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Magic

Marginal lands for Growing Industrial Crops

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1 Summary

Industrial crops provide valuable resources for bioenergy, biofuels, biochemicals and biomaterials. In the MAGIC project, 20 crops were selected, and these are matched with conversion technologies in this document. For each combination of crop and conversion technology, the suitability of the properties of the crop, TRL, market potential of the end product, and data availability are assessed. A distinction was made between oil crops, lignocellulosic crops, and carbohydrate and multipurpose crops. Due to the different nature of the conversion technologies, these crops are discussed separately.

In total, 140 technically feasible routes were found, of which 82 are the most promising candidates. These results were the basis for the selection of ten promising value chains for the conversion of industrial crops. These ten routes were analysed in detail in order to provide quantitative data for environmental and economic assessments.

2 Introduction

Industrial crops provide valuable resources for bioenergy, biofuels, biochemicals and biomaterials. Industrial crops could be defined as crops that are not specifically grown for food purposes but are specifically grown to produce resources useful to industrial processes (Fleenor, 2001). In task 1.3 (D1.3), a selection was made of 20 industrial crops that will be further investigated. These 20 crops are divided into three categories: oil crops, lignocellulosic crops, and carbohydrate and multipurpose crops. An overview of the selected crops is given in Table 1.

Table 1: The 20 industrial crops selected in the MAGIC project.

Oil crops	**Lignocellulosic crops**	**Carbohydrate & Multipurpose crops**
Camelina	Switchgrass	Sorghum
Castor bean	Miscanthus	Safflower
Crambe	Giant reed	Cardoon
Ethiopian mustard	Tall wheatgrass	Wild sugarcane
Pennycress	Reed canary grass	Lupin
	Willow	Industrial hemp
	Poplar	
	Black locust	
	Siberian elm	

Each of the crops listed in Table 1 is matched to a number of technologies and the resulting intermediate and end products. The combination of the technology and the crop is investigated in terms of data availability, TRL and market potential. Data availability depends on the amount of in-house knowledge and the availability of open literature. The TRL will be evaluated based on current research projects or operational pilots or factories. Finally, the market availability will be determined by an indication of the market size for the product, as well as the feasibility of the product entering this market. This will be the basis on which nine value chains will be selected for a more in-depth study for D6.3.

3 Crop properties

The selected crops in MAGIC can be divided into three main categories: oil crops, lignocellulosic crops, and sugar crops. However, some crops fall into multiple categories. An overview of the selected crops and their respective category can be found in Table 1.

Due to the large differences between the three different types of crops, and the requirements for their related conversion technologies, each of the three crop types will be discussed separately

3.1 Properties of selected oil crops

The crops discussed possess different fatty acid profiles. The high content of the fatty acids of interest and the ability to isolate them makes the particular plant to be more apt for further industrial applications. Multipurpose crops with a high oil content, such as safflower and lupin, will be discussed here purely on basis of their usage as oil crop.

Fatty acids of the oilseed crops could be classified into four major classes according to the presence and the number of double bonds in their carbon chain, saturated fatty acids (SFA) contain no double bonds, monounsaturated fatty acids (MUFA) contain one, and polyunsaturated fatty acids (PUFA) contain more than one double bond.

Classes	Fatty acids
Saturated fatty acids (SFA)	C6:0, C8:0, C12:0, C14:0, C16:0, C18:0, C20:0, C22:0, C24:0
Monounsaturated fatty acids (MUFA)	C16:1 n-7, **C18:1 n-9**, C20:1 n-9, **C22:1 n-9**, C24:1 n-9
Polyunsaturated fatty acids (PUFA)	**C18:2 n-6**, **C18:3 n-3**, C18:3 n-6, C20:2 n-6, C22:2 n-6
Functional group	**C18:1,OH**

The following sections compare the selected nine crops with major existing crops in the market.

3.1.1 Monounsaturated fatty acids (MUFA).

The two types of MUFA present largely among the selected crops are oleic and erucic acid.

3.1.1.1 MUFA-Oleic acid

The two major crops rich in oleic acid existing in the market are rapeseed and the high-oleic variety sunflower. Lately, there are also high oleic soybean oil arriving in the market to respond to the oleic acid demand. There Figure 1 shows that among the two chosen crops, the high oleic variety safflower has a fatty acid profile similar to sunflower, however, as safflower is not a well-known food crop and the oil being relatively cheaper than sunflower it could be well-exploited on an industrial scale. Lupin on the other hand is relatively low in oleic acid content. Besides, lupin's oil being rich in PUFA and SFA may complicate further downstream processes. It may however find better applications in food market than in industrial processes.

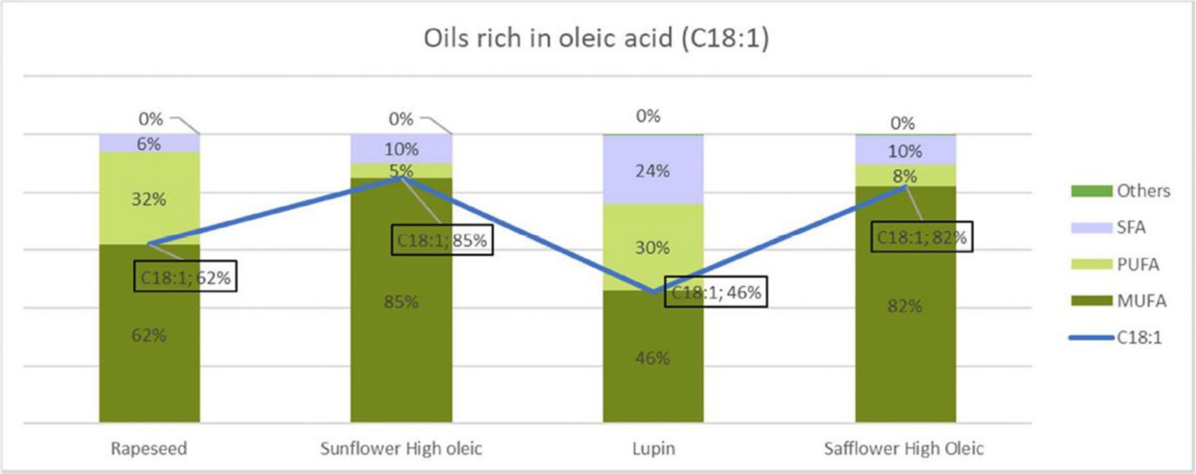


Figure 1: Vegetable oil rich in oleic acid.

3.1.1.2 MUFA-Erucic acid

The high-erucic acid rapeseed (HEAR) has around 48% of erucic acid. When compared to HEAR, crambe oil has higher erucic acid content of 59% and also has relatively low PUFAs. As new researches are being conducted to develop crambe varieties richer in C22:1 and lower in PUFA, crambe plant may soon be a better feedstock choice than HEAR in erucic acid applications. Ethiopian mustard and pennycress despite possessing high concentration of erucic acid, the higher amount of PUFAs may complicate the erucic acid isolation and downstream processes thus, making these oils less attractive when compared to HEAR or crambe oil.

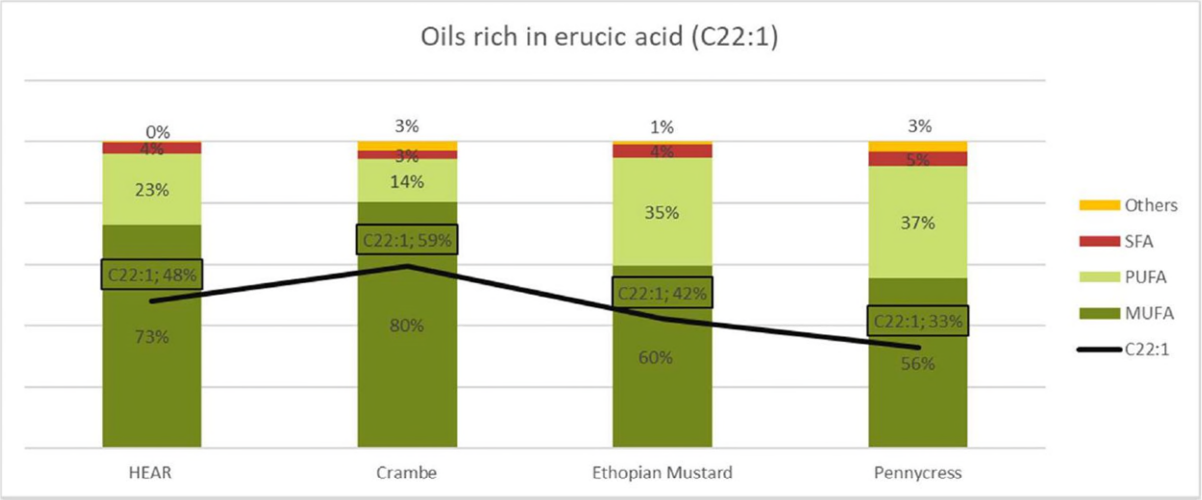


Figure 2: Vegetable oils rich in eructic acid.

3.1.2 Polyunsaturated fatty acids (PUFA)

Polyunsaturated fatty acids that are mainly found in the plants are linoleic acid and linolenic acid.

3.1.2.1 Linoleic acid

The current source of linoleic acid in the market is soybean oil and high-linoleic sunflower oil. Cardoon and safflower oil are relatively richer in linoleic acid with the latter having up to 75% of linoleic acid compared to the existing plant.

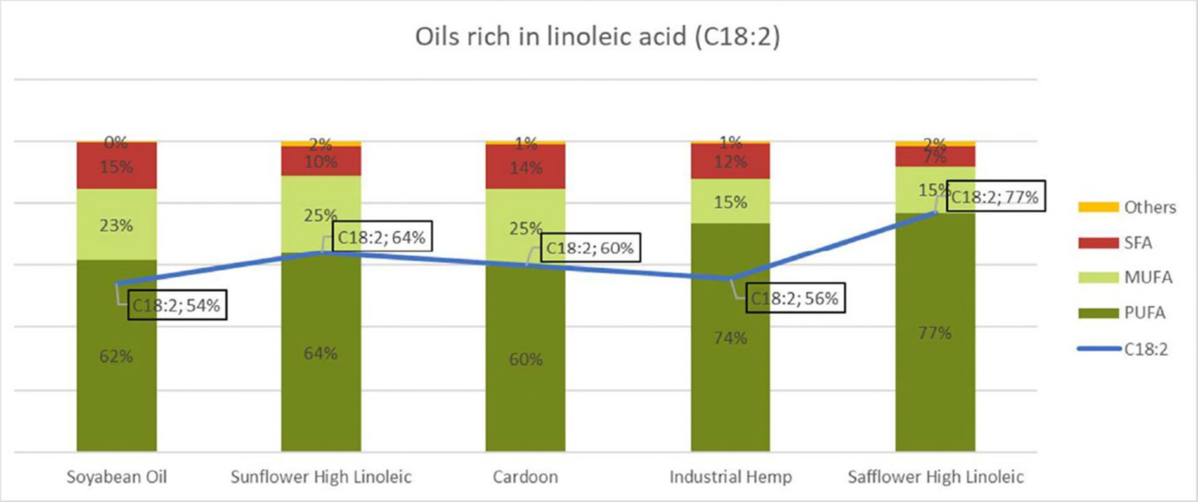


Figure 3: Vegetable oils rich in linoleic acid.

3.1.2.2 Linolenic acid

Linseed oil is rich in PUFA mainly linolenic acid (around 76%). Its fatty acid profile is comparable to that of camelina oil. However, camelina oil exhibits unique fatty acid profile as it also contains around 16% of gondoic acid (C20:1). Once the latter is isolated, linseed oil and camelina oil would have very similar fatty acid composition.

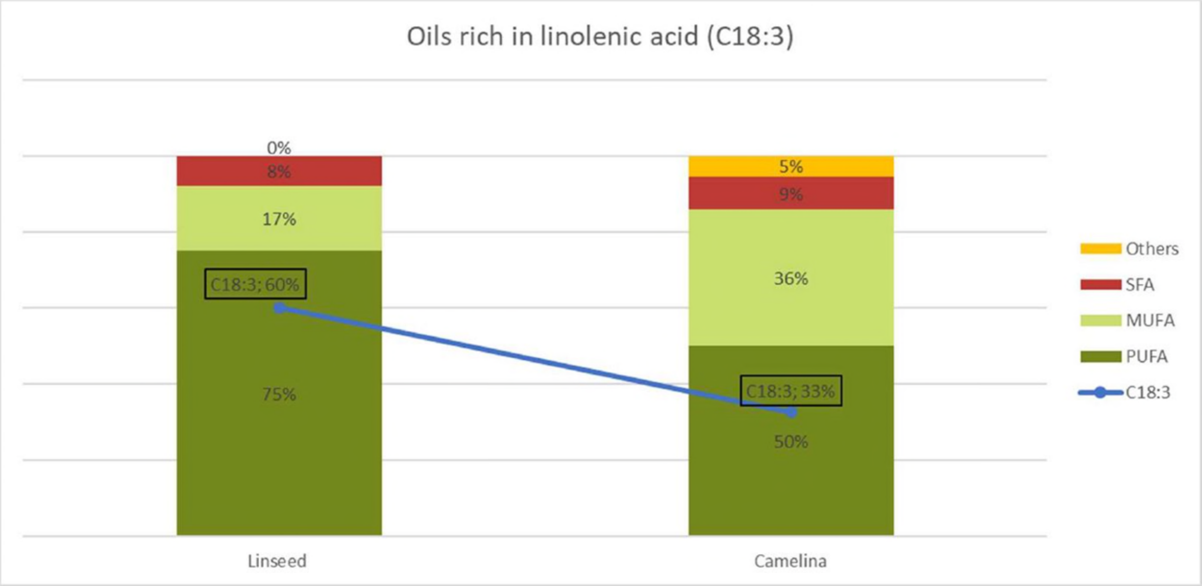


Figure 4: Vegetable oils rich in linolenic acid.

3.1.2.3 Ricinoleic acid

Castor bean oil has unique fatty acid profile as it is readily very rich in ricinoleic acid. It contains 85% of ricinoleic acid (RA) and less than 10% of PUFA. The presence of the hydroxyl group in RA provides a functional group location for performing a variety of chemical reactions. Ricinoleic acid is also physico-chemically very different from the other fatty acids, which facilitates its isolation (example: in solvent extraction) and which in turns reduces the need for ricinoleic acid isolation. Due to this, castor bean finds itself in numerous industrial applications.

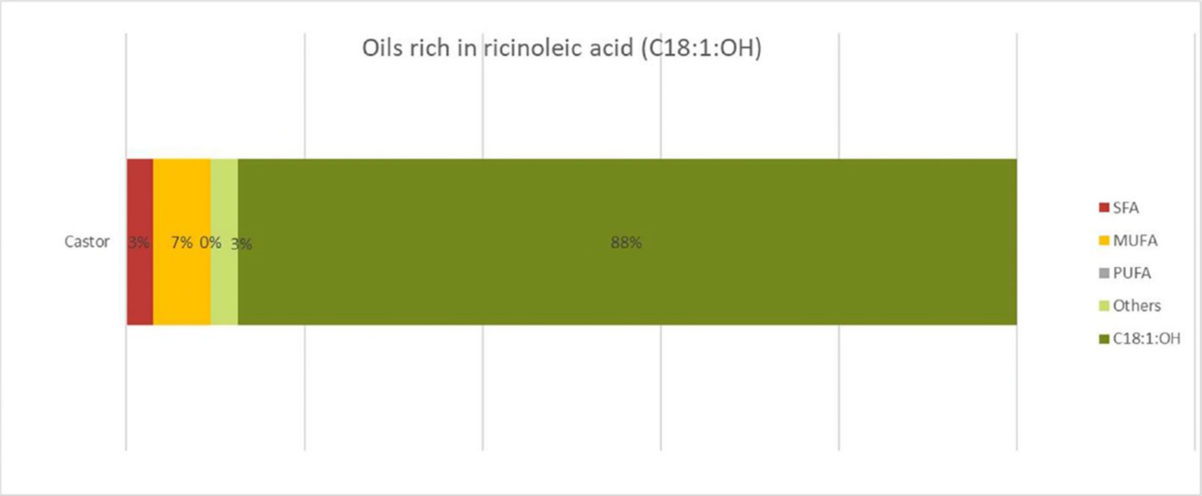


Figure 5: Vegetable oil rich in ricinoleic acid.

3.2 Properties of selected lignocellulosic crops

The crops selected to represent the lignocellulosic crops are all chosen for their relatively high hemicellulose, cellulose and lignin content. In order to assess their suitability for the conversion technologies, the most relevant properties for lignocellulosic crops are presented in Table 2.
Next to the cellulosic material and lignin, other components, such as the ash content and nitrogen content is relevant for many conversion technologies, these data are represented in Table 3 for the selected industrial crops.

The exact values in Table 2 and Table 3 for the selected biomass will depend on many factors, such as the growing conditions and harvesting methods. To achieve a basic understanding of the composition of the selected biomass, compiled data were selected from the S2Biom project. This was completed with an average from the Phyllis database and data from several literature sources. For some woody biomass, i.e. Black Locust and Siberian Elm, there are only a few data sources for their wood biomass properties. The data that is available in open literature are from old publications. However, it can be assumed that the properties of these two woody biomass types are within a similar range as the other wood biomass.

Table 2: Properties of the selected lignocellulosic crops.

Crop	**Moisture (ar, %)**			**Bulk density (ar, kg/m^3)**			**Traded form**	**Net Cal. Value (ar, MJ/kg)**			**Net Cal. Value (dry, MJ/kg)**			**Gross Cal. Value (MJ/kg)**			**Ash metling behavious (°C)**			**Source**
Value type	Typ	Low	High	Typ	Low	High		Typ	Low	High	Typ	Low	High	Typ	Low	High	Typ	Low	High	
Switchgrass (SG)	12	8	15	175	150	200	Baled straw	14.86	13.90		16.64	15.95	17.66	19.04	18.29	20.05	1098	1035	1160	1
Miscanthus (Mi)	40	24	46	175	150	200	Pellets	10.16	7.70	16.34	17.98	17.14	20.39	19.98	19.61	20.48	851	650	980	1
Giant Reed (GR)	39	36	42	175	150	200	Pellets	9.63	9.17	10.09	17.38	17.17	17.58	18.00	17.81	18.20	5.50	4.80	17.40	1
Tall Wheatgrass (TW)	11	-	-	175	150	200	Baled straw	-	-	-	17.89	17.68	18.10	16.3	15.7	16.5	-	-	-	2, 3, 4
Reed Canary Grass (RCG)	9	7	14	175	150	200	Pellets	12.70	12.70	13.10	16.50	16.50	17.00	17.70	17.70	18.00	1227	990	1540	1
Willow (W)	40	30	50	330	300	390	Chips	10.10	7.60	11.50	18.40	17.70	19.00	19.90	19.20	20.40	1363	1164	1467	1
Poplar (P)	40	30	50	340	320	400	Chips	10.10	7.40	12.40	18.40	17.30	18.80	19.80	19.50	20.10	1320	1320	1370	1
Black Locust (BL)	40	-	-	730 (dry)	600 (dry)	855 (dry)	Chips	-	-	-	19.12	15.33	20.38	19.87	-	-	-	-	-	5, 6, 7
Siberian Elm (SE)	-	-	-	-	-	-	Chips	-	-	-	19.66	18.94	20.28	-	-	-	-	-	-	8

Ar = as received, cal = calorific, typ = typical). Sources: 1. (*S2Biom*, 2016), 2. (Danielewicz *et al.*, 2015), 3. (Lalak, Martyniak, *et al.*, 2016), 4. (Yi Zheng *et al.*, 2005), 5. (Energy research Centre of the Netherlands, 2018), 6. (Geyer and Walawender, 1993), 7. (Panayotov *et al.*, 2015), 8. (Geyer, Argent and Walawender, 1987).

Table 3: Composition of the selected industrial lignocellulosic crops.

Crop	**Cellulose (%)**			**Hemicellulose (%)**			**Lignin (%)**			**Ash (%)**			**Nitrogen (%)**			**Chlorine (%)**			**Source**
Value type	Typ	Low	High	Typ	Low	High	Typ	Low	High	Typ	Low	High	Typ	Low	High	Typ	Low	High	
Switchgrass (SG)	36.9	32.0	38.5	32.1	30.8	33.6	6.8	5.3	12.1	6.3	4.5	10.5	0.63	0.40	1.30	0.19	-	-	1
Miscanthus (Mi)	44.6	44.1	45.0	23.9	17.8	30.0	21.3	21.0	21.6	3.8	1.6	4.0	0.51	0.19	0.67	0.30	0.10	0.50	1, 2
Giant Reed (GR)	32.9	26.6	43.8	27.2	25.7	28.3	18.0	16.8	19.4	5.5	4.8	17.4	0.47	0.31	0.62	0.20	-	-	1
Tall Wheatgrass (TW)	35.3	33.4	38.0	23.9	21.0	27.8	18.3	-	-	7.5	5.8	12	0.5	-	-	0.27	0.25	0.39	3, 4, 2
Reed Canary Grass (RCG)	32.2	26.0	38.5	24.6	16.5	28.0	4.6	4.0	5.3	6.5	1.0	8.2	1.30	0.40	2.00	0.60	0.02	0.90	1, 2
Willow (W)	44.4	35.2	50.8	25.3	12.7	39.8	26.3	-	-	2.0	1.1	4.0	0.50	0.20	1.12	0.02	0.02	0.04	1
Poplar (P)	44.4	35.2	50.8	25.3	12.7	39.8	22.9	15.5	31.9	2.0	0.2	3.4	0.40	0.10	0.60	0.05	0.03	0.08	1
Black Locust (BL)	46.2	41.5	46.2	27.0	20.9	33.2	18.7	17.7	19.7	0.9	0.2	1.6	0.87	0.57	1.17	0.08	-	0.08	3, 5, 6
Siberian Elm (SE)	-	-	-	-	-	-	-	-	-	1.7	0.6	2.9	0.33	0.20	0.46	-	-	-	7, 8

All data on dry basis, typ = typical. Sources: 1. (*S2Biom*, 2016), 2. (Lalak, Martyniak, *et al.*, 2016), 3. (Energy research Centre of the Netherlands, 2018), 4. (Danielewicz *et al.*, 2015), 5. (Geyer and Walawender, 1993), 6. (Kačík *et al.*, 2016), 7. (Geyer, Argent and Walawender, 1987), 8. (Sundar, 1985).

3.3 Properties of selected carbohydrate and multipurpose crops

Several crops are selected in the MAGIC project for their carbohydrate content or special properties to make them valuable as multipurpose crops. In these cases, there are overlaps with oil crops and lignocellulosic crops since these crops combine opportunities of several application and usage areas in specific plants. The specific properties that make these crops fall in this category are described below for each of the carbohydrate and multipurpose crops.

3.3.1 Sorghum (*Sorghum bicolor*)

Sorghum bicolor is mainly cultivated in tropical and subtropical regions primarily for its grain, which can be used for food, feed and ethanol production. In many parts of Africa and Asia, sorghum is a staple food. Most cultivars are annual. In general, sorghum can grow in a wide range of temperatures, altitudes and even on toxic soils. Thanks to several features (large root-to-surface area, C4 fixation), Sorghum is among one of the most drought resistant crops. Especially wild sorghum is a very resistant plant that can be used for bioremediation to clean-up and for the prevention and control of soil erosion in affected areas.

Cultivars with high sugar content in their stalks are referred to as sweet sorghum, which grow best under dry and warm conditions. Sweet sorghum is used as forage, silage and syrup, but also plays an important role in the production of bio-ethanol. The global sorghum biomass production already equalled more than 42 million metric tons. Sorghum seeds are traded in bags, syrup (molasses) in flasks and containers (for bigger amounts). Silage is produced and stored in silage clamps.

Sorghum bicolor stalks have a lignin content of around 7,05 %, a cellulose content of around 15,08 % and a hemicellulose content of 12,25% (Energy research Centre of the Netherlands, 2018). The sugar content of sweet sorghum stalks ranges between 6.2 – 21.4 %, depending on the physiological growth stage of the plant (Atokple, Oppong and Chikpah, 2014). Subramanian and Jambunathan have determined grain properties among 45 sorghum cultivars. Mean protein content accounted for 10.6 %, starch for 68.7 % (of which 27.2% are amylose) and fat for 3.3 % (Subramanian and Jambunathan, 1982).

