Marginal lands for Growing Industrial Crops

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1 Introduction

This ‘Report on system description of selected value chains’ (Deliverable D 6.2) represents the status as of 31 January 2020. It corresponds to the description of work of task 6.1.2 as summarised in the Grant Agreement Annex 1 of the Horizon 2020 project MAGIC (GA no. 727698).

The goal of this report is to provide a full **qualitative system description** of those value chains that were selected for in-depth analysis within the sustainability assessment, covering the entire life cycle from cradle to grave.

On 18 July 2019, an internal project workshop on the selection of value chains for further analysis in WP 6 and on interlinkages between WP 6 and other WPs was successfully held in Catania, Italy [Rettenmaier et al. 2019]. During the workshop, ten value chains were finally selected for in-depth analysis within the sustainability assessment in WP 6 (see Table 1).

The final selection of value chains shows a good representation of:

1. Crop categories (lignocellulosic crops, oil crops & carbohydrate/multipurpose crops)
2. Final products: energy, fuels, chemicals & materials

Table 1: Final selection of value chains for in-depth analysis within the sustainability assessment

Crop	Conversion	Main products[1]	Type
Miscanthus	Pyrolysis	Energy (industrial heat)	energy
Poplar	Gasification	Energy (SNG)	energy
Switchgrass	Fermentation	Ethanol	fuel
Willow	Pyrolysis	Biochemicals (biotumen)	material
Safflower	Oxidative cleavage	Azelaic and pelargonic acid	chemical
Camelina	Metathesis	Methyl decenoate	chemical
Castor	Several oleochem. processes	Diacids	chemical
Industrial hemp	Mechanical processing	Insulation material	material
Sorghum	Anaerobic digestion	a) heat & power b) biomethane	energy
Lupin	Extraction	Adhesives	chemical / material

The ten selected value chains are described in detail in the following chapter 2.

2 Qualitative system description

The value chains (or life cycles) are divided into two parts: i) biomass provision and ii) biomass conversion, product use and end-of-life (EoL). The biorefinery inlet gate is defined as the interface between the two parts.

Biomass provision and alternative land use

This part covers the first part of the life cycle from **biomass production** through **harvesting**, **logistics** and **conditioning** up to the biorefinery inlet gate.
Since a broad range of crops is investigated in MAGIC (perennial and annual crops, lignocellulosic, oil and carbohydrate/multipurpose crops, etc.), cultivation and harvesting practices as well as conditioning requirements vary significantly among the crops. Also, agricultural co-products and their use are described in the following sections.

A number of characteristics of the biomass provision scenarios were already determined in D 6.1 on definitions and settings for the sustainability assessment [Rettenmaier 2018]. This includes e.g. that all scenarios represent mature agriculture practice in 2030.
Also, the **alternative land use** was defined in D 6.1 [Rettenmaier 2018]. For the outcome of the sustainability assessment, the alternative land use is usually a major factor which determines the results significantly. The alternative land use describes what the cultivation area would be used for if the crops under investigation were not cultivated [Jungk et al. 2002; Koponen et al. 2018]. Within the MAGIC project, the default setting is that cultivation takes place on former idle land. Idle land is defined as land that is currently not in use. Thus, the MAGIC industrial crops are set not to displace food or fodder crops to other, previously unused, areas and indirect land use changes (iLUC) can be excluded from this assessment. However, impacts from direct land use changes (dLUC) are considered. Within the MAGIC project, the alternative vegetation on marginal land is defined as either grassland or woody grassland / shrubland.
In addition, wheat and barley are chosen as reference crop in the economic assessment, because the revenue of a common crop like wheat helps farmers to judge the economic advantage or disadvantage of industrial crops.

Biomass conversion, product use and end-of-life

This part covers the second part of the life cycle from **biomass conversion** (the biorefinery inlet gate is defined as the interface) through **product use** and **end of life (EoL)**. The **conventional reference system(s)** is/are also covered in order to obtain full **life cycle comparisons**.

2.1 VC 1: Industrial heat from Miscanthus (via pyrolysis)

This value chain describes the conversion of Miscanthus (*Miscanthus x giganteus* GREEF ET DEUTER EX HODKINSON ET RENVOIZE) to pyrolysis oil, which is then used for the production of industrial heat. This life cycle is compared to conventional ways of providing the same products or services (Figure 1).

