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Life Cycle Assessment of biochar produced from waste wood in the furnace Kon-Tiki

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Content

3. Goal and Scope definition 4
3.1. Goal of the study 4
3.2. Scope of the study 4
3.2.1. Function 4
3.2.2. Functional unit 4
3.2.3. System boundary 4
3.3. Impact categories 5
3.4. LCA Software 7
3.5. Product system description 8
4. Life cycle inventory analysis (LCI) 10
4.1. LCI outcomes 10
5. Life cycle impact assessment (LCIA) 11
5.1. Characterization method 11
5.2. Characterization results 11
6. Life cycle interpretation 16
6.1. Significant findings formulation 16
6.2. Sensitivity analysis 16
6.2.1. Production of the kiln Kon-Tiki 16
6.2.2. Source of the wood 18
6.2.3. Transportation 18
7. Carbon sequestration 21
8. Conclusion 22

1. Introduction

The goal of this study is to define the environmental impact of the biochar produced from the waste wood in the furnace Kon-Tiki using the Life Cycle Assessment (LCA).

Life cycle assessment (LCA) is an analytical tool, which can be used to evaluate the impact of a product, a system, an activity, an enterprise on the environment. The LCA method is applied according to ISO 14040[1] and ISO 14044. It is a transparent tool for quantification of potential environmental impacts connected with individual input and output materials and energies. LCA is an internationally used method. The principle of LCA is the determination of the material and energy flows coming in and out of the studied system. The quantity, composition, nature and magnitude of the flows are monitored. From these flows, the causes and consequences are then devised to determine the resulting changes in the environment. Basic data are processed by inventory analysis.

2. Description of biochar

Plants remove carbon from the atmosphere in the form of CO_2 via photosynthesis and convert it into biomass. Up to half of that carbon can be transformed into biochar by pyrolysis. Due to its porosity, biochar retains water and the pores are an ideal space for colonization by micro life. Healthy and fertile soil is a natural source of nutrients.

The kiln Kon-Tiki produces biochar from waste wood produced during cutting trees in the forest or from the waste product from sawmills or other waste wood. Kiln Kon-Tiki is a top-lit updraft gasifier, it is suitable for the onsite process of biochar production in smaller amounts. It has a conical shape, it is made from steel, it weighs 80 kg and it is possible to transport it to the location where the wood waste is produced or the wood waste can be transported to the kiln.

The usual load of the kiln is 400 kg of the untreated soft wood and produces 150 kg of the biochar. After burning the waste wood at the temperature 650 – 750 °C for 10-15 min the kiln is flooded with 50 l of water. The flue gases leave the kiln with a large excess of combustion air. The biochar composition and some properties of the biochar produced in the kiln Kon-Tiki from the untreated soft wood are shown in Table 1.

1 ČSN EN ISO 14040 Environmental management – Life Cycle Assessment – Principles and Framework

Table 1: Properties of the biochar

Property of biochar	Value
Combustible substances in the dried sample in %	min. 86,0
Dry matter in %	min. 60,0
Total carbon as C in dry matter in %	min. 76,5
Total nitrogen as N in dry matter in %	min. 1,4
Total phosphorus as P_2O_5 in dry matter in mg/kg	1,2 (± 20 %)
Total potassium as K_2O in dry matter in mg/kg	9,6 (± 20 %)
Calcium as CaO in dry matter in mg/kg	2,4 (± 20 %)
Magnesium as MgO in dry matter in mg/kg	2,5 (± 20 %)
pH value	8-10
BET	340 m^2/g (± 10 %)

3. Goal and Scope definition

3.1. Goal of the study

This study is made for the biochar produced in the Kon-Tiki kiln of the Biochar Foundation, endowment fund and should serve as background for the registration to Puro CO_2 removal market place.

3.2. Scope of the study

3.2.1. Function

The function of the studied system is the purpose for which the system is built. The function of the Kon-Tiki kiln is the production of biochar.

3.2.2. Functional unit

In LCA studies, a functional unit is the reference value against which individual product system variants are compared. It is a unit which can be used to measure the output function of the assessed product. As the function of the Kon-Tiki kiln is to produce biochar, 1 kg of biochar is chosen as a functional unit in this LCA study.

3.2.3. System boundary

It is the cradle-to-gate LCA, it begins with the production of the wood waste in the forest and with the fabrication of the kiln Kon-Tiki, continues with the transportation of the kiln to the site or with the transportation of the wood to the kiln, continues with the burning of the wood and ends with the packaging of the product.

3.3. Impact categories

An important contribution to the use of the LCA method is the ability to express potential environmental impacts not simply by listing emissions of substances in individual environmental compartments but by transferring these data to the so-called results of impact category indicators. The characterization model CML-IA baseline V3.05 was used in this study.

Evaluated impact categories with midpoint indicators with their units are briefly described in Table 2.