Especially for sweet sorghum cultivars the direct production of sugars (saccharose) is an option already in place. Beside the use in the food industry the sugar can be utilised via fermentation or chemical processes. Especially in Africa Sorghum is already used to produce local sorghum beer. Based on the saccharose a high-fructose syrup can be produced and used for food, drinks and also for technical uses. The main aim at the moment is to produce ethanol based on sorghum sugars. Sorghum stalks and total biomass also can be used as lignocellulosic feedstock to produce 2nd generation sugars (glucose) via biomass hydrolysis. As valuable byproducts lignin and hemicelluloses will be made available. The technology is the same as established in other grass lignocellulosic biomasses, mainly wheat straw. Some specific cultivars are grown with a high cellulose fibre content especially for the 2nd generation sugar production. The fibres can be used as an analogue to hemp or flax fibres for the production of construction materials and pulp/paper.

Specialty sorghum hybrids contain high levels of diverse phenolic compounds that may provide health benefits. Sorghums could thus be an important source of ingredients for use in functional foods and other applications. However, data are hard to find on antioxidant activities of the specialty sorghums and/or their products.

3.3.2 Safflower (*Carthamus tinctorius*)

Safflower is a thistle-like, herbaceous, annual plant that is commercially cultivated for its oil. Plant height varies between 30 – 150 cm. The flowers are of yellow, orange or red colour and can be used as a natural dye. Flower heads contain 15 to 20 seeds per head. Safflower thrives best in arid regions with seasonal rain, thanks to its deep taproot. It further only requires small amounts of N fertilisation. According to FAOSTAT, annual safflower seed yield in 2013 was 718,161 tons. The biggest producer of safflower seeds was Kazakhstan, among other producing countries such as USA, India, Mexico and Argentina.

Safflower seeds yield a colourless and flavourless oil. However, two types of safflower are producing oil of different properties: one high in MUFA (60% oleic acid, n9), used in cooking or as drying and semi-drying oil for paints; the other high in PUFA (70-80 % linoleic acid, n6), used as edible oil, e.g. in margarines. Safflower oil might also be used in human health. However, results are rather controversial. Safflower seed products can be used in animal feeds, either the seeds themselves, or for example as extraction meals. Safflower foliage and stems (straw) can be used as green fodder, hay or silage. The protein content of safflower seeds ranges around 15.6 % (Energy research Centre of the Netherlands, 2018). Seeds are traded in bags and the oil in container or flasks. Dried petals are also traded in bags.

The traditional use of safflower is for the production of organic dyes mainly for textiles. The flower contains carthamine and carthadimine that can be used to extract red-, brown- and yellow-coloured extracts for dyeing of wool, cotton and other fibres. Partly these extracts can also be used for cosmetics. Due to modern chemical dyes safflower dyes are not competitive but are still on the markets in small shares as organic and natural dyes.

Like other plants safflower is also an object of research for pharmaceutical uses and for the use of functional foods and feed. This includes the use of the safflower oil and the use of leaf extracts with a high antioxidative and antimicrobial potential. Recent research show impacts as functional feed / pharmaceuticals for fish feed to protect trouts against e.g. *Streptococcus iniae* (Zargari, Mazandarani and Hoseini, 2018). For humans functional properties of safflower oil may include treatment against skin infections, bone related disorders, menopause and artherosclerosis (Khalid *et al.*, 2017).

3.3.3 Cardoon (*Cynara cardunculus*)

Cardoon is a thistle in the sunflower family, native to the western and central Mediterranean regions, where It occurs both in cultivated and wild forms. It is an herbaceous perennial plant growing 80 – 150 cm tall. It is adapted to dry climates and native to various regions with such conditions (e.g. Morocco, Libya, Greece, Cyprus, Canary Islands). In Australia, California and the pampas of Argentina it is considered an (invasive) weed. As opposed to the artichoke, which is selected for its edible flower buds, cardoon has been selected for its edible stems. Cardoon stems can be covered in small spines which cause severe pain upon contact, however, spineless cultivars have been developed.

Cardoon requires a long, cool growing season of about five months, yet it is frost-sensitive. In addition to that, it also requires a lot of growing space per plant. Cardoons are used as a vegetarian source of enzymes for cheese production as a rennet substitute. While it is also used as an ornamental plant, it has gained great interested in terms of bio-diesel production. The oil properties of cardoon seed oil are similar to those of safflower and sunflower. Cardoon further is used as feedstock for a biorefinery, functioning as biomass and oils for the building blocks of bioplastics.

Cardoon is traded as fresh vegetable for gastronomy, or as biomass feedstock for biorefineries. Oil is, as usual, traded in flasks and container. Information on cardoon biomass properties is scarce. The plant oil of cardoon seeds is very similar to sunflower oil so there is a potential to be used as an alternative for sunflower oil in some specific applications. It was discussed as an oil for methylisation for the Biodiesel production and also as a base for the production of chemicals and building-blocks for bioplastics ((Fernández, Curt and Aguado, 2006; Sengo *et al.*, 2010). Press cakes can be used as protein-rich feed for cattle.

Cardoon-based enzymes extracted from cardoon flowers are already used as alternative rennet substitutes in cheese making, especially in Portugal. As a vegetarian sourced rennet alternative, it may have a potential for vegetarian cheese production or vegan cheese alternatives but also for wine-making and other processes. Cardoon roots contain inulin as an alternative sugar source in a relatively high concentration. Therefore, there may be an option to extract inulin from cardoon roots as a substitute or addition from inulin from other sources, mainly chicories roots or (potentially) topinambur.

Because of the high growth rates Cardoon stalks and total biomass were also discussed as energy crops for solid biofuels (Fernández, Curt and Aguado, 2006). As lignocellulose it also has the potential to be used to produce 2nd generation sugars (glucose) via biomass hydrolysis. As valuable by-products, lignin and hemicelluloses will be made available. The technology is the same as established in other grass lignocellulosic biomasses, mainly wheat straw. The potential of cynara biomass for paper pulp production was studied within the framework of a European project. This application is seen as an interesting alternative within the sector of hardwood pulps given that the properties of cynara pulp are similar to those of the eucalypt pulp (Fernández, Curt and Aguado, 2006).

3.3.4 Wild sugarcane (*Saccharum spontaneum*)

Wild sugarcane (aka Kans grass) is a perennial grass native to the Indian Subcontinent, growing up to three meters in height. Kans grassland is an important habitat for the Indian rhinoceros. In Nepal, it is harvested to thatch roofs or fence vegetable gardens. In many other regions, wild sugarcane is considered an invasive species. Wild sugarcane can grow on most soils and can tolerate moderate levels of salinisation.

Its main use is in the breeding of cultivated sugarcane, as it provides genes for vigour, hardiness and resistances to many major diseases. The canes can be used as a source of sugar, however (compared to cultivated sugar cane), the sucrose content is low and the fibre content high. Other parts of the plant (e.g. hearts of young shoots, young inflorescences etc.) can be eaten. The ash from burnt plants can be used as a salt substitute. The high carbohydrate content of the plant stem (67.85 wt%) makes it a putative candidate for bioethanol production. Like its cultivars grown as sugar cane in the worldwide tropics, also wild sugarcane contains a relatively how amount of sugar (but not as high as cultivated sugar cane) that can be extracted and used as sweetener in the food industry or as industrial sugar for fermentation.

The bagasse of sugarcane can be used for solid biofuels or as a lignocellusic feedstock to be used for the production of 2nd generation sugars (glucose) via biomass hydrolysis as valuable by-products lignin and hemicelluloses will be made available. The technology is the same as established in conventional bagasse treatment available mainly in Brazil.

Unfortunately, hardly any information is available on its biomass properties or traded forms.

3.3.5 Lupin (Lupinus mutabilis)

Lupinus mutabilis, also known as tarwi, is a species of lupin originally grown in the Andean regions of Ecuador, Peru and Bolivia as a protein plant. It is an annual plant which can reach 50 – 280 cm in height. One pod contains on average 2-3 seeds, but up to 8 seeds are possible. The growing cycle varies from 150 – 360 days. It is a crop for cool climates and can be grown in altitude ranges between 800 – 3000 m. It is exceptionally drought resistance. Mature plants are resistant to frost. Seedlings however are sensitive to low temperatures.

Lupines are one of the focus plants for a green biorefinery concept to produce proteins, oils and also sugar-rich substrates for fermentation processes. The composition of the lupin seeds are shown in Table 4. The bean contains more than 40% protein and 20% fat (28% LA n-6, 2% ALA n-3) and is used as food. It is also rich in lysine, an essential amino acid. It has a high alkaloid content which makes it bitter in taste, however these alkaloids can be removed by soaking in water for several days or by denaturation with heat treatment. Lupine seeds have a considerable value for alternative protein production in the food and feed industry. Press cakes can be used as protein-rich feed for cattle. Especially in the area of vegan food products like milk and meat alternatives lupines can be used. In general, the proteins, especially in case of contaminations, can also be used in industrial applications of specific adhesives, paper coatings, polymers and other uses.

Table 4: Composition of lupin seeds.

Ingredient	Typical amount (%)	Range (%)
Protein	42.6	37.7-49.7
Oil	18.7	12.8-22.2
Fibre	6.27	4.29-7.51
Ash	3.69	3.10-4.24
Carbohydrates	27.3	23.7-29.9
Alkaloids	3.26	2.56-4.14

As a legume, tarwi is capable of fixing nitrogen from the air and can therefore be used as green manure and soil improver. The whole plant contains nitrogen in the form of ammonium that is directly usable for other plants. As a soil improver the harvested lupins can be worked into the ground to enrich the soil with nitrogen and rhizobacteria to fix additional nitrogen from the air as a fertiliser and additionally would stabilise the soil structure. This traditional usage can bring up to 100kg/ha additional nitrogen

3.3.6 Industrial hemp (Cannabis sativa)

Hemp is indigenous to Central Asia / China, but nowadays widespread in temperate countries. It grows best with average temperatures between 13 and 22 °C. It adapts well to different soils, especially heavy, non-acid ones. It does not require irrigation or herbicides in temperate countries, and only requires low levels of N fertilisation.

Industrial hemp contains very low levels of psychoactive chemicals and are grown for the production of fibre, seeds and oil. Hemp bast and stem fibre has a lignin content of 4,37 % and cellulose content of 69,37% and are extremely durable. Hemicellulose accounts for 8,7 %. Plant fibre is already used for several applications. Long fibres can be used for woven and non-textiles, ropes and other purposes. Short fibre is mainly used as reinforcement for composite materials for several products. It can also be used as pulp for the production of special paper types, mainly cigarette papers. Shives as a by-product of the fibre production are utilised for several purposes like bedding for animals (horses and rodents) or growing substrate for plants. They also can be used for the production of low-weight particle boards or as a solid fuel for energy production.

Cold pressed seeds yield a green, edible oil. Hemp oil consists of 82 % PUFA (22% ALA n3, 54% LA n6). A second pressing with heat gives a brown oil, which is used in paints, varnishes (as a drying oil) or as a Luminant. Oil extracted from the hemp seeds is a high-value oil for food applications but in general it can also be used for several technical applications and also for fuel production (but will not likely be competitive here). The press cake from oil extraction can be used as fodder for livestock. Hemp contains several molecules that are of very high value for the production of pharmaceuticals. It is grown as a drug plant for centuries mainly for the effects of THC that is a psychoactive substance and can be used as a painkiller or analgesic. Other compounds have a potential for medical uses as well, mainly CBD for several effects.

Hemp seeds are mostly traded in bags. Straw is traded in bales, however this straw is further divided into fibre and shives. Fibre is traded coiled or balled, shives in bags.

4 Conversion technologies

There are many potential conversion technologies for the conversion of crops to energy, fuels, biochemicals or biomaterials. In order to limit the number of technologies that are considered here, only conversions technologies that are applicable on a reasonable time-scale will be discussed. This means that conversion technologies that are only recently proven feasible and are still in early development (TRL <5) will not be taken into account.

The goal of this assessment is to discover the most promising combinations of crops and technology, which will be analysed in further detail in D6.3. The most promising combinations are defined as having a suitable combination of technology and crop, a high TRL and a large market potential. In order to enable a full analysis of the entire value chain, data availability is of utmost importance as well and value chains that have not sufficient data available will be excluded.

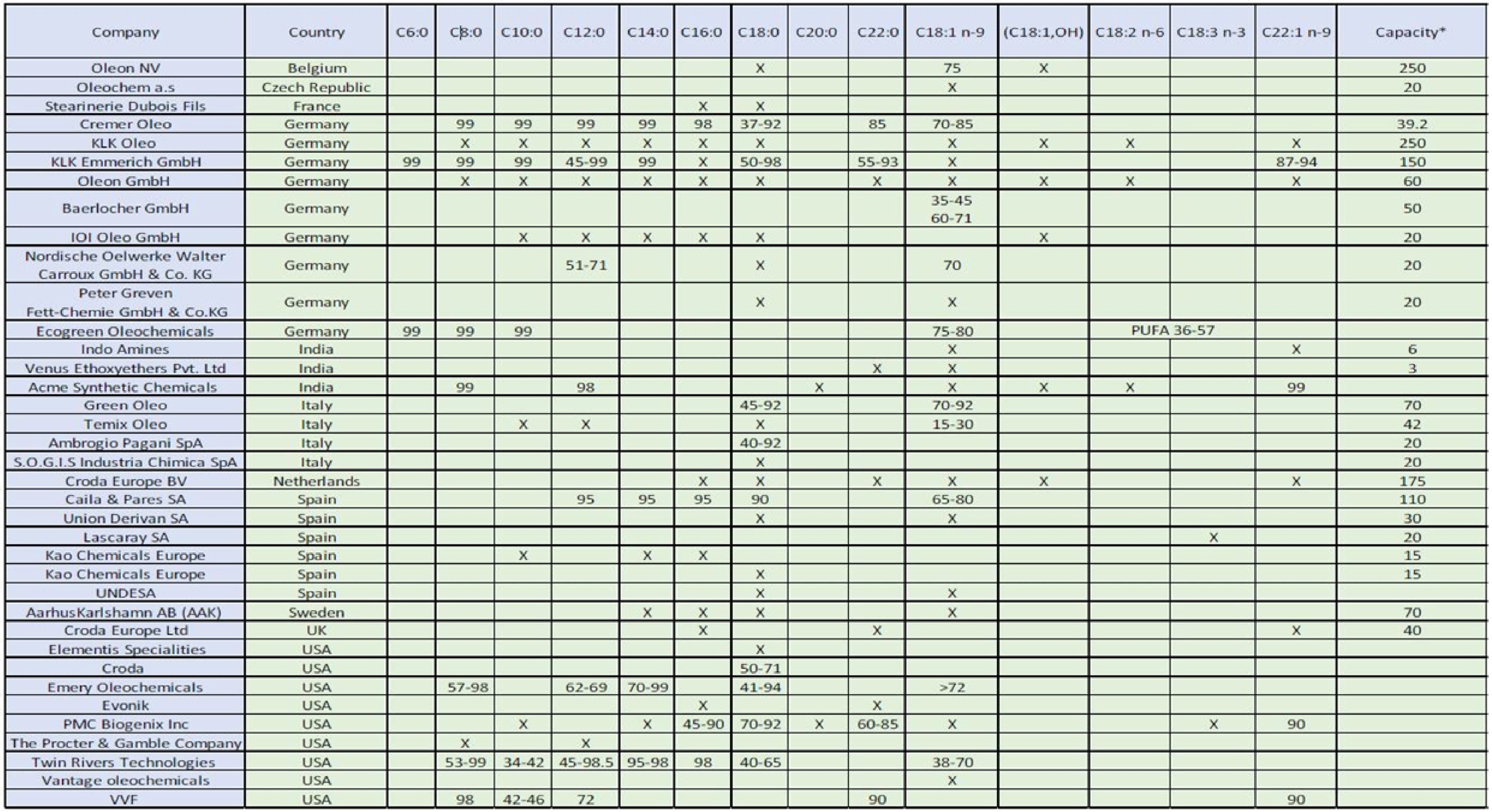
The suitability of each technology for a crop will be evaluated by using available literature and/or using the biomass composition of each crop. The TRL will be evaluated based on current research projects or operational pilots or factories. Finally, the market availability will be determined by an indication of the market size for the product, as well as the feasibility of the product entering this market.

4.1 Conversion technologies for oilseed crops

4.1.1 Hydrolysis

Fatty acids are produced by hydrolysis of fats and oils. This reaction could be catalysed by acid, base or enzymes. On an industrial scale, fatty acids are produced by employing fat splitting technology which occurs at around 250°C and 20-60 bars without the aid of a catalyst. Counter current water flow removes the glycerol formed resulting in around 99% conversion of fatty acids.(Scrimgeour, 2005) Global natural fatty acid consumption accounts for around 6.6 million metric tons in 2017. It is growing at 3% annual rate for the coming five years. In Western Europe, the market has been growing at an average annual rate of 1.4% and the consumption of all fatty acids is expected to increase to 1.73 million metric tons in 2022. Markets with above average growth include esters and amphoteric surfactants whereas direct applications of fatty acid and fatty alcohols see below average growth rates. Hence, companies tend to emphasise marketing efforts on value-added fatty acid derivatives to obtain better profit margin. Asia is the largest fatty acid producing region accounting 53% of the world's production. On the other hand, Western European accounts only 22% of the global total. As the annual capacity is shifting to Asia, demand for Western Europe material continues to decrease domestically and in export markets.(Wu *et al.*, 2018) Table 5 shows major producers of fatty acids in the world and their capacity as of March 2018. Most of the producers besides fatty acids manufacture other derivatives of fatty acids, however their capacity is not disclosed. The total splitting capacity for producers in North America is estimated to be around 1.0-1.1 million metric tons.

Table 5: Fatty acid producers around the world, communicated purity and plant capacity in 1000 metric tons as of March 2018.



Company	Country	C6:0	C8:0	C10:0	C12:0	C14:0	C16:0	C18:0	C20:0	C22:0	C18:1 n-9	(C18:1,OH)	C18:2 n-6	C18:3 n-3	C22:1 n-9	Capacity*
Oleon NV	Belgium							X			75	X				250
Oleochem a.s	Czech Republic										X					20
Stearinerie Dubois Fils	France						X	X								
Cremer Oleo	Germany		99	99	99	99	98	37-92		85	70-85					39.2
KLK Oleo	Germany		X	X	X	X	X	X			X	X	X		X	250
KLK Emmerich GmbH	Germany	99	99	99	45-99	99	X	50-98		55-93	X				87-94	150
Oleon GmbH	Germany		X	X	X	X	X	X		X	X	X	X		X	60
Baerlocher GmbH	Germany										35-45 60-71					50
IOI Oleo GmbH	Germany			X	X	X	X	X				X				20
Nordische Oelwerke Walter Carroux GmbH & Co. KG	Germany				51-71			X			70					20
Peter Greven Fett-Chemie GmbH & Co.KG	Germany							X			X					20
Ecogreen Oleochemicals	Germany	99	99	99							75-80		PUFA 36-57			
Indo Amines	India										X				X	6
Venus Ethoxyethers Pvt. Ltd	India									X	X					3
Acme Synthetic Chemicals	India		99		98				X		X	X	X		99	
Green Oleo	Italy							45-92			70-92					70
Temix Oleo	Italy			X	X			X			15-30					42
Ambrogio Pagani SpA	Italy							40-92								20
S.O.G.I.S Industria Chimica SpA	Italy							X								20
Croda Europe BV	Netherlands						X	X		X	X	X			X	175
Caila & Pares SA	Spain				95	95	95	90			65-80					110
Union Derivan SA	Spain							X			X					30
Lascaray SA	Spain													X		20
Kao Chemicals Europe	Spain			X		X	X									15
Kao Chemicals Europe	Spain							X								15
UNDESA	Spain							X			X					
AarhusKarlshamn AB (AAK)	Sweden					X	X	X			X					70
Croda Europe Ltd	UK						X			X					X	40
Elementis Specialities	USA							X								
Croda	USA							50-71								
Emery Oleochemicals	USA		57-98		62-69	70-99		41-94			>72					
Evonik	USA						X			X						
PMC Biogenix Inc	USA			X		X	45-90	70-92	X	60-85	X			X	90	
The Procter & Gamble Company	USA		X		X											
Twin Rivers Technologies	USA		53-99	34-42	45-98.5	95-98	98	40-65			38-70					
Vantage oleochemicals	USA										X					
VVF	USA		98	42-46	72					90					90	

4.1.2 Esterification

Fatty acid esters are produced by esterifying fatty acids by an alcohol in the presence of an acidic catalyst (strong mineral acids, organic acids, or metal chlorides). The yield of the reaction depends on the nature of the alcohol (primary, secondary or tertiary alcohol) and the catalyst used. The typical catalyst employed are sulphuric acid and methane sulfonic acid (MSA). Yields up to 97% are obtained. Esters exhibit excellent solubility in organic phase and have very good properties as emollient which represents one of the largest market for esters. (Garrier and Packet, 2012)

350,000 metric tons of fatty acids were used in 2017 to produce different types of fatty acid esters. This amount excludes fatty acid methyl esters which are labelled under biodiesel in Western Europe. Fatty acid esters contribute to the largest quantity of fatty acid derivatives consumed due to its wide applications in various industries.

Fatty acid esters are widely used in industrial applications as release and anti-stick agents, lubricants, emulsifiers, plasticisers, lubricants and viscosity regulators. Growth in the sector is estimated to be on par with GDP ranging around 1-2% per year.

Despite cosmetics being a mature market in Western Europe, fatty acid esters see an above average annual growth of 1.4%. This is largely due to the aging population in this region. A major market of fatty acid esters is in the food and animal feed segments where they are used as emulsifiers. The growth in urbanisation and convenience shopping is estimated to favour the growth in this sector with a rate of 1.5% per year over the forecast period. (Wu *et al.*, 2018)

Table 6: The major producers of fatty esters in France/Europe

Carbon number	Esters	Producers	Purity
C8:0	Methyl caprylate	Temix Oleo	
C12:0	Methyl laurate	Emery Oleochemicals	98
	Hexyl laurate	BASF emollients	
		Stearinerie Dubois Fils	
C14:0	Methyl myristate	Emery Oleochemicals	98
		Evonik	
C16:0	Methyl palmitate	Emery Oleochemicals	98
		Acme synthetic chemicals	99
	Ethyl palmitate	Stearinerie Dubois Fils	
C18:0	Methyl stearate	Valtris Specialty Chemicals	
		PMC Biogenix Inc	
		Acme synthetic chemicals	99
C18:1 n-9	Methyl oleate	Berg Schmidt GmbH& Co	
		PMC Biogenix Inc	
		BASF EU	
		Acme synthetic chemicals	99

	Ethyl oleate	Acme synthetic chemicals	99
		Stearinerie Dubois Fils	
	Methyl linoleate	Acme synthetic chemicals	
	Ethyl linoleate	Caymen chemicals	98
		Stearinerie Dubois Fils	
		Acme synthetic chemicals	99
C18:3 n-3			
C18:3 n-6			
C20:0	Methyl arachidate	Acme synthetic chemicals	99
	Ethyl arachidate	Acme synthetic chemicals	99
C22:0	Methyl behenate	Acme synthetic chemicals	99
	Ethyl behenate	Acme synthetic chemicals	99
C22:1 n-9	Methyl erucate	(lab quantities) DEBYESCI, MuseChem, LGC Standards, Yuhao Chemical, TCI (Tokyo Chemical Industry) (>90)	
	Ethyl erucate		
(C18:1,OH)	Methyl ricinoleate	Acme synthetic chemicals	85

4.1.3 Transesterification

Fatty acid methyl esters are prepared by transesterification of triglycerides in the presence of a base catalyst (sodium methoxide solution) at 80°C. This process is also referred as methanolysis. Vegetable oils such as rapeseed, palm and soybean are transesterified with a large presence of alcohol to displace the reaction to the right equilibrium. High yields are reached >98% to in a short time. The most important application of methyl esters is biodiesel but they are also used as solvents or they can be converted to other oleochemical derivatives such as fatty alcohols. (Garrier and Packet, 2012) Archer Daniels Midland (ADM) also runs plants Germany and also in Brazil, India, Indonesia and the United States with its global production capacity attaining 1,700 Ml/yr.

Table 7 resumes the main producers of biodiesel in Europe. Diester Industries remains the largest producer of biodiesel in the EU in 2009. German subsidiary of the American group Archer Daniels Midland (ADM) also runs plants Germany and also in Brazil, India, Indonesia and the United States with its global production capacity attaining 1,700 Ml/yr.

Table 7: Biodiesel producers in Europe and their production quantity.

