Deliverable R E P O R T

Multipurpose hemp for industrial bioproducts and biomass

(Ref n. 311849)

D7.3 Final report on integrated sustainability assessment

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Abbreviations

Av.	Average
AD	Abiotic Depletion
AP	Acidification Potential
CBD	Cannabidiol
CH_4	Methane
CO_2	Carbon dioxide
ECO	Economic allocation
EOL	End of life
EP	Eutrophication Potential
Eq.	Equation
GHG	Greenhouse gas emissions
GWP	Global Warming Potential
ISO	International Organization for Standardization
KTBL	Association for Technologie and Structures in Agriculture
LCA	Life cycle assessment
MASS	Mass allocation
Max.	Maximum
Min.	Minimum
n.a.	not applied
PET	Polyethylene terephthalate
PLA	Polylactic acid
PS	Pig Slurry
tdm	metric tonnes dry matter (0% moisture content)
tfm	metric tonnes fresh matter
UK	United Kingdom

1 Introduction

The present document constitutes the Deliverable 7.3, which reports about the integrated assessment of environmental and economic sustainability of the processes developed in the MultiHemp project.

The sustainability assessment of WP7 is based on a system level analysis (from field to fibres, shivs, residues, seeds) and a product level analysis (from fibres, shivs, residues, seeds to application). On the system level, the new harvesting and processing technologies developed in MultiHemp are compared to the reference system of the single-cut-harvesting system and the total fibre line, a mechanical fibre separation process which can be considered to be the state of the art of European hemp fibre processing technology. This technology has been developed by the companies van Dommele and Temafa / La Rouche and realised in the UK (HempTechnology), in France (AGROFIBRE), and also in South Africa. Regarding the product level, innovative hemp based products developed in MultiHemp are compared with conventional counterparts.

In the framework of MultiHemp, field trials have taken place at different locations (in France, the Netherlands, Germany and Italy) as well as with two different selected hemp varieties (Futura and Biaolobrzeskie). While these field trials provide a good idea of the ranges of yields, it was not possible with the given data to distinguish between effects of region, variety or cultivation system. We therefore also do not assess the effects of region or variety separately in the sustainability assessment but assume a typical situation of European industrial fibre hemp cultivation.

In the following section 2, the goal and scope of the environmental and economic assessment is defined. Then, in section 3, a description of the processes and the corresponding life cycle inventory data follows. Inventory data for both the environmental and economic assessment largely overlap, therefore both are described in the same section. Section 4 presents results and discussion and section 5 draws integrated conclusions at the system and product level. Background information is presented in Annexes I (chapter 7) to III (chapter 9).

2 Goal and scope definition

The hemp biorefinery system is divided into two stages; the first stage, called the “system level” encompasses the cultivation of hemp and the processing of hemp straw into fibres. The second stage includes the processing of hemp fibres into final products and hence is referred to as the “product level”. Figure 1 highlights the distinction of the hemp value chain into the two broad levels of systems and products.

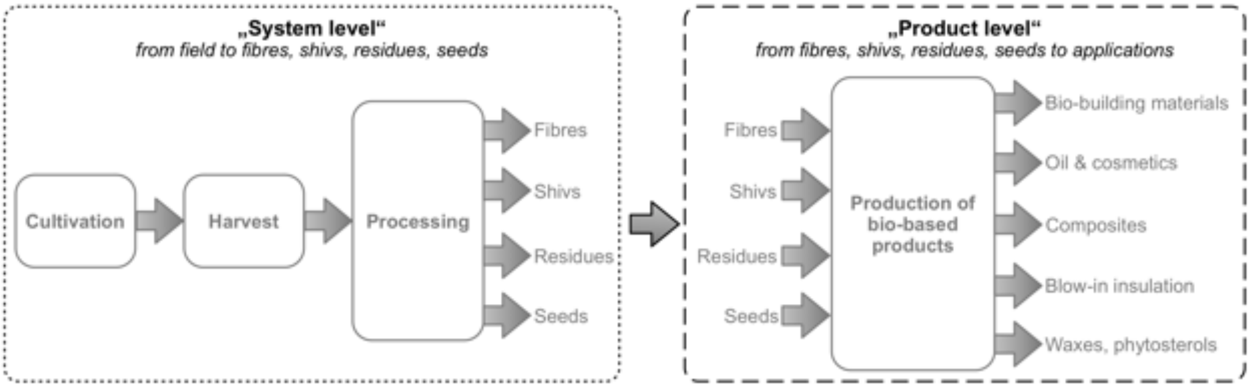

Figure 1: Life cycle stages of the system level and the product level

From the multitude of innovations developed in the project, sufficient data for the environmental and economic assessment has become available at the system level for the single-use cultivation for hemp straw as well as for the dual-use cultivation for straw and leaves or seeds as well as the European state-of-the-art fibre processing system. At the product level, sufficient data is available for two innovative products, a blow-in insulation material and a construction panel, and these are compared to reference products. In the case of the blow-in insulation material, this is mainly the hemp-based insulation material THERMO HANF® and in the case of the construction panel, it is compared to a wood wool panel produced by Heraklith. Additionally, the environmental assessment compares the hemp fibres with jute, kenaf and flax fibres produced for similar applications. The scope is therefore narrowed down as depicted in Figure 2.

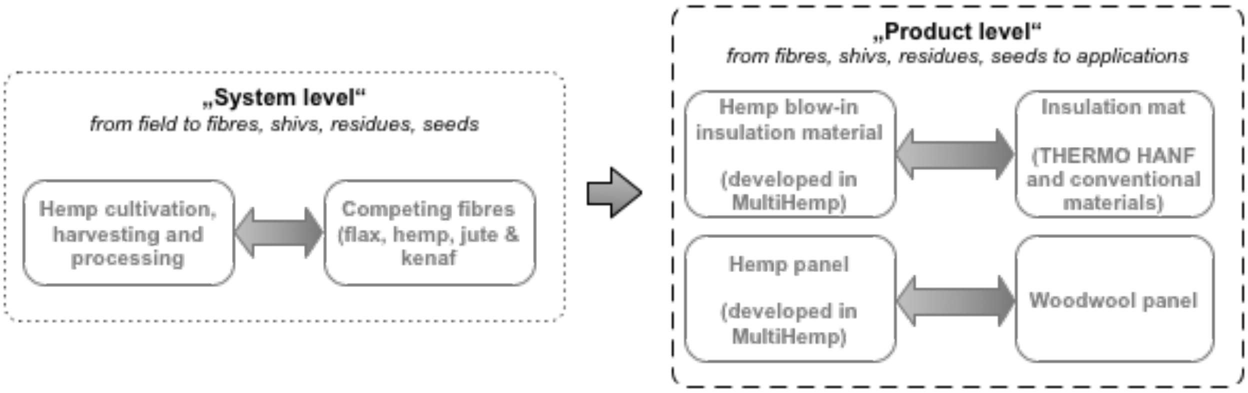

Figure 2: Environmental assessment on system and product level

The ultimate goal of the environmental assessment is to determine the potential environmental impacts from the developed hemp biorefinery system and its products as well as to determine the most efficient use of resources in every pathway. The environmental assessment is implemented within the scope of a Life Cycle Assessment (LCA).

Within both the system and product stage, the goal of the environmental analysis is two-fold: it aims to identify environmental hotspots, which allow for directing future research, and it aims to compare the hemp biorefinery products with competitive products.

The life cycle assessment (LCA) for system and product level will largely follow the ISO standards (ISO 14044 and ISO 14040). The LCA will be conducted under an attributional approach, i.e. the potential environmental impacts associated with the hemp biorefinery and its products are assessed at one point in time in a ‘snap-shot’ perspective (Curran et al. 2005).

The techno-economic evaluation will mainly assess process/production costs of the targeted hemp products and will contrast these with achievable market prices based on thorough market research. The market research will also need to take into account competing uses of hemp for food and feed (e.g. 95% of hemp seeds are currently used as bird and fish feed).

The Target Costing methodology links market prices with production costs in order to define the allowable production costs and identify need and potentials for cost reductions.

The overall aim will be to assess the value-added potential of using the whole hemp crop. Due to climatic reasons, in some areas cultivation for fibre or for seeds dominate, while in others, dual use for fibre and seeds is feasible. Accordingly, the portfolio of products from hemp that could maximise the total added-value from the crop will differ between regions.

The analysis will need to be differentiated between relatively well-established processes such as for fibre or for bioenergy for which production cost estimates will be relatively easy to obtain, and innovative processes such as in biorefineries for which estimations will need to mainly rely on expert judgements. The analysis will also include a sensitivity and risk analysis, especially for hemp straw and fibre prices.

2.1 Functional Unit

Since the environmental and techno-economic assessment is divided over several phases of the hemp value chain, different functional units are used.

On the system level the functional unit is one tonne of product (technical fibres, short and super short fibres, shives and dust). After careful consideration, this functional unit was preferred over the functional unit hectare, as the amount of products generated from a hectare varies in the different scenarios. When the functional unit is chosen per tonne of product, the different cultivation scenarios can be compared easily. The disadvantage of this choice of functional unit is that one tonne of different products requires different cultivation areas. In the comparison with other technical fibres, the functional unit is 1 t technical fibre.

For the hemp based insulation material, both the reference product THERMO HANF® and the blow-in insulation material, the functional unit is chosen as one tonne of product. From experiments, it was found that the difference in thermal insulation properties between THERMO HANF® and the blow-in insulation material is negligible. Therefore, a similar amount of material is required to obtain the desired thermal resistance. When the hemp based insulation materials are compared to other insulation materials the functional unit is changed to obtain a similar thermal resistance. When the thermal conductivity of a material is lower, more material is required to obtain a similar thermal resistance. Since more material is required, the environmental impact with the desired thermal resistance will be higher. For the hemp construction panels, the functional unit is chosen as one tonne of product.

For the techno-economic assessment, results on the system and product level are expressed per hectare of hemp or per tonne product. Both functional units are useful for the techno-economic assessment because they indicate how profitably the prime resource land and the main primary output hemp straw are utilised in the different value chains.

2.2 System Boundaries

As the functional units, the system boundaries also differ between the system level and product level.

The system level LCA focusses on the life cycle stages of hemp cultivation (harvesting, transport and the processing of its main constituents), following the "Cradle-to-gate-approach". The gate represents here the gate of the fibre processing factory. In the system level LCA, the seed production for sowing is not included since it is considered negligible. Emissions during field retting are also not included mainly due to a lack of reliable data. The geographical coverage of the system level LCA is mainly the Netherlands and Germany, therefore the German electricity mix is used in the assessment. The utilisation of agricultural machinery is included in the LCA, however the impacts associated with the production, maintenance and disposal of the machinery is not taken into account.

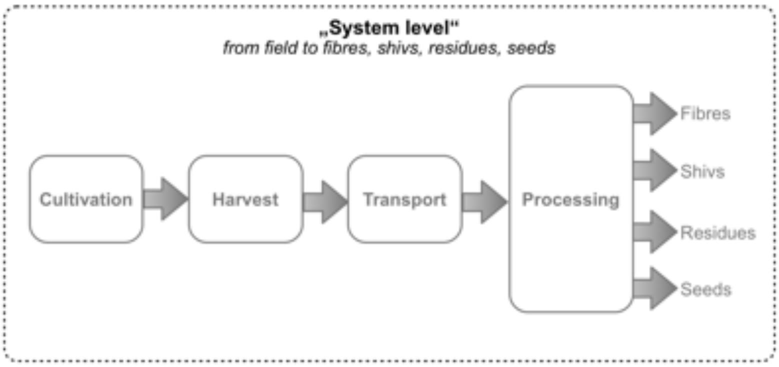

Figure 3: System boundaries of the system level

The system boundaries for the product level LCA are slightly different per product since the production processes differ. For details on the product level system boundaries see section3.2.

2.3 Definition of competitive products

For benchmarking purposes, the technical hemp fibres produced on the system level are compared with data from Barth and Carus (2015) on flax, hemp, jute and kenaf fibres used in the automotive industry. The hemp fibres Barth and Carus assessed are based on commercial cultivation data, while new cultivation systems have been researched in the MultiHemp project. For the life cycle inventory on these other natural fibres, see section 3.1.4.

On the product level, innovative hemp based products developed in MultiHemp should be compared with mainly petro-based counterparts to analyse environmental benefits and drawbacks of bio-based products. The product level assesses especially the products which are generated from the fibres, shivs, residues and seeds, based on the assessment in the system level. In the product group “thermal insulation” a new material has been developed within MultiHemp. This new hemp based blow-in insulation material is compared to a bio-based reference product called “THERMO HANF®” and compared with conventional insulation materials. To compare the hemp based blow-in insulation with THERMO HANF®, the cultivation is assumed to be similar. Furthermore, on the product level, a hemp based construction panel is compared with woodwool construction panels. The data for the woodwool construction panel is obtained from Ecoinvent and and environmental product declaration from Heraklith (2012).

2.4 Allocation

Within LCA, allocation occurs whenever a process produces more than one product (multi-output process), in which case the environmental burden caused by the process needs to be distributed over the different products. The ISO 14040 provides a list of how to approach allocation, with the following preference:

- Avoid allocation by system expansion or increased detail
- Partitioning based on physical relationships
- Partitioning based on other relationships such as income (Baumann & Tillmann 2004).

Allocation was necessary within the study as hemp cultivation provides more than one product: e.g. during straw processing, fibres and shives are produced, but also in the cultivation where dual harvest systems result in multiple products (straw and seeds or straw and leaves).

In order to investigate the impact of different allocation methods, it was decided to evaluate the environmental impact according to both mass allocation and economic allocation. The effect of different distribution is discussed in the results section for the respective part of the hemp biorefinery or hemp product.

Economic allocation is another often applied allocation method. By taking the economic value (revenue) of different products and by-products as a basis for allocation, economic partitioning addresses the economic motivation behind a multifunctional process. The rationale is that allocation should be based on the reason for the existence of the multifunctional process and its co-products, which is most often economic (Tillman, 2000).

Despite its limitations, economic allocation has certain qualities that make it flexible and potentially suitable for different contexts. In some situations, economic allocation should not be the last methodological resort. The option of economic allocation should be considered, for example, whenever the prices of co-products and co-services differ widely (Ardente, 2012).

2.5 Sources of Life Cycle Inventory Data

Foreground data has been collected from project partners throughout the MultiHemp project through conference calls, email and/or in person-meetings, or is based on empirical data. For competing products, the data has been obtained from literature, environmental product declarations and, when necessary to fill data gaps, approximations based on estimates of appropriate staff members.

For the background processes (e.g. electricity and nutrient production), LCI data mainly originated from the Ecoinvent LCI inventory database (version 3.1). This database is internationally recognized, both from a qualitative (completeness of data, quality of validation process) as well as from a quantitative perspective (scope of included processes). For inputs not represented in Ecoinvent, data were taken from literature.

2.6 Choices of Impacts and Impact Assessment Method

In order to ease the interpretation of an LCA, the data collected during the assessment's Life Cycle Inventory phase are aggregated and expressed as environmental impacts (e.g. Global Warming). This is done during the Life Cycle Impact Assessment (LCIA) phase, and the below section provides the details for this step as conducted in this study.

This screening LCA investigated the following environmental impact potentials:

- Global Warming (100 years) (GWP) expressed in kg CO_2eq (equivalent)
- Acidification (AP) in kg SO_2eq
- Eutrophication presented (EP) in kg PO_4eq
- Abiotic Depletion (fossil resources) (ADP) in MJ

All four impacts belong to the group of impacts that shall be investigated by default according to the ILCD Handbook (European Commission JRC, 2010). Moreover, considering the current political and societal discussion with regard to climate change and the reduced use of fossil resources, they are of significant relevance. This applies particularly to the impact Global Warming and Resource Depletion.

The impacts were calculated with the software SimaPro 8.0, using the scientifically robust and inter-nationally recognized LCIA method CML (version 4.2 as implemented in SimaPro).

3 Process description and Life Cycle Inventory

This chapter describes the processes and data on which the environmental and economic assessment is based. The system level is discussed first, which encompasses the processes from the pre-sowing activities up to the baled hemp fibres. The product level describes the processing from the hemp fibres into final products.

3.1 System level

The following section describes the data for the system level, with different data for different scenarios. The data is generally split into the stages cultivation, harvest, transport and processing. As an example, the conventional hemp processing is shown in Figure 4.

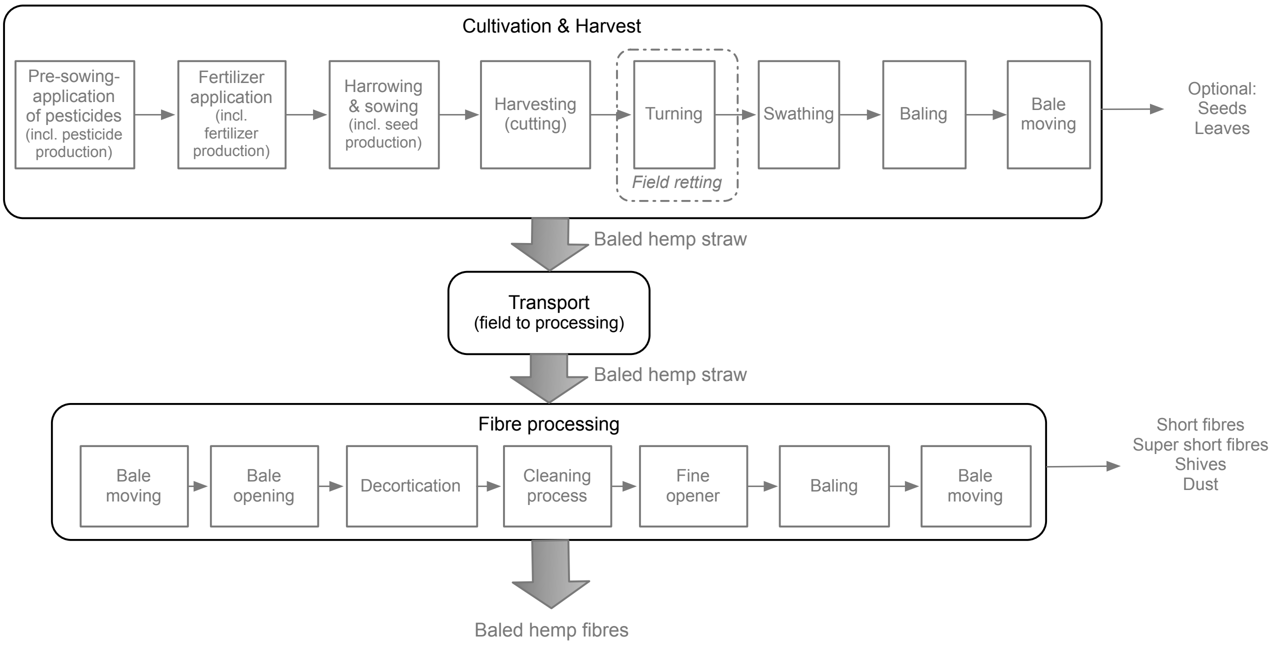

Figure 4: Detailed depiction of the system level

Apart from the original field trial data, especially the KTBL database (www.ktbl.de), a renowned German institution for the provision of technical and economic agricultural data, was used as a data source for cultivation stage, as well as additional information from project partners.

The costs calculations include all costs of the respective production processes, including fixed and variable costs. The **variable costs** comprise the costs for material inputs, also called direct costs, e.g. seeds, fertilizer and pesticides, the variable machinery costs (costs for fuel, lubricating oil and repair) and the variable labour costs. For all scenarios, we make the assumptions regarding unit prices of variable inputs as shown in Table 1. Regarding the use of lubricating oil, we follow the assumptions by KTBL that it amounts to 1% of diesel use. For the costs of maintenance and repair, we follow the machinery-specific assumptions by KTBL.

Table 1: Unit prices for variable inputs in the cultivation and harvesting scenarios

	Unit	Value
Labour price	€/h	16.00
Fertilizer prices		
P_2O_5	€/kg	1.02
K_2O	€/kg	0.78
N	€/kg	0.95
Pig slurry	€/kg	
Seed price	€/kg	3.00
Price for seed coating (Tyram)	€/kg seeds	1.60
Variable machinery costs		
Diesel price	€/l	1.00
Lubricating oil	€/l	3.00

The labour cost of 16 €/h is the average in the combined sector agriculture, forestry and fishing in the countries Germany, France, Italy and the Netherlands over the period 2006-2015 (Figure 5). It can therefore be regarded to be a representative value for hourly labour cost for agricultural operations.

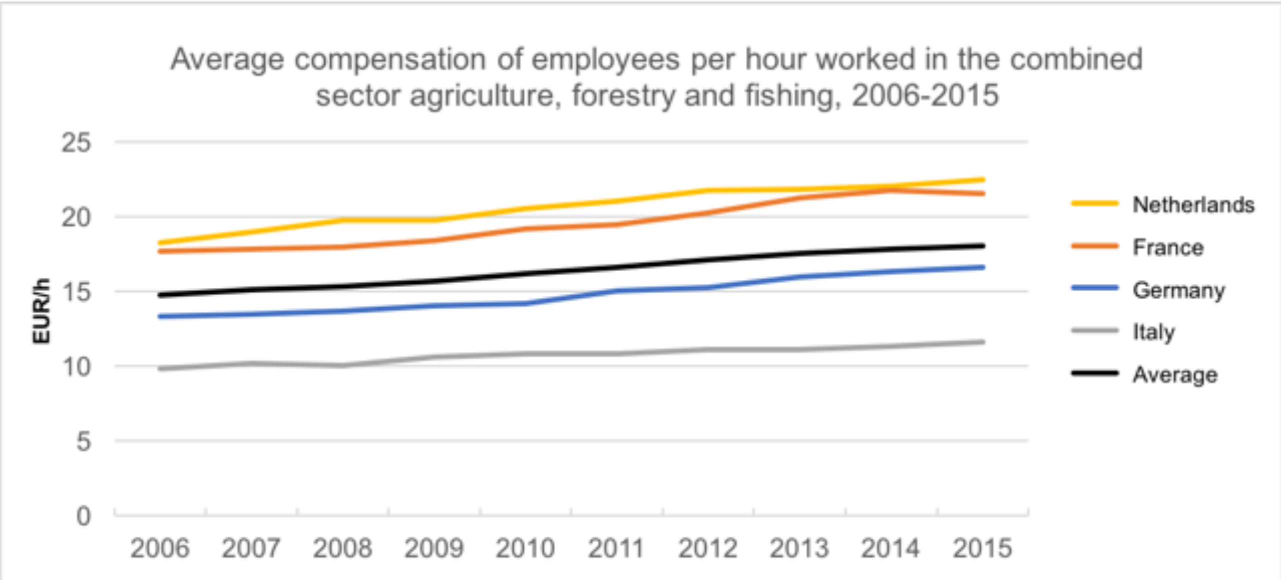

Figure 5: Average compensation of employees per hour worked in the combined sector agriculture, forestry and fishing, 2006-2015
Source: Eurostat 2016, own calculations

As **fixed costs** we account for the costs of land rent (187 €/ha) and the fixed machinery costs. The latter comprise depreciation, interest charges and other fixed costs like insurances and taxes. The former are calculated as the average rent paid per utilised agricultural area (UAA) in Germany, France, the Netherlands and Italy over the period 2009-2013 (Figure 6). This data was taken from the Farm Accountancy Data Network (FADN).

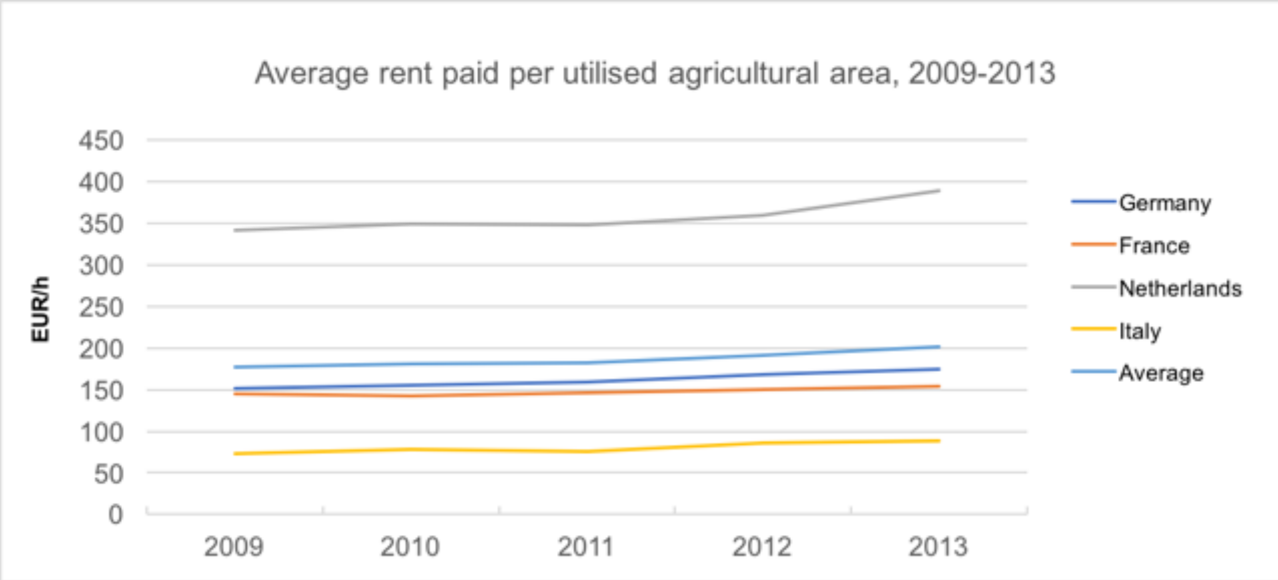

Figure 6: Average rent paid per utilised agricultural area, 2009-2013
Source: FADN 2016, own calculations

The **depreciation** of machinery is calculated as follows. KTBL typically assumes for machinery a capacity utilisation at the threshold between time-dependent depreciation and performance-dependent depreciation. This threshold is calculated by diving the technical utilisation potential of a machinery in hours (n) by the economic utilisation potential in years (N). As an example, if the technical utilisation potential is 10,000 h and the economic utilisation potential 12 years, the threshold, which is then assumed to be the utilisation of the respective machinery per year, is equal to 833 h/a:

$$\frac{10{,}000\ h}{12\ a} = 833\ h/a$$

It is reasonable, not to assume an annual utilisation above this threshold since this implies that the technical potential would be used up before the end of the economic lifetime of a machinery. On the other hand, for specialised machinery, as needed at least for some of the hemp harvesting technologies, it may not be possible to actually use it up to the foreseen annual threshold. In this case, more realistic assumptions have to be made as to the level of utilisation.

Given the capacity utilisation of a machinery in h/a, or ha/a, the annual depreciation is calculated by dividing the initial value of the machinery by this annual capacity utilisation.

The **interest charges** refer the interest foregone due to the capital tied-up in the machinery. The capital that is tied-up in the machinery is reduced annually according to the annual depreciation. The average annual tied-up capital can be calculated by dividing the initial value (*I*) plus the scrap value at the end-of-life (*S*) by 2 and multiplying with the interest rate (*i*):

$$\left(\frac{I+S}{2}\right) * i = Interest\ charge\ in\ €/a$$

For simplicity, we assume for all machinery a scrap value of 1 Euro, which is common practice in the KTBL database. As interest rate, we assume for all scenarios 4% p.a.

Regarding the **other fixed costs**, like insurances and taxes, we are using the pre-set values given in KTBL.

3.1.1 Cultivation

Four different generic cultivation scenarios are developed by using the data collected in the field trials and literature data. In all cultivation scenarios, the same assumptions have been made regarding the cultivation stages of pre-sowing activities, soil preparation and sowing.

The scenarios differ in fertilizer application and yield, the minimum scenario has the lowest fertiliser application and lowest yield. The average scenario has a higher fertiliser application and a higher yield. The maximum scenario applies the most fertiliser and obtains the highest yields. In the fourth scenario, pig slurry is used as organic fertiliser to supply nitrogen to the crops and yields are assumed to be same as in the maximum scenario. The application of seeds will not be modelled within the LCA, since the impacts are negligibly low.

In the following, we describe the inventory data for these cultivation scenarios.

3.1.1.1 Pre-sowing activities

To prepare the field for hemp cultivation, herbicides are used to remove weeds in all four scenarios. It is assumed that glyphosate is used and applied at the rate given in Table 2. The amount of glyphosate use is similar in all four scenarios as the weed growth is at the start of the cultivation, thus the fertiliser rates do not have any influence.

Also for these pesticide applications, we assume the same technology in all cultivation scenarios, i.e. a sprayer, with a working width of 18 m and a tank with a capacity of 1,500 liters, drawn by a tractor of 83 kW power.

Table 2: Calculatory data for pesticide applications

	Unit	All 4 scenarios	Source
Material costs			
Glyphosate (pre-sowing)	kg/ha*a	3	Dun 2014
Price of glyphosate	€/kg	11	Dun 2014
Costs of glyphosate	*€/ha*	*33*	
Labour costs			
Labour demand	h/ha	0.22	KTBL 2015
Labour costs	*€/ha*	*3.52*	
Machinery costs			
Depreciation	€/ha	3.76	KTBL 2015
Interest charges	€/ha	0.81	KTBL 2015
Maintenance and repair	€/ha	2.04	
Diesel	€/ha	1.22	
Lubricating oil	€/ha	0.04	KTBL 2015
Other	€/ha	0.22	KTBL 2015
Total	*€/ha*	*8.09*	
Total costs	***€/ha***	***44.61***	

3.1.1.2 Soil preparation

In all cultivation scenarios, it is assumed, that soil preparation before sowing takes place by using a reversible plough with 6 blades, a working width of 2.1 m, drawn by a standard tractor of 102 kW power. For this system, the KTBL database contains all necessary calculatory data, which is summarized in Table 3. Since this is an established technology, we assume an annual capacity utilisation at the threshold between time-dependent depreciation and performance-dependent depreciation.

Table 3: Calculatory data for soil preparation

	Unit	
Labour costs		
Labour demand	h/ha	1.74
Labour costs	*€/ha*	*27.84*
Machinery costs		
Depreciation	€/ha	25.25
Interest charges	€/ha	4.82
Maintenance and repair	€/ha	24.79
Diesel	€/ha	25.40
Lubricating oil	€/ha	0.76
Other	€/ha	1.57
Total	*€/ha*	*82.59*
Total costs	***€/ha***	***110.43***

3.1.1.3 Sowing

Also for the sowing, we assume the same technology in all cultivation scenarios, i.e. a sowing machine with rotary harrow with a working width of 6 m, drawn by a tractor with 140 kW power. The following Table 4 shows the respective data as extracted from KTBL.

Table 4: Calculatory data for sowing

	Unit	All 4 scenarios	Source
Seed costs			
Sowing rate	kg/ha*a	48.00	Amaducci 2014
Seed success rate (incl. self-thinning)	%	90.00	Amaducci 2014
Resulting cultivation density	Mln plants/ha	2.40	Amaducci 2014
Specific seed weight	g/1000 seeds	18.00	Amaducci 2014
Seed price	€/kg	3.00	Beherec 2014
Seed coating (Tyram)	g/kg seeds	1.60	Heusele 2014
Seed costs	*€/ha*	*144.00*	
Labour costs			
Labour demand	h/ha	0.79	KTBL 2015
Labour costs	*€/ha*	*12.64*	
Machinery costs			
Depreciation	€/ha	25.19	KTBL 2015
Interest charges	€/ha	5.51	KTBL 2015
Maintenance and repair	€/ha	16.45	KTBL 2015
Diesel	€/ha	15.05	KTBL 2015
Lubricating oil	€/ha	0.45	KTBL 2015
Other	€/ha	0.41	KTBL 2015
Total	*€/ha*	*63.06*	
Total costs	***€/ha***	***219.70***	

3.1.1.4 Fertilizer applications

Since fertilizer, and especially nitrogen, is considered to be one of the most important inputs in cultivation, we define three cultivation scenarios with increasing levels of mineral fertilizer applications as well as one scenario with the application of pig slurry. The assumptions regarding the amount of fertilizer applied and the corresponding stem yields are shown in Table 5.

Table 5: Fertilizer data and corresponding stem yield of the four cultivation scenarios

		Min.	Av.	Max.	Pig slurry	Source
Fertilizers						
Nitrogen input	kg N/ha	30	60	120	n.a.	Multihemp
Nitrogen price	€/kg N	0.95	0.95	0.95	–	nova 2015
Phosphorous (P_2O_5)	kg P_2O_5/ha	30	40	60	n.a.	nova 2015
Phosphorous price (P_2O_5)	€/kg P_2O_5	1.02	1.02	1.02	–	nova 2015
Potassium (K_2O)	kg K_2O /ha	100	130	160	n.a.	nova 2015
Potassium price (K_2O)	€/kg K_2O	0.78	0.78	0.78	–	nova 2015
Pig slurry	m^3/ha	n.a.	n.a.	n.a.	27.6	Dun 2014
Pig slurry costs	€/m^3	–	–	–	3	Dun 2014
Pig slurry transportation distance (from pig-farm to the field)	km	–	–	–	100	nova 2015
Fertilizer costs	***€/ha***	***137.1***	***199.2***	***300.0***	***82.8***	derived from sources above
Stem yield						
Fresh matter yield (40% moisture)	tfm/ha*a	13.3	14.5	16.0	16.0	Based on UCSC 2017
Retted stem yield (15% moisture)	t/ha*a	9.4	10.2	11.3	11.3	Based on UCSC 2017
Dry matter yield (0% moisture)	tdm/ha*a	8.0	8.7	9.6	9.6	Based on UCSC 2017

We assume that fertilizer is either applied in a combined NPK dry-bulk application or as an organic fertilizer. The basis for the fertilizer and yield combinations were field trials at different European locations (see Figure 7). From these trials, a polynomial function has been derived over all locations in order to determine average yields at nitrogen fertilizer levels of 30, 60 and 120 kg/ha. Since the phosphorus and potassium application rates were not known, assumptions have been made based on expert estimation.

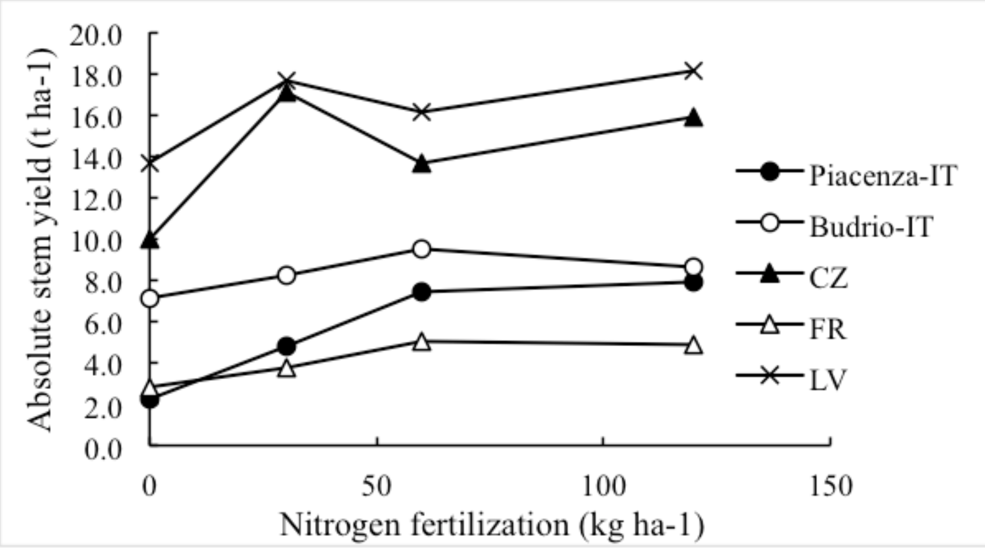

Figure 7: N-fertilization rates and stem yields in MultiHemp field trials
Source: nova 2017 based on UCSC 2017

For the minimum scenario, the assumptions result in a nitrogen fertiliser application of 30 kg N/ha, phosphorus application of 30 kg P_2O_5/ha and potassium of 100 kg K_2O/ha. The final stem yield in the minimum scenario is 8.0 tdm straw/ha. The average scenario has the following fertilisation rates: 60 kg N/ha, 40 kg P_2O_5/ha and 130 kg K_2O/ha. The stem yield in this scenario is 8.7 tdm straw/ha. For the maximum scenario, nitrogen is applied at a rate of 120 kg N/ha and phosphorus and potassium are applied at rates of 60 kg P_2O_5/ha 160 kg K_2O /ha. The yield in the maximum scenario is 9.6 tdm straw/ha.

In the pig slurry scenario, we assume that pig slurry is used as an organic fertilizer instead of mineral fertilizer. This scenario is assessed due to the fact, that hemp tolerates organic fertilization and especially in the North of the Netherlands there are manure surpluses to be turned into organic fertilizers. Based on average nutrient contents (Landwirtschaftskammer NRW 2014), an application of 23 m^3 pig slurry will lead to average nutrients of 125 kg N/ha, 65 kg P_2O_5/ha and 90 kg K_2O/ha. Despite the fact that there is a difference in fertilisation rates between the pig slurry scenario and the maximum mineral fertilizer scenario, we neglect these differences and assume the same achievable stem yield for both scenarios. Contrary to mineral fertiliser, nitrogen in pig slurry can be organically bound (Gutser et al. 2005). This means that it must be mineralised before it can be assimilated by the plants. Sánchez and González (2005) point out that the high urea content of pig slurry results in rapid decomposition into ammoniacal nitrogen which is more prone to volatilisation. They measured that the inorganic ammonia was roughly 75% of the total nitrogen and mainly present as ammoniacal nitrogen. Nemecek and Käagi (2007) report that between 56-84% of the total N in pig slurry is in TAN form.

For the application of mineral fertilizer, we assume a mounted centrifugal spreader with a capacity of 1.5 m^3, drawn by a tractor of 83 kW. For the pig slurry scenario, we assume a slurry tank with 24

m^3 capacity, a working width of 18 m, drawn by a tractor of 160 kW. The complete cost data for fertilizer applications are shown in Table 6.

Table 6: Calculatory data for fertilizer applications

	Unit	Min.	Av.	Max.	Pig slurry scenario
Fertilizer costs (see calculation above)	€/ha	*137.1*	*199.2*	*300.0*	*82.8*
Labour costs					
Labour demand	h/ha	0.15	0.15	0.15	0.50
Labour costs	*€/ha*	*2.40*	*2.40*	*2.40*	*8.00*
Machinery costs					
Depreciation	€/ha	1.03	1.03	1.03	21.66
Interest charges	€/ha	0.25	0.25	0.25	4.65
Maintenance and repair	€/ha	1.02	1.02	1.02	15.47
Diesel	€/ha	0.85	0.85	0.85	6.00
Lubricating oil	€/ha	0.03	0.03	0.03	0.18
Other	€/ha	0.08	0.08	0.08	0.31
Total	*€/ha*	*3.26*	*3.26*	*3.26*	*48.15*
Total costs	***€/ha***	***142.76***	***204.86***	***305.66***	***139.07***

Since the application of fertiliser results in additional emissions associated with the fertilizer, these have to be taken into account. For more details on the estimation of fertilizer induced field emissions, see Appendix I. The results of the estimations can be found in the Table 7 below.

Table 7. Estimated field emissions for the fertilizer scenarios

	Minimum	Average	Maximum	Pig slurry	Unit	Eq. (Appendix 1)
NH_3	1.70	3.39	6.79	12.93	kg NH_3/ha	Eq. 3
NO_x	0.78	1.56	3.12	3.25	kg NO_x/ha	Eq. 5
N_2O total	0.80	1.59	3.18	3.37	kg N_2O/ha	Eq. 6
NO_3 (leaching)	39.86	79.71	159.43	166.07	kg NO_3/ha	Eq. 4
PO_4 total	0.79	0.80	0.83	0.84	kg PO_4/ha	Eq. 7
CO_2 (from NH_3)	7.98	15.97	31.94	49.27	kg CO_2/ha	Eq. 8

3.1.1.5 Summary

Table 8 below compares the total costs of cultivation, excluding the harvest, for the four cultivation scenarios per hectare as well as per tonne of dry retted stem. The results show, first, that the high fertilizer costs in the maximum scenario lead to the highest cultivation costs per hectare, which is only partly offset by the high yield of 9.6 tdm/ha. Second, the results show that from all cultivation scenarios, the pig slurry scenario leads to the lowest costs per tonne dry matter.

