

ENERGY USE IN THE LIFE CYCLE OF A LOW-ENERGY BUILDING

Rasa Dziugaite-Tumeniene¹, Vidmantas Jankauskas²^{1,2} Vilnius Gediminas technical university, Saulėtekio ave. 11, LT-10223 Vilnius, Lithuania.
E-mails:¹ rasa.dziugaite@vgtu.lt; ² vidmantas.jankauskas@vgtu.lt

Abstract. Nowadays a new generation building has a variety of definitions, namely, low energy building, passive house, nearly zero energy building. These definitions refer to the building with a very high energy performance and a significant share of energy supply from renewable energy sources. Therefore, the common target of implementing these types of buildings is to reduce the demand for operating energy. However, the energy use, related to the production, construction and delivery of the building and its components, is ignored.

The article's subject is the evaluation of the energy and environmental performance of the low energy building in a life cycle perspective. A detailed Life Cycle Assessment (LCA) has been performed for the low energy family house built in Lithuania.

Keywords: low energy building, life cycle assessment, energy performance, environmental performance.

Definitions

Standard building: Refers to a building built according to the rated design criteria determined by local regulations (STR 2.05.01:2005).

Low-energy building: Refers to a building built according to special design criteria aimed at minimizing the building's operating energy.

Nearly zero energy building: A building with a very high energy performance and a significant share of energy supply from renewable energy sources.

Operating energy: Energy used in buildings during their operational phase: heating, cooling, ventilation, hot water, lighting and other electrical appliances.

End-use energy: Energy measured at the final use level.

Primary energy: Energy used to produce the end-use energy, including extraction, transformation and distribution losses.

Embodied energy: The sum of all the energy needed to manufacture a product.

1. Introduction

Buildings account for 40 % of total energy consumption in the European Union. The sector is expanding, which is bound to increase its energy consumption. Therefore, the reduction of energy consumption and greenhouse gas emissions in the buildings sector is becoming a common target in energy and environmental policies in European Union.

The buildings of a new generation, namely, a low energy building, a passive house, a nearly zero energy building with a very high energy performance and a significant share of energy supply from renewable energy sources, reduce the demand for the operating energy. However, the reduction of the demand for the operating energy is achieved by increased use of passive and active technologies (Sartori *et al.* 2007). Passive technologies include increased insulation, better performing windows, reduction of air infiltration losses, and heat recovery from ventilation air. Active technologies include heat pumps coupled with air or ground/ water heat sources, solar thermal collectors, solar photovoltaic panels and biomass boilers. An excessive use of passive and active features leads to an increase of an embodied energy (Ramesh *et al.* 2010). Therefore, the energy use, related to the production, construction and delivery of the low energy building and its components, has to be evaluated (Hernandez *et al.* 2010).

The purpose of this article is:

- to clarify the relative importance of operating and embodied energy in the low energy building's life cycle,
- to evaluate the overall environmental impact of the low energy building during the whole life cycle, in order to improve the environmental sustainability of the buildings.

The paper focuses on operating energy and embodied energy in the life cycle of the low energy building. The recycling phase has not been taken into account.

2. Methodology

Life Cycle Assessment (LCA) is defined as an objective methodology to analyze and quantify the environmental consequences of products and services during their whole life cycle, from extraction of raw materials, through production, use phase and end-of-life, with a from-cradle-to-grave approach (LST EN ISO 14040). The research presented in this paper is based on the application of LCA according to ISO standards (LST EN ISO 14040, LST EN ISO 14044).

2.1. Goals and purpose of LCA

The goal of LCA for the low energy building is to measure the impacts of the products used for the construction and maintenance of the building. Therefore, the evaluation of production, use and recycling phases of the low energy building with the energy system is presented. The reason of the need of the study is to determine, if the low energy building is the optimal solution for the consumer taking into account the primary energy demand and environmental impact.

The functional unit of the low energy building and its energy system is primary energy demand (kWh).

2.2. Scope

This study is carried out the life cycle analysis of the low energy building with the energy system. LCA includes the production, use and recycling phases.

Time scope. LCA of the low energy building with the energy system is performed on 100 years. This period is the lifetime of the low energy building. The lifetime of the equipments of the energy system is from 15 years to 30 years. Therefore, the parts of the energy system's equipments are expected to be replaced during a 100 year period, taking into account the lifetime of these parts.