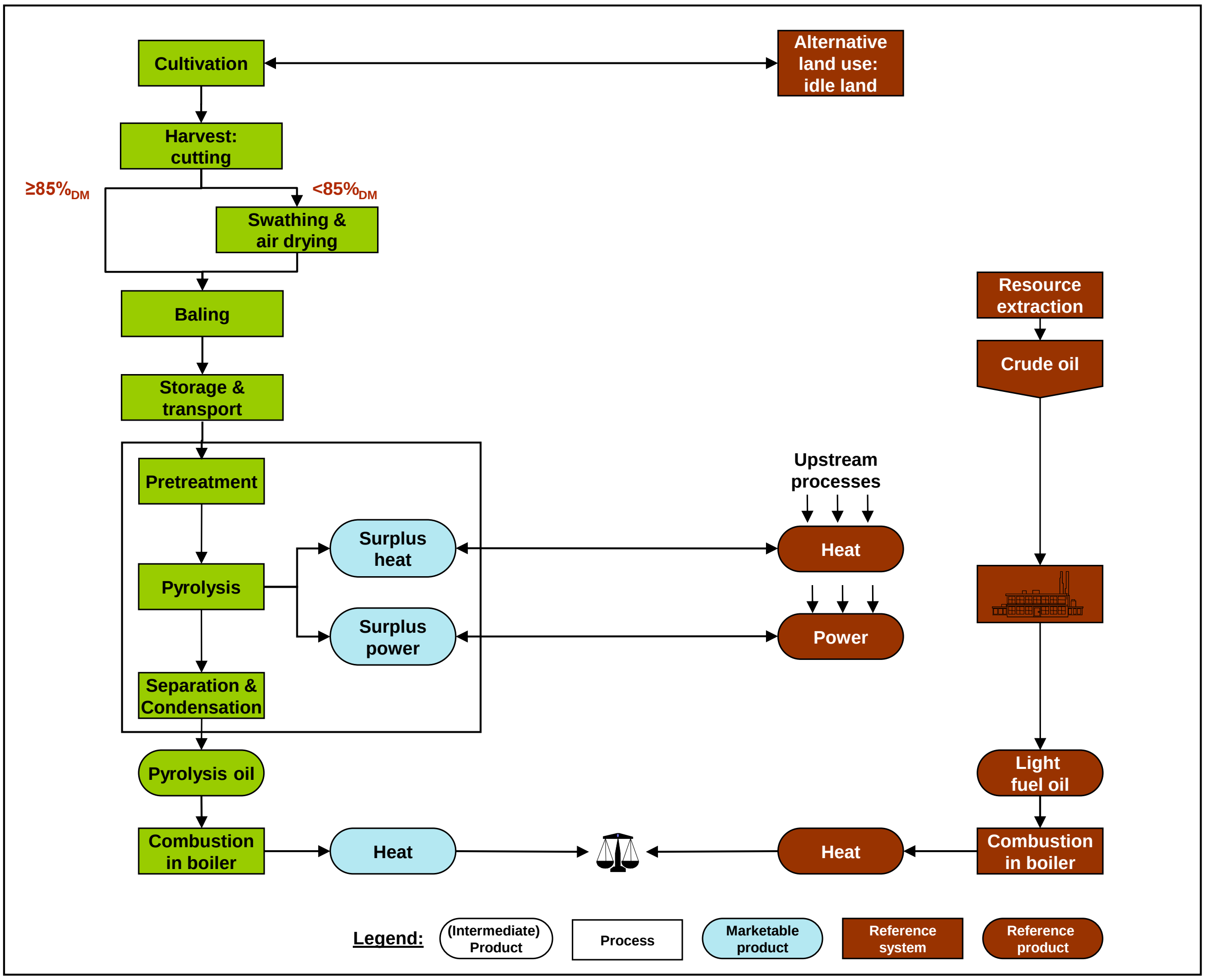

Figure 1: Simplified life cycle comparison for VC 1: industrial heat from Miscanthus via pyrolysis.

Before the value chain description, a general description of fast pyrolysis technologies is given. Next, the specific pyrolysis of Miscanthus is described together with an elaboration on the selected pyrolysis technology.

Fast pyrolysis is the action of rapidly heating a feedstock in the absence of oxygen in order to convert the feedstock to smaller parts. In the case of biomass fast pyrolysis, the biomass is heated to temperatures of 400-600 °C. This result in a breakdown of the biomass to form vapours. Condensation of the vapours results in a liquid called pyrolysis oil. Next to pyrolysis oil, char, and some non-condensable gases are formed, which can be used to supply heat to the pyrolysis process. The only waste stream that remain are the minerals from the biomass in the form of ash.

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Several different pyrolysis oil technologies for biomass conversion have been developed. [Venderbosch 2018] From these technologies, the rotating cone technology developed by BTG and marketed by BTG-BTL shows both the best promise on large scale application and has the best data availability. Therefore, this process was selected to model the pyrolysis conversion within the MAGIC project. The detailed value chain is presented in chapter 7 (Annex). On large scale, the process has been proven to work reliably on woody biomass, for example in the commercial scale demo plant EMPYRO in Hengelo. [Venderbosch 2018] Data from this plant was used and adapted to Miscanthus using the in-house knowledge of BTG.

Figure 14 in chapter 7 (Annex, p. 37) shows a more detailed process description for industrial heat production from Miscanthus via pyrolysis. Before biomass can be converted to pyrolysis oil, a pre-treatment is required to make the biomass input suitable for pyrolysis. The pre-treatment exists of a sizing step (1) and a drying step (2). The drying step is required to get the moisture content below 5% right before the biomass enters the pyrolysis reactor to prevent reabsorption of moisture form the air. The energy obtained from combusting the char and non-condensable gases is more than sufficient to provide energy for the pyrolysis step (3). Rapid heat transfer is required in pyrolysis and often a heat carrier material, like sand, is used to improve the process. After pyrolysis, the sand and the formed char are separated from the pyrolysis vapours (5). Followed by condensation, the gases form pyrolysis oil, which can be used directly for combustion to heat. The non-condensable gases and the char is sent to a combustor (6) to provide energy for the pyrolysis process. Excess energy from flue gases can be converted to steam in a boiler (7) and is used for the drying of the biomass (2). The produced ash leaves the system at the boiler as well. The remaining steam can either be directly sold to nearby industry or (partially) converted to electricity in a steam turbine.