Table 2: Impact categories, units and description[2]

IMPACT CATEGORY	UNIT	DESCRIPTION OF IMPACT CATEGORY
Abiotic depletion potential	kg Sb eq	This impact category is concerned with the protection of human welfare. This impact category indicator is related to the extraction of minerals and fossil fuels due to inputs in the system. The Abiotic Depletion Potential (ADP) is determined for each extraction of minerals (kg antimony equivalents/kg extraction) based on concentration reserves and rate of de-accumulation. The geographic scope of this indicator is on a global scale.
Abiotic depletion potential (fossil fuels)	MJ	Abiotic depletion of fossil fuels expressed in MJ of fossil fuels corresponding to inputs of fossil fuels in the system.
Global warming potential (GWP100a)	kg CO_2 eq	It is related to emissions of greenhouse gases to the air. The primary carbon footprint indicator is the midpoint global warming potential (GWP), expressed in kg CO_2 Equiv. The characterization model as developed by the Intergovernmental Panel on Climate Change (IPCC) is selected for the development of characterization factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in kg carbon dioxide/kg emission. The geographic scope of this indicator is on a global scale

2 SimaPro Database Manual – Methods v. 4.1, simapro.com

Ozone layer depletion potential (ODP)	kg CFC-11 eq	Because of stratospheric ozone depletion, a larger fraction of UV-B radiation reaches the earth surface. This can have harmful effects upon human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and on materials. This category is output-related and on a global scale. The characterization model is developed by the World Meteorological Organization (WMO) and defines the ozone depletion potential of different gasses (kg CFC-11 equivalent/ kg emission). The geographic scope of this indicator is on a global scale. The time span is infinity.
Human toxicity potential	kg 1,4-DB eq	This category concerns the effects of toxic substances on the human environment. Health risks of exposure in the working environment are not included. Characterization factors, Human Toxicity Potentials (HTP), are calculated with USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon. For each toxic substance, HTP's are expressed as 1,4-dichlorobenzene equivalents/ kg emission. The geographic scope of this indicator determines the fate of a substance and can vary between local and global scale.
Freshwater aquatic ecotoxicity potential	kg 1,4-DB eq	This category indicator refers to the impact on freshwater ecosystems, as a result of emissions of toxic substances to air, water and soil. Eco-toxicity Potential (FAETP) are calculated with USES-LCA, describing fate, exposure and effects of toxic substances. The time horizon is infinite Characterization factors are expressed as 1,4-dichlorobenzene equivalents/kg emission. The indicator applies at global/continental/ regional and local scale.
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	Marine eco-toxicity refers to impacts of toxic substances on marine ecosystems (see description of freshwater aquatic ecotoxicity potential).
Terrestrial ecotoxicity potential	kg 1,4-DB eq	This category refers to impacts of toxic substances on terrestrial ecosystems (see description of freshwater aquatic ecotoxicity potential).

Photochemical oxidation potential	kg C_2H_4 eq	Photo-oxidant formation is the formation of reactive substances (mainly ozone) which are injurious to human health and ecosystems and which also may damage crops. This problem is also indicated with "summer smog". Winter smog is outside the scope of this category. Photochemical Ozone Creation Potential (POCP) for the emission of substances to air is calculated with the UNECE Trajectory model (including fate), and expressed in kg ethylene equivalents/kg emission. The time span is 5 days and the geographical scale varies between local and continental scale.
Acidification potential	kg SO_2 eq	Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). Acidification Potential (AP) for emissions to air is calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances. AP is expressed as kg SO_2 equivalents/ kg emission. The time span is eternity and the geographical scale varies between local scale and continental scale. Characterization factors including fate were used when available. When not available, the factors excluding fate were used (In the CML baseline version only factors including fate were used). The method was extended for Nitric Acid, soil, water and air; Sulphuric acid, water; Sulphur trioxide, air; Hydrogen chloride, water, soil; Hydrogen fluoride, water, soil; Phosphoric acid, water, soil; Hydrogen sulfide, soil, all not including fate. Nitric oxide, air (is nitrogen monoxide) was added including fate.
Eutrophication potential	kg PO_4^{3-} eq	Eutrophication (also known as nutrification) includes all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil. Nutrification potential (NP) is based on the stoichiometric procedure of Heijungs (1992), and expressed as kg PO_4^{3-} equivalents per kg emission. Fate and exposure are not included, the time span is eternity, and the geographical scale varies between local and continental scale.

3.4. LCA Software

For calculations and modelling of the product or organization life cycles, specialized software and inventory data databases are used. Professional LCA software SimaPro 9.0 was used in this study. This software was created by Dutch company PRé Sustainability and it was built on 25 years of sustainability metrics. It's the tool for creating ISO-compliant LCAs.[3]

3.5. Product system description

1. Production of the kiln Kon-Tiki

The kiln is made from 80 kg of the steel.

As the kiln is produced in different metal production sites, it is not possible to get the data from the production of the kiln so the average data were used to calculate the impact of the kiln production.

1.1. Steel for the fabrication

Steel is produced by two basic technologies from iron ores - production of pig iron, smelting with scrap additives (share in world production approx. 70%, in the Czech Republic share 90%) and from scrap (world approx. 30%, Czech Republic approx. 10%). [4]

As the exact source of the iron and exact ratio between pig iron and scrap iron is unknown the national ratio 90 % of pig iron and 10 % of scrap iron was used and as the source of the steel is unknown the general data from the Ecoinvent v3.5 database was applied for the production processes, while the kiln dimensions are known from its producer.

1.2. Welding method

Producer states that there are 10 m of welded joints.

The most common method of welding is a MIG/MAG method to which corresponds the process Welding, arc, steel from the Ecoinvent 3.5 database.

1.3. Lifetime of the kiln Kon-Tiki

Producer estimates that the kiln is used 500 times before the end of life.

2. Transportation – all the data are approximations based on the current practice

2.1. Transport from the producer of the kiln to the user

On average the kiln is transported from production site to final user to 200 km with the light commercial vehicle. This transport is effectuated once a lifetime of the kiln.