Dimensional scope. All main components of the low energy building are analyzed in this study. The air - water heat pump, ventilation unit and storage tank with integrated back-up electric heater are the main components of energy system, which are analyzed in the study.

Technological scope. The primary energy demand, used for the production, maintenance and recycling of the low energy building and energy system, is evaluated. Transportation phase is not evaluated, because each component of the building and energy system is produced by plants and factories in different countries, so it is difficult to determine the primary energy demand for a separate transported product.

Environmental impact scope. The amount of CO₂ emissions, obtained from the production, maintenance and recycling of the low energy building and energy system, is evaluated, in order to determine, which product has the greatest impact on the environment.

2.3. Assumptions

These assumptions have been made, in order to perform the life cycle assessment of the low energy building with energy system:

- the costs of the design, construction, installation and etc. are not assessed;
- parts of energy system will not be replaced earlier than their end of lifetime;
- the components of heating system (multilayer polyethylene pipes, manifolds, radiators, stop and control valves, room thermostats) are not evaluated;
- the components of ventilation system (ducts, air flow control dampers, air supply and exhaust devices, silencers) are not evaluated;
- during the use phase of building energy system, the required annual energy demand for heating system and domestic hot water preparation is supplied from the air - water heat pump. The seasonal coefficient of performance (SCOP) of heat pump is 2,2, which is evaluated according to the energy efficiency of heat pump at different outdoor air temperatures;
- the air – water heat pump will give the priority to the preparation of domestic hot water;
- the operation of the back-up electric heater, installed in the storage tank, is evaluated. It is in operation when the outdoor air temperature decreases below -15 °C, which makes up to 7,5 % of the required annual energy demand. When the outdoor air temperature is lower than -23 °C, the lower inside air temperature will be in the rooms.

2.4. Data collection and modeling

The data was collected from the drawings of the existing building and carried out surveys in the building. The inventory datasets for materials fabrication, energy production chains were mostly extracted from the Ecoinvent database, integrated in SimaPro 7.1 software. The LCA modelling was performed using the SimaPro 7.1 software application (SimaPro 7 2008).

2.5. Selection of environmental indicator

The Global Warming Potential (GWP) is used in this study as an environmental indicator. GWP is an indicator of greenhouse emissions with a time horizon of 100 years, including the contribution of biogenic carbon dioxide.

3. Description of the low energy house

The low energy building in this study is an existing individual family house, which is the main home of four occupants. It is built in Vilnius. The main geographical

and climatic data, also some relevant building features are shown in Table 1.

Table 1. Main features and climatic data of the house in Vilnius

Geographical and climatic data		Building features	
Latitude	N 54° 41'	Total floor area	149,12 m ² (one floor)
Longitude	E 25° 19'	Heated area	149,12 m ²
Degree days	4005	Total volume	430,22 m ³
Average yearly temperature	6,7 °C	Orientation of Entrance	North-East
Lowest outdoor air temperature	-23 °C		

The existing low energy building in Vilnius fulfills the following requirements:

- an annual heat demand for space heating is 58 kWh/m² per year, the thermal capacity of heating system is 3560 W (24 W/m²), calculation is made according to (STR 2.09.04:2008). Cooling of this building is not considered in this case;
- an air tightness of building construction is 0,6 h⁻¹ at 50 Pa, resulting in approximately 0,05 h⁻¹ infiltration rate under normal conditions;
- a heat recovery ventilation system, with a heat recovery rate of 83 % and high-efficiency electronically commutated motors (ECM), is used to maintain air quality;
- specific fan power efficiency rating (SFP) is 1,5 kW/(m³/s);
- since the building is essentially airtight, the rate of air change is 0,6 h⁻¹ ($L_{\text{supply}} = L_{\text{exhaust}} = 260 \text{ m}^3/\text{h}$, $t_{\text{ext}} = -23 \text{ °C}$, $t_{\text{int}} = 21 \text{ °C}$). All ventilation ducts are insulated and sealed against leakage;
- average internal gains, caused by lighting, electrical equipments and people, is 4 W/m²;
- the internal temperature is 21°C, in order to maintain thermal comfort in the rooms. For studies of energy demand and peak load, the maximum allowed internal temperature is 25°C. Above this temperature, the occupants are assumed to reduce the air temperature by using shading devices;
- heat is produced by the air-to-water heat pump with a seasonal coefficient of performance (SCOP) of 2,2 (defined using Daikin Altherma Simulator 3.5.5). The energy system of the low energy building is shown in Figure 1.