Interim appraisal of VC 1:

- Pyrolysis is currently only performed on woody biomass on commercial scale, but there is a large interest in expanding the feedstock range.
- Direct combustion of Miscanthus (for heat and/or power generation) is state of the art technology and has been extensively studied in the past. It has proven very favourable and easy to implement. This might be covered in a sensitivity analysis.

2.2 VC 2: SNG from poplar (via gasification)

This value chain describes the production of synthetic natural gas (SNG) from poplar (*Populus spp.* L.) by gasification. This life cycle is compared to conventional ways of providing the same products or services (Figure 2).

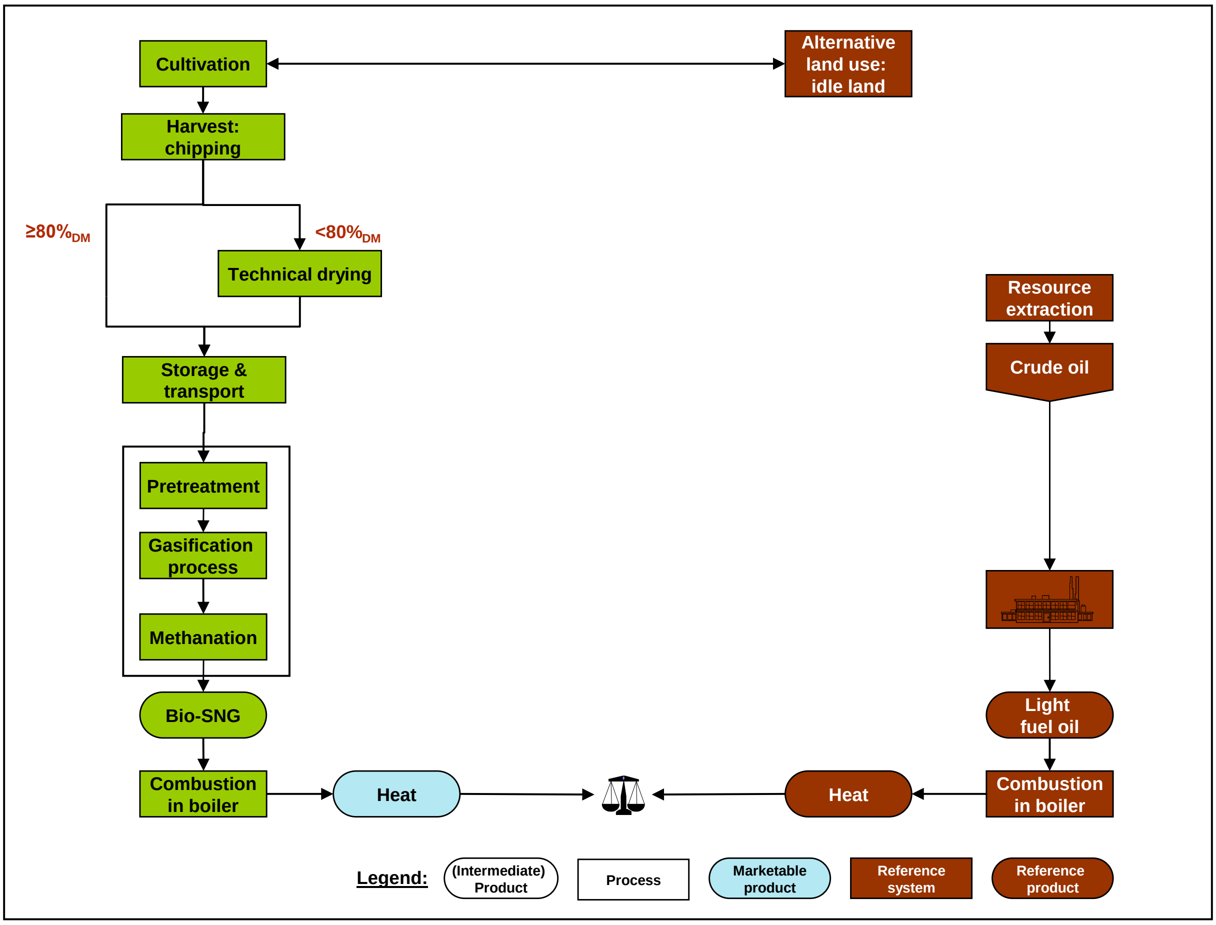

Figure 2: Simplified life cycle comparison for VC 2: synthetic natural gas from poplar via gasification.

