich: Institut für Internationale Architektur-Dokumentation.

Lelek, L. et al., 2016. Life cycle assessment of energy generation in Poland. *The International Journal of Life Cycle Assessment*, 21, pp.1–14.

Molenbroek, M., Stricker, E. & Boermans, T., 2011. *Primary energy factors for electricity in buildings*, Utrecht.

National Energy Conservation Agency, 2011. *Manual of typology of residential buildings with examples of actions toward reduction of their energy use [Podręcznik typologii budynków mieszkalnych z przykładami działań mających na celu zmniejszenie ich energochłonności]*, Warsaw.

OECD, 2017. Inflation forecast (indicator). Available at: https://data.oecd.org/price/inflation-forecast.htm [Accessed August 2, 2017].

Oferteo.pl, 2014. What houses built Polish in 2014 - Report [Jakie domy budowali Polacy w roku 2014 - Raport]. Available at: http://www.oferteo.pl/raporty/jakie-domy-budowali-polacy-w-roku-2014 [Accessed April 11, 2016].

Ökobaudat.de, 2015. ÖKOBAUDAT. Available at: http://www.oekobaudat.de/ [Accessed July 29, 2017].

PN-EN12831, 2006. *Heating systems in buildings — Method for calculation of the design heat load [Instalacje ogrzewcze w budynkach -- Metoda obliczania projektowego obciążenia cieplnego]* 2006th ed., Warsaw: Polski Komitet Normalizacyjny.

Polish Ministry of Economy, 2009. *Energy policy of Poland until 2030 [Polityka energetyczna Polski do roku 2030]*, Poland.

Stiebel Eltron, 2017. STIEBEL ELTRON. Available at: https://www.stiebel-eltron.com/en/home.html [Accessed August 15, 2017].

Szalay, Z., 2007. *Life cycle environmental impacts of residential buildings*. Budapest University of Technology and Economics, Hungary.

The World Conservation Union, 2008. *The IUCN Programme 2005 – 2008 Many Voices , One Earth*, Bangkok.

Thiers, S. & Peuportier, B., 2012. Energy and environmental assessment of two high energy performance residential buildings. *Building and Environment*, 51, pp.276–284.

tradingeconomics.com, 2017. Poland Government 10 Years Bond Forecast. Available at: https://tradingeconomics.com/poland/government-bond-yield [Accessed August 2, 2017].

United Nations General Assembly, 2005. *World Summit Outcome*, Available at: http://www.un.org/womenwatch/ods/A-RES-60-1-E.pdf.

Wang, L., Gwilliam, J. & Jones, P., 2009. Case study of zero energy house design in UK. *Energy and Buildings*, 41(11), pp.1215–1222.

WCED, 1987. *Our Common Future: Report of the World Commission on Environment and Development*,

Wolters Kluwer, 2016. *Price list of works and investment objects, Q3 2016. [Katalog cen jednostkowych robót i obiektów inwestycyjnych, III kwartał 2016]*, Warsaw: Wolters Kluwer SA.