Producer	**Plant location**	**Production (Million tonnes/year)**
Diester Industries	France	2250
ADM Biodiesel	Germany	1130
Biopetrol Industries	Schwarzheide, Germany	220
Biopetrol Industries	Rostock, Germany	170

Biopetrol Industries	Rotterdam, the Netherlands	450
Verbio	Schwedt, Germany	280
Verbio	Bitterfeld, Germany	230

4.1.4 Interesterification

Fats hardened by partial hydrogenation contain transisomers which are now regarded as undesirable for health. Liquid fats are now hardened with fully saturated fats raising the solid fat content without isomerising the fatty acids. The use of interesterification to produce margarine, cocoa butter is particularly on the rise in Europe.

Interesterification is applied to either an individual oil or a blend of oils to modify the properties such as the melting point and the solid fat content of the triaglycerols obtained. Two types of interesterifications are usually carried out; chemical-interesterification and enzyme interesterification. Chemical interesterification is carried out at moderate temperatures (70–100°C) and a low concentration of caustic soda. Once subjected to interesterification with a chemical catalyst, the triacylglycerol becomes a random mixture of molecular species. Enzymatic interesterification on the other hand is more selective (Scrimgeour 2005) and reorganises the acid chains on glycerol in a selective way.

4.1.5 Amines via the nitrile route

When fatty acids are reacted with ammonia at elevated temperature, fatty nitriles are produced. These nitriles have little or no direct use, but they are hydrogenated under catalytic conditions to yield primary, secondary and tertiary amines. Primary amines are the biggest category, which accounts for over half of the production. Tertiary amines and ethoxylated amines take about 40%. The rest are from secondary amines and polyamines.

In 2017, 40,000 metric tons of fatty acids were consumed to produce various amines, most of which were used as such or as their salts in various end-use applications. It is estimated that fatty amine derivatives will grow at 1.0 % per year going forward. (Wu *et al.*, 2018) Table 8 shows the major producers of fatty amines in Western Europe.

Table 8: The major Western European producers of fatty nitrogen derivatives via the nitrile route.

Producer	Country	Products
DHW Deutsche Hydrierwerke GmbH (Ecogreen Oleochemicals)	Germany	Lauryl amine, Stearyl amine
Akzo Nobel	Germany	Oleyl amine (95-98%)
Kao Corporation SA	Germany, Spain	Lauryl dimethylamine
ARKEMA CECA SA	France	Stearyl amine
Clariant GmbH	Germany	Ethoxylated amine

4.1.6 Amidation

Amides are commonly formed from the reaction of carboxylic acid with an amine (including ammonia). This reaction could be carried out without a catalyst at high pressure and temperature or with a catalyst at reduced pressure. Short reaction time promotes higher yield of amide. Fatty amides produced demonstrate strong hydrogen bonding, high melting points and low solubility in most solvents. (Garrier and Packet, 2012)

N, N- Ethylene bis (stearamide) (EBSA) represents one of the largest portions of fatty amide production as it the least expensive; followed by erucamide, oleamide and stearamide. EBSA is used in polyvinyl chloride (PVC) resins as an internal lubricant during injection moulding. Growth in the fatty amide market is strongly correlated with the growth in plastics. (Wu *et al.*, 2018) In 2017, 31,000 tons of fatty acids were consumed to produce fatty amides and the annual growth rate is estimated to be 1.5% up to 2022. Growth in this market largely parallels the growth in plastics. (Wu *et al.*, 2018)

Table 9: The major producers of fatty amides.

Producer	**Country**	**Products**
Akzo Nobel Chemicals NV	Belgium, USA	Oleamide, Erucamide, Steramide, Oleonitrile
KLK Oleo	Germany	Ethylene bis stearamide (EBS), Ethylene bis oleamide (EBO)
Kao Corporation SA	Spain	Ethylene bis stearamide (EBS)
FACI Spa	Italy	Ethylene bis stearamide (EBS)
S.O.G.I.S. Industria Chimica Spa	Italy	Ethylene bis stearamide (EBS)
UNDESCA	Spain	Ethylene bis stearamide (EBS)
PMC Biogenix Inc	USA	Palmitamide, Stearamide, Behenamide
CRODA		Behenamide

4.1.7 Hydrogenation

On an industrial scale, catalytic hydrogenation is usually employed to produce fatty alcohols, however the preferred starting material is fatty acid methyl ester. Fatty acids are deemed to be too corrosive and require harsh conditions leading to unwanted by-products. Methyl esters are converted to saturated alcohols in the presence of copper chromite catalyst (~2%) at 250–300°C and 250–300 bar hydrogen in a suspension system or at 200–250°C with a fixed-bed catalyst. The methanol released is the recycled to produce methyl esters. Unsaturated alcohols such as oleyl alcohol are produced in the presence of zinc or copper based catalyst as they do not hydrogenate the double bonds. (Scrimgeour, 2005)

In 2017, 56,000 metric tons of fatty acid were consumed in Western Europe. Growth is expected around 1.1% till the forecast year (2022). Sasol Germany GmBH is one of the major producers in the Western Europe with an annual capacity of 30,000 metric tons in Brunsbüttel and 110,000 in Marl, Germany. However, Brunsbüttel is producing fatty alcohols mostly from ethylene (a petroleum derivative), hence the share of natural products is low. Ecogreen Oleochemicals with plants located in Europe (Germany, France) and Asia (Singapore and Indonesia) has a total production capacity of 360,000 tonnes per year. Table 10 shows the producers of fatty alcohols around the globe.

Table 10: Fatty alcohol producers and their communicated purity.

Carbon number	Fatty Alcohol	Producer	Purity (%)
C8:0	Octyl alcohol	Emery Oleochemicals[1]	55-99
		Sasol[3]	
		KLK Oleo[2]	
C10:0	Decyl alcohol	Emery Oleochemicals[1]	45-99
		KLK Oleo[2]	
		Sasol[3]	
		Temix Oleo[4]	
C12:0	Lauryl alcohol	Emery Oleochemicals[1]	
		VVF[5]	68-99
		KLK Oleo[2]	
		Temix Oleo[4]	70-99,2
		Sasol[3]	
		Ecogreen Oleochemicals[6]	52-98
		BASF EU[7]	
C14:0	Myristyl alcohol	Emery Oleochemicals[1]	78-99
		KLK Emmerich GmbH[2]	99
		KLK Oleo[2]	
		Sasol[3]	
		Temix Oleo[4]	98
C16:0	Cetyl alcohol	VVF[5]	98
		KLK Oleo[2]	
		Temix Oleo[4]	98
		Kao Chemicals Europe[9]	
		Sasol[3]	
		Cremer Oleo[8]	95-98
C18:0	Stearyl alcohol	Emery Oleochemicals[1]	99
		VVF[5]	95-98
		KLK Emmerich GmbH[2]	
		Elementis Specialties[12]	
		KLK Oleo[2]	
		Temix Oleo[4]	99
		Sasol[3]	
		Kao Chemicals Europe[9]	
		Cremer Oleo[8]	95-98
C18:1 n-9	Oleyl alcohol	BASF[8]	

		CRODA[11]	
		Sasol[3]	
		Elementis Specialties[12]	
		Ecogreen Oleochemicals[6]	55-98
		Acme synthetic chemicals[13]	99
C18:2 n-6	Linoleyl alcohol	Acme synthetic chemicals[13]	
C18:3 n-3		NA	
C18:3 n-6		NA	
C20:0	Arachidyl alcohol	Sasol[3]	45-55
C20:1 n-9		NA	
C22:0	Behenyl alcohol	VVF[3]	42-92
		Cremer Oleo[10]	70
		Sasol[3]	
C22:1 n-9	Erucyl alcohol	NA	

1.Emery Oleochemicals: fatty alcohols made entirely from oils and fats derived mainly from palm oil and palm kernel oil.
2. KLK Oleo: fatty alcohols are derived from vegetable oils.
3. Sasol: fatty alcohols are also made from synthetic routes using an ethylene derived process.
4. Temix Oleo: fatty alcohols are derived from natural fats and oils.
5. VVF: fatty alcohols derived from palm oil, palm kernel oil and mustard oil
6. Ecogreen Oleochemicals: fatty alcohols based on tropical plant oils (palm oil and palm kernel oil)
8: BASF: Synthetic alcohols
9: Kao Chemicals: Natural fatty alcohols
10: Cremer Oleo: Resourced from vegetable oils.
11: CRODA: fatty alcohols of natural, non-animal origin
12: Elementis Specialities: natural and synthetic alcohols
13: Acme synthetic chemicals: natural alcohols

4.1.8 Intermolecular condensation (to monomers and oligomers)

Different dimers and oligomers are produced from fatty acids and alcohols. Unsaturated fatty acids are heated with cationic clay catalyst. A typical procedure uses (2%-10%) at 180- 270°C for 4-8 hours. On a commercial scale, intermolecular condensation of oleic and linoleic acid mixtures produces a 60:40 mixture of dimer diacids (C36 and higher polycarboxylic acids) and C18 isomerised fatty acids. After distillation, dimer acids can be further separated into distilled dimer diacids (purity >94%) and trimer acids. Branched-chain compounds produced from this reaction have significantly low melting point than straight chain structures of similar molecular weight. Saturated dimers exhibit excellent oxidative stability. This property along with their extended liquid range are exploited in their use as lubricants and cosmetic field. Dimer diacids are dibasic and react with diamines and triamines to give polyamide. (Scrimgeour, 2005)

Rapeseed and tall oil fatty acids (TOFA) are largely used in the production of dimer and trimer acids. The choice of the fatty acid depends highly on the cost of the raw material although some applications may impose exigence on the properties of the resulting dimer. Dimer acids find applications across a variety of diverse industries and are used in synthesis of non-nylon polyamides, hot melt adhesives, printing inks and paints & coatings; and as epoxy curing agents, in corrosion inhibitors for oil field applications; and in lubricants, among others. Monomers find their way into applications such as paste soaps and detergents and are also used as esters in lubricant applications, such as metalworking fluids and textile lubricants. Trimer acid is mainly used in corrosion-inhibiting chemicals for oil field applications. Table 11 shows the major producers of dimer acids are mainly located in the USA and in Europe due to the availability of the raw materials. This sector consumed 89,000 metric tons of fatty acids in the Western Europe and is to see an annual growth rate of 1.9% till 2022.

Table 11: Major producers of monomer, dimer and trimer fatty acids in the world.

Producers	**Country**
Kraton Polymers	USA
Emery Oleochemicals	USA
Ingevity	USA
Kraton Chemical Ltd.	United Kingdom
Croda	The Netherlands
Oleon	Belgium
KLK Oleo	Germany

4.1.9 Heat polymerisation (to blown/stand oil)

There are mainly two types of heat polymerised oils which are stand and blown oil. Stand oils are heat polymerised in the absence of oxygen at the temperature ranging around 200°C. Blown oil on the other is obtained by bubbling air through the oils at temperature ranging from 40 to 150°C. Both reactions produce macromolecular tri-dimensional network with mixtures of monomers, dimers and trimers. The oxygen link present in blown oil makes it very reactive and dry considerably quicker than the corresponding stand oil. However, blown oils are darker in colour, more viscous and acidic than stand oils. Blown linseed oil is used in the manufacture of electrical insulation varnishes and in the preparation of cheap high gloss varnishes where colour is unimportant. Stand oils are usually used in the manufacturing of alkyd resins, binder for paintings and coatings and additive for paints.

Types of oil	**Company**	**Country/Region**
Blown linseed oil	Vandenputte Oleochemicals	Belgium
	Croda coatings and polymers	Europe
	Alderdingk Boley GmbH	Germany
	Vliegenthart BV	The Netherlands
Blown castor oil	Croda lubricants	Europe
Blown soybean oil	United Soybean Board	USA
	Vandenputte Oleochemicals	Belgium
Blown rapeseed	Oleon	Italy

	Croda lubricants	Europe
	BIONA JERSÍN	Czech Republic
	Ch. DAUDRUY VAN CAUWENBERGHE & FILS	France
	Industria Chimica Fina Srl	Italy
	Rübelmann GmbH & Co KG	Germany
	TRAQUISA	Spain
	Vandenputte Oleochemicals	Belgium
Linseed stand oil	Oleon	Europe
	Croda coatings and polymers	Europe
Soybean stand oil	Oleon	Europe

4.1.10 Polycondensation (to Alkyd resins)

Alkyd resins are unsaturated hydroxylated polyesters resins modified with vegetable oils or their fatty acid. Therefore, alkyd resins are the main product of polycondensation reactions between poly carboxylic acids and poly alcohol in presence of fatty acids or vegetable oils. This kind of reaction can be represented by the following formula:

Poly carboxylic acid + Poly alcohols + Fatty acids/ Vegetable oils → Alkyd Resin + water

Alkyd resins are the largest volume base of coatings because of their easy manufacturing, low processing cost, and inexpensive raw material. About 48,500 metric tons of fatty acids were used as drying oils in alkyd resin-based coating in 2017. Most of this consumption was accounted for by tall oil fatty acid, but these acids compete with various oils (soybean, linseed and dehydrated castor oil are the most common) in this application. This might be due to solventborne alkyds being replaced with waterborne emulsions. These products have lower odour, lower solvent content, easy clean-up and fats drying properties. The choice of fatty acid or oil is used is based entirely on cost/performance criteria. Fatty acids have some favourable properties compared with oils, but most are also expensive.

Germany is the major producer of alkyd resins in Europe, with approximately 50% markets share. The stagnation of the Western Europe market for alkyd resins has led to large restricting over the recent years. Fatty acids used in alkyd resins are estimated to declined -1.6% on an annual basis for the 5 years.

4.1.11 Polyamidation

Polyamides are polymers in which the monomeric units are linked together by amide bonds. providing an extremely broad range of available properties. Polyamide is used in the production of film and fibre, but is also available as a moulding compound. The majority of nylons tend to be semi-crystalline and are generally very tough materials with good thermal and chemical resistance. The current manufacturers of bio-based polyamide are shown in Table 12. The polyamides are produced from castor oil.

Table 12: Polyamides based on castor oil manufacturers in Europe.

Polyamide(s)	**Company**	**Country**
Rilsan® (PA-11, PA-10 and others)	Arkema	France
Ultramid® S Balance (PA-6,10)	BASF	Germany
Zytel® RS (PA10, PA-6,10)	DuPont	USA
EcoPAXX® (PA-4,10)	DSM	The Netherlands
VESTAMID® Terra (PA-6,10; PA-10,10; and PA10,12)	Evonik	Germany
Technyl® eXten	Solvay (Rhodia)	Belgium
Grilamid® 2S (PA-6,10; PA-10,10)	EMS-GRIVORY	Switzerland

4.1.12 Ozonolysis and other oxidative cleavage

Industrially, ozonolysis is carried out at low temperatures without catalyst. Ozone, however, is toxic and unstable. High purity feedstock is preferred to avoid excess consumption of oxidants and unwanted by-products. Oleic acid ozonolysis produces azelaic acid (DC9) and pelargonic acid (C9) while ozonolysis of erucic acid produces brassylic acid. Emery Oleochemicals and CRODA Sipo are producers of ozonolysis. Although ozonolysis of unsaturated fatty acids has been now developed on an industrial scale, hazardous problems associated with the use of ozone is still a controversial challenge. Replacing ozone with a more benign oxidant such as hydrogen peroxide has been proven to be an alternative. (Scrimgeour, 2005) This reaction, also known as oxidative cleavage, has been developed by Matrica SpA. This oxidation process is called oxidative cleavage, since during the reaction carbon-carbon double bond(s) get cleaved.

In 2017, 31,000 metric tons of oleic acid were consumed to produce azelaic and pelargonic acids. Azelaic acid is an important component in the production of esters used as adhesives, fibres and films. Pelargonic acid on the other hand is used in the synthesis of polyol esters which serve as synthetic lubricants and in the making of alkyd resins. It is also used as herbicide in the agricultural sector and as a bleach activator in laundry detergents.

4.1.13 Epoxidation

During epoxidation, double bonds react with hydrogen peroxide in the presence of a catalyst and sulphuric acid was found to be the most efficient inorganic acid. Maximum conversion of unsaturated fatty acids into fatty epoxides is obtained from hydrogen peroxide that produces in situ peracetic acid and acetic acid in the presence of sulphuric acid. Oils which are mainly rich in PUFA are epoxidized and used in coatings, resins and rubbers. Epoxides are reactive and are easily functionalised making them widely available for chemical modifications. These epoxides are transformed into polyols used in polymer production, plasticisers and stabilisers.

Table 13: Epoxidized Oils manufacturers.

Epoxidized Oils	Manufacturer
Epoxidized soybean oil	Hobum Oleochemicals
	Arkema
	Hallstar
	Valtris Specialty Chemicals
	BERCEO CHEMICALS SL
	FACI SPA
	Galata Chemicals GmbH
	BioBased Technologies (Agrol® 3.6)
	Cargill (BiOH®)
Epoxidized linseed oil	Oleon
	Valtris Specialty Chemicals
	BASF Personal Care and Nutrition GmbH
	HOBUM Oleochemicals GmbH
	TRAQUISTA
	Arkema
Epoxidized sunflower oil	Hobum Oleochemicals

4.1.14 Olefin metathesis

Olefin metathesis, a catalyst technology which swaps molecular fragments on either side of a carbon-carbon double bond, has become an efficient and widely-used chemical process in petroleum refining and other industries. It enables new chemical compounds and manufacturing processes once thought to be impossible. The technology is efficient, stable and predictable, and enables relatively simple processing using widely available industrial equipment. (BioAge Group, 2009)

Wilmar International and Elevance Renewable Science are in the stage of initial commercialisation of 9-decenoic methyl ester. It is produced in the commercial scale manufacturing facility in Gresik, Indonesia and has a capacity of 180,000 M tonnes oil with the ability to expand up to 360,000 M tonnes. The feedstock could range from rapeseed, soybean, palm oil and also other renewable oils with low quantity of free fatty acids depending on its supply and price. (Lane, 2013)

4.2 Conversion technologies for lignocellulosic crops

4.2.1 Combustion for energy

An obvious conversion technology is to burn the biomass in order to obtain the chemical energy stored in biomass. This could be done in a controlled manner to obtain heat and/or electricity in a combined heat and power plant (CHP)(Obernberger, Hammerschmid and Bini, 2001). The combustion can for example be performed with a fluidised bed reactor. This constantly moves the material and gas flow, which ensures a complete combustion (Martin, 2002). With the EU promoting the development of bioenergy combined with the huge energy market, there is no doubt that the market for this technology is very large. In 2016 the total primary production of renewable energy from biomass was 130.9 MToe (5.5 EJ) (Eurostat, 2018).

Combustion is available at high TRL and can be applied at large or small scale. There has been a lot of research on converting non-woody biomass into energy. The main conclusions show that the ash content and its behaviour are a crucial element to designing the technology. Moreover, the different behaviour of the volatiles in grasses make it a more challenging conversion to control (Horvat and Dović, 2018).

4.2.2 Gasification

Gasification of biomass is thermal process where biomass is converted to a useful gas mixture. An intricate process that involves drying, pyrolysis, partial combustion and gasification of char results in a mixture of hydrogen, carbon monoxide, carbon dioxide and methane, which is called producer gas. Producer gas can be further worked up to generate syngas, which gives access to methane, methanol, dimethyl ether or other liquid fuels and chemicals. The production of methane (SNG) is currently running on pilot scale in Sweden (20 MW) and Austria (1 MW). It has since been demonstrated that a plant should produce at least 20 MW in order to be economically feasible (Sikarwar *et al.*, 2016). With the GoBiGas plant in Gothenburg operation for >10.000 hours on woody biomass, the TRL can be seen as 8-9 (Larsson, 2017). However, using woody biomass from short rotation coppice may impact the process and therefore the TRL is estimated at 7-8. For energy crops, gasification on miscanthus has been performed at a 100 kW pilot scale (TRL 5-6) (Samson *et al.*, 2018), but for other crops there have only been reports from lab scale tests, which puts the technology at a TRL of 4-5. Low moisture content and low ash content are preferable. Woody biomass is ideal for gasification, but other lignocellulosic crops can be converted as well (Sikarwar *et al.*, 2016).

4.2.3 Torrefaction

Torrefaction is a heat pre-treatment of biomass in an oxygen free environment, which results in a solid material. This material is then pelletised to obtain a homogeneous, solid fuel. The treatment increases the energy density of the material. The material is suitable for direct combustion in boilers, co-firing in large power plants or gasification to syngas. A typical torrefaction plant will have a capacity of 50 to 70 kton per year (Vis *et al.*, 2015).

The market for torrefied pellets is dependent on the energy market. This is a large market and there is a clear incentive for the market to reduce their carbon footprint, with the EU and its Member States promoting the production of bioenergy. There are several operational torrefaction units in Europe, with a capacity ranging from 8 kton/year to 96 kton/y, giving the technology a TRL of 9 (Ribeiro *et al.*, 2018). However, torrefaction of the selected lignocellulosic crops are at a slightly lower TRL (4 -7), where especially for woody biomass the time to market is expected to be relatively short.

4.2.4 Pyrolysis

Pyrolysis is a conversion technique where the biomass is heated rapidly to a high temperature in an oxygen free environment. This converts lignocellulosic rich biomass into pyrolysis oil. The pyrolysis oil can be used for combustion or could be further upgraded to a range of higher value products. One option is to convert pyrolysis oil with a hydrogenation step to allow for distillation. Another option is to separate the sugar fraction and the lignin fraction. Each fraction has their own range of applications, for example a bitumen replacement, wood preservatives, resins, or a hydrogenation to fuels. Currently, the two largest facilities are under operation by Fortum (Finland) and Empyro (The Netherlands).

Pyrolysis is currently operating on woody biomass, which is preferred due to its availability and favourable ash composition. Therefore, pyrolysis on woody biomass is estimated at a TRL of 6-7. However, in several EU projects the use of other lignocellulosic biomass for pyrolysis is investigated. For example, the use of miscanthus in Residue2Heat and the use of giant reed in BeCool. Currently, the European production of pyrolysis oil is still relatively small, with a capacity of 5 ton/hour in the Netherlands and 10 ton/hour in Finland. However, the market of pyrolysis oil is large due to the energy market being a huge market and the large desire of the energy market to convert to more sustainable techniques. Moreover, the transportation fuel and range of products that can be obtained from pyrolysis oil cover different end-markets.

4.2.5 Anaerobic digestion

Anaerobic digestion to convert biomass to biogas, a gas with a high methane content, is commonly applied for the conversion of waste streams such as manure. The resulting biogas can be applied in CHP units or it can be upgraded to methane and the remaining digestate can be applied as fertiliser (Kiesel, Wagner and Lewandowski, 2017). Energy crops have a higher conversion rate to biogas, which results in a higher methane yield. However, for lignocellulosic crops, the digestion is difficult due to the complex chemical structure. The degradability of the crop can be improved by using a pre-treatment, which can either be physical, chemical or biochemical (Lalak, Kasprzycka, *et al.*, 2016). For woody biomass, the anaerobic digestion becomes further complicated and a more severe pretreatment is required (Matsakas, Rova and Christakopoulos, 2016). Due to the required pre-treatment, the TRL is assessed to be slightly lower for the selected crops than the current commercial installations.

In current commercial digesters, the agricultural residues are often supplemented with a feed of energy crops. For example, in Germany 52% of the feed existed out of energy crops in 2014, of which most consisted of maize (Kiesel, Wagner and Lewandowski, 2017). With the current push for bioenergy and the large amount of digesters already in operation, the market potential for biogas is large.

4.2.6 Fermentation (Cellulosic Ethanol)

By separating the cellulosic material from the lignin and depolymerising it to its sugars, a feedstock can be obtained for fermentation processes. Currently, the main feedstock for are first generation crops that are high in sugar, such as sugarcane in Brazil (Zhang *et al.*, 2017). In order to obtain bioethanol from lignocellulosic crops, the biomass needs to be pre-treated in order to make the cellulosic material available. This can, for example, be done by steam explosion, after which the cellulose is broken down by enzymes in a saccharification step. The resulting mixture can be fed to the fermentation to produce bio-ethanol. Finally, the remains from the fermentation broth can be incinerated to supply energy for the process (Meyer, Wagner and Lewandowski, 2017).