Gasification is a thermochemical process that can be used to convert solid biomass into a gas. It is performed at high temperatures and with controlled amounts of oxidizing agents such as steam, air or oxygen to avoid full combustion of the feed. This produces a gas mixture (H_2 / CO) commonly called a syngas. The process is highly developed (TRL 9) and commonly used to produce heat and power [Knoef 2012]. Production of synthetic natural gas (SNG) via gasification means using the syngas as a raw material for the synthesis of SNG. The composition of SNG is mainly methane with small amount of hydrogen. Methane is readily available from natural gas, thus methanation in industrial scale has not been established. However, technology for methane production from syngas is well-known [Jensen et al. 2011] and commercial systems for methanation exist.

SNG production from solid biomass via gasification has so far only been demonstrated in the GoBiGas project at 20 MW_{SNG} scale in years 2014-2018 in Gothenburg, Sweden. The project was technologically a success and showed that it possible to produce SNG from woody biomass. The GoBiGas plant was shut down in 2018, due to economic reasons as the price of natural gas remained low compared to the price of SNG. It is expected that by 2030 this type of SNG production becomes more compatible with natural gas [Rüegsegger & Kast 2019]. As the technology used in the demonstration of GoBiGas proved to be successful for the purpose of producing SNG from biomass (TRL 6-7), it is reasonable to use similar process description for evaluating SNG production from poplar.

Figure 15 in chapter 7 (Annex, p. 38) shows a more detailed process description for SNG production from poplar via gasification. The process is divided into 2 parts, namely gasification and methanation. It should be noted that process flows like steam recycling or flue gas recycling are not shown to keep the scheme simplified. The main parts of the process are numbered and explained below.

Biomass acquired in the upstream processes is fed to the process (1). For gasification the raw material should be relatively fine and dry. Typically, suitable size is approximately 7-10 cm in diameter and moisture content around 10% [Thunman 2018]. If the wood is fed as chips with typical moisture content of 40%, a dryer is necessary to reach suitable plant efficiencies at a commercial scale (*e.g.* 100 $MW_{biomass}$) [Alamia et al. 2017].

Gasification (2) is done in a dual fluidised bed gasifier (DFB) operated in 2 zones, respectively a gasifier and a combustor (not shown separately). Combustion fuelled by natural gas and the by-products from the process creates the required heat for the gasification. For oxidizing the feed to syngas in the gasification, steam is introduced.

Gasification of biomass produces many products than just gas, like ash, char and tars, which have to be removed prior to methanation. (3) Ash is removed in a cyclone and partly recycled back to the process. Subsequently, tars are removed (4). The by-products are then recycled back to combustion in order to improve the efficiency of the process.

Methanation is preferred at high pressures and for process optimisation compression of the product gas is carried out prior to methanation (5). Further, conditioning of the gas is required prior to methanation, where the gas composition is optimised for methanation in a Water Gas Shift Reactor (WGSR, 6).

After the WGSR, methanation (7) is carried out over a catalyst. This is carried out in series and can require 3-4 steps. Commercial well-defined methanation systems are available, e.g. Haldor Topsoe TREMP [Jensen et al. 2011]. Followed by methanation, the feed is cleaned up from CO_2 and the synthetic natural gas is dried (8). Further, compression of the SNG may be necessary to provide it to the grid.

Interim appraisal of VC 2:

- Biomass gasification is challenging. Woody biomass is preferred.
- Direct combustion of poplar might be added and covered in a sensitivity analysis.

2.3 VC 3: Ethanol from switchgrass (via hydrolysis & fermentation)

This value chain describes the conversion of switchgrass (*Panicum virgatum* L.) to ethanol via hydrolysis and fermentation. This life cycle is compared to conventional ways of providing the same products or services (Figure 3).

