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Corresponding Author:	Jorge M. Branco, Ph.D University of Minho Guimaraes, PORTUGAL
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	University of Minho
Corresponding Author's Secondary Institution:	
First Author:	Ana C. Coelho, MS.c
First Author Secondary Information:	
Order of Authors:	Ana C. Coelho, MS.c
	Jorge M. Branco, Ph.D
	Helena Gervásio, Ph.D
Order of Authors Secondary Information:	
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Page containing contact details

Coelho, A. C.
Master student, ISISE, Dept. of Civil Engineering, University of Minho, Guimarães, Portugal
coelho.ana.arq@gmail.com Tel: +351 253510200 Fax: +351 253510218

Branco, J. M.
Assistant Professor, ISISE, Dept. of Civil Engineering, University of Minho, Guimarães, Portugal
jbranco@civil.uminho.pt Tel: +351 253510200 Fax: +351 253510218

Gervásio, H.
Assistant Professor, ISISE, Dept. of Civil Engineering, University of Coimbra, Coimbra, Portugal
hger@dec.uc.pt Tel: +351 239797211 Fax: +351 239797217

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ABSTRACT: This paper aims to produce a "cradle-to-cradle" life-cycle assessment for a single-family timber house, prefabricated in northern Portugal, to be assembled in France. The three-story building has concrete foundations and basement. Above ground level, all the structure is made of solid wood and OSB panels, with gypsum boards on the inside and red cedar wood on the outside. All the thermal insulation is made of rockwool. GaBi software and extensive databases from several sources, including data supported directly from the building manufacturer, were used in the life-cycle assessment. In addition, a sensitivity analysis has been performed in order to identify the most influent parameters in the life cycle analysis, in particular, end-of-life scenarios and transportation needs.

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1INTRODUCTION

Wooden construction is empirically known for its sustainability. When performing a life-cycle analysis (LCA) of wooden buildings, it is usually considered that trees store carbon dioxide in their tissues, which will only be released by decay or combustion of wood. This wood feature is highlighted on long lifespan wood-based products, among which are the main construction materials [1], [2].

Nevertheless, the quantification of this wood feature has not a consensus among the scientific community. The use of different approaches has a noticeable impact on the quantification of Global Warming Potential [3].

Forestry industry has social and economic importance in many regions of the world. Besides that it also contributes to control soil erosion, helps to regulate the climate and has a decisive role in the efficiency of the water cycle and on the biodiversity of wildlife and flora [4]. Moreover, wood is a material that requires a relatively low processing power to be prepared for building industry, unlike most building materials [5]. On the other hand, it can be assumed that the transformation process of wood produces virtually no waste, since all the "waste" can be used for production of wood-based products or fuel, decreasing the demand for fossil fuels [2], [5]. Although wooden constructions need maintenance throughout its lifetime, the common wooden building systems allows partial replacement of modules or damaged elements, without compromising the entire structure. The use of wood also contributes to the energy efficiency of buildings, since it is a material with low thermal conductivity.

When dismantling a wooden building, the recovered wood can be directly reused in another building or used as raw material for wood-based products, either by extending its useful life or simply used as biofuel, avoiding the need for fossil fuels. On landfill, wood decomposes slowly, further extending carbon storage period. This is particularly efficient in modern landfills, equipped to capture methane emissions. Otherwise, the methane emissions partially offset the benefit from the carbon storage in the landfill [2]. Nevertheless, both combustion and decomposition of wood cause the release of the stored CO_2 back to the atmosphere [6]. Some European countries do not allow wood deposition on landfill, because it is a combustible material. In these cases, wood residues have necessarily to be burned as biofuel or reprocessed in new products manufacturing [7].

Countries like Sweden, which restrain the landfill of wood, use its residues to generate district heat and electricity, reuse it directly as solid wood, use it as raw material to the production of particleboard or pulp it to form paper products [7]. When wood residues are used to produce biofuel, its carbon offset becomes permanent, due to the avoidance of emissions from fossil fuel combustion [2].

2 LCA APPLIED TO TIMBER BUILDINGS

LCA methodology, as described by ISO standard 14040 [8], is not particularly directed to buildings assessment. It was designed to assess the sustainability of general products throughout its lifetime, based on the quantification and evaluation of material flows, at first place in an environmental perspective, but more recently also in economical and social perspectives [4]. One can find some applications of that methodology to timber buildings, like Perez-Garcia et al. [4] who compared three different structural materials for the same house (timber, concrete and light steel framing), concluding that the timber solution achieved a better score for all the categories under analysis.