The EU pushes for the use of renewable feedstock for the production of transport fuels, where especially the use of non-food sources is promoted. This creates a very large market for bio-ethanol for the use as fuel in the transport sector (Littlewood *et al.*, 2014). Where first generation bioethanol is commonplace, second generation bioethanol is less common. An example of the production of second generation bio-ethanol is the activities of Borregaard, which produces 20 million litre bio-ethanol per year from woody biomass (Borregaard, 2018). Cellulosic ethanol reached a TRL of 9, with a wide implementation around the globe. However, cellulosic ethanol from lignocellulosic material is at a lower TRL (6-7). The TRL of woody biomass, and giant reed is slightly higher (7-8) due to the experiences from Borregaard on woody biomass (Borregaard, 2018), and Beta Renewables on giant reed (Ardundo-donax.com, 2014). However, research indicates that the cellulosic ethanol production is not too sensitive to the biomass feed and miscanthus and switchgrass could be used as well (Zhang *et al.*, 2018).

4.2.7 Fermentation (other chemicals)

Next to ethanol, fermentation of lignocellulosic material can also be performed to obtain other products. An example is the production of butanol in the ABE process, which produces acetone, butanol and ethanol. However, the use of these fermentation processes on lignocellulosic crops are less advanced and are now starting to see application on easier substrates such as corn (Tao *et al.*, 2014; Baral *et al.*, 2016). Their low TRL on cellulosic material, and the related low data availability, leaves them out of the scope of this study.

4.2.8 Pulping

There are several pulping processes in order to produce pulp and paper from fibrous material. This is generally done with woody biomass, however, over 11% of the papermaking pulp is produced from non-woody biomass. Since non-woody biomass has a different structure, many of its cells are not suitable for papermaking. Therefore, an adapted pre-treatment is required in order to successfully make paper from non-woody biomass. This is especially interesting as an alternative for woody biomass when this is not available, for example in developing countries without access to forestry. This has mainly been applied to straw, bagasse and bamboo (Cappelletto *et al.*, 2000). However, other lignocellulosic crops could be used as well, but a study comparing paper production from switchgrass and miscanthus shows that the resulting pulp has short fibres and high proportion of fines. Moreover, their low tear strength may inhibit the printability (Madakadze *et al.*, 2010). Other studies conclude that the technique is promising (Cappelletto *et al.*, 2000; Biswas and Scientific, 2016). Currently, paper is being produced from miscanthus on a demo scale (TRL 5-6) in the Netherlands (Driessen, 2016).

For woody biomass, poplar and willow are already applied in the industry (TRL 8-9), although only in small amounts. Less than 2% of the biomass used for European pulp and paper consisted out of poplar and willow in 2016 (Confederation of European Paper Industries (CEPI), 2017). Black locust and Siberian elm are considered similar enough to the currently used processes, that no major technical challenges are foreseen (Panayotov *et al.*, 2015). Therefore, it's TRL is estimated to be at 6-7.

Since paper from the selected crops would compete with current paper production, it is competing with another bio-based material. Therefore, the advantages are only clear for countries without access to forestry. Moreover, the pulping process requires a large scale to be profitable, with a size of at least 400,000 tons of pulp per year (Finell, 2003). In Europe it could, for example, be used to blend with the paper recycling industry in Italy (Cappelletto *et al.*, 2000). This market is relatively small compared to the products from other techniques for lignocellulosic material.

4.2.9 Pressing (particleboards)

Particle boards can be obtained by pressing particles of lignocellulosic material under high temperature and often using an adhesive. This is commonly done using softwood residues such as spruce, pine or firs, but there has been research interest in using crops such as miscanthus and tall wheatgrass (Sam-Brew, 2017). Currently, particle board is already made from several different wood species. Therefore, the use of another type of wood should not have a large effect on the product. This is demonstrated by the possibility to make particleboard from willow or black locust with similar properties as commercial particleboard (Archanowicz *et al.*, 2013). Moreover, particleboard using poplar is already commercially available (Lombardo SpA, 2018).

Even though particle board has a large market in the furniture and construction sector, the replaced product is already bio-based and therefore there are no immediate advantages of replacing traditional particle board by particle board made with one of the selected lignocellulosic crops. Therefore, the market potential of particle board is estimated to be medium.

4.2.10 Biocomposites

The fibres from lignocellulosic crops can be used to reinforce plastic in the production of biocomposites that finds it applications in the automotive industry, construction and consumer goods. This gives biocomposites a large and diverse market (Carruthers, 2014).

Popular plant fibres to use are long fibres from hemp and flax, but also wood fibres can be used in the production of wood-plastic composites (WPC). The wood fibre or flour used in its production often originate from fir, pine, spruce, maple, oak and beech (Carruthers, 2014). The selected lignocellulosic crops are not yet used in commercial scale biocomposites production. However, many researchers have made materials on lab-scale using switchgrass stems with polypropylene (Zou, Xu and Yang, 2010), miscanthus in a blend of PBS and PBAT (Muthuraj, Misra and Mohanty, 2017), and PP or PLA with reed canary grass (Harlin and Vikman, 2010).

For woody biomass, it was shown that the wood species has a significant impact on the characteristics. WPCs of poplar and willow have been prepared at labscale (Wieland and Dickson, 2015).

4.2.11 Insulation

The fibres form the stems of miscanthus can be used as insulation material. When the miscanthus is harvested after winter, it lost the leaves, and the stems can be harvested and processed into insulation material without further separation steps. The stems are treated with steam explosion to break up the material into fibres. After the addition of 4% additives (fire inhibitors and fungicides), the material is ready to be used as insulation material (Meyer, Wagner and Lewandowski, 2017).

The process shows promising results on small scale, where commercial scale would need a miscanthus input of 3 kton of biomass per year (Meyer, Wagner and Lewandowski, 2017). Compositions using Giant Reed show promising insulation properties as well, with a thermal conductivity of 0.06 to 0.09 W/mK (wood particle board has a conductivity of 0.12-0.18 W/mK)(Ferrández-García *et al.*, 2012). However, the little information that is available discusses lab scale results applying giant reed particle boards, and the giant reed value chain towards insulation is therefore estimated at TRL 3-4.

4.2.12 Concrete additive

Miscanthus can be applied as an additive to concrete for, for example, the production of masonry blocks. A mineralisation pre-treatment with $CaCO_3$ reduces the water uptake of the miscanthus to ensure a binding between the organic and concrete materials. To save costs, this treatment can also be performed during the mixing step of the miscanthus and concrete. Miscanthus can improve the insulation and reduce the weight of the material, which reduces the required amount and reduces the effects of overheating in summer (Barth *et al.*, 2016).

The application of miscanthus in concrete has been performed in several demo scale projects in the Netherlands (BioBound, 2018), indicating a fairly advanced technology at TRL 7-8. The market for concrete is large and there is a drive for more sustainable construction materials.

4.3 Conversion technologies of carbohydrate and multipurpose crops

For the multipurpose crops, many of the technologies described for oil crops and lignocellulosic crops can be applied, especially those that are available for whole biomass and lignocellulosic parts of crops. Beside all already mentioned technologies used for oil crops and for lignocellulosic crops there are some special options for multipurpose crops, which are described in this section.

4.3.1 Sugar production / fermentation (e.g. Ethanol and other chemicals)

Carbohydrate crops provide a high concentration of sugar in the whole plant or in parts of it. This is mainly true for sorghum and wild sugarcane that have a high sugar content in their stalks. This sucrose can be extracted by pressing the biomass to get the sugar out in a similar process conventionally used in sugar production from sugar cane. As a by-product the bagasse also can be utilised as lignocellulosic feedstock.

A technical use for sucrose is several fermentation processes to produce biofuels such as ethanol, platform chemicals and building blocks such as lactic acid, succinic acid. Moreover, bioplastics such as PHAs can also be directly produced from sucrose.

4.3.2 Extraction of specific molecules

Depending on the plant species, several specific molecules can be extracted from the biomass or specific parts of it. This is true for dyes in case of safflower, enzymes and inulin from cardoon or molecules for the medical or nutraceutical use. Extraction can be done chemically with specific sorbents such as hexane, water, or steam, or with other extraction processes depending on the target molecules.

4.3.3 Lignocellulosic fibres

In some cases, lignocellulosic fibres can be produced from specific fibre plants such as industrial hemp. Plant fibre is already used for several applications. Long fibres can be used for woven and non-textiles, ropes and other purposes. Short fibre mainly is used as reinforcement for composite materials for several products. Also, it can be used as pulp for the production of special paper types, mainly cigarette papers. Shives will be available as a by-product of the fibre production and can be utilised for several purposes such as bedding for animals (horses and rodents) or as growing substrate for plants. They also can be used for the production of low-weight particle boards.

5 Selection of value chains

There are many potential conversion routes for the selected 20 industrial crops. In order to summarise the routes found in chapter four for each of the crops and their potential, an overview is presented here for the combination of each crop and conversion technology. The best candidates are labelled green. The combinations of crops and technologies that are still possible, but less favourable due to a smaller market potential, lower TRL or lower data availability are shown in yellow. The combinations that score even lower are not preferred and are shown in red. Combinations that are not possible, either for technical reasons or the lack of data availability, are coloured grey.

In total, 140 feasible routes were found, of which 82 are the most promising candidates. 58 routes are also promising, but generally show better options due to another crop matching better with the technology or another technology matching better with that crop. This can either be due to the properties of the crop, TRL, market potential of the end product, or data availability. These tables will be the basis for the selection of nine routes that will be studied in depth in the remainder of the MAGIC project.

Table 14: Potential routes for the conversion of oil crops.

Product	Lupin	Safflower (HO)	Safflower (HL)	Cardoon	Industrial Hemp	Crambe	Ethiopian Mustard	Pennycress	Castor	Camelina
FAME	🟥	🟩	🟨	🟥	🟥	🟨	🟩	🟥	⬜	⬜
Interestified fats	🟥	🟨	🟨	🟨	🟨	⬜	⬜	⬜	⬜	🟩
Fatty esters	🟥	🟩	🟥	🟥	🟥	🟩	🟨	🟥	🟩	⬜
Fatty amides	🟥	🟩	🟥	🟥	🟥	🟩	🟨	🟥	⬜	⬜
Fatty amines	🟥	🟩	🟥	🟥	🟥	🟩	🟨	🟥	🟥	🟨
Fatty alcohols	🟥	🟩	🟥	🟥	🟥	🟩	🟨	🟥	🟥	🟨
Oligomers	🟥	🟩	🟩	🟨	🟨	🟥	🟨	🟨	🟩	🟨
Blown / stand oil	🟥	🟩	🟩	🟨	🟨	🟩	🟨	🟥	🟩	🟩
Alkyd resins	🟥	🟩	🟩	🟨	🟨	🟩	🟨	🟥	🟩	🟩
Polyamide	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥
Short chain FA	🟥	🟩	🟥	🟥	🟥	🟩	🟨	🟥	🟩	🟥
Epoxidized oil	🟥	🟩	🟩	🟨	🟨	🟥	🟥	🟥	🟨	🟩
Olefin metathesis	🟥	🟩	🟨	🟥	🟨	🟥	🟥	🟥	🟥	🟥
Oxidative cleavage	🟥	🟩	🟥	🟩	🟥	🟩	🟥	🟥	🟥	🟥

Legend:

🟩 Good candidate
🟨 Technically possible, but better options available (smaller market, lower TRL, or medium data availability)
🟥 Technically possible, but low interest (very small market, low TRL, less data available)
⬜ No potential (technically impossible or not sufficient data available)

Table 15: Potential routes for the conversion of lignocellulosic crops.

Techniques	**Products**	Switchgrass	Miscanthus	Giant Reed	Tall wheatgrass	Reed canary grass	Willow	Poplar	Black locust	Siberian Elm
Combustion	Heat and/or power	🟩	🟩	🟩	🟨	🟨	🟨	🟩	🟨	⬜
Gasification	Energy, methane, syngas	⬜	🟨	🟥	⬜	⬜	🟩	🟩	⬜	⬜
Torrefaction	Energy	🟨	🟨	⬜	⬜	⬜	🟩	🟩	⬜	⬜
Pyrolysis	Energy, fuels, materials	🟨	🟩	🟩	🟨	🟨	🟩	🟩	🟩	🟩
Anaerobic digestion	Energy, methane	🟩	🟩	🟩	🟩	🟩	🟩	🟨	⬜	⬜
Fermentation	Ethanol	🟩	🟩	🟨	⬜	⬜	🟩	🟩	🟩	⬜
Pulping	Paper	⬜	🟥	🟥	⬜	🟥	🟨	🟨	🟨	⬜
Pressing	Particle board	⬜	⬜	🟥	⬜	⬜	🟥	🟨	🟥	⬜
	Biocomposites	🟥	🟨	⬜	⬜	⬜	🟨	🟥	🟨	⬜
	Insulation	⬜	🟨	⬜	⬜	⬜	⬜	⬜	⬜	⬜
	Concrete additive	⬜	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜

Legend:

🟩	Good candidate
🟨	Technically possible, but better options available (smaller market, lower TRL, or medium data availability)
🟥	Technically possible, but low interest (very small market, low TRL, less data available)
⬜	No potential (technically impossible or not sufficient data available)

Table 16: Potential routes for the conversion of carbohydrate and multipurpose crops.

Techniques	**Products**	Sorghum	Safflower	Cardoon	Wild sugarcane	Lupin	Industrial hemp
Combustion	Energy, CHP	🟩	⬜	🟩	🟨	⬜	🟥
Gasification	Energy, methane, syngas	🟩	⬜	🟥	🟨	⬜	🟥
Torrefaction	Energy	🟩	⬜	🟥	🟨	⬜	🟥
Pyrolysis	Energy, fuels, materials	🟩	⬜	🟥	🟨	⬜	🟥
Anaerobic digestion	Energy, methane	🟩	🟩	🟩	🟩	🟩	🟩
Fermentation	Ethanol	🟩	⬜	⬜	⬜	⬜	⬜
Sucrose fermentation	Chemicals	🟩	⬜	⬜	🟩	⬜	⬜
Pulping	Paper	🟥	⬜	⬜	⬜	⬜	🟥
Pressing	Particle board	🟥	⬜	⬜	⬜	⬜	🟥
Fibre production	Lignocellulosic fibres	⬜	⬜	⬜	⬜	⬜	🟩
	Biocomposites	⬜	⬜	⬜	⬜	⬜	🟩
	Insulation	⬜	⬜	⬜	⬜	⬜	🟩
	Concrete additive	⬜	⬜	⬜	⬜	⬜	🟨
Extraction	Specialty chemicals, dyes	🟨	🟨	🟨	⬜	⬜	🟨
Protein extraction		⬜	⬜	⬜	⬜	🟩	🟩
Green Fertiliser		⬜	⬜	⬜	⬜	🟩	⬜

Legend:

🟩 Good candidate
🟨 Technically possible, but better options available (smaller market, lower TRL, or medium data availability)
🟥 Technically possible, but low interest (very small market, low TRL, less data available)
⬜ No potential (technically impossible or not sufficient data available)

6 Value chains

During the progress meeting of MAGIC, the overview with the besat candidates were presented. The consortium decided that the following value chains would be further analysed within the MAGIC project.

Table 17. Selected value chains.

Value chain	Crop	Technology	Product
1	Miscanthus	Pyrolysis	Industrial heat
2	Poplar	Gasification	SNG
3	Switchgrass	Fermentation	Bioethanol
4	Willow	Thermochemical fractionation (TCF)	Biotumen
5	Safflower	Oxidative cleavage	Acids
6	Castor	Fatty acids	Fatty acids
7	Lupin	Biorefinery/extraction	Protein
8	Hemp	Fibre production	Insulation
9	Sorghum	Anaerobic digestion	Methane

These value chains are aimed at giving an overview of the options and highlight the range of possiblibilities and opportunities. It should be noted that many other value chains are feasible and some could indeed be a better option than the selected value chains here. These value chains are a small sample size of the options and should by no means be taken as a the only potential options.

6.1 Value chain 1: Industrial heat from Miscanthus (via pyrolysis)

There are several challenges for the use of biomass feedstock for the production of industrial heat. Biomass is often heterogeneous, with fluctuating properties throughout the year. Moreover, it contains a significant ash content and the solid particles are difficult to handle. A solution to these challenges is to convert the biomass to pyrolysis oil. In this conversion, a homogeneous liquid is produced that solves the handling and heterogeneity issues. Moreover, during pyrolysis the minerals are separated from the pyrolysis oil. Therefore, the pyrolysis oil can be used for the production of industrial heat without further modification or upgrading of the pyrolysis oil and with only minor modifications of the industrial boilers.

The pyrolysis process consists of two steps. First, a pre-treatment is performed where the biomass is sized and dried. This pre-treatment uses excess energy from the second process step and therefore requires no additional energy input. In the second step, the biomass is heated for a short time in the absence of oxygen to produce pyrolysis oil. Next to pyrolysis oil, excess energy is produced in the form of steam, which can partly be converted to electricity using a steam turbine.

Production of industrial heat from Miscanthus via pyrolysis in comparison to current industrial heat production from fossil-based natural gas is described in detail in Figure 6.

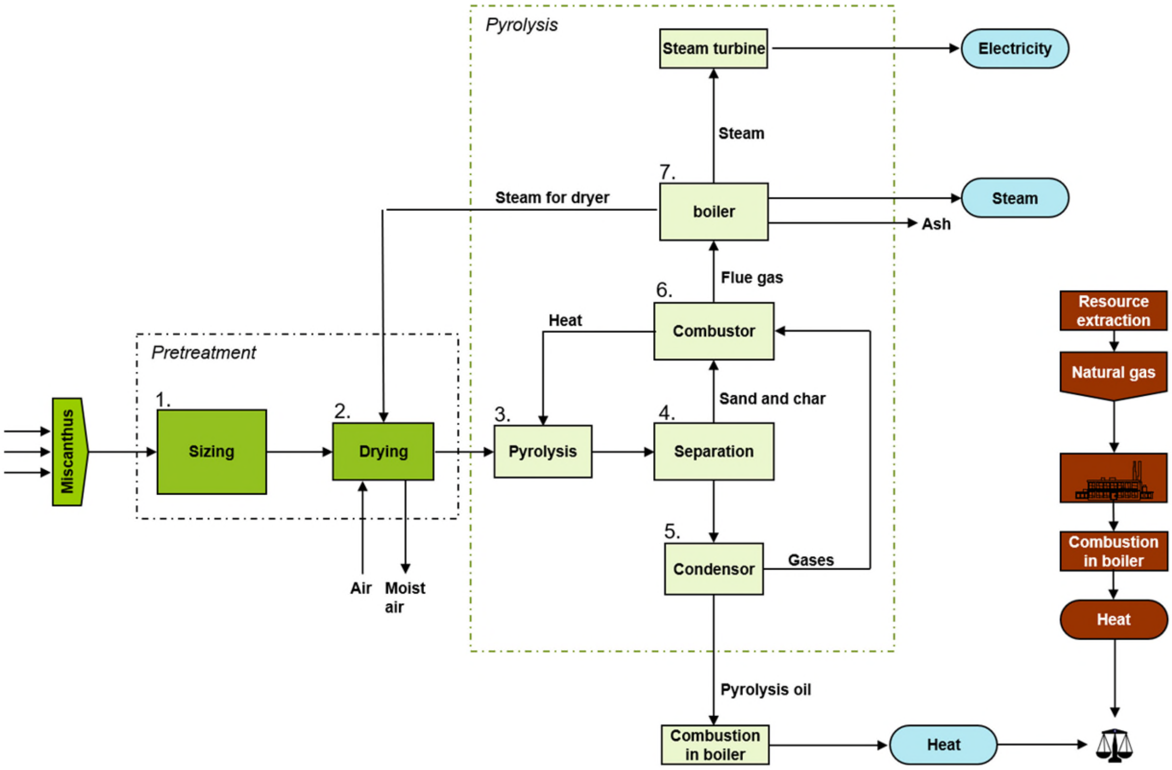


Figure 6: Life cycle comparison scheme for VC 1: industrial heat from Miscanthus via pyrolysis oil.

Financial and organisational data including the main material input and outputs for a pyrolysis plant is shown in Table 18. This includes the entire operation to produce pyrolysis oil from Miscanthus as shown in Figure 6, including the pre-treatment and steam turbine. It does not include biomass harvesting, transport or storage and also excludes the further transport and combustion of pyrolysis oil to produce industrial heat. The operational hours are 7500 h/a requiring manpower of 11 FTE per year, consisting of 10 operators and 1 plant manager. Investment costs of a pyrolysis plant are estimated at 25 million euros (BTL 2020). The maintenance costs are estimated at 2%.

Table 18. Financial and organisational data for a pyrolysis plant including the main material and energy inputs and outputs.

Financial and organizational data		
operational hours	7500	h/a
manpower	11	FTE
investment cost	25	M€
maintenance cost	2%	
Main material and energy inputs		
Miscanthus	45	ktonne/a
Water from canal	45	ktonne/a
Main material and energy outputs		
Pyrolysis oil	23.3	ktonne/a
Ash	1.3	ktonne/a
steam	152	TJ/a
Electricity	2.3	TJ/a
Water to canal	30	ktonne/a

6.1.1 Mass flows in a pyrolysis process

The mass flows in the pyrolysis process are based on the current available economic size. Figure 7 describes the mass and energy flows in the pyrolysis process. The numbers indicate the flow of the streams in Table 19 and Table 20. For example, in Table 19 (ID 1) shows the 5.9 Tonne mass input of Miscanthus to the process. As a product output (ID 4) pyrolysis oil is produced and water is evaporated from the drying of biomass. Other mass flow-description shows the mass flow (ID 2) of dried Miscanthus to the pyrolysis process.

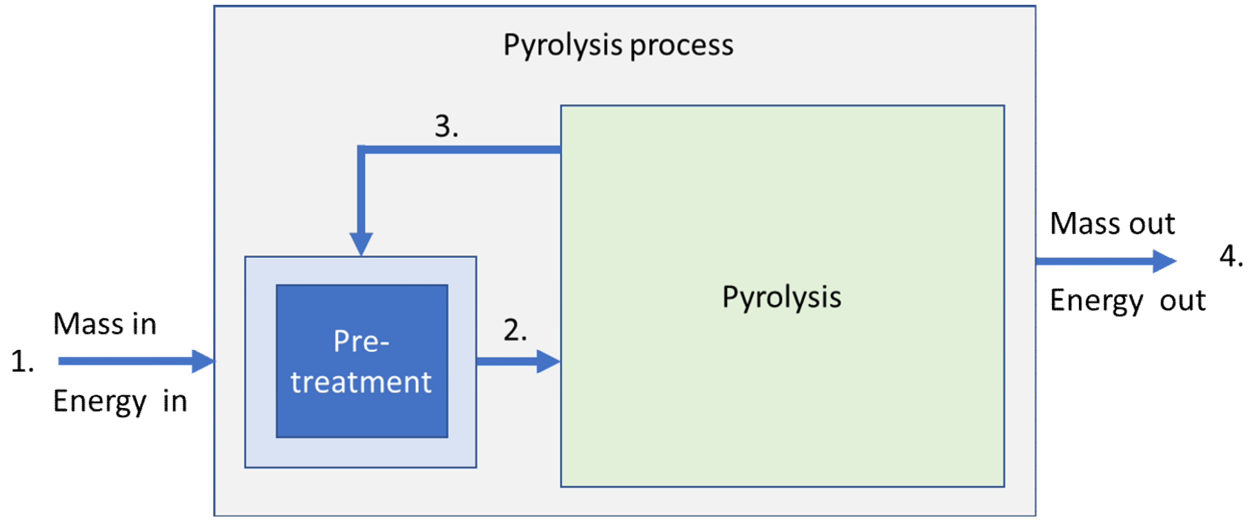


Figure 7. Mass and energy flows in the pyrolysis process.

Table 19. Mass flows in the pyrolysis process.

Based on 1h operation				
ID	**Mass in**			
1	Miscanthus	5.94	Tonne	*Wet (20% moisture)*
1	Natural gas	0.02	Tonne	*Only used for start-up*
	Sum	5.96	Tonne	
	Mass out			
4	Pyrolysis oil	3.1	Tonne	
4	Ash	0.17	Tonne	
4	Water	0.94	Tonne	
4	Carbon in CO_2 (biogenic)	1.7	Tonne	*Total biogenic CO_2 emission is 3.2 tonne (extra mass from inclusion of oxygen from the air), other emissions <2 kg.*
	Sum	5.94	Tonne	
	Loss	0.3%	%	
	Other emissions (<2 kg)			
	NOX	1.5	kg	
	SOX	25	g	
	Fine particulate matter	164	g	
	Other mass flows			
2	Miscanthus	5.0	Tonne	*dry*

6.1.2 Energy flows in a pyrolysis process

The pyrolysis process produces more energy than required for its own operation. Therefore, no external electricity or natural gas is required to run the pyrolysis process. The excess energy can be sold as steam and electricity. A small amount of natural gas is required in the start-up of the process. In Table 20 the energy flows in pyrolysis of Miscanthus is shown. The ID-numbers correspond to the flow in Figure 7.