2.2. Transport wood-kiln

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3 https://simapro.com/

4 https://www.mpo.cz/assets/cz/prumysl/politika-druhotnych-surovin-cr/2019/8/Analyza_materialove-toky_PDS-CR.pdf

There are 2 possibilities for transportation. The first possibility is the transportation of the kiln to the site of production of the wood and the second possibility is the transportation of the wood to the kiln. This transportation is effectuated before (and after) every load of the kiln.

1st variant is the transportation of the kiln to the site where the cutting of the trees is effectuated-it is the transport of 80 kg kiln for a distance of 10 km and back. 2nd variant is the transport of the wood waste to the kiln. Usually, it means transport of 3 t of the wood for a distance of 20 km and then 7-8 loads of the kiln are effectuated.

After evaluation of the data, it was found out that if we use the average values for the transportation the deviation of the results will be 5 % in the impact category abiotic depletion, 3 % in the impact category ozone layer depletion and less than 1 % in other impact categories so the average results of the impacts of these categories were used.

3. Wood

One load of the wood is 400 kg.

The most common source of the waste wood for the biochar production in the kiln Kon-Tiki are spruce branches or waste wood from the sawmill so the soft wood was used for the analysis.

4. Packaging material

The most common packaging material is the big-bag which is reused approximately 10 times.

All the data used for the analysis are summarized in Table 3.

Table 3: The input data summary

Entry	Value	Information about the data
Spruce wood, wet	400 kg	Primary data
Transport of the furnace from production to user - light commercial vehicle	16 tkm	Assumption
Transport wood - kiln: small lorry or light commercial vehicle	8 tkm	Assumption
Packaging - big bag for 150 kg	1 reused 10 times	Assumption
Burning of the waste wood	400 kg	Primary data
Water for the final pouring of the kiln	50 l	Primary data

Kiln Kon-Tiki	1 p reused 500 times	Assumption
Pig iron	72 kg	Amount of the steel is primary data but the source of the steel is tertiary data
Scrap steel	8 kg	Amount of the steel is primary data but the source of the steel is tertiary data
Welding steel	10 m	Primary data
Biochar	**150 kg**	**Yield from 400 kg of the wood**

4. Life cycle inventory analysis (LCI)

4.1. LCI outcomes

The outcomes of the inventory analysis show the data which concerns the seriousness of inputs of the biochar production on the material resources and the emissions to particular components of the environment. It’s a large data set and the whole output is in the supplementary material in the xlsx format. The significance of individual emissions and their harmfulness is expressed in the next chapter of the life cycle impact assessment

5. Life cycle impact assessment (LCIA)

5.1. Characterization method

Expression of potential environmental impacts of inventory outputs was performed using the method CML-IA baseline V3.05/EU25.

5.2. Characterization results

Table 4 lists the results of the impact categories of the inputs to the process of biochar production in the kiln Kon-Tiki including the pre-production transport and packaging of the product. The values listed in Table 4 are graphically displayed for better visualization as a contribution to each impact category as a percentage in Figure 1. Separately in Figure 2, the results of the impact category global warming are showed. The flows of the CO_2 emissions are shown on the schema in Figure 3, on this figure all the inputs are expressed in values corresponding to the production of 1 kg of the biochar.

According to the Analysis of the Global Warming Potential of Biogenic CO_2 Emission in Life Cycle Assessments[5], the characterization factor of global warming potential for biogenic carbon (GWP_{bio}) was chosen 0,32. This GWP_{bio} corresponds to the products which have a pulse of CO_2 right after harvesting and the age of trees is close to 100 years.

As it is not still a rule to include the impact of the biogenic CO_2[6] to the LCA analysis, the characterization results without taking account the impact of the biogenic CO_2 are set out in the Attachment 1 on the Table 9.

5 Liu, W., Zhang, Z., Xie, X. *et al.* Analysis of the Global Warming Potential of Biogenic CO_2 Emission in Life Cycle Assessments. *Sci Rep* 7, 39857 (2017). https://doi.org/10.1038/srep39857

6 Biogenic CO_2 is the emission related to the natural carbon cycle, resulting from the combustion, harvest, digestion, fermentation, decomposition or processing of biologically based materials.

Table 4: Results of the impact category indicators of inputs to the process of producing 1 kg of the biochar in the kiln Kon-Tiki – midpoint indicators CML IA baseline V3.05

Impact category	Unit	Transport of the kiln from production to user	Transport wood - kiln	Soft wood	Packaging of product	Kiln Kon-Tiki	Burning of wood	Total
Abiotic depletion potential	kg Sb eq	8,92E-10	3,47E-08	8,13E-08	3,39E-10	1,27E-08	0,00E+00	1,30E-07
Abiotic depletion potential (fossil fuels)	MJ	6,11E-03	3,69E-01	4,45E-01	1,64E-02	1,85E-02	0,00E+00	8,54E-01
Global warming potential (GWP100a)	kg CO_2 eq	4,31E-04	2,61E-02	3,28E-02	8,03E-04	3,09E-03	1,71E+00	1,77E+00
Ozone layer depletion potential (ODP)	kg CFC-11 eq	6,67E-11	4,03E-09	4,69E-09	1,82E-11	1,51E-10	0,00E+00	8,96E-09
Human toxicity potential	kg 1,4-DB eq	2,46E-04	1,25E-02	1,19E-02	5,80E-04	4,05E-03	5,04E+00	5,07E+00
Fresh water aquatic ecotoxication potential	kg 1,4-DB eq	1,48E-04	7,00E-03	6,85E-03	1,20E-03	1,14E-03	2,35E-02	3,99E-02
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	3,97E-01	2,00E+01	2,05E+01	1,43E+00	2,43E+00	2,64E+02	3,09E+02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	6,52E-07	4,01E-05	1,12E-04	1,14E-06	-2,51E-06	3,89E-02	3,90E-02
Photochemical oxidation potential	kg C_2H_4 eq	1,71E-07	7,14E-06	1,16E-05	2,05E-07	1,01E-06	6,27E-03	6,29E-03
Acidification potential	kg SO_2 eq	1,88E-06	1,16E-04	1,63E-04	2,06E-06	-9,36E-06	2,85E-03	3,13E-03
Eutrophication potential	kg PO_4^{3-} eq	7,93E-07	4,61E-05	4,87E-05	3,48E-06	3,30E-06	1,67E-03	1,77E-03