Buchanan [6] and Sathre [5] show that timber buildings take greater advantage in the low energy processes required to its manufacture, than on the carbon storage itself, considering the whole life-cycle. Borjesson & Gustavsson [9] compared greenhouse gas emissions between timber and concrete solutions for a Swedish building, concluding that the timber option decreases Greenhouse Gas (GHG) emissions from 2 to 3 times, assuming that wood waste and logging residues are used to replace fossil fuels.

More recently, Nassén et al. [10] compared the use of concrete versus wood in buildings, from the energy system perspective, concluding that is not clear that the use of wood is a cost-effective option for carbon mitigation, recommending further studies on this subject.

3 CASE STUDY

In order to analyse the environmental impacts of a timber building, a case study was selected to perform a life-cycle assessment. Furthermore, a sensitivity analysis was performed in order to determine which parameters produce higher variations on the environmental impacts over the whole life-cycle of the building.

3.1Goal and scope definition

A single-family prefabricated timber house, designed for a service life of 50 years, was defined as the functional unit. The building was assumed to be prefabricated in Vila Nova de Cerveira (Portugal) and assembled in the periphery of Paris (France), inserted on a narrow plot, following a "anonymous" urban architecture, considering that any other material rather than wood could be used instead of it. In other words, if the house was to be built with concrete or steel structure, its shape would virtually be the same.

The system boundaries for this study are cradle-to-grave, as far as they include material production, manufacturing and end-of-life scenarios, although use-phase is here excluded. According to [11], the current thermal efficiency of new buildings highlights the need to focus on the materials included in the construction, rather than on operational energy, that tends to be "zero" or even positive values (energy gains) in new generation zero-energy buildings.

Therefore, this study includes all the elements that characterize timber construction, except those that are not dependant from the structural system adopted for the building, for instance: window frames, floor finishes, bathroom and kitchen fixtures. Although foundations and basement depend on the structural system, being less demanding as the construction is lighter (like what happens when replacing concrete by wood), these elements were also excluded from this study, for practicability reasons. In other words, the elements included in this study are the structure (above ground level) and the exterior walls, as represented in figure 1. Energy use for erecting, operating and maintaining the building were not included in this study.

The impact categories considered in this LCA are in agreement with the "CML2001 – Dec.07" methodology, namely: Abiotic Depletion (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP 100 years), Ozone Layer Depletion (ODP, steady state) and Photochemical Ozone Creation (POCP).

Inventory data was provided by the manufacturer and by the databases included in the software GaBi 4 [12]. The collected data is considered to be reliable and accurate.

3.2 Life-cycle inventory analysis

The life-cycle of the timber house was here defined into 5 different phases. The construction of the foundations and basement represent the first one. Even thought a timber structure is lighter than a concrete one, requiring less and simpler foundations, this stage was not considered in the current study. It was assumed that foundations and basement would be similar for most of the building systems available, therefore not being a specific feature of using timber.

The second phase corresponds to the prefabrication process of the house, prepared in the factory, and based on the definition of the timber elements required to build the house. All structural elements are produced in factory, and then transported to the building site, where they are assembled using, essentially, stainless steel connections. Both prefabrication and assembling processes are relatively low-tech, as far as they use very simple tools and require small amounts of energy to be completed. The tools used are mostly the electric saw and the screwdriver. For this reason, even a small wood-workshop can manage to produce a timber house like this one. As the energy amounts required are hard to measure and not very significant, its consumption will be dismissed from this study.

The third phase considered is the in situ assembling of the prefabricated elements. As mentioned before, this phase requires a very simple process: only a forklift or a small crane is used to put the pieces on place. Then, the structural elements are connected to each other using stainless steel joints and screws.

The fourth phase corresponds to the operation and maintenance of the building, during the 50 years defined as life span. The simulation of the energy amounts required during this phase overcomes the goals of this study, therefore it was excluded. The maintenance processes and materials are excluded for simplification reasons. However, for the 50-year life span, there is no significant demand for maintenance of the house. According to the manufacturer, the Canadian red cedar used in the façade is extremely weather resistant, avoiding any maintenance process.