7 APPENDIX

A. Cumulative cost of respective scenarios

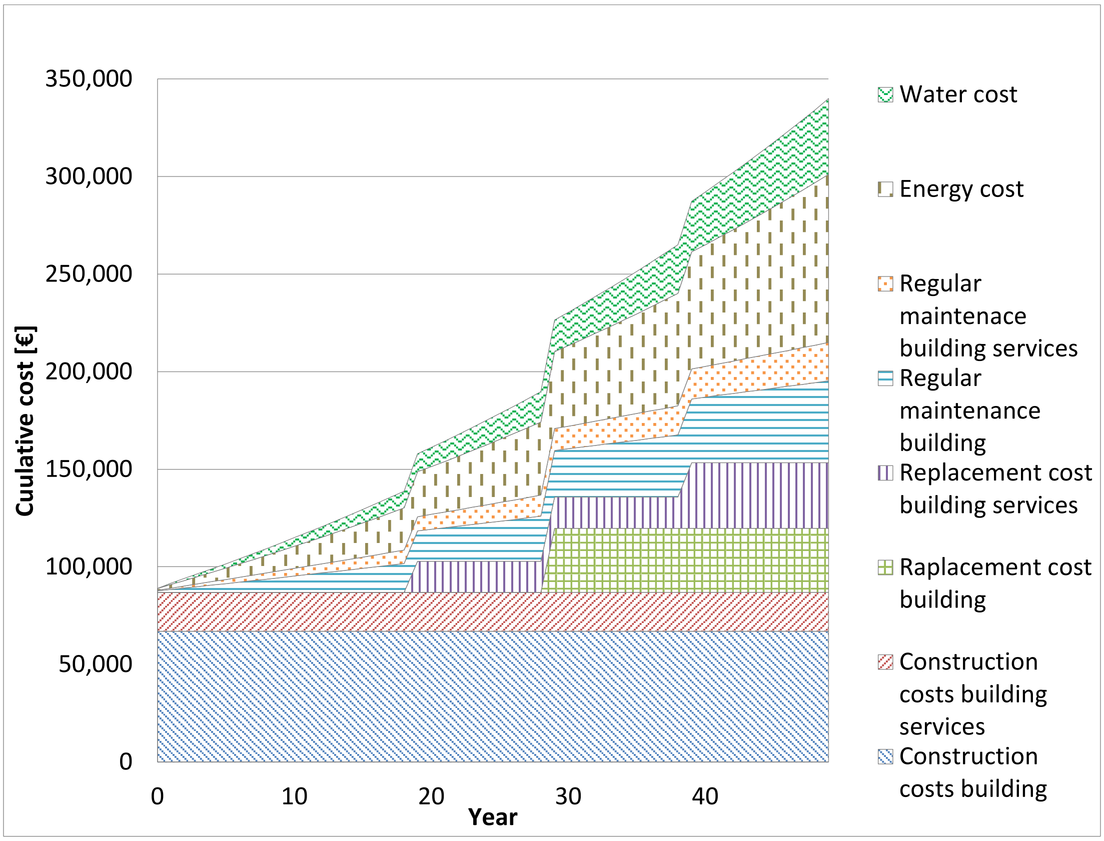

Figure 36 Cumulative nominal cost of Scenario 1

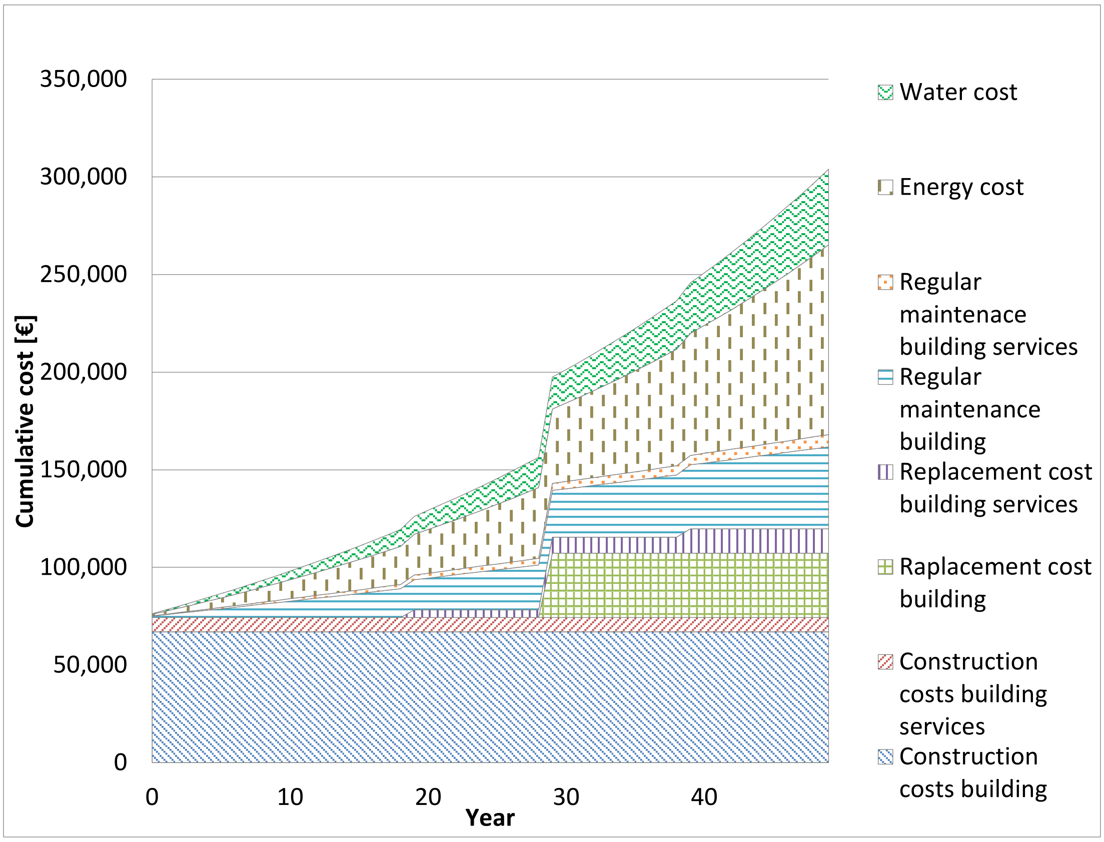

Figure 37 Cumulative nominal cost of Scenario 2

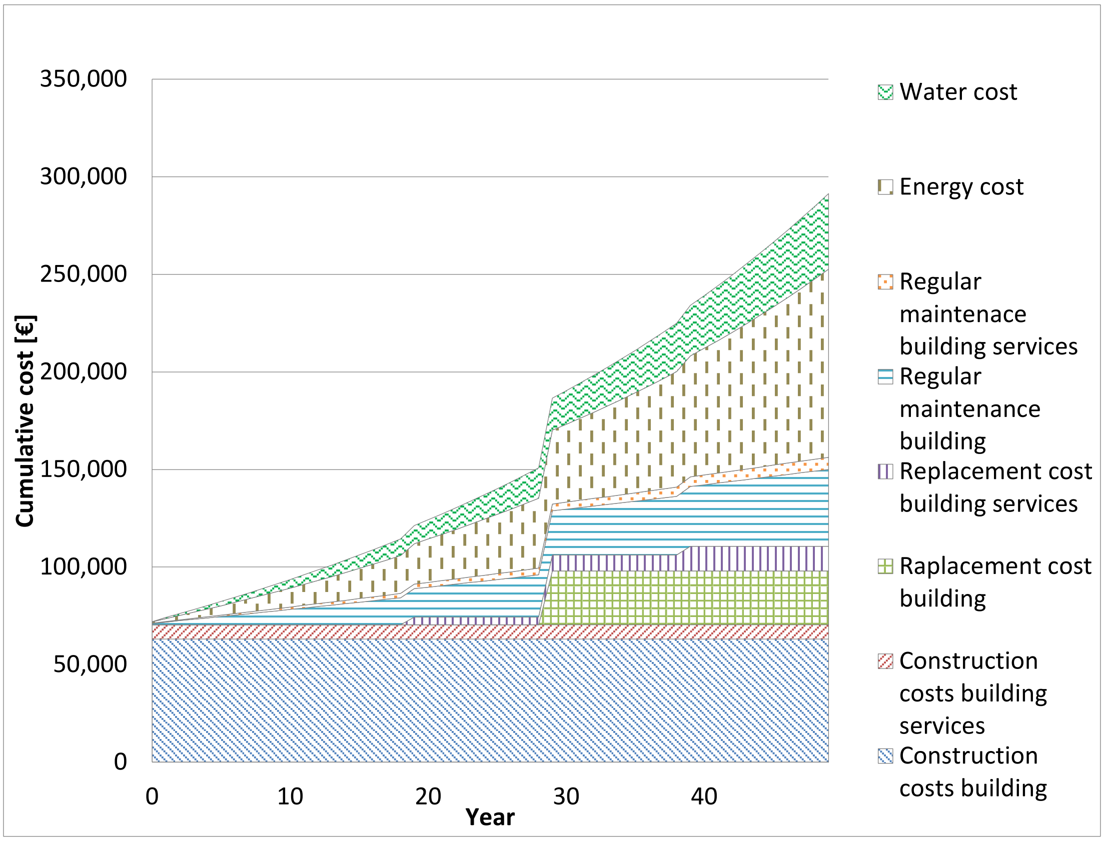

Figure 38 Cumulative nominal cost of Scenario 3

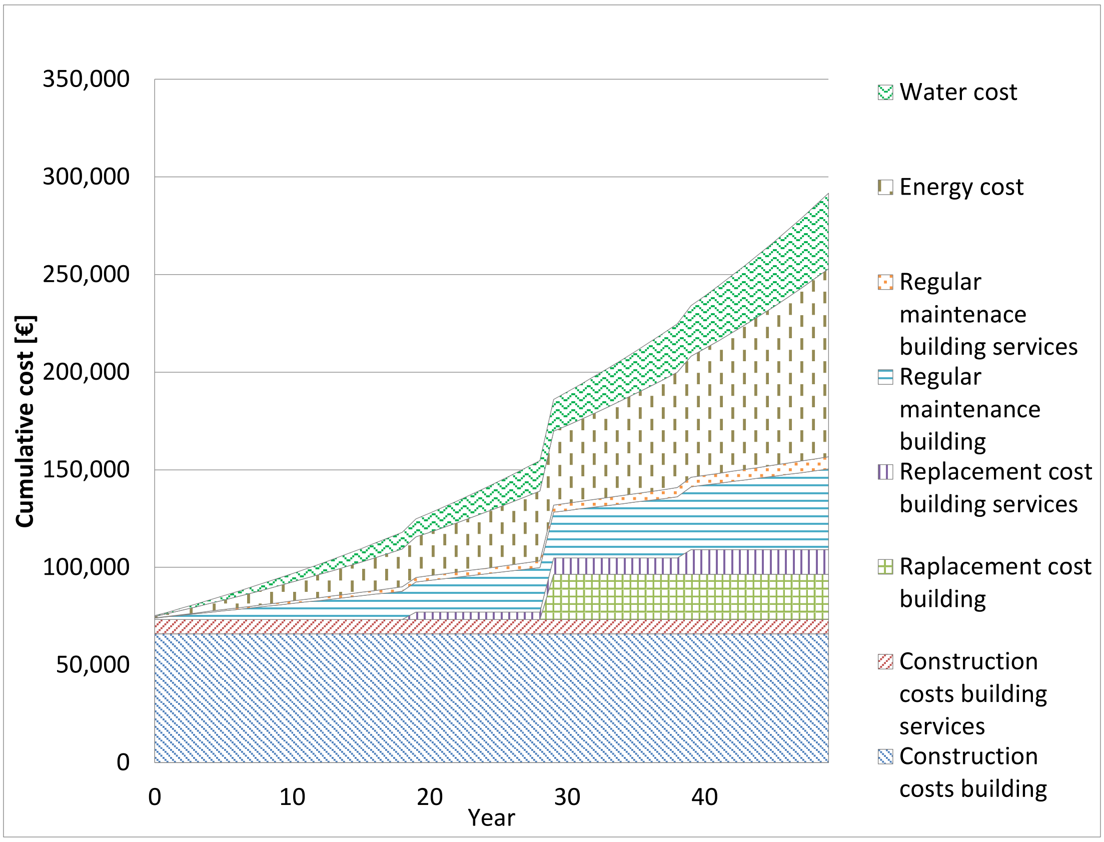

Figure 39 Cumulative nominla cost of Scenario 4

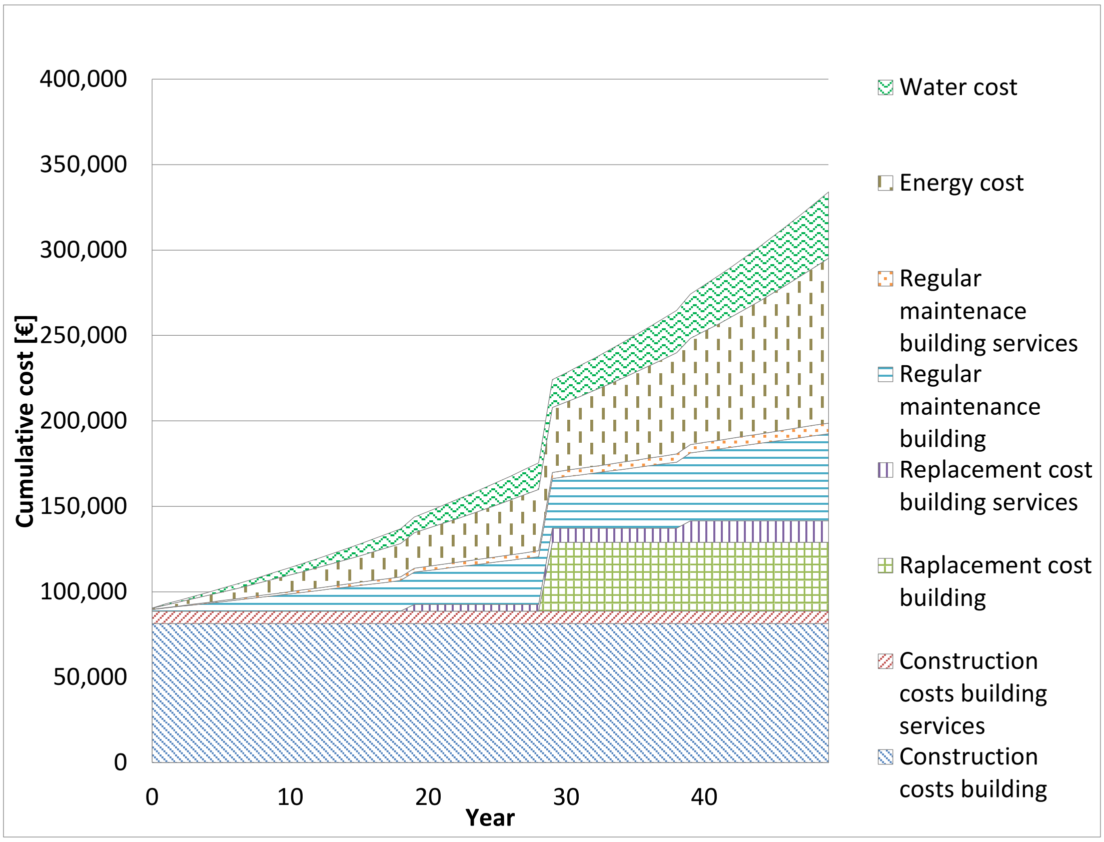

Figure 40 Cumulative nominal cost of Scenario 5