Table 8: Total cultivation costs (excl. harvesting) for the four scenarios
Source: nova 2015

		Min.	Av.	Max.	Pig slurry
Soil preparation	€/ha	110.43	110.43	110.43	110.43
Sowing	€/ha	219.70	219.70	219.70	219.70
Pesticide applications	€/ha	44.61	44.61	44.61	44.61
Fertilizer applications	€/ha	142.76	204.86	305.66	139.07
Land rent	€/ha	187.00	187.00	187.00	187.00
Total cultivation costs (excl. harvest)					
Per hectare	***€/ha***	***704.50***	***766.60***	***867.40***	***700.81***
Per tonne dry, retted stem	***€/tdm***	***88.06***	***88.11***	***90.35***	***73.00***

The following Table 9 shows in more detail the diesel consumption for the field operations (excluding the harvesting operations). It is assumed that despite different mineral fertilizer applications, the field operations and especially the fuel use is in the same range. Since the pig slurry is diluted (and thus also weighs more), more fuel is required to spread the fertilizer over the cultivation area.

Table 9: Fuel use for field operations (excl. harvest) divided into the application of mineral and organic (pig slurry) fertilizers

		Mineral fertilizer scenarios	Pig slurry	Data source
Fuel use for field operations				
Soil preparation (Reversible plough with 6 blades, working width: 2.1 m; 102 kW)	l/ha*a	25.4	25.4	KTBL 2015
Sowing (Sowing machine with rotary harrow, working width: 6 m; 140 kW)	l/ha*a	15.05	15.05	KTBL 2015
Pesticide applications (Sprayer, working width: 18 m, 1.500 litre; 83 kW)	l/ha*a	1.22	1.22	KTBL 2015
Fertilizer applications (For mineral fertilizer: Fertilizer spreader, 1.5 m^3; 83 kW For pig slurry: Slurry tank with 24 m^3; working width: 18 m; 160 kW)	l/ha*a	0.85	6	KTBL 2015

3.1.2 Harvest

In this section, we report about the inventory data for the different harvesting technologies, state of the art and developed ones in MultiHemp. In the case of hemp, the harvesting stage includes all processes from the cutting and swathing to various cycles of turning as well as baling.

Several different harvesting systems have been researched in the Multihemp project. These include the reference system of a single harvest for straw, harvest of straw and leaves and harvest of straw and seeds. In the scope of MultiHemp, several other harvesting systems have also been reseached and/or developed, however due to lack of data or further processing possibilities of these harvesting techniques, these systems are not included in the enviornmental assessment. Nevertheless, the machines and data will be discussed briefly.

3.1.2.1 Harvest of straw

Using a modified maize chopper based on the principle of the “one-knife cutting drum” (e.g. the HempCut (Figure 8) which cuts the hemp stems into lengths of 60-80 cm and puts the stems in disordered swaths) can be characterised to be the most common technology of harvesting only hemp stalks in Europe. Purchase costs of such a field chopper amount to about 300,000 € and, according to KTBL, the technical utilisation potential is 3,000 h and the economic utilisation potential 10 years. Since the HempCut is basically a standard field chopper which could also be used for the harvest of silage maize, we assume an actual annual utilisation at the threshold, i.e. 300 h/a.

We therefore use the data as reported in Table 10 which is based on information provided by Frank 2015 as well as based on KTBL 2015. As above, these costs are calculated based on a diesel price of 1 €/litre and an hourly labour costs of 16 €/hour.

Regarding the further operations of turning, swathing and baling, we are using for all cultivation scenarios the KTBL data as specified in Table 10, taking into account slightly higher labour and diesel demand for the baling in the maximum and pig slurry scenarios, due to the high amount of straw.

Again, a more detailed view on the diesel use for this harvesting system is shown in Table 11.

Figure 8: Harvesting system HempCut 3000/4500
Source: Pari 2013

Table 10: Data to be used for the most common one-knife cutting drum harvesting technology

	Unit	Min.	Av.	Max. & Pig Slurry	Source
Cutting					
Labour costs					
Labour demand	h/ha	1.20	1.27	1.36	Frank 2015
Labour costs	*€/ha*	*19.20*	*20.32*	*21.76*	
Machinery costs					
Depreciation	€/ha	120.00	127.00	136.00	
Interest charges	€/ha	24.00	25.40	27.20	
Maintenance and repair	€/ha	15.00	24.00	31.17	
Diesel	€/ha	22.00	23.75	26.00	
Lubricating oil	€/ha	0.66	0.71	0.78	
Other	€/ha	2.26	3.62	4.70	
Total Machinery costs	€/ha	*183.92*	*204.48*	*225.85*	
Costs for cutting	***€/ha***	***203.12***	***224.80***	***247.61***	
Turning Twice turning with rotary tedder, working width: 7.5 m; 67 kW					
Labour costs					
Labour demand	h/ha	0.64	0.64	0.64	Frank 2015
Labour costs	*€/ha*	*10.24*	*10.24*	*10.24*	
Machinery costs					
Depreciation	€/ha	6.00	6.00	6.00	
Interest charges	€/ha	1.34	1.34	1.34	
Maintenance and repair	€/ha	7.46	7.46	7.46	

Diesel	€/ha	5.98	5.98	5.98	
Lubricating oil	€/ha	0.18	0.18	0.18	
Other	€/ha	0.24	0.24	0.24	
Total Machinery costs	€/ha	*21.20*	*21.20*	*21.20*	
Costs for turning	***€/ha***	***31.44***	***31.44***	***31.44***	
Swathing One time swathing with dual-rotor swather (central), working width: 7.5 m, 67 kW					
Labour costs					
Labour demand	h/ha	0.32	0.32	0.32	
Labour costs	*€/ha*	*5.12*	*5.12*	*5.12*	
Machinery costs					
Depreciation	€/ha	4.54	4.54	4.54	
Interest charges	€/ha	0.98	0.98	0.98	
Maintenance and repair	€/ha	4.38	4.38	4.38	
Diesel	€/ha	3.27	3.27	3.27	
Lubricating oil	€/ha	0.10	0.10	0.10	
Other	€/ha	0.12	0.12	0.12	
Total Machinery costs	*€/ha*	*13.39*	*13.39*	*13.39*	
Costs for swathing	***€/ha***	***18.51***	***18.51***	***18.51***	
Baling Square bales 1.2x0.7x2.2m; approx. 305 kg/bales; 83 kW					
Labour costs					
Labour demand	h/ha	0.69	0.69	0.70	
Labour costs	*€/ha*	*11.04*	*11.04*	*11.20*	
Machinery costs					
Depreciation	€/ha	32.30	32.30	32.30	
Interest charges	€/ha	5.55	5.55	5.55	
Maintenance and repair	€/ha	18.61	18.61	18.61	
Diesel	€/ha	5.15	5.92	6.70	
Lubricating oil	€/ha	0.15	0.18	0.20	
Other	€/ha	0.37	0.37	0.37	
Total Machinery costs	*€/ha*	*62.13*	*62.93*	*63.73*	
Costs for baling	***€/ha***	***73.17***	***73.97***	***74.93***	
Total harvesting costs					
Per hectare	***€/ha***	***326.24***	***348.72***	***372.49***	
Per tonne dry, retted stem	***€/tdm***	***40.78***	***40.08***	***38.80***	

Table 11: Fuel use for the one-knife cutting drum harvesting technology

	Unit	Min.	Av.	Max. & Pig Slurry	Data source
Cutting					
Diesel use	l/ha	22.00	23.75	26.00	Frank 2015
Turning Twice turning with rotary tedder, working width: 7.5 m; 67 kW					
Diesel use	l/ha	5.98	5.98	5.98	KTBL 2015
Swathing One time swathing with dual-rotor swather (central), working width: 7.5 m, 67 kW					
Diesel use	l/ha	3.27	3.27	3.27	KTBL 2015
Baling Square bales 1.2x0.7x2.2m; approx. 305 kg/bales; 83 kW					
Diesel use	l/ha	5.15	5.92	6.70	KTBL 2015

In the following variations of this common technology, mainly the type of cutting is varied. For those harvesting technologies which also produce disordered swaths of stems, the same procedures for swathing, turning and baling have been assumed as in this standard scenario.

3.1.2.2 Harvest of straw and leaves

Harvest of leaves in addition to straw allows for the extraction of Cannabidiol (CBD) from the leaves. In recent years, interest in CBD has increased due to potential wide application in pharmaceuticals and food supplements.

By project partner DunA, a variant of the one-knife cutting drum technology has been applied in which a combine harvester (Xerion 4000) with an additional stripper has been used to cut the straw and rip the leaves at the same time (Figure 9). Purchase costs of for this machinery amount to about 600,000 €. Due to the fact that the Xerion is a system tractor, which can be used for many different purposes, we assume for the base case a technical utilisation potential of 10,000 h and an economic utilisation potential of 12 years. This results, in an optimal situation, in an annual utilisation of 833 hours. This higher annual utilisation potential compared to the HempCut system has important economic implications, which will be further discussed in section 4.1.1.1.

Figure 9: Impression of the harvest with a Xerion 4000 (DunA, 2014)
Source: DunA 2014

In order to directly compare the impacts of this harvesting technology we assume that all other cultivation operations take place as in the standard scenario except the cutting (see Table 12 and Table 13).

Table 12: Cost data to be used for the harvesting technology for straw and leaves (Xerion 4000)

	Unit	Min.	Av.	Max. & Pig Slurry	Source
Cutting					
Labour costs					
Labour demand	h/ha	1.00	1.07	1.16	Based on Dun 2014 & 2015
Labour costs	*€/ha*	*16.00*	*17.12*	*18.56*	
Machinery costs					
Depreciation	€/ha	60.00	64.20	69.60	
Interest charges	€/ha	14.40	15.41	16.70	
Maintenance and repair	€/ha	15.00	24.00	31.17	
Diesel	€/ha	23.00	24.75	27.00	
Lubricating oil	€/ha	0.69	0.74	0.81	
Other	€/ha	2.26	3.62	4.70	
Total Machinery costs	*€/ha*	*115.35*	*132.72*	*149.98*	
Costs for cutting	***€/ha***	***131.35***	***149.84***	***168.54***	
Costs for turning	***€/ha***	***31.44***	***31.44***	***31.44***	
Costs for swathing	***€/ha***	***18.51***	***18.51***	***18.51***	
Costs for baling	***€/ha***	***73.17***	***73.97***	***74.93***	
Total harvesting costs					

Per hectare	***€/ha***	***254.47***	***273.76***	***293.42***	
Per tonne dry, retted stem	***€/tdm***	***31.81***	***31.47***	***30.56***	

Table 13: Fuel use for the harvesting technology for straw and leaves (Xerion 4000)

	Unit	Min.	Av.	Max. & Pig Slurry	Data source
Cutting					
Diesel use	l/ha	23.00	24.75	27.00	Based on Dun 2014 & 2015
Turning Twice turning with rotary tedder, working width: 7.5 m; 67 kW					
Diesel use	l/ha	5.98	5.98	5.98	KTBL 2015
Swathing One time swathing with dual-rotor swather (central), working width: 7.5 m, 67 kW					
Diesel use	l/ha	3.27	3.27	3.27	KTBL 2015
Baling Square bales 1.2x0.7x2.2m; approx. 305 kg/bales; 83 kW					
Diesel use	l/ha	5.15	5.92	6.70	KTBL 2015

According to the data provided by DunA, the harvest of leaves from the field trials of 2014 amounted to 0.37 kg/kg straw for the variety Bialobrzeskie and 0.48 kg/kg straw for Futura.

Based on these field trials we assume that the average leave yield, compared to the straw yield, is 0.4 kg leaves/kg straw. The hemp leaves contain large amounts of moisture, around 65%. The comparison between leave and straw ratio has to be adjusted since the leaves yield is independent of the straw yield. We calculate the yield of leaves by applying the yield ratio on the average cultivation scenario and using this yield for all scenarios. This resulted in a leave yield of roughly 1.4 tdm leaves/ha, which is in line with expert estimates (Frank 2017). Furthermore, we assume that the straw yield using this technology is the same as for the standard harvesting technology.

3.1.2.3 Harvest of straw and seeds

This scenario considers a dual use harvesting of straw and seeds as performed by project partner PlanC, using a combine harvester with a Kemper header. This system, also referred as the Total Harvester, can be considered to be the standard technology for the harvest of seeds and straw in Europe, with long-time record of experience and improvements (Mastel und Stolzenburg 2002).

Purchase costs for this machinery amount to about 300,000 € and, since it is likely that the capacity of such a combine could be sufficiently utilised also for the harvest of other crops, we make the same assumptions as for the HempCut and the Xerion systems, resulting in an annual utilisation of 300 h. The data on labour and diesel demand shown in Table 14 are based on information provided by Frank 2015. Again, the field operations following the cutting (swathing, turning, baling) are considered to be the same as in the standard scenario.

According to data provided by Frank, the average commercial yields for dual purpose hemp (straw and seeds) within Europe is 1 tdm/ha seeds and 6.5-7 tdm/ha straw. In the scope of MultiHemp, field trials have been performed in order to establish the seed and straw harvest. These field trials resulted in similar seed yields, but higher straw yields compared to the commercial average. Based on this knowledge, we have assumed a seed yield of 1 tdm/ha for all cultivation scenarios with a dual harvest of straw and seeds. While the straw yield can be expected to be the same as in a single use system, its shives content after processing will be about 10% lower according to expert estimates.

Table 14: Data to be used for the harvesting technology for straw and seeds

	Unit	Min.	Av.	Max. & Pig Slurry	Source
Cutting					
Labour costs					
Labour demand	h/ha	1.40	1.47	1.56	Frank 2015
Labour costs	*€/ha*	*22.40*	*23.52*	*24.96*	
Machinery costs					
Depreciation	€/ha	140.00	147.00	156.00	
Interest charges	€/ha	28.00	29.40	31.20	
Maintenance and repair	€/ha	15.00	24.00	31.17	
Diesel	€/ha	25.00	26.75	29.00	Frank 2015
Lubricating oil	€/ha	0.75	0.80	0.87	
Other	€/ha	2.26	3.62	4.70	
Total Machinery costs	*€/ha*	*211.01*	*231.57*	*252.94*	
Costs for cutting	***€/ha***	***233.41***	***255.09***	***277.90***	
Costs for turning	***€/ha***	***31.44***	***31.44***	***31.44***	
Costs for swathing	***€/ha***	***18.51***	***18.51***	***18.51***	
Costs for baling	***€/ha***	***73.17***	***73.97***	***74.93***	
Total harvesting costs					
Per hectare	***€/ha***	**356.53**	**379.01**	**402.78**	
Per tonne dry, retted stem	***€/t***	**44.57**	**43.56**	**41.96**	

Table 15: Fuel use for the harvesting technology for seed and straw

	Unit	Min.	Av.	Max. & Pig Slurry	Data source
Cutting					
Diesel use	l/ha	25.00	26.75	29.00	Frank 2015
Turning Twice turning with rotary tedder, working width: 7.5 m; 67 kW					
Diesel use	l/ha	5.98	5.98	5.98	KTBL 2015
Swathing One time swathing with dual-rotor swather (central), working width: 7.5 m, 67 kW					
Diesel use	l/ha	3.27	3.27	3.27	KTBL 2015
Baling Square bales 1.2x0.7x2.2m; approx. 305 kg/bales; 83 kW					
Diesel use	l/ha	4.61	5.27	5.92	KTBL 2015

3.1.2.4 Other harvesting technologies

In the scope of MultiHemp, some other agricultural machinery have been developed and these are briefly discussed in this chapter. Project partner ATB has developed a harvesting technology to harvest the straw, seeds and threshing residues. However, field trials for this machine proved to be difficult and unfortunately insufficient data was gathered on the harvest, and further processing, of the threshing residues. During the project, a different harvesting technique called the longitudinal harvest has also been developed. However, due to poor weather conditions during the field trials, insuffucient data was available to make a reliable assessment of the environmental impacts of this technique. Furthermroe, harvesting of wet silage bales has been investigated. For this technique, the final application was unclear, thus it was also excluded from the final environmental and techno-economic assessment.

3.1.3 Processing

After the cultivation process, the fibres are transported to the fibre processor. For the transportation from the field to the processing facility, we have assumed for all scenarios that it would be done by a lorry (EURO5) and that the distance from field to processing facility would be 60 kilometres (roundtrip). Given the assumption of an average speed of 50 km/h as well as 0.5 h each for loading and unloading the lorry and transportation capacity of 9 t retted stem, the labour demand for the transportation amounts to 0.24 h or about 4.9 € per tonne or retted stem, given the wage rate of 16 €/t. Furthermore, given an assumed diesel consumption of the lorry of 6 l/100 km, diesel demand amounts to 0.4 l or 0.4 € per tonne retted stem, given a diesel price of 1 €/l.

Due to the different biomass output per hectare in different cultivation and harvesting scenarios, transportation costs still differs substantially, as shown in Table 16.

Table 16: Transportation costs from field to processing facility

	Unit	Min.	Av.	Max. & Pig Slurry
Harvest of straw	€/ha	25.01	37.33	49.65
Harvest of straw and leaves	€/ha	25.01	37.33	49.65
Harvest of straw and seeds	€/ha	18.67	31.11	43.56

3.1.3.1 Total fibre line

While the cultivation and harvesting both follow a similar methodology, which builds mainly on the KTBL system of cost calculations, the calculation of the processing stage mainly uses the FibreCalc spreadsheet, at least for those technologies which involve the processing of straw into technical fibres, which has been developed by nova-Institute in 2007 and has been applied since in many projects on the evaluation of fibre processing plants (e.g. Pauls und Carus 2008, Dammer et al. 2008, Piotrowski and Carus 2011). This spreadsheet allows the definition of about 70 entry parameters.

In the following, we describe the technologies for the processing of hemp straw and propose the data and yields to be used for the techno-economic assessment and the LCA.

According to Essel 2013, the processing capacity of a large total fibre line can be considered to be about 4 t/h of straw. Total electricity consumption amounts to about 300 kWh/t fibre and total diesel consumption to 1.6 l/t fibre. These values as reported in Essel 2013 were mainly based on the processing plant installed in the UK by the company HempTechnology. The total electricity consumption can be divided into approx. 240 kWh/t fibre (80%) for the decortication and 60 kWh/t fibre (20%) for the fine opening and cleaning (Frank 2015). The average material flow in the total fibre line is shown in Figure 10.

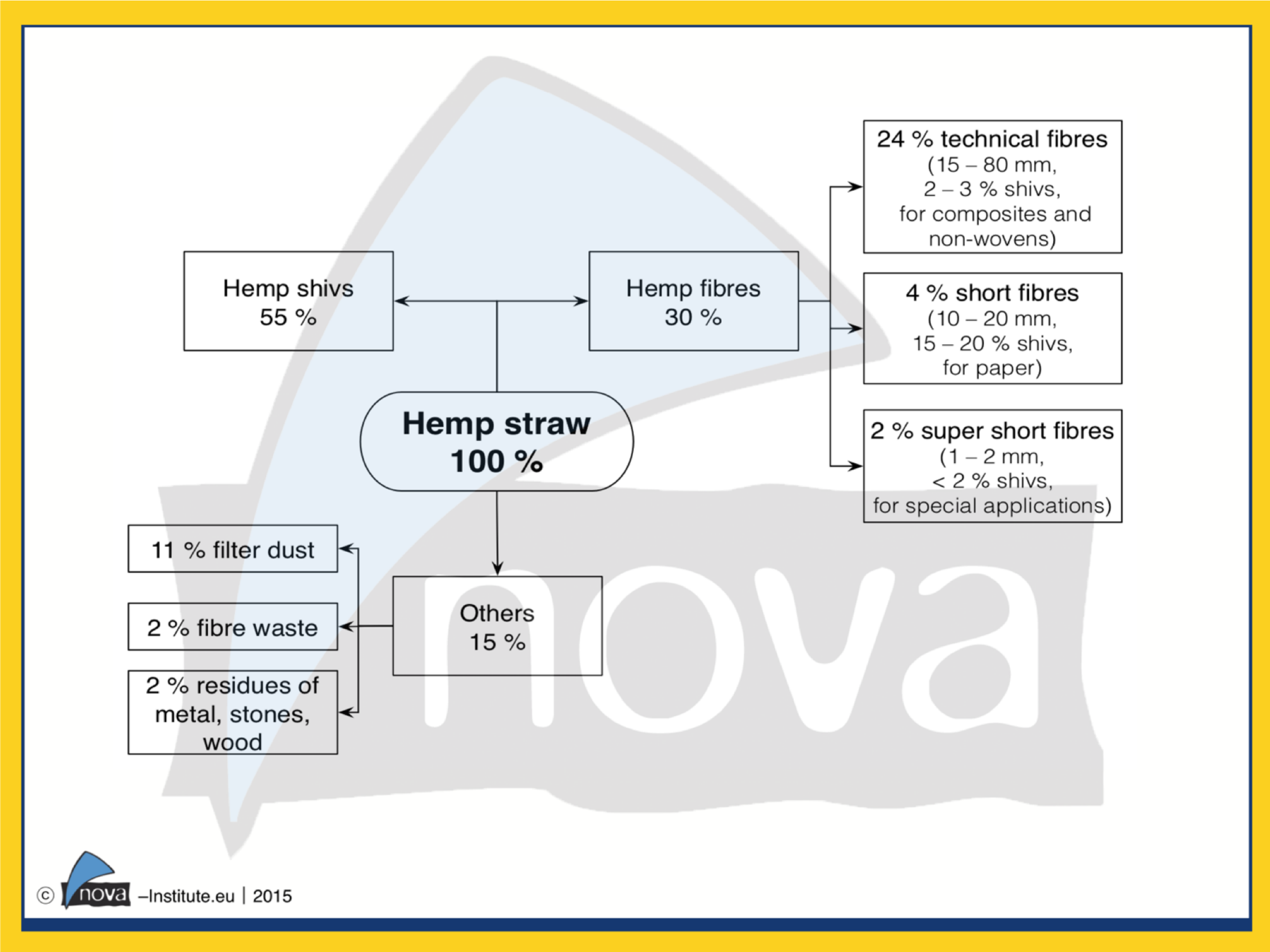

Figure 10: Average material flow in the total fibre line
Source: nova 2015

Table 17 shows the FibreCalc spreadsheet with an overview of all calculation data to be used for a large total fibre line as well as, for a sensitivity analysis, the data of a small total fibre line. This exemplary calculation has been made for a price for the straw of 130 €/t, which is a typical price currently paid in Europe.

The calculation shows that, given today's input costs and product prices, both the small and the large plant could operate profitably but the larger one would clearly be preferable due to economies of scale (Table 17). According to Carus et al. 2013, the price range for hemp fibres in 2013 was from about 500 €/t for the cigarette paper industry (ca. 25% shiv content) to around 750 €/t for the automotive and insulation industry (2-3% shiv content). According to Frank 2015, ex factory prices for technical fibres for composites in the automotive industry were around 700-720 €/t and for technical fibres for insulation material 630-650 €/t in 2015. For the calculation shown Table 17, we assumed a price for the **technical fibres** of 700 €/t. Also according to Frank 2015, the price for **short fibres** for the paper industry can be assumed to be 300 €/t. Regarding the super short fibres, price depend a lot on the customers. According to Frank 2015, prices can go up to 600 €/t for special applications. For the present calculation, however, we assume a more moderate price of 400 €/t. The price for **shives** may vary between 230-250 €/t if sold loose to 350 €/t if sold packaged. For our calculation, which includes the packaging, we assume a price of 300 €/t. Finally, the price for the filter **dust** may range between 30 €/t if sold loose to 150 €/t if sold as heating briquettes. Since our calculation does not include the briquetting, we assume that the dust could be sold for a price of 40 €/t.

Table 17: Data to be used for the reference hemp fibre processing (small and large plant)
Source: nova 2015

Investment and financing	***Unit***	***Small plant***	***Large plant***
1. Investments			
All movable assets (machinery, vehicles, other equipments)	€	2,580,000.00	4,800,000.00
Buildings			
Space for production facility in m^2	m^2	700.00	1,000.00
Storage space in m^2	m^2	1,000.00	2,000.00
Administration building in m^2	m^2	0.00	0.00
Construction costs in €/m^2	€/m^2	280.00	280.00
Total investment buildings	€	476,000.00	840,000.00
Floor space			
Floor space required in m^2	m^2	5,000.00	10,000.00
Price in €/m^2	€/m^2	25.00	25.00
Total investment floor space		125,000.00	250,000.00
Total investment	**€**	***3,181,000.00***	***5,890,000.00***
2. Useful life of movable assets and buildings			
Movable assets	Years	10.00	10.00
Buildings	Years	30.00	30.00
3. Depreciation of movable assets and buildings			
Movable assets	€/a	258,000.00	480,000.00
Buildings	€/a	15,866.67	28,000.00
4. Financing			
Total investment		***3,181,000.00***	***5,890,000.00***
Capital owned respectively venture capital	€	1,590,500.00	2,945,000.00
Investment subsidy (if applicable)	€	0.00	0.00
Regional investment grants	€	0.00	0.00
Loan	€	1,590,500.00	2,945,000.00
Imputed interest rate for the capital owned	%	4.00	4.00
Duration of Loan in years	Years	10.00	10.00
Effective interest rate in %	%	7.00	7.00
Payment rate per annum		12.00	12.00
Monthly interest and repayment costs	€/month	18,467.05	34,193.95
Annual interest and repayment costs	€/a	221,604.64	410,327.37

Process capacity and output	***Unit***	***Small plant***	***Large plant***
1. Capacity of the process	**kg/h**	1,500.00	4,000.00
2. Effective running time	**%**	90.00	80.00
3. Raw material costs incl. transport costs	**€/kg**	0.13	0.13
4. Nominal realizable yield			
Technical fibres	%	24.00	24.00
Short fibres	%	4.00	4.00
Super short fibres	%	2.00	2.00
Shives	%	55.00	55.00
Dust	%	11.00	11.00
5. Output			
Technical fibres	t/a	1,270.08	3,010.56
Short fibres	t/a	211.68	501.76
Super short fibres	t/a	105.84	250.88
Shives	t/a	2,910.60	6,899.20
Dust	t/a	582.12	1,379.84

Operating time and labour costs	*Unit*	*Small plant*	*Large plant*
1. Salaries incl. costs accessory to salaries			
Managing director	€/month	4,500.00	4,500.00
Managing engineer	€/month	3,750.00	3,750.00
Sales manager	€/month		
Office staff + internal logistics	€/month	2,000.00	2,000.00
Agronomist	€/month		
2. Wages (shift work)			
Skilled workers	€/h	24.00	24.00
Number of workers per shift	Workers per shift	1.00	5.00
Unskilled workers	€/h	13.00	13.00
Number of workers per shift	Workers per shift	1.00	1.00
3. Duration of shifts			
Skilled workers	h/shift	8.00	8.00
Unskilled workers	h/shift	8.00	8.00
4. Working weeks per year	Weeks/a	49.00	49.00
5. Number of shifts per week	shifts/week	10.00	10.00
6. Number of shifts per day	shifts/day	2.00	2.00
7. Capacity utilisation	h/a	3,920.00	3,920.00
8. Total labour costs			
Managing director	€/a	54,000.00	54,000.00
Managing engineer	€/a	45,000.00	45,000.00
Sales manager	€/a	0.00	0.00
Office staff + internal logistics	€/a	24,000.00	24,000.00
Agronomist	€/a	0.00	0.00
Skilled workers	€/a	94,080.00	470,400.00
Unskilled workers	€/a	50,960.00	50,960.00
Workers Union	€/a	5,924.22	5,924.22
Total labour costs	**€/a**	**268,040.00**	**644,360.00**

Energy costs	*Unit*	*Small total fibre line*	*Large total fibre line*
1. Electricity			
Constant power	kW	200.00	300.00
Electricity price	€/kWh	0.05	0.05
Electricity costs	€/a	35,280.00	47,040.00
2. Diesel			
Diesel demand	l/t fibre	1.60	1.60
Diesel price	€/l	1.00	1.00
Diesel costs	€/a	4,656.96	11,038.72
3. Total energy costs	**€/a**	**39,936.96**	**58,078.72**

Packaging costs	*Unit*	*Small plant*	*Large plant*
1. Packaging costs (Material)			
Fibres	€/kg	0.001	0.001
Super short fibres	€/kg	0.01	0.01
Shives	€/kg	0.02	0.02
Fibres	€/a	1,481.76	3,512.32
Super short fibres	€/a	1,058.40	2,508.80
Shives	€/a	64,033.20	151,782.40
Total packaging costs	**€/a**	**66,573.36**	**157,803.52**

Feedstock costs	*Unit*	*Small plant*	*Large plant*
1. Hemp straw costs incl. storage and transportation	**€/kg**	0.13	0.13
2. Straw demand	**t/a**	5,292.00	12,544.00
3. Total feedstock costs	**€/a**	**687,960.00**	**1,630,720.00**

Other costs	*Unit*	*Small plant*	*Large plant*
1. Replacement parts & maintenance	**€/a**	44,750.00	89,500.00
2. Insurance	**€/a**	6,112.00	12,224.00
3. Disposal costs	**€/a**	0.00	0.00
4. Other costs	**€/a**	49,140.19	98,280.38
Total other costs	**€/a**	**100,002.19**	**200,004.38**

Cost shares	Unit	Small total fibre line	Large total fibre line
Per year:			
Capital costs	€/a	221,604.64	410,327.37
Depreciation	€/a	273,866.67	508,000.00
Labour costs	€/a	268,040.00	644,360.00
Energy costs	€/a	39,936.96	58,078.72
Packaging costs	€/a	66,573.36	157,803.52
Feedstock costs	€/a	687,960.00	1,630,720.00
Other costs	€/a	100,002.19	200,004.38
Total costs	€/a	**1,657,983.82**	**3,609,293.99**
Per tonne straw:			
Capital costs	€/t straw	41.88	32.71
Depreciation	€/t straw	51.75	40.50
Labour costs	€/t straw	50.65	51.37
Energy costs	€/t straw	7.55	4.63
Packaging costs	€/t straw	12.58	12.58
Feedstock costs	€/t straw	130.00	130.00
Other costs	€/t straw	18.90	15.94
Total costs	€/t straw	**313.30**	**287.73**
Per ha:			
Capital costs	€/ha	335.00	620.30
Depreciation	€/ha	414.01	767.95
Labour costs	€/ha	405.20	974.09
Energy costs	€/ha	60.37	87.80
Packaging costs	€/ha	100.64	238.55
Feedstock costs	€/ha	1,040.00	2,465.19
Other costs	€/ha	151.17	302.35
Total costs	€/ha	**2,506.40**	**5,456.23**

Revenues, profits or losses	Unit	Small total fibre line	Large total fibre line
1. Market prices			
Technical fibres	€/kg	0.70	0.70
Short fibres	€/kg	0.30	0.30
Super short fibres	€/kg	0.40	0.40
Shives	€/kg	0.30	0.30
Dust	€/kg	0.04	0.04
2. Revenues			
Per year			
Technical fibres	€/a	889,056.00	2,107,392.00
Short fibres	€/a	63,504.00	150,528.00
Super short fibres	€/a	42,336.00	100,352.00
Shives	€/a	873,180.00	2,069,760.00
Dust	€/a	23,284.80	55,193.60
Total Revenues	€/a	**1,891,360.80**	**4,483,225.60**
3. Profits or loss			
Annual profit (target: 10% profit margin)	€/a	233,376.98	873,931.61
Profit margin (target: 10%)	%	12.34%	19.49%
Value added	€/a	996,888.29	2,436,618.98
Value added	€/tdm straw	188.38	194.25
Profit	€/tdm straw	44.10	69.67
Calculatory minimum price for technical fibres for covering costs	€/kg	0.52	0.41
Max. straw price for covering all other costs	€/kg	0.17	0.20

3.1.3.2 Other processing lines

Several other processing lines have been researched during the MultiHemp project. However, data proved to be insufficient for a reliable economic and environmental assessment. These systems include the innovative wet line, the simplified disordered line and the longitudinal line.

The innovative wet line evaluated and demonstrated by the project partner ATB is based on anaerobically stored whole crops and processing into semi-finished or final products like fibre boards. The anaerobically stored whole hemp straw is cominunted in an extruder and then dried. Until the end of the MultiHemp project, a mass and energy balance of the extrusion and drying process has been achieved, but not project data on the further processing into end products was gathered.

In the so-called simplified disordered line, only a decortication takes place but no fine-opening follows. This process therefore produces tow (also called "bulk hemp") which is a mixture of fibres and shives. According to CMF, this raw material is suitable for the bio-building material (see Piotrowski and Barth 2016) which does not require a separation of fibres and shivs. Until the end of project, however, complete data was only available for the production of the CMF panels (see section 3.2.3) from shives, not from "bulk hemp". Therefore, this processing technology was also not included in the final sustainability assessment.

Finally, the longitudinal line, i.e. the processing of the parallel oriented hemp straw, suffered from the difficulties of the harvesting technology as well as the fact that no final high-tech composites with measurable properties could be produced.

3.1.4 Other Fibres

3.1.4.1 Flax fibres

Data for flax fibre production were gathered from flax fibre producers in Middle Europe and complemented with data from the literature. The inventory data used are shown Appendix II. Figure 11 shows the stages in the life cycle of flax fibre production included in this study. Cultivation and harvesting consists of the following stages: pre-sowing application of pesticides, ploughing and harrowing, fertilizer application, sowing, pesticide application, cutting the plants, turning, swathing, baling and bale moving. Lorries transport the baled flax straw. The fibres are processed in a total fibre line, followed by lorry transport of the fibres to the gate of the non-woven producer.

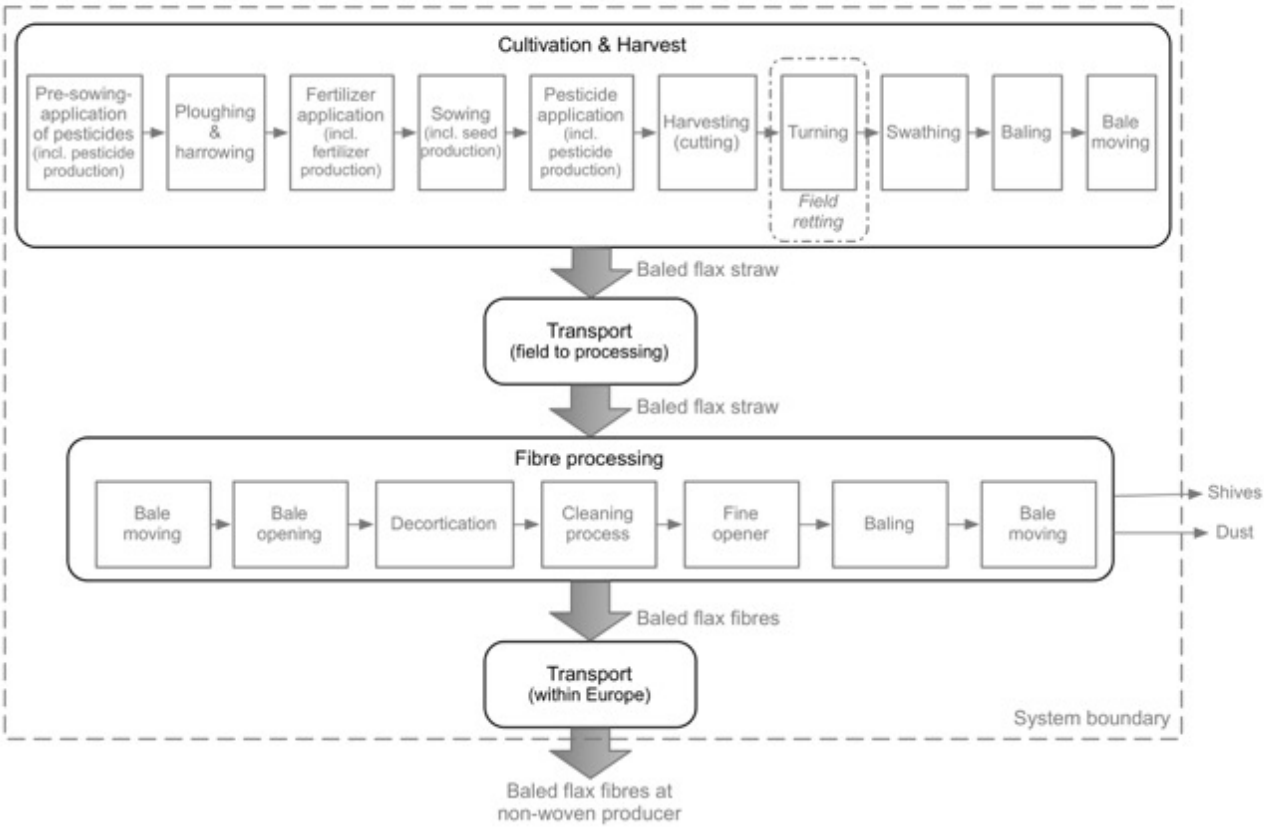

Figure 11: System boundary and process chain of flax fibre production (total fibre line) (nova 2015)

3.1.4.2 Commercial Hemp

The cultivation system for hemp is similar to the flax system, with the following differences: higher application of mineral fertilizer, harrowing and sowing are done in one step and no application of pesticides takes place after sowing. However, pesticide application can take place before sowing as pre-treatment of the field with herbicides. Further process steps are shown in Figure 12. Inventory data of the hemp fibre process is shown in Appendix II.

Two different scenarios are described for hemp fibre cultivation in the Netherlands: the first involves fertilizing hemp with mineral fertilizer and the second uses organic fertilizer, in particular pig slurry. The latter scenario was based on two reasons: (1) Pig slurry is available in large amounts in the north of the Netherlands. (2) Hemp tolerates organic fertilizer. For the other fibres, the use of organic fertilizers is not assessed, since flax does not tolerate organic fertilizer. Moreover, India and Bangladesh, the main cultivation regions for jute and kenaf, have no manure surpluses.

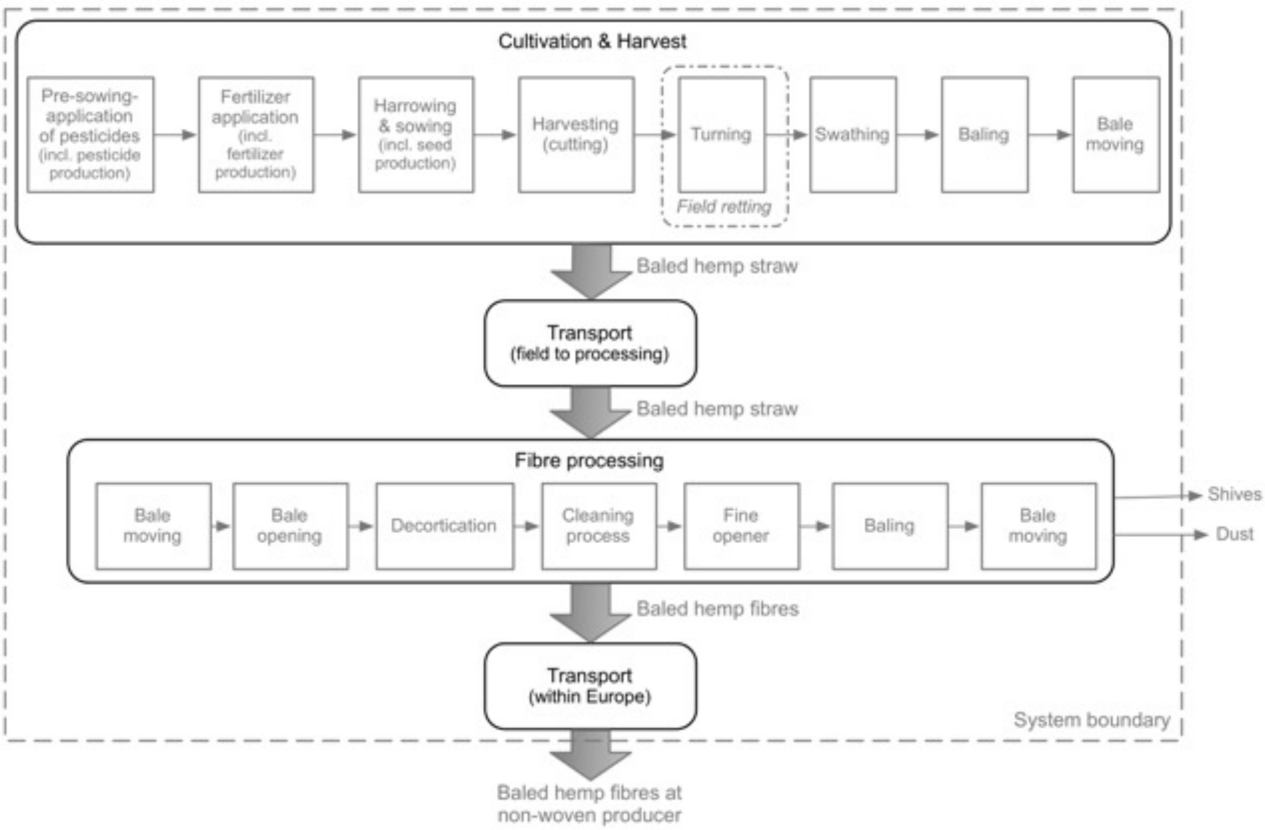

Figure 12: System boundary and process chain of hemp fibre production (total fibre line) (nova 2015)

3.1.4.3 Jute fibre

Figure 13 indicates the system studied for cradle to gate jute fibre production. Cultivation to fibre processing steps are assumed to take place in India and Bangladesh; transportation from India to a harbour in Hamburg, Germany, is done by ships and continues on land with lorries headed to the factory gate of German non-woven producers. Inventory data and assumptions are summarized in Appendix II. The jute life cycle starts with agricultural cultivation; the jute is then cut and submerged in a pond or in a river for water retting. After retting, the fibres are manually extracted from the stems, then washed and dried. Farmers do this manually. Sobhan et al. (2010) state that not all agricultural and decortication work is done manually, but for example bullock- or tractor-driven ploughs are used to produce fine tilth. Lastly, the sun-dried fibres are delivered in rough fibre bundles to the so-called “fine-opening-processing” site, where the fibres are refined and cut into the desired length for selling to the non-woven producer (this is only the first part of the whole textile process, which leads to sliver for yarn production).