The fifth and last phase of the building's life cycle is its dismantlement, after the 50-years use phase. When dismantling a building, one can hardly separate all the materials for recycling. It's expected to have some of them mixed or damaged in a way that makes them going to landfill. Nässén et al. [10] points out that "estimates of feasible recycling rates for building materials differ considerably in the literature". Moreover, it concludes that these rates do not produce significant variations in the results, as long as recycling is assumed to occur "100 years into the future when CO_2 emissions of the surrounding energy systems are assumed to be low". In practice, this author assumes a recycling rate of 80% for wood, which value is considered reasonable and has been adopted in this study

The flow diagram of the timber house life cycle, including the quantities of materials assumed in the inventory, is represented in Figure 2.

3.2.1 End-of-life scenarios

Three different end-of-life scenarios were considered. The default one considers for untreated solid wood an average recycling rate of 80% and its use as raw material for new wood products. For wood products and treated wood existing in the house a rate of 80% is considered for its use as bio-fuel. The remaining 20% of solid wood and wood products are assumed to be disposed on landfill. The assumption for steel screws and big steel parts is that 80% of them are recycled, but the other 20% go to landfill mixed with other waste. Steel nails are more difficult to separate from the wood, so it has been considered that 80% of those are not recycled. The amounts of materials assumed in this scenario are summarized in Table 1.

The second end-of life scenario (Table 2) assumes that all the wood, steel and PVC products are separated when dismantling the building, being fully conducted to recycling or reuse. As in the first end-of-life scenario, untreated wood is recycled into wood products, while treated wood and general wood products are used as bio-fuel.

The third end-of-life scenario (Table 3) does not consider any recycling or reuses processes. It actually considers the whole building as "waste" (and consequent deposition on landfill) after the 50 years use, without any material separation.

3.3 Sensitivity analysis

With the aim to analyse the sensitivity of the environmental impacts related to the different variables involved, several composed scenarios have been assumed considering some variations on the reference model. The defined scenarios are summarized in table 4.

4 LIFE-CYCLE IMPACT ASSESSMENT

Impact assessment of the timber house life-cycle was performed under the impact categories defined on "CML2001 – Dec.07", using the normalization factors listed on table 5.

The results for the default version of the building life-cycle environmental impacts are listed on table 6, divided into the three phases of the LCA model: prefabrication (including raw materials acquisition and transport to the factory), transport of the prefabricated pieces to the construction site (from Portugal to France) and, finally, the end-of-life scenario. Comparing the impacts of the different life-cycle phases one can conclude that the large majority of the impacts are associated with the "Prefabrication" phase. For instance, for the category of Abiotic Depletion, prefabrication accounts for 99,38%, while the end-of-life phase and the transport of the prefabricated house from the factory to the construction site, account for 0,07% and 0,55%, respectively. For all the other impact categories analysed in this study, the proportion between different life-cycle phases is even less expressive.

The sensitivity analysis provided the variations listed on Table 7. They are not very significant between the scenarios defined in this study, because the variations represent a small fraction of the whole process.

Nevertheless, comparing the results of the sensitivity analysis (Figure 3), it can be concluded that the variation that produces a higher decrease in the overall environmental impacts is the decrease of the transportation. The elimination of the transport from the factory to the construction site (V3) produces a noticeable decrease in most of the categories. Moreover, this elimination combined with the removal of the transport of raw materials to the factory, produces a remarkable decrease in the global environmental impact (V6). In fact, wood products are supplied by overseas sources like Canada and Scandinavia countries, which means a long distance to be travelled by large amounts of materials, both by cargo ship and by truck. This could be avoided if a local source of timber and wood products would be used, highlighting the need to increase the development of local economies for economic, social and environmental reasons.

Removing the recycling process from the life-cycle (V5) produces remarkable environmental impacts increase for all the indicators. On the other hand, the difference between V1 and V4 is negligible. This means that the additional effort in recycling the totality of the materials, comparing with an average 80% recycling, does not produce an evident impact.

According to the observed pattern, the variables that produce a higher decrease in "Abiotic Depletion" (ADP) indicator are the V3 and V6. The use of plywood panels instead of OSB also produces a decrease in ADP. It can be furthermore noticed that the elimination of recycling process (V5) increases the potential for ADP.