Table 20. Energy flows in the pyrolysis process

Based on 1h operation				
ID	**Energy in**		Unit	*Comment*
1	Miscanthus	82	GJ	*Wet (20% moisture)*
1	Natural gas	1.0	GJ	*Only used for start-up*
	Sum	83	GJ	
	Energy out			
4	Pyrolysis oil	47.7	GJ	
4	Steam	20.3	GJ	
4	Electricity	0.3	GJ	*Electricity produced from steam, ratio can be optimised to the local situation*
3	Steam	3.8	GJ	*Energy consumed by drying the biomass*
	Sum	72	GJ	
	Loss	13	%	
	Other energy flows			
2	Miscanthus	77	GJ	*Dry*

6.2 Value chain 2: SNG from poplar (via gasification)

Description of synthetic natural gas (SNG) production via gasification as presented in D6.2 is shown in Figure 8. A small change has been made to the scheme from D6.2, which is removal of hydrogen addition to Methanation section. This stream is not required in the current model. The mass and energy balances for this process are shown in the following sections.

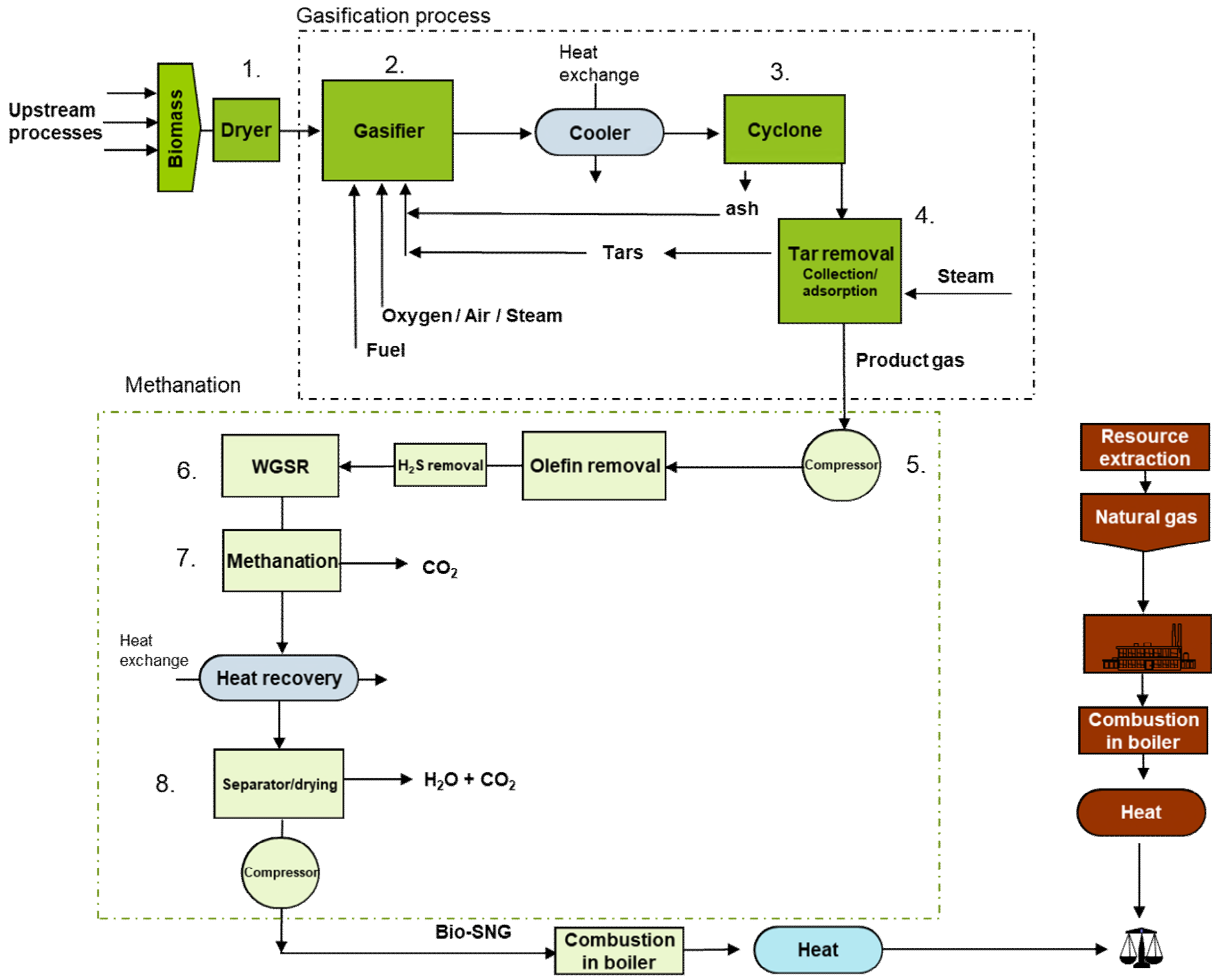


Figure 8. Production of synthetic natural gas via gasification of poplar.

Table 21 shows the financial and organizational data of the SNG production from poplar in a 20MW plant. These numbers are based on the GoBiGas-plant that has been used as a reference system for this value chain. GoBiGas-plant was a commercial demonstration in the years 2014-2017 that proved viability of the technology used for SNG production from forestry biomass. Despite that the GoBiGas-plant was technologically successful not all the aspects of the design and costs related to the plant were optimised. For example, a large part of the maintenance costs is due to the methanation process that operates at high pressure. The pressure vessels need regular inspection and maintenance for proper operation and safety. (Thunman et al. 2019). In a recent study the cost data of the GobiGas plant was used as a reference for optimisation of costs for 20 MW plant and a commercial full scale plant of 200 MW. (Thunman et al. 2019) Based on the study, 200 MW plant was found to be most suitable scale. To offer a better understanding of financial and organisational data, the estimations for

200 MW capacity plant is shown in Table 22. In this table, also a reference plant of 20 MW scale is presented. This 20 MW plant is similar in technology than the actual GoBiGas-plant with excluding costs that were project specific and would not be actualised in any other installation. As can be seen, the costs are significantly lower for a full commercial scale plant that is operates at most optimal technology.

Table 21. Financial and organisational data for SGN production from poplar based on GoBiGas-plant and the required consumables.

Financial and organizational data		
operational hours	8000	h/a
manpower	28	FTE
investment cost	130	M€
maintenance cost	21%	
Main material and energy inputs		
Poplar (dry mass)	46	ktonne/a
Steam	25.5	ktonne/a
Air	101.5	ktonne/a
Rapeseed Methyl Ester (RME)	27.6	TJ/a
Electricity	34.6	TJ/a
Natural gas	28.1	TJ/a
Main material and energy outputs		
SNG	571.4	TJ/a
District heating	144	TJ/a
Ash	2.4	ktonne/a

Table 22. Financial and organisational data for an optimized 200MW SGN plant compared to 20MW reference plant. The data is based on forest residues (45% moisture as received) and 20 year-life time, and 70% plant efficiency.

Financial and organizational data	20MW	200MW	
operational hours	8000	8000	h/a
manpower	28	28	FTE
Capital costs	70	23	M€/MWh
Operational costs (excl. feedstock)	33	12	M€/MWh

6.2.1 Mass and energy flows of SNG production

Figure 9 illustrates the mass and energy flows in the SNG process. The data corresponding to these sections are presented in Table 23 and Table 24. The ID number in the tables reflects the corresponding flow of mass or energy.

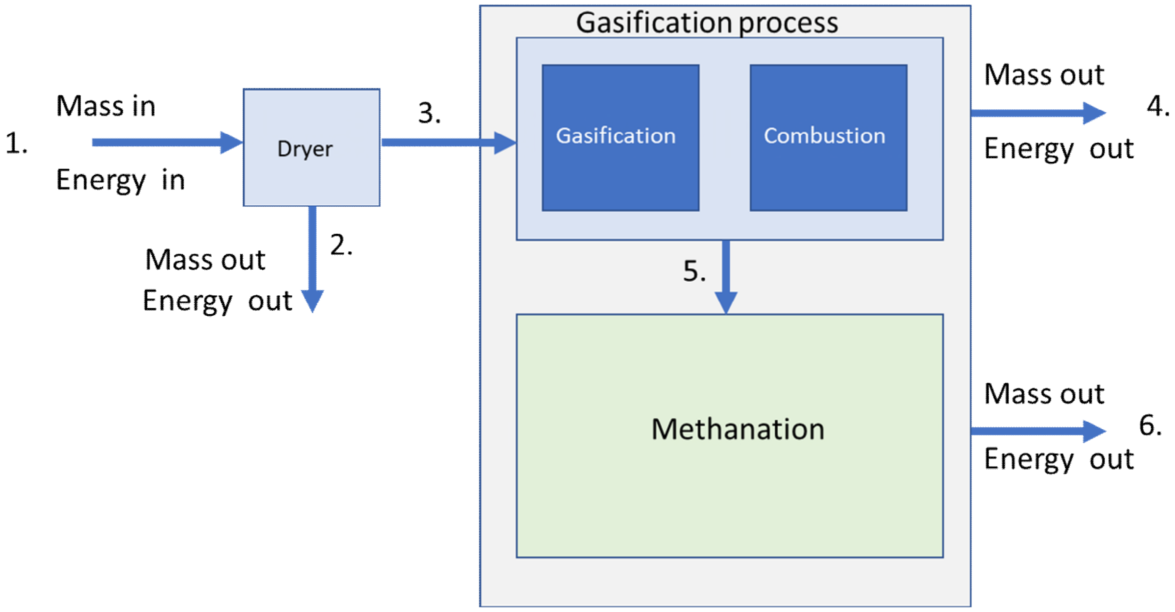


Figure 9. Mass and energy flows in the SNG process.

6.2.1.1 Mass flows in SNG process

Table 23 shows the material flows in the SNG process. Poplar enters the plant with 20% moisture content. It will be dried to 8% of moisture in the dryer. Based on the model system, 8% of moisture is required for the plant efficiencies (shown in Table 23). In gasification the feed is converted to a product gas, which then goes through methanation to SNG. Part of the incoming materials are combusted to provide energy to the gasification, which results in flue gas, containing mostly nitrogen, water and carbon dioxide. The water streams for the whole plant are balanced for the oxygen and hydrogen inputs. Product gas is converted the methane, carbon dioxide and water, along with a small amount of hydrogen in the dried SNG. The model system uses nitrogen as a purge gas, however in an optimised plant the produced carbon dioxide could be recycled to be used as a purge gas. The exiting carbon dioxide is a mixture of biogenic and fossil carbon. The consumables needed are based on GoBiGas-plant operation (20 MW_{SNG}). (Alamia et al. 2017; Thunman 2018) Emissions were estimated based on typical gasification to methane (Wernet 2016). Typical wood gasification to methane in this scale (20 MW methane) produces 77 kg in one hour operation, nitrogen oxides 4 kg and particulates (<2,5 my) 1139kg.

Table 23. Mass flows in the SNG process.

Based on 1h operation				
ID	**Mass inputs**		Unit	*Comment*
1	Dryer			
1	Poplar	7192	kg	*20 wt% moisture*
3	Gasification			
3	Dried poplar	6254	kg	*8 wt% moisture*
3	Water in poplar	500	kg	*moisture in poplar*
3	Poplar	5754	kg	*dry*
3	RME	86	kg	*tar scrubbing, will be burned*
3	N_2	5	kg	*gasifier*
3	steam	3189	kg	*gasifier*
3	combustion air	10634	kg	*gasifier*
3	post combustion air	2058	kg	*gasifier, acts as a catalyst and bed material*
3	Olivine	60	kg	*gasifier*
3	Calcine	101	kg	*gasifier, acts as a catalyst and bed material*
3	K_2CO_3 solution	115	kg	*activator for olivine*
	Total	23440	kg	
	Mass outputs			
2	H_2O	938	kg	*Dryer*
4	Ash	300	kg	
4	Flue gas	17801	kg	
	Flue gas composition			
	N_2	9455	kg	
	CO_2	2754	kg	
	H_2O	4833	kg	*balanced*
	CO	3	kg	
	O_2	756	kg	
5	Product gas	5339	kg	
	Methanation			
6	CO_2 scrubbed from the methanation	2224	kg	
6	H_2O removed from final product	1671	kg	*balanced*
	Final SNG gas composition			
6	CO_2	1	kg	
	H_2	1	kg	
	N_2	130	kg	
	CH_4	1313	kg	
	Total	23440	kg	
	Balance	100%		
Consumables				
	Active carbon	2,7	kg/h	*Used for adsorbing tar*

6.2.1.2 Energy balance gasification

Energy balance for the SNG process are given below. The efficiencies and energy requirements are based on information provided in the Gobigas-project and the balances are based on output of the plant 20 MW synthetic natural gas (SNG). (Alamia et al. 2017; Thunman 2018). Biomass drying is included as it’s own step, showing the energy requirements for the process. Drying is not included in the design of the Gobigas-plant and was added to this design to enable using biomass with optimal moisture content. The dryer efficiency is 76,5%, resulting in energy requirement of 3,9 GJ for 1 hour of operation. The plant (excluding dryer) requires electricity 7,2 GJ based on 1 hour operation, natural gas is required as a combustion fuel, and RME (Rapeseed Methyl Ester) is used for tar scrubbing and also combusted to provide extra heat for the gasification. Product gas is converted to biomethane and heat generated in the methanation process this is harvested to provide electricity for the plant via steam cycle (4,2 GJ), part of the energy is sold to the grid as electricity (18 GJ). The plant capacity is 20 MW-SNG, which is 65,6 GJ in an hour operation (heat capacity of methane 50 MJ/kg was used). Biomass to SNG efficiency is therefore 62%. Energy losses in the system are 29% of all the combustible energy provided to the system.

Table 24. Energy inputs and outputs of the SNG process.

Based on 1h operation				
ID	**Energy efficiencies of the plant**		Unit	*Comment*
	Energy content of the fuel (Ef)			
	Efficiency gasification (ηCG)	72,0%		
	biomass to methane (ηCH4)	62,0%		
	raw gas efficiency (ηRG)	87,3%		
	Plant efficiency (ηplant)	57,7%		
	Heat loss system	5,2%		
	Electricity for the plant	4%		*dry ash free fuel*
	Energy in			
1	Energy required by the dryer	3,9	GJ	
3	Electricity	7,2	GJ	
3	natural gas	3,5	GJ	
3	Rapeseed methyl ester (RME)	3,2	GJ	
1& 3	Fuel (Biomass/Poplar)	105,9	GJ	
	Energy outputs			
2	Consumed by dryer	3,9	GJ	
5	Product gas	75,9	GJ	
6	Biomethane	65,6	GJ	
6	district heating	5,0	MW	
		18,0	GJ	
	Electricity for the plant	4,2	GJ	
	Energy lost	35,8	GJ	
	Biomass to SNG energy	62%		
	Balance	100%		
	Energy produced	88	GJ	
	loss	36	GJ	
	Energy loss (loss/input)	29%		

6.3 Value chain 3: Ethanol from switchgrass (via hydrolysis & fermentation)

Production of ethanol from switchgrass is presented in this section. The scheme of the process is presented in Figure 10. The description of the process is provided in D6.2, however, a small change is made in the scheme to provide better understanding of current status of this technology. Marketable by-products stream from lignin and by-products is removed as the technology is not mature enough yet, especially for switchgrass. All the carbon containing by-streams from the ethanol process are combusted. The scheme is based on NREL-simulated process, this means that no plant exists in which the technology has been demonstrated. However, this simulation resulted in detailed enough description of ethanol production via fermentation to be used in this exercise.

The capacity of the plant is 40.000 tonne/year ethanol (EtOH), which is a capacity of Versalis (former Biochemtex-plant) in Italy. This capacity is chosen due the fact it has been a suitable demonstration scale plant in Europe. NREL-simulation is based on 182.000 tonne/year EtOH from corn stover, which is readily available in US. This scale is too ambitious for a plant that would like to utilise feeds from marginal lands.

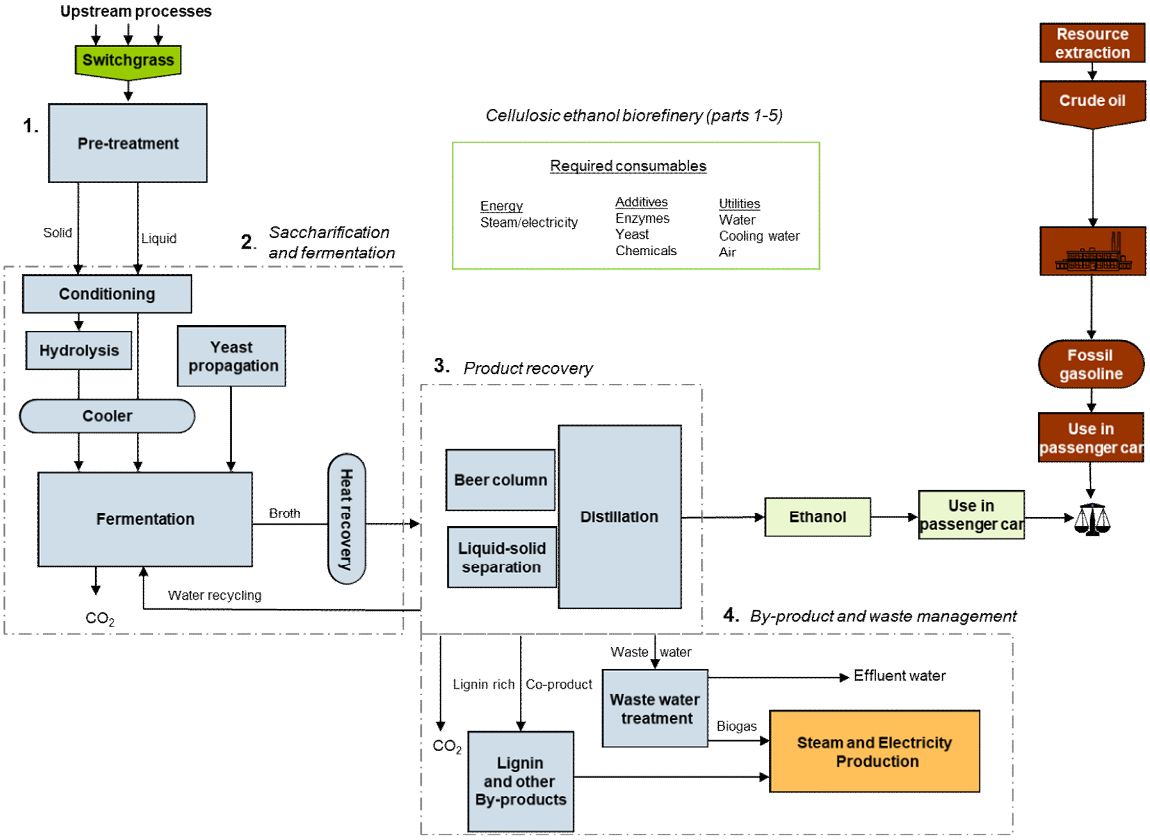


Figure 10: Schematic presentation of ethanol production from switchgrass.

Data for investments and organisational requirements are shown in Table 25. As the ethanol production is done in batch-process and it is not continuous, the operational time is shown in days, rather than hours. The plant operates annually approximately 333 days, the investment costs of building a plant this scale are estimated to be around 153 MEUR. This number is scaled down from NREL (380 MEUR) using a scale factor (0.6) typically used for calculating investment costs for plants with similar complexity. The labour requirement is scaled down using the standard factor of (0.25).

The main material and energy inputs are shown also in Table 25. The main input is naturally the biomass (211 Mtonne/year), glucose used for growing the micro-organisms for the process and sulphuric acid which is used for the biomass pre-treatment. Ammonia is used as pH regulating agent. Caustic soda is used to neutralise ammonium ions and lime is used to neutralise sulphates produced in the process.

Table 25. Financial and organisational data, and the main material and energy inputs for the ethanol production.

Financial and organizational data		
operational time	333	d/a
manpower	41	FTE
investment cost	153	M€
maintenance cost	3%	
Main material and energy inputs		
Switch grass (20% moisture)	211	Mtonne/a
Glucose	49	Mtonne/a
H_2SO_4	8,8	Ktonne/a
Caustic soda	4,0	Ktonne/a
Ammonia	2,0	Ktonne/a
Lime	1,6	Ktonne/a

6.3.1 Mass and energy flows in ethanol production

Figure 11 shows the scheme of the main material and energy flows in the biomass processing to ethanol. The numbered arrows refer to the main flows marked with an ID-number of the tables presenting mass and energy flows.

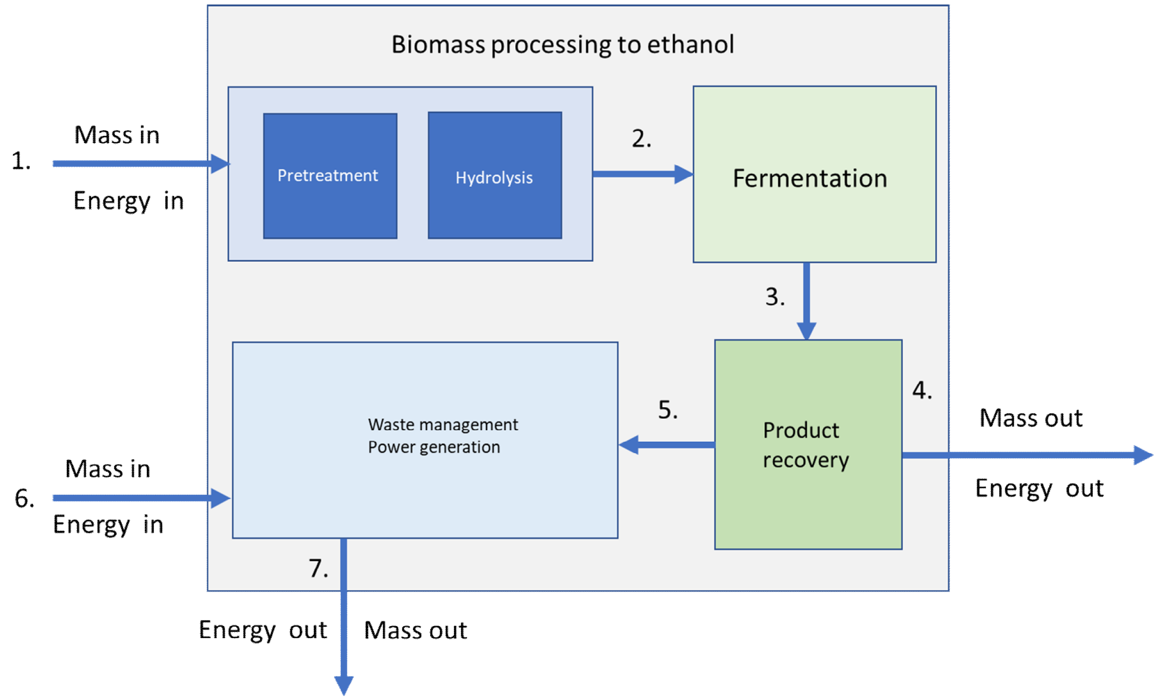


Figure 11. Scheme of mass and energy flows in the ethanol plant.

6.3.1.1 Mass flows in biomass processing to ethanol

Flows of material in switchgrass processing to ethanol via acid hydrolysis are shown in Table 26. The conversion efficiency of biomass carbon to ethanol is 20%. The efficiency of the biomass conversion is 21%, meaning 4,7 tonnes of biomass is needed for 1 tonne of EtOH. Biomass composition was taken from Table 3. In the calculations the typical values were used, respectively cellulose 36.9%, hemicellulose 32.1%, lignin 6.8% ash 6.3%, extractives 18%. It should be noted that lignin content is low and the extractives is therefore high, due to the balancing of the composition.

Biomass pre-treatment in this process requires no previous drying process as the biomass will be broken down under steam and with a help of an acid catalyst (H_2SO_4). The mass flows are created with 20% moisture of the biomass. Hydrolysis and fermentation processes require large quantities of water; 7,35 L water is needed for 1 liter of ethanol (Humbird 2011). Glucose is used to propagate enzymes for this process. Enzymes are expensive and commercial plants should aim at propagating their own enzymes on site. Waste streams in the plant are large, thus they are mostly treated on site by combustion requiring air. Combustion provides also energy for the plant via steam generation to electricity. After pre-treatment of the biomass the streams go to fermentation. In this process the conversion of biomass components cellulose and hemicellulose to fermentable sugars glucans (glucose) and xylans (xylose) is 88 and 25%, respectively (ref Biochemtex). It is assumed that the conversion of cellulose is fully to glucose (C6) and hemicellulose to xylose (C5). Typically, saccharification produces many C6 and C5 components, however this relies heavily on the feedstock composition, conditions and technology used, and therefore, for simplicity it is only assumed that glucose and xylose is formed.