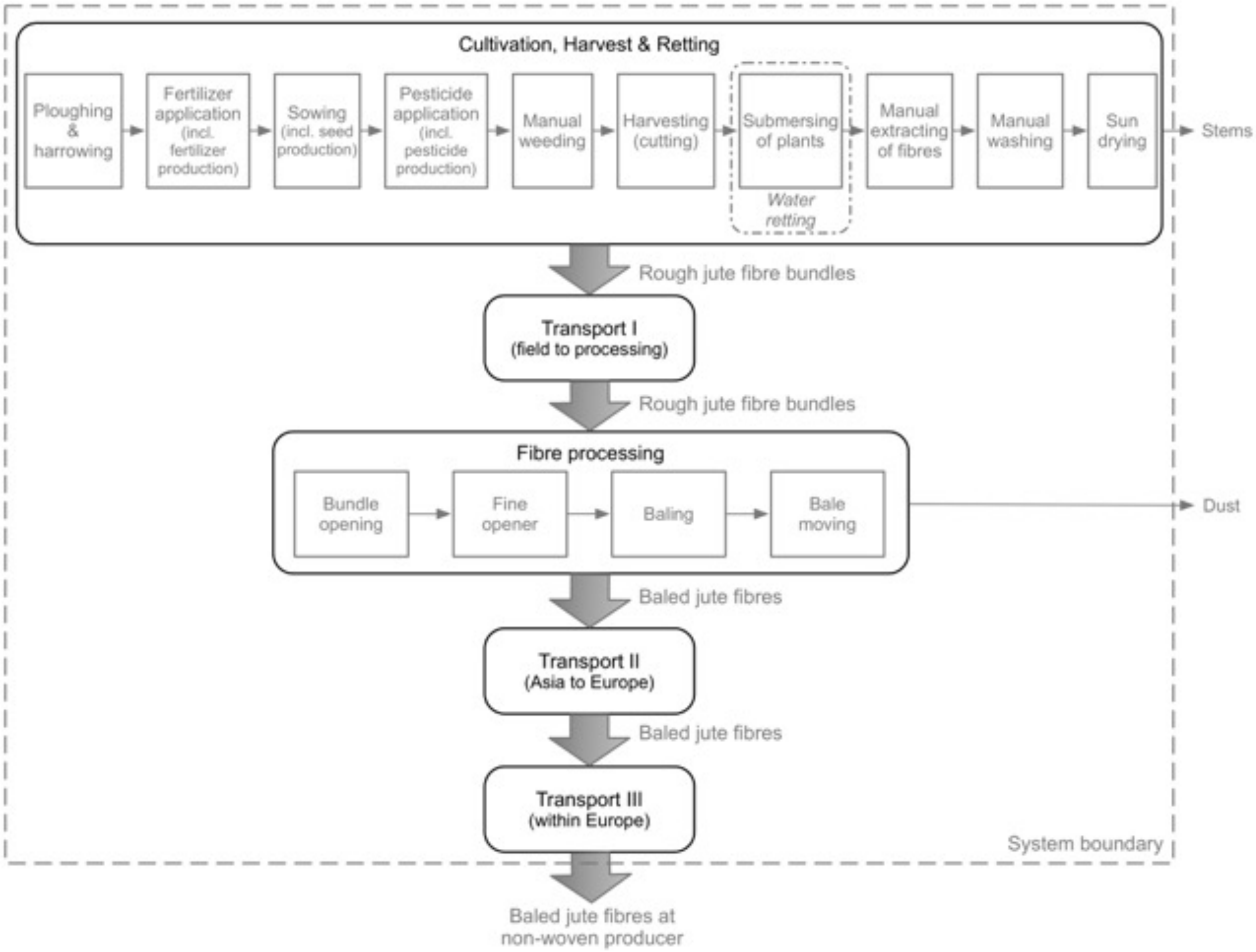

Figure 13: System boundary and process chain of jute fibre production (nova 2015)

3.1.4.4 Kenaf fibre

Figure 14 below presents the system studied for cradle to gate kenaf fibre production, for which cultivation and fibre processing are assumed to take place in India and Bangladesh. Transportation to the harbour in Hamburg, Germany, happens via ship and continues with lorries go to the factory gate of the non-woven producer in Germany. Inventory data and assumptions are summarized in Appendix II. Kenaf – like jute – is cut and water retted. After retting, the fibres are manually extracted from the stems, then washed and sun-dried. These activities are done manually by farmers, but not all agricultural and decortication steps are done manually: some field applications involve tractors (Sobhan et al. 2010). Lastly, the dried fibres are delivered in rough fibre bundles to the so-called “fine-opening-processing” site, where they are refined and cut into the desired length for selling to the non-woven producer. These finishing steps are done with machines.

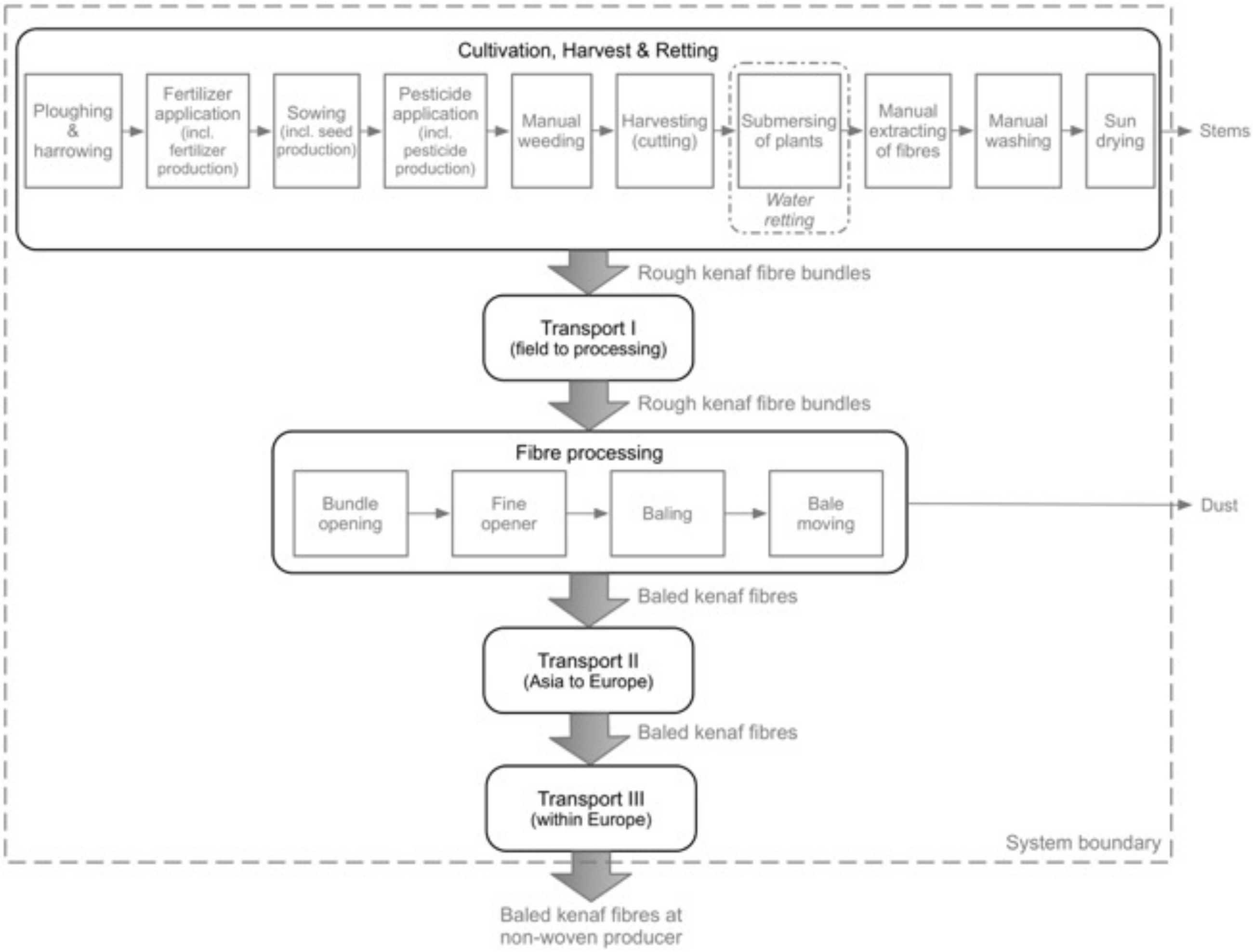

Figure 14: System boundary and process chain of kenaf fibre production (nova 2015)

3.2 Product level

As described in section 2, the environmental and economic sustainability assessment is divided into the system level, i.e. the agricultural production and the fibre processing, and the product level, where final products from the raw materials of the fibre processing stage are produced. Several products have been developed during the MultiHemp project. Unfortunately, some products did not have sufficient data or required too many assumptions for those to be completely assessed. The products which are assessed in this environmental and techno-economic assessment are hemp based insulation material and hemp based construction panels. In MultiHemp, blow-in insulation material made from hemp has been developed. This is compared to a commercially available hemp insulation material, called THERMO HANF® . In this comparison, the cultivation process described in the system level is used for both products to avoid comparing different hemp cultivation processes. The two hemp based insulation materials are also compared to literature data available on other often used, commercially available insulation materials.

The hemp based construction panels are used as part of interior walls or flooring. Data for two different types of construction panels were obtained, one contains clay in the panel while the other is without clay. An environmental hotspot analysis is performed and the construction boards are compared to wood wool boards.

3.2.1 Hemp based blow-in Insulation

In the Multihemp project, blow-In insulation material made from hemp has been developed and tested with success. For the final user, the main difference between board or roll insulation and blow-in insulation is the amount of labour required during installation. Blow-in insulation materials require different equipment compared to insulation boards or rolls. Often, insulation boards or rolls can be installed with construction adhesives. Blow-in insulation is installed by blowing the insulation material into a hollow space in the wall. While this requires blowing equipment on the installation site, the process of producing the blow-in material itself is relatively simple. There are several advantages of using blow-in insulation compared to other types of insulation. Blow-in insulation materials have good insulation properties compared to their price, provide acoustic insulation and can be made from recycled or renewable materials. The added borate acts as a mould and pest control and also as a fire retardant. Disadvantages of blow-in insulation include lower thermal insulation compared to some other materials (i.e. polyurethane foam) and the requirement of special installation equipment and proper handling. Improper installation can result in settling of the material and the production of dust.

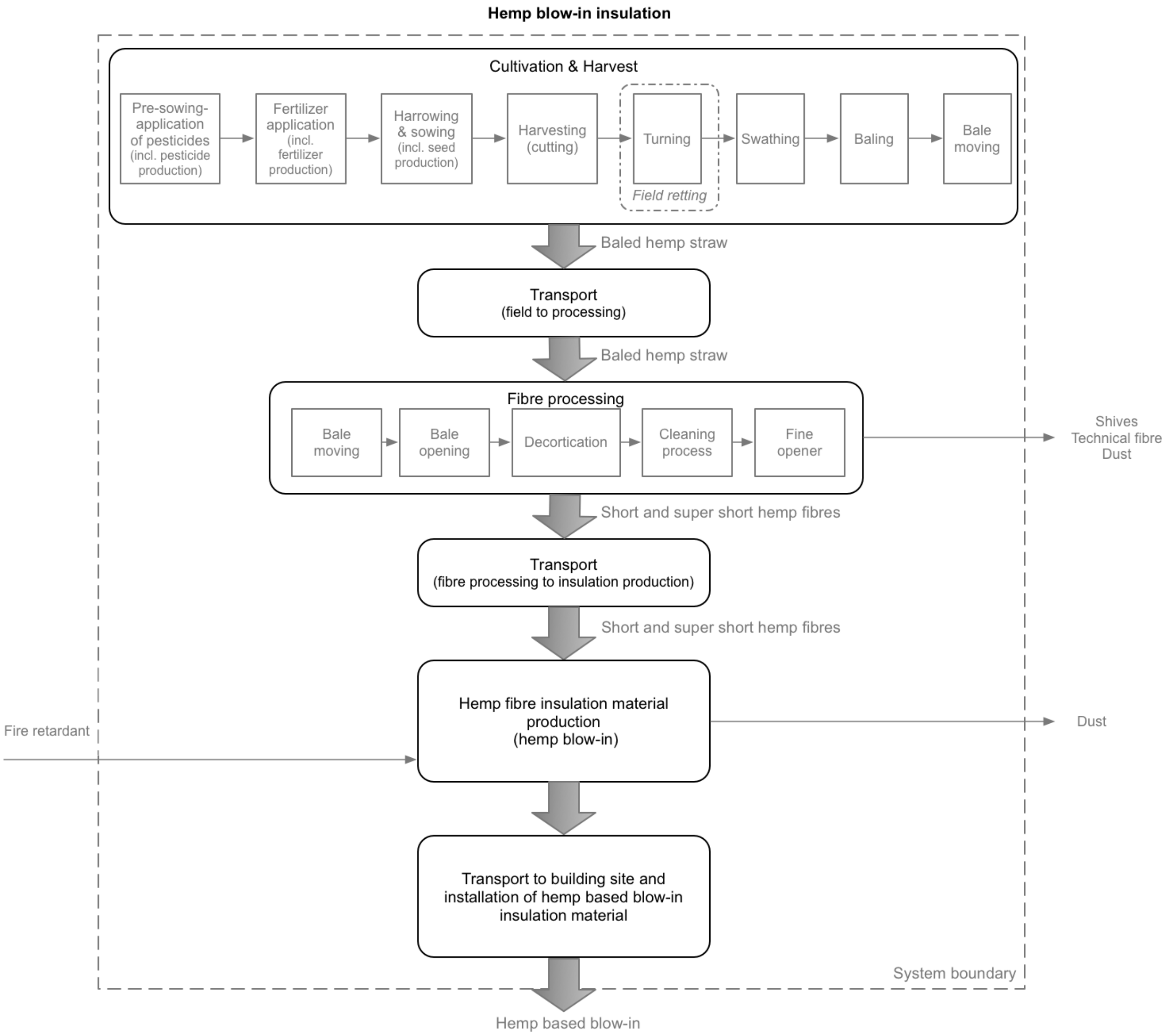

Figure 15: Hemp based blow-in production process

The transport distance from the fibre producer to the blow-in producer is assumed to be 300 km by road. Various fibre fractions of the Total Fibre Line (see section 3.1.3.1) as well as unprocessed straw have been evaluated by project partners Ventimola, ZIMIC and HSB for their suitability as a blow-in insulation material. Of these raw materials, only the mix of short and super short fibres had the desired properties for blow-in insulation. The technical fibres proved to be not suitable mainly due their settling behaviour of forming into bundles. The straw also had several disadvantages. First, the straw had to be sorted by hand since it still contained a lot of stones. Hence, in a first test, about 20 minutes of preparation were needed for each 60 kg sample. This was an important drawback of using hemp straw from the field as raw material. Due to these reasons, technical fibres and unprocessed straw had been eventually discarded from the list of suitable raw materials for a blow-in insulation material.

Data regarding the production of hemp blow-in insulation material was obtained from Ventimola (Dirk Niehaus). It is assumed that due to the loss of input material as dust, 2 tonnes of hemp short fibres and super short fibres are required to produce 1 tonne blow-in insulation material. During the production of the blow-in insulation material, the dust is recovered and valorised as briquettes similar to the dust produced in the Total Fibre Line.

From testing the blow-in insulation material, it was found that there is no additional flame retardant required in order to pass safety tests. However, it is likely that in commercial production, 5% borate is added for safety measures.

After sorting the raw material, it is first comminuted in a shredder. For the testing at ZIMIC, four shredders of the type RMZ 700 with a connected power of 44 kW each (two motors of 22 kW) had been used. The material was then transported via a conveyor belt to a whirlmill of the type UTM 1200 (connected power of 132 kW) in which it was further comminuted and homogenized. According to ZIMIC, the whirlmill is operating much faster than the shredder and in order to use the capacity of the whirlmill, 4 shredders had to be operated simultaneously. After the whirlmill, the material was cleaned in a cyclone and packaged.

The total energy consumption required for the production of the blow-in insulation material is estimated by project partner Ventimola at 1,500 kWh/t blow-in material. Roughly 60% of this electricity consumption is required for the shredding of the hemp material and for the whirl mill. The remaining 40% is required for packaging, dust removal and other electric demands.

It has to be noted that these numbers are based on pilot plant production and thus un-optimised processes. Process optimisation, i.e. reduction of electricity consumption or dust production, will decrease the environmental footprint. Packaging material for the blow-in insulation can be reused, especially when packed in big-bags. Therefore, the environmental impact of the packaging material is neglected. Transport to the final costumer is assumed to be 500 km on average. The energy requirement for the installation of the blow-in insulation material is 21 kWh/t blow-in insulation material.

Project partner HSB has tested the relevant material properties for the hemp blow-in insulation material. According to the results, the hemp blow-in insulation produced from short and super short hemp fibres exhibits a thermal conductivity between 0.038 and 0.043 W/(m*K), at a density of 35 kg/m^3.

The following Figure 16 shows a simplified process flow diagram for the production of blow-in insulation material made from short and super short fibres.

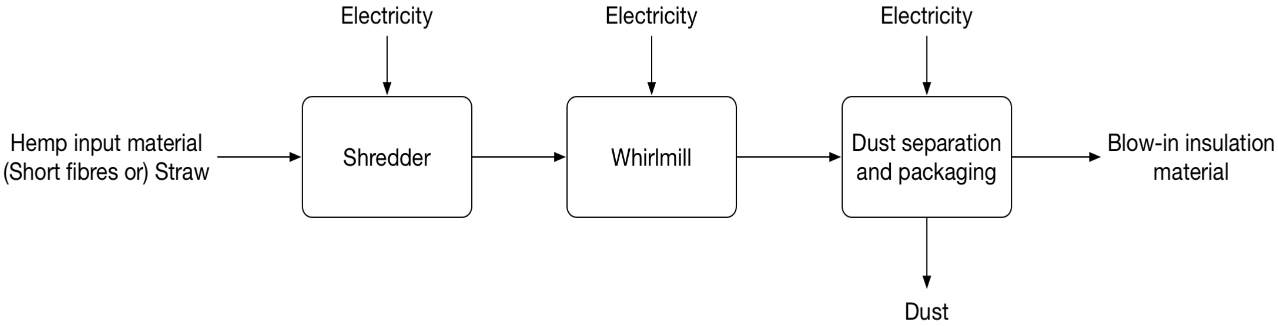

Figure 16: Process flow diagram for the production of hemp blow-in insulation material
Source: nova 2017

3.2.2 THERMO HANF®

THERMO HANF® is a commercially available hemp based insulation roll which provides thermal, acoustic, impact and fire resistance (www.thermo-natur.de). The following Figure 17 shows the analysed life cycle stages of THERMO HANF® production.

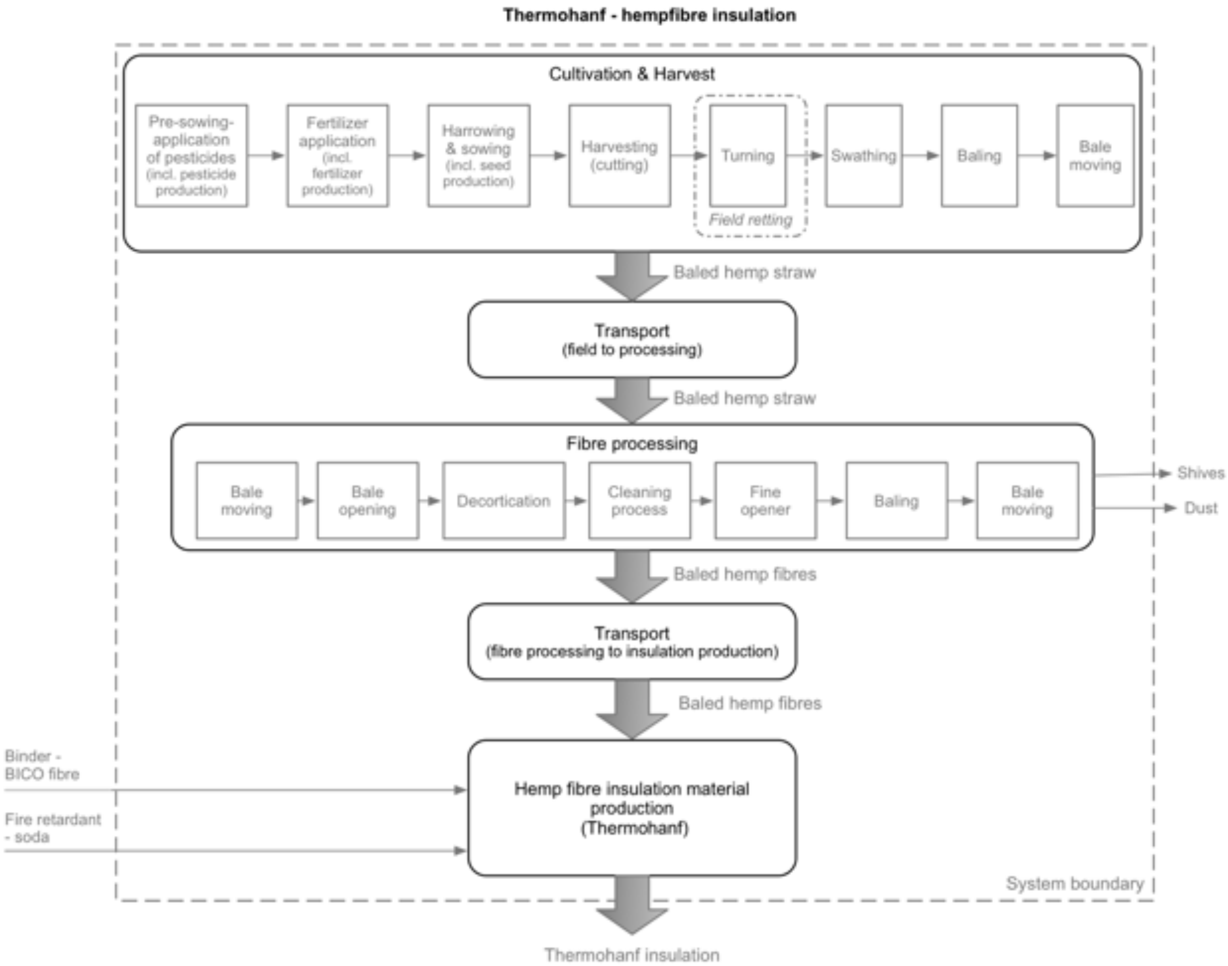

Figure 17: Visualisation of the assessed THERMO HANF® model (cradle-to-gate approach)

Table 18 shows the inventory data (inputs and outputs) used for the THERMO HANF® production including the data source. Table 19 below shows the inventory data for the production of 1 kg of BICO fibre.

Table 18: Inventory data for the THERMO HANF® production
Data source: TIM-LCA refers to Spirinchx et al. 2013

Materials / Energy	Unit	Quantity	Data source /Reference
Inputs			
Materials			
hemp fibre	kg/kg Thermohanf	0,87	[illegible] hemp straw (france) and 0.087 hemp straw (germany)
fire retardant - soda	kg/kg Thermohanf	0,03	TIM-LCA, Table 1
binder - BICO PE fibre	kg/kg Thermohanf	0,1	TIM-LCA, Table 2
Transport of raw material to factory gate			
processing in NL to thermohanf-processing in DE)	km (roundtrip)	800	own assumption (forth and back)
distance soda	km (roundtrip)	18	one way 9 km (Table 11, TIM-LCA)
distance BICO PE fibre	km (roundtrip)	120	one way 60 km (Table 11, TIM-LCA)
SUM Transport raw material			
Energy			
Electricity	kWh/kg Thermohanf	0,62	TIM-LCA, Table 12
Natural gas	MJ/kg Thermohanf	1,8	TIM-LCA, Table 12
Packaging of insulation material			
PE film	kg/kg Thermohanf	0,0121	TIM-LCA, Table 12
Transport of PE film to Thermohanf-processing	km/kg Thermohanf	72	TIM-LCA, Table 12
pallet one way	pieces/kg Thermohanf	0,0072	TIM-LCA, Table 13
Transport pallet one way	km/kg Thermohanf	356	TIM-LCA, Table 14
Outputs			
Product: 1 kg Thermohanf			

Table 19: Inventory data for the BICO fibre production
Data source: TIM-LCA refers to Spirinchx et al. 2013

Processing of BICO PE fibre			
Inputs			
Materials			
Polyethylene terephthalate, granulate, amorphous	kg/kg BICO PE fibre	0,5	TIM-LCA, Table 10
Polyethylene terephthalate, granulate, bottle grade	kg/kg BICO PE fibre	0,5	TIM-LCA, Table 10
Energy			
Extrusion process; Electricity	kg/kg BICO PE fibre	1,004	TIM-LCA, Table 10: Extrusion, (plastic pipes: 1.5 kg)
Outputs			
Product: 1 kg BICO PE fibre			

3.2.3 Construction panels

Project partner CMF has developed a construction panel produced from the shives of the Total Fibre Line. These construction boards are branded as Canapalithos. The production process, see Figure 18, includes the mixing of the ingredients, pressing of the construction panels and finally the drying of the panels. Two types of construction panels produced by CMF have been assessed: Canapalithos 350 (CA 350) and Canapalithos 1100 (CA 1100). The main difference between the two construction panels is the density (350 kg/ m^3 of the CA 350 and 1,100 kg/ m^3 of the CA 1100). Furthermore, in the production of the CA 1100, clay is used but not for the CA 350.

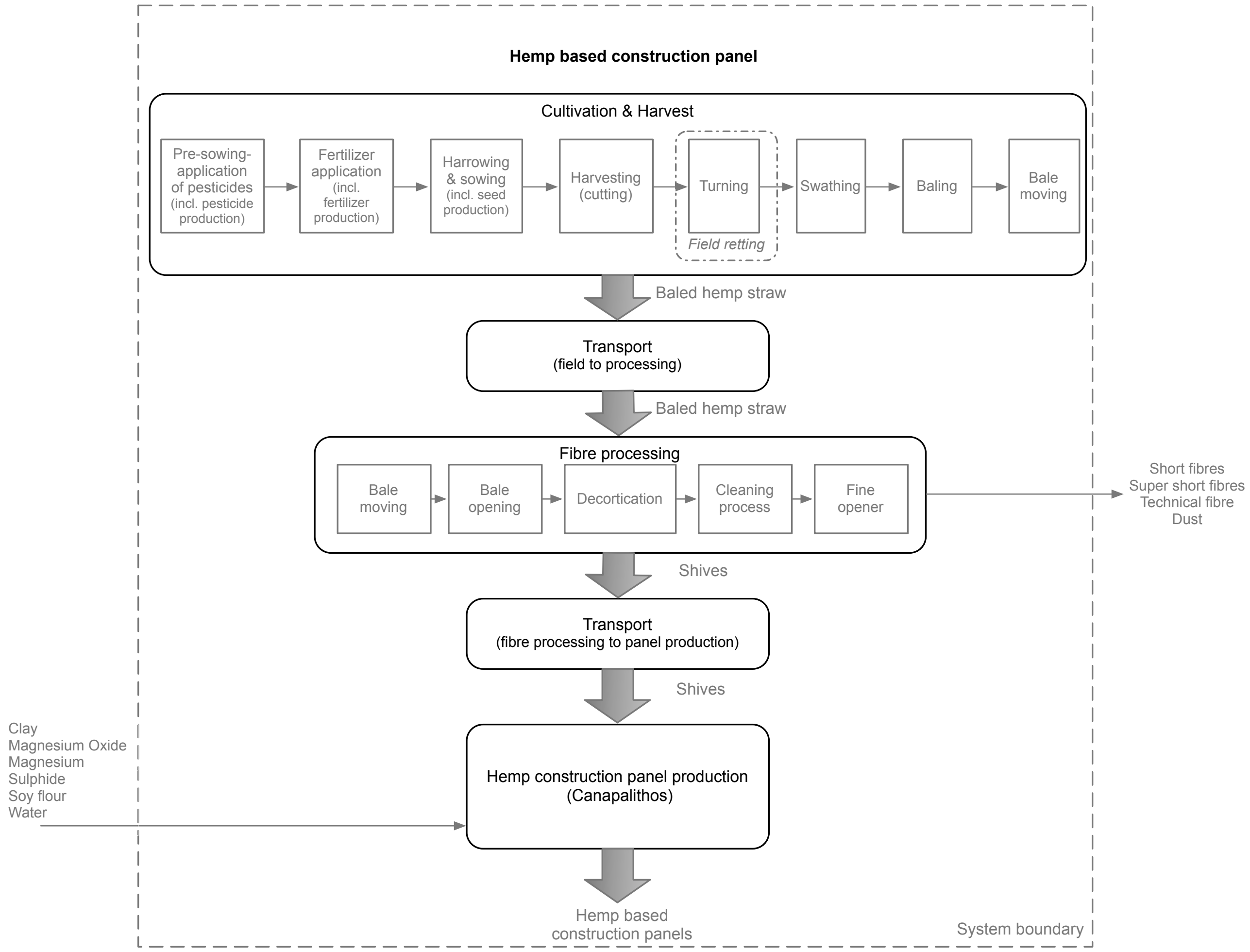

Figure 18: Production process and system boundaries for hemp construction panels

For both construction panels production data was obtained and environmental hotspot analysis was performed. Table 20 below shows the material input for the production of one cubic meter of panels for both types, based on data obtained from CMF.

Table 20: Canapalithos Life Cycle Inventory data

Material	CANAPALITHOS 350	CANAPALITHOS 1100	Unit
Hemp shives	178	296	kg
Clay	-	296	kg
Magnesium Oxide	100	344	kg
Magnesium Sulphate	38.3	131.5	kg
Soy flour	33.5	86	kg
Water	89	262,7	kg
Electric energy	280	630	MJ
Natural gas calorific energy	2,465	3,330	MJ

For the life cycle inventory data for clay, magnesium oxide, magnesium sulphate, soy flour, tap water and the energy requirements, Ecoinvent 3.0 was used. The life cycle inventory for magnesium oxide and magnesium sulphate contain relatively large uncertainties since they are based on an approximation (Althaus et al. 2007). The life cycle inventory for hemp shives was taken from the system part described in section 3.1. For the packaging of the hemp panels no data was obtained.

A simplified process flow diagram for the production of the hemp construction panels is depicted in Figure 19.

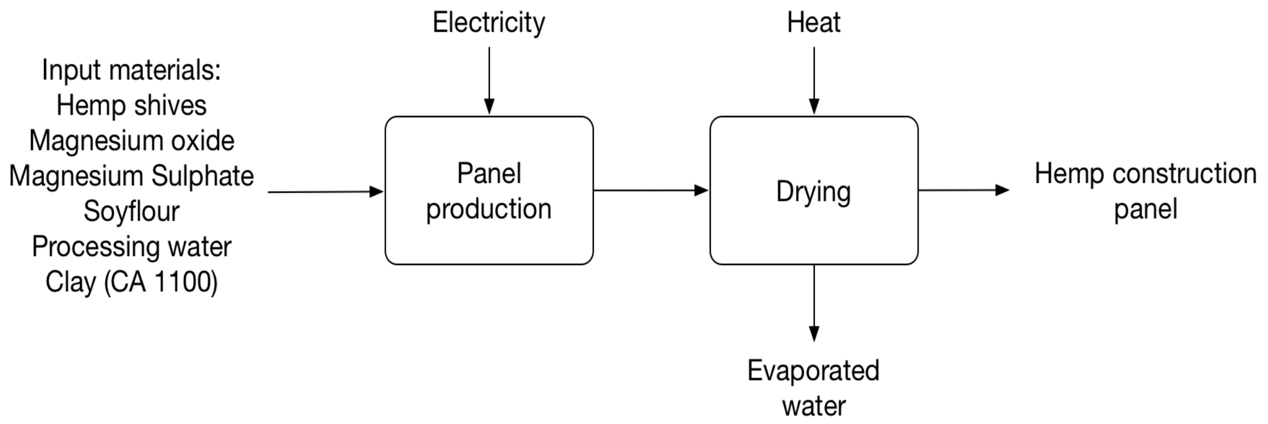

Figure 19: Process flow diagram for the production of hemp construction panels
Source: nova 2017

According the CMF business plan (Montecchi 2015), targeted market prices for the two products are 510 €/ m^3 for CA 350 and 1,060 €/ m^3 for CA 1100. The business plan provides a quite detailed view of the envisaged production plan, including a gradual build-up from the first year until the final commercial production scale in the fourth year of operation.

4 Results and Discussion

This section discusses the results for the system level and product level environmental and techno-economic assessment.

4.1 System level

4.1.1 Techno-economic assessment

On the system level, the techno-economic assessment first shows comparative results for the cultivation scenarios and the three harvesting technologies, followed by an evaluation of the processing system of the total fibre line.

Final results on the system level as well as the product level will be expressed in terms of *profits* as well as *value added*. The value added is defined as the revenue minus the intermediate inputs, i.e. the inputs that are bought and consumed by a certain value stage. The value added therefore still includes the costs generated by a value stage itself, which are mainly labour and deprecation. While the profit is a more important indicator for a single actor, the value added introduces wider economic perspective since it accounts for the generation of employment. This means in turn that processes which are labour intensive and hence contribute highly to the value added may be preferable from an economy-wide perspective but not from business perspective.

4.1.1.1 Cultivation and harvesting

Due to the definition of the cultivation scenarios, the only variation is due to different fertilizer/yield combinations and different harvesting technologies. First, we compare the cultivation costs excluding the harvesting operations. This comparison is shown by types of operations (Figure 24 and Figure 25) as well as by cost items (Figure 26 and Figure 27) and per ha and per tonne of dry matter straw. The results show that the increase in fertilization from the minimum to the maximum scenario increases costs by about 160 Euro/ha while costs per ha in the minimum scenario and the maximum scenario using pig slurry are about the same. Due to the increase in yields, however, costs in the minimum, average and maximum scenario are approximately the same while they are again markedly lower in the pig slurry case. In terms of costs items, fertilizer dominates at least in the average and maximum scenario, followed by seed costs and the cost of land.