Acidification Potential also suffers a significant variation in the scenario where the transport of large amounts of materials is suppressed or reduced (V6). For all the other scenarios under study, the values for this impact category remain very close to each other (Figure 3).

In the performed LCA, Eutrophication Potential seems to be closely related to the deposition of waste in landfill (V5). This may be due to the hazardous gases released on the decomposition processes of the various landfilled materials. For all the other scenarios under study, the environmental impact "Eutrophication Potential" remains barely unchanged.

Global Warming Potential (100 years) indicator gets negative results for all the assumed versions of the timber house. This is due to the wood ability to store carbon, creating temporary “carbon pools”, which may result in a negative carbon balance within its life-cycle [2], [4]. For the success of this process, forest management assumes a very relevant role. In fact, most of the carbon fixing occurs during the trees fast growing process, which represents mostly the period between 20-100 years of their life. After that period, in order to increase the carbon storage, it is encouraged to cut down the tree, giving place for a new one to grow [13]. Also before 20-years-old, it is not recommended to harvest the trees, for effective carbon-mitigation results. According to Lippke et al. [2], the use of wood materials in amounts that make the stored carbon higher than the emitted amount, leads the way for a “better-than-carbon-neutral” era in construction.

Carbon storage on V5 is partially offset by the end-of-life scenario defined, where no recycling or reuse is considered, which may lead to an increase of the Global Warming Potential of the solution. In any case, even though all the materials are landfilled in these circumstances, the global life-cycle assessment also gets negative values when it comes to this indicator, giving evidence that wood carbon storage may offset some of the emissions over the life-cycle.

Ozone Layer Depletion is a bigger threat when it comes to V5, which considers no recycling at all. This impact category gets the lower values for V2, due to the replacing of OSB by plywood panels. Plywood gets a more favourable result for this impact category due to its lower-energy manufacturing processes, when compared with OSB [2].

“Photochemical Ozone Creation Potential” gets its higher values for V5 and its lower values for V6. The default scenario gets a mid-way score between the two opposites, being V3 (partial transport avoidance) relatively close to V6 (total transport avoidance). It is a pattern between all the categories that V5 gets the “worst” results, considering that lower environmental impacts are “better”. As stated before, this is due to the amount of solid waste on landfill on the house end-of-life, which affects the air and soil quality. V6 dismisses the need for long-distance transport, which leads to less fuel consumption and therefore lower emissions.

5 DISCUSSION OF RESULTS

The LCA results showed that the use of plywood instead of OSB means overall environmental advantages, mostly supported on “Ozone Depletion Potential” and “Abiotic Depletion Potential” impact categories. A similar result was achieved by Lippke et al. [2], who shows that plywood production (average data for United States production, NW of the country), on a cradle-to-gate approach, produces roughly 30% less carbon emissions than the production of OSB (average data for United States production, SE of the country).

Negative values for GWP (Global Warming Potential) have been an actively discussed issue when it comes to the sustainability of wooden products. In fact, this assumption can lead to a perverse effect, as one may think that the increase of construction (and consequent further carbon storage) means a decrease of GWP for a certain area considered. It should be taken into account that buildings cause some other environmental impacts that can not be completely offset by its “function” as carbon pools. It’s certainly better, from a sustainability point of view, to replace other common materials by the increased use of wood, but probably that is not reasonable to build wooden buildings or to manufacture wooden products with the only aim of getting carbon sequestered for some decades more than if it was on forests.

6 CONCLUSIONS

The results of this study highlight the need to decrease the transportation distances, favouring the use of local sources and manufacturers, for an environmental-friendly construction. Local sources fulfil the requirements for the three sustainability main issues: environment, economy and social improvement.

Recycling and reuse both play an important role as a mean to decrease the environmental impacts of the building’s end-of-life. This is highlighted on timber products, because its lifespan is related to its role in carbon storage. Conceive buildings to last for long periods also “helps making the most” of this feature.

Wood products have different impacts. In order to choose the one that better suits project’s purpose (may it be economical, environmental or social concerns), a previous assessment should be made.

It has been stated that wood is a suitable construction product when it comes to reduce the Global Warming Potential, due to its ability to store carbon on its tissues. This ability can lead to a negative carbon balance, which, combined with a zero-energy building policy, results in a highly sustainable construction in the whole life cycle.

