

Environmental impact assessment of materials used in nearly zero-energy buildings

1. Introduction

The building sector contributes up to 30% of global annual greenhouse gas emissions and consumes up to 40% of all energy [1]. Environmental impact of the factories involves CO₂ emissions, air and water pollution, because carbon and hydrogen are widely used in fossil fuels [2]. The European Union has a number of official documents and guidelines aimed at reducing CO₂ emissions up to 20% by 2020 [3], up to 40% by 2030 [4] and the energy performance of Buildings Directive requires all new buildings to be nearly zero-energy by the end of 2020 [4].

2. Methodology

This research examines emissions from exterior wall constructional materials (in manufacturing stage) of the new build nearly zero-energy building in further order to compare this exterior wall model with alternative exterior wall construction. The main factor for comparing different types of exterior wall constructions is the heat transfer coefficient $U=0,105$ (W/m²K). Environmental impact is calculated and analysed by using a life cycle analysis assessment program SimaPro.

2.1. Life cycle analysis

Buildings have an impact on the environment at all stages of their lifecycle - materials have to be quarried, mined or harvested, transported to factories and manufactured. The final products have to be transported to site, lifted into place and fixed in position. The buildings have to be operated, heated and cooled. All of those listed stages have an impact on the environment that can be calculated and analysed with lifecycle assessment (LCA) calculation program such as SimaPro. It should be noted that an important use is for assessing carbon emissions that contribute to global climate change.

The following research is viewed by using LCA program SimaPro 8, which is led by standards - ISO 14040: Principles and Framework and ISO 14044: Requirements and Guidelines [6,7]. SimaPro includes many lifecycle inventory (LCI) databases, including the renowned ecoinvent v3 database (covering over 10,000 processes) [5], the new industry-specific Agri-footprint database and the ELCD database. SimaPro contains a number of impact assessment methods, which are used to calculate impact assessment results. In this research is used CML-IA baseline V3.04 (ecoinvent v3.4) method. This CML method is created by the University of Leiden in the Netherlands in 2001 and contains more than 1700 different flows. [8]

Generally, this CML method is divided into baseline and non-baseline, the baseline being the most common impact categories used in LCA, and this CML-IA baseline method is used in this research.

The following shows the impact categories CML-IA baseline method contains:

- Acidification - the acidification potential of nitrogen and sulphur oxides, which is expressed by using the reference unit, kg SO₂ equivalent. This impact category views acidic gases such as sulphur dioxide (SO₂) react with water in the atmosphere to form "acid rain", a process known as acid deposition. Gases

that caused acid deposition include ammonia (NH₃), nitrogen oxides (NO_x) and sulphur oxides (SO_x). This includes acidification due to fertiliser use, according to the method developed by the Intergovernmental Panel on Climate Change (IPCC). CML has based the characterisation factor on the RAINS model developed by the University of Amsterdam [5,9].

- Global Warming Potential (GWP) express climate change. GWP is an index to measure the contribution to global warming of a substance that is released into the atmosphere. The GWP is impacted mainly by the emission of greenhouse gases, i.e. carbon dioxide (CO₂) and methane (CH₄). It was calculated for a time frame of 100 years. The GWP is measured in CO₂ equivalents [5,9].

- Abiotic Depletion Potential (ADP) - in a general way, is the impact category in referred to the consumption of non-biological resources such as fossil fuels, minerals, metals, water, etc. It records the abiotic resource consumption. The value of the abiotic resource consumption of a substance (e.g. lignite or coal) is a measure of the scarcity of a substance. That means it depends on the amount of resources and the extraction rate. ADP is represented by natural gas, hard coal, lignite, and crude oil. It is formed by the amount of resources that are depleted and measured in antimony equivalents. ADP is expressed in MJ [5,9].

- Human toxicity potential (HTP) - is calculated index that reflects the potential harm to a unit of a chemical released in the environment, is based on both the inherent toxicity of a compound and its potential dose. These by-products, mainly arsenic, sodium dichromate, and hydrogen fluoride, are caused, for the most part, by electricity production from fossil sources. These are potentially dangerous chemicals to humans through inhalation, ingestion, and even contact. Cancer potency, for example, is an issue here. HTP is measured in 1,4-dichlorobenzene equivalents [5,9].