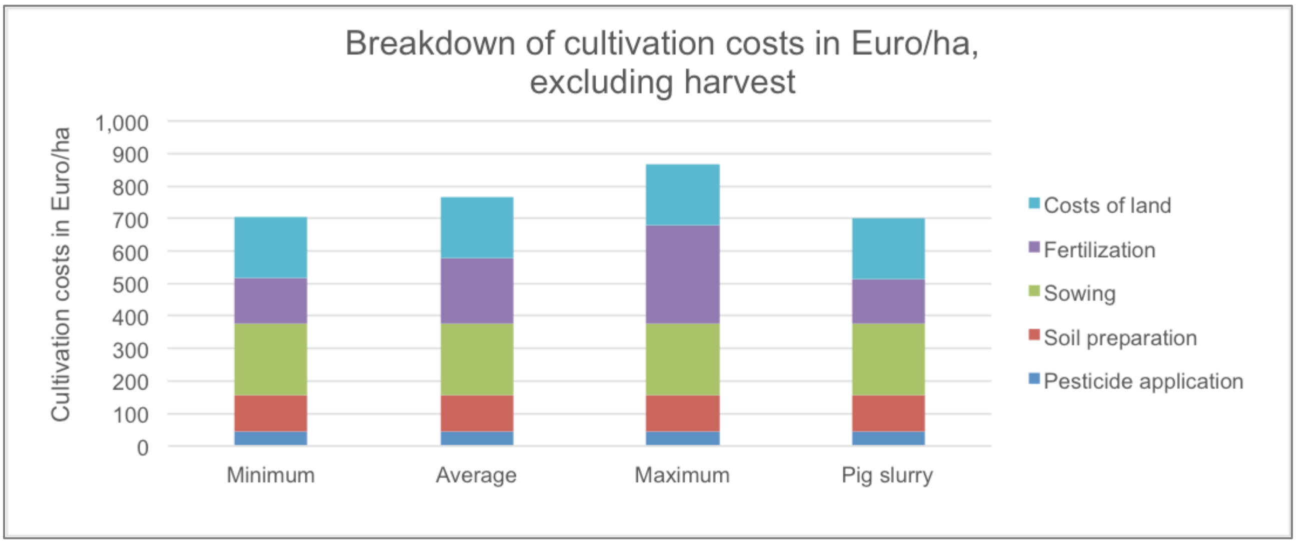

Figure 20: Breakdown of cultivation costs in Euro/ha, by type of operations, excluding harvest
Source: nova 2017

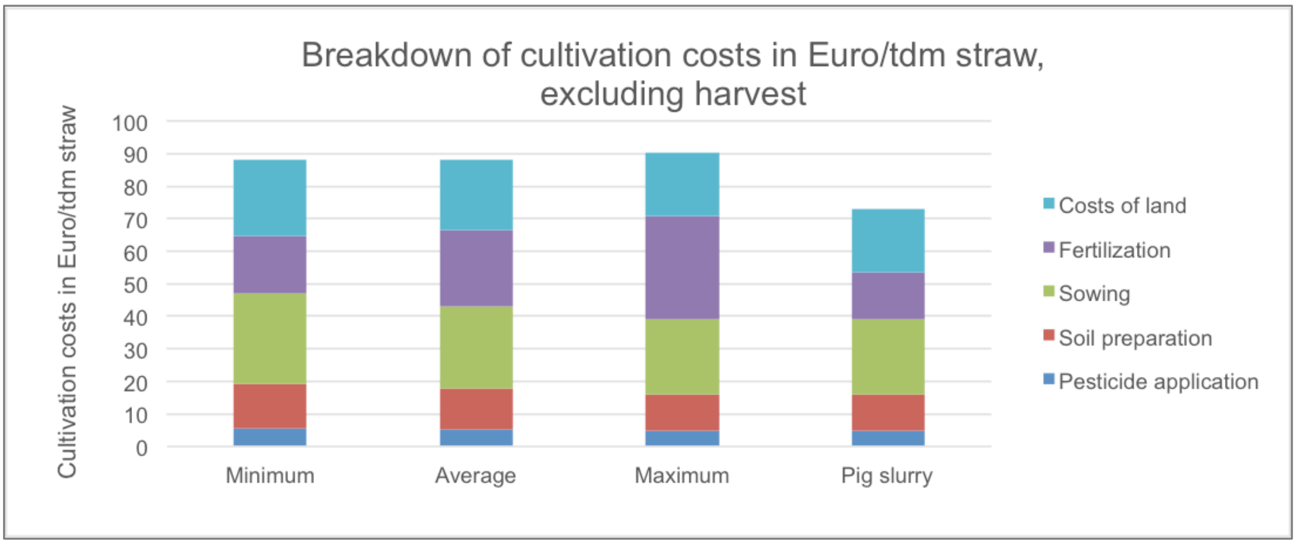

Figure 21: Breakdown of cultivation costs in Euro/tdm straw, by type of operations, excluding harvest
Source: nova 2017

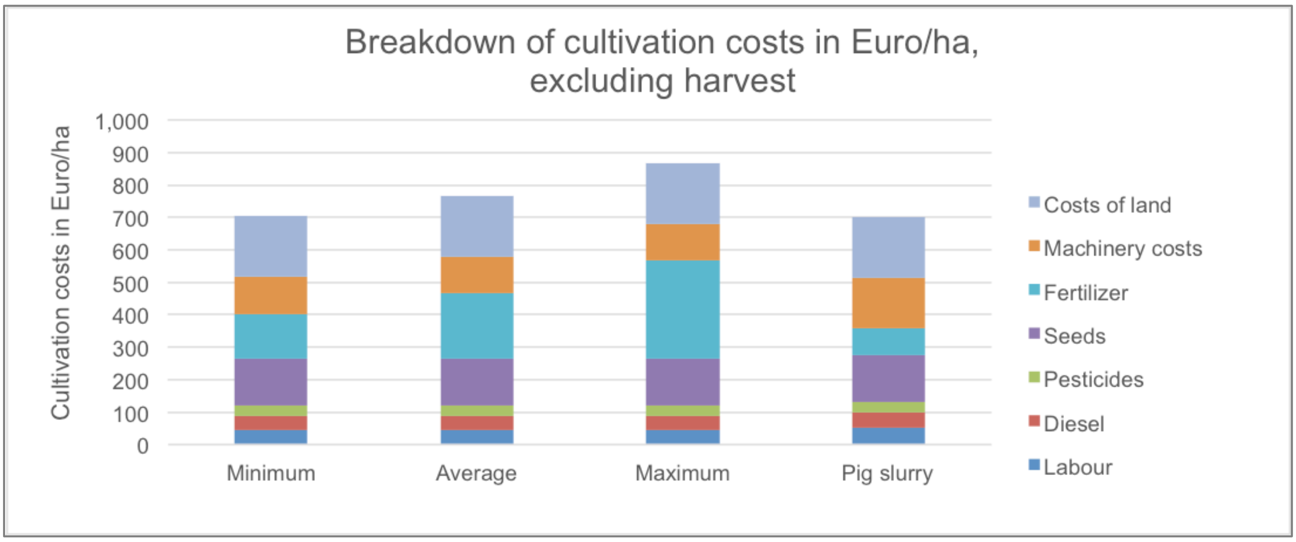

Figure 22: Breakdown of cultivation costs in Euro/ha, by cost items, excluding harvest
Source: nova 2017

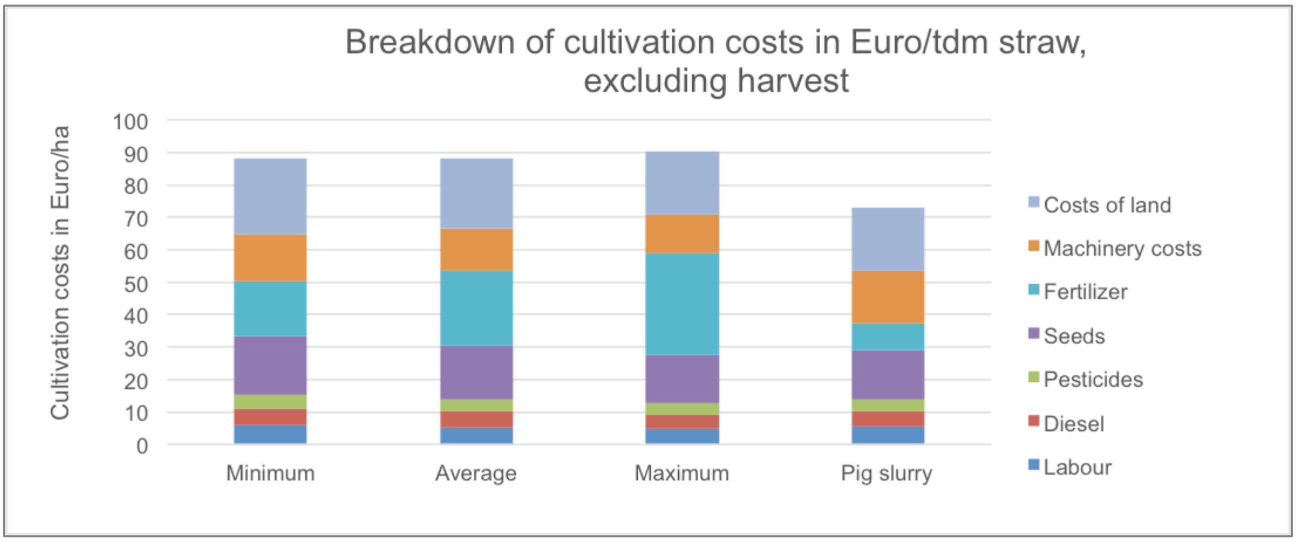

Figure 23: Breakdown of cultivation costs in Euro/tdm straw, by cost items, excluding harvest
Source: nova 2017

Regarding the relative performance of the three harvesting technologies evaluated in this study (the HempCut, the Total Harvester and the Xerion system), several main assumptions clearly have an important influence. These are discussed in the following.

While the HempCut and the Total Harvester are technologies that are established in European hemp cultivation for many years, the Xerion system, with the simultaneous harvest of leaves, is a technology that is still relatively new. In order to account for the different levels of experience and, therefore, different levels of learning and optimisation, we assume for the calculated results according to sections 3.1.2.1 to 3.1.2.3 positive and negative errors of 10% for the two established technologies and 20% for the less-well established Xerion technology.

The comparison of the three technologies, including the point estimates as well as the uncertainty ranges, is shown for the base case in Figure 24. The results show for the average cultivation scenario that the Xerion system is apparently characterised by the lowest labour demand, due to the higher area performance (working width of 6 m instead of 4 m, as the HempCut) and the lowest harvesting costs per ha. The Total Harvester is characterised by the highest labour requirements and since these also lead to higher fixed machinery costs per hectare, this technology exhibits slightly higher overall harvesting costs than the HempCut.

Figure 24 shows the base case of a capacity utilisation of 833 h/a for the Xerion system and 300 h/a for the HempCut and the Total Harvester. As explained in section 3.1.2, the difference is due to the fact the Xerion system is based on a system tractor which can potentially be utilised many other types of agricultural operations compared to the HempCut (based on a maize chopper) and the Total Harvester, which can only be used in other harvesting operations. This assumption significantly reduces depreciation and capital costs per ha of the expensive Xerion technology. If, in turn, an equal utilisation of all systems of 300 h/ha is assumed, results turn around and the higher costs for depreciation and interest charges outbalance the saved labour costs, so that overall the costs for the Xerion system are higher (Figure 25 and Figure 26). Therefore, it should be carefully observed in commercial operations which assumption appears to be more realistic.

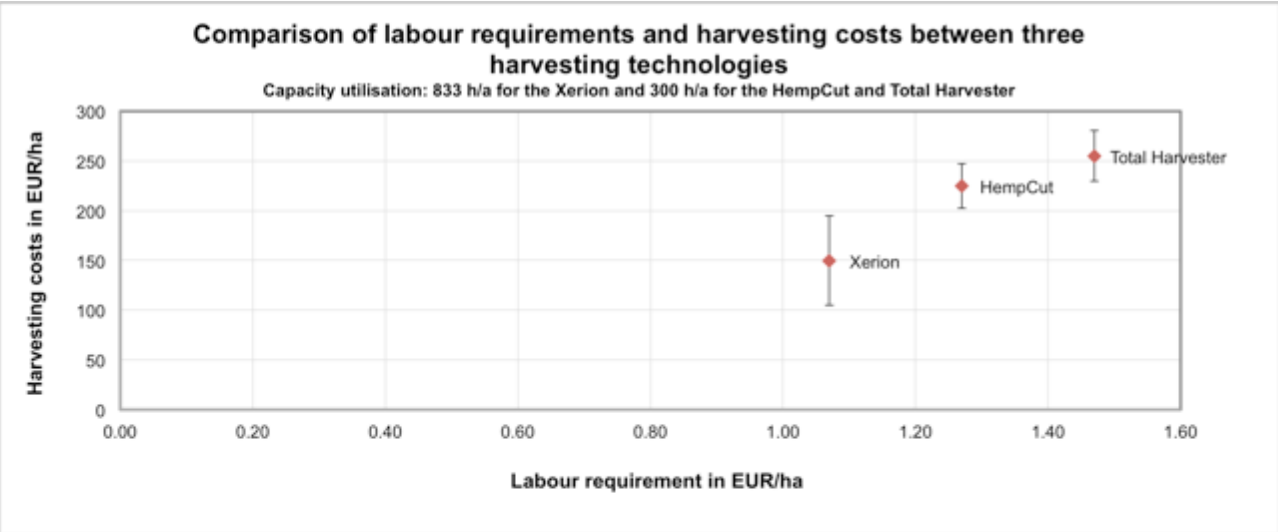

Figure 24: Comparison of labour requirements and harvesting costs between three harvesting technologies (base case)
Source: nova 2016

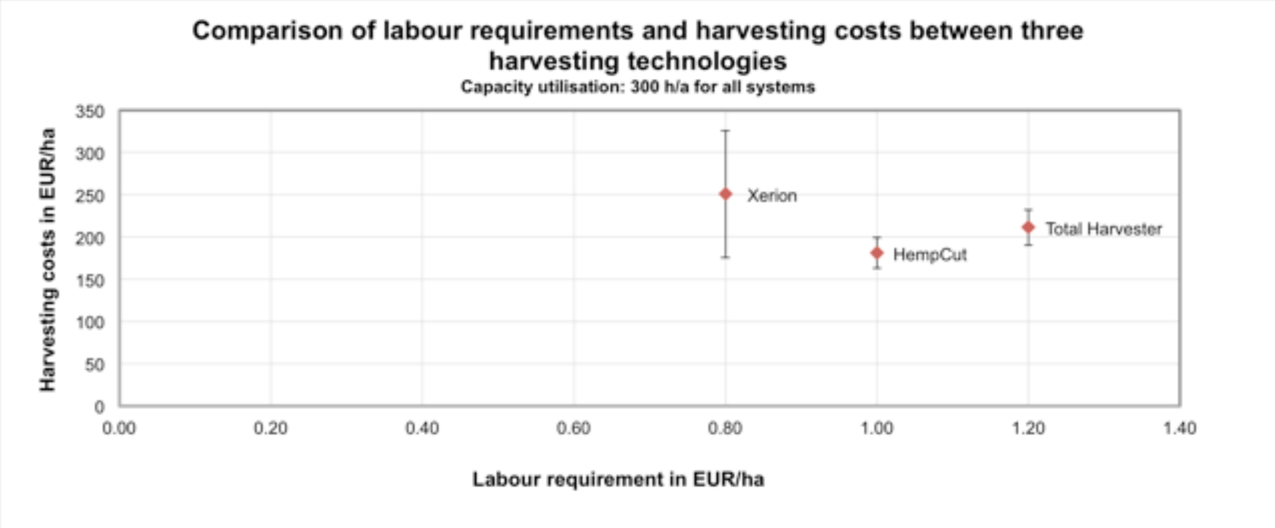

Figure 25: Comparison of labour requirements and harvesting costs between three harvesting technologies (300 h/a for all systems)
Source: nova 2016

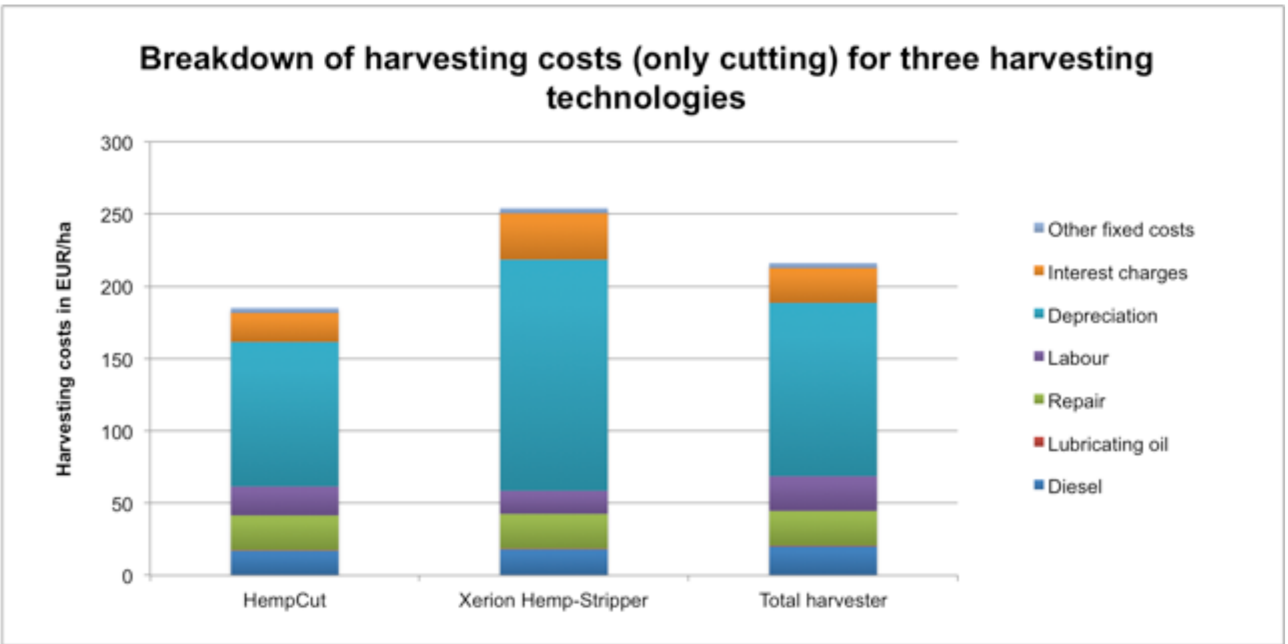

Figure 26: Breakdown of harvesting costs for three harvesting technologies (at 300 h/ha for all systems)
Source: nova 2016

Revenues, profits, costs and value added

In order to evaluate the relative economic performance of the cultivation and harvesting systems, Figure 27 to Figure 29 show the revenues, profits, costs and value added generated in all four cultivation and three harvesting scenarios. For the dual harvesting scenarios, we assume that the leaves and seeds are sold to external drying and cleaning facilities for prices of 400 €/tdm for the leaves and 800 €/tdm for the seeds. For all scenarios, a price of 130 €/tdm for the straw is assumed.

The comparison shows clearly that a dual use production target, whether for leaves or for seeds, has very significant impacts on the profitability. While in the single use system only the maximum fertilizer scenario using pig slurry is able to generate profits, the dual use systems generate profits of about 60 to 100 €/tdm straw, with the highest profits in the pig slurry scenarios, followed by the minimum mineral fertilizer scenarios. Note, however, that the single harvest of straw still generates positive *gross margins* (defined as revenues minus variable costs) in all scenarios and therefore this system can still be economically sustainable as part of the portfolio of a farm's operations.

However, the result of higher profits and value added in dual use systems is dependent on a well-established and reliable market of both products. For leaves for CBD-extraction, this market is currently highly volatile, which needs to be taken as a caveat for the dual use of straw and leaves.

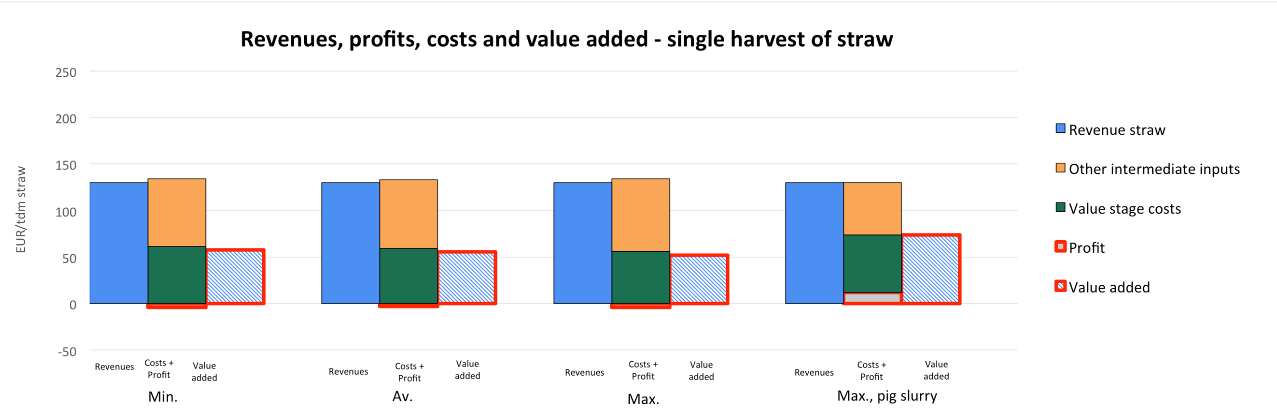

Figure 27: Revenues, profits, costs and value added – single harvest of straw
Source: nova 2017

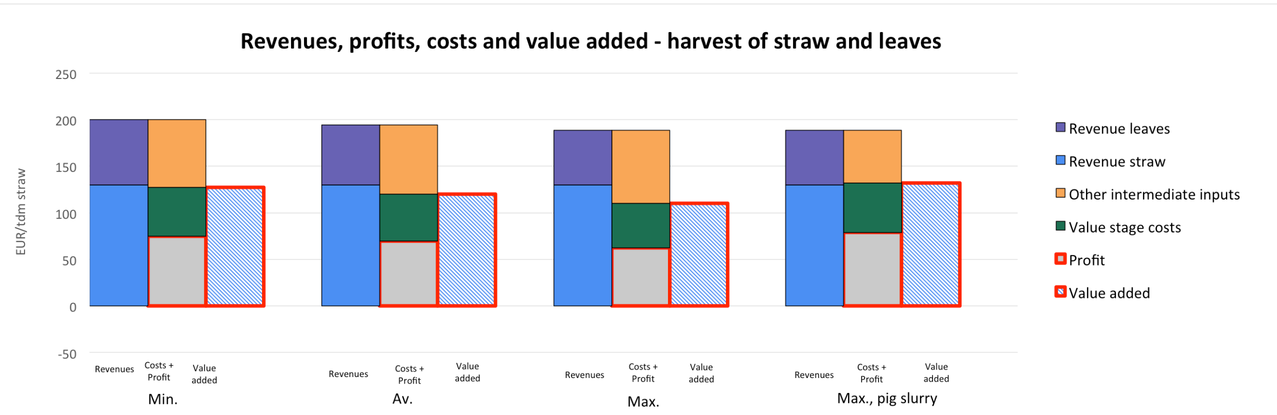

Figure 28: Revenues, profits, costs and value added – harvest of straw and leaves
Source: nova 2017

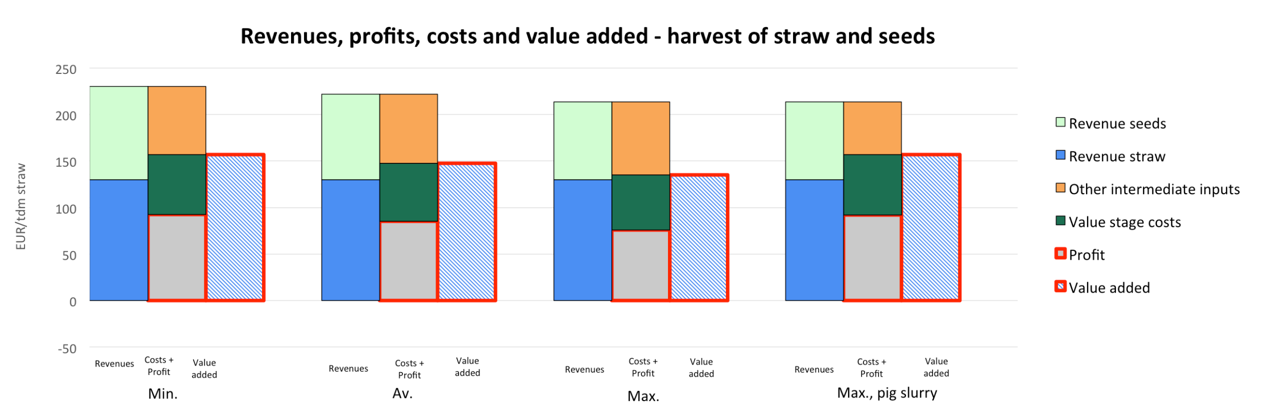

Figure 29: Revenues, profits, costs and value added –harvest of straw and seeds
Source: nova 2017

4.1.1.2 Processing

In general, the larger Total Fibre Line performs better than the smaller one in terms of both profits and value added. As Figure 30 shows, this is mainly due to lower value stage costs per tonne straw and, more precisely, due to lower capital and depreciation due to the higher capacity.

Figure 30: Revenues, profits, costs and value added – total fibre line
Source: nova 2017

4.1.2 Environmental assessment

The environmental assessment first discusses the global warming potential of the system level, followed by the abiotic depletion, acidification potential and eutrophication potential. For each impact category, the effect of different allocation keys is also discussed.

In dual use harvesting strategies, the impacts associated with the further processing of the second product (leaves or seeds) is not considered. Instead, the allocation of environmental impacts is performed based on estimated prices a farmer would receive for the unprocessed products. For hemp seeds, this price is estimated at 800 Euro/tdm, while the price for the hemp leaves is estimated at 400 Euro/tdm. Since these products still require more processing compared to their normal trade value, the prices are lower.

A brief discussion on the biogenic carbon storage in hemp fibres is presented in chapter **4.1.2.3**. The system level environmental assessment is ended with a comparison of hemp fibre produced in the MultiHemp project with flax, commercial hemp, jute and kenaf fibres.

4.1.2.1 Global warming potential

The Global warming potential of the different cultivation and harvesting strategies is shown in Figure 31 below. In total, 12 scenarios were assessed;

- Min S: Low mineral fertiliser inputs, single use (straw)
- Ave S: Average mineral fertiliser inputs, single use (straw)
- Max S: High mineral fertiliser inputs, single use (straw)
- PS S: Organic fertilisation, single use (straw)
- Min S+L: Low mineral fertiliser inputs, dual use (straw and leaves)
- Ave S+L: Average mineral fertiliser inputs, dual use (straw and leaves)
- Max S+L: High mineral fertiliser inputs, dual use (straw and leaves)
- PS S+L: Organic fertilisation, dual use (straw and leaves)
- Min S+S: Low mineral fertiliser inputs, dual use (straw and seeds)
- Ave S+S: Average mineral fertiliser inputs, dual use (straw and seeds)
- Max S+S: High mineral fertiliser inputs, dual use (straw and seeds)
- PS S+S: Organic fertilisation, dual use (straw and seeds)

Figure 31 figure shows the environmental impact based on mass allocation expressed per t products (technical fibre, shives, seeds, leaves, etc.). The GWP of all the total fibre line products (fibres, shives and dust) is the same in mass allocation, since a division and multiplication by the mass fraction takes place.

When only considering single use hemp cultivation (the four bars on the left in Figure 31), the GWP of the total fibre line products is the lowest in the minimum scenario and highest in the maximum scenario. The difference between the minimum scenario and maximum scenario is roughly 200 kg CO_2eq./t product. This difference originates from different inputs and outputs and it illustrates the uncertainty associated with agricultural processes. The average and pig slurry scenario perform more or less the same. This figure implies that the additional environmental impact from the additional inputs in the average, maximum and pig slurry scenario are not offset by the increased yield.

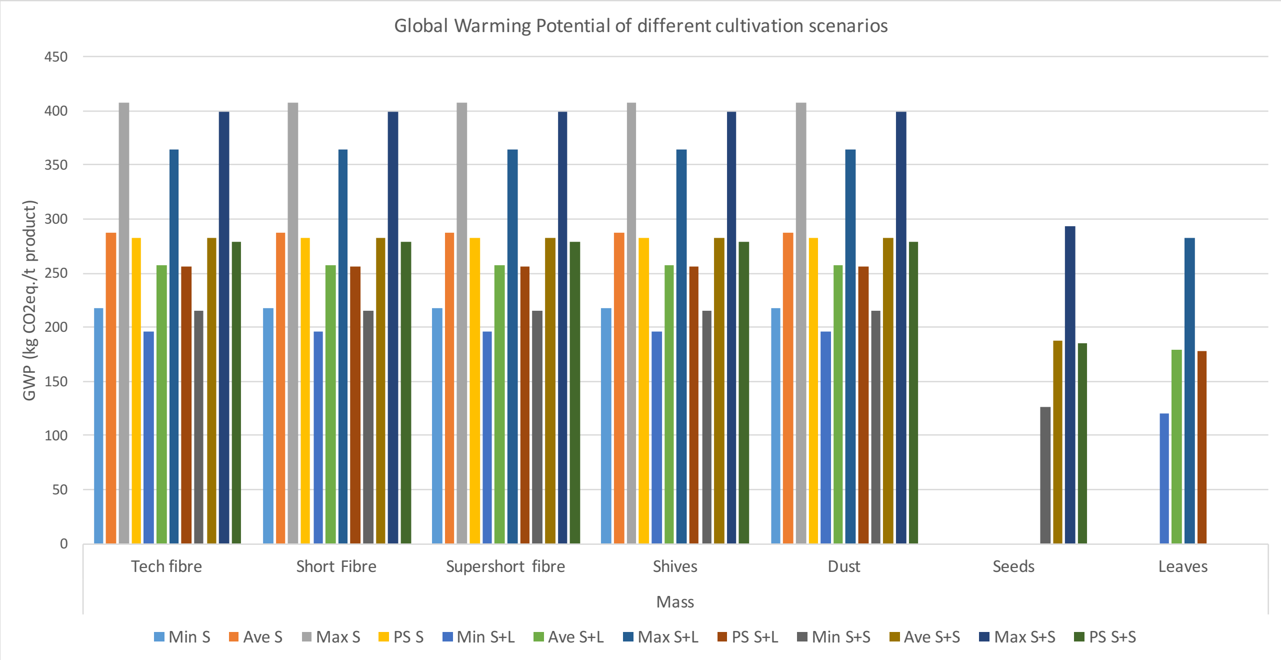

Figure 31: Global warming potential per tonne product for system level using mass allocation

The harvest of the side products results in lower environmental burden on the total fibre line products. The effect is most visible when comparing the maximum scenario of straw with the maximum scenario of straw and leaves. In Figure 31 mass allocation is used to allocate the environmental impact over the products. Due to the low mass yield of leaves and seeds, relatively little impact is allocated to these products. To illustrate this, the straw yield is 8 tdm/ha in the minimum scenario while the seed yield is 1 tdm/ha.

To investigate the effect of the allocation key, the results for allocation according to economic value are presented in Figure 32. The total fibre line products have different categories in Figure 32 because the economic value of the products is different. High valued products are allocated more environmental burden compared to lower valued products. The high valued products in the system level are the seeds, the leaves and the technical fibres. Compared to mass allocation (Figure 31) the environmental impact of the technical fibres has increased roughly two times, the impact for seeds has increased roughly 4 times and for leaves roughly twice. The GWP with economic allocation for short fibres, super short fibres and shives show a small decrease.

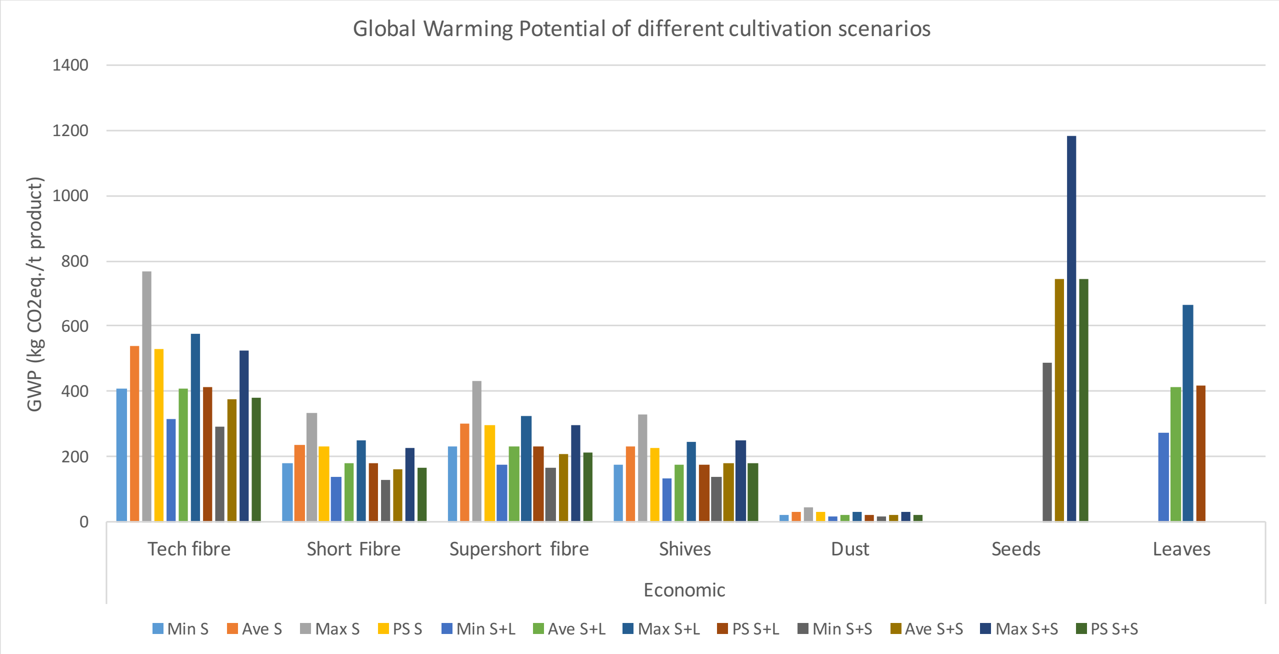

Figure 32: Global warming potential per tonne product for system level using economic allocation

In Figure 32 the impact for dust has decreased significantly compared to the mass allocation in Figure 31, due to the low price of the dust (40 Euro/t). Dual harvest is still preferable over single use harvest and the differences between single use and dual use harvest have become more pronounced in economic allocation. Furthermore, due to the high value of the seeds, seed harvest has become environmentally preferable over leave harvest. The advantage of economic allocation is that it considers the value of the products in the allocation, whereas in mass allocation low valued products with substantial mass output can lower the environmental impact of high valued products. The disadvantage of economic allocation is the dynamics in value over time, especially for volatile products, and thereby the introduction of another uncertainty in the environmental assessment.

In Table 21, the results for technical fibre with mass and economic allocation are shown for all assessed impact categories.

Table 21: Impact assessment for technical fibres using mass and economic allocation

Harvest strategy	GWP (kg CO_2eq)		AD (MJ)		AP (kg SO_2eq.)		EP (kg PO_4eq.)	
	Mass	Eco	Mass	Eco	Mass	Eco	Mass	Eco
Min S	220	410	2 000	3 800	1.2	2.2	1.2	2.2
Ave S	290	540	2 200	4 200	1.7	3.2	1.8	3.2
Max S	410	765	2 600	4 900	2.6	4.9	2.8	5.3
PS S	280	530	2 500	4 650	2.9	5.4	2.9	5.4
Min S+L	200	315	1 900	3 200	1.0	1.5	1.0	1.6
Ave S+L	260	410	2 100	3 500	1.5	2.2	1.6	2.4
Max S+L	360	575	2 400	4 000	2.3	3.5	2.5	3.8

PS S+L	255	410	2 300	3 850	2.5	3.9	2.5	3.9
Min S+S	210	300	2 050	3 100	1.1	1.4	1.1	1.5
Ave S+S	280	390	2 250	3 400	1.6	2.1	1.7	2.3
Max S+S	400	545	2 600	3 900	2.5	3.3	2.7	3.6
PS S+S	280	390	2 500	3 750	2.8	3.6	2.8	3.7

The use of pig slurry, compared to the maximum fertiliser scenario, only reduces the impact in the two categories Global Warming Potential and Abiotic Depletion. In Acidification and Eutrophication Potential, the pig slurry scenario scores slightly worse compared to the maximum scenario.

4.1.2.2 Hotspot analysis

In this section, a hotspot analysis is presented for the impact categories GWP, abiotic depletion and acidification and eutrophication potential. For this analysis, the impacts have been grouped into the five groups fertilisers & pesticides, fertiliser induced field emissions, field operation, transport and fibre processing.

4.1.2.2.1 Global warming potential

For economic allocation, the impacts per category are shown in Figure 33. Three groups are responsible for most of the impacts in all the scenarios: fertilisers & pesticides, field emissions and fibre processing. From this figure, the increase in the fertilisation rate has the double effect of requiring more production of fertiliser and thus more emissions (see the blue bar in Figure 33) and more field emissions as more of the applied fertiliser is lost (see orange bar in Figure 31). In the fertiliser and pesticides category, the main contributor is the nitrogen production, especially at higher fertilisation levels. In the minimum scenario, the nitrogen fertiliser accounts for 45% of the group total while in the maximum scenario this has increased to almost 75%. In the organic fertilisation scenario, the fertilisers and pesticide group only includes the transport of pig slurry to the cultivation site. The pig slurry is considered a waste product and the environmental impact of the production is allocated to the pig farmer. However, due to the difference in pig slurry and mineral fertiliser, the application of pig slurry results in higher field emissions. Therefore, the orange bar increases in the pig slurry scenarios. The energy requirement of the fibre processing equipment is another hotspot. The use of renewable electricity, mainly wind or solar, could significantly reduce this impact.

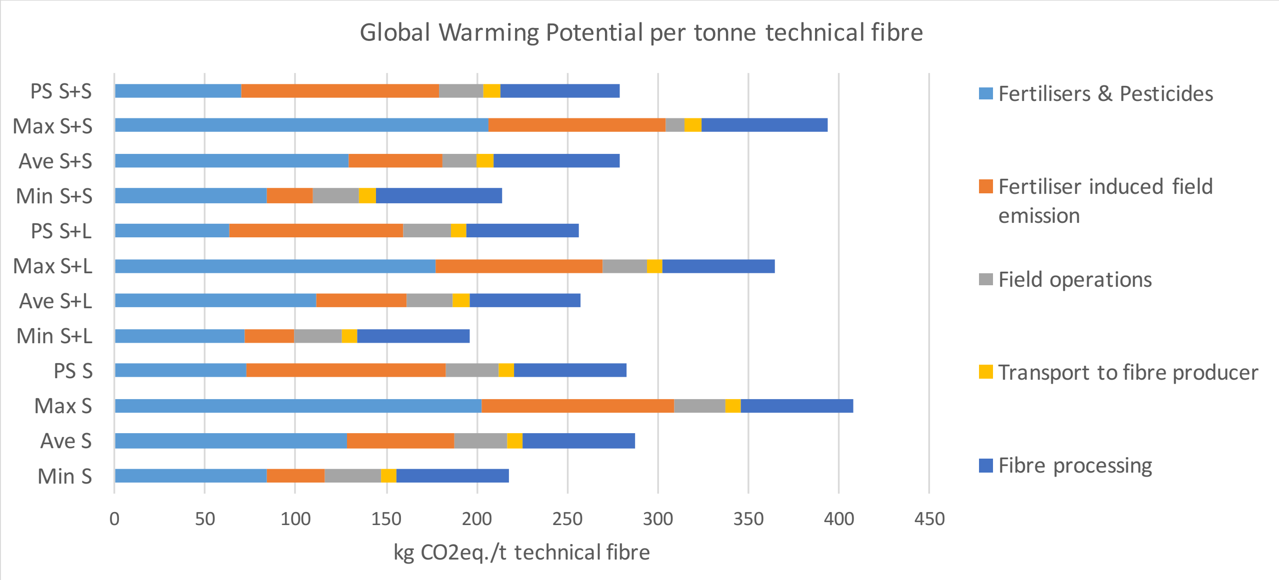

Figure 33: Global warming potential hotspot analysis per tonne technical fibre using mass allocation

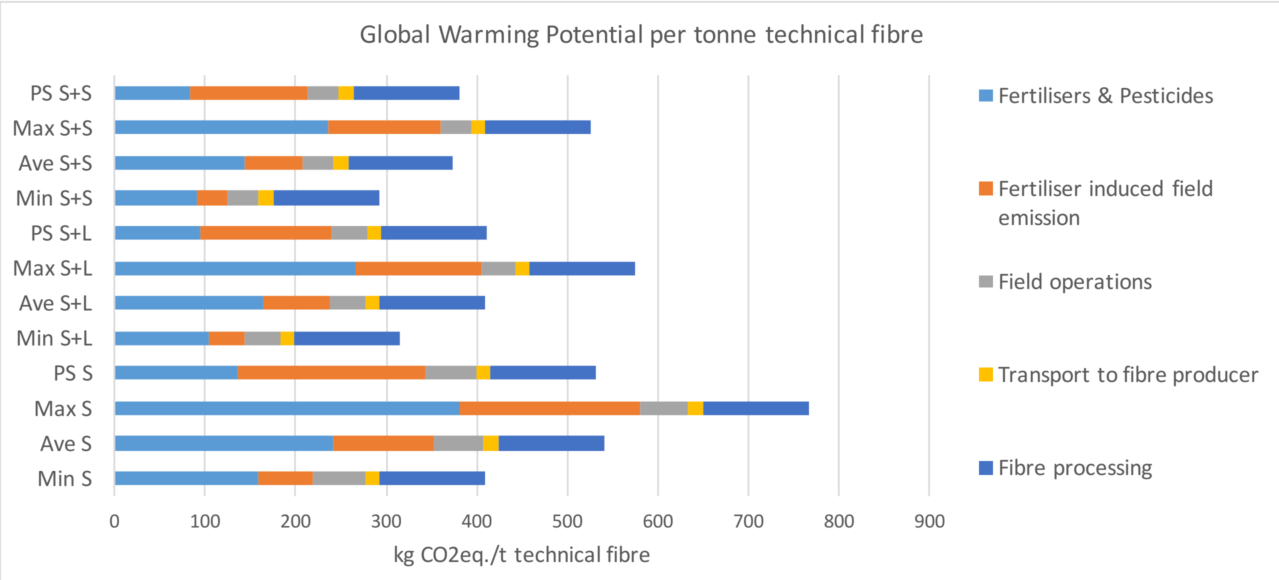

Figure 34: Global warming potential hotspot analysis per tonne technical fibre using economic allocation

The fertilisation rate should be considered very carefully as this has a high consequence for the environmental impact of the cultivation. Good agricultural practices can mitigate the fertiliser field emissions, as the nitrogen uptake efficiency increases with good agricultural practices. Similarly, mismanagement results in high environmental impacts. The development of precision farming may increase the nitrogen uptake efficiency of the crops and thereby reduce both the impacts associated with fertiliser production and the losses in soil.

4.1.2.2.2 Abiotic depletion

The abiotic depletion is shown in Figure 35 for mass allocation and Figure 36 for economic allocation. The two main environmental hotspots that can be identified for the abiotic depletion impact category are field operations and fibre processing. The machinery used in the cultivation of hemp straw requires diesel, which results in abiotic depletion of fossil fuels. The fibre processing is the biggest contributor to abiotic depletion as it requires electricity which is generated from fossil fuels. Increasing the shares of wind and/or solar energy in the electricity mix results in a decrease of abiotic depletion through electricity consumption. The abiotic depletion from the fertiliser application is highly dependent on the application rate: higher fertilisation rates require more fertiliser production and thus contribute more to abiotic depletion through the production process. This effect is visible as the minimum scenario only applies 30 kg N/ha and the maximum 120 kg N/ha.