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Figure
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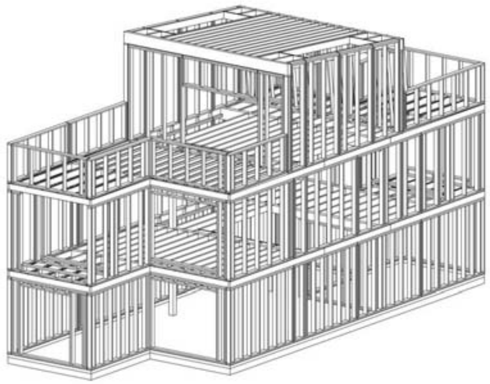
Figure 1 - Structural frame of the timber house

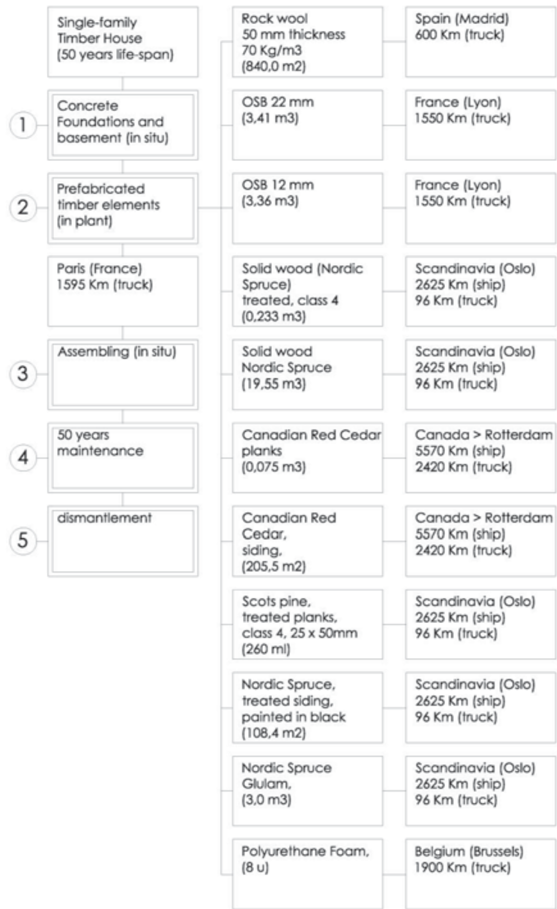

Figure 2 - Diagram of the house life-cycle, with reference to raw material quantities and transport distances

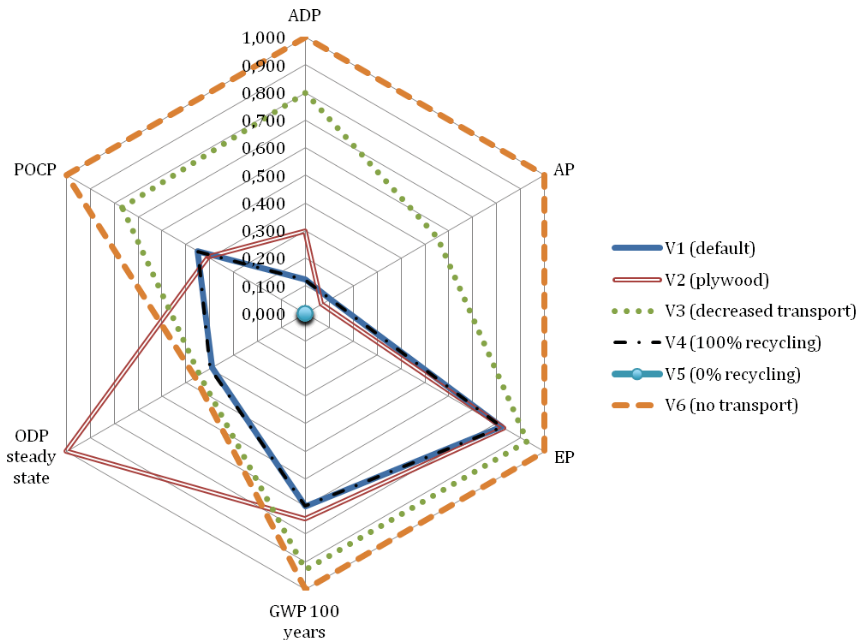

Figure 3 – Sensitivity analysis balance (normalised results: higher values are better)

table
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Table 1 - Inventory of materials for the first end-of-life scenario (Scenario 1)