Figure 1: Contribution of each input of the biochar production to each impact category expressed as a percentage

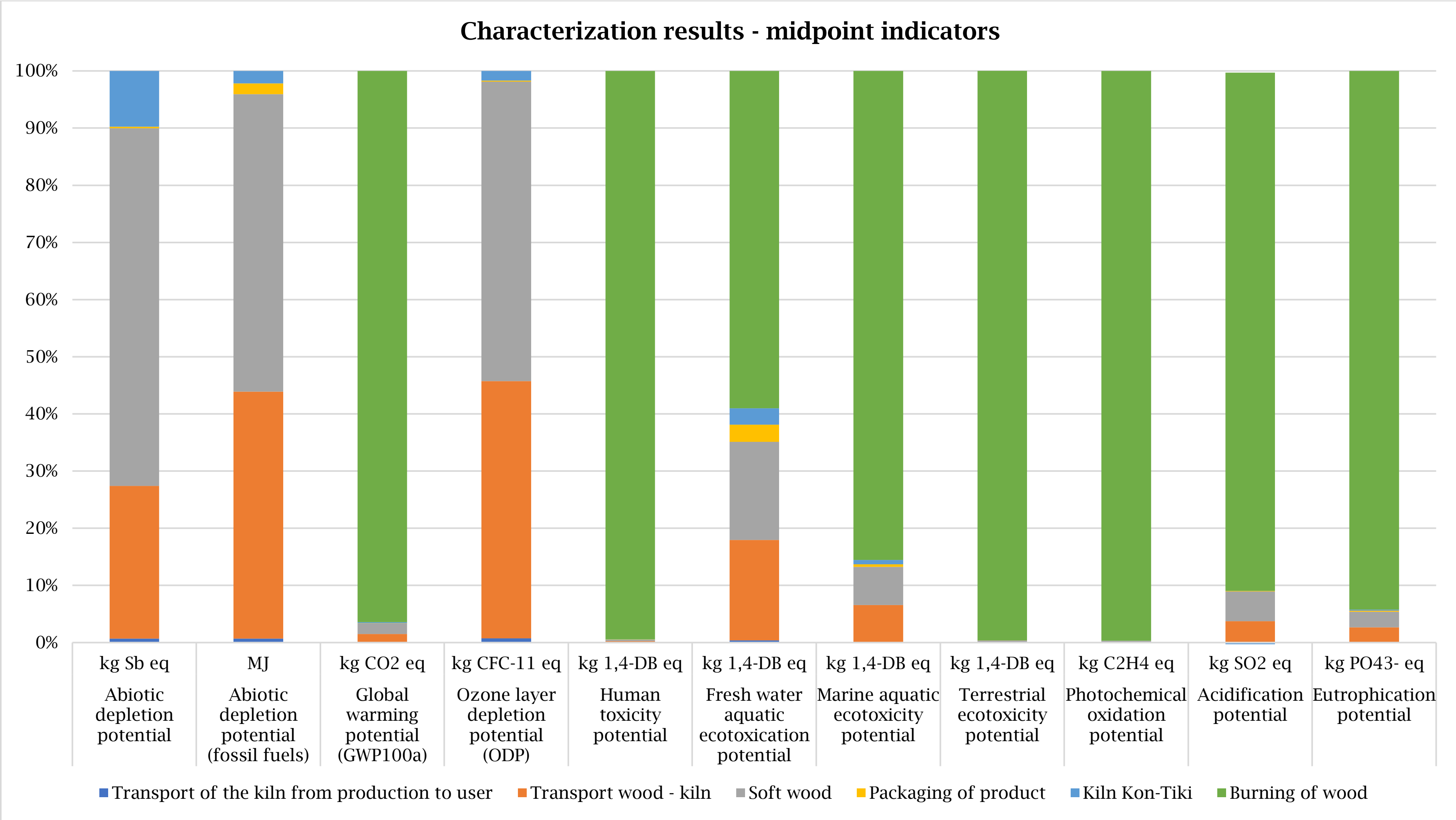


Figure 2: Comparison of the impacts to the impact category global warming caused by individual inputs to process of producing 1 kg of the biochar made in the kiln Kon-Tiki