- Ozone layer depletion potential (ODP) - expresses the damage of various gases into stratospheric ozone or the "ozone layer". The combined effects of different gases in the stratosphere, and all chlorinated and brominated compounds that are stable enough to reach the stratosphere can have an effect. CFCs, halons and HCFCs are the major causes of ozone depletion. Damage to the ozone layer reduces its ability to prevent ultraviolet (UV) light entering the earth's atmosphere. The ODP of different gases relative to the reference substance chlorofluorocarbon-11 (CFC-11), expressed in kg CFC-11 equivalent [5,9].

- Photochemical oxidation (PO) - is the impact category that determines pollution of photochemical ozone, also called "ground level ozone", which is formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight. The impact category depends largely on the amounts of carbon monoxide (CO), sulphur dioxide (SO₂), nitrogen oxide (NO), ammonium and NMVOC (non-methane volatile organic compounds), and is expressed by using the reference unit, kg ethylene (C₂H₄) equivalent [5,9].

- Ecotoxicity - environmental toxicity that is measured as three separate impact categories which examine freshwater, marine and land. The emission of some substances, such as heavy metals, can have impacts on the ecosystem. Assessment of toxicity has been based on maximum tolerable

concentrations in water for ecosystems [5,9]. Characterisation factors are expressed using the reference unit, kg 1,4-dichlorobenzene equivalent (1,4-DB), and are measured separately for impacts of toxic substances on:

- Fresh-water aquatic ecosystems
- Marine ecosystems
- Terrestrial ecosystems

2.2. Description of exterior wall construction

The exterior wall construction of the zero- energy building is designed from wooden frame filled with thermal insulation glass wool. The exterior wall construction layers are given in Table 2.2.1. and with heat transfer coefficient $U=0,10$ (W/m²K) for all wall structure.

Table 2.2.1. *The construction of exterior wall.*

The material	Thickness, mm
Plasterboard	13
Thermal insulation <i>Isover KL33</i>	45
Vapour control layer <i>Siga Marjrex</i>	1
Thermal insulation <i>Isover KL33</i>	195
Wind protection insulation <i>Isover RKL</i>	100
Vertical lathing	25
Horizontal lathing	45
Facade cladding wood board	22

For this type of construction as bearing frame is used wooden beams, apart 600mm. The bearing frame in further research work is included for more precise LCA analyse results in all made emission in environment impacts.

3. Results

3.1. The external wall constructions (1m²) impact on the environment

The LCA calculations analyse is made for exterior wall (1m²) material in manufacturing stage by using SimaPro8 in Table 2.2.1. For calculating and analysing use, previously viewed CML-IA baseline V3.04 method. As a result, have exterior wall's components emissions impact on the environment separately to analyse each layer in impact categories – acidification, photochemical oxidation (PO), ozone layer depletion potential (ODP), human toxicity potential (HTP), abiotic Depletion Potential (ADP), eutrophication, global Warming Potential (GWP) and ecotoxicity.

The data of exterior wall layer's inputs is chosen from available defined database (ecoinvent v3.4), also is used manufacturer's given information [10,11,12,13,14] of material properties (density) for each material Table 3.1.1., this information is used for precise material input definition in SimaPro8 program. The result is viewed in a Table 3.1.2. and Fig. 3.1.1.

Table 3.1.1. The exterior wall's construction layers' percentage distribution by density of 1m² wall.

The material	Thickness, mm	Density, Kg/ m ²	%
Plasterboard	13	8,94 [13]	12
Thermal insulation <i>Isover KL33</i>	45	16,25 [10]	22
Thermal insulation <i>Isover KL33</i>	195		
Vapour control layer <i>Siga Marjrex</i>	1	0,15 [11]	Under 1%
Wind protection insulation <i>Isover RKL</i>	100	7,00 [10]	9
Vertical lathing	25	6,51 [12,14]	9
Horizontal lathing	45		
Facade cladding wood board	22	11,88 [12,14]	21
Wooden beams (bearing frame)	-	20,04 [12,14]	27
Total	446	74,29	100