The structural system of the building is a residual formworks system from polystyrene foam blocks. The physical basis of the system of polystyrene foam blocks is composed of the hollow blocks, which are connected with each other tightly and has formed connections on the connecting surface. During the construction works, the inner cavity of hollow blocks has been reinforced using

reinforcement bars and filled with the fluid mixture of concrete.

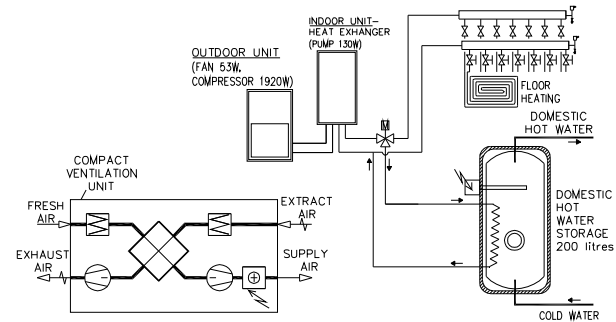


Fig 1. Energy system of low energy building in Vilnius

The extra insulation of 15 cm polystyrene foam slabs is equipped on the exterior facades. The windows are with exceptionally low U values, triple-pane insulated glazing (with a good solar heat-gain coefficient, low-emissivity coatings, argon gas fill, and 'warm edge' insulating glass spacers) with air-seals and specially developed thermally-broken window frames. The U values of the building components are shown in Table 2.

Table 2. The U-values of the low energy building components

Building component	Structure of the component	U value (W/m ² K)
External walls	Stucco, polystyrene foam blocks EPS100-M30, reinforcement bars, concrete, polystyrene foam slabs EPS70-M15, gypsum plaster boards	0,110
Roof	PVC roofing, cement mortar, polystyrene foam slabs EPS100-M20, reinforced concrete slabs PK24-2	0,070
Floor	Three layered laminated board, cement mortar, polystyrene foam slabs EPS80-M17, flashing, concrete with gravel and stone rubble B15 S4	0,106
Windows	Plastic frame of 82 mm thickness, with 6 cells, triple-pane insulated glazing	0,80
External door	Plastic frame of 82 mm thickness, with 6 cells, triple-pane insulated glazing	0,80

As can be seen from Table 2, the super insulation is used to significantly reduce the heat transfer through the walls, roof and floor compared to standard residential buildings.

4. Description of the LCA model

The main inventory data relevant to the low energy house in Vilnius is described in the following paragraphs. A flowchart of system boundaries for life cycle energy analysis is shown in Figure 2.

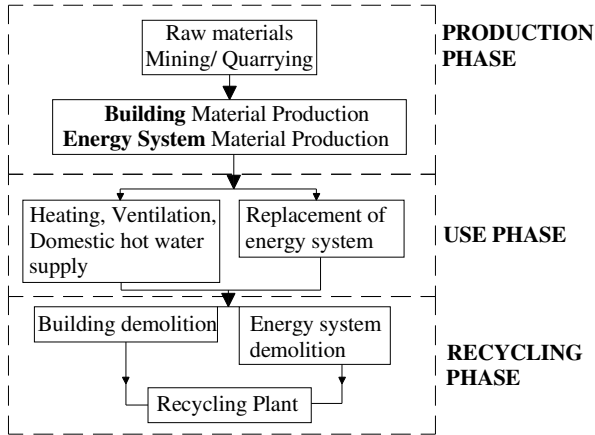


Fig 2. A flowchart of system boundaries for LCA

4.1. Production phase

In this study the production phase includes the production of the building materials and main equipments of the energy system. Before the collection of the data and modelling, the materials have been grouped into 4 components of building envelope and 3 equipments of building energy system, as described in Table 3.