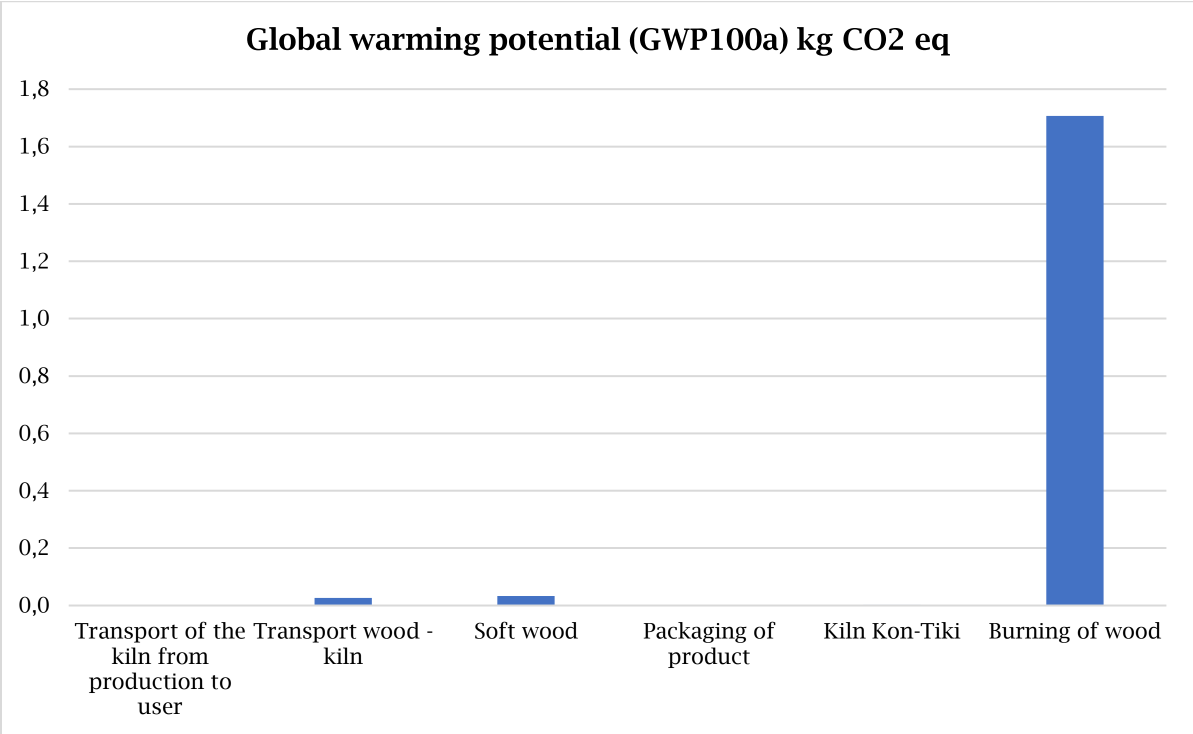
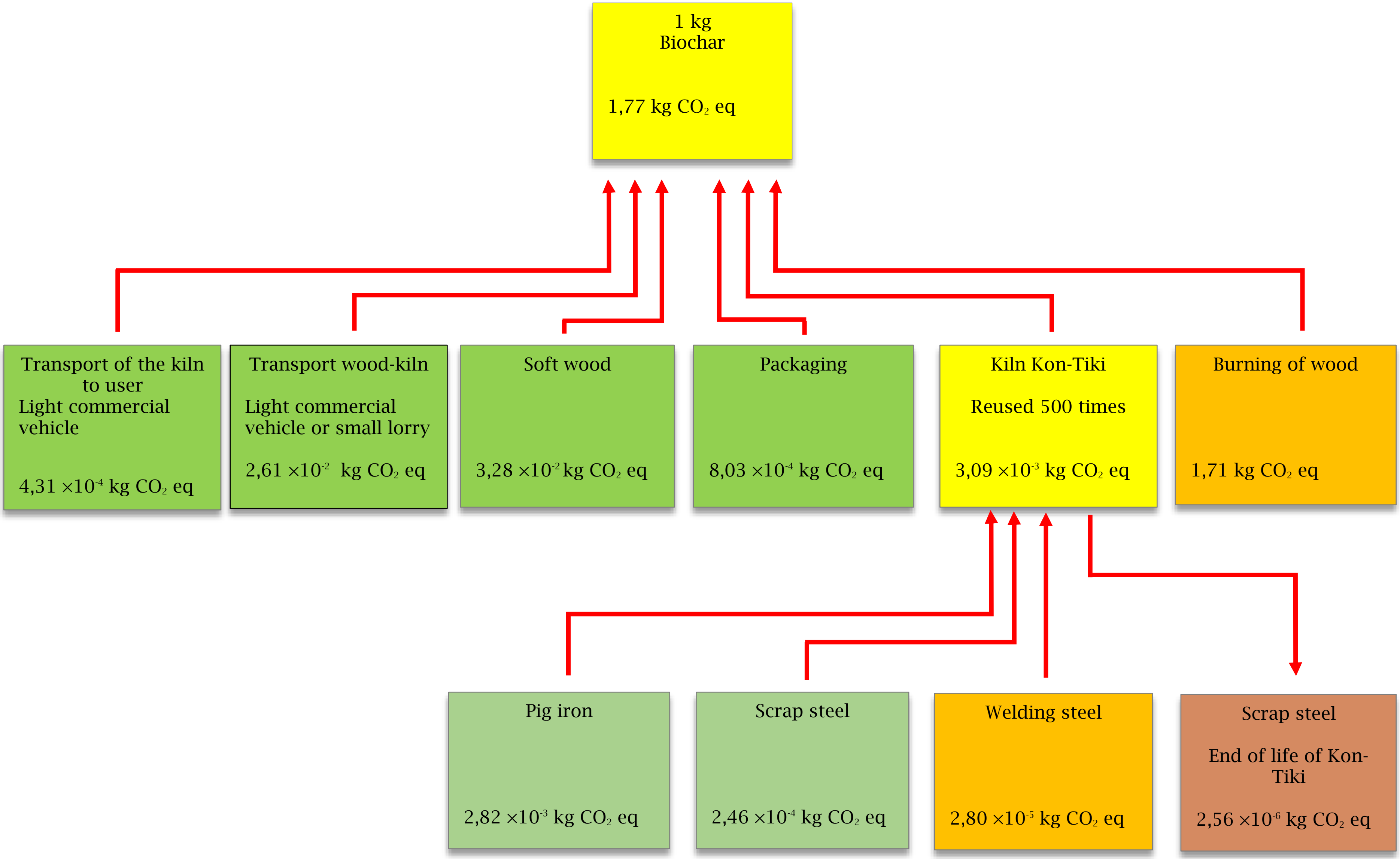