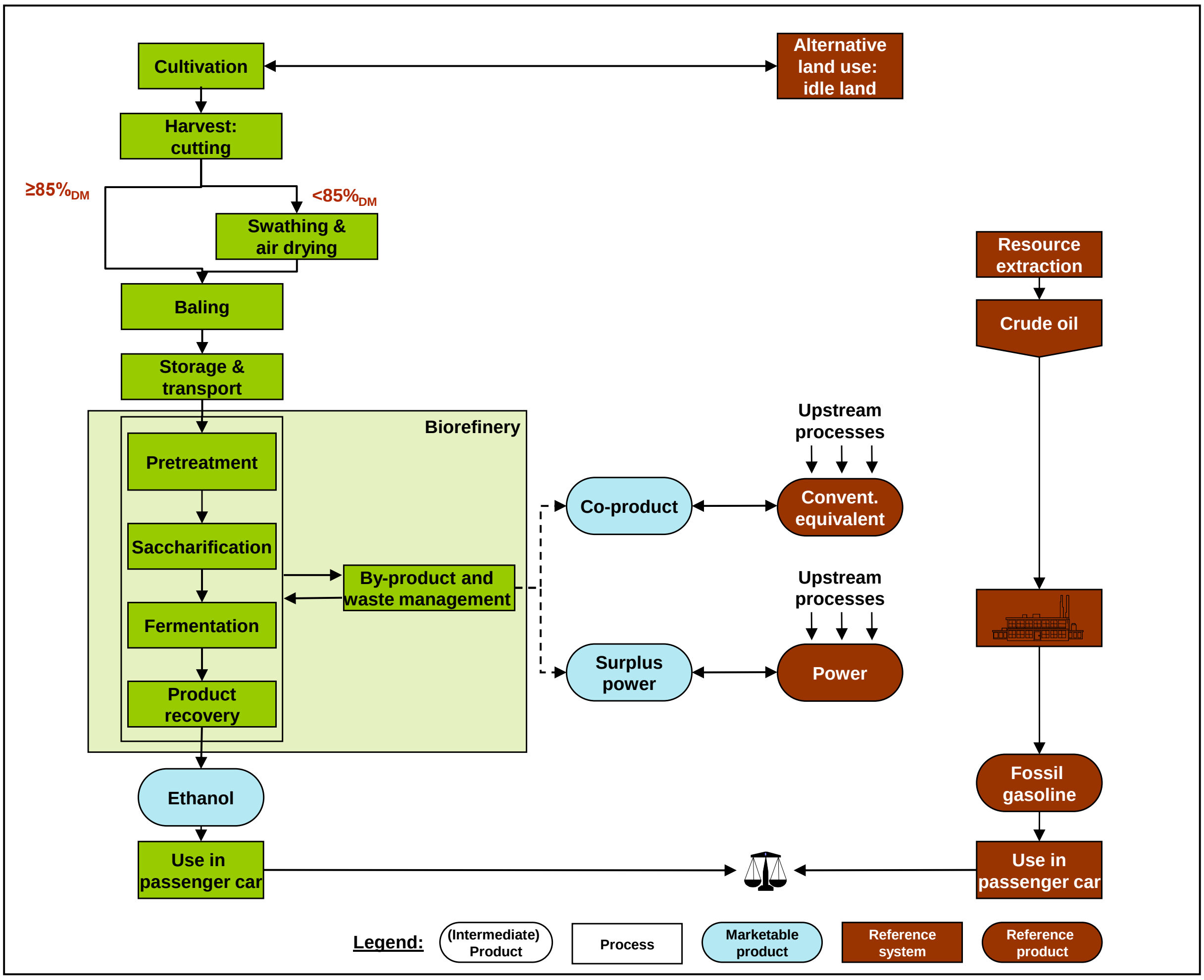

Figure 3: Simplified life cycle comparison for VC 3: ethanol from switchgrass via hydrolysis and fermentation.

Hydrolysis is a method that converts the starch of the biomass to sugars, which are then converted by microorganisms to ethanol in the fermentation process. Ethanol produced this way from lignocellulosic biomass is called 2nd generation ethanol whereas 1st generation ethanol production utilises biomass with high sugar and starch content absent of (ligno)cellulosic material. The most challenging part for the 2nd generation ethanol production is the efficient hydrolysis of the cellulosic part of the biomass to fermentable sugars. Lignin part of the biomass will not be converted in this process. Many efforts have been made in the field of cellulosic ethanol production resulting in development of various technologies and process configurations. Currently in Europe (November 2019), the only operational commercial 2nd generation ethanol plant is the Borregaard Industries AS plant in Norway producing 16 kton ethanol per year [Padella et al. 2019]. In the years 2013 – 2017, Beta

Renewables in Crescentino, Italy produced 40 kton ethanol per year from giant reed (*Arundo donax* L.), but due to ownerships change the plant has been idle. The new owner (Versalis) is planning to restart the production at the plant. In addition, St1 in Finland is planning to commission 40 kton ethanol (Cellunolix®) plant in 2020 [Padella et al. 2019].

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Figure 16 in chapter 7 (Annex, p. 39), shows a schematic presentation of ethanol production from switchgrass. This system description adapts the known designs of Borregaard, St1 and Versalis as well as information acquired from the US National Renewable Energy Laboratory (NREL) report [Mergner et al. 2013; Rødsrud 2017; Tao et al. 2014]. The main parts of the process are each marked with a number and are part of the cellulosic ethanol biorefinery. Biomass acquired in the upstream processes arrives in bales at the site. The bales will be broken down at the plant (de-baling) followed by a clean-up of the biomass from stones and possible other foreign particles. As lignocellulosic biomass is very stable towards decomposition by micro-organisms, a pre-treatment (1) of the material is required. Pre-treatment is a process that reduces the crystallinity of the cellulose and its polymerisation. Furthermore, it increases the surface area of the biomass, removes hemicellulose and breaks the lignin seal. These changes will make it possible to harvest the sugars in the hydrolysis. There are several pre-treatment methods available, but the most advanced are steam explosion (TRL 6-8), acid or alkali-pre-treatment (TRL 5-7) and hydrothermal pre-treatment (TRL 4-6) [Alberts et al. 2016]. Each pre-treatment method has their advantages and disadvantages depending on the feedstock used and the further process steps combined. From the ones mentioned above, steam explosion and acid hydrolysis are the most suitable candidates for a material such as switchgrass [Alberts et al. 2016]. Pre-treatment produces solid and liquid streams; hemicellulose is degraded to a C5 sugars solution and the solid part remaining is cellulose and lignin.