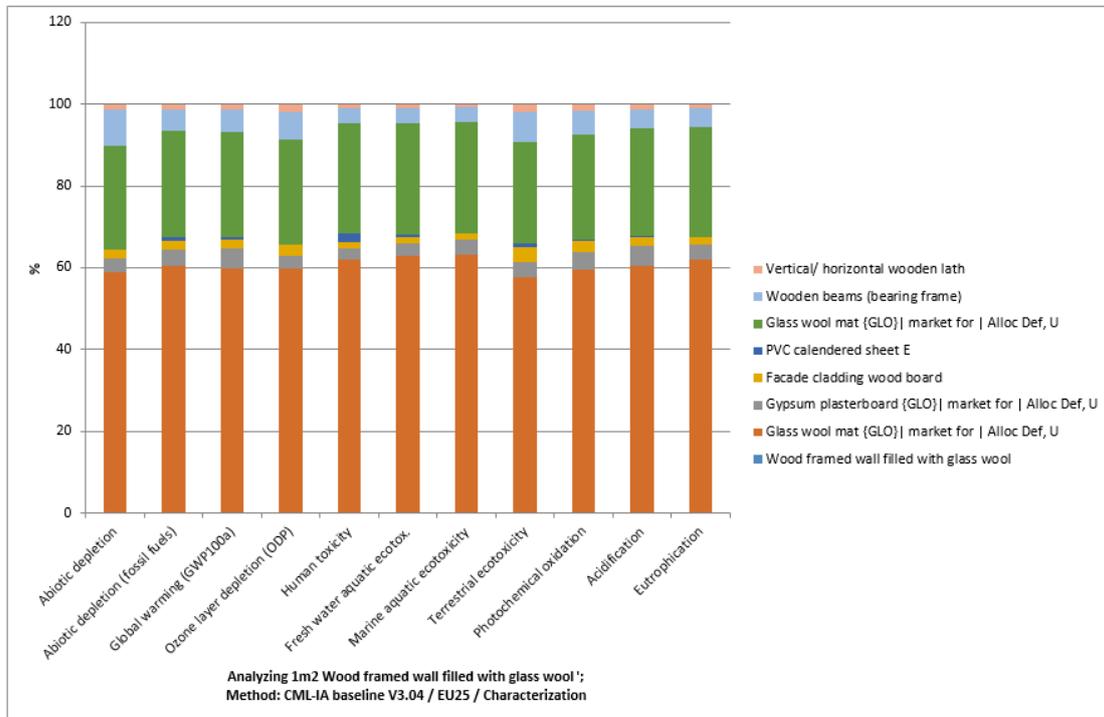


Fig. 3.1.1. Analyzing 1m² wood framed exterior wall by method: CML-IA baseline V3.04 / EU25 / Characterization.

Table 3.1.2. Impact assessment from 1m² wood framed exterior wall by method: CML-IA baseline V3.04 / EU25 / Characterization.

Impact category	Unit	Total	Glass wool mat {GLO} market for Alloc Def, U	Gypsum plaster board {GLO} market for Alloc Def, U	Facade cladding wood board	PVC calendered sheet E	Glass wool mat {GLO} market for Alloc Def, U	Wooden beams (bearing frame)	Vertical/horizontal wooden lath
Abiotic depletion	kg Sb eq	0.00016	5.69E-06	3.15E-06	4.90E-08	4.06E-05	1.44E-05	2.13E-06	9.44E-05
Abiotic depletion (fossil fuels)	MJ	1024.347	39.49739	21.66749	8.849579	267.3404	52.17777	14.20296	620.6116
Global warming (GWP100a)	kg CO2 eq	74.82988	3.69626	1.662927	0.488905	19.25413	3.981888	1.048684	44.69709
Ozone layer depletion (ODP)	kg CFC-11 eq	6.89E-06	2.08E-07	1.90E-07	0	1.77E-06	4.64E-07	1.34E-07	4.12E-06
Human toxicity	kg 1,4-DB eq	40.1416	1.067301	0.603122	0.938798	10.72005	1.548085	0.378408	24.88584
Fresh water aquatic ecotox.	kg 1,4-DB eq	24.91565	0.739231	0.391957	0.172049	6.75625	0.949127	0.222886	15.68415
Marine aquatic ecotoxicity	kg 1,4-DB eq	95880.61	3352.565	1388.993	37.14087	26156.5	3435.467	789.4927	60720.45
Terrestrial ecotoxicity	kg 1,4-DB eq	0.189306	0.007193	0.0069	0.001357	0.047022	0.013966	0.003713	0.109157
Photochemical oxidation	kg C2H4 eq	0.026325	0.001065	0.000745	0.000103	0.006762	0.00153	0.000425	0.015697
Acidification	kg SO2 eq	0.483595	0.023736	0.009807	0.002093	0.126107	0.02299	0.006113	0.292748
Eutrophication	kg PO4---eq	0.154296	0.005334	0.00305	0.000184	0.041235	0.006977	0.001793	0.095723