Fermentation produces a dilute ethanol stream (110 tonne/day) from which the product is recovered by distillation. The purity of the product is 99,5 wt%, the rest is water. Fermentation produces also CO_2, which is scrubbed from the product stream and sent to vent. The unreacted biomass (cellulose and hemicellulose) and lignin are dried and combusted to provide energy for the plant. This produces significant amounts of CO_2, which is all biomass based. It is assumed that all the unreacted carbon goes to CO_2 and to waste and ash. The main mass loss in the process is evaporation of water in the cooling towers used for the fermentation and waste water treatment (WWT) lagoons, which also causes losses of energy. The waste streams contains the salts formed in the process, $NaNO_3$, $CaSO_4$, water and some organics that were not processed in WWT system. Based on NREL model all the carbon that is not converted to ethanol is burned, either directly after de-watering or by conversion to methane via biogas production. For the mass balance it is assumed, based on the NREL carbon distribution, that most of the carbon (99,2%) that remains after ethanol conversion, is combusted. Some carbon (0,8%) leaves in ash and WWT brine. The mass flows are balanced with the amount of water exiting the system.

Table 26. Mass flows in ethanol production from switchgrass.

Based on 1 day operation				
ID			Unit	*Comment*
	Ethanol conversion	20%		*Conversion of input carbon to Ethanol*
	Efficiency	21%	kg EtOH / kg dry biomass	
	Mass inputs			
1	Biomass (Switchgrass)	529	Tonne	*dry*
1	Water in biomass	106	Tonne	*20 % moisture*
1	Water needed for process	1168	Tonne	*7,35 L/L EtOH produced*
1	Glucose	147	Tonne	*Enzyme production*
1	Sulphuric acid (93%)	27	Tonne	*Hydrolysis*
1	Ammonia	6,2	Tonne	*Used for controling pH*
6	Caustic soda	12	Tonne	*Neutralization of Ammonium*
6	Lime	4,7	Tonne	*Neuralization of sulphates*
6	Air	2225	Tonne	*Combustion + waste water treatment + product recovery*
	Total mass in	4225	Tonne	
	Mass outputs			
2	Processed biomass	1803	Tonne	*Pretreatment +Hydrolysis*
3	Product + side streams	1803	Tonne	*Ethanol, unreacted biomass and lignin*
4	EtOH	110	Tonne	
	H2O	1	Tonne	*Water in product (99.5% EtOH)*
	CO2	105	Tonne	*From fermentation, goes to vent, biomass based*
5	Unreacted biomass	151	Tonne	*Non-hydrolysed cellulose and hemicellulose*
	Lignin	36	Tonne	*Based on biomass composition*
	Ash	33	Tonne	*Based on biomass composition*
	Extractives	95	Tonne	*Based on biomass composition*
	H2O	1274	Tonne	
7	CO2	720	Tonne	*From combustion of ligning and unreacted biomass to produce steam and electricity, enzyme production and WWT production, biomass based*
7	H2O	1441	Tonne	*Evaporation and discharge*

7	Waste	86	Tonne	*Contains water, carbon and inorganics from the process*
7	Ash	34	Tonne	*Based on biomass composition*
7	N2	1707	Tonne	*From air used for combustion + waste water treatment*
	Mass out total	4204	Tonne	
	Balance	100%		

6.3.1.2 Energy flows in biomass processing to ethanol

Energy flows in the ethanol plant are shown in Table 27. Efficiency to ethanol is 32%, meaning the amount of energy that is brought in converted to ethanol. The main energy input is the biomass itself. In the model of NREL, the plant is self-sufficient and creates its own energy from the combusted biomass and waste streams, the excess is sold as electricity to the grid for extra income. In the calculations it is assumed that the efficiency is similar to NREL efficiency due to simplicity. It can be expected that plants with differences in capacity have variations in efficiencies, however due the lack of data for this similar efficiency is assumed (24%, energy for the plant per ethanol produced). Major losses of energy are the evaporation of water via cooling systems for the fermentation and WWT. Efficiency of power generation is calculated based on the known energy streams. The small differences in the energy balance is due the uncertainty in the heating value of the extractives. The heating values (gross) used for the biomass components are as follows, switchgrass 19.04 MJ/kg (M6.4), lignin 25,8 MJ/kg, extractives 28 MJ/kg. Unreacted cellulose and hemicellulose were considered as switchgrass.

Due the low lignin content of the biomass, available combustible energy is low. In case a higher lignin content switchgrass would be available the energy produced from it would also increase. This would also affect number of extractives and the energy provided from it.

Table 27. Energy flows in ethanol production from switchgrass.

Based on 1 day operation				
ID			Unit	*Comment*
	Efficiency to ethanol	32%		*Energy in EtOH / Energy in biomass*
1	Biomass (Switchgrass)	10072	GJ	
	Glucose	2283	GJ	
2	Processed biomass	12355	GJ	*Pretreatment +Hydrolysis*
3	Product + side streams	12355	GJ	*Ethanol, unreacted biomass and lignin*
4	EtOH	3255	GJ	
5	Unreacted biomass	2871	GJ	*Non-hydrolysed cellulose and hemicellulose*
	Lignin	928	GJ	*Based on biomass composition*
	Extractives	2443	GJ	*Based on biomass composition*
	Used by plant	537	MJ	
7	Energy to grid	778	MJ	*Energy to be sold as electricity (2,8 MW)*
	Energy losses			
7	Waste	284	MJ	
7	Water evaporation	3252	MJ	*Lost in cooling tower evaporation*
7	In power generation	4211	MJ	
	Efficiency of generating power for plant	15%		
	Energy out total	12317	MJ	*There is a small error due to the unknown nature of the extractives in the biomass*
	Balance	100%		

6.4 Value chain 4: Biotumen from willow (via pyrolysis)

Here, the production of biotumen from willow via pyrolysis is presented. The value chain is similar to the value chain of pyrolysis oil from Miscanthus. However, the starting material is willow instead of Miscanthus, and the pyrolysis oil is not used directly as a product. Instead, part of the pyrolysis is converted by thermochemical fractionation (TCF). This results in a biotumen fraction that can be combined with other materials to produce a partially bio-based roofing material. The other fractions from the pyrolysis oil can be mixed back with the untreated pyrolysis oil, which is then used for industrial heating.

The financial and organisational data is presented in Table 28 with the main material and energy inputs and outputs. Note that the pyrolysis section is identical as the pyrolysis section presented in Figure 6. For clarity, this process is simplified in one pyrolysis unit. More details on this operation can be found in section 6.1. The investment costs are equal to the combined investments of a pyrolysis plant (25 million euro) and the investments of a fractionation plant. The cost of a fractionation plant is difficult to estimate at this stage, however, using the 0.6 rule gives an estimation of 4 million euro. Combined with the pyrolysis plant, this results in a total estimation of 29 million euros for the investment.

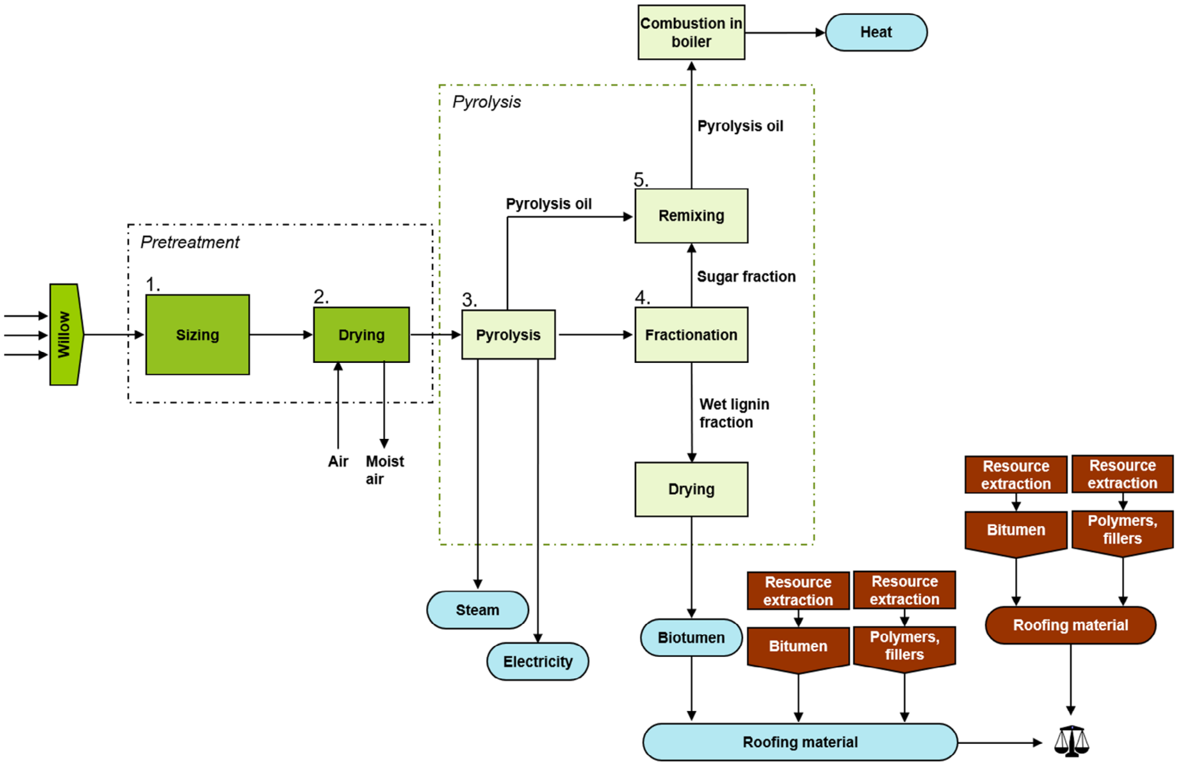


Figure 12: Life cycle comparison scheme for VC 4: Willow to biotumen, via pyrolysis. A more detailed scheme for the pyrolysis section can be found in Figure 6.

Table 28. Financial and organizational data for biotumen production via pyrolysis oil fractionation including the main material and energy inputs and outputs.

ID	Financial and organizational data		
	operational hours	7500	h/a
	manpower	11	FTE
	investment cost	29	M€
	maintenance cost	2%	
	Main material and energy inputs		
1	Willow	45	kton/a
1	Water from canal	45	kton/a
	Main material and energy outputs		
4	Pyrolysis oil	20.8	kton/a
4	Biotumen	1.2	Kton/a
4	Ash	1.0	kton/a
4	Steam	113	TJ/a
4	Electricity	2.3	TJ/a
4	Water to canal	30	kton/a

6.4.1 Mass and energy flows in biotumen production

The mass and energy flow in pyrolysis oil fractionation to biotumen are shown in Figure 7. The ID number in Table 29 and Table 30 refer to the numbered arrows in the figure.

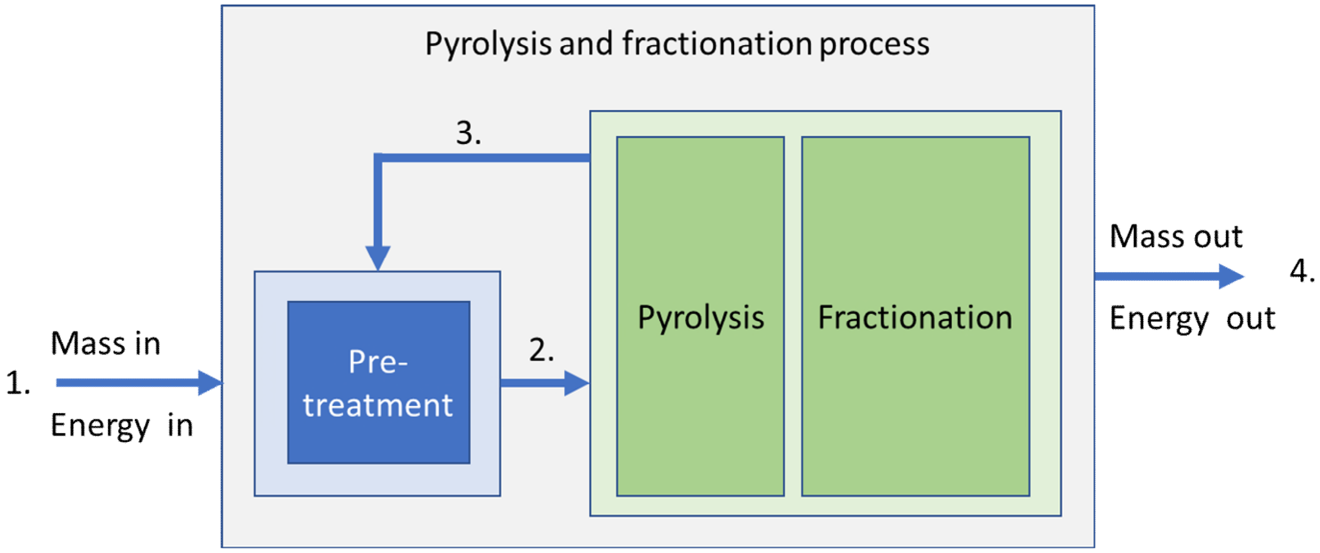


Figure 13. Mass and energy flows in the pyrolysis oil fractionation to biotumen process.

6.4.1.1 Mass flow in biotumen production

Table 29 shows the corresponding mass flows in pyrolysis oil fractionation to biotumen. The ID numbers refer to the numbered arrows in Figure 13. The production process and numbers are estimated based on work performed in the Bio4Products project. It was assumed that 50% of the pyrolysis oil would be fractionated and that the sugar fraction would be fed back into the pyrolysis oil. The biotumen is a result from the lignin fraction of the pyrolysis oil.

Table 29. Mass flow in biotumen production from willow via pyrolysis.

Based on 1h operation				
ID	**Mass in**			
1	Willow	5.94	Tonne	*Wet (20% moisture)*
1	Natural gas	0.02	Tonne	*Only used for start-up*
	Sum	5.96	Tonne	
	Mass out			
4	Pyrolysis oil	2.77	Tonne	
4	Biotumen	0.155	Tonne	
4	Water	0.94	Tonne	
4	Biomass to CO_2 (biogenic)	2.0	Tonne	*Total CO_2 emission is 3.6 tonne (extra mass from inclusion of oxygen from the air), other emissions <2 kg.*
4	Ash	0.14	Tonne	
	Sum	5.76	Tonne	
	Loss	3	%	*Other losses assumed to be in gases.*
	Other emissions (<2 kg)			
	NOX	1.5	kg	
	SOX	25	g	
	Fine particulate matter	164	g	
	Other mass flows			
2	Willow	5.0	Tonne	*dry*

6.4.1.2 Energy flows in biotumen production

Table 29 shows the corresponding mass flows in pyrolysis oil fractionation to biotumen. The ID numbers refer to the numbered arrows in Figure 13. The LHV of pyrolysis oil is lower when part of the lignin is removed, due to the high energy content of biotumen at 27 GJ/tonne.

Table 30. Energy flows in biotumen production from willow via pyrolysis.

Based on 1h operation				
ID	**Energy in**		Unit	*Comment*
1	Willow	82	GJ	*Wet (20% moisture)*
1	Natural gas	1.0	GJ	*Only used for start-up*
	Sum	83	GJ	
	Energy out			
4	Biotumen	4.2	GJ	
4	Pyrolysis oil	43	GJ	*LHV is 15.4 GJ/tonne*
4	Steam	15	GJ	
4	Electricity	0.3	GJ	*Electricity produced from steam, ratio can be optimised to the local situation*
3	Steam	3.8	GJ	*From pyrolysis, to dry the biomass*
	Sum	66	GJ	
	Loss	21	%	
	Other energy flows			
2	Willow	77	GJ	*Dry*

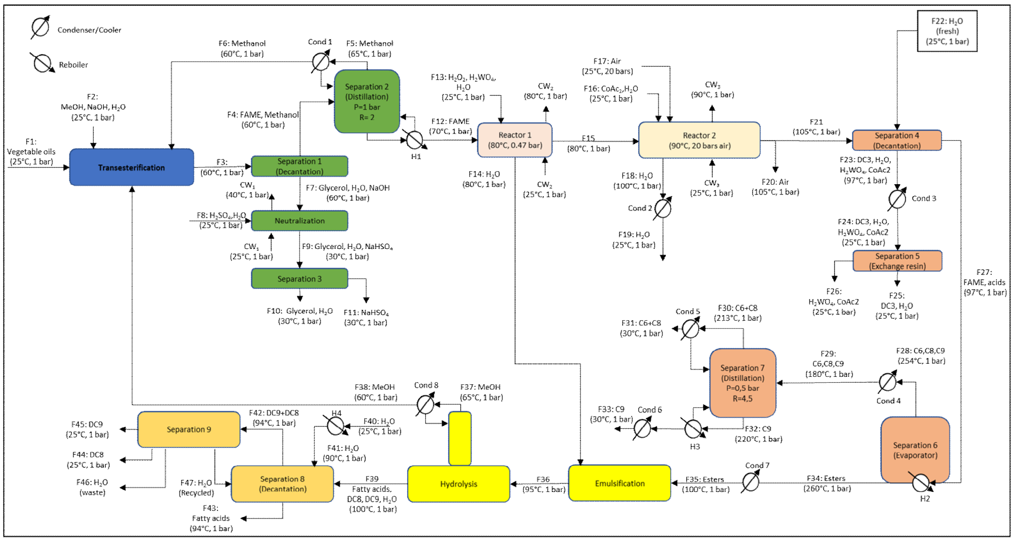
6.5 Value chain 5: Production of azelaic and pelargonic acid from high oleic safflower oil via oxidative cleavage

In this section, the production of azelaic and pelargonic acid is presented in Figure 14. The raw materials used is the high oleic safflower oil (with Oleic acid representing about 82.3 wt % in the total fatty acid composition in the oil). The process for the oxidative cleavage of safflower oil is described in detail in Figure 14 and in report D6.2. The process is a succession of several reaction steps as follow:

1) Transesterification of vegetable oils with methanol.
2) Separation of fatty acid methyl esters (FAME) from Glycerol.
3) Dihydroxylation of the unsaturation with hydrogen peroxide under slight vacuum to facilitate water evaporation for temperature control of the reactor, and to maintain a high concentration of hydrogen peroxide to speed up the reaction.
4) Oxidative cleavage of the diol esters with oxygen as oxidant.
5) Catalysts recovery and separation of light monocarboxylic acids (C9 - Pelargonic and mixture of C6+C8- hexanoic and octanoic acids).
6) Emulsification and hydrolysis of fatty acids and esters (estolides), production of methanol recycled to transesterification step 1.
7) Separation of long chain monoacids from diacids (Azelaic (DC9) and Suberic (DC8) acids.

Other raw materials include hydrogen peroxide with a concentration of 60 wt % in water. It is used in reactor 1 for dihydroxylation reaction. But then is diluted to 40 wt % with water, to favor water evaporation from the reactor for cooling purpose. For the oxidative cleavage in reactor 2, air with pressure of 20 bars (partial pressure of 4 bars of O_2), is used. In addition, catalysts such as tungstic acid is needed to catalyze the dihydroxylation reaction of the double bonds in reactor 1 (i.e. to obtain intermediate compound containing diol esters); and cobalt acetate is used in reactor 2 to catalyze the oxidation reaction of the diol esters to carboxylic acids/diacids. The reactor 1 operates under vacuum at 0.47 bar to facilitate water evaporation at 80°C; and reactor 2 operates at 90°C and at a pressure of 20 bar.

Figure 14: Production of azelaic and pelargonic acid via oxidative cleavage



6.5.1 Mass balance for the oxidative cleavage of safflower oil

The mass flow of the process is shown in Table 31. The calculation is based on a production of 10 000 tonnes/ year of azelaic acid. The mass balance includes and optimization of the energy consumption and a calculation of the amount of water needed for cooling, and process.

Table 31: Energy balance for oxidative cleavage of safflower oil
(data in italics should not be counted twice)

		Flux	Kg/h	Tons/year
Raw materials	High oleic safflower oil	F1	2727	21815
	Aqueous sulfuric acid (98 wt %)	F8	1.39	11.12
	Aqueous sodium hydroxide (98 wt %)	F2	0.57	4.56
	Aqueous hydrogen peroxide (60 wt% in water)	F13	647	5176
	Tungstic acid (dry)		11.62	92.96
	Water added to reduce concentration H_2O_2 from 60 wt% to 40 wt%		323	2584
	Aqueous cobalt acetate (0.80 wt % in water)	F16	1053	8424
	Oxygen equivalent to 21 vol % in air		3777	30220
	Oxygen in air	*F17*	*880*	*7040*
	Fresh water (separation of DC3)	F22	190.6	1525
Total			**5834**	**46672**
Products	Glycerol	F10	284	2272
	Water		0.289	2.312
	Sodium bisulfate (dry)	F11	1.67	13.36
	Clean waste water from reactor 2	F19 to wastewater	1535	12280
	Carbon dioxide produced by decarboxylation of DC9 and C9	F20	140	1120
	Oxygen in waste gas after reaction in reactor 2		334	2672
	Malonic acid (DC3)	F25 to wastewater	73	584
	Water		190.6	1525
	Tungstic acid (dry)	F26	11.62	92.96
	Cobalt acetate (dry)		8.43	67.44
	Mixture hexanoic + octanoic acid (C6+C8)	F31	300	2400
	Pelargonic acid (C9)	F33	962	7696
	Fatty acids (staurated)	F43	266	2128
	Suberic acid (DC8)	F44	289	2312
	Azelaic acid (DC9)	F45	1250	10000
	Wastewater	F46 to wastewater	188	1504
Total			**5834**	**46669**
Utilities	Total cooling water consumed		**115**	**920**
	Natural gas (CH_4)		**220**	**1760**
	Electricity		**492 kWh/ h**	**3939 kWh / year**

6.5.2 Energy balance for the oxidative cleavage of safflower oil

The oxidative cleavage reaction of high oleic safflower oil produces more energy than required in the operation, and that heat is generated at low temperature. However, external heat source is needed to run the process since the separation of the light acids (C6-C8-C9) is done at high temperature by distillation. The excess energy produced at low temperature (below 100 °C) cannot be sold as steam and electricity, but could be used for another process. In Table 32, the energy balance of the process is shown.

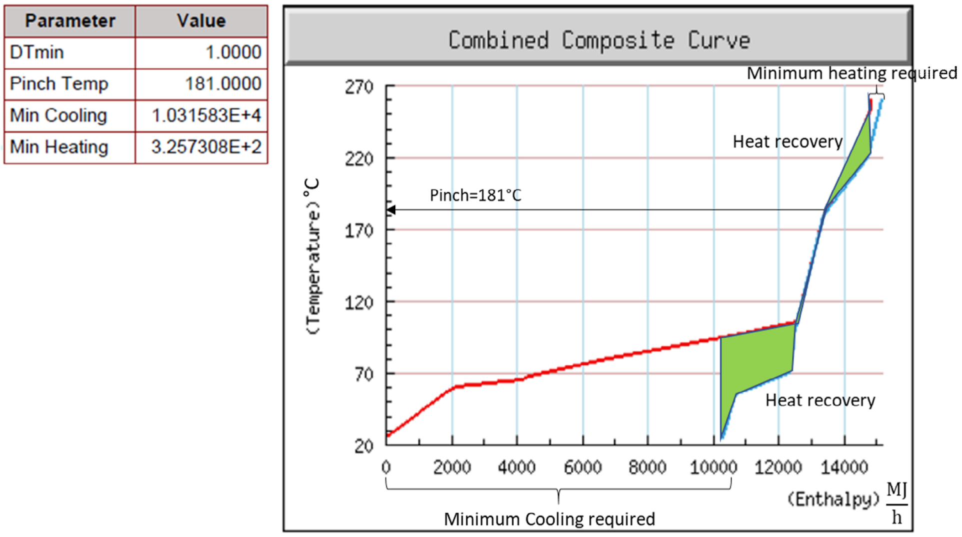
Table 32: Energy balance for oxidative cleavage of safflower oil

🟨	Energy produced by the system			
🟩	Energy required by the system			
Reaction step	**Reaction**	**Energy (MJ/h)**	**T_{in} (°C)**	**T_{out} (°C)**
1	Transesterification	226	25	60
2	Separation 1 (Decantation)	0	70	68
	Neutralization	-40.1	60	55
	Separation 2: Distillation (H 1)	1509	55	70
	Separation 2: Distillation (condenser 1)	-1399	65	60
3	Dihydroxylation (reactor 1)	-1719	80	68
4	Oxidative cleavage	-4486	105	80
	Condenser 2	-3945	100	25
5	Separation 4 (Decantation)	0	105	97
	Condenser 3	-68	97	25
	Separation 6: Evaporator (H 2)	1782	97	260
	Separation 6: Evaporator (condenser 4)	-882	254.5	180
	Separation 7: Distillation at 0.5 bar (H 3)	882	180	220
	Separation 7: Distillation at 0.5 bar (condenser 5)	-885	213	30
	Separation 7: C9 cooled from 220°C to 30°C (condenser 6)	-419	220	30
6	Condenser 7: Cooling of FAME	-648	260	100
	Emulsification	0	100	95
	Hydrolysis	22	95	100
	Condenser 8: Methanol separation	-351	65	60
7	Hot water for decantation (H 4)	431	25	90
	Crystallization	-	-	-
Minimum heating utilities needed after energy optimization (pinch analysis)		**360**		
Minimum cooling utilities needed after energy optimization (pinch analysis)		**11000**		

As observed from in Table 32, the oxidative cleavage of the oil produces a lot energy, but most of the energy required in the process is to heat the acids mixture at distillation columns. Here, a pinch analysis was carried out to analyze the heat flow in the process in order to minimize the energy consumption, and the cooling water, by optimizing the energy recovery methods. By using a pinch analysis tool available online (Umbach et al, 2010), the minimum energy required to heat and to cool the streams after energy optimization are directly determined as shown in Figure 15 and 16.