Recycling: wood products (kg)	Production of bio-fuel (kg)	Wood waste on landfill (kg)	Other solid residues on landfill (kg)	Recycling: steel products (kg)	Recycling: PVC (kg)
8825,544	5048,08	3468,406	2965,8	253,081	3,636

Table 2 - Inventory of materials for the second end-of-life scenario (Scenario 2)

Recycling: wood products (kg)	Production of bio-fuel (kg)	Wood waste on landfill (kg)	Other solid residues on landfill (kg)	Recycling: steel products (kg)	Recycling: PVC (kg)
11031,93	6310,1	0	2940	277,945	4,572

Table 3 - Inventory of materials for the third end-of-life scenario (Scenario 3)

solid residues on landfill (kg)
20588

Table 4 - Summary of the analysed variables

	Brief description	End-of-life
V1	Base version, According to inventory (figure 2)	Scenario 1
V2	Base version, but substituting OSB panels by plywood panels	Scenario 1
V3	Base version, but removing transport of prefabricated house from Portugal to France (assuming the house was to be prefabricated and built in the same location)	Scenario 1
V4	Base version, but assuming 100% recycling of wood and steel products	Scenario 2
V5	Base version, but assuming 0% recycling (100% landfill)	Scenario 3
V6	Base version, but removing transport for wood supply and transport of the prefabricated house from Portugal to France (assuming the house is prefabricated only with locally produced timber, and built near the prefabrication factory)	Scenario 1

Table 5 - Normalization factors for the impact categories considered [12]

Quantity	Equivalences	Unit	Factor
Abiotic Depletion (ADP)	1,69E+10	kg Sb-Equiv.	5,92E-11
Acidification Potential (AP)	1,68E+10	kg SO2-Equiv.	5,95E-11
Eutrophication Potential (EP)	1,85E+10	kg Phosphate-Equiv.	5,41E-11
Global Warming Potential (GWP 100 years)	5,21E+12	kg CO2-Equiv.	1,92E-13
Ozone Layer Depletion Potential (ODP, steady state)	7,70E+06	kg R11-Equiv.	1,30E-07
Photochem. Ozone Creation Potential (POCP)	2,66E+09	kg Ethene-Equiv.	3,76E-10

Table 6 - LCA results for V1

Impact Categories	units	**Total**	Prefabrication	Transport	End of life
Abiotic Depletion (ADP)	kg Sb-Equiv.	**3,31E-07**	3,29E-07	1,82E-09	2,31E-10
Acidification Potential (AP)	kg SO2-Equiv.	**9,16E-07**	9,15E-07	1,61E-09	1,58E-10
Eutrophication Potential (EP)	kg Phosphate-Equiv.	**8,41E-08**	8,38E-08	2,54E-10	4,31E-11
Global Warming Potential (GWP 100 years)	kg CO2-Equiv.	**-4,47E-07**	-4,48E-07	8,85E-10	1,38E-10
Ozone Layer Depletion Potential (ODP, steady state)	kg R11-Equiv.	**2,01E-09**	2,01E-09	9,90E-13	-1,43E-12
Photochem. Ozone Creation Potential (POCP)	kg Ethene-Equiv.	**3,83E-07**	3,82E-07	8,22E-10	1,39E-10

Table 7 - Variation of results from the sensitivity analysis performed

	V1	V2	V3	V4	V5	V6
Abiotic Depletion (ADP)	**3,31E-07**	-0,14%	-0,55%	0,00%	0,10%	-0,72%
Acidification Potential (AP)	**9,16E-07**	0,01%	-0,18%	0,00%	0,04%	-0,35%
Eutrophication Potential (EP)	**8,41E-08**	-0,02%	-0,30%	0,00%	2,34%	-0,51%
Global Warming Potential (GWP 100 years)	**-4,47E-07**	0,04%	0,20%	0,00%	-0,61%	0,26%
Ozone Layer Depletion Potential (ODP, steady state)	**2,01E-09**	-0,56%	-0,05%	-0,01%	0,36%	-0,06%
Photochem. Ozone Creation Potential (POCP)	**3,83E-07**	0,03%	-0,21%	0,00%	0,31%	-0,37%