Followed by the pre-treatment, saccharification and fermentation takes place (2). The produced liquid and solid streams might need conditioning, for instance removal of acids formed in the pre-treatment to prevent inhibition of microorganisms in hydrolysis and fermentation. Cellulosic material will undergo saccharification in hydrolysis to release the sugars (C6) for fermentation. This is done with enzymes, which is also one of the major cost factors of the whole process. The enzymes can cost 30-50% of the whole ethanol production [Mergner et al. 2013]. Benefits of enzyme usage are operational as corrosion-durable materials are not needed and difficult separation steps can be avoided (*e.g.* acidic hydrolysis). In enzymatic hydrolysis the target is to produce as high concentration of sugars as possible without compromising the hydrolysis process. Enzyme inhibition is a challenge in the hydrolysis as side products can be formed that prevent further conversion of cellulose to sugars. Recycling of enzymes is necessary, and it should be considered to produce the enzymes at the plant itself to lower the costs.

Degradation of hemicellulose and cellulose material results in C5 and C6 sugars, pentoses and hexoses respectively. These sugars can be fermented to ethanol. However, one of the main factors in cellulosic ethanol production is that pentose fermenting microorganism are scarce. A second important factor is that the stream produced in earlier process parts contain also compounds that are inhibitory for the fermentation. Therefore, multiple options for fermentation exists depending on the previous process steps chosen. Some of them combine hydrolysis with fermentation, or have separate units for both, some ferment hexoses and pentoses separately or combine the both saccharification and fermentation. Fermentation sugar to alcohol produces also heat and CO_2. Furthermore, in this process part, yeast propagation is carried out for fast production of the yeast. Part of the sugars produced in hydrolysis can be used for this step.

The by-product streams formed are wastewater and lignin with other products that can be extractable from the stream (by-product and waste management, 4). The amount of lignin recovered depends on the composition of the biomass. Lignin is a high energy value product that can be burned for steam to be used in the plant itself and/or for electricity production. Other options for lignin utilisation are gasification for syngas production or pyrolysis for pyrolysis oil production. Both these intermediary energy carries can be further refined to value-added products like hydrocarbons. Wastewater contains organics from the process, such as acetic acid, furfural, HMF, and residual sugars. It can be purified in multiple ways, *e.g.* anaerobic digestion to produce biogas (CH_4).

By-products could also be utilised further to marketable chemicals (5). Part of these chemicals originate from the cellulose/hemicellulose part of the biomass and some are lignin derived chemicals. Naturally, the quantities are dependent on the original biomass composition and process conditions applied. Borregaard is producing vanillin as a by-product in the ethanol biorefinery and mannose on a pilot scale [Rødsrud 2017]. St1 can produce vinasse, furfural and turpentine as by-products from ethanol from pine saw dust [Yamamoto 2018]. Possible future products that could be marketed are, for instance, higher alcohols, diols, acids and furthermore from lignin, aromatics and phenols extracted from lignin [Mergner et al. 2013].

Interim appraisal of VC 3:

- The pre-treatment of biomass is challenging and most demonstration and commercial plants are facing problems with this step. Some of them even had to shut down.
- Due to economies of scale, this value chain needs to be established at fairly large scale, corresponding to 250,000 tonnes dry matter biomass input.
- The co-products arising from the biorefinery are not fully clear yet and still need to be defined.

2.4 VC 4: Biotumen from willow (via pyrolysis)

This value chain describes the conversion of willow (*Salix spp.* L.) by pyrolysis to form biotumen, which can be replace fossil-based bitumen in roofing material. This life cycle is compared to conventional ways of providing the same products or services (Figure 4).