Figure 3: Schema of flows of the CO_2 (carbon footprint) for 1 kg of the biochar produced in the kiln Kon-Tiki



6. Life cycle interpretation

6.1. Significant findings formulation

- The highest environmental impact has the process of burning wood in the kiln Kon-Tiki.
- The lowest environmental impact has the life cycle of the kiln Kon-Tiki if used at least 500 times before the end of life and the packaging material in case of reusing big-bags at least 10 times.
- Burning of the wood has the highest environmental impact in the impact categories: global warming, human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication.
- Cutting of wood has the highest environmental impact in the impact categories abiotic depletion and ozone layer depletion.
- Transportation has a significant impact in the categories abiotic depletion, ozone layer depletion and fresh water aquatic ecotoxicity.
- During the production of 1 kg of the biochar in the kiln Kon-Tiki 1,77 kg CO_2 eq. is produced.

6.2. Sensitivity analysis

Sensitivity analyses are used in LCA studies to verify whether the chosen assumptions affect the final interpretation of the results. It is therefore verified whether the results obtained are valid under other input conditions or under alternative scenarios.

The sensitivity analysis is divided into 3 parts:

1. Production of the kiln Kon-Tiki – deviations caused by predefined assumption concerning the source and type of steel and the end of life of the kiln
2. Different type or source of the wood
3. Transportation – means of transport and transport distances

6.2.1. Production of the kiln Kon-Tiki

As the kiln is produced in different metal production sites, it is not possible to get the data from the production of the kiln so the average data were used to calculate the impact of the kiln production.

As the exact source of the iron and exact ratio between pig iron and scrap iron is unknown, the national ratio of 90 % of pig iron and 10 % of scrap iron was used. As the source of the steel is unknown the general data from the Ecoinvent v3.5 database was applied for the production processes, while the kiln dimensions are known from its producer.

For the purpose of the sensitivity analysis in scenario one, all the steel used for the production was replaced with pig iron, in another scenario with scrap steel only and in another, a global average for unalloyed steel was used, a scenario of the alternative end of life of the kiln, namely landfilling was added. In Table 5 the total results of all impact categories of biochar production for all mentioned scenarios of the kiln production are shown.

Table 5: Comparison of the life cycles of the kiln Kon-Tiki with different scenarios of production

Impact category	Unit	Original	Kon-Tiki - end of life landfilling	Kon-Tiki - from pig iron only	Kon-Tiki - from scrap steel only	Kon-Tiki - from unalloyed steel global market average
Abiotic depletion potential	kg Sb eq	1,30E-07	1,30E-07	1,18E-07	1,56E-07	1,27E-07
Abiotic depletion potential (fossil fuels)	MJ	8,54E-01	8,54E-01	8,55E-01	8,48E-01	8,55E-01
Global warming potential (GWP100a)	kg CO_2 eq	1,77E+00	1,77E+00	1,77E+00	1,77E+00	1,77E+00
Ozone layer depletion potential (ODP)	kg CFC-11 eq	8,96E-09	8,96E-09	8,92E-09	8,92E-09	8,97E-09
Human toxicity potential	kg 1,4-DB eq	5,07E+00	5,07E+00	5,07E+00	5,08E+00	5,07E+00
Fresh water aquatic ecotoxication potential	kg 1,4-DB eq	3,99E-02	3,97E-02	3,93E-02	4,05E-02	3,98E-02
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	3,09E+02	3,09E+02	3,08E+02	3,09E+02	3,09E+02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	3,90E-02	3,90E-02	3,90E-02	3,90E-02	3,90E-02
Photochemical oxidation potential	kg C_2H_4 eq	6,29E-03	6,29E-03	6,29E-03	6,29E-03	6,29E-03
Acidification potential	kg SO_2 eq	3,13E-03	3,13E-03	3,14E-03	3,13E-03	3,13E-03
Eutrophication potential	kg PO_4^{3-} eq	1,77E-03	1,77E-03	1,77E-03	1,77E-03	1,77E-03

The deviation of the results caused by all the changes in the different scenarios does not exceed 2 %, only in the impact category abiotic depletion the deviation is higher but we can conclude that the deviation is not significant and the predefined assumptions do not affect the results.