Table 3. Components of building envelope and energy system

Components	Main materials
Building envelope	Life time: 100 years
External walls	Stucco, polystyrene foam, steel, concrete, gypsum board
Roof	Polyvinylchloride, cement mortar, polystyrene foam, reinforced concrete
Floor	Untreated wood, cement mortar, polystyrene, not reinforced concrete, gravel, stone rubble
Windows and external door	Plastic, aluminium, glass
Energy system	Life time: 20 years
Air-to-water heat pump	Steel, rubber, polyurethane, plastic, copper, brass, aluminium foil
Storage tank	Steel, stainless steel, polyurethane, plastic, copper
Ventilation unit	Steel, stainless steel, rubber, rock wool, aluminium, plastic, wool fiber

The inventory dataset, shown in Table 4, summarizes the collected data.

Table 4. The inventory dataset for the production phase

Materials	Weight (kg)	Database input
Building envelope		
Steel	660	ECCS steel from 80 % scrap
Stucco	8980	Stucco, at plant/kg/CH
Polystyrene foam	4740	Polystyrene foam slab, at plant/kg/RER
Concrete	162750	Concrete not reinforced ETH
Gypsum board	4120	Gypsum plaster board, at plant/kg/CH
Polyvinylchloride	360	PVC powder
Cement mortar	44880	Cement mortar, at plant/kg/CH
Reinforced concrete	45600	Prefab concrete: cement, sand, gravel, steel, water
Three layered laminated board	2,24 m ³	Three layered laminated board, at plant/m ³ /RER
Window frame, plastic	6,41 m ²	Window frame, plastic (PVC), U=1,6 W/m ² K, at plant/m ² /RER
Glazing, triple	25,64 m ²	Glazing, triple (3-IV), U<0,5 W/m ² K, at plant/m ² /RER
Energy system		
Steel	109,51	ECCS steel from 80 % scrap
Stainless steel	49,3	X20Cr13
Rubber	2,82	EPDM rubber ETH
Polyurethane	31,35	Polyurethane rigid foam E
Rock wool	6	Rock wool, at plant/kg/CH
Aluminium	0,75	Aluminium 80% rec.
Plastic	19,82	PP ETH
Wool fiber	0,6	Wool, at field
Copper	11	Copper ETH
Brass	22,6	Brass, at plant/kg/CH
Aluminium foil	0,002	Aluminium foil 7-12 μ

The transportation, energy consumption, machinery use and cutting waste, generated during the building process, maintenance of the building envelope (repairing the finishes) during 100 years period are not included in this study.

4.2. Use phase

In this study the use phase includes:

- the total energy demand for heating, ventilation and domestic hot water preparation;
- the total amount of energy, required to produce electricity in thermal power plant;

- the amount of CO₂ emissions, which is released during the production of electricity;
- the required amount of energy and released CO₂ emissions due to the production of the new components during the operation period of the energy system (100 years).

Total energy demand for heating, ventilation and domestic hot water preparation is given in Table 5.

Table 5. The total energy consumption during the use phase

Net Energy (kWh/a)		Total Energy Use (kWh/a)			Delivered energy (kWh)
		Energy use	Energy source		
Mechanical systems	3437	3437	Electricity	3437	3437
Space Heating	8660	8660	Electricity	5900	5900
DHW	4320	4320	Heat Pump SCOP =2,2		
Circulation losses	-	Is not assessed	Outdoor air	-	-
Conversion losses	-	Is not assessed			
Total	16417	16417		9337	9337

Mechanical systems, shown in Table 5, include the energy power, required for circulating pump (0,130 kW), fans of ventilation unit (2 x 0,140 kW), and fan of air-to-water heat pump (0,053 kW), back-up electrical air heater of ventilation unit (0,660 kW).

Inventory data relevant to electricity production in thermal power plant has been retrieved using SimaPro 7.1.

4.3. Recycling phase

In this study the recycling phase introduces the materials, which can be recycled. End-of-use materials of the building envelope and equipments are described in Table 6.

Table 6. End-of-use materials of envelope and equipments

Materials	Possibility to re-use or recycle
Steel, copper	90 % recycling
Aluminium	90 % recycling
Glass	90 % recycling
Concrete, mortar	100 % recycling
Plastic, gypsum	100 % landfill

Inventory data relevant to re-use or recycling of steel, copper, aluminium, glass, concrete, mortar, plastic, gypsum has been retrieved from the Ecoinvent database, integrated in SimaPro 7.1. However, the extend evaluation of recycling phase is not presented in this study.