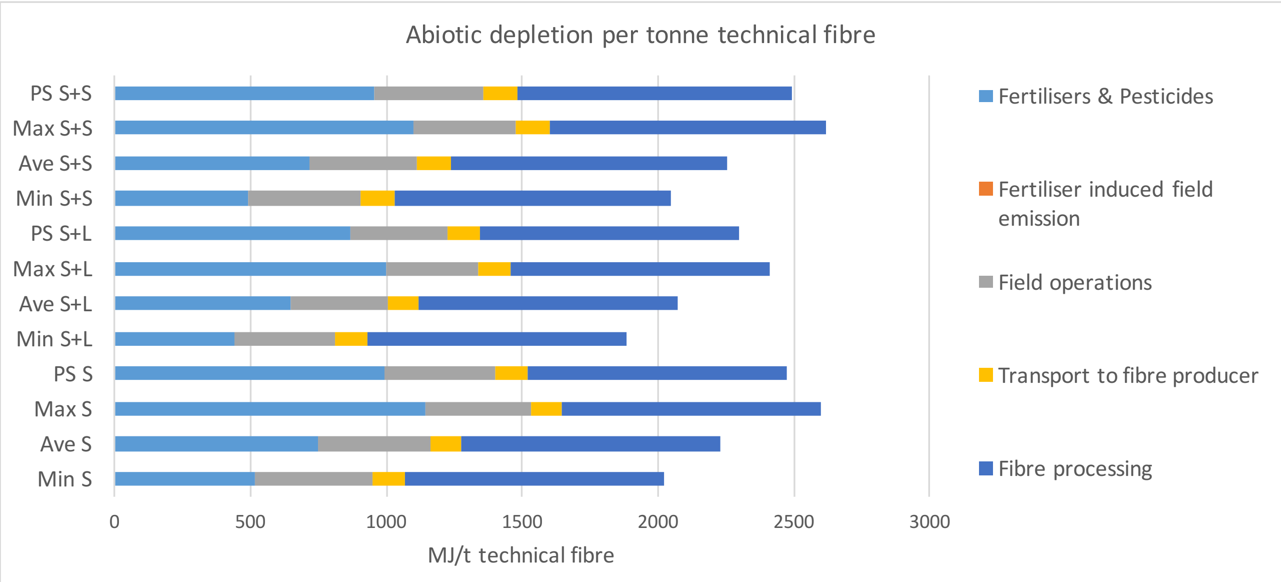

Figure 35: Abiotic depletion hotspot analysis per tonne technical fibre using mass allocation

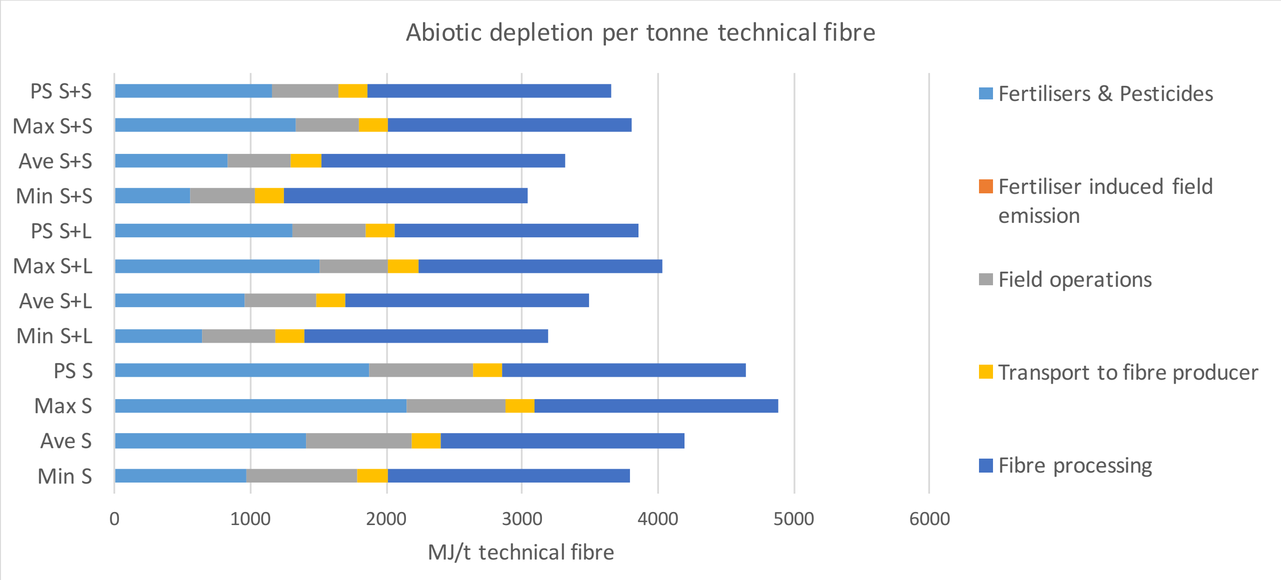

Figure 36: Abiotic depletion hotspot analysis per tonne technical fibre using economic allocation

4.1.2.2.3 Acidification & Eutrophication potential (AP & EP)

While acidification and eutrophication are different impact categories, field emissions are the biggest hotspot in both of them. Inefficiency in the fertilisation means that part of the supplied fertiliser ends up in the environment. This contributes to enriching the environment in nitrogen and phosphorus. In turn, nitrogen and phosphorus contribute to acidification and eutrophication through various mechanisms. Key to minimising the impact of agriculture is to increase nutrient uptake efficiency, and thereby reduce the losses of nutrients to the environment. This can be achieved by good agricultural practices which, however, cannot eliminate nutrient losses. Precision farming is a new technology that has the potential to mitigate the negative effect by reducing nutrient losses. Furthermore, the production of fertiliser contributes to acidification through industrial waste water. Nitrogen released into the air through combustion of fossil fuels contributes to eutrophication.

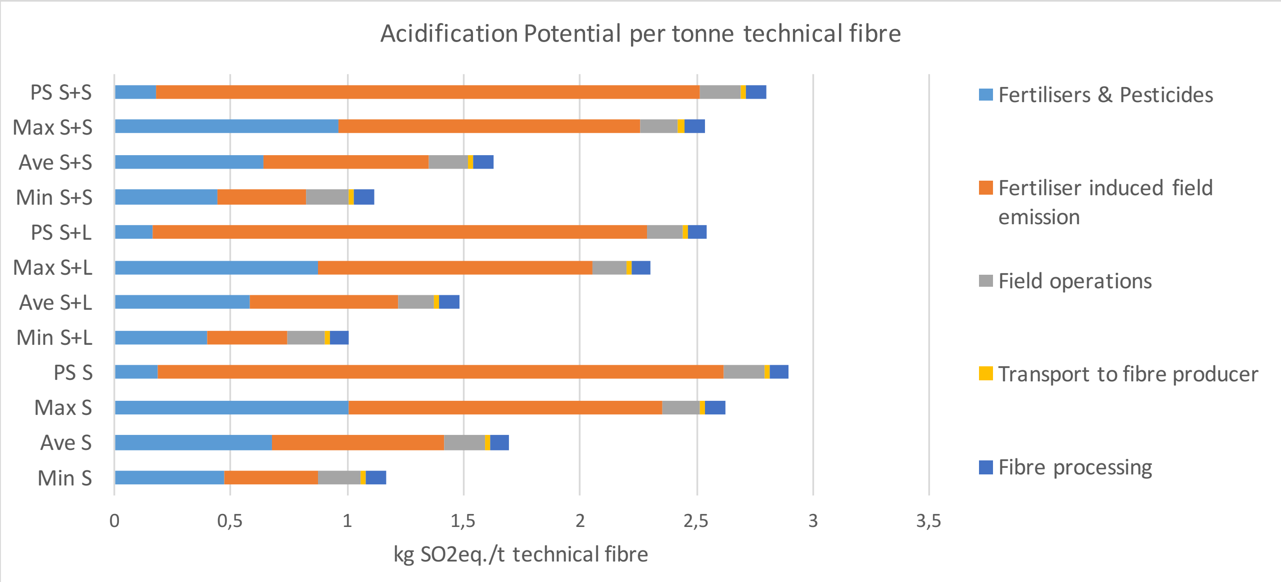

Figure 37: Acidification potential hotspot analysis per tonne technical fibre using mass allocation

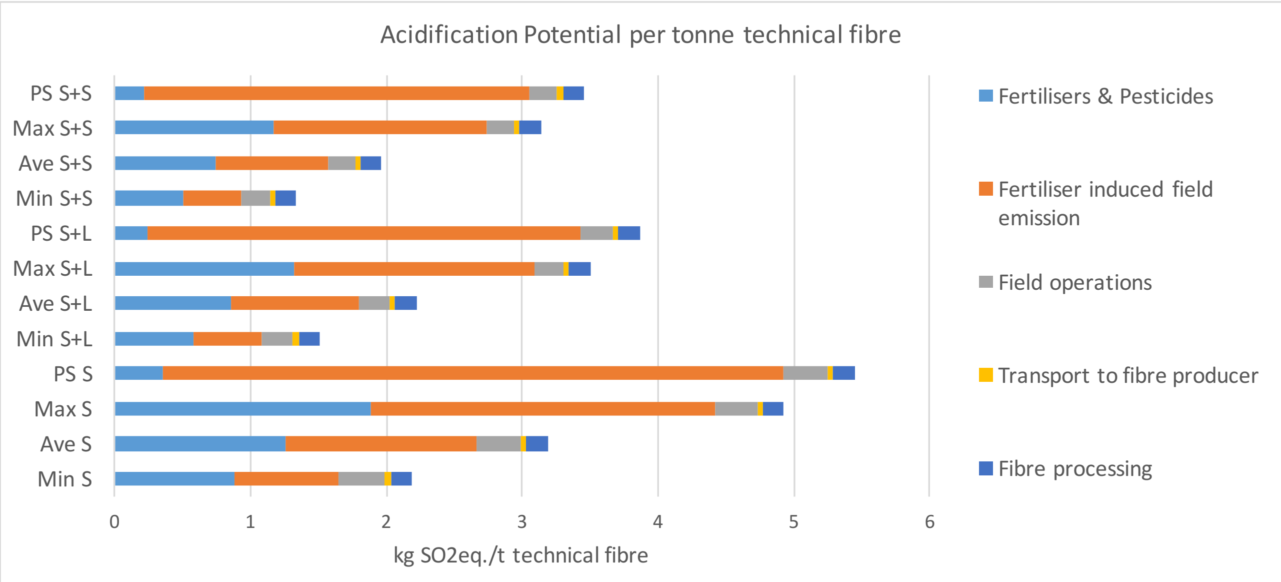

Figure 38: Acidification hotspot analysis per tonne technical fibre using economic allocation

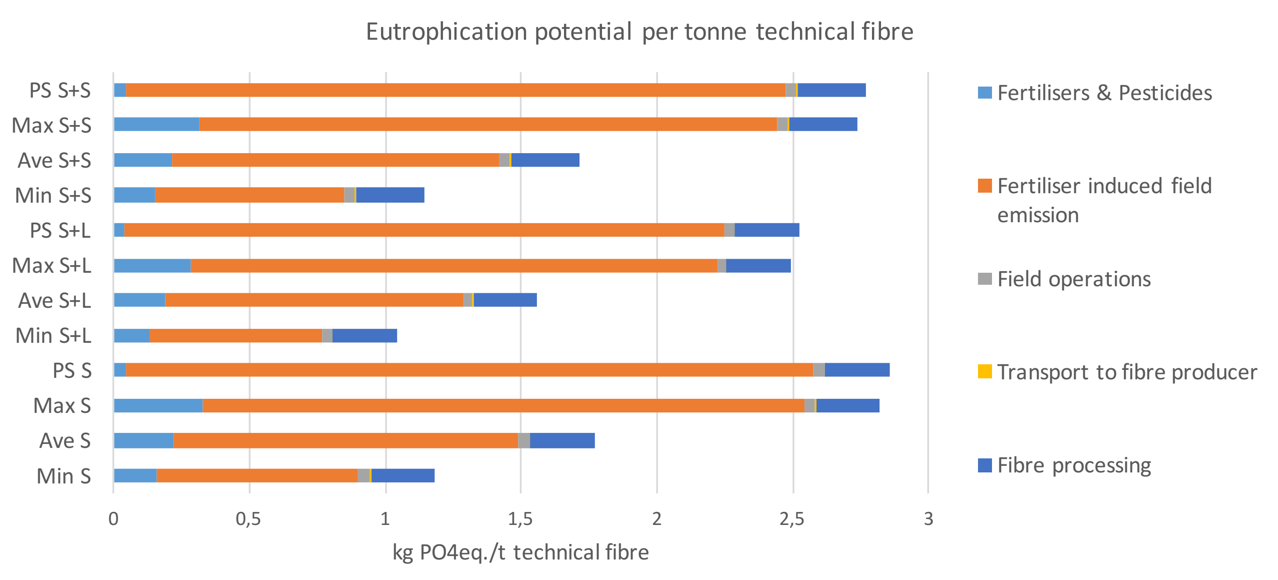

Figure 39: Eutrophication potential hotspot analysis per tonne technical fibre using mass allocation

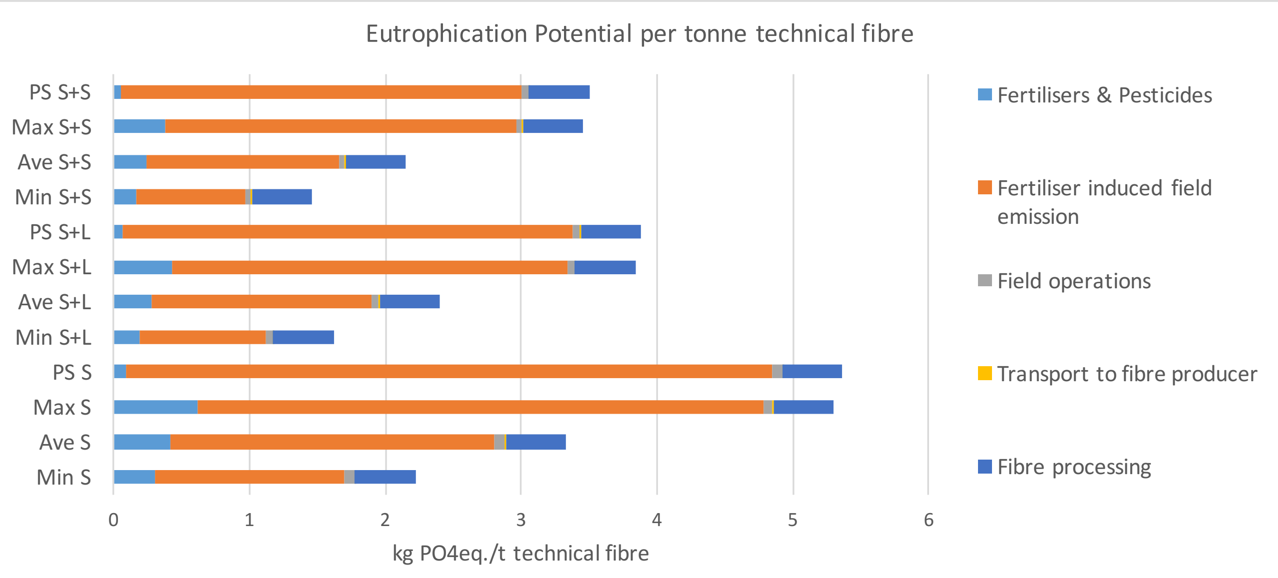

Figure 40: Eutrophication potential hotspot analysis per tonne technical fibre using economic allocation

4.1.2.3 Impact of biogenic carbon storage

To date, no international agreement has been reached on how to integrate the storage of biogenic carbon in LCA and carbon footprint (further readings for example: PAS 2050 (2011), Grießhammer & Hochfeld (2009) and Liptow et al. (2017)). In accordance to Liptow et al. 2017, biogenic carbon has been modelled separately - see Table 22.

Table 22: Typical values of compositions and stored carbon of hemp fibres

	Unit	Mass	Carbon	Embedded	Carbon dioxide

		distribution [kg/kg fibre]	content [%]	carbon [kg C/kg fibre]	removal from the atmosphere during plant growth [kg CO_2/kg fibre]
Cellulose	kg/kg fibre	0.65	40	0.26	0.95
Hemicellulose	kg/kg fibre	0.15	40	0.06	0.22
Lignin	kg/kg fibre	0.1	60	0.06	0.22
TOTAL		**1.00**	**100**	**0.38**	**1.39**

Through photosynthesis, carbon dioxide is split into oxygen and carbon. The carbon is used for plant growth and maintenance. Part of the carbon is reemitted through cellular respiration. During plant growth, more carbon is stored in the plant, since it is a key element in all known life. Therefore, plant growth results in the reduction of carbon dioxide from the atmosphere. In order to determine this reduction, the carbon content of the plant is considered and used to calculate how much CO_2 has been removed from the atmosphere to enable plant growth. This is calculated on the basis of typical cellulose, hemicellulose and lignin content of the fibres (data based on *https://www.ecn.nl/phyllis2/Browse/Standard/ECN-Phyllis##1010*) and their embedded carbon. Since the embedded carbon of hemp fibre is 0.38 kg/kg hemp fibre and the carbon source for plants is atmospheric carbon, the carbon dioxide removed from the air should be 0.38/12x44 = 1.39 kg CO_2 (where 12 is the molecular weight of C, and 44 is the molecular weight of CO_2). Since the scope of this LCA is cradle to gate, it is unknown in which form the stored carbon is released. Different forms of carbon have different global warming potentials (CO_2 = 1 CO_2eq. while CH_4 = 24 CO_2eq., hence, subtracting the carbon dioxide removed from the atmosphere from the GWP found in the study is inaccurate and debatable.

4.1.2.4 Comparison with other technical fibres

The MultiHemp cultivation and fibre processing is compared to other natural fibres. An assessment was performed comparing the environmental impact of the technical fibres with flax, commercial hemp, jute and kenaf technical fibres used in the automotive industry. It should be considered that the Multihemp cultivation data is based on field trials when assessing the results since agricultural field trials often result in higher yields compared to commercial production. For the life cycle inventory of the commercial hemp, kenaf, flax and jute production see Appendix II. Both economic and mass allocation are considered in the comparison for GWP, however jute and kenaf by-products are locally utilised for various purposes. This means that the value of the by-products is difficult to determine which hinders economic allocation. Therefore, economic allocation is not considered for jute and kenaf technical fibres. It is difficult to conclude that one fibre outperforms another due to the large variability in agricultural processes (shown in Chapter 4.1.1). The results for the GWP using mass allocation are presented in Figure 41 and using economic allocation in Figure 42.

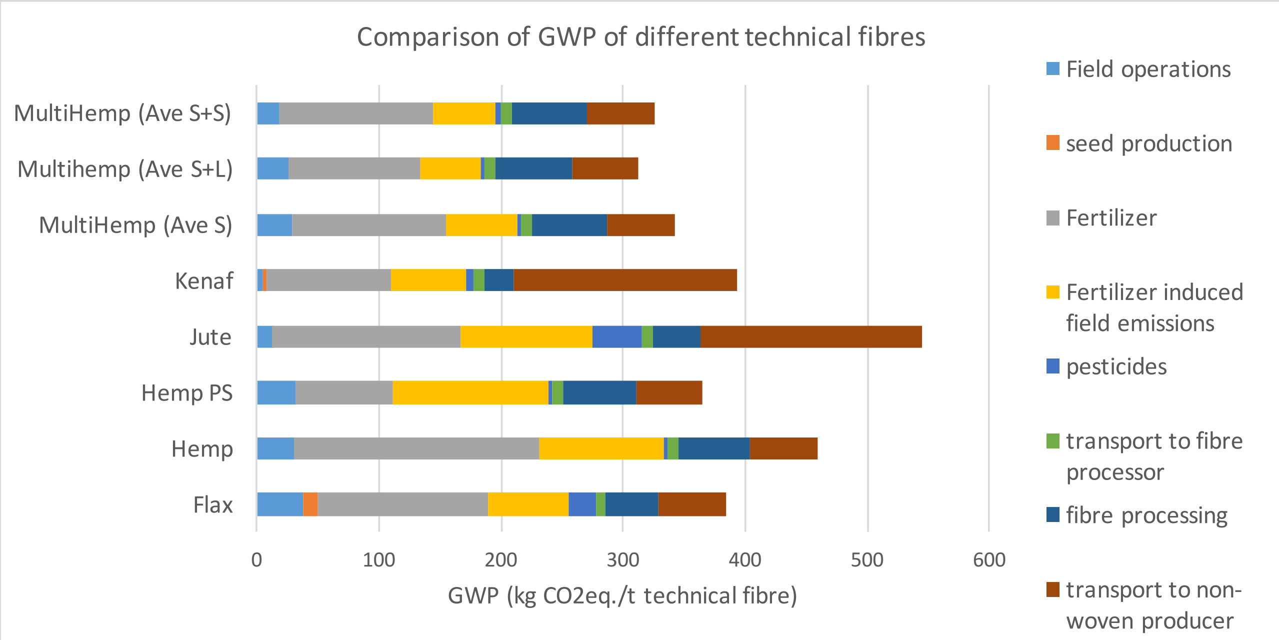

Figure 41: Comparison of global warming potential for different technical fibres for the automotive industry using mass allocation

According to the results in Figure 41, the global warming potential associated with the transport to the non-woven producer is high for kenaf and jute as these fibres are shipped from Asia to Europe. The MultiHemp cultivation scenarios compare favourably to the other technical fibres. Compared to the commercial hemp production, the MultiHemp data has lower fertiliser inputs and higher yields. It should be noted that the commercial hemp production (Hemp and Hemp PS) perform roughly similar to the other technical fibres. The impact of jute fibres are high compared to the others, especially kenaf, due to the low yield of jute in the data inventory. Jute straw yield is 3.9 t/ha while kenaf yield is 7.6 t/ha. While Jute straw is processed more efficiently into fibres (30% compared to 18% for kenaf), this benefit is not outweighed by the lower yield. Considering the variability in the agricultural process, Figure 41 should only serve as an indication. Possibly, there are no significant differences between the technical fibres.

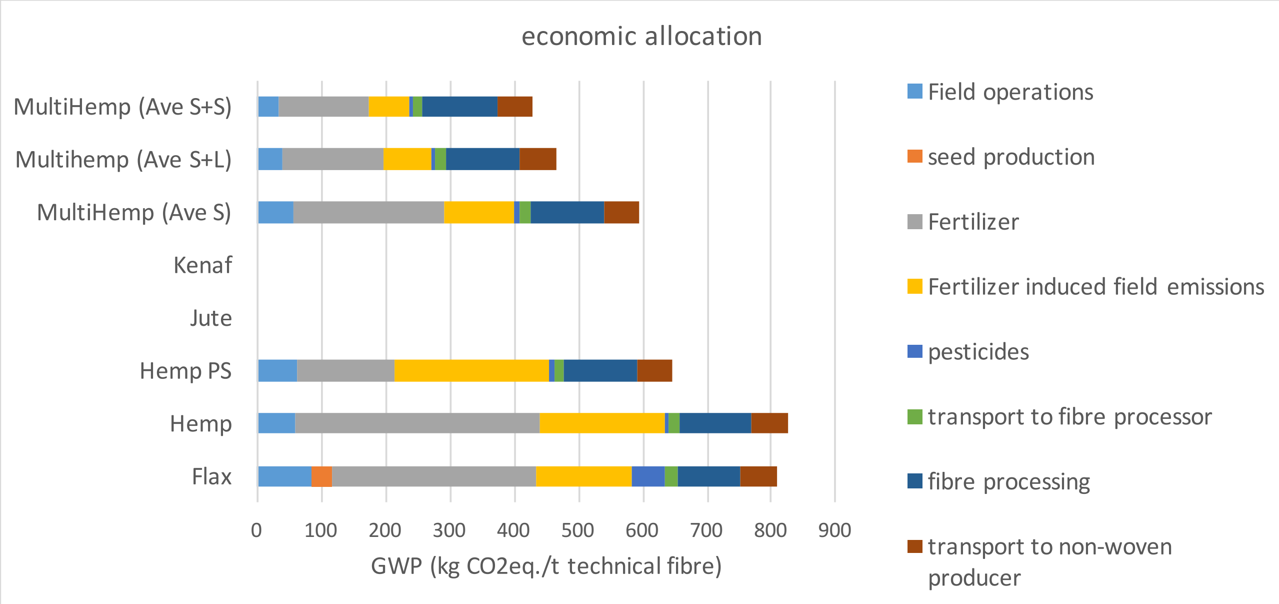

Figure 42: Comparison of global warming potential for different technical fibres for the automotive industry using economic allocation

Figure 42 shows the comparison based on economic allocation, in which jute and kenaf are excluded due to the difficulty of determining the value of by-products. The value of flax fibres depends on fashion trends and is therefore slightly higher compared to hemp fibres. This results in a higher share allocated to the fibre in economic allocation. Furthermore, the benefit of dual use hemp is illustrated as well as the advantages of organic fertiliser.

The abiotic depletion, acidification potential and eutrophication potential can be found in Figure 43, Figure 44 and Figure 45, respectively.

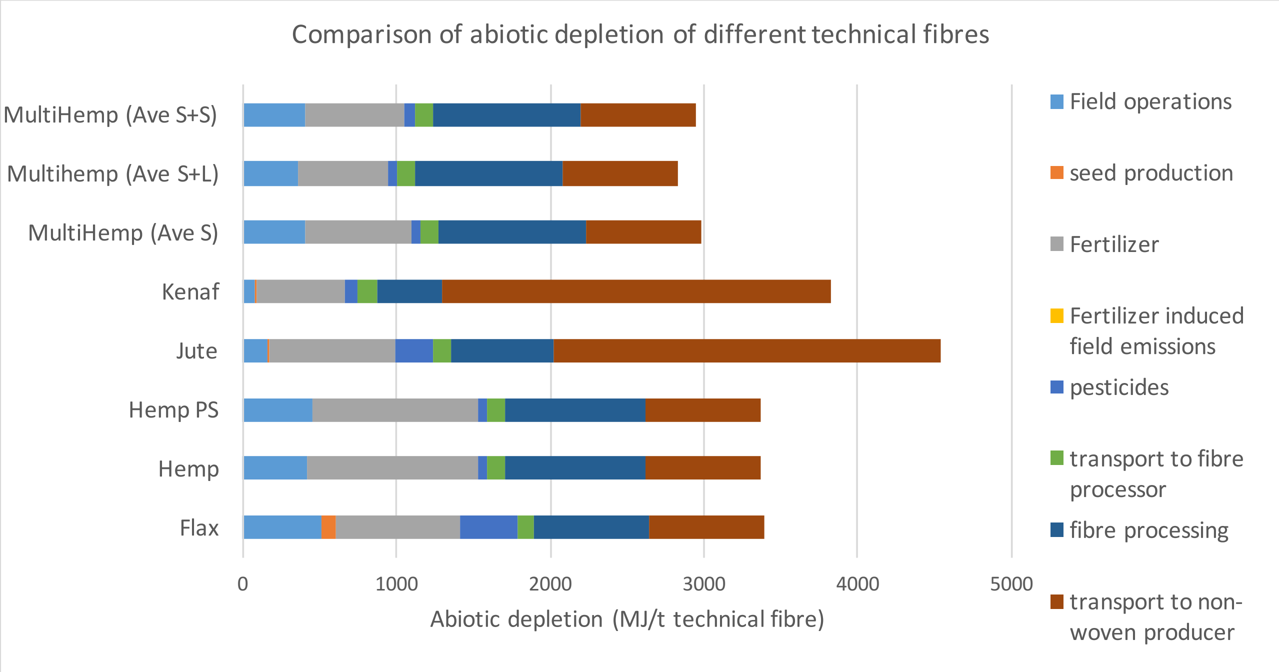

Figure 43: Comparison of abiotic depletion for different technical fibres for the automotive industry using mass allocation

Figure 43 shows the abiotic depletion for the technical fibres. While the cultivation and processing of jute and kenaf contribute less to abiotic depletion, the transport to Europe negates this advantage. If jute and kenaf would be used locally, they have an advantage over hemp and flax. Commercial hemp and flax have similar abiotic depletion potentials; the cultivation of hemp has higher fertiliser inputs, but flax requires more pesticides since the plant has weak competition characteristics.

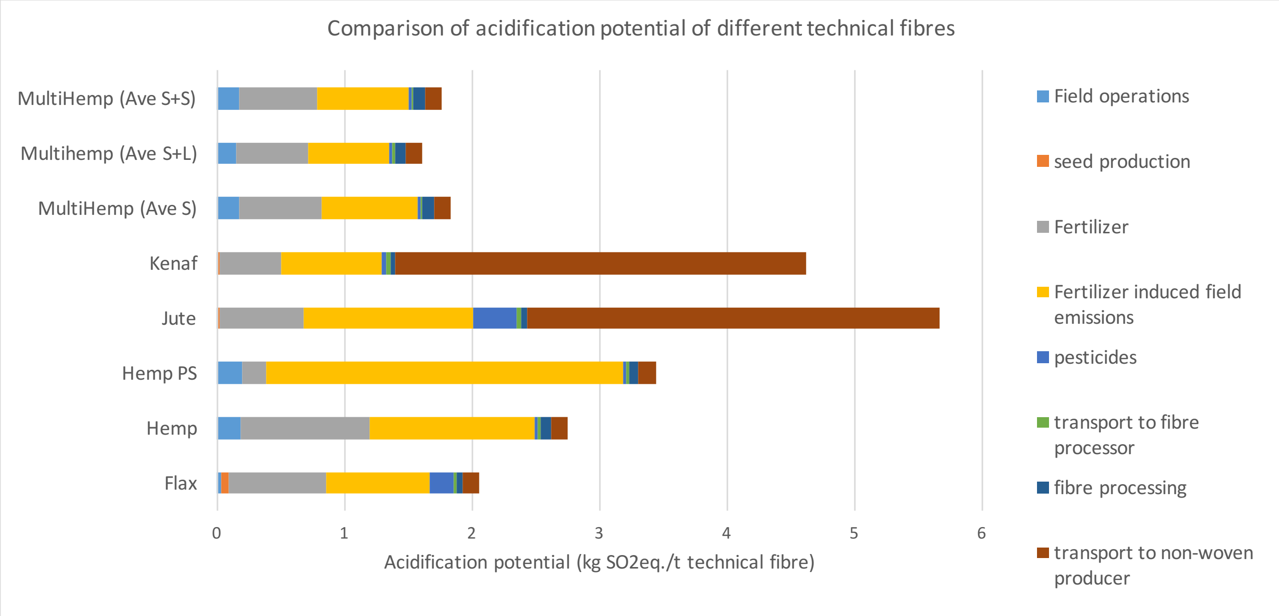

Figure 44: Acidification potential of different technical fibres for the automotive industry using mass allocation

The sea transport from Asia to Europe of jute and kenaf contributes heavily to acidification. Furthermore, the utilisation of organic fertiliser results in higher acidification potential. Flax has an advantage over hemp as it has low fertiliser inputs and this reduces the impacts from fertiliser production and the effects from field emissions. The MultiHemp hemp performs better due to relatively low fertiliser input and high yield.

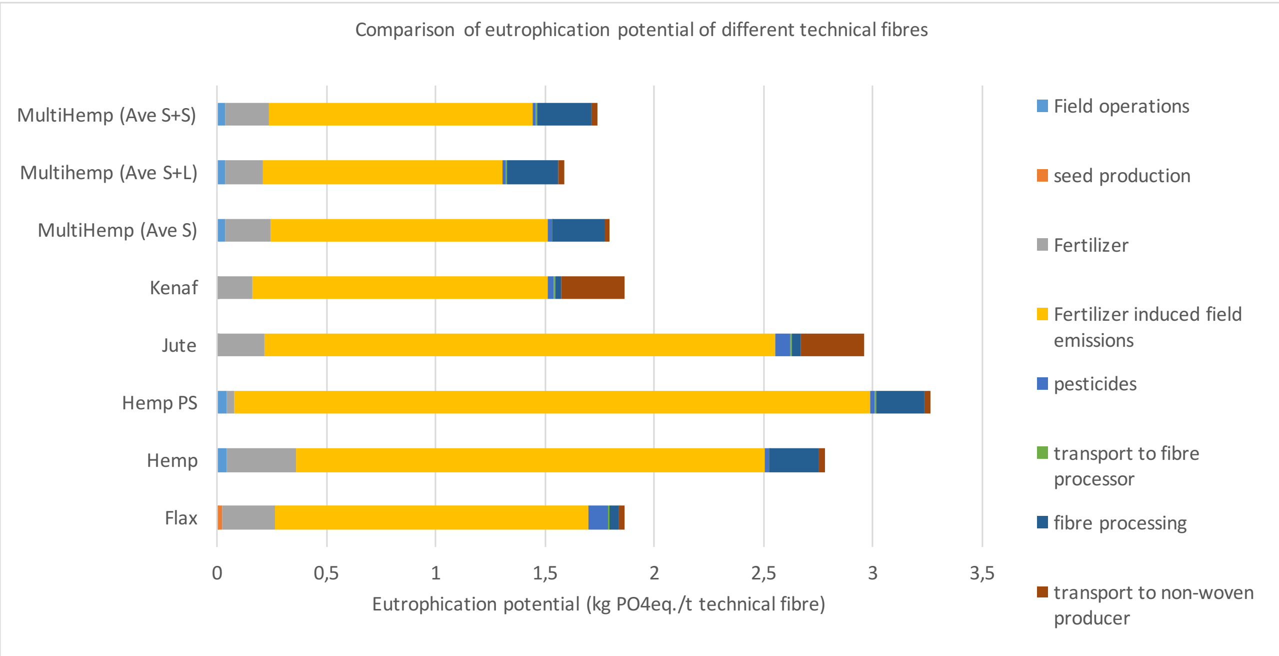

Figure 45: Eutrophication potential for different technical fibres for the automotive industry using mass allocation

In the eutrophication potential impact, the technical fibres with high fertilisation rate have a high impact. The organic fertiliser has the highest eutrophication potential from all scenarios. Also, the jute and hemp cultivation have high eutrophication potential. Transportation by sea, which is required for kenaf and jute, has an eutrophication impact. The other fibres are roughly equal.

4.2 Product level

4.2.1 Techno-economic assessment

On the product level, results are shown for the blow-in insulation material and construction panels as well as a theoretical value chain from cultivation to final products.

4.2.1.1 Blow-in insulation material

As shown in Figure 46 , total costs for the blow-in insulation material amount to 0.95 €/kg. 75% of these costs accrue to the input material of short and super short fibres. According to the inventory data in section 3.1.3.1, we assumed a price of 300 €/t for the short fibres and 400 €/kg for the super sort fibres and further assumed that the input material is an equal mix of both raw materials.

The calculated minimum price for the blow-in insulation material is therefore between that for cellulosic material (0.45 €/kg) and good quality wood fibre material (1.5 Euro/kg). According to Dirk Niehaus (Ventimola), a blow-in insulation material with a good thermal resistance could even achieve the price of up to 1.5 €/kg, but not more. In order to achieve a calculated profit margin of 10%, the blow-in production facility would have to fetch a price of about 1 €/kg, which would be in an achievable range. The whole process therefore appears to be economically sustainable.

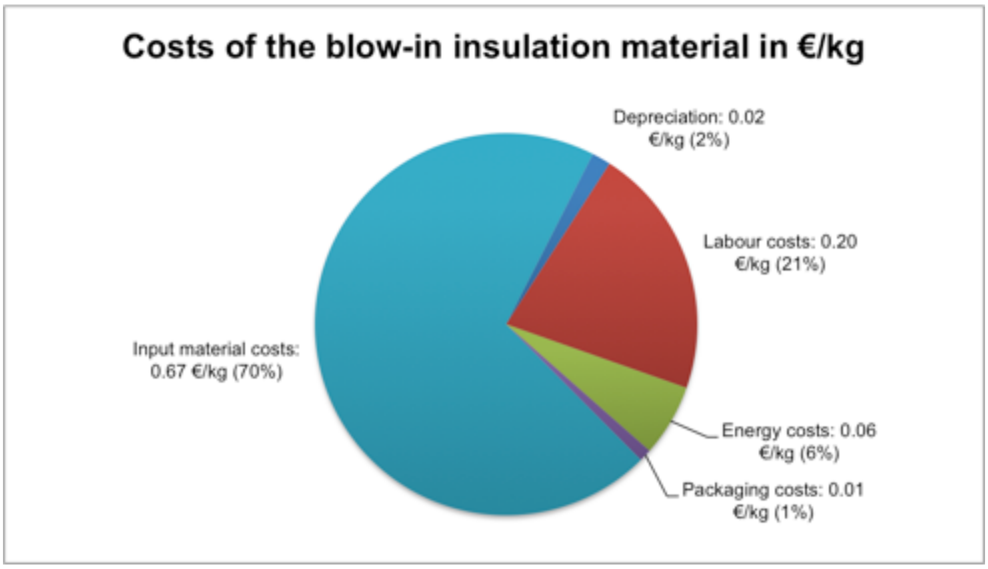

Figure 46: Costs for the blow-in insulation material in €/kg
Source: nova 2017

Figure 47 compares revenues from selling the blow-in material (assuming a price of 1.5 €/kg) and the by-product dust with the costs, profit and value added per tonne of hemp straw. As explained in section 2.1, the expression of the results per tonne of straw indicates the contribution that the respective process adds to the profitability and value added of the whole hemp value chain since straw is the primary output from hemp cultivation. In case of the blow in material, the profit amounts to about 18 €/t straw and the value added to about 24 €/t straw.

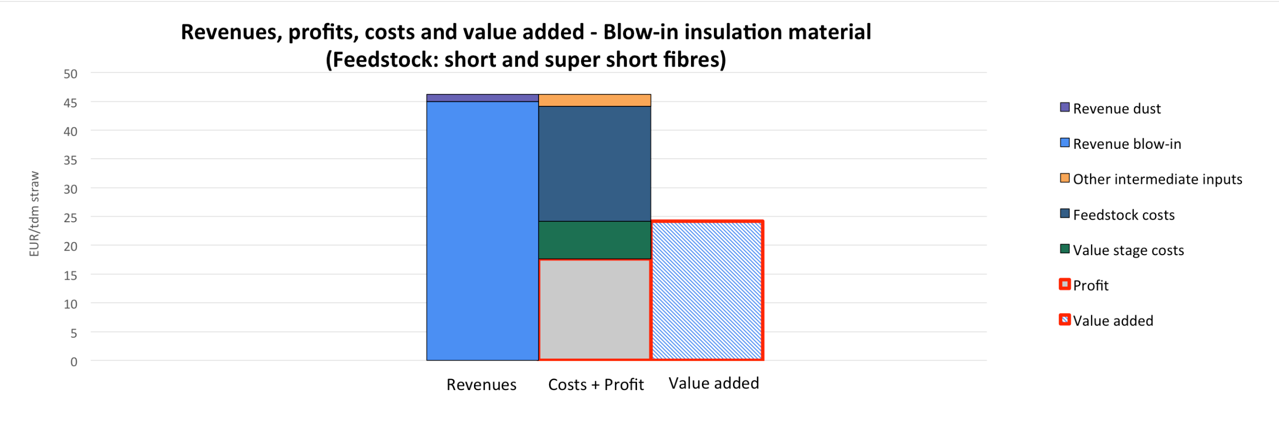

Figure 47: Revenues, profits, costs and value added – Blow-in insulation material
Source: nova 2017

The economic comparison of the blow-in insulation material to the THERMO HANF® product is not easy insofar as the process of installing the products into a wall is completely different and the respective costs of installation have not been part of this assessment. Still, the indicative price of THERMO HANF® of around 3 €/kg shows that the blow-in material could become a competitive product.

4.2.1.2 Hemp construction panels

As described in the inventory data in section 3.2.3, the CMF business plan includes a gradual build-up of operation until the fourth year of operation. As Figure 48 to Figure 51 show, both the production processes for the CA 350 and the CA 1100 generate losses in the first year but become more and more profitable from year 2-4. Main reason is that the scale of production gradually increases and hence economies of scale are exploited.