After given results (Table 3.1.1., Fig. 3.1.1.) is viewed that the biggest impact in all categories is made by glass wool thermal and wind protection insulation material. The less impact in impact categories of all materials belongs to vapour control layer, except, in HTP impact category – 5% (the same as plasterboard), in which this layer shows large impact from its production; insignificant result in categories - Eutrophication, Marine aquatic ecotoxicity, Abiotic depletion, ODP – under 1%. The result in GWP is 74,82 kg CO₂ eq emissions Table 4 from exterior wall construction with density of 74,29 kg/m² and 446 mm thickness.

The given result from calculation with SimaPro 8 is summarized in the impact category of GWP for each exterior wall construction layer, shown in Table 3.1.3.

Table 3.1.3. *The CO₂ emissions of exterior wall's construction layers of 1m² wall.*

The material	Thickness, mm	GWP CO ₂ emissions, kg CO ₂ eq	GWP CO ₂ emissions, %
Plasterboard	13	3,70	5
Thermal insulation <i>Isover KL33</i>	45	44,70	60
Thermal insulation <i>Isover KL33</i>	195		
Vapour control layer <i>Siga Marjrex</i>	1	0,49	1
Wind protection insulation <i>Isover RKL</i>	100	19,25	26
Vertical lathing	25	1,05	1
Horizontal lathing	45		
Facade cladding wood board	22	1,66	2
Wooden beams (bearing frame)	-	3,98	5
Total	446	74,82	100

As in Table 3.1.1. and Table 3.1.2., including Fig. 3.1.1., is shown the similar or same materials are counted together – glass wool thermal insulation (*Isover KL33*) two layers of different thickness, and vertical and horizontal lath of wood. Those corrections have no influence in LAC results.

By following results on Table 3.1.3., we can see that the largest impact in GWP category is increased by thermal insulation (glass wool) material from all exterior wall construction, which summary is 60% from all construction of exterior wall – 44,70 kg CO₂ eq from all emissions 74,82 kg CO₂ eq. All wooden structures of wall gives only 8% of all CO₂ emissions – 6,69 kg CO₂ eq. The insignificant result in this category belongs to vapour control layer - 1 % 0,49 kg CO₂ eq.

3.2. The alternative exterior wall constructions (1m²) impact on the environment

The alternative exterior wall construction of the zero- energy building is designed from wooden frame filled with thermal insulation from cellulose fibre. The exterior wall construction layers are given in Table 3.2.1. and with heat transfer coefficient U=0,10 (W/m²K) for all wall structure.

Table 3.2.1. *The alternative construction of exterior wall.*

The material	Thickness, mm
Plasterboard	13
Wooden fibreboard	50
Thermal insulation – cellulose fibre	400
Wooden fibreboard	25
Vertical lathing	25
Horizontal lathing	45
Facade cladding wood board	22

Also for this type of construction as bearing frame is used wooden beams, apart 600mm. The bearing frame in further research work is included for more precise LCA analyse results in all made emission in environment impacts.

The same like the previous exterior wall design this alternative wall is calculate with SimaPro8 to find out the possible impact to environment. In the following Table 3.2.2. is viewed the alternative exterior wall's construction layers percentage distribution by density of 1m² wall.

Table 3.2.2. *The alternative exterior wall's construction layers percentage distribution by density of 1m² wall.*

The material	Thickness, mm	Density, Kg/ m ²	%
Plasterboard	13	8,96	6
Wooden fibreboard	50	11,5	8
Thermal insulation – cellulose fibre	400	24	16
Wooden fibreboard	25	5,75	4
Vertical lathing	25	6,31	4
Horizontal lathing	45		
Facade cladding wood board	22	15,4	10
Wooden beams (bearing frame)		80,16	53
Total	580	152,26	100

As we can see the biggest part of exterior wall structure is from wood – bearing frame, façade cladding, lathing – about 67%.