B. Service life of the building components

Table 9 Service life of building components of Scenario 1(Association of the generally sworn and legally certified experts of Austria 2006)

Category	Material	Service life [years]
Garage doors	Multiple	30
Outside doors	Multiple	30
Ceiling	GypsumBoard Rigips Activ Air	30
Ceiling	Mineral wool ISOVER Multimax	30
Ceiling	Mineral wool ISOVER Supermata	30
Ceiling	Plastering internal	As building
Floor	Reinforced concrete slab	As building
Floor	Wooden floor	60
Floor	XPS slab insulation	As building
Floor	Vapor Retarder	As building
Reinforcing	Carbon Steel Reinforcing Bar	As building
Roof	Steel sheeting Ruukki Emka Click	30
Roof	Wind protection	30
Structural framing	Reinforced concrete	As building
Steel profile for suspended ceiling	Steel	50
Roof construction	Wood	50
Wall	Calcium silicate block Silka A12	As building
Wall	Calcium silicate block Silka A18	As building
Wall	Mineral wool ISOVER TF Profi	30
Wall	Plastering external silicate-silicone	30
Wall	Plastering internal	As building
Window	Window	30
Building services	Solar flat collector	20
Building services	Underfloor radiant heating	50
Building services	Photovoltaic panel	20
Building services	Inverter	25
Building services	Circulation pump	15
Building services	Buffer tank	20
Building services	Ventilation system with heat recovery	20
Building services	Electric heater	30

Table 10 Service life of building components of Scenario 2 (Association of the generally sworn and legally certified experts of Austria 2006)