6.2.2. Source of the wood

The most common source of the waste wood for the biochar production in the kiln Kon-Tiki are spruce branches so the residual soft wood was used for the analysis. For the sensitivity analysis, there was analysed also hard wood, wood chips from saw mill and saw dust from saw mill, which can be also a source of the wood for biochar. In Table 6, the total results of all impact categories of biochar production for all mentioned scenarios concerning the source of the wood are shown.

Table 6: Comparison of different scenarios concerning the source of the wood

Impact category	Unit	Original	Hard wood	Wood chips	Saw dust
Abiotic depletion potential	kg Sb eq	1,30E-07	1,71E-07	1,19E-07	9,87E-08
Abiotic depletion potential (fossil fuels)	MJ	8,54E-01	1,03E+00	1,05E+00	9,07E-01
Global warming potential (GWP100a)	kg CO_2 eq	1,77E+00	1,78E+00	1,79E+00	1,78E+00
Ozone layer depletion potential (ODP)	kg CFC-11 eq	8,96E-09	1,09E-08	8,49E-09	7,77E-09
Human toxicity potential	kg 1,4-DB eq	5,07E+00	5,08E+00	5,08E+00	5,07E+00
Fresh water aquatic ecotoxication potential	kg 1,4-DB eq	3,99E-02	4,30E-02	5,24E-02	4,67E-02
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	3,09E+02	3,16E+02	3,57E+02	3,38E+02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	3,90E-02	3,92E-02	3,91E-02	3,90E-02
Photochemical oxidation potential	kg C_2H_4 eq	6,29E-03	6,32E-03	6,29E-03	6,29E-03
Acidification potential	kg SO_2 eq	3,13E-03	3,16E-03	3,22E-03	3,15E-03
Eutrophication potential	kg PO_4^{3-} eq	1,77E-03	1,79E-03	1,83E-03	1,80E-03

The most significant deviation of the results of the biochar production is in the impact category abiotic depletion, ozone layer depletion and fresh and marine aquatic ecotoxicity but the deviations of the results does not exceed 20 % and usage of the different source of the wood wouldn’t affect significantly the final result.

6.2.3. Transportation

In the Czech Republic, the kiln is transported from production to user by a light commercial vehicle to 200 km on average.

The secondary transportation wood-kiln has 2 possibilities:

1. The transportation of the kiln to the site where the cutting of the trees is effectuated – it is the transport of 80 kg kiln for a distance of 10 km and back by a light commercial vehicle.
2. The transport of the wood to the kiln. Usually, it means transport of 3 t of the wood for a distance of 20 km by a small lorry and then 7-8 loads of the kiln are effectuated.

2 variants of transportation for the sensitivity analysis were studied:

1. Change of means of transport
   For the transport of the kiln from producer to user, we replaced the light commercial vehicle with a small lorry. For the transport of the kiln to the wood, we replaced a light commercial vehicle with a large passenger car.
2. Change of transport distances
   For the transport of the kiln from producer to user, we replaced the distance 200 km with the distance 300 km and for the transport wood-kiln we replaced the distance 10 or 20 km with 50 km.

In Table 7, the total results of all impact categories of biochar production for all mentioned scenarios concerning the transportation are shown.

Table 7: Comparison of different scenarios concerning the transportation

Impact category	Unit	Original	Transport of the kiln from productio n to user - 300 km	Transport distance wood-kiln 50 km	Means of transport
Abiotic depletion potential	kg Sb eq	1,30E-07	1,30E-07	2,38E-07	2,68E-07
Abiotic depletion potential (fossil fuels)	MJ	8,54E-01	8,57E-01	1,79E+00	9,00E-01
Global warming potential (GWP100a)	kg CO_2 eq	1,77E+00	1,77E+00	1,84E+00	1,77E+00
Ozone layer depletion potential (ODP)	kg CFC-11 eq	8,96E-09	9,00E-09	1,92E-08	9,51E-09
Human toxicity potential	kg 1,4-DB eq	5,07E+00	5,07E+00	5,10E+00	5,08E+00
Fresh water aquatic ecotoxication potential	kg 1,4-DB eq	3,99E-02	3,99E-02	5,96E-02	4,39E-02
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	3,09E+02	3,09E+02	3,64E+02	3,09E+02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	3,90E-02	3,90E-02	3,91E-02	3,90E-02
Photochemical oxidation potential	kg C_2H_4 eq	6,29E-03	6,29E-03	6,31E-03	6,29E-03

Acidification potential	kg SO_2 eq	3,13E-03	3,13E-03	3,42E-03	3,12E-03
Eutrophication potential	kg PO_4^{3-} eq	1,77E-03	1,77E-03	1,89E-03	1,77E-03

The deviation of the results of the biochar production is in case of increasing the transport distance of the kiln from the producer to the user negligible. In case of using different means of the transport the significant deviation is in the category abiotic depletion but in other impact categories the deviation is negligible and the usage of the different means of the transport would not affect the final result of the LCA study.

In case of multiplying the transport distance wood-kiln 3 times, the results of the biochar production in the impact categories abiotic depletion, ozone layer depletion and fresh water and marine aquatic ecotoxicity are significantly higher than the original analysed version, in the other impact categories the deviation of the results does not exceed 10 % which means that it is not significant. In the case of increasing the transport distances of wood-kiln, the new LCA study is recommended.