Figure 15: Combined Composite curve (*Umbach et al,2010)*

Composite Curves



Parameter	Value
DTmin	1.0000
Pinch Temp	181.0000
Min Cooling	1.031583E+4
Min Heating	3.257308E+2

Figure 16: Grand Composite curve (*Umbach et al,2010)*

The Figure 16, illustrates the heat consumption at high temperature for distillation, and the energy released at low temperature (below 100 °C) mostly from the oxidation reactions.

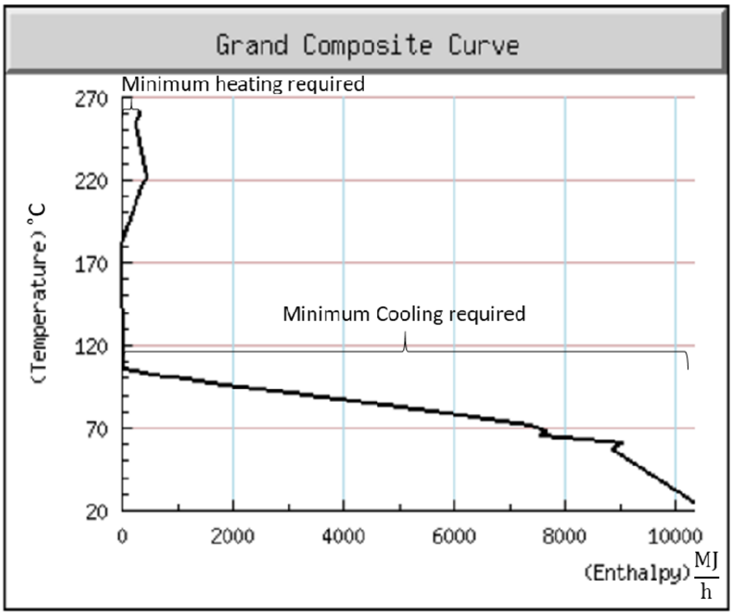


Figure 15 represents the combined composite curve between the hot and the cold streams in our system. By fixing the minimum approach temperature at 1°C, the pinch temperature determined is at 181°C. From Figure 16, the grand composite curve represent the cascade profile of the hot and the cold streams. The minimum heating utilities after energy optimization, required to heat the cold stream is 325.73 MJ/h ≈360 MJ/h and the minimum cooling utilities needed to cool the hot streams (to recover energy produced) is 10315.83 MJ/h ≈11000 MJ/h.

6.6 Value chain 6: Fatty acids from castor oil

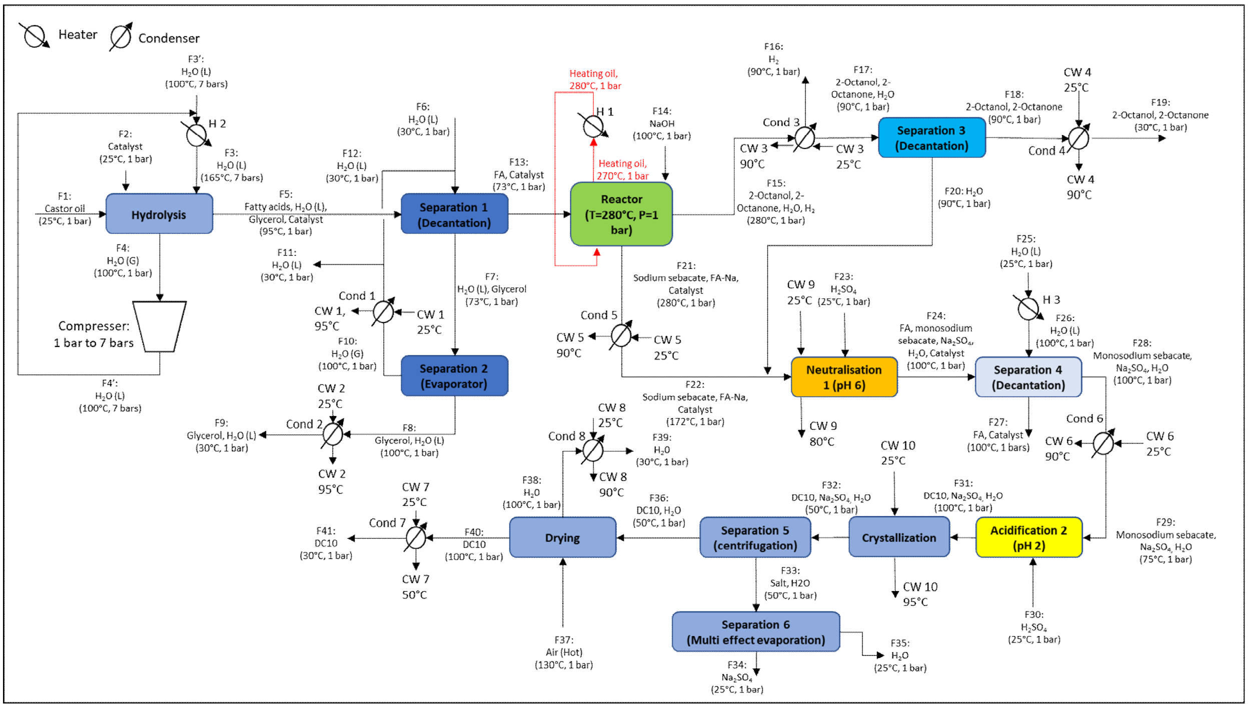
In this value chain, the production of sebacic acid and 2-octanol is presented in Figure 17. The raw materials used is castor oil (with Ricinoleic acid representing about 85 wt % in the total fatty acid composition in the oil). The process for the alkali pyrolysis (also called alkaline cleavage) of castor oil is described in detail in Figure 17 and in report D6.2.

The process is a succession of several reaction steps as follow:

1) Hydrolysis of vegetable oil with water in the presence of catalyst.
2) Separation of fatty acids from glycerol.
3) Alkaline pyrolysis with the addition of sodium hydroxide to produce 2-octanol and sodium sebacate (everal reactions taking place at the same time).
4) Separation of 2-octanol from water.
5) First acidification with sulfuric acid to pH 6 to produce monosodium sebacate and fatty acids.
6) Separation of unreacted fatty acids.
7) Second acidification to pH 2 to produce sebacic acid (DC10).
8) Separation and purification of sebacic acid.

Other raw materials include sodium hydroxide. It is needed for the saponification of the castor oil to form soaps at high temperature, leading then to the formation of sebacic acid and 2-octanol. Aqueous sulfuric acid is also used to recover the cleaved products by acidify the reaction mixture down below a pH of 6.

Figure 17: Production of sebacic acid and 2-octanol via alkali pyrolysis



6.6.1 Mass balance for the alkaline pyrolysis of castor oil

The mass flow of the process is shown in table 33. The calculation is based on a production of 10 000 tonnes/ year of sebacic acid. The mass balance includes water optimization and the amount of cooling water required calculated from the 2 pinch analysis as shown below.

Table 33: Global mass balance with water optimization

	Value in italic should not be counted	**Flux**	**Kg/h**	**Tons/year**
Raw materials	Castor oil	F1	2262	18096
	Zinc Oxide	F2	3.65	29.2
	Water (before optimization)	*F3' from F11*	*1161*	*9288*
	Water needed after optimization	F3'	144	1152
	Sodium hydroxide (48 wt %)	F14	541	4328
	Water in sodium hydroxide		586	4688
	Aqueous sulfuric acid to pH 6 (98 wt %)	F23	360	2880
	Water in sulfuric acid		7.4	59.2
	Water for decantation	*F25 from F35*	*13313*	*106504*
	Aqueous sulfuric acid to pH 2 (98 wt %)	F30	303	2424
	Water in sulfuric acid		6.19	49.52
	Hot air at 130°C	F37	14179	113432
Total			**18392.24**	**147137.92**
Products	Glycerol (95 wt % purity)	F9	225	1800
	Water in glycerol		11.87	94.96
	Waste water from 10 wt % glycerol (recycled to F3')	*F11 to F3'*	*1017*	*8136*
	Hydrogen	F16	12.55	100.4
	2-Octanone	F19	11.89	95.12
	2-Octanol		793	6344
	Fatty acid	F27	324	2592
	Zinc Oxide		3.65	29.2
	Sodium sulfate	F34	960	7680
	Wastewater (recycled to F25)	*F35 to F25*	*13795*	*110360*
	Wastewater (purge)	F35	617	4936
	Air	F39	14179	113432
	Wastewater (9.7 wt % of sebacic acid) (recycled to F25)	*F39 to F25*	*135*	*1080*
	Sebacic acid (purity 0.30 wt %)	F41	1250	10000
	Water in sebacic acid		3.76	30.08
Total			**18391**	**147134**
Utilities	Heating Oil (assuming 5 % loss by purge)		**6470**	**51760**
	Electricity		**379 kWh/h**	**3030 kWh/year**
Utilities (Pinch analysis 1)	Total cooling water consumed		**261**	**2088**
	Natural gas (CH4)		**300**	**2400**
Utilities (Pinch analysis 2)	Total cooling water consumed		**1522**	**12176**
	Natural gas (CH4)		**60**	**480**

6.6.2 Energy balance for the alkaline pyrolysis of castor oil

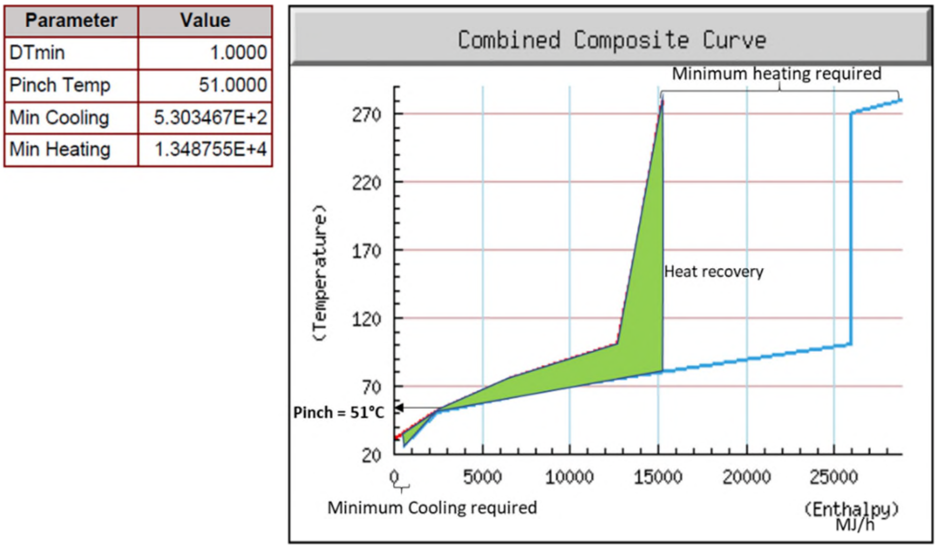
The alkaline pyrolysis reaction of castor oil required energy which is mostly needed to heat the pyrolysis reactor to 280°C. In table 34, the energy balance of the process is shown and the results from the 2 pinch analysis as shown below.

Table 34: Global heat balance

🟨	Energy produced by the system			
🟩	Energy required by the system			
Reaction step	**Reaction**	**Energy (MJ/h)**	**T_{in} (°C)**	**T_{out} (°C)**
1	Hydrolysis	-60.5	165	95
	Heater H2	397	100	165
2	Separation 1: Decantation	0	-	-
	Separation 2: Evaporator	6137	73	100
	Condenser 1	-6580	100	30
	Condenser 2	-41.8	100	30
3	Pyrolysis reactor	2771	73	280
	Heater H1	2771	270	280
4	Separation 3: Decantation	0	-	-
	Condenser 3	-2580	280	90
	Condenser 4	-122	90	30
5	Condenser 5	-397	280	172
	Acidification 1 to pH 6	-201	172	100
6	Heater H3	4174	25	100
	Separation 4: Decantation	0	-	-
7	Condenser 6	-1538	100	75
	Acidification 2 to pH 2	1572	25	100
8	Crystallization (100°C to 50°C)	-3062	100	50
	Separation 5: Centrifugation	0	-	-
	Separation 6: Evaporator	13536	50	100
	Drying	0	-	-
	Condenser 7	-137.6	100	30
	Condenser 8	-1046	100	30
Minimum heating utilities needed after energy optimization (pinch analysis 1)		15000		
Minimum cooling utilities needed after energy optimization (pinch analysis 1)		600		
Minimum heating utilities needed after energy optimization (pinch analysis 2)		3000		
Minimum cooling utilities needed after energy optimization (pinch analysis 2)		3500		

As observed from in Table 34, the alkaline pyrolysis of the castor oil needed a lot of energy, mostly in heater 1 to heat up the heat transfer oil to 280°C at the pyrolysis reactor and in separation 6 for water evaporation. Here, two pinch analysis wer carried out to analyze the heat flow in the process in order to minimize the energy consumption, and the cooling water, by optimizing the energy recovery methods. The first analysis include all the energy required in the operation and the second analysis is done without the energy in separation 6 (separation 6 is considered as multi-effect evaporator and the energy calculated is just the electrical energy). By using a pinch analysis tool available online (Umbach et al, 2010), the minimum energy required to heat and to cool the streams after energy optimization are directly determined as shown from Figure 18 to 21.

Figure 18: Combined Composite Curve with water evaporation in separation 6 (Analysis 1)



Parameter	Value
DTmin	1.0000
Pinch Temp	51.0000
Min Cooling	5.303467E+2
Min Heating	1.348755E+4

The figure 18 illustrates the huge amount of heat consumption needed in separation 6 for water evaporation, and the energy recovered is at very low temperature.

Figure 19: Grand composite curve with water evaporation in separation 6 (Analysis 1)

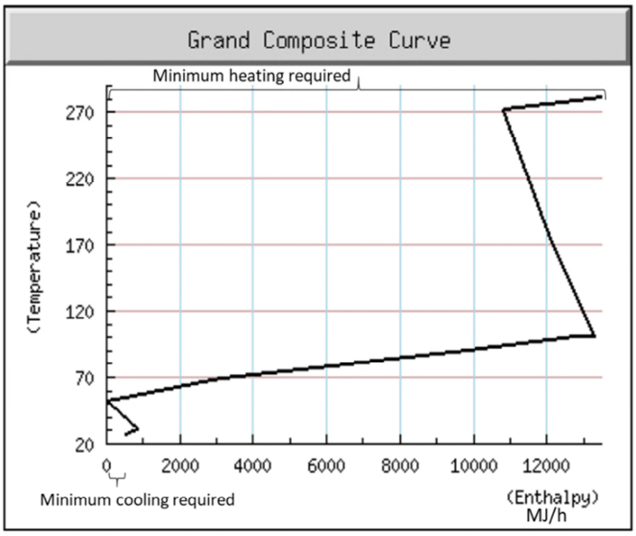
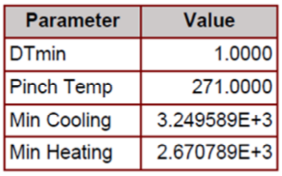
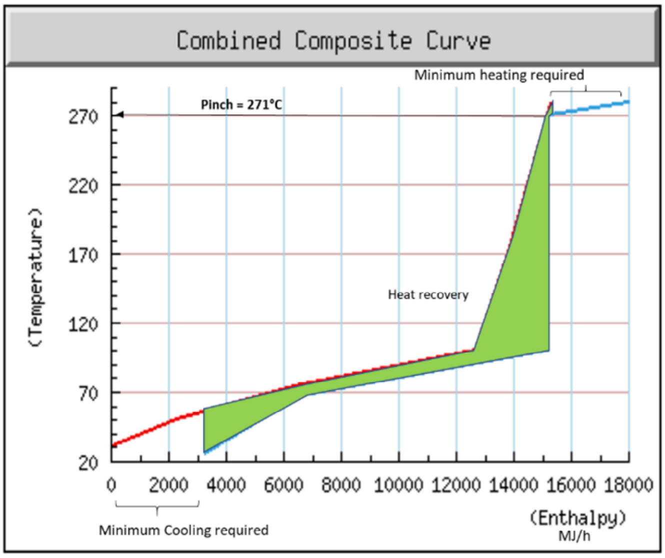


Figure 19 shows the combined composite curve between the hot and the cold streams in our system. By fixing the minimum approach temperature at 1°C, the pinch temperature determined is at 51°C. From figure 19, the minimum heating utilities after energy optimization, required to heat the cold stream is 13488 MJ/h ≈15000 MJ/h and the minimum cooling utilities needed to cool the hot streams (to recover energy produced) is 530 MJ/h ≈600 MJ/h.

Figure 20: Combined Composite Curve without energy in separation 6 (Analysis 2)

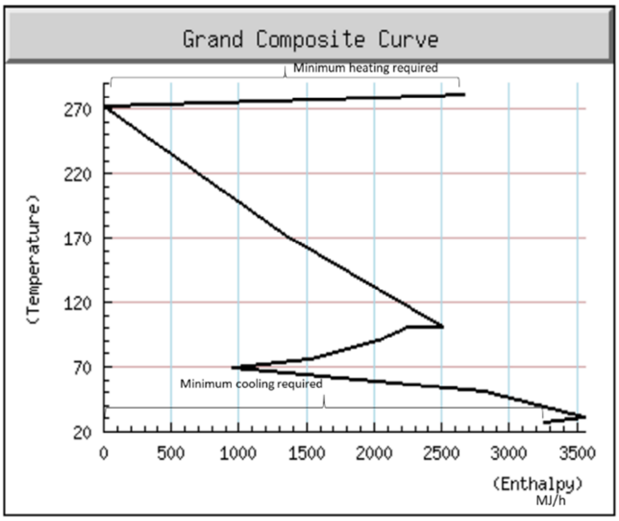


Parameter	Value
DTmin	1.0000
Pinch Temp	271.0000
Min Cooling	3.249589E+3
Min Heating	2.670789E+3



The second pinch analysis shows the results by considering that separation 6 is a multiple-effect evaporator and the energy calculated is electrical energy, thus is not taken into account in the (heat) analysis. Figure 20 illustrates that energy required is mostly for heater 1 to heat up the heat transfer oil to supply energy for the pyrolysis reactor at 280°C. The heat produced is at temperature lower than the energy required in heater 1 thus, an external heat source is still needed.

Figure 21: Grand composite curve without energy in separation 6 (Analysis 2)



In the second analysis in figure 21 without taking into account the energy required in separation 6 and by fixing the minimum approach temperature at 1°C, the pinch temperature determined by the online tool is at 271°C. The minimum heating utilities required to heat the cold stream (energy required) is 2671 ≈ 3000 MJ/h and the minimum cooling utilities needed to cool the hot streams (to recover energy) is 3250 MJ/h ≈ 3500 MJ/h.

6.7 Value chain 7: Lupin to protein

The conversion of lupin into micellar lupin protein (MLP), which can be used as a food packaging adhesive, is described in detail in D6.2. Among the several cultivars available *Lupinus angustifolius L. Vitabor*, exhibited good qualities for the production of MLP (Muranyi et al. 2016; Muranyi 2017). Below in Figure 14 schematic description of the process is presented.

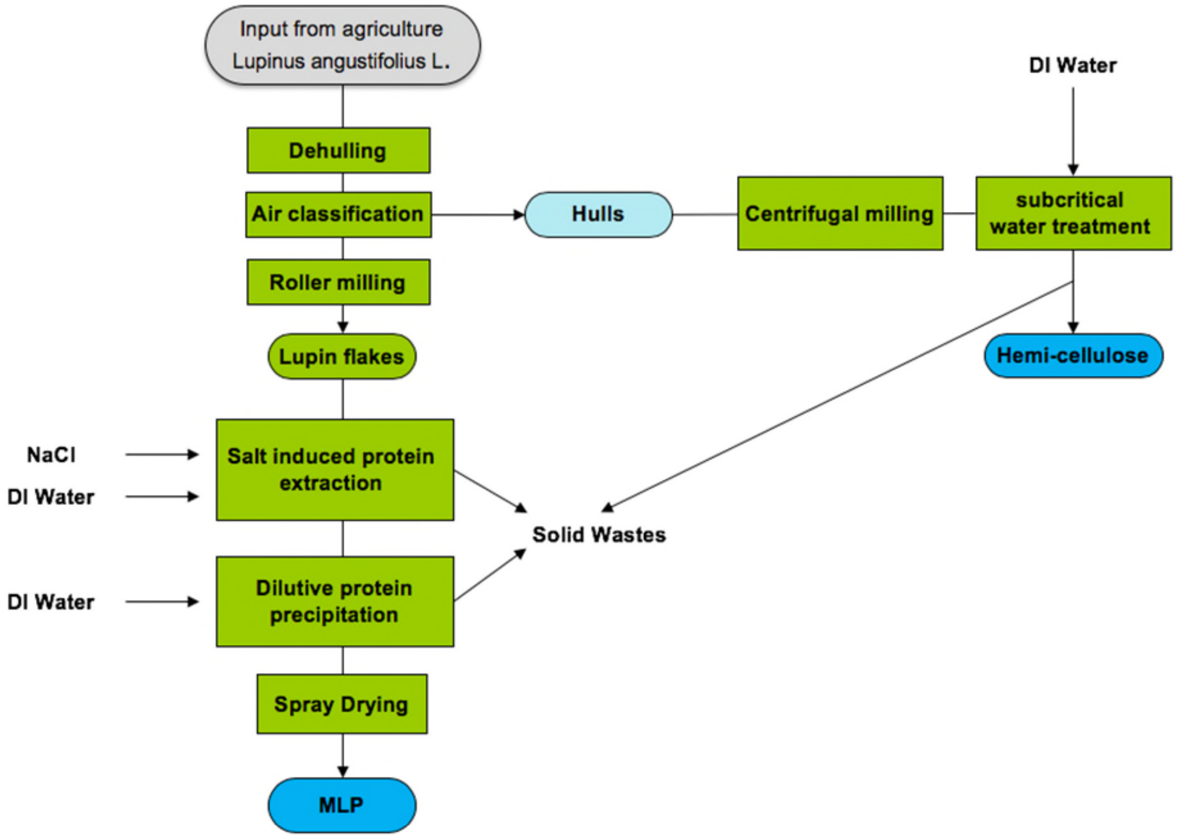


Figure 14: Production steps of lupin-based adhesive.

In this value chain, seeds pre-treatment is followed by salt induced protein extraction and dilutive protein precipitation. Furthermore, it is possible to obtain hemi-cellulose from the lupin hulls, via centrifugal milling and subcritical water treatment. The financial and organisational data are presented in Table 31 with the main material and energy inputs and outputs. The investment cost for the MLP production equipment has been estimated from a rapeseed protein isolate production plant with a very similar process to the MLP production (Dekkers 2018), accounting to 3 million euro. Infrastructure costs are not accounted in this estimation.