Table 3.2.3. *Impact assessment from 1m² wood framed exterior wall filled with cellulose fibre by method: CML-IA baseline V3.04 / EU25 / Characterization.*

Impact category	Unit	Total	Gypsum plasterboard {GLO} market for Alloc Def, U	Wood fibre board	Cellulose fibre, inclusive blowing in {GLO} market for Alloc Def, U	Wooden beams (bearing frame)	Vertical/ horizontal wooden lath	Facade cladding wood board
Abiotic depletion	kg Sb eq	0.013754	5.69E-06	0.000139	0.013546	5.77E-05	2.13E-06	3.15E-06
Abiotic depletion (fossil fuels)	MJ	999.0585	39.49739	583.5598	131.4198	208.7111	14.20296	21.66749
Global warming (GWP100a)	kg CO2 eq	102.4183	3.69626	68.74688	11.336	15.92755	1.048684	1.662927
Ozone layer depletion (ODP)	kg CFC-11 eq	7.24E-06	2.08E-07	3.74E-06	1.11E-06	1.86E-06	1.34E-07	1.90E-07
Human toxicity	kg 1,4-DB eq	53.50075	1.067301	15.28309	29.97649	6.192339	0.378408	0.603122
Fresh water aquatic ecotox.	kg 1,4-DB eq	29.88947	0.739231	7.377694	17.36119	3.796509	0.222886	0.391957
Marine aquatic ecotoxicity	kg 1,4-DB eq	83796.26	3352.565	25610.29	38913.05	13741.87	789.4927	1388.993

Terrestrial ecotoxicity	kg 1,4-DB eq	0.24642	0.007193	0.094099	0.078653	0.055862	0.003713	0.0069
Photochemical oxidation	kg C2H4 eq	0.025057	0.001065	0.010737	0.005968	0.006118	0.000425	0.000745
Acidification	kg SO2 eq	0.473546	0.023736	0.198384	0.143546	0.091959	0.006113	0.009807
Eutrophication	kg PO4--- eq	0.139355	0.005334	0.049617	0.051652	0.027909	0.001793	0.00305