5. Results

As described in the methodological section, the LCA results are presented using two criteria:

- the primary energy demand during the life cycle of the building and energy system (kWh/ 100 years);
- the amount of CO₂ emissions during the life cycle of the building and energy system (kg CO₂ ekv/ 100 years).

Primary energy demand required to build the low energy building is shown in Figure 3.

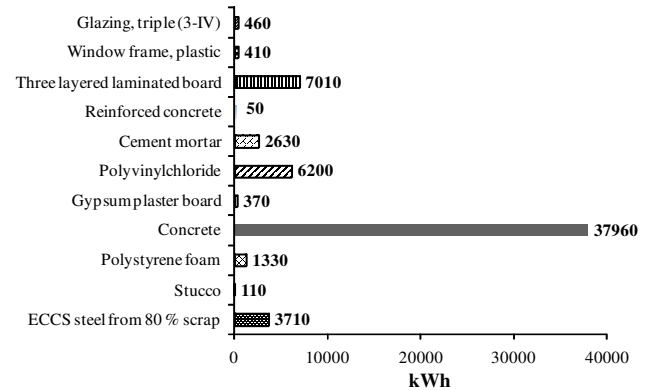


Fig 3. Primary energy demand for low energy building

As can be seen from Figure 3, the most important contribution to the total primary energy use of the building production phase is concrete (37960 kWh of primary energy), namely, it is 63 % of the total primary energy demand (60220 kWh). As far as the total primary energy use is concerned, wooden (three layered laminated boards used for flooring) and plastic (polyvinylchloride used for roofing) items come after concrete. This confirms that the use of traditional materials (concrete, wood, PVC) for the construction of low energy building plays an important role in terms of embodied energy, as reported in studies (Blengini 2009).

The amount of CO₂ emissions, caused by the production of building materials, is shown in Figure 4.

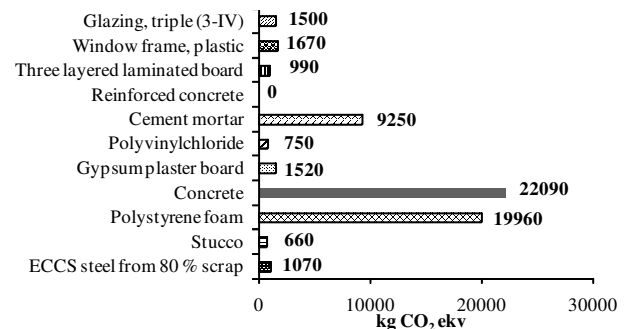


Fig 4. The amount of CO₂ emissions during the production phase of building materials

As can be seen from Figure 4, the environment is mainly influenced by the production of concrete (22090 kg CO₂ ekv), polystyrene foam (19960 kg CO₂ ekv) and cement mortar (9250 kg CO₂ ekv). These items make 86

% of total pollution during the production of building materials. Therefore, the results show the importance to select right materials for insulation and construction, in order to lower the impact on environment.

Primary energy demand required to produce the energy system for the low energy building is shown in Figure 5.

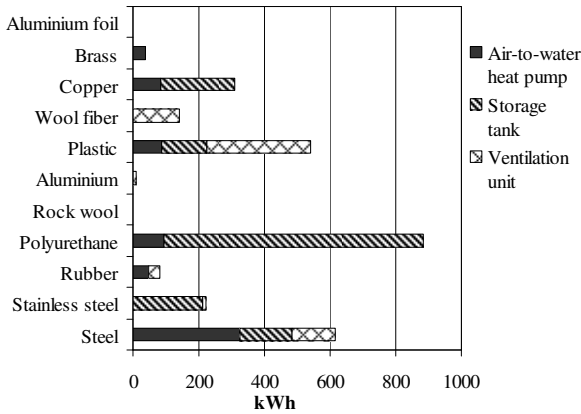


Fig 5. Primary energy demand for energy system

As can be seen from Figure 5, the most important contributions to the total primary energy use of the energy system production phase are polyurethane (880 kWh of primary energy), steel (620 kWh) and plastic (540 kWh). These items make 72 % of total primary energy demand (2840 kWh) during the production of materials of energy system.