7. Carbon sequestration

In the context of the carbon sequestration, biochar production has a potential to remove 2,72 kg CO_2 per kg of biochar. The result is based on the values identified in this study and shown in Table 8. The calculation of the CO2 removal is following:

1(3,39*(1-0,025))-(0,0043+0,523)-(0,0327+0,0253) = 2,72 kg CO_2 removed by 1 kg of biochar*

The calculation is in accordance with the Puro biochar quantification which is as follows:

$$Q_{biochar} * (C_{biochar} * (100\% - B_{biochar})) - (E_{biochar} + L_{biochar}) - (E_{rawmaterial} + ET_{rawmaterial}) = CO_2 \text{ Removal (in kg)}$$

Table 8: Values for calculation of CO2 removal

Segment	Description of the segment	Value
$Q_{biochar}$	Quantity of biochar produced and sold to end user in kg	1 kg
$C_{biochar}$	CO_2 storage volume of the biochar in kg CO_2 / kg biochar	3,39 CO_2/kg
$B_{biochar}$	Buffer for possible CO_2 re-emitted during Product life-time (The molar O/C_{org} ratio of the biochar is 1,98/91,5 = 0,02 which means it is less than 0,2 so the buffer is set at 2,5% of the CO_2 storage volume.)	2,5%
$E_{biochar}$	Net emissions from biochar production (in CO_2e) to the atmosphere, taking into account the own use of energy in a closed system.	4,30E-03
$L_{biochar}$	Possible leakage from biochar production (e.g. waste heat, in CO2e)	5,23E-01
$E_{rawmaterial}$	Emissions from harvesting the raw material, including possible loss of sinks in CO_2	3,27E-02
$ET_{rawmaterial}$	Emissions from transport of raw material to production site in CO2	2,53E-02

8. Conclusion

The environmental impact of the biochar production in the kiln Kon-Tiki is caused mostly by gases escaping into the air during open burning in the kiln Kon-Tiki. During the production of 1 kg of the biochar with this method escapes to the air 1,77 kg CO_2 eq. This relatively high production of the CO_2 eq. per 1 kg of product is caused mainly by the open burning without flue gas cleaning. Approximately 65% of the CO_2 production comes from the biogenic CO_2. According to the study of Liu, W., Zhang, Z., Xie, X. et al.[5] when performing the LCA study it is necessary to consider the GWP of the biogenic CO_2 even though the growth of biomass compensates the CO_2 emissions from burning biomass because the CO_2 emission will remain in the atmosphere for a certain time. Otherwise, the total GHG emissions will be underestimated.

It is a convenient method of processing wood waste which provides benefit in form of biochar which thanks to its porosity helps to retain water in the ground and the pores of biochar are also an ideal space for microlife colonization.

Sensitivity analyses showed that in the case of increasing the transport distance kiln-wood 3 times, the LCA analysis should be remade. But none of the changes made for the sensitivity analyses did not affect the CO_2 eq. formation significantly.

The results of the study open a question if another way of processing of the wood waste would have a lower or higher environmental impact. The results could be compared to burning of the wood waste in the power plant or heating plant with the cleaning of the escaped gases or it could be compared to a composting of the wood waste or to leaving the waste wood on site in the forest and last but not least it could be compared to other methods of producing biochar.

References

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Attachment 1: The characterization results without biogenic CO2 emissions

Table 9: Results of the impact category indicators of inputs to the process of producing 1 kg of the biochar in the kiln Kon-Tiki – midpoint indicators CML IA baseline V3.05 without the impact of the biogenic CO2

Impact category	Unit	Transport of the kiln from production to user	Transport wood - kiln	Soft wood	Packaging of product	Kiln Kon-Tiki	Burning of wood	Total
Abiotic depletion potential	kg Sb eq	8,92E-10	3,47E-08	8,13E-08	3,39E-10	1,27E-08	0,00E+00	1,30E-07
Abiotic depletion potential (fossil fuels)	MJ	6,11E-03	3,69E-01	4,45E-01	1,64E-02	1,85E-02	0,00E+00	8,54E-01
Global warming potential (GWP100a)	kg CO2 eq	4,19E-04	2,53E-02	3,27E-02	7,99E-04	3,08E-03	5,23E-01	5,85E-01
Ozone layer depletion potential (ODP)	kg CFC-11 eq	6,67E-11	4,03E-09	4,69E-09	1,82E-11	1,51E-10	0,00E+00	8,96E-09
Human toxicity potential	kg 1,4-DB eq	2,46E-04	1,25E-02	1,19E-02	5,80E-04	4,05E-03	5,04E+00	5,07E+00
Fresh water aquatic ecotoxication potential	kg 1,4-DB eq	1,48E-04	7,00E-03	6,85E-03	1,20E-03	1,14E-03	2,35E-02	3,99E-02
Marine aquatic ecotoxicity potential	kg 1,4-DB eq	3,97E-01	2,00E+01	2,05E+01	1,43E+00	2,43E+00	2,64E+02	3,09E+02
Terrestrial ecotoxicity potential	kg 1,4-DB eq	6,52E-07	4,01E-05	1,12E-04	1,14E-06	-2,51E-06	3,89E-02	3,90E-02
Photochemical oxidation potential	kg C2H4 eq	1,71E-07	7,14E-06	1,16E-05	2,05E-07	1,01E-06	6,27E-03	6,29E-03
Acidification potential	kg SO2 eq	1,88E-06	1,16E-04	1,63E-04	2,06E-06	-9,36E-06	2,85E-03	3,13E-03
Eutrophication potential	kg PO43- eq	7,93E-07	4,61E-05	4,87E-05	3,48E-06	3,30E-06	1,67E-03	1,77E-03