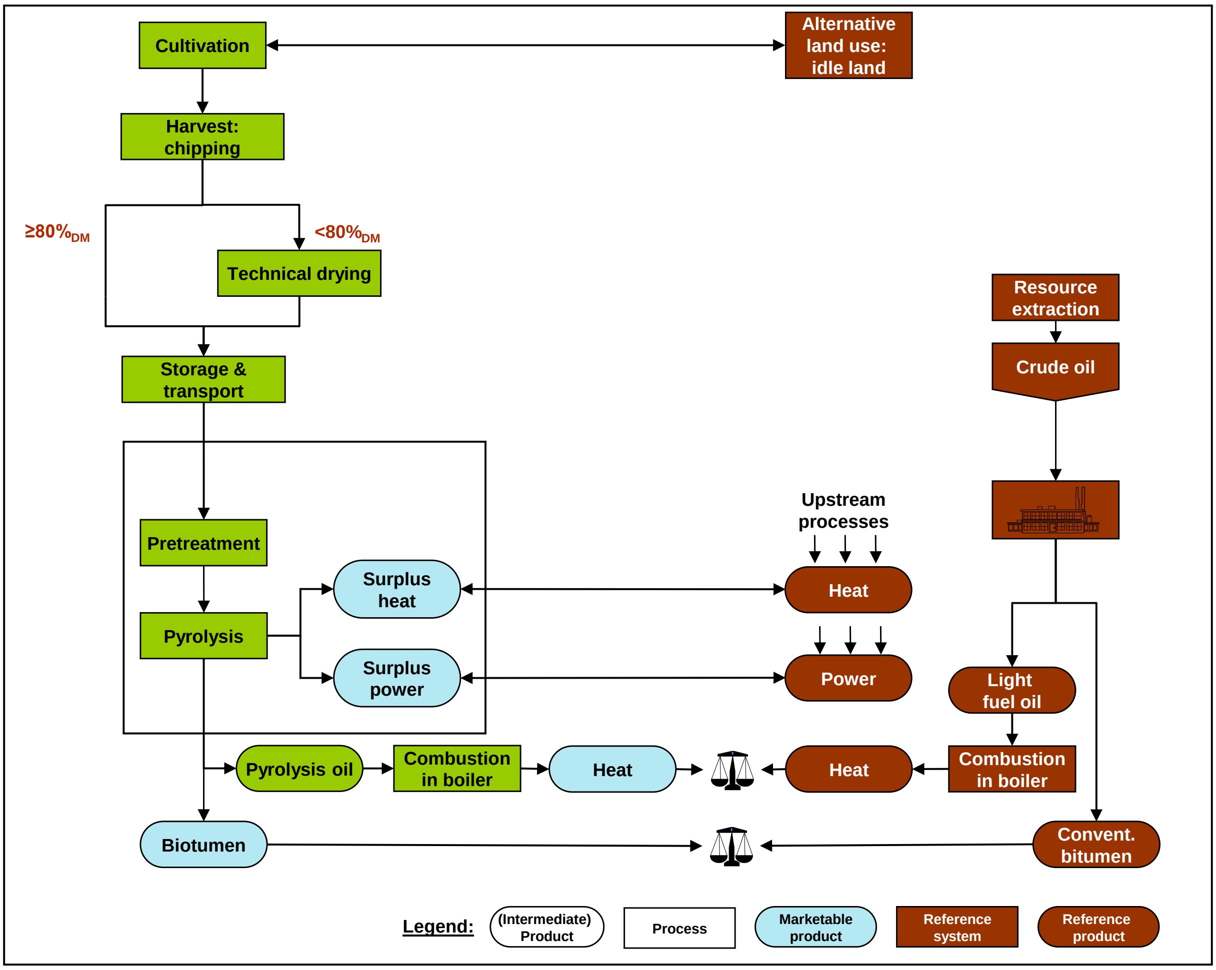

Figure 4: Simplified life cycle comparison for VC 4: biotumen from willow via pyrolysis.

In order to obtain biotumen, the willow undergoes pyrolysis, identical to the value chain described in chapter 2.1. The produced pyrolysis oil is then partly separated into 2 fractions, sugars and lignin fraction. The lignin fraction can then be used in the roofing application and the sugar fraction can be mixed with the remaining oil.

A detailed value chain description is found in Figure 17 in chapter 7 (Annex, p. 40). As can be seen in Figure 17, willow undergoes a pre-treatment before the pyrolysis similar to the Miscanthus in value chain 1. Here, a sizing (1) and drying (2) step is required as well, which can be powered from the energy obtained from the pyrolysis step (3). However, after the pyrolysis process the value chain changes from the process shown in Figure 1. Rather than having the pyrolysis oil as a final output, the pyrolysis oil is separated into fractions. This fractionation (4) results in two main fractions, a pyrolytic sugar fraction and a pyrolytic lignin fraction. Since the pyrolytic sugars will be mixed back with the pyrolysis oil (5), the fractionation is performed at the pyrolysis factory.

The pyrolytic sugar fraction contains the products from the cellulosic material of the biomass and could be applied as wood preservative treatment or as a foundry resin. However, in order to focus the value chain on a single product, the pyrolytic sugar fraction is mixed back with the pyrolysis oil, which is then used for the production of industrial heat.

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The pyrolytic lignin contains the lignin parts of the biomass. This fraction contains a lot of water, which needs to be removed in a drying step before the final product is obtained. The structure of the lignin, compared to lignin obtained from for example the Kraft process, is different due to the pyrolysis step. This makes the material more suitable in an application such as a roofing material. The lignin can be mixed with standard roofing material ingredients, replacing part of the fossil-based bitumen.

Interim appraisal of VC 4:

- The use phase and end-of-life treatment of the roofing material still need to be defined.

2.5 VC 5: Organic acids from safflower (via oxidative cleavage)

This value chain describes the conversion of high-oleic safflower (*Carthamus tinctorius* L.) by oxidative cleavage to form organic acids. This life cycle is compared to conventional ways of providing the same products or services (Figure 5).