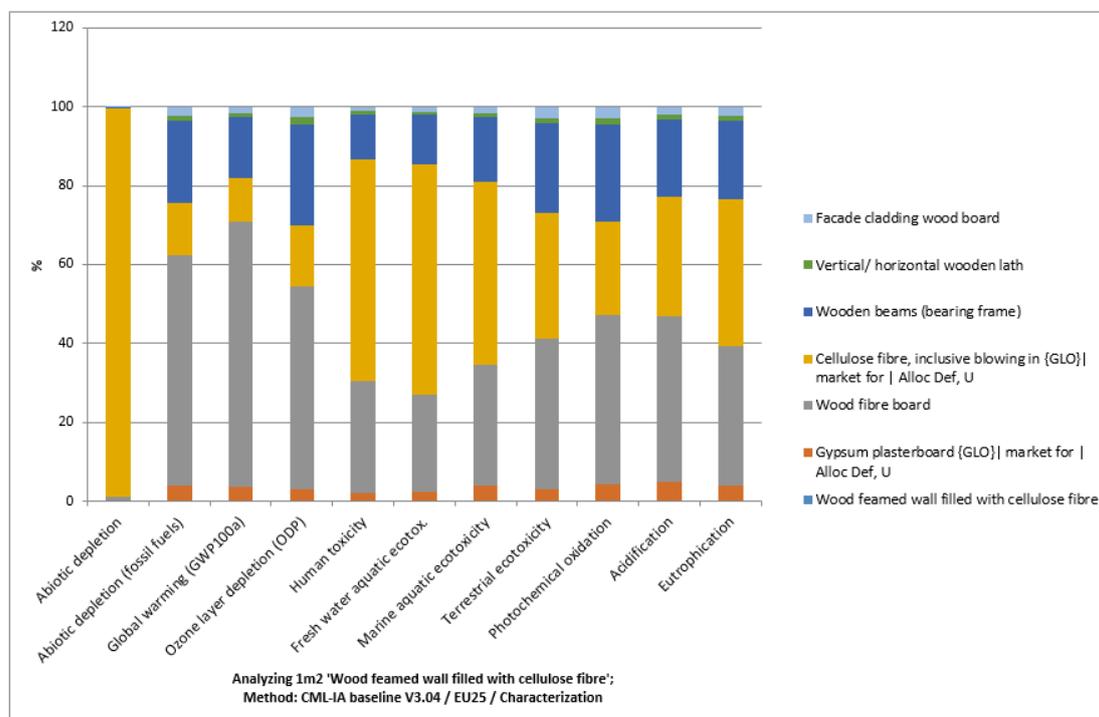


Fig. 3.2.1. Analyzing 1m² wood framed exterior wall by method: CML-IA baseline V3.04 / EU25 / Characterization.

After given results (Table 3.2.3., Fig.3.2.1.) is viewed that the biggest impact in all categories is made by wood fibreboard, except in impact category - abiotic depletion. Also the big impact is from cellulose fibre thermal insulation – from all wall layers in impact category abiotic depletion – 98%, and in human toxicity 56%, marine aquatic ecotoxicity 46%, fresh water aquatic ecotoxicity 58%. The less impact on environment in all categories is from wood – lath and facade cladding. The result in GWP is 102,42 kg CO₂ eq emissions Table 3.2.3 from exterior wall construction with density of 152,26 kg/m² and 580 mm thickness.

The given result from calculation with SimaPro 8 is summarized in the impact category of GWP for each exterior wall construction layer, shown in Table 3.2.4. As it is shown in Table 3.2.4. the biggest emissions are from wooden fibreboard 67%, the cellulose fibre thermal insulation consists only 11 % and also wood structures in wall consist 18%.

Table 3.2.4. The CO₂ emissions of alternative exterior wall's construction layers of 1m² wall.

The material	Thickness, mm	GWP CO ₂ emissions, kg CO ₂ eq	GWP CO ₂ emissions, %
Plasterboard	13	3,70	4
Wooden fibreboard	50+25	68,75	67
Thermal insulation – cellulose fibre	400	11,34	11
Vertical lathing	25	1,05	1
Horizontal lathing	45		
Facade cladding wood board	22	1,66	2
Wooden beams (bearing frame)		15,93	16
Total	580	102,42	100

3.3. Comparing nearly zero-energy building exterior wall constructions

The SimaPro8 is used for comparing two previously viewed exterior wall constructions - wood framed wall filled with glass wool and wood framed wall filled with cellulose fibre, both of those walls is with heat transfer coefficient $U=0,10$ (W/m²K). The result is shown in Table 3.3.1. and Fig. 3.3.1.

Table 3.3.1. Impact assessment comparing from 1m² wood framed exterior wall filled with glass wool and filled with cellulose fibre by method: CML-IA baseline V3.04 / EU25 / Characterization.

Impact category	Unit	wood feamed wall filled with glass wool	wood feamed wall filled with cellulose fibre
Abiotic depletion	kg Sb eq	0.000160453	0.013753932
Abiotic depletion (fossil fuels)	MJ	1024.3471	999.05851
Global warming (GWP100a)	kg CO ₂ eq	74.829881	102.4183
Ozone layer depletion (ODP)	kg CFC-11 eq	6.89E-06	7.24E-06
Human toxicity	kg 1,4-DB eq	40.141603	53.500752
Fresh water aquatic ecotox.	kg 1,4-DB eq	24.915653	29.889467
Marine aquatic ecotoxicity	kg 1,4-DB eq	95880.609	83796.26
Terrestrial ecotoxicity	kg 1,4-DB eq	0.18930649	0.24642037
Photochemical oxidation	kg C ₂ H ₄ eq	0.026324721	0.025057426
Acidification	kg SO ₂ eq	0.48359475	0.47354568