The main material and energy inputs are shown also in Table 31. The main input is water (625 Kton/a), which is used for the protein extraction from the raw lupin seed (75 kton/year). NaCl (17,2 Kton/a) is used for the salt induced protein extraction. As a by-product, 15,7 kton/a of hemicellulose are obtained from lupin hulls. The overall electricity consumption throughout the several processing steps performed is 157,7 TJ/a.

Table 31: Financial and organizational data for MLP plant including the main material and energy inputs and outputs.

Financial and organizational data		
operational hours	7500	h/a
manpower	3	FTE
investment cost	3	M€
annual maintenance cost	7%	
Main material and energy inputs		
Lupin seeds	75	kton/a
Electricity	157,7	TJ/a
Water	625	kton/a
NaCl	17,2	kton/a
Main material and energy outputs		
MLP	21,7	kton/a
Hemicellulose	15,7	kton/a
Solid waste	25,3	kton/a
Wastewater	457,6	kton/a

6.7.1 Mass flows in MLP production

The mass and energy flow in the Lupin to MLP process is shown in Figure 15. As explained in the previous sections, the ID number in Table 32 and Table 33 refer to the numbered arrows in the figure.

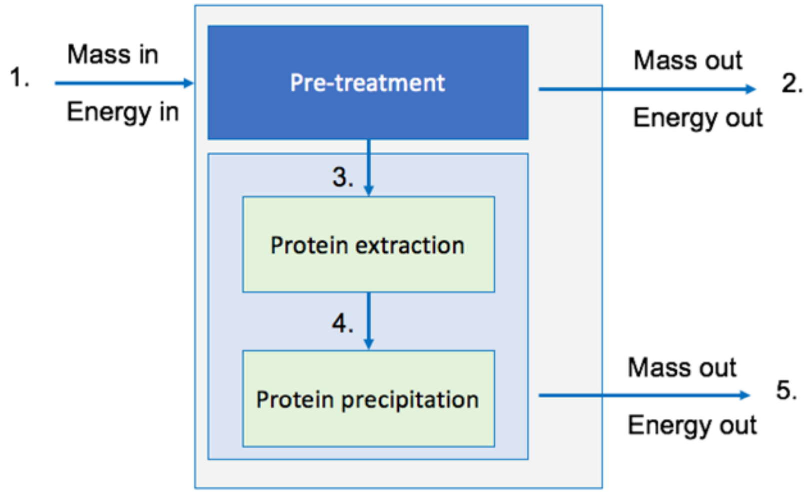


Figure 15: Mass and energy flows in the MLP process

Table 32 shows the material flows in the Lupin to MLP process. Lupin seeds enter the processing chain with 8% moisture content undergoing three main pre-treatment steps: seeds dehulling, air classification and kernels flaking. Given the hull removal, at this point ca. 75% of the initial biomass is available for the recovery of protein isolates. Lupin flakes have now to be suspended in 29,2 g L^{-1} NaCl solution at a ratio of 1 kg in 8 l (w/v). In order to precipitate the MLP the supernatant has to be diluted with DI water (Deionized water) at room temperature at a ratio of 1:3 (v/v) (Muranyi et al., 2016). After a final DI water washing and centrifugation step the MLP (2,9 tons in one-hour operation) is obtained, showing an oily and highly viscous micelle texture. That generates 3,4 tons of solid wastes, 61 tons of wastewater and 2,1 tons of CO_2 eq in one-hour operation. Furthermore 2,1 tons/hour of hemicellulose are obtained via subcritical water treatment, according to Ciftci & Saldaña (2015) the optimum process conditions for maximum hemicellulose sugar yield in the extracts was found to be 180 °C, 50 bar, 5 mL/min, and pH 6.2 with a yield of 85.5%.

Table 32 Mass flows in the Lupin to MLP process.

Based on 1h operation				
ID	**Mass inputs**		Unit	*Comment*
1	Lupin seeds (with hull)	10	Tonne	*DM = 91%* [estimated from Dekkers (2018)]
3	Water	80	Tonne	
3	NaCl	2,3	Tonne	
4,2	DI Water	3,3	Tonne	
	Mass in total	95,6	Tonne	
	Mass outputs			
5	MLP	2,9	Tonne	*Range value: 26.4–31.7% (average 29%)*
2	hemicellulose	2,1	Tonne	
5	CO2 eq	2,1	Tonne	0,215 kg CO2 eq/ kg lupin processed [estimated from Dekkers (2018)]
5, 2	Wastewater	61	Tonne	
5, 2	Solid waste	3,4	Tonne	
	Mass in total	71,5	Tonne	
	Balance	75%		

6.7.2 Energy balance in MLP production

Energy balance for the MLP production process are given in Table 33. The efficiencies and energy requirements are estimated on information from Dekkers (2018), from a rapeseed protein isolate production plant with a very similar process to the MLP production. The Lupin kernels, MLP and hemicellulose energy contents were estimated from the biomass composition, this information were respectively gathered form Carvajal-Larenas et al. (2016), Lopez (2014) and Chen et al. (2018). Overall the energy produced at the factory gate is 285239,5 MJ in one-hour operation.

Table 33. Energy inputs and outputs of the Lupin to MLP process.

Based on 1h operation				
ID	**Energy in**		Unit	*Comment*
1	Lupin kernels (seed + hull)	203200	MJ	Estimated from Carvajal-Larenas et al. (2016)
1	Electricity	26280,5	MJ	Estimated from Dekkers (2018)
	Total energy in	229480,5	MJ	
	Energy out			
5	MLP	482821	MJ	Estimated from Lopez (2014)
2	Hemicellulose	31899	MJ	Estimated from Chen et al. (2018)
	Total energy out	514720	MJ	
	Energy produced	285239,5	MJ	

6.8 Value chain 8: Hemp as raw material for insulation material

Production of insulation material from hemp is described in detail in D6.2. Below in Figure 16 a schematic description of the process is shown. It displays the production steps from the cultivation of hemp, through the fibre processing, to the final insulating product.

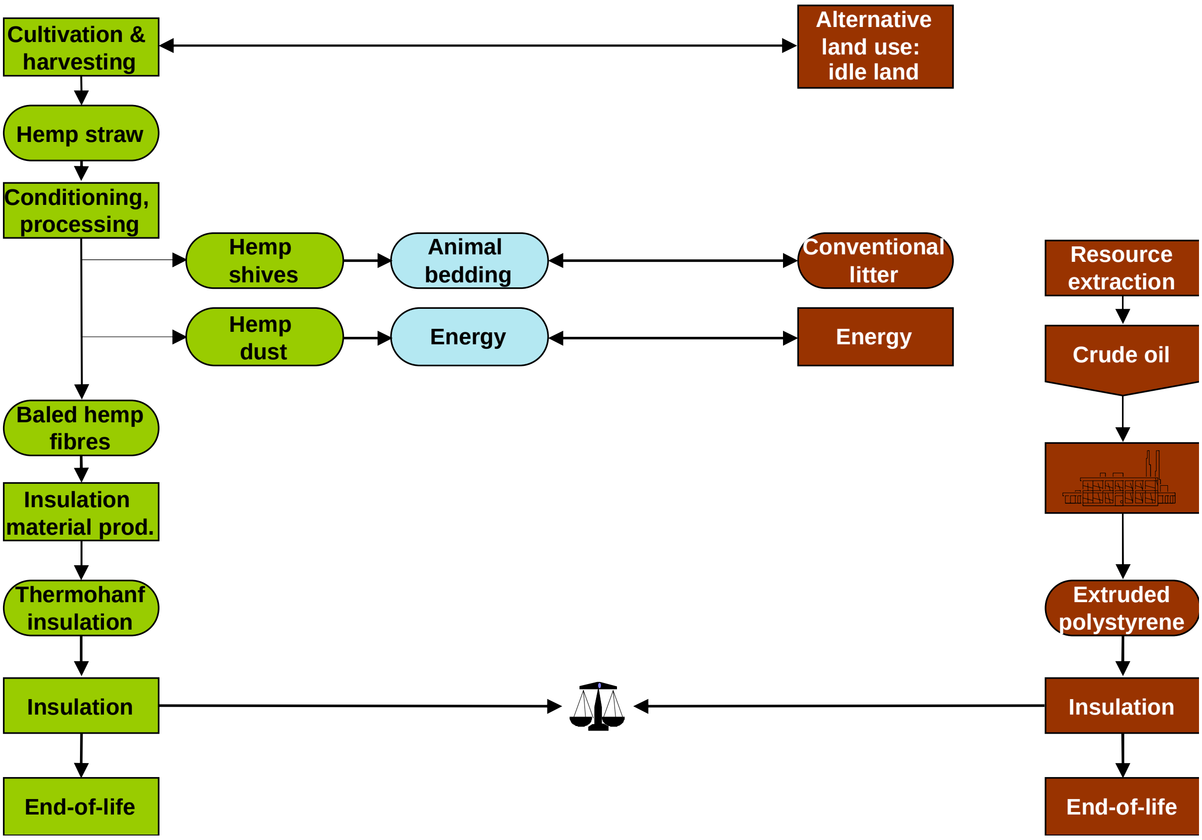


Figure 16: Life cycle comparison scheme: production of insulation material from hemp

Financial and organizational data including the main material input and outputs for an insulation material processing plant is shown in Table 34. The operational hours are 3920 h/a requiring manpower of 5-8 FTE/year. Investment costs of a processing plant is highly depending on the capacity of the processing line. The costs for a large fibre processing line are estimated to be about 6 million euros with annual maintenance costs at 1-2 % of the overall investment (de Beus & Piotrowski 2017). This plant is capable of processing 15680 kton of hemp straw per year, resulting in over 4000 kton/a of insulation material.

Table 34. Financial and organizational data for fibre processing plant including the main material and energy inputs and outputs.

Financial and organizational data		
operational hours	3920	h/a
manpower	5-8	FTE
investment cost	6	M€
annual maintenance cost	1-2%	
Main material and energy inputs		
Hemp straw	15680	ktonne/a
Electricity	25,6	TJ/a
Main material and energy outputs		
Thermohemp (insulation product)	4312	ktonne/a

6.8.1 Mass flows in hemp insulation production

Figure 17 describes the mass and energy flows along the processing of hemp fibres and the subsequent production of insulation material. The numbers indicate the flow of the streams

For example,

Table 35 (ID 1) shows a mass input of 4 t/h hemp straw to the process and a mass output of a round 1t insulation material at the end (ID 4). ID 3 describes the mass flow of processed hemp fibres into the insulation material production. Further material output comes in the shape of by-products like shives, dust and too short fibres (ID 2).

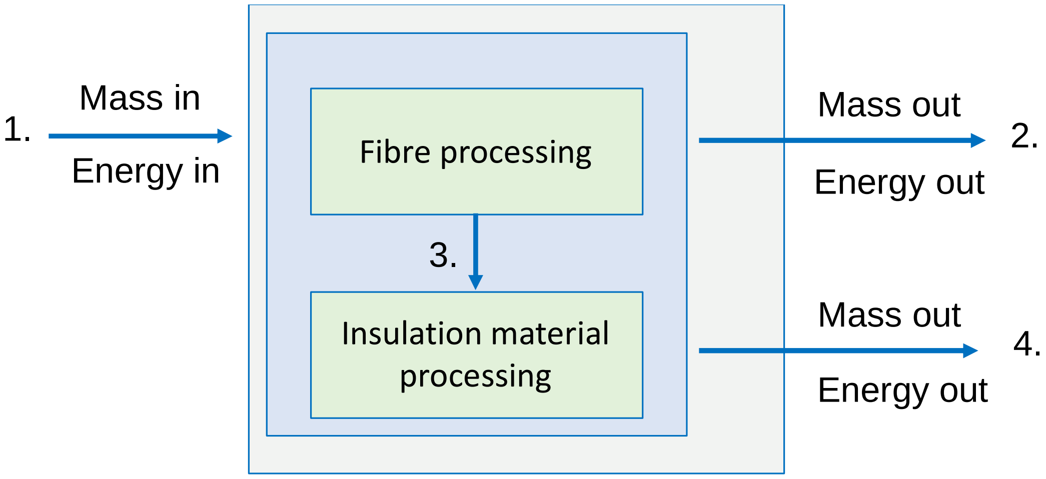


Figure 17. Mass and energy flows in the insulation material production

Table 35. Mass flows in the production of insulation material from hemp

Based on 1h operation				
ID	**Mass in**			
1	Hemp straw	4000	kg	*Dry matter/ Fibre processing*
1	Fire retardant (soda)	33	kg	*Insulation material processing*
1	Binder (bi-component polyester fibre) (PET)	110	kg	*Insulation material processing*
	Mass out			
2	Hemp shives	2200	kg	*55% of the raw material*
2	Hemp dust (residues, wastes)	600	kg	*15% of the raw material*
2	Short fibres	160	kg	*4% of the raw material*
2	Super short fibres	80	kg	*2 of the raw material*
4	Thermohemp (insulation product)	1103	kg	
	Other mass flows			
3	Hemp fibre	960	kg	*24% of the raw material*

6.8.2 Energy flows in hemp insulation production

In Table 36 the energy flows in the insulation material processing from hemp are shown. The ID-numbers correspond to the flow in Figure 17
Figure 17. Based on the net calorific value for hemp (17,93MJ/kg dry matter), the major energy input (ID 1) is coming from hemp straw (68.000 MJ) (Phyllis2 database, 2020). According to de Beus & Piotrowski (2017) additional energy input for the process originates from diesel (229 MJ), natural gas (7200 MJ), electricity (6551 MJ) and bi-component polyester fibre (2403.5 MJ), which is used during the processing of the insulation material. Since the net calorific value for hemp known, the energy output of the mostly hemp-based by- and intermediate products can be estimated (ID 2&3). Unfortunately, the exact energy content of the final insulation product couldn't be found during research. Following own assumptions, the energy output for the insulation material would be between 19000 and 20000 MJ.

Table 36. Energy flows in the production of insulation material from hemp

Based on 1h operation				
ID	**Energy in**		Unit	*Comment*
1	Hemp straw	68000	MJ	*Fibre processing*
1	Diesel	229	MJ	*Fibre processing*
1	Natural gas	7200	MJ	*Insulation material processing*
1	Electricity	6551	MJ	*Fibre & Insulation material processing*
1	Binder (bi-component polyester fibre) (PET)	2403.5	MJ	*Insulation material processing*
	Energy out			
2	Hemp shives	37400	MJ	
2	Hemp dust (residues, wastes)	10200	MJ	
2	Short fibres	2868,8	MJ	
2	Super short fibres	1434,4	MJ	
	Sum	51903,2	MJ	
	Other energy flows			
3	Hemp fibre	17213	MJ	*17.93MJ/kg (Phyllis2)*

6.9 Value chain 9: Sorghum as substrate for biomethane via anaerobic digestion

Sorghum shows similarities to maize which is commonly utilized for biogas production (Hermann et al. 2016). The scheme below is displaying the production steps from the cultivation of Sorghum to the final product – biogas or biomethane. The financial and organizational data are presented in Table 37 with the main annual material and energy inputs and outputs.

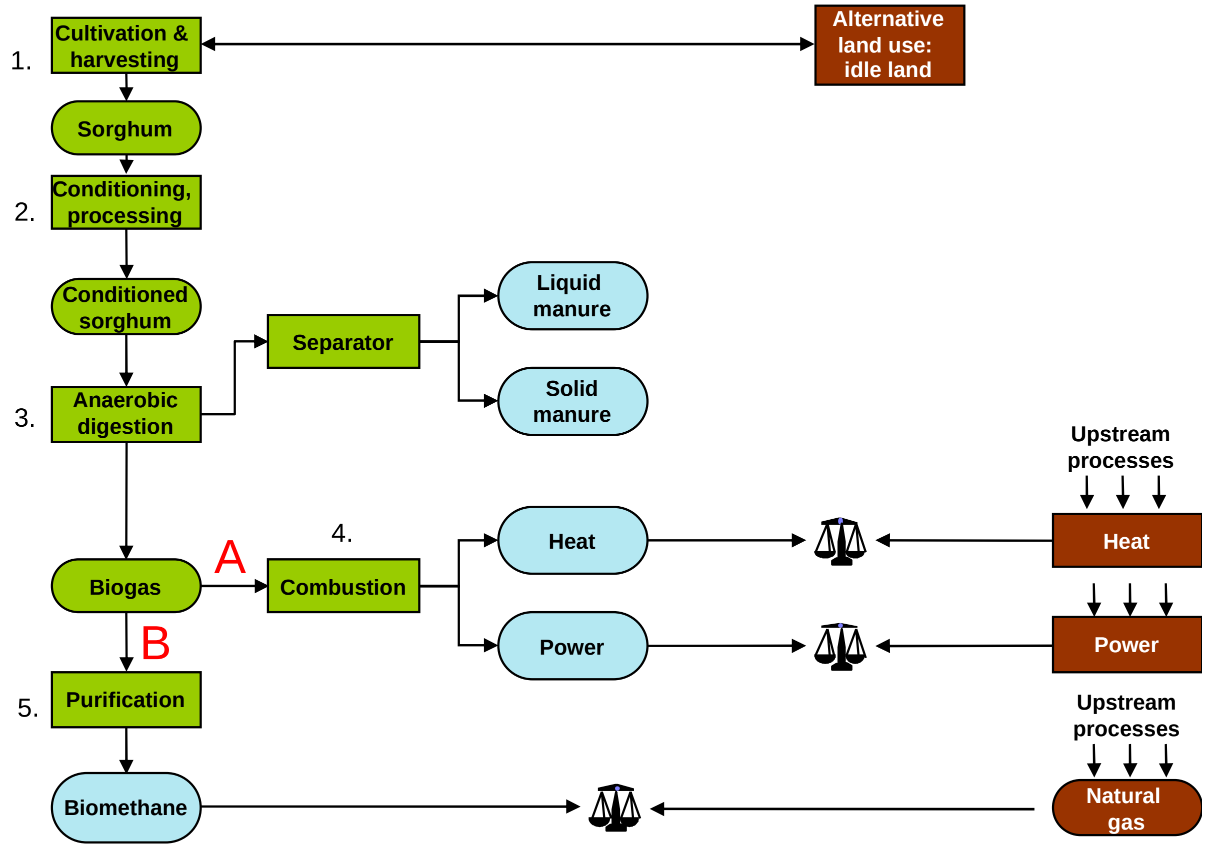


Figure 18: : Life cycle comparison scheme for biogas production from Sorghum as substrate.

Table 37 shows the financial and organizational data of a biogas production with sorghum as substrate. On the basis of a medium sized biogas plant with an annual biogas output of around 1.533.000 m^3 per year (Hutňan 2016) the initial investment costs are 962.500 €. The initial investment costs are highly depending on the scale of the biogas plant and can be calculated by multiplying 3.500 € with the electrical output (kW) of the biogas plant. The operational hours are 7500 h/a with annual maintenance costs estimated at 1-3 % of the investment costs as is possible to notice in Table 37. The main material flow of 8.800 tons of Sorghum and the same amount of water per year resulting in a biogas yield of 1.533.000 m^3 of biogas. The 15.700 tons/a digester sludge as side product can be utilized as manure.

Table 37: Financial and organisational data for a biogas plant including the main material and energy inputs and outputs.

Financial and organizational data		
operational hours	7500	h/a
manpower	3	FTE
investment cost	962.500	€
annual maintenance cost	1-3 %	
Main material and energy input		
Sorghum silage	8,8	ktonne/a
Water	8,8	ktonne/a
Main material and energy output		
Biogas	1.533.000	m^3/a
Digester sludge / manure	15,7	ktonne/a

6.9.1 Mass flows in the biomethane production process

Figure 19 describes the mass and energy flows in the biogas production process. The ID numbers of the following Table 38 and Table 39 are indicating the flows presented here below.

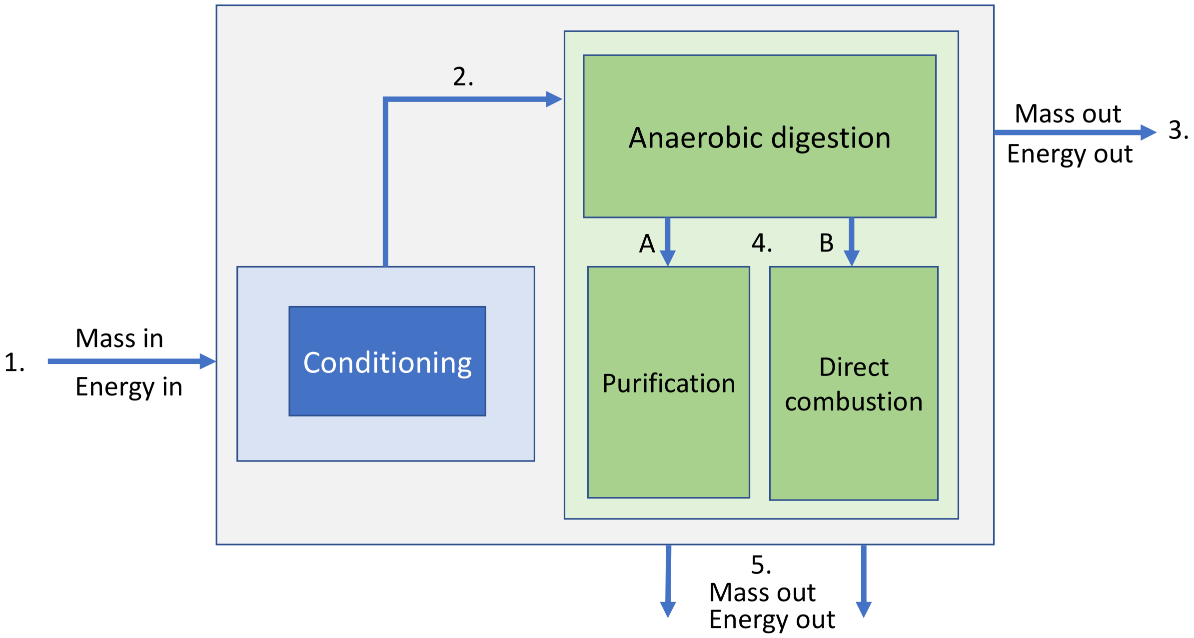


Figure 19: Mass and energy flows in the anaerobic digestion process.

Table 38 shows the material flow of the anaerobic digestion process. Sorghum silage as main substrate is mixed with water (ratio 1:1). In the present case a total amount of 2 tons will be filled into the fermenter every operation hour. Here the actual biogas production takes place. Based on one operation hour the outputs are 0,213 tons of biogas and 1,787 tons of digester sludge. There is no loss of mass noted for this process.

Table 38: Mass flows in the anaerobic digestion process.

Based on 1h operation				
ID	**Mass in**		**Unit**	
1	Sorghum silage	1	Tonne	*Value from same amount maize silage*
1	Water	1	Tonne	*Substrate / Water ratio 1:1*
	Sum	2	Tonne	
	Mass out			
4	Biogas	0,213	Tonne	*Calculated with density of 1,22 kg/m3 for biogas*
3	Digester sludge / manure	1,787	Tonne	*Estimated*
	Sum	2	Tonne	
	Loss	0	%	

6.9.2 Energy flows in the biomethane production process

Purification of biogas is needed for feeding biomethane into the gas grid. But not necessary in the case of direct incineration for energy generation.

As input energy Table 39 shows sorghum silage (5000 MJ) as substrate and electricity (99,54 MJ) and heat (612,5 MJ) for operating the biogas plant. The energy output from biogas incineration shown in Table 39 is based on Hutňan (2016) with a conservative energy yield of 2714 MJ. Other literature indicates a possible energy yield from up to 3800 MJ from the same amount of biogas. In the present case the digester sludge accounts for 2286 MJ energy output. A total energy loss of 12,5 % is noted for the energy flows in the anaerobic digestion process including the energy needed for operation the system.

Table 39: Energy flows in the anaerobic digestion process.

Based on 1h operation				
ID	**Energy in**		Unit	*Comment*
1	Sorghum silage	5000	MJ	*Ca. 5 MJ/KG Sorghum silage = 5000 MJ*
2	Electricity	99,54	MJ	
2	Heat	612,5	MJ	
	Sum	5712,04	MJ	
	Energy out			
5	Electrical energy (from biogas)	990	MJ	*incineration in cogeneration unit of biogas*
5	Heat energy (from biogas)	1724	MJ	*incineration in cogeneration unit of biogas*
3	Digester sludge / manure	2286	MJ	*Estimated from biomass composition*
	Sum	5000	MJ	
	Loss	12,5	%	

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