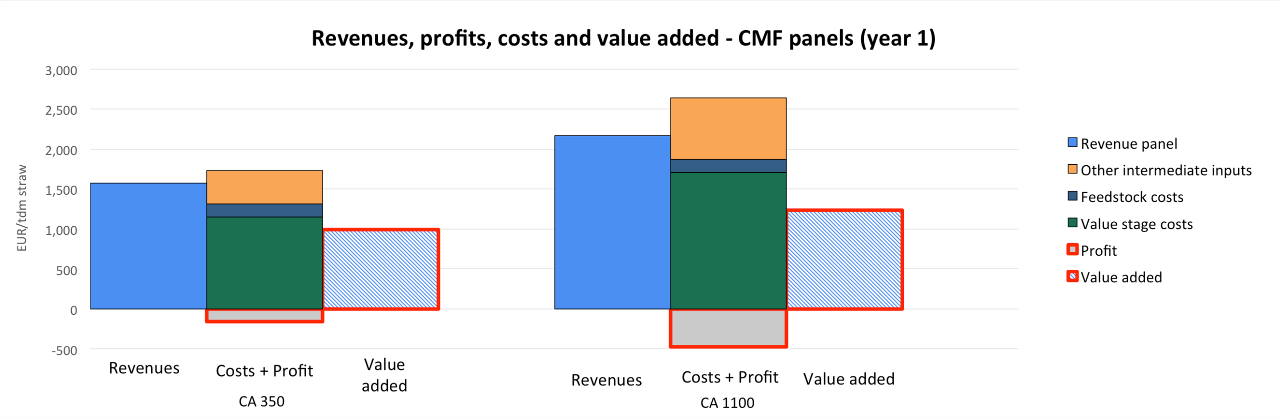

Figure 48: Revenues, profits, costs and value added – CMF panels (year 1)
Source: nova 2017

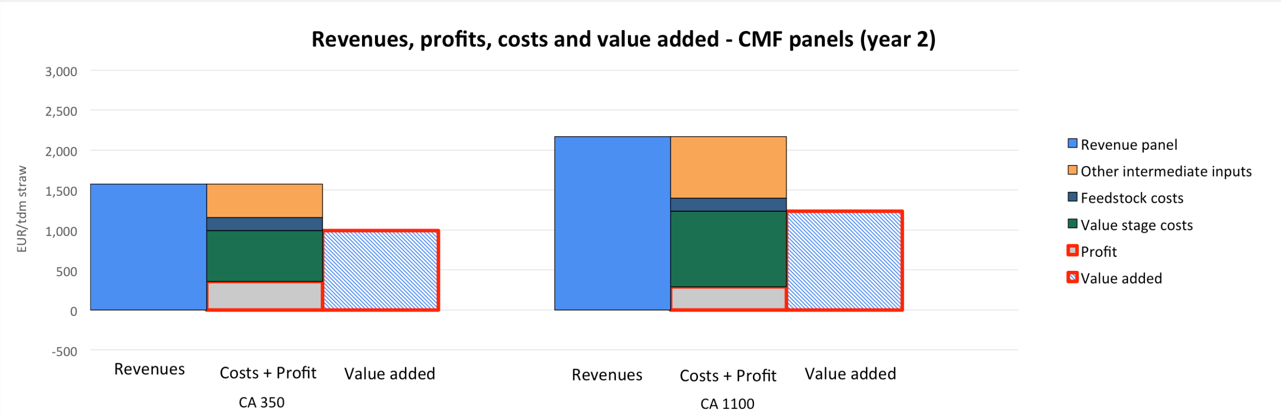

Figure 49: Revenues, profits, costs and value added – CMF panels (year 2)
Source: nova 2017

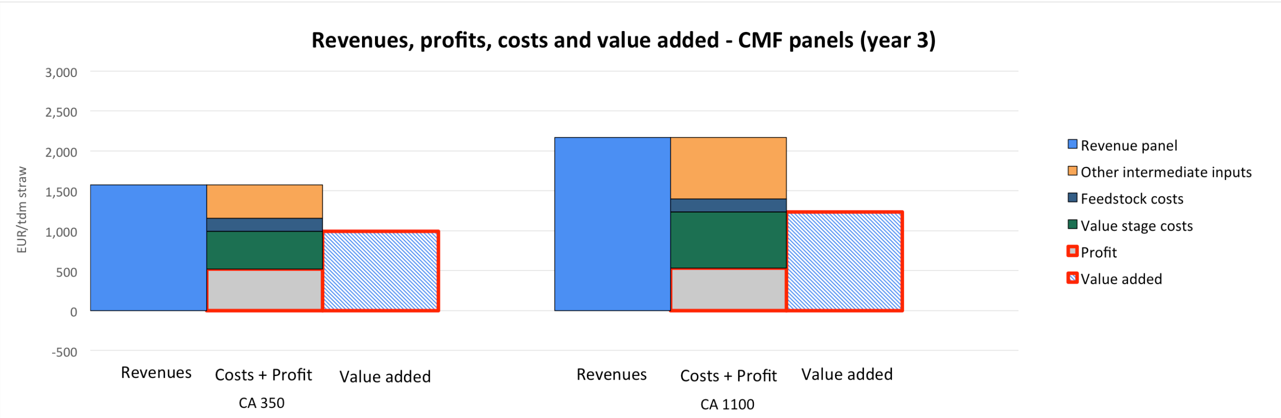

Figure 50: Revenues, profits, costs and value added – CMF panels (year 3)
Source: nova 2017

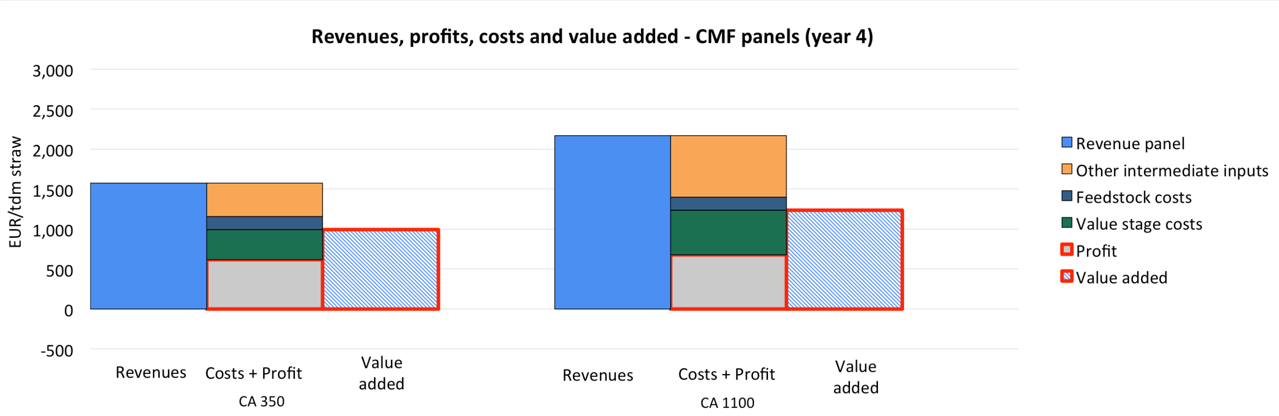

Figure 51: Revenues, profits, costs and value added – CMF panels (year 4)
Source: nova 2017

If only considering production from the fourth year onwards, calculated costs result in 310 €/m^3 for the CA 350 and 730 €/m^3 for the CA 1100 (Figure 52 and Figure 53). The fact that the production costs of the CA 1100 is more than double that of the CA 350 is mainly due to the fact that the CA 1100 is much denser and hence the production capacity of this process is much lower than for the CA 350 (about 12,000 m^3 are produced per year instead of 26,000 m^3).

According to the business plan, market prices of 510 €/m^3 for the CA 350 and 1,060 €/m^3 for the CA 1100 are envisaged. These prices are well in the range of published market prices for the conventional counterpart, the Heraklith panel, of 500-800 €/m^3. With these market prices, the facility could achieve a profit margin of 30-40%.

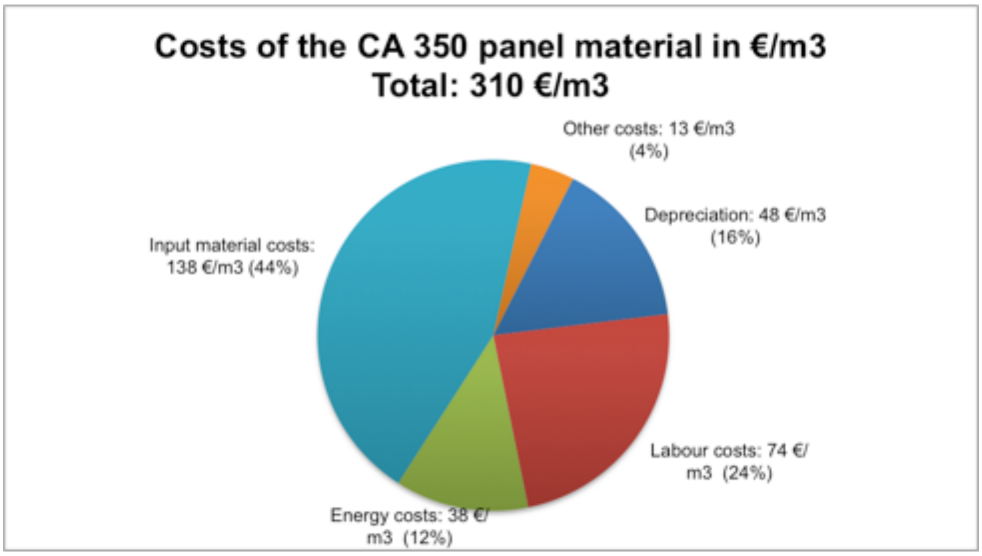

Figure 52: Costs for the CA 350 panel in €/m^3
Source: nova 2017

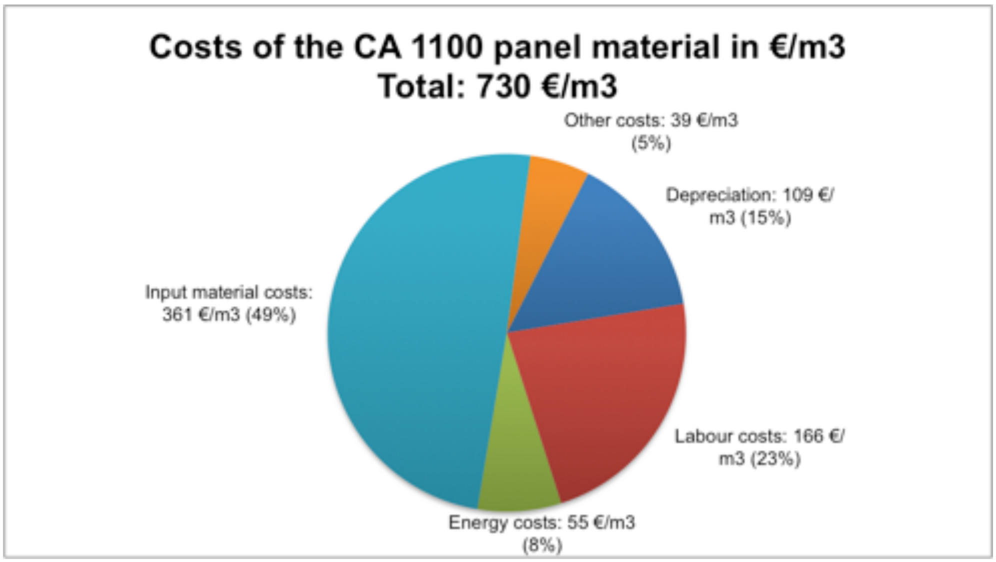

Figure 53: Costs for the CA 1100 panel in €/m^3
Source: nova 2017

While the share of input material costs for the CA 350 and CA 1100 are similar, the input mix mainly differs in the share of costs for magnesium oxide (MgO). Moreover, the high cost share of MgO for both products could be an issue where reduction potentials should be targeted, also considering that MgO has negative environmental implications (see section 4.2.2.2). However, it should be noted that the assumed price for MgO was 0.65 €/kg, based on Eurostat, while CMF themselves reported a current price for their MgO of 0.37 €/kg. Even this lower price was used, MgO would still be an important cost item.

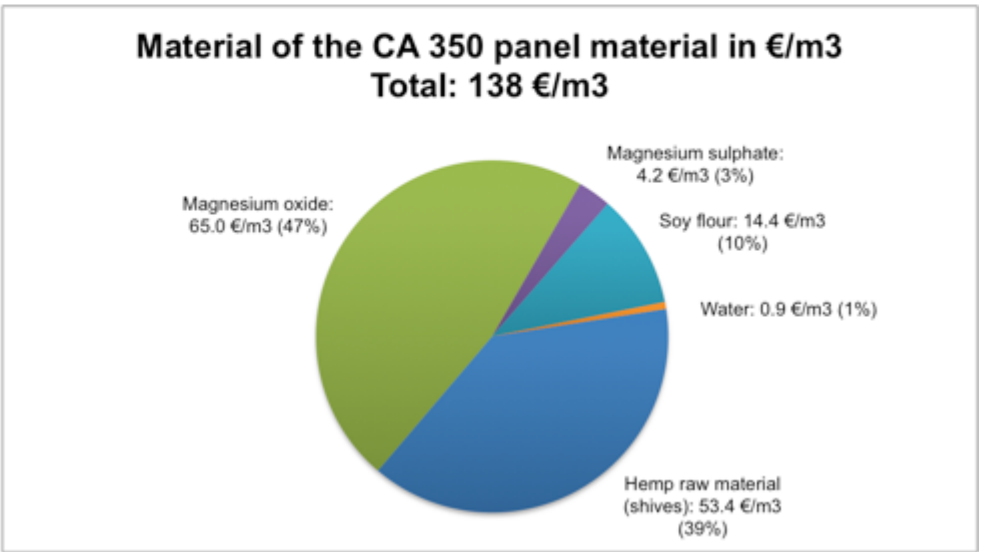

Figure 54: Material costs for the CA 350 panel in €/m^3
Source: nova 2017

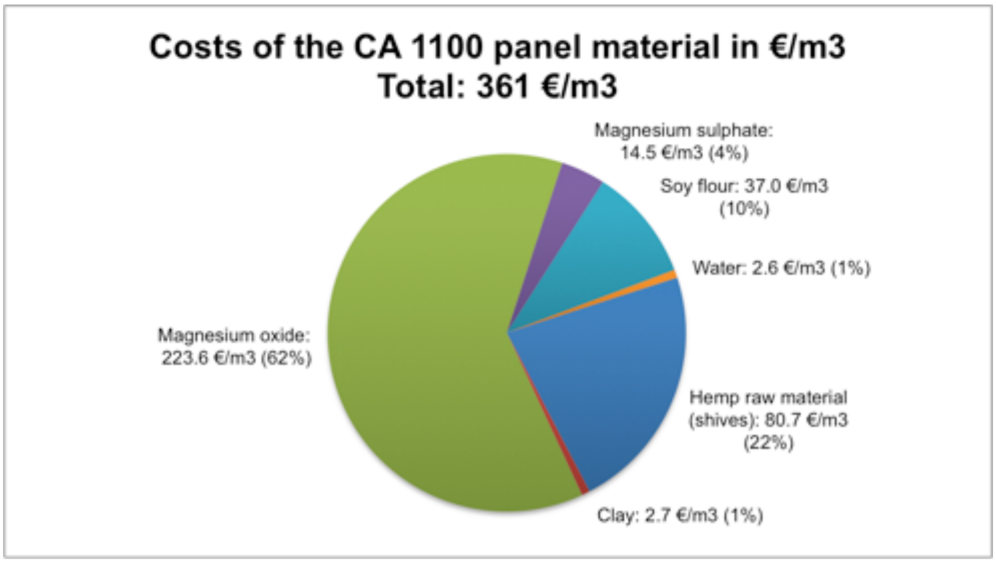

Figure 55: Material costs for the CA 1100 panel in €/m^3
Source: nova 2017

4.2.1.3 Value chain level

Apart from the evaluation on the system and product level, an assessment can also be made on the level of a whole value chain, in effect integrating both the system and product level. Questions to be answered with this level of assessment include the amount of revenue, profits, costs, value added and employment generated by a particular value chain from cultivation until final products.

Due to the level of data available, it is possible to compare a complete value chain which produces as final product a blow-in insulation material from the short and super short fibres as well as construction panels from the shives. The technical fibres, for which complete data for a final product are not available, would be sold at the current market price while the dust would be sold for incineration.

The representation of such a value chain is shown in Figure 56. As shown in section 4.1.1.1, the highest profit and value added could generated in the pig slurry cultivation scenario while the large total fibre line would be superior to the smaller plant. Furthermore, per tonne of straw, the production of the CA 1100 panel from the shives would generate a slightly higher profit and value added than the CA 350.

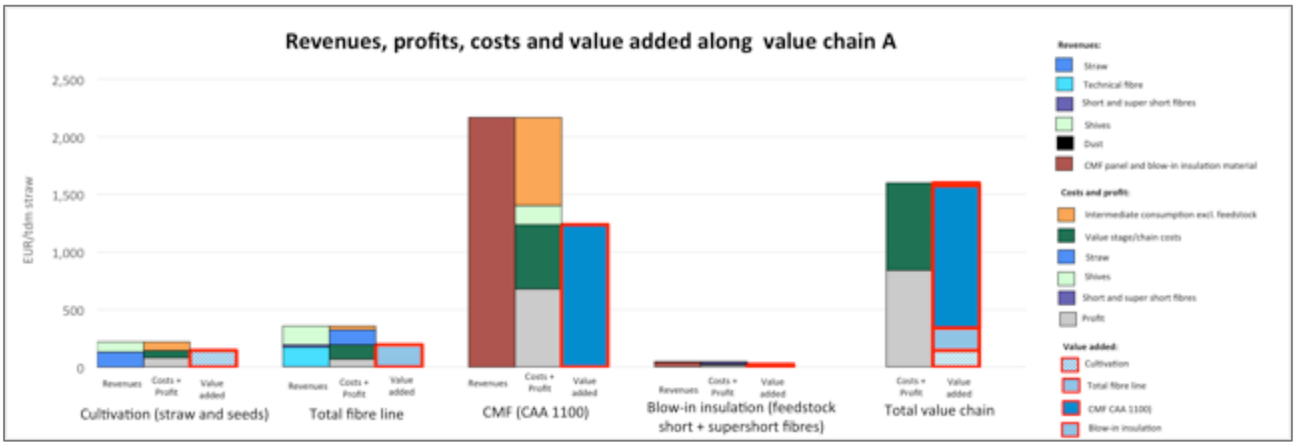

Figure 56: Revenues, profits, costs and value added along a hemp value chain
Source: nova 2017

Furthermore, Figure 56 shows that even though the short and super short fibres are apparently a very suitable raw material for the blow-in insulation material, it generates comparatively little added value to the whole chain due to the low share in volume. Finally, on the right side of Figure 56, the costs, profits and the value added are added up over all stages of the value chain.

Not considering the further uses of the technical fibre, it can therefore be concluded that one tonne of hemp straw could generate a value added of more than 1,500 €/t. Only adding up the labour hours over this value chain results in about 25 labour hour per tonne of straw. Given that it is commonly assumed that one full-time equivalent (FTE) works 2,000 hours per year, a rough estimate is that 1 hectare of hemp could generate at least 0.1 FTE (given the straw yield of 9.6 tdm/ha in the pig slurry scenario).

Evidently, by far the highest contribution to profits and value added in the value chain depicted in Figure 56 would be due to the production of the CMF panel. It needs to be noted that this is a particular business case which may be a commercial reality but does not necessarily has to be.

4.2.2 Environmental assessment

The product level environmental assessment first discusses the hotspots for the production of hemp blow-in insulation material, developed in the MultiHemp project, and for a hemp insulation material named “THERMO HANF®”. The hotspot analysis covers the global warming potential, abiotic depletion, acidification potential and eutrophication potential. This is followed by a comparison of the two hemp based insulation materials. Finally, the GWP of the hemp based insulation materials are compared to conventional insulation materials. The structure for the Canapalithos 350 hemp construction panel is similar, thus first the hotspots in the production process are discussed followed by a comparison with a counterpart. The identified counterpart is a wood wool board. For the other hemp construction panel, Canapalithos 1100, only the hotspot analysis is presented since no environmental assessment was available for suitable counterparts.

4.2.2.1 Hemp blow-in insulation material

In the production process of the blow-in insulation material, significant quantities of dust are produced which have the potential to be valorised as briquettes. Since the discrepancy between mass and price multiplied by mass in this process is big, economic allocation is the only allocation which is considered. When using economic allocation, more than 95% of the impacts are allocated to the blow-in material, while mass would only allocate 50%. Mass allocation is not used as the main product, has a much higher value compared to the briquettes. Thus allocation based on mass allocates a high share of the impacts to a low value product, making it unsuitable in this situation.

4.2.2.1.1 Hotspot analysis

In Figure 57, the results for the global warming potential of blow-in insulation are shown for the 12 cultivation and harvesting scenarios. These scenarios give an indication of how wide the range of global warming potential for blow-in insulation is due to variability in the cultivation. The lowest GWP can be found at 1,350 kg CO_2eq./t blow-in insulation while the highest is close to 1,800 kg CO_2eq./t. The calculated values for the blow-in insulation should be considered as a range of possibilities.

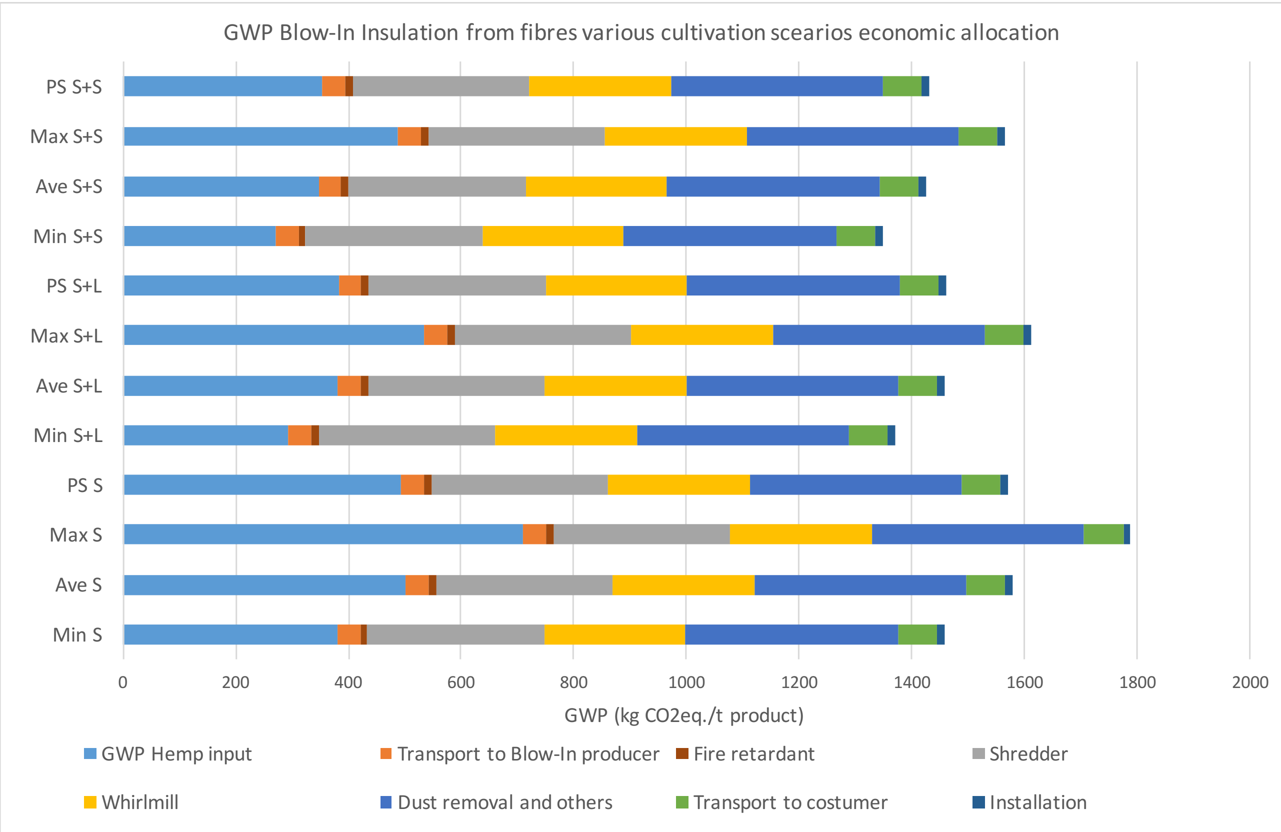

Figure 57: Global warming potential for hemp blow-in insulation material using economic allocation

it is clear from Figure 57 that there are several hotspots in the production of blow-in insulation material. The short and super short fibres are responsible for a significant part of the GWP. However, the main impact is associated with the electricity consumption during the production of the insulation material. The shredder, whirl mill and dust removal and others account for roughly 50% of the total global warming potential. The production of blow-in insulation was based on small scale production, thus further optimisation can reduce the environmental impact of the production. Based on an expert estimate, the energy requirement for the production of cellulose blow-in insulation material can be around 200 kWh/t. Therefore, there is significant room for optimisation even when the hemp blow-in production requires more electricity compared to the cellulose blow-in.

In the abiotic depletion impact category, the main impact is the blow-in insulation production, which requires high amounts of electrical energy. It can also be seen that the hemp cultivation has a relatively small part of the final impact.

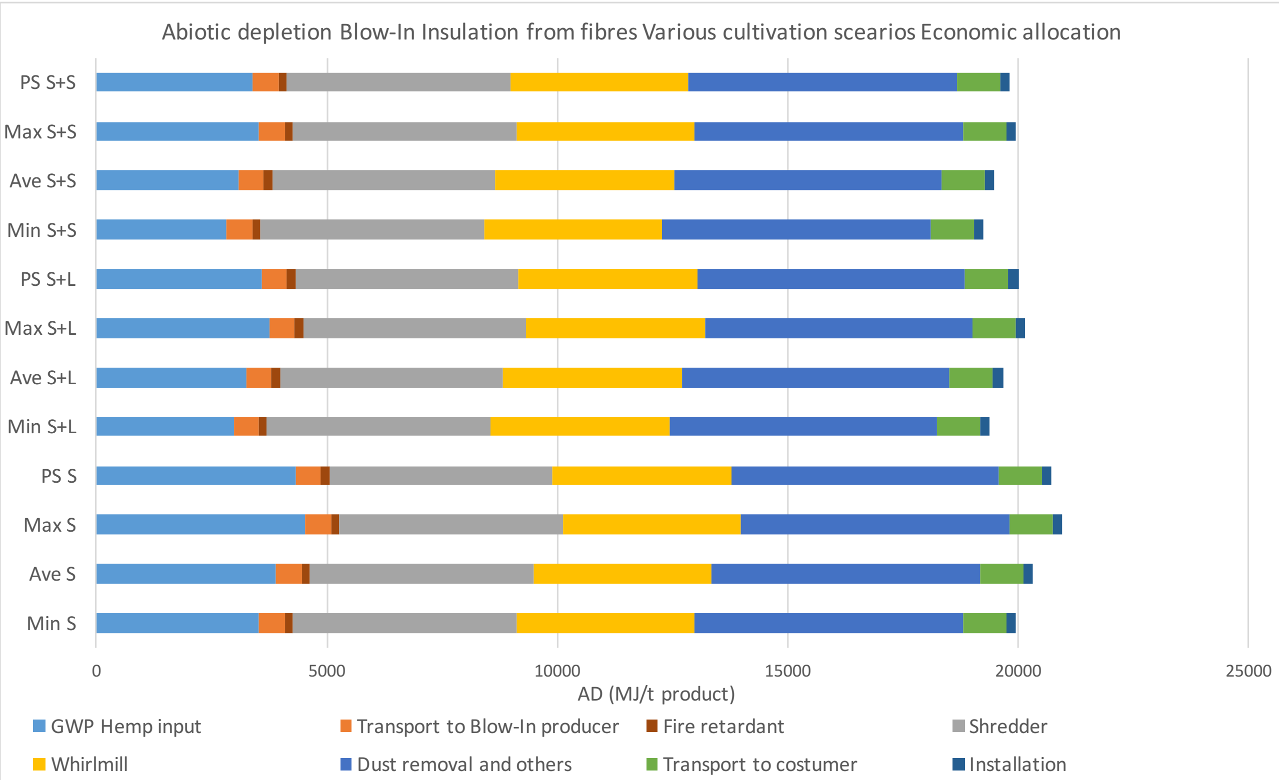

Figure 58: Abiotic depletion for hemp blow-in insulation material using economic allocation

In the acidification and eutrophication potential, the cultivation of hemp biomass used in the blow-in insulation material is high. Due to the high fertiliser use, and associated losses, the cultivation systems with high fertiliser input have a high acidification and eutrophication potential.

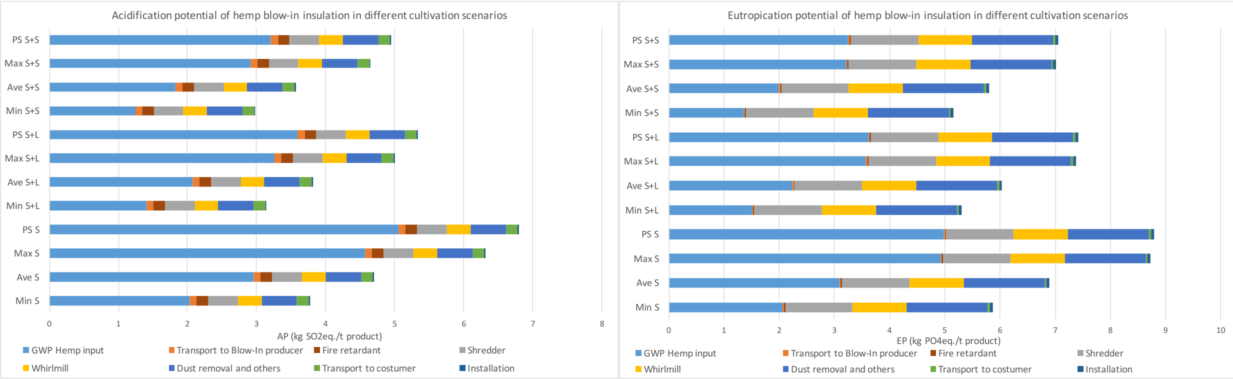

Figure 59: Acidification (left) and eutrophication (right) potential for hemp blow-in insulation material using economic allocation

4.2.2.1.2 THERMO HANF®

The global warming potential for the production of THERMO HANF® is roughly similar to the global warming potential of the blow-in insulation product. Given the data used, the global warming potential is found between 1,300 kg CO_2eq./t and 1,750 kg CO_2eq./t. This variation is a result of the different cultivation scenarios and does not consider uncertainties and variations within other parts of the life cycle. The hemp fibres, BICO fibre and the energy for the production of THERMO HANF® are the biggest contributors. It is noteworthy that THERMO HANF® only contains 10% BICO fibre, but the impact of the BICO fibre is more than 10% (see figure 56). Energy required for the production of THERMO HANF® is another hotspot.

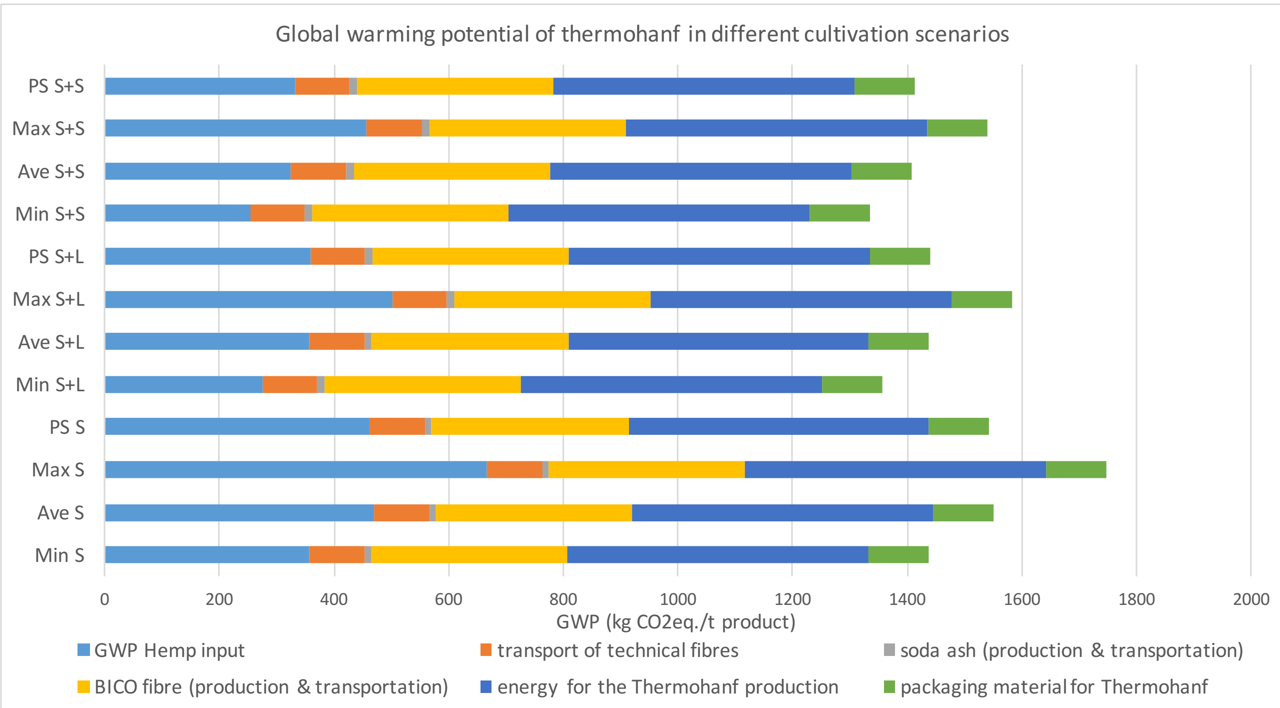

Figure 60: Global warming potential of THERMO HANF® using economic allocation

For the other impact categories, the conclusions are similar to the blow-in production. The energy required for the THERMO HANF® production and the BICO fibres make up the bulk of the abiotic depletion, while the production of the hemp fibres has relatively little impact on the abiotic depletion. The production of hemp fibres is the main hotspot for acidification and eutrophication in the environmental assessment of THERMO HANF®. The production of the BICO fibre contributes to the acidification. In eutrophication, another hotspot is found in the electricity consumption, due to the combustion of fossil fuels required for fossil fuel production.

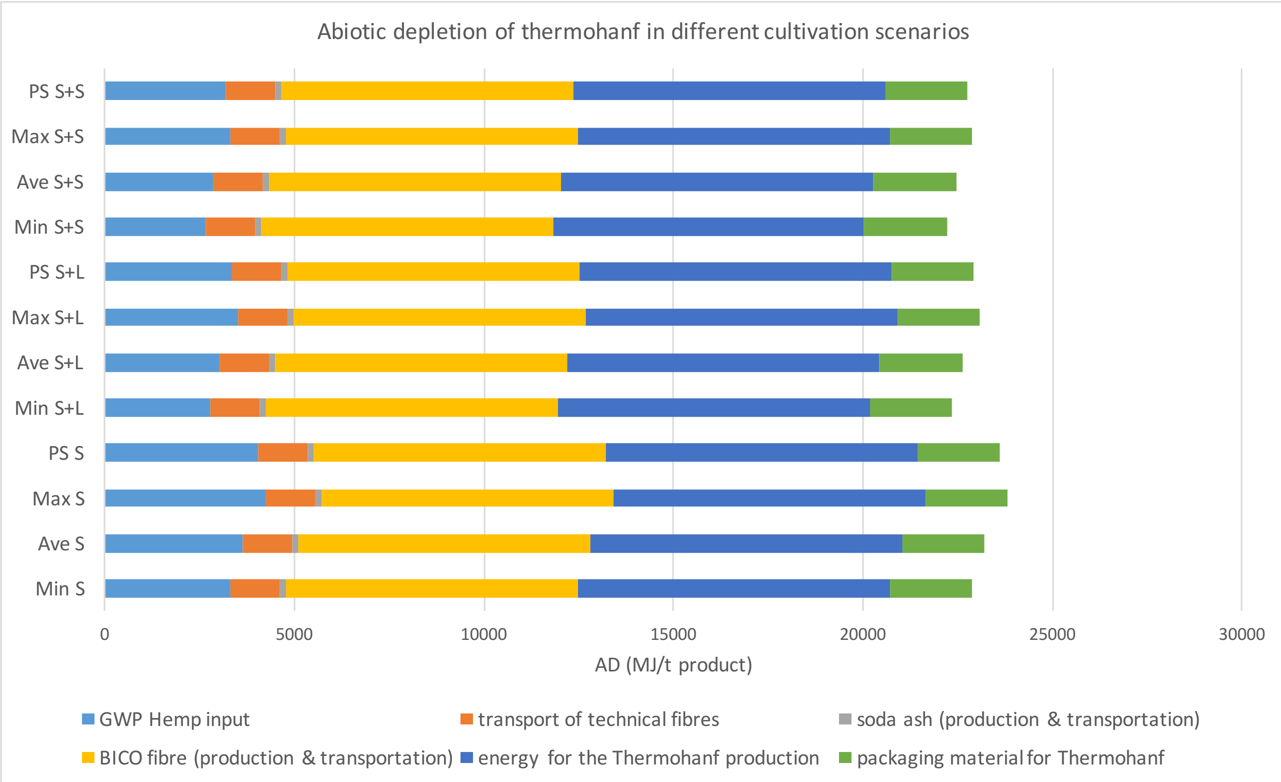

Figure 61: Abiotic depletion per tonne THERMO HANF® using economic allocation

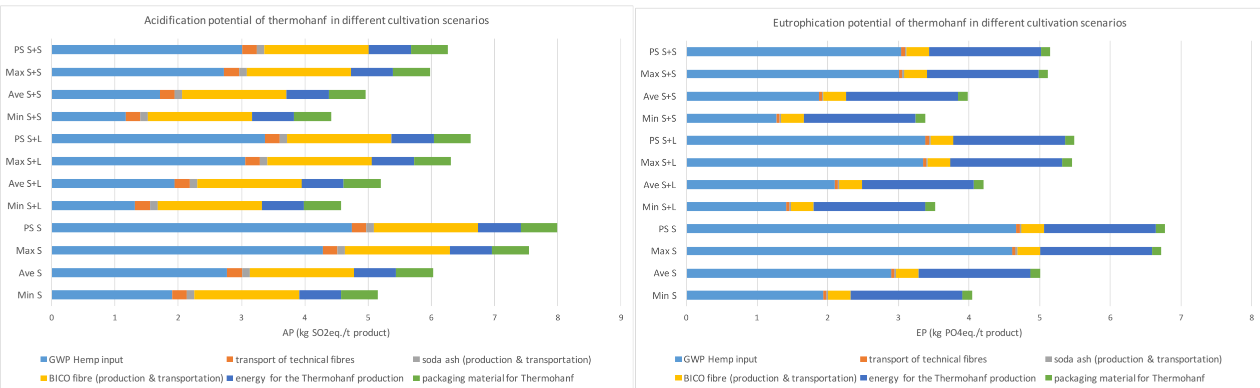

Figure 62: Acidification and eutrophication potential per tonne THERMO HANF® using economic allocation

4.2.2.1.3 Blow-In Insulation compared with THERMO HANF®

In this section, the hemp blow-in insulation developed in the Multihemp project is compared with the assessment of THERMO HANF®. In the figures below (Figure 63, Figure 64 and Figure 65), the guide value refers to a value found on www.Baubook.info which refers to the tabulated heat protection values in the ÖNORM 8110-7 on insulation in building construction. The figures show the average value of the 12 scenarios and the bars represent the highest and lowest value found in the scenarios. For comparison, only economic allocation is used, because in mass allocation, a disproportionate amount of burden is placed on the dust.