Eutrophication	kg PO ₄ ⁻⁻⁻ eq	0.15429598	0.13935502
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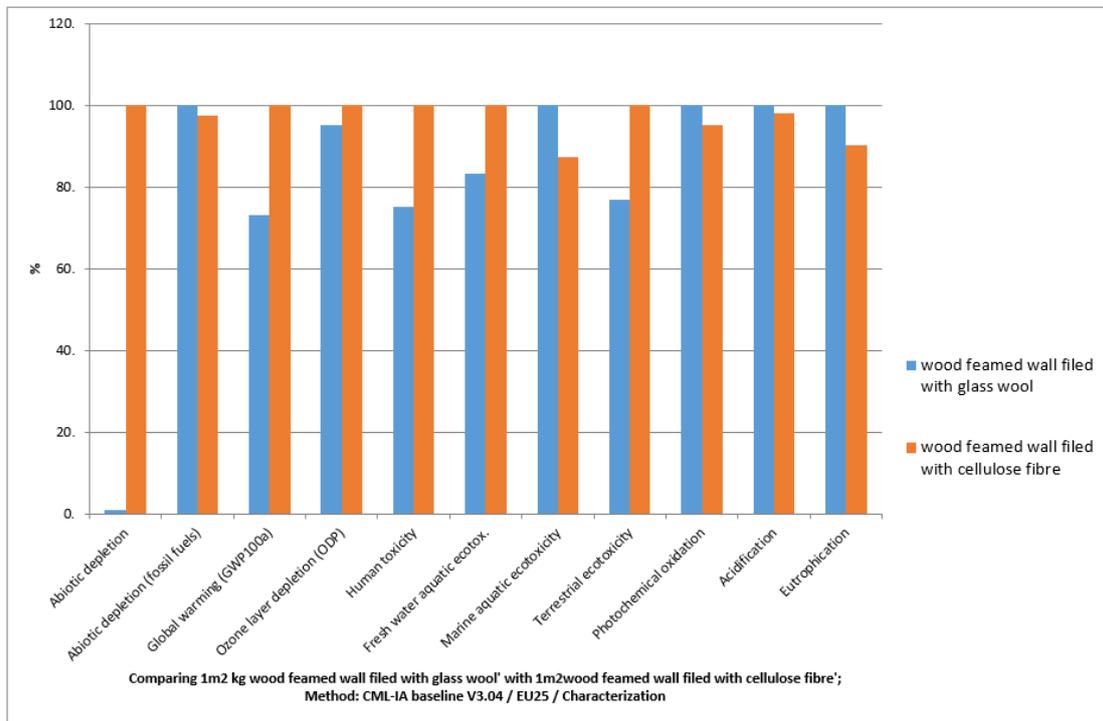


Fig. 3.3.1. Comparing 1m² wood framed exterior wall with glass wool and cellulose fibre by method: CML-IA baseline V3.04 / EU25 / Characterization.

By Simapro8 given results we can see that biggest impact is from wall filed with glass wool in impact categories - ADP (fossil fuels), marine aquatic ecotoxicity and eutrophication. But biggest impact from wall filed with cellulose fibre is in categories - abiotic depletion, GWP, HTP, fresh water aquatic ecotoxicity and terrestrial ecotoxicity. Similar emissions for both wall types are in the impact categories - ADP (fossil fuels), ODP, PO, acidification. The reason of big emissions from wall with glass wool is thermal insulation, but in chosen alternative wall filed with cellulose fibre reason of emissions is from wooden fibreboard. And in this case from LCA analyse point of view wooden wall filed with glass wool is with less CO₂ emissions in GWP (about 27%) than alternative wall filed with cellulose fibres.

7.4. Conclusions

LAC calculation using SimaPro8 for new build zero-energy house exterior wall construction (with glass wool) (1m²) showed that largest impact in GWP category is made by thermal insulation material (glass wool)– 63,95 kg CO₂ eq from all emissions 74,82 kg CO₂ eq (86% from all wall layers). This wall was compared with alternative wall with same heat transfer coefficient U=0,10 (W/m²K). This wall's insulation is cellulose fibre and this wall model give only 11,34 kg CO₂ eq from all emissions 102,42 kg CO₂ eq (11% from all wall layers), but the biggest impact in GWP emissions is from wooden fibreboard – 68,75 kg CO₂ eq (67%). By comparing those two type of walls in summary the biggest impact on environment is from alternative wall with cellulose

fibres. If construction bearing frame would be designed by other material, for example – aerated concrete, we would have different result.

The following execution of those results is planned to compare with other alternative exterior wall construction of the same project, same heat transfer coefficient.

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