The amount of CO₂ emissions, caused by the production of energy system's materials, is shown in Figure 6.

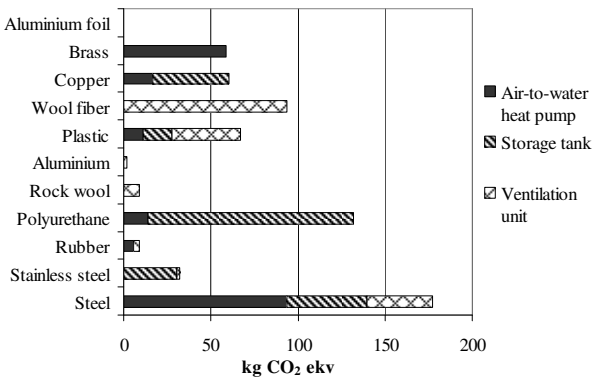


Fig 6. The amount of CO₂ emissions during the production phase of energy system's materials

As can be seen from Figure 6, the environment is mainly influenced by the production of steel (177 kg CO₂ ekv), polyurethane (132 kg CO₂ ekv) and wool fiber (94 kg CO₂ ekv). These items make 63 % of total pollution (640 kg CO₂ ekv) during the production of energy system's materials.

The comparison between the life cycle impacts of the low energy building and the standard building has been made, in order to highlight the role and significance of the different subsystems. Therefore, the standard house

has been evaluated. The structural system of the standard building is the same as has been selected for the low energy building. Only the thickness of the insulation has been reduced, in order to maintain the standard thermal transmission coefficients for: external walls ($U_N = 0,25 \text{ W/m}^2\text{K}$), roof ($U_N = 0,135 \text{ W/m}^2\text{K}$), ground floor ($U_N = 0,18 \text{ W/m}^2\text{K}$), windows and external door ($U_N = 1,4 \text{ W/m}^2\text{K}$). The comparison of the buildings with different thicknesses of insulation has shown a relatively small increase in the production impact from the standard house to the low energy house. In case of the low energy house, during the production phase the primary energy demand increases 1 % and the amount of CO₂ emissions increases 13 %. Therefore, other types of structural systems of buildings have to be considered, in order to highlight the significance of the different subsystems.

The total delivered energy, non-renewable primary energy demand and CO₂ equivalent emissions for the low energy building are given in Table 7. The values of non renewable primary energy factor and CO₂ equivalent emissions factor are taken from the reference (Hastings and Wall 2007).

Table 7. Total delivered energy, non-renewable primary energy demand and CO₂ equivalent emissions for low energy building

	Delivered energy (electricity, kWh/a)	Non renewable primary energy		CO ₂ equivalent emissions	
		factor (-)	(kWh/a)	factor (kg/kWh)	(kg/a)
Mechanical systems	3437	2,35	8077	0,43	1478
Heating	5900	2,35	13865	0,43	2537
DHW					
Total	9337		21942		4015

As can be seen from Table 7, the main contribution to the total primary energy demand is the energy use for space heating and domestic hot water supply.

The significance of the production and use phases in the low energy building is shown Figure 7.

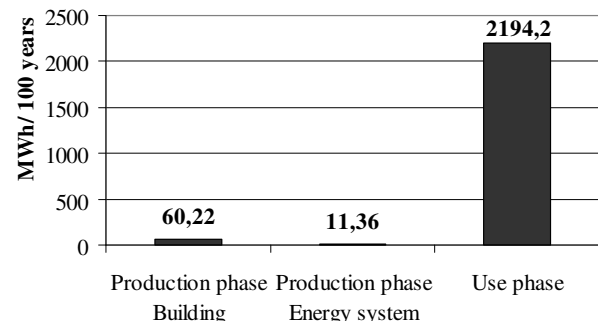


Fig 7. Non-renewable primary energy demand of the low energy building in production and use phases

As can be seen from Figure 7, the use phase in the low energy building remains responsible for 96 % of the

life cycle energy use (Blengini and Di Carlo 2010, Bribian *et al.* 2009).

The amount of CO₂ emissions during the production and use phases of the low energy building is shown Figure 8.