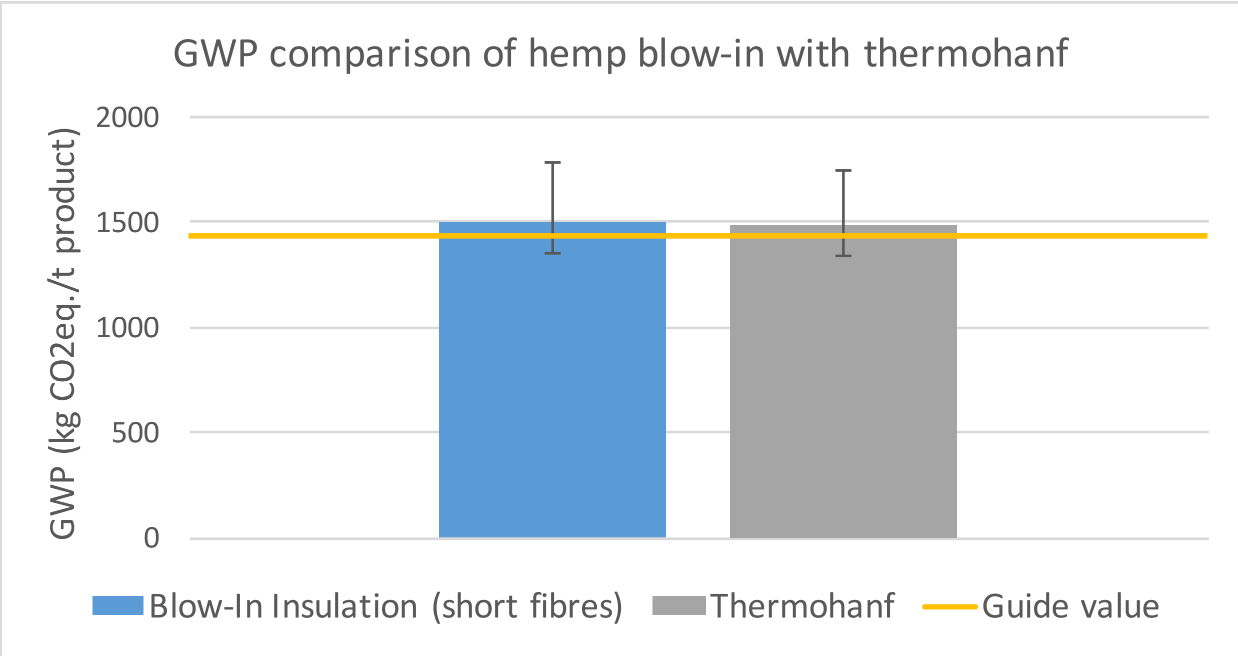

Figure 63: Comparison between the global warming potential of hemp blow-in insulation, THERMO HANF® and guide values given in ÖNORM 8810-7

The GWP of the blow-in insulation and THERMO HANF® is very similar. The guide value falls within the range values found for both materials. Through process optimisation, it is likely that the blow in insulation will improve and thus the global warming potential decreases.

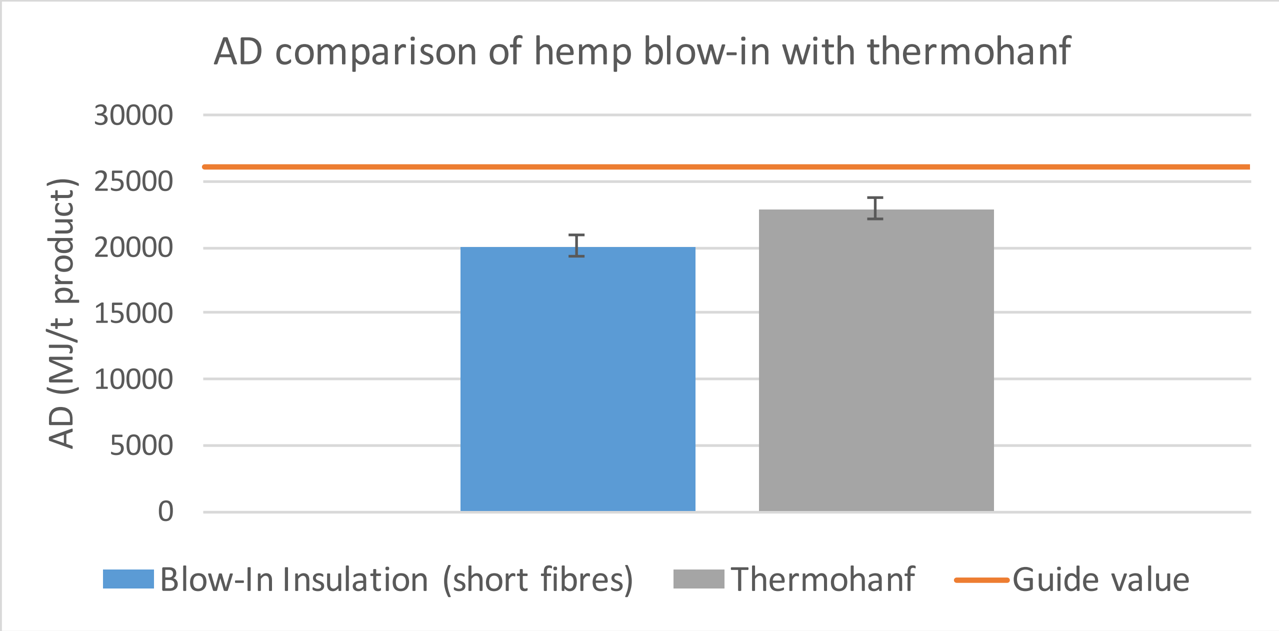

Figure 64: Comparison between the abiotic depletion of hemp blow-in insulation, THERMO HANF® and guide values given in ÖNORM 8810-7

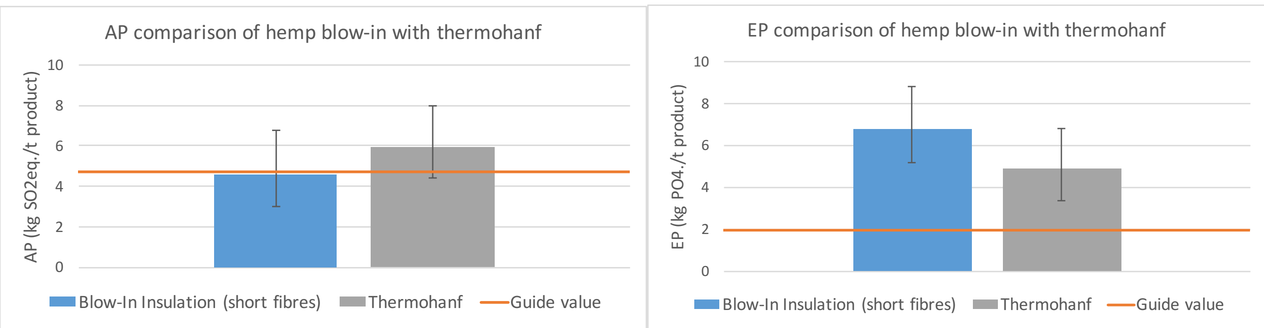

Figure 65: Comparison between the acidification and eutrophication potential of hemp blow-in insulation, THERMO HANF® and guide values given in ÖNORM 8810-7

The average acidification potential of the blow-in insulation materials is lower compared to the average acidification potential of THERMO HANF®. The maximum acidification potential found for the blow-in material is higher than the lowest value for THERMO HANF®, thus there are cultivation scenarios in which THERMO HANF® outperforms the blow-in insulation. However, in similar cultivation conditions, the blow-in insulation performs better than THERMO HANF®. In the eutrophication impact category, the reverse occurs due to the high energy consumption compared to THERMO HANF®. The acidification potential of THERMO HANF® is higher due to the BICO fibre production. The hemp blow-in insulation requires more electrical input per tonne product which contributes heavily to eutrophication.

An interesting aspect which is not visible in the environmental assessment is the difference in hemp raw material required for the production of both insulation materials. In the environmental assessment it was found that the impact of technical fibres was higher compared to the impact of short and super short fibres. However, due to the high amount of dust produced during the manufacturing, this advantage diminishes. By achieving a more efficient conversion from short and super short fibres to blow-in insulation material, the impact associated with the hemp raw material can be decreased.

Another aspect which is not considered in this environmental assessment is the possibility to use the technical fibre for other applications when the hemp blow-in insulation is produced from the short and super short fibres. Performing an environmental assessment with system expansion allows such questions to be answered. Unfortunately, insufficient data on substitution of products was available to perform such assessment.

4.2.2.1.4 Comparison of hemp based insulation materials with other insulation materials

First, the method to reach a comparable functional unit is described, followed by the actual comparison. In order to compare the environmental impact of THERMO HANF® with other, currently available insulation materials (see Table 23 for materials), the functional unit (FU) thermal resistance of $1m^2$*K/W was established. This FU was based on the materials' common function of limiting conduction, or transfer of heat, or energy. The FU excludes time, based on the simplification of all materials having the same life time.

Literature, used for the comparison, provided impact data for FUs other than the one chosen here. Therefore, these data were converted to fit the FU of $1m^2$*K/W, following the below procedure.

1. Normalization of the provided impact data to 1 kg insulation material – e.g. 12 kg $CO_{2\ eq}$/kg insulation material (see Table 23 for results).
2. Calculation of the amount of insulation material needed to achieve a thermal resistance of $1m^2$*K/W, using the below formula:

$$m = R * \lambda * \rho * A$$

m	= mass of insulation material [kg]
R	= thermal resistance[1] = $1m^2$*K/W
λ	= thermal conductivity[2] [W/m*K]
ρ	= density [kg/m^3]
A	= area = 1 m^2

[1] „Thermal Resistance is defined as the difference in temperature between two closed isothermal surfaces divided by the total heat flow between them.“ http://samunet.hu/extfil/Temperature_saturation_voltage.pdf

[2] „Is a measure of the ability of a material to allow the flow of heat from its warmer surface through the material to its colder surface, determined as the heat energy transferred per unit of time and per unit of surface area divided by the temperature gradient, which is the temperature difference divided by the distance between the two surfaces (the thickness of the material).” http://www.thefreedictionary.com/thermal+conductivity

3. Multiplication of the mass derived under (2.) with the impact data per kg calculated under (1.).

Table 23: Insulation materials used for comparison

Material	λ [W/(m*K)]	ρ [kg/m^3]	Global Warming Potential [kg CO_2-eq/kg material]	Global Warming Potential [kg CO_2-eq/R]
Glass wool	0.035	22	2.37	1.82
Rock wool	0.0385	54.5	1.34	2.81
Expanded polystyrene (EPS)	0.032	15	4.42	2.12
Extruded polystyrene (XPS)	0.035	35	3.74	4.58
Polyurethane (PUR)	0.023	33.17	4.96	3.78
THERMO HANF®	0.04	37	1.34 - 1.75	1.97-2.58
Hemp blow-in insulation	0.038-0.043	35	1.34 - 1.77	1.79-2.69

In addition to the self-assessed THERMO HANF® ("Multihemp THERMO HANF®") impact data, Figure 66 also presents data for alternative insulation materials as assessed in Spirinckx et al. (2013). As shown, the impact of the Multihemp THERMO HANF® and hemp blow-in insulation are in a comparable range with the majority of materials, with the exception of PUR and XPS. Particularly the latter is having double times the impact of THERMO HANF®.

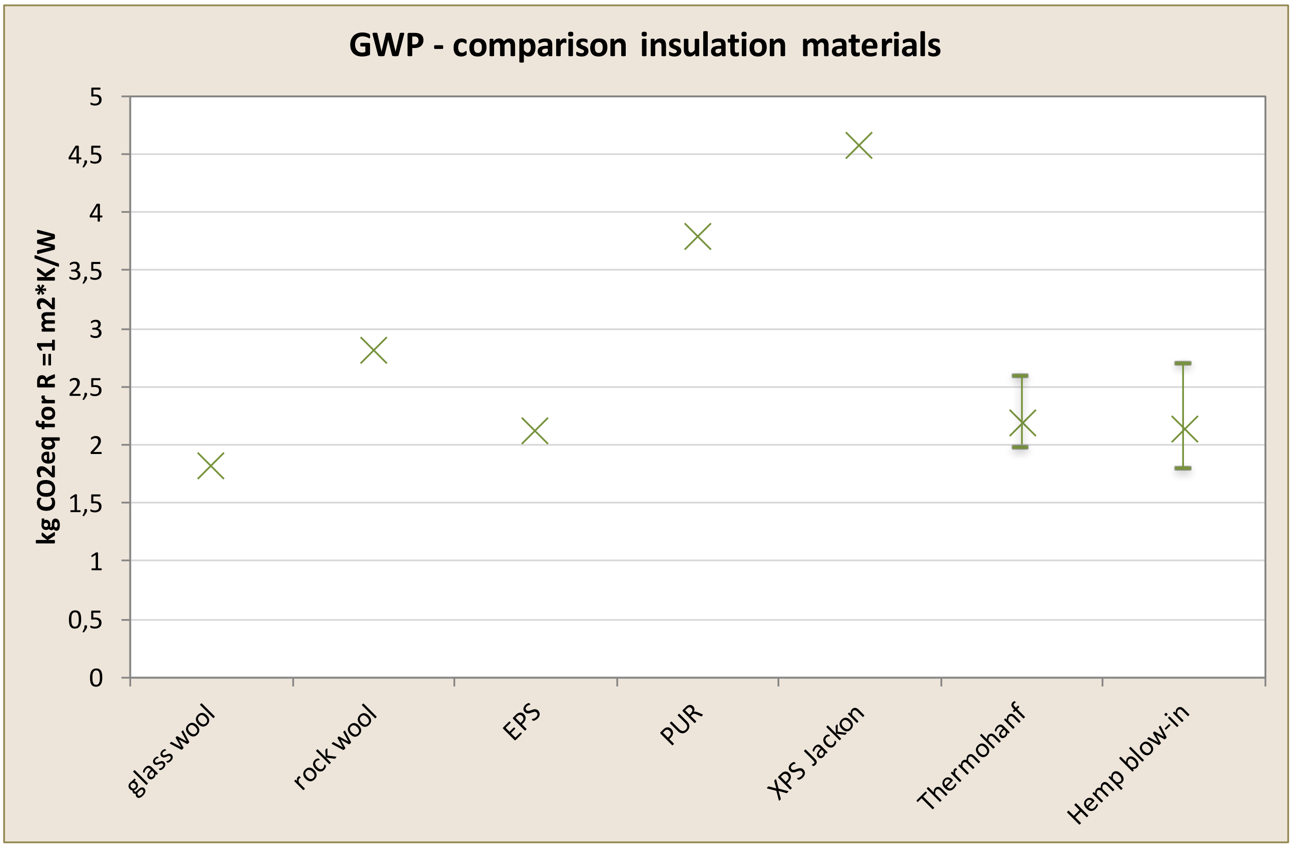

Figure 66: Global Warming Potential for THERMO HANF® versus alternative insulation materials

A factor that influences the comparison and its validity is the circumstance that for the alternative materials, choices regarding allocation and electricity supply are unknown. For this reason, the comparison is only an indication, and THERMO HANF® and the hemp blow-in insulation might perform better or worse, if choices would be equalized.

4.2.2.2 Hemp construction panels

This section discusses the environmental assessment of the hemp based construction panels. First, the hotspot analysis of the Canapalithos 350 hemp panel is discussed, followed by a comparison with literature values. Finally, a hotspot analysis on the Canapalithos 1100 panel is discussed. The Canapalithos panels are different in composition and in density, for more information see chapter **3.2.3**.

4.2.2.2.1 Canapalithos 350

The global warming potential of the hemp construction panel with a density of 350 kg/m^3 is found between 900 and 1,000 kg CO_2eq./t. The heat required to dry the hemp panels at the end is a main contributor to this value. Per tonne hemp panel, roughly 125 kg water have to be evaporated which is achieved by using natural gas. The combustion of the natural gas contributes roughly 270 kg CO_2eq./t hemp panel.

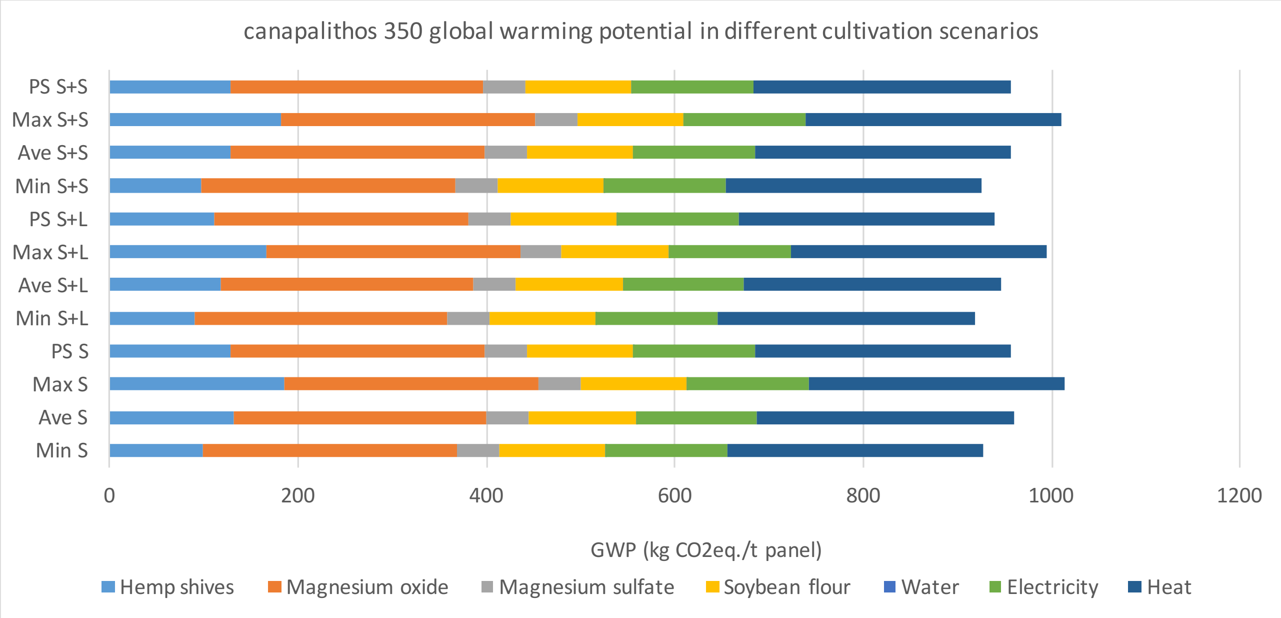

Figure 67: Global warming potential per tonne Canapalithos 350 using mass allocation

Magnesium oxide also contributes also roughly 270 kg CO_2eq./t hemp panel to the global warming potential of the hemp construction panel. The two reasons for the high impact of magnesium oxide are the magnesite use and the energy requirements. First, the raw material for the production of magnesium oxide is $MgCO_3$. In the production process, CO_2 is released to form MgO. Second, the production of construction panels requires caustic magnesia, which is calcined at a temperature of around 1,000 °C (Özkan et al. 2016). The high use of magnesium oxide in the hemp construction panels and the high impact of magnesium oxide result in a high share of the total global warming potential. The data quality for the magnesium oxide is questionable as it is an approximation. Therefore, the GWP should be used as an indication. The hemp shives contribute relatively little to the GWP, especially when considering that their share in the final product is the highest.

The heat required to evaporate water in the construction panel is also the main source of impact in the abiotic depletion impact category. This is followed by the electricity consumption of the production process. The shives are only a minor impact compared to the heat and electricity impacts. The low abiotic depletion for magnesium oxide can have different explanations. First, it should be considered that the raw material, magnesite, releases CO_2 during the production of MgO which does not contribute to abiotic depletion. Furthermore, the background data may be inaccurate as this is based on an approximation.

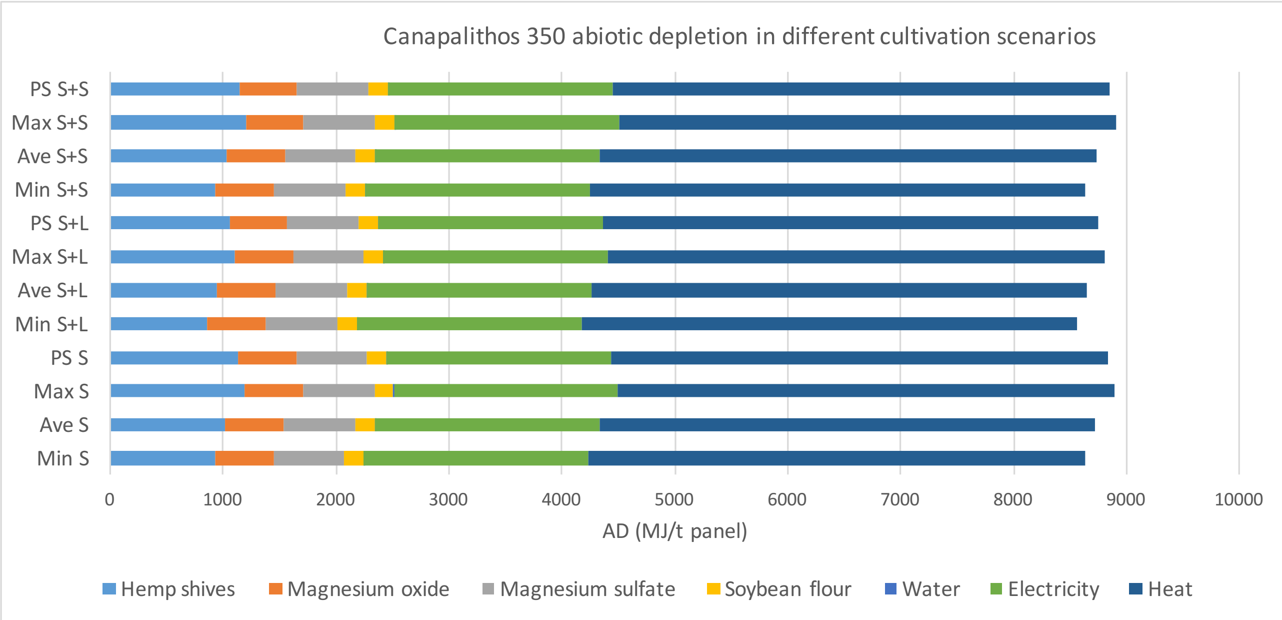

Figure 68: Abiotic depletion per tonne Canapalithos 350 using mass allocation

Contrary to the other impact categories, the acidification and eutrophication are dominated by the production of hemp shives. In the eutrophication impact category, the electricity consumption is a hotspot. This trend is visible in most agricultural products due to the acidification and eutrophication impacts associated with the cultivation. Since soy flour is also an agricultural process, it contributes to eutrophication.

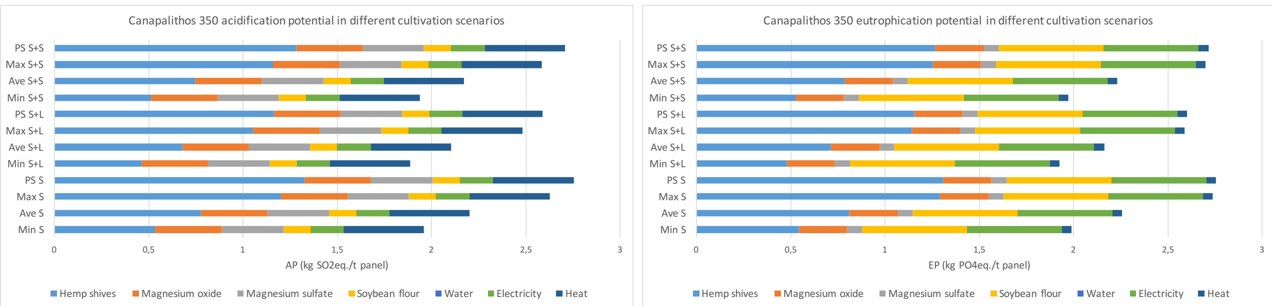

Figure 69: Acidification & eutrophication potential per tonne Canapalithos 350 using mass allocation

4.2.2.2.2 Comparison with Heraklith

In this section, the impact categories GWP, abiotic depletion and acidification & eutrophication potential are compared between the hemp-based panel CA 350 and the conventional counterparts wood wool boards and Heraklith construction panels.

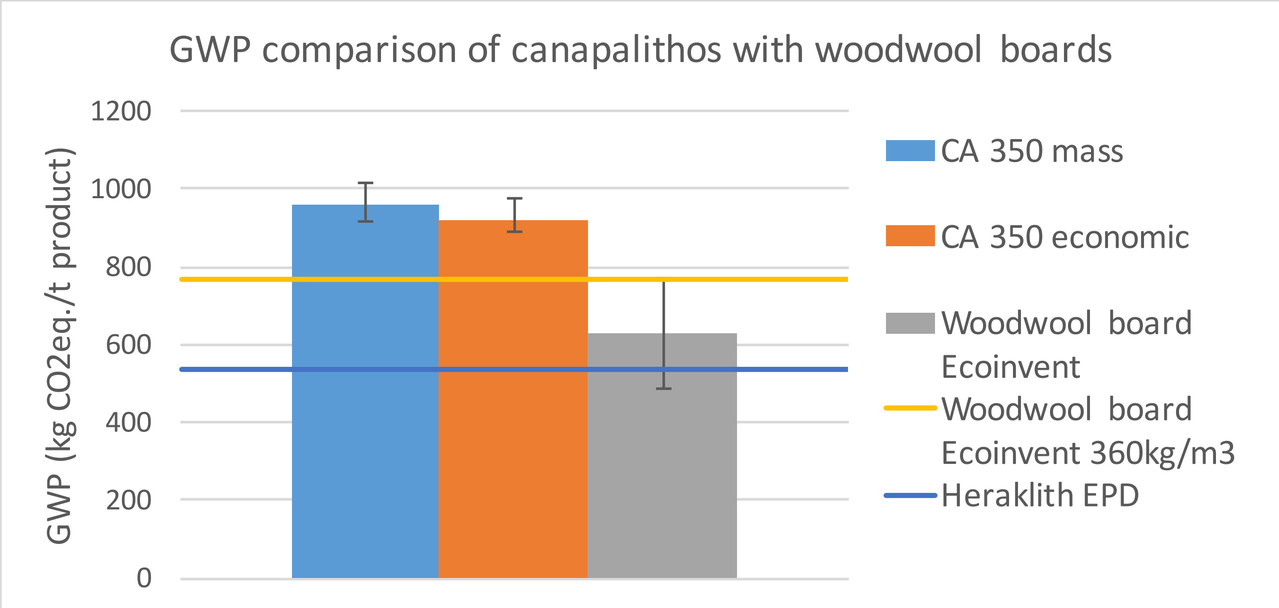

Figure 70: Comparison of global warming potential of Canapalithos 350 (CA 3530) for both mass and economic allocation with wood wool boards and Heraklith construction panels

Due to the high impacts from drying and magnesium oxide, the CA 350 hemp panels compare unfavourably to the Heraklith EPD (Heraklith 2012). It is roughly 1.5 times higher in the category global warming potential (Figure 70). The wood wool board product modelled in Ecoinvent has a range associated with the impact because the density of the final product is not specified. Due to differences in density, the impact per tonne product can vary.

Many agricultural products compare unfavourably towards forestry products due to the intensity of the agricultural process compared to the forestry process and specific assumptions made in the evaluation of the forestry products. Due to the lack of information given regarding the modelling choices in the Heraklith EDP, it is difficult to compare final products.

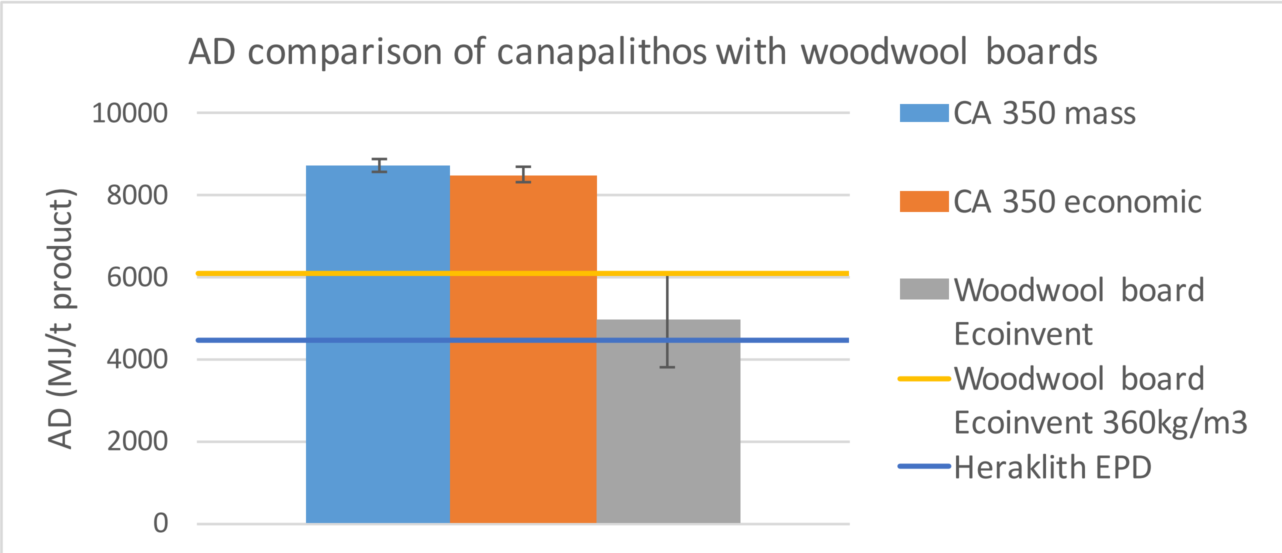

Figure 71: Comparison of abiotic depletion of Canapalithos 350 (CA 350) for both mass and economic allocation with wood wool boards and Heraklith construction panels

The abiotic depletion for the production of Canapalithos panels is higher compared to the Heraklith and Ecoinvent wood wool boards (Figure 71). Abiotic depletion is mainly driven by the fossil fuel use required to dry the hemp panels. Finding alternative drying methods can reduce the abiotic depletion for the hemp based construction panel.

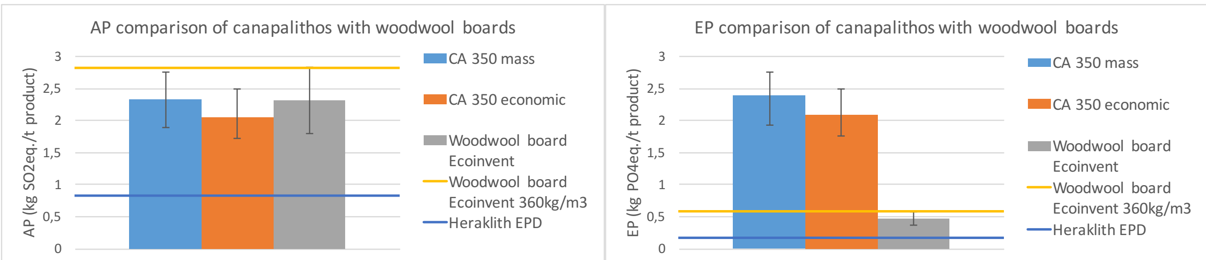

Figure 72: Comparison of acidification (l) and eutrophication (r) potential of Canapalithos 350 (CA 350) for both mass and economic allocation with wood wool boards and Heraklith construction panels

In the acidification potential impact category, the wood wool board from Ecoinvent is in the same range as the impact from the Canapalithos hemp panel (Figure 72). The value reported by Heraklith is lower. In the GWP and abiotic depletion, the wood wool board data from Ecoinvent was relatively close to the values declared for Heraklith. For acidification and eutrophication this is not the case. Because the assumptions in the Heraklith EPD are unknown, this assessment should serve as an indication only. For the eutrophication potential, Figure 72 (right), the wood wool boards of both Heraklith and an assessment based on the data in Ecoinvent are lower compared to the hemp based construction panel. The agricultural processes are responsible for this increase compared to the wood wool boards.

4.2.2.2.3 Canapalithos 1100 hotspot analysis

The Canapalithos 1100 hemp panel is different in composition and therefore density compared to the Canapalithos 350 hemp panel. In the Canapalithos 1100 panel, part of the hemp shives are replaced by clay. There are also other minor changes in the composition. Due to these changes, the density of the panel is roughly 1100 kg/m^3. The difference in density means that a panel of Canapalithos 1100 is much heavier compared to a Canapalithos 350 panel with similar dimensions. This results in a higher impact for the Canapalithos 1100 per panel compared to the Canapalithos 350 panel.

Similar to the Canapalithos 350 hemp panels, the magnesium oxide has a high environmental impact (Figure 73). In the 1100 panel, less water needs to be evaporated per tonne product and this reduces the GWP impact. Furthermore, compared per tonne product, the impact of hemp shives is less in the 1100 panels as there are less hemp shives per tonne panel. The replaced clay has little impact on the GWP of the Canapalithos 1100 panel.

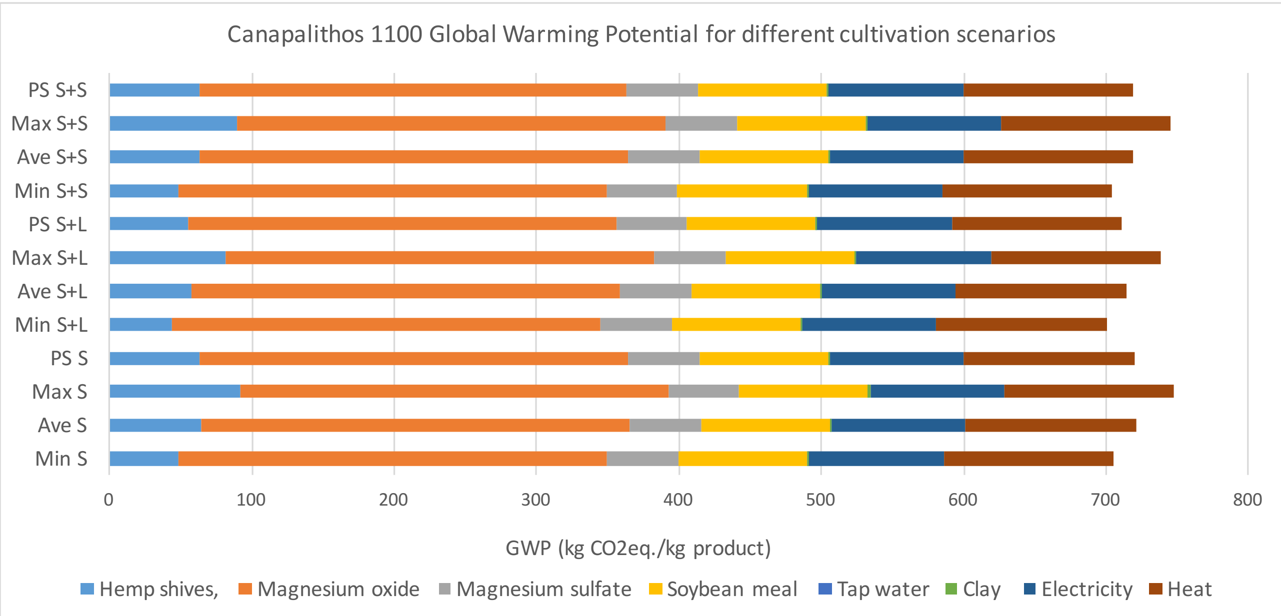

Figure 73: Global warming potential for Canapalithos 1100 hemp panel

In Figure 74, the abiotic depletion for the Canapalithos 1100 hemp panel is presented. The conclusions are similar to the Canapalithos 350 hemp panel, although the impact per tonne is lower.

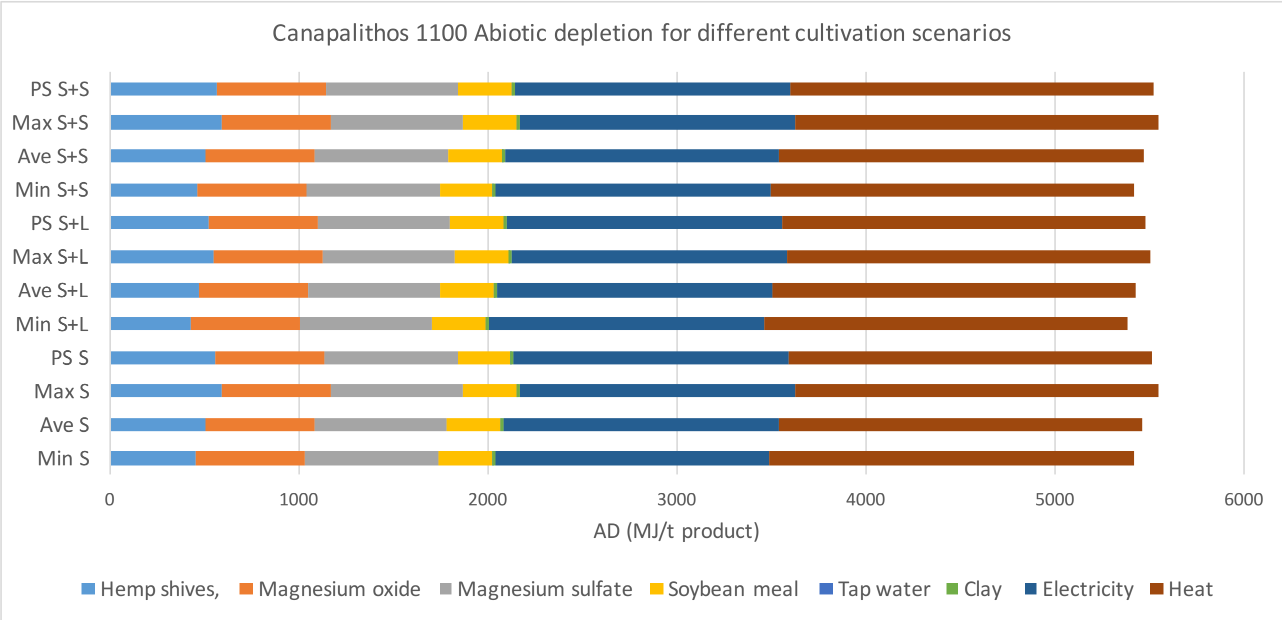

Figure 74: Abiotic depletion for Canapalithos 1100 hemp panel

Figure 75 shows the acidification and eutrophication potential for the Canapalithos 1100 hemp panel. The trend is very similar to the Canapalithos 350 hemp panel as the production process is largely similar. The lower hemp shives content does result in lower acidification and eutrophication potential per tonne product, compared to Canapalithos 350 hemp panel.

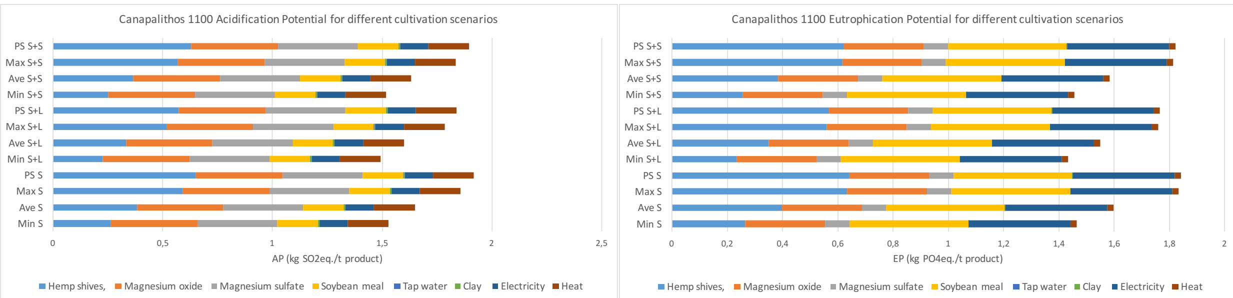

Figure 75: Acidification (l) and eutrophication (r) potential for Canapalithos 1100 hemp panel

5 Conclusions

In this section, the main conclusions of the environmental and techno-economic assessment are presented and compared in an integrated approach. The conclusions are divided per part, first the conclusions regarding agricultural systems are presented, followed by the conclusions on the insulation material and finally the construction panels.

5.1.1 Cultivation and fibre processing

Within the sustainability assessment, twelve different cultivation scenarios have been assessed which are comprised of four different fertilisation strategies and three different harvesting strategies (single use of straw, harvest of straw and leaves, and harvest of straw and seeds). The cultivation scenarios are based on field trials and as discussed above, the transfer of field trial results to commercial scale can result in significant differences.

Given the definition of the cultivation scenarios, the overall environmental performance of the minimum scenario is superior compared to the average, maximum and pig slurry scenarios. This implies that the additional environmental impact from the additional inputs in the average, maximum and pig slurry scenario are not offset by the increased yield. The application of pig slurry results in reduced global warming potential and abiotic depletion, however it results in increased acidification and eutrophication. In terms of economics, the pig slurry scenarios turned out as the most profitable since they allow high yields at low fertilizer costs. The three mineral fertilizer scenarios all resulted in approximately the same costs per tonne of dry, retted hemp straw since the increase in yield is offset by the increased fertilizer costs. Again, this result based on the field trial data and may be very different in commercial situations.