Category	**Material**	**Service life [years]**
Garage doors	Multiple	30
Outside doors	Multiple	30
Ceiling	Gypsum Board Rigips Activ Air	30
Ceiling	Mineral wool ISOVER Multimax	30
Ceiling	Mineral wool ISOVER Supermata	30
Ceiling	Plastering internal	As building
Floor	Reinforced concrete slab	As building
Floor	Wooden floor	60
Floor	XPS slab insulation	As building
Floor	Vapor Retarder	As building
Reinforcing	Carbon Steel Reinforcing Bar	As building
Basic Roof	Mineral wool_ISOVER Multimax	30
Basic Roof	Steel sheeting Ruukki Emka Click	30
Basic Roof	Wind protection	30
Structural framing	Reinforced concrete	As building
Steel profile for suspended ceiling	Steel	50
Roof construction	Wood	50
Wall	Calcium silicate block Silka A12	As building
Wall	Calcium silicate block Silka A18	As building
Wall	Mineral wool ISOVER TF Profi	30
Wall	Plastering external silicate-silicone	30
Wall	Plastering internal	As building
Window	Window	30
Building services	Radiators	30
Building services	Boiler	20
Building services	Circulation pump	15
Building services	Buffer tank	20

Table 11 Service life of building components of Scenario 3 (Association of the generally sworn and legally certified experts of Austria 2006)

Category	**Material**	**Service life [years]**
Garage doors	Multiple	30
Outside doors	Multiple	30
Ceiling	Gypsum Board Rigips Activ Air	30
Ceiling	Mineral wool ISOVER Multimax	30
Ceiling	Mineral wool ISOVER Supermata	30
Ceiling	Plastering internal	As building
Floor	Reinforced concrete slab	As building
Floor	Wooden floor	60
Floor	XPS slab insulation	As building
Floor	Vapor Retarder	As building
Reinforcing	Carbon Steel Reinforcing Bar	As building
Roof	Steel sheeting Ruukki Emka Click	30
Roof	Wind protection	30
Structural framing	Reinforced concrete	As building
Steel profile for suspended ceiling	Steel	50
Roof construction	Wood	50
Wall	EPS	30
Wall	Plaster acrylic	30
Wall	Plaster concrete sand	As building
Wall	Porotherm 8 P+W	As building
Wall	Porotherm 25 P+W	As building
Window	Window	30
Building services	Radiators	30
Building services	Boiler	20
Building services	Circulation pump	15
Building services	Buffer tank	20

Table 12 Service life of building components of Scenario 4 (Association of the generally sworn and legally certified experts of Austria 2006)

Category	**Material**	**Service life [years]**
Garage doors	Multiple	30
Outside doors	Multiple	30
Ceiling	Gypsum Board Rigips Activ Air	30
Ceiling	Mineral wool ISOVER Multimax	30
Ceiling	Mineral wool ISOVER Supermata	30
Ceiling	Plaster concrete sand	30
Floor	Reinforced concrete slab	As building
Floor	Wooden floor	60
Floor	XPS slab insulation	As building
Floor	Vapor Retarder	50
Reinforcement	Carbon Steel Reinforcing Bar	As building
Roof	Steel sheeting Ruukki Emka Click	30
Roof	Wind protection	30
Structural framing	Reinforced concrete	As building
Steel profile for suspended ceiling	Steel	50
Roof construction	Wood	50
Wall	Plaster acrylic	50
Wall	Plaster concrete sand	As building
Wall	Ytong Energo+	As building
Wall	Ytong G4	As building
Wall	Ytong PP3	As building
Window	Window	30
Building services	Radiators	30
Building services	Boiler	20
Building services	Circulation pump	15
Building services	Buffer tank	20

Table 13 Service life of building components of Scenario 5 (Association of the generally sworn and legally certified experts of Austria 2006)

Category	**Material**	**Service life [years]**
Garage doors	Multiple	30
Outside doors	Multiple	30
Ceiling	Clay cealing panel	30
Ceiling	Wood fiber insulation	30
Ceiling	Clay plaster	30
Floor	Reinforced concrete slab	As building
Floor	Wooden floor	60
Floor	Foam glass	As building
Floor	Vapor Retarder	50
Reinforcement	Carbon Steel Reinforcing Bar	As building
Basic Roof	Steel sheeting Ruukki Emka Click	30
Basic Roof	Wind protection	30
Structural framing	Reinforced concrete	As building
Steel profile for suspended ceiling	Steel	50
Roof construction	Wood	50
Wall	Clay plaster	30
Wall	Lime plaster	30
Wall	Rammed earth	50
Wall	Dry brick	As building
Wall	Wood fiber insulation	30
Window	Window	30
Building services	Radiators	30
Building services	Boiler	20
Building services	Circulation pump	15
Building services	Buffer tank	20