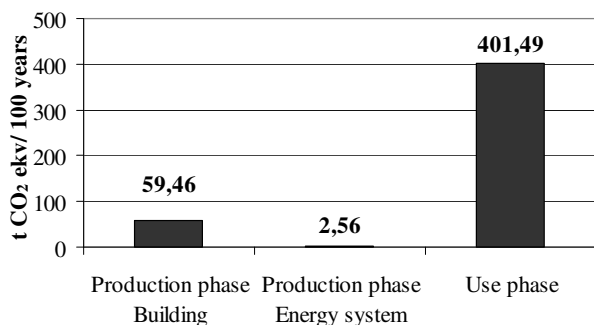


Fig 8. CO₂ equivalent emissions of the low energy building in production and use phases

As can be seen from Figure 8, the use phase in the low energy building has the greatest impact (87 %) on the environment (Blengini and Di Carlo 2010, Bribian *et al.* 2009).

The comparison of the buildings with different thicknesses of insulation has shown a significant decrease in the use impact from the standard house to the low energy house. It was assumed that a condensing gas boiler is installed in the standard building. The air flow rate and domestic hot water supply remain the same as in the low energy building. Consequently, in case of the low energy house during the use phase the primary energy demand decreases 41 % and the amount of CO₂ emissions decreases 48 %. Therefore, the findings show that the correct choice of building materials can be useful to lower life cycle impact.

6. Conclusions

The results of the LCA applied to the low energy building in Vilnius have highlighted that:

- the more energy, needed during the use phase, decreases, the bigger attention has to be paid to energy required for the production of materials;
- concrete is the most important contribution to the total primary energy use in the production phase of the building. It is 63 % of the total primary energy demand;
- the environment is mainly influenced by the production of concrete, polystyrene foam and cement mortar. It makes 86 % of total pollution during the production of building materials;
- polyurethane, steel and plastic make 72 % of total primary energy demand during the production of energy system's materials;

- steel, polyurethane and wool fiber make 63 % of total pollution during the production of energy system's materials;
- the use phase in the low energy building is responsible for 96 % of the life cycle energy use and has the greatest impact (87 %) on the environment, when the life time of the building is 100 years;
- According to the results it can be assumed, that the low energy building is the optimal solution for the consumer taking into account the primary energy demand and environmental impact.

References

- Blengini, G. A. 2009. Life cycle of buildings, demolition and recycling potential: a case study in Turin-Italy. *Building and Environment*. 44(2), 319-330.
- Blengini, G. A., Di Carlo, T. 2010. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and Buildings*. 42(6), 869-880.
- Bribian, I. Z., Uson, A. A., Scarpellini, S. 2009. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment*. 44(12), 2510-2520.
- Hastings, R., Wall, M. 2007. *Sustainable Solar Housing. Volume 1 – Strategies and Solutions*. UK: Earthscan. 292 p. ISBN-13: 978-1-84407-325-2.
- Hernandez, P., Kenny, P. 2010. From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB). *Energy and Buildings*. 42(6), 815-821.
- LST EN ISO 14040 Environmental management – Life cycle assessment – Principles and framework (ISO 14040:2006). Lithuanian standards board. Vilnius, 2007. 27 p.
- LST EN ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006). Lithuanian standards board. Vilnius, 2007. 51 p.
- Ramesh, T., Prakash, R., Shukla, K.K. 2010. Life cycle energy analysis of buildings: An overview. *Energy and Buildings*. 42(10), 1592-1600.
- Sartori, I., Hestnes, A. G. 2007. Energy use in the life cycle of conventional and low-energy buildings. *Energy and Buildings*. 39(3), 249-257.
- SimaPro 7 2008. Software and Database Manual, Pre' Consultants BV, The Netherlands. Available on the Internet: <<http://www.pre.nl/simapro/manuals/default.htm#ecoinvent>>.
- STR 2.09.04:2008 Pastato šildymo sistemos galia. Šilumos poreikis šildymui [Building heating system capacity. Heat demand for heating]. Lithuanian ministry of environment. Vilnius, 2008.
- STR 2.05.01:2005 Pastatų atitvarų šiluminė technika [Thermal technique of building elements]. Lithuanian ministry of environment. Vilnius, 2005.