Based on these strategies, it is concluded that the dual use of hemp results in a lower environmental impact since the burden is spread over the different products rather than all on one. The effect is more pronounced when economic allocation is used due to the high value of the leaves and seeds, assuming that it is possible to valorise these side products. As discussed above, however, due to the high volatility of the market for hemp leaves for CBD-extraction, the dual use of straw and leaves cannot be recommended per se.

Whether straw and leaves or straw and seeds is the better dual use option depended on the allocation method: in mass allocation, straw and leaves scored better compared to straw and seeds, while the opposite is true in economic allocation. This signifies the potential environmental benefit for multipurpose hemp cultivation.

In terms of economic performance, the conclusion that a dual use is superior to a single of straw is also valid. However, the pig slurry scenario resulted in the highest profit and value added in all cultivation scenarios. This effect was only due to the fact that the nutrient supply from pig slurry was assumed to be cheaper than mineral fertilizer while in the environmental assessment, pig slurry did only score better than the maximum mineral fertilizer scenario in some of the impact categories.

The comparison of technical hemp fibres with other natural fibres was only done in terms of their environmental performance and not in terms of economics. On most environmental impact categories, the hemp fibres performed almost similar to the other technical fibres. While comparing commercial data and field triall data is difficult, it seems that the hemp fibres cultivated in the MultiHemp project perform slightly better compared to commercial hemp products. The main reason for this difference is a higher yield with less or similar fertiliser application. Cultivation of dual purpose hemp further reduces the environmental impact of the technical fibres.

In the hotspot analysis, the fertiliser production and the field emissions cause significant environmental impacts in most assessment categories. This is also true for the other technical fibres. The processing of straw into hemp fibres is the third biggest contributor to the environmental impact in most scenarios. In scenarios with low fertiliser application, the processing of straw is responsible for a higher percentage of the impact. For the fertilisers and field emissions, precision farming can offer possibilities to reduce the impact. For the processing, clean electricity (i.e. wind or solar) and a better process efficiency can reduce the environmental impact.

5.1.2 Insulation material

The GWP of hemp blow-in Insulation material, produced from the short and super short fibres developed in MultiHemp, can be found between 1,350 kg CO_2eq./t and 1,800 kg CO_2eq./t blow-in insulation. The main impact is associated with the electricity consumption during the production of the insulation material. Process optimisation offers the potential to reduce the electricity consumption and thereby the GWP and AD. The global warming potential for THERMO HANF®, a hemp based insulation material produced from technical fibres, is found between 1,300 kg CO_2eq./t and 1,750 kg CO_2eq./t. In the comparison of the blow-in insulation and THERMO HANF® it was concluded that the abiotic depletion for the blow-in was lower. The acidification potential of the blow-in was also lower, but the values were close to each other. For eutrophication, THERMO HANF® performed better but the values were close. When the electricity consumption for the blow-in insulation material and the production of dust could be reduced, the blow-in insulation will most likely outperform THERMO HANF® in all impact categories assessed in this environmental assessment. When the GWP of hemp based insulation material was compared with conventional insulation materials, it was found that both materials are in a comparable range with the majority of materials, with the exception of PUR and XPS, which have higher GWP than the hemp based insulation. However, the comparison is only an indication as a factor that influences the comparison and its validity is the circumstance that for the alternative materials choices regarding allocation and electricity supply are unknown.

Also the economic assessment showed that the blow-in insulation material could become a competitor of THERMO HANF®, given indicative prices of THERMO HANF® of around 3 €/kg and necessary prices for the blow-in of around 1 €/kg. Note, however, that differences in the costs of installation and further costs during the product lifetime have not been taken into account.

5.1.3 Construction panels

The hotspot analysis for the hemp construction panels showed similar results for both Canapalithos 350 and 1100. Hotspots regarding the GWP were the evaporation of water and the magnesium oxide. For the 1100 panel, the magnesium oxide was the biggest hotspot as there was less energy required for the evaporation per tonne product compared to the 350 panel. Unfortunately, the background data for magnesium oxide is an approximation. For abiotic depletion, the main hotspots are related to the energy consumption, both thermal and electric, in the production process. The hemp shives used in the production contributed significantly to acidification and especially eutrophication in the Canapalithos 350. For Canapalithos 1100, this impact is lower because the share of hemp shives is lower. It is replaced by clay, which as a low environmental impact.

From the comparison of Canapalithos 350 hemp panels with wood wool panels, it was concluded that the wood wool panels have a lower impact. This comparison should be interpreted carefully, as forestry and agricultural value chains are difficult to compare. Assumptions and modelling choices made in one value chain may not make sense when applied to the other value chain. Beside this, it is not surprising that forestry products outperform agricultural products due to the relative high intensity of the agricultural production system.

Magnesium oxide appears to be not only a major contributor to the GWP but also a major cost item in the production of the Canapalithos panels. This is the main result from the techno-economic assessment, according to which MgO accounts for 20%-30% of productions costs (for the CA 350 and CA 1100, respectively). Even when the lower price for MgO as reported by CMF is used, it still accounts for 10-20% of the costs. The MgO is a major part of the Canapalithos panel, associated with significant costs and environmental impact and therefore it is recommended to research potential alternatives to MgO in the product.

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7 Appendix I. Estimating field emissions

7.1 Ammonia

Ammonia emissions occurs when NH_3 in solution is exposed to the atmosphere. Ammonia volatilisation is a physic-chemical process driven by the equilibrium between gaseous ammonia and ammonia in solution. The ammonia in solution is in equilibrium with the ammonium in solution. This system is shown in Eq. 1 and Eq. 2.

Eq. 1

$$NH_3(aq) \leftrightarrow NH_3(g)$$

Eq. 2

$$NH_4^+(aq) \leftrightarrow NH_3(aq) + H^+(aq)$$

The emission of ammonia contributes to eutrophication and acidification. Ammonia emissions were estimated at 53 000 tonnes by Thöni et al. (2007). In Europe, agriculture is a responsible for a large fraction of the ammonia emissions (Eurostat, 2012). Therefore, the ammonia emission from ammonium containing fertilisers should be estimated to get an indication on the contribution towards eutrophication and acidification.

As nitrogen in manure is in a different form, a different model is used to estimate the emissions form field application. The emissions only include the emissions after application on the field. Emissions during storage, treatment and housing are not taken into account.

7.1.1 Mineral fertiliser emission

Ammonia volatilisation is influenced by many factors including temperature, soil pH, buffering capacity of the soil and fertiliser type. To estimate the ammonia emissions, a model used by Hutchings et al. (2013) is used. This tier 2 model distinguishes different impacts from different fertilisers. The total ammonia emission is calculated by summing the quantity of a fertiliser type multiplied by the fertilisers types emission factor (Eq. 3). This equation is used to estimate the emission from mineral fertiliser use.

Eq. 3

$$NH_3 = \sum_{=1}^{I} (m_i * EF_i +) * (1 - EF_{NH3-N2O})$$

In Eq. 3, $Em_{fert, NH3}$ is the ammonia emission in kg/(ha*yr). m_i is the mass of fertilizer type i applied in kg/(ha*yr). EF_i is the emission factor for fertiliser type I in kg NH_3/kg N. $EF_{NH3-N2O}$ is the ammonia which is converted into N_2O and should therefore not be counted as NH_3 emission, in kg N2O -N/kg NH3 emitted.

Table 24. Emission factor per fertilizer and soil type

Fertilizer type	**abbr.**	**EF (kg NH_3 / kg N)**
Ammonium Nitrate	AN	0.037
Anhydrous ammonia		0.011
Ammonium phosphate	MAP & DAP	0.113
Ammonium sulphate	AS	0.013
Calcium ammonium nitrate	CAN	0.022
Calcium nitrate	CN	0.009
Ammonium solutions	AN	0.037
Ammonium solutions	Urea AN	0.125
Urea ammonium sulphate	UAS	0.195
Urea		0.243
other NK and NPK		0.037

The emission factors for different types of fertilisers are given in Table 24. The composition of the applied fertiliser is based fertiliser sales data of West Europe given in Hutchings et al. (2013). The quantity of fertiliser per type is shown in Table 25, as is the estimated ammonia emission.

Table 25. Fertilizer composition in different scenarios based on average West-Europe fertilizer composition

	min scenario	ave scenario	max scenario	unit
total N applied	30.00	60.00	120.00	kg N
Urea	5.06	10.13	20.26	kg N
AN	6.68	13.36	26.73	kg N
Ammonia	14.38	28.77	57.54	kg N
CAN	3.08	6.16	12.32	kg N
AS	0.79	1.58	3.15	kg N

7.1.2 Pig slurry NH_3 emission

It is common practise to estimate the ammonia volatilisation from pig slurry using the Total Ammonia Nitrogen (TAN), since the ammonium in solution is the main source of ammonia emission (Eq. 1 and Eq. 2). In pig slurry, between 56 and 84 % of the total N is in TAN form Nemecek and Käagi (2007). From the TAN, the ammonia emission can be estimated using an emission factor. Andrianandraina et al. (2014) uses an average emission factor of 0.12, citing Nemecek & Kägi (2007). When this emission factor is used, and 75% of the total N in the pig slurry is assumed to be TAN, the NH_3 emission from pig slurry is 12.93 kg NH_3/ha.

7.2 Nitrate

The nitrogen in the fertiliser is subject to nitrification and denitrification. An intermediate product in the denitrification process is Nitrate (NO_3^-). Nitrate is very soluble in water, increasing the chances of losing nitrogen through leaching. When nitrate leaches into either ground water or river water it contributes to eutrophication. Due to the high solubility of nitrate, the degree of leaching is influenced by the soil type and structure (water retention capacity), rooting depth of plants, precipitation and the current Nitrogen content in the soil. Since these factors are location dependent, a tier 1 approach is chosen. The nitrate leaching is estimates from the amount of N in the fertiliser multiplied by an emission factor. Van Eynde (2015) uses an emission factor of 0.3 kg leached NO_3-N/kg applied N. converting this into NO_3 resulted in the following nitrate leached: 39.86 kg NO_3/ha in the minimum scenario, 79.71 kg NO_3/ha in the average scenario, 159.43 kg NO_3/ha in the maximum scenario and 166.1 kg NO_3/ha when pig slurry is used.

Eq. 4

$$NO_3 = EF_{NO3} * N_{tot} * 62/14$$

In Eq. 4, NO_3 is the nitrate emission in kg NO_3-N/(ha*a). EF_{NO3} is the emission factor for nitrate in kg leached NO_3/kg applied N. N_{tot} is the applied fertiliser given in kg N/ha. The factor 62/14 is used to convert kg NO_3-N into kg NO_3.

7.3 Mono-nitrogen oxides (NO_x)

Mono-nitrogen oxides, NO_x, can be emitted during the nitrification and denitrification process, Ludwig et al. (2001) reported that the nitrification process is mainly responsible for NO_x emissions in Europe. Hutchings et al. (2013) use a tier 1 approach, multiplying the applied N in the fertiliser with an emission factor, 0.026 (kg NO/ kg applied N). The emission factor does not distinguish between the source of N. This results in nitrous oxide emissions of 1.5, 2.1, 2.6 and 3.3 for the minimum, average, maximum and pig slurry scenario, respectively.

Eq. 5

$$NO_x = EF_{NOx} * N_{tot} * (1 - EF_{NOx-N2O})$$

in Eq. 5 NO_x is the kg NO_x emitted expressed in kg NO/(ha*a). EF_{NOx} is the emission factor of mono-nitrogen oxides in kg NO/kg applied N. N_{tot} is the applied nitrogen in kg N/ha. $EF_{NOx\text{-}N2O}$ is the emission factor of mono-nitrogen oxides to nitrous oxides in kg N_2O-N/kg NO_x (see table Table 26).

7.4 Nitrous oxide

Nitrous oxide, N_2O, is an air pollutant and greenhouse gas which has more than 200 times as much impact as carbon dioxide. It is produced during nitrification and denitrification processes in soil microbes. Therefore, part of the nitrogen in fertilisers ends up as nitrous oxide. Direct and indirect nitrous oxide emission can be estimated. Direct nitrous oxide emission relates to the applied nitrogen in fertiliser. Generally, 1% of the N in the applied fertiliser is converted into N_2O. indirect emission of nitrous oxide comes from the conversion of other molecules into nitrous oxide. De Klein (2006) gives emission factors to estimate indirect emission of nitrous oxide. These emission factors are given in Table 26.

Eq. 6

$$N_2O = \left(EF_{N2O,N} * N_{tot} + EF_{N2O,NH3} * N_{NH3} + EF_{N2O,NOx} * N_{NOx} + EF_{N2O,NO3} * N_{NO3}\right) * 44/28$$

In Eq. 6 N_2O is the nitrous oxide emission in kg N_2O/(ha*a). $EF_{N2O,N}$ is the nitrous oxide emission directly from the applied N fertiliser in kg N_2O-N/kg applied N. N_{tot} is the total applied nitrogen fertiliser in kg N/(ha*a). $EF_{N2O,NH3}$ is the fraction of emitted NH_3 converted into N_2O in kg N_2O-N/kg NH3 emitted. N_{NH3} is the ammonia emission calculated from Eq. 3 in kg NH_3/(ha*a). $EF_{N2O,NOx}$ is the fraction of emitted NO_x converted into N_2O in kg N_2O-N/kg NO_x emitted. N_{NOx} is the mono-nitrogen oxide emission calculated from Eq. 5 in kg NO_x/(ha*a). $EF_{N2O,NO3}$ is the fraction of emitted NO_3 converted into N_2O in kg N_2O-N/kg NO_3 emitted. N_{NO3} is the nitrate emission calculated from Eq. 4 in kg NO_3/(ha*a). the factor 44/28 is used to convert N_2O-N into N_2O. all the emission factors are given in Table 26. The indirect N_2O emissions are subtracted from their original source by multiplying them with their respective (1-EF_{N2O}). The total N_2O emission for the minimum scenario was 0.8 kg N_2O/ha, for the average scenario 1.6 kg N_2O/ha, for the maximum scenario 3.18 kg N_2O/ha and 3.37 kg N_2O/ha for the pig slurry scenario.

Table 26. Direct and indirect emission factors for N_2O emission

Source	Abbreviation	Emission factor	unit
N_2O-N from applied N	$EF_{N2O,N}$	0.01	kg N_2O -N / kg applied N
N_2O -N from NH_3 emission	$EF_{N2O,NH3}$	0.01	kg N_2O -N / kg NH_3 emitted
N_2O -N from NO_x emission	$EF_{N2O,NOx}$	0.01	kg N_2O -N / kg NO_x emitted
N_2O-N from NO_3 emission	$EF_{N2O,NO3}$	0.0075	kg N_2O -N / kg NO_3 emitted

7.5 Phosphate

Phosphate leaching is described in Nemecek and Kägi (2007), two types of phosphate loss are taken into account, run off and leaching. A standard factor (0.07 kg PO_4-P/ha) for leaching is used. The formula to calculate the phosphate emissions is given in Eq. 7

Eq. 7

$$PO_4 = (0.07 + 0.175 * \left(1 + \left(0.0025 * P_{fert}\right)\right)) * W$$

In Eq. 7, the PO_4 is the phosphate loss in kg PO_4/(ha*a). P_{fert} is the applied P_2O_5 fertiliser in kg P_2O_5/(ha*a). The 0.07 kg PO_4-P/ha. 0.175, 1 and 0.0025 are values found by the regression analysis for run off of phosphate. Finally, W is a conversion factor from PO_4-P to PO_4. Calculated emissions can be found in Table 27.

7.6 Carbon dioxide

When the fertiliser includes urea, decomposition results in CO_2 emissions. De Klein et al. (2006) use an emission factor, EF_{CO2}, of 0.43 kg CO_2/ kg Urea-N. Urea, a form of organic nitrogen, is excreted by pigs. It is assumed that the non-TAN part of the total N in pig slurry consists mainly of urea. Calculated CO_2 emissions can be found in Table 27

Eq. 8

$$CO_2 = EF_{CO2} * N_{Urea} * W_{CO2}$$

In Eq. 8, CO_2 is the Carbon dioxide emission resulting from decomposition of urea in kg CO_2/(ha*a). EF_{CO2} is the emission factor related to CO_2-C release from urea decomposition. N_{urea} is the amount of Urea in the fertilizer given in kg/(ha*a). W_{CO2} is a factor to convert CO_2-C into CO_2, this factor is 44/12 and is unitless.

7.7 Summary

Table 27 contains a summary of all estimated direct field emissions related to the application of fertiliser.

Table 27. Estimated field emissions for the fertilizer scenarios

	minimum	average	maximum	Pig slurry	unit	Eq.
NH_3	1.70	3.39	6.79	12.93	kg NH_3/ha	Eq. 3
NO_x	0.78	1.56	3.12	3.25	kg NO_x/ha	Eq. 5
N_2O total	0.80	1.59	3.18	3.37	kg N_2O/ha	Eq. 6
NO_3 (leaching)	39.86	79.71	159.43	166.07	kg NO_3/ha	Eq. 4
PO_4 total	0.79	0.80	0.83	0.84	kg PO_4/ha	Eq. 7
CO_2 (from NH_3)	7.98	15.97	31.94	49.27	kg CO_2/ha	Eq. 8

7.8 References

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8 Appendix II. Life Cycle Inventory Data flax, commercial hemp, jute and kenaf

This appendix contains the life cycle inventory for the comparison on the system level. See Barth and Carus (2015) for more details.

8.1 Flax

FLAX					
Materials / Energy	Units	Value	Range (+/-)	Data source /Reference	Comments
Inputs					
Seeds (sowing rate)	kg/ha*a	110	10		in Vetter et al. (2002): 120-140 kg/ha in Schmidt et al. (2004): 80 kg/ha in Müller-Sämann et al. (2003): 110-140 kg/ha in Pless (2001): 100-130 kg/ha in van der Werf & Turunen (2008): 115 kg/ha
Fertilizers					
Nitrogen	kg N/ha*a	40	10		N-P-K: (60-120)-(80-160)-(70-120) in Schmidt et al. (2004): N-P-K: 40-17-70 in Dissanayake (2011): N-P-K: 40-50-50 in Carus et al. (2008): N-P-K: 40-40-40 in Pless (2001): N-P-K: 50-80-80 in van der Werf & Turunen (2008): N-P-K: 40-30-60
Phosphorus	kg P_2O_5 /ha*a	40	10		
Potassium	kg K_2O/ha*a	80	10		
Lime	kg $CaCO_3$/ha*a	60	15		in Salmon-Minotte & Franck (2005): 60-75 kg/ha in Dissanayake (2011): 666 kg/ha in van der Werf & Turunen (2008): 333 kg/ha
Pesticides			-		in van der Werf & Turunen (2008): 2.6 kg/ha - active ingredient of pesticide in Pless (2001): 0.5 kg/ha unspecified pesticides
Insectizide - Trafo WG (active substance: Lambda-Cyhalothin)	kg Trafo WG/ha*a	0,15		Thüringer Landesanstlat für Landwirtschaft (2009)	
Herbicide - Callisto	litre Callisto/ha*a	2	0,5		Thüringer Landesanstlat für Landwirtschaft (2009): 1.5 litre/ha Vetter et al. (2002): 1.5 litre/ha
Herbicide - Roundup (active substance: Glyphosate)	litre Roundup/ha*a	4	0,5	Thüringer Landesanstlat für Landwirtschaft (2009) - ripening-accelertation	
Fuel use for field operations					
Soil prepartion: primary and secondary tillage (mouldbord ploughing)	litre/ha*a	20,1	2		based on Dissanayake (2011): mouldboard plough: 15.1 litre/ha
Sowing: grain drill	litre/ha*a	6,6	2,3		litre/ha
Pesticide-application (sprayer)	litre/ha*a	7,5	1,5		based on Pless (2001) 3 times sprayer: pre-sowing - Callisto, at pest infestation - Insecticide, for ripening-acceleration - Roundup
Fertilizer spreader (mineral fertilizer application)	litre/ha*a	4,5	0,5		adapted from hemp scenario: value-area based on an interview with M. Reinders (2014)
Cutting	litre/ha*a	5,4	2,9	Pless (2001)	
Turning (2-times)	litre/ha*a	6	1		Pless (2001): 4-12.4 litre/ha per 2-times windrowing turning of hemp based on an interview with M. Reinders (2014): 2litre/ha per one-time-turning
Swathing	litre/ha*a	2	0,25	adapted from hemp scenario: value-area based on an interview with M. Reinders (2014)	in Pless (2001): 2-6.2 litre/ha (windrow)
Baling (round bales)	litre/ha*a	6,6	0,5	Pless (2001): 6.6 litre/ha	
Bale moving	litre/ha*a	3	1	scenario: value based on an interwiev with M. Reinders (2014)	in Pless (2001): 5.6 litre/ha (tractor with front-end loader)

Transport					
Transport I					
Transport of hemp straw from the field to the processing-site	km (roundtrip)	60	20	assumption from nova based on hemp-scenario	
Type of transportation	lorry 16-32t, EURO 5				
Transport II					
Transport of hemp fibre to the harbour in Hamburg	km (one-way)	-		does not apply for this process, because flax is produced in Europe	
Type of transportation	transoceanic freight ship				
Transport III					
Tranport of hemp fibre on the road in Europe	km (roundtrip)	400	100	assumption from nova for all transportation within Europe on the road to the non-woven-producer	
Type of transportation	lorry 16-32t, EURO 5				
Fibre processing					
Energy and fuel input					
Electricity use	kWh/t fibre	279		Essel (2013)	
Diesel fuel use	litre/t fibre	1,67		Essel (2013)	
Yields					
Straw yield (only stems)	t retted straw/ha*a	6		Dissanayake (2011): 6 t/ha Carus et al. (2008): 5-6 t straw/ha	Yields can vary largely depending on producers, climatic conditions, region, soil characteristics, sowing and harvesting date, and the type of seed sown.
Water content of straw	%	15		Carus et al. (2008)	
Land requirement					
Cultivated area	ha*a/t fibre	0,8			Calculation based on straw yield, water content and fibre yield
Outputs					
Products and co-products					
Flax-fibre	% of retted and transported straw	24,5		based on Essel (2013): 25-50-25	
Flax-shives		51			
Flax-dust		24,5			

8.2 Commercial hemp

HEMP					
Materials / Energy	Units	Value	Range (+/-)	Data source /Reference	Comments
Inputs					
Seeds (sowing rate)	kg/ha*a	33	2	based on interviews (2014)	35 kg/ha in NL (interview with M. Reinders-2014) 32-33 kg/ha in NL (interwiew tih A. Dun-2014) 30-40 kg/ha are mentioned in Carus et al. (2008)
Fertilizers					
Nitrogen	kg N/ha*a	100	25		interview with M. Reinders (2014): N-P-K: 120-80-120 in Carus et al. (2008): N-P-K: 100-75-80 in González-García et al. (2010a) and (2010b): N-P-K: 85-65-125 in Heyland et al. (2006): suggestion of: N-P-K: (60-150)-(40-140)-(75-200)
Phosphorus	kg P_2O_5/ha*a	75	5		
Potassium	kg K_2O/ha*a	100	20		
Lime	kg $CaCO_3$/ha*a	-	-		with a rate of 200 kg/ha depending on the pH of the soil (interview with A. Dun-2014)
Pig slurry	m^3 slurry/ha*a	22,5	2,5	interview with M. Reinders (2014)	23 m^3/ha (interview with A. Dun-2014) in van der Werf (2004): 20,000 kg/ha
Transport of pig slurry from pig-farm to the field	km	200			
Pesticides			-		Hemp crops are rarely threatened by dangerous pests. Only in some cases is glyphosate used prior to sowing.
Herbicide - Glyphosate	kg Glyphosate/ha*a	2,57	2,57	based on interviews (2014)	2 litre/ha in Rumania (interview with M. Reinders-2014) 3 litre/ha in NL (interview with A. Dun-2014) in Cherrettt et al. (2005): 2 litre/ha
Fuel use for field operations					
Soil-preparation with a "spar-machine" (harrowing, drill and sowing in one machine)	litre/ha*a	32	2	value-area based on an interview with M. Reinders (2014)	
Pesticide-application (boom sprayer)	litre/ha*a				in Pless (2001) a range of literature values from 0.4-1.6 litre/ha is mentioned
Fertilizer spreader (mineral fertilizer application)	litre/ha*a	4,5	0,5	interview with M. Reinders (2014)	
Slurry tank with tractor (organic fertilizer application)	litre/ha*a	11	1,5	value-area based on an interview with M. Reinders (2014)	25,000 litre-slurry-tank; including loading
Cutting	litre/ha*a	11	1	value-area based on an interview with M. Reinders (2014)	Double-Cut-Combine; 4.5-meter-working-width; cutting the stems at pieces of 60 centimers
Turning (2-times)	litre/ha*a	4	0,5	interview with M. Reinders (2014)	
Swathing	litre/ha*a	2	0,25	interview with M. Reinders (2014)	in Pless (2001): 2-6.2 litre/ha (windrow)
Baling (square bales)	litre/ha*a	7,5	0,5		interview with M. Reinders (2014): 8.3 litre/ha
Bale moving	litre/ha*a	3	1	value based on an interwiev with M. Reinders (2014)	in Pless (2001): 5.6 litre/ha (tractor with front-end loader)

Transport					
Transport I					
Transport of hemp straw from the field to the processing-site	km (roundtrip)	60	20	value-area based on an interview with M. Reinders (2014)	
Type of transportation	lorry 16-32t, EURO 5				
Transport II					
Transport of hemp fibre to the harbour in Hamburg	km (one-way)	-		does not apply for this process, because hemp is produced in Europe	
Type of transportation	transoceanic freight ship				
Transport III					
Tranport of hemp fibre on the road in Europe	km (roundtrip)	400	100	assumption from nova for all transportation within Europe on the road to the non-woven-producer	
Type of transportation	lorry 16-32t, EURO 5				
Fibre processing					
Energy and fuel input					
Electricity use	kWh/t fibre	310	10	Essel (2013)	
Diesel fuel use	litre/t fibre	1,67	0,06	Essel (2013)	
Yields					
Straw yield (only stems)	t retted straw/ha*a	8,5		Bocsa et al. (2000): 7-9 t retted stem/ha Carus et al. (2008): 6-8 t straw/ha in Germany	producers, climatic conditions, region, soil characteristics, sowing and harvesting date, and the type of seed sown.
Water content of straw	%	15		Carus et al. (2008)	
Land requirement					
Cultivated area	ha*a/t fibre	0,5			Calculation based on straw yield, water content and fibre yield
Outputs					
Products and co-products					
Hemp-fibre	% of retted and transported straw	28		Carus et al. (2008)	
Hemp-shives		55		Carus et al. (2008)	
Hemp-dust		17		Carus et al. (2008)	

8.3 Jute

JUTE					
Materials / Energy	Units	Value	Range (+/-)	Data source /Reference	Comments
Inputs					
Seeds (sowing rate)	kg/ha*a	6	2	Mahapatra et al. (2009): olitorius and capsularis jute: 4 to 6 and 6 to 8 kg/ha	Rahman (2010): 5-5.5 kg/ha (broadcast methode) (general information) Islam & de Silva (2011): 10-12 kg/ha (Bangladesh)
Fertilizers					
Nitrogen	kg N/ha*a	40	20	Mahapatra et al. (2009): 60-20	
Phosphorus	kg P_2O_5 /ha*a	10	10	Mahapatra et al. (2009): 0 - 13	
Potassium	kg K_2O/ha*a	45	20	Mahapatra et al. (2009): 25 - 63.3	
Lime	kg $CaCO_3$/ha*a	62	2		Sobhan et al. (2010): for tossa jute requirement: 128 kg CaO and white jute 120 kg CaO; Mahapatra et al. (2009): 0.5 LR (Lime Requirement)
Magnesium Oxide	kg MgO/ha*a	16	6		Sobhan et al. (2010): for tossa jute: 22 kg/ha Mahapatra et al. (2009): 10 kg/ha
Pesticides			-		
Pesticide Metolachlor	kg Metolachlor/ha*a	1	1	Mahapatra et al. (2010): for olitorius jute + hand-weeding	control; Üllenberg et al. (2011): unspecified pesticides: 0.5 kg/ha Islam (2014): weeds are generally controlled by raking and niri (hand weeding)
Fuel use for field operations					
Soil prepartion	litre/ha*a	10	2		assumption based on Sobhan et al. (2010): where bullock- or tractor driven ploughs (3–5 times) used for the fine tilth), assumption small tractor and 3–5 times plough
Sowing: grain drill	litre/ha*a	0	0		manpower based on Rahman (2010) and Islam & de Silva (2011): broadcast methode - sower is walking
Pesticide-application (sprayer)	litre/ha*a	1	0		assumption: manpower, but using production machinery as a tool
Fertilizer spreader (mineral fertilizer application)	litre/ha*a	1	0		assumption: manpower, but using production machinery as a tool
Cutting	litre/ha*a	0	0		manpower based on Islam & de Silva (2011) and Sobhan et al. (2010): plants usually cut by hand.

Transport					
Transport I					
Transport of hemp straw from the field to the processing-site	km (roundtrip)	60	20	assumption from nova based on hemp-scenario	
Type of transportation	lorry 16-32t, EURO 3			assumption from nova	
Transport II					
Transport of hemp fibre to the harbour in Hamburg	km (one-way)	13□996	1□822	based on www.hafen-hamburg.de: distance between Hamburg-Mumbai and Hamburg-Singapur (last accessed: 2014-11-01)	www.searates.com: Port Chittagong (Bangladesh) - Port Hamburg: 14,986 km Port Mumbai (India) - Port Hamburg: 12,193 km (last accessed: 2014-11-01)
Type of transportation	transoceanic freight ship			assumption from nova	
Transport III					
Tranport of hemp fibre on the road in Europe	km (roundtrip)	400	100	assumption from nova	
Type of transportation	lorry 16-32t, EURO 5				
Fine fibre processing					
Energy and fuel input					
Electricity use	kWh/t fibre	200	20	assumption from nova	
Diesel fuel use	litre/t fibre	1,5	0,05	assumption from nova	
Yields					
Straw yield (only stems)	t retted straw/ha*a	3,9		(2010)	
Water content of straw	%	20		(2010)	
Land requirement					
Cultivated area	ha*a/t fibre	1,1		Calculation based on straw yield, water content and fibre yield	
Outputs					
Products and co-products					
Jute-fibre	% of retted and transported straw	30		own assumptions based on Gosh (1983)	
Jute-shives (stems)		60			
Jute-dust		10			

8.4 Kenaf

KENAF					
Materials / Energy	Units	Value	Range (+/-)	Data source /Reference	Comments
Inputs					
Seeds (sowing rate)	kg/ha*a	25	5	Behmel (2014): 25-30 kg/ha	http://andhrabank.in/download/mesta.pdf (last accessed: 2015-02-27) and Singh: 13-17 kg/ha
Fertilizers					
Nitrogen	kg N/ha*a	50	10	http://andhrabank.in/download/mesta.pdf: 40-60 kg N/ha	Behmel (2014): no fertilizer data for India or Bangladesh
Phosphorus	kg P_2O_5/ha*a	25	5	http://andhrabank.in/download/mesta.pdf: 20-40 kg P_2O_5/ha	
Potassium	kg K_2O/ha*a	25	5	http://andhrabank.in/download/mesta.pdf: 20-40 kg K_2O/ha	
Lime	kg $CaCO_3$/ha*a	0	0		no lime according to literature
Magnesium Oxide	kg MgO/ha*a	0	0		no lime according to literature

Pesticides			-		Behmel (2014): herbicide extration via handweeding
Herbicide	litre Glyphosate/ ha*a	2	0,5		http://andhrabank.in/download/mesta .pdf: 2.2 litre/ha Fluchloralin; calculated with Glyphosate because in SimaPro no Fluchloralin found
Fuel use for field operations					
Soil prepartion	litre/ha*a	10	2		(2010): where bullock- or tractor driven ploughs (3-5 times) used for the fine tilth
Sowing: grain drill	litre/ha*a	0	0		manpower
Pesticide-application (sprayer)	litre/ha*a	1	0,5		assumption: manpower, but using production machinery as a tool
Fertilizer spreader (mineral fertilizer application)	litre/ha*a	1	0,5		assumption: manpower, but using production machinery as a tool
Cutting	litre/ha*a	0	0		manpower
Transport					
Transport I					
Transport of hemp straw from the field to the processing-site	km (roundtrip)	60	20	assumption from nova based on hemp-scenario	
Type of transportation	lorry 16-32t, EURO 3			assumption from nova	
Transport II					
Transport of hemp fibre to the harbour in Hamburg	km (one-way)	13 996	1 822	based on www.hafen-hamburg.de: distance between Hamburg-Mumbai and Hamburg-Singapur (last accessed: 2014-11-01)	(Bangladesh) - Port Hamburg: 14,986 km Port Mumbai (India) - Port Hamburg: 12,193 km (last accessed: 2014-11-01)
Type of transportation	transoceanic freight ship			assumption from nova	
Transport III					
Tranport of hemp fibre on the road in Europe	km (roundtrip)	400	100	assumption from nova	
Type of transportation	lorry 16-32t, EURO 5				
Fine fibre processing					
Energy and fuel input					
Electricity use	kWh/t fibre	200	20	assumption from nova	
Diesel fuel use	litre/t fibre	1,5	0,05	assumption from nova	
Yields					
Straw yield (only stems)	t retted straw/ha*a	7,6		based on Singh: 7.6 t dry raw ribbons and dry wood stem	
Water content of straw	%	15		based on Singh	
Land requirement					
Cultivated area	ha*a/t fibre	0,8		Calculation based on straw yield, water content and fibre yield	
Outputs					
Products and co-products					
Kenaf-fibre	% of retted and transported straw	18		based on Singh: 18% of dry raw ribbons and dry wood stems are processed to retted and dried fibre	
Kenaf-shives (stems)		64			
Kenaf-dust		17			

8.5 References

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9 Appendix III. Life Cycle Inventories

9.1 Minimum scenario straw only harvest

	unit	quantity
inputs		
Diesel	kg/ha	68,92
Glyphosate	kg/ha	3
Nitrogen	kg N/ha	30
Phosphorus	kg P_2O_5/ha	30
Potassium	kg K_2O	100
outputs		
Hemp straw	kg	8000

9.2 Average scenario straw only

	unit	quantity
inputs		
Diesel	kg/ha	74,69
Glyphosate	kg/ha	3
Nitrogen	kg N/ha	60
Phosphorus	kg P_2O_5/ha	40
Potassium	kg K_2O	130
outputs		
Hemp straw	kg	8700

9.3 Maximum scenario Straw only

	unit	quantity
inputs		
Diesel	kg/ha	80,47
Glyphosate	kg/ha	3
Nitrogen	kg N/ha	120
Phosphorus	kg P_2O_5/ha	60
Potassium	kg K_2O	160
outputs		
Hemp straw	kg	9600

9.4 Pig slurry scenario straw only

	unit	quantity
inputs		
Diesel	kg/ha	85,62
Glyphosate	kg/ha	3
Pig slurry	m^3	23
Transport pig slurry	km	100
Phosphorus	kg P_2O_5/ha	40
Potassium	kg K_2O	130
outputs		
Hemp straw	kg	9600

9.5 Minimum scenario straw and leaves harvest

	unit	quantity
inputs		
Diesel	kg/ha	69,92
Glyphosate	kg/ha	3
Nitrogen	kg N/ha	30
Phosphorus	kg P_2O_5/ha	30
Potassium	kg K_2O	100
outputs		
Hemp straw	kg	8000
Hemp leaves	Kg	1400

9.6 Average scenario straw and leaves

	unit	quantity
inputs		
Diesel	kg/ha	75,69
Glyphosate	kg/ha	3
Nitrogen	kg N/ha	60
Phosphorus	kg P_2O_5/ha	40
Potassium	kg K_2O	130
outputs		
Hemp straw	kg	8700
Hemp leaves	Kg	1400

9.7 Maximum scenario Straw and leaves

	unit	quantity
inputs		

Diesel	kg/ha	81,47
Glyphosate	kg/ha	3
Nitrogen	kg N/ha	120
Phosphorus	kg P_2O_5/ha	60
Potassium	kg K_2O	160
outputs		
Hemp straw	kg	9600
Hemp leaves	Kg	1400

9.8 Pig slurry scenario straw and leaves

	unit	quantity
inputs		
Diesel	kg/ha	86,62
Glyphosate	kg/ha	3
Pig slurry	m^3	23
Transport pig slurry	km	100
Phosphorus	kg P_2O_5/ha	40
Potassium	kg K_2O	130
outputs		
Hemp straw	kg	9600
Hemp leaves	kg	1400

9.9 Minimum scenario straw and seeds harvest

	unit	quantity
inputs		
Diesel	kg/ha	71,92
Glyphosate	kg/ha	3
Nitrogen	kg N/ha	30
Phosphorus	kg P_2O_5/ha	30
Potassium	kg K_2O	100
outputs		
Hemp straw	kg	8000
Hemp seeds	Kg	1000

9.10 Average scenario straw and seeds

	unit	quantity
inputs		

Diesel	kg/ha	77,69
Glyphosate	kg/ha	3
Nitrogen	kg N/ha	60
Phosphorus	kg P_2O_5/ha	40
Potassium	kg K_2O	130
outputs		
Hemp straw	kg	8700
Hemp leaves	Kg	1000

9.11 Maximum scenario Straw and seeds

	unit	quantity
inputs		
Diesel	kg/ha	83,47
Glyphosate	kg/ha	3
Nitrogen	kg N/ha	120
Phosphorus	kg P_2O_5/ha	60
Potassium	kg K_2O	160
outputs		
Hemp straw	kg	9600
Hemp seeds	Kg	1000

9.12 Pig slurry scenario straw and seeds

	unit	quantity
inputs		
Diesel	kg/ha	88,62
Glyphosate	kg/ha	3
Pig slurry	m^3	23
Transport pig slurry	km	100
Phosphorus	kg P_2O_5/ha	40
Potassium	kg K_2O	130
outputs		
Hemp straw	kg	9600
Hemp seeds	kg	1000

9.13 Fibre processing

	unit	quantity
inputs		
Hemp straw	kg	3330

Diesel	l	1,60
Electricity		
Decortication	kWh	240
Fine opening	kWh	60
outputs		
Technical fibre	kg	800
Short fibre	kg	133
Super short fibre	kg	67
Shives	kg	1830
Dust	kg	500

9.14 Fibre processing dual use seeds harvest

	unit	quantity
inputs		
Hemp straw	kg	3150
Diesel	l	1,60
Electricity		
Decortication	kWh	240
Fine opening	kWh	60
outputs		
Technical fibre	kg	800
Short fibre	kg	133
Super short fibre	kg	67
Shives	kg	1650
Dust	kg	500

9.15 Blow in production

	unit	quantity
inputs		
Short hemp fibres	kg	1333
Super short hemp fibres	kg	667
Electricity		
Shredder	kWh	500
Whirl mill	kWh	400
Dust removal & packaging	kWh	600
outputs		
Hemp blow-in material	kg	1000
Dust	kg	1000

9.16 THERMO HANF®

	unit	quantity
inputs		
Technical hemp fibre	kg	870
Soda ash	kg	30
BICO fibre	kg	100
LDPE (packaging)	kg	12,1
Pallet	p	7,2
Electricity	kWh	620
Heat	MJ	1800
outputs		
THERMO HANF®	kg	1000

9.17 Canapalithos 350

	unit	quantity
inputs		
Hemp shives	kg	457,7
Magnesium oxide	kg	257,1
Magnesium Sulfate	kg	98,5
Soybean flour	kg	86,1
water	kg	228,9
Electricity	kWh	200
Heat	MJ	6400
outputs		
Canapalithos 350	kg	1000
water	kg	128,3

9.18 Canapalithos 1100

	unit	quantity
inputs		
Hemp shives	kg	225
Magnesium oxide	kg	287,7
Magnesium Sulfate	kg	110
Soybean flour	kg	71,9
water	kg	219,7
Clay	kg	225
Electricity	kWh	150
Heat	MJ	2800
outputs		

Canapalithos 1100	kg	1000
water	kg	139,3