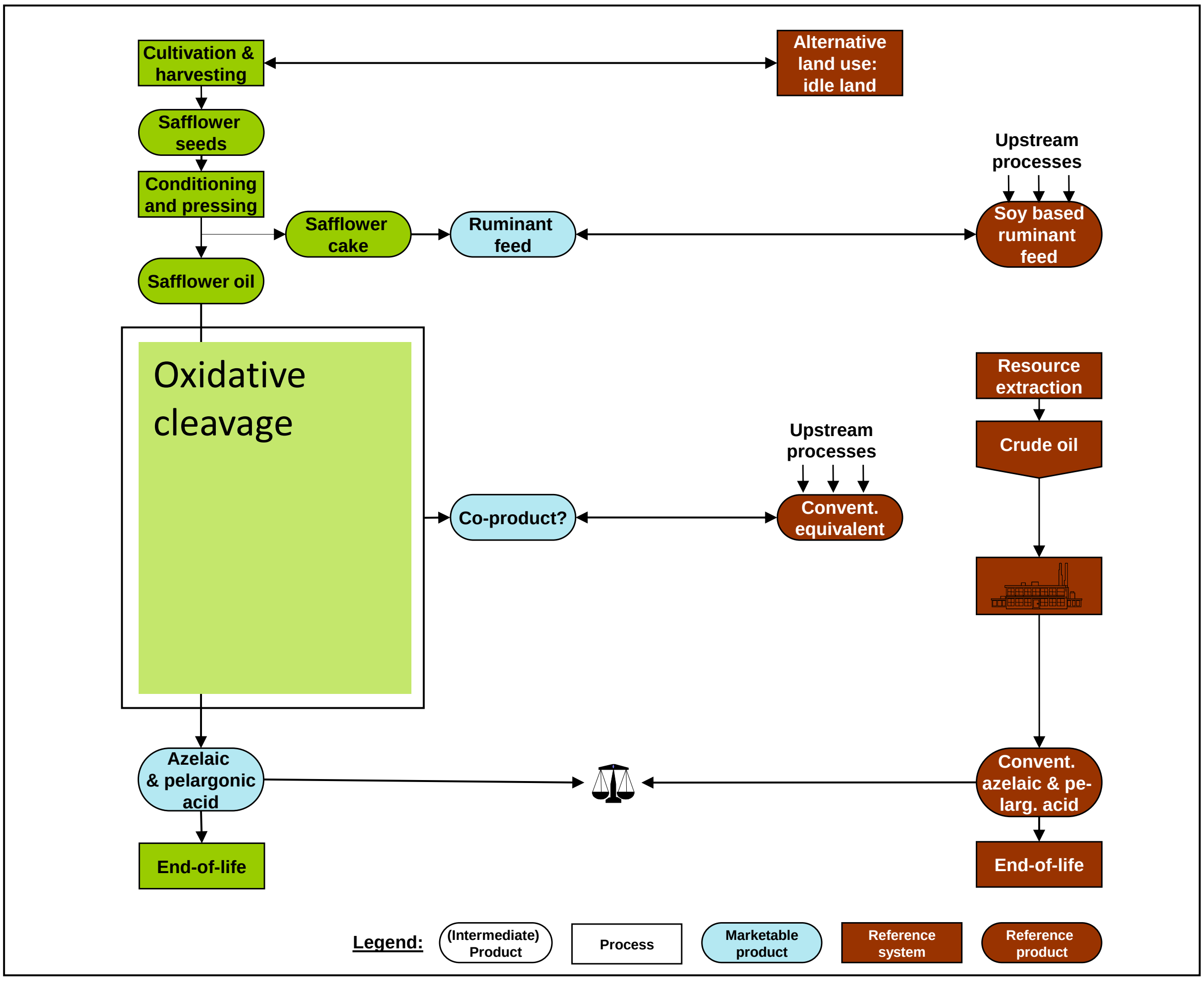

Figure 5: Life cycle comparison for VC 5: organic acids from safflower via oxidative cleavage.

In the following, for the time being only the provision of safflower is described.

Cultivation

Safflower belongs to the aster family (Asteraceae) and is a branching thistle-like herbaceous annual (spring or winter) annual plant, with numerous spines on leaves and bracts. The growing period is 110 to 150 days. The crop is grown for local use as an oilseed or a food colorant. Two safflower varieties are distinguished: a high-oleic acid variety (74 – 80%) and a high-linoleic acid variety (70 – 80%). The crop is adapted to semiarid regions and marginal conditions, however, it cannot survive on soils with standing water even for few hours when the air temperature is above 20ºC. During the rosette stage, the young plants can survive low temperatures (-7°C) but during elongation period the plant is sensitive to cold [Alexopoulou et al. 2018].

Harvesting

Safflower can be harvested with conventional combines equipped with a standard header (grain platform). Preferably, the moisture content at harvest should be <10%; if higher, the crop can be windrowed and threshed after the seeds are dry enough [Pari & Scarfone 2018]. Appropriate measures (such as small-meshed screen enclosures and blowing out radiators with air once or twice daily) should be taken to prevent overheating of the combine (fire hazard) due to fuzz from the seed heads which may clog radiators and air intakes.

Logistics, pre-treatment, oil extraction and refining

The oil content of the seeds is 34 – 36% and the moisture content should be < 8% for safe long-term storage, i.e. technical drying might be neccessary. The protein content of the seed meal is 24% with a high fibre content. Meal form decorticated seeds (most of hulls removed) has about 40% protein content with a reduced fibre content. Safflower meal is used as a protein supplement for livestock.

Interim appraisal of VC 5:

- This value chain still needs to be defined.

2.6 VC 6: Methyl decenoate from Camelina (via metathesis)

This value chain describes the conversion of high-oleic camelina (*Camelina sativa* (L.) CRANTZ) to methyl decenoate via metathesis. This life cycle is compared to conventional ways of providing the same products or services (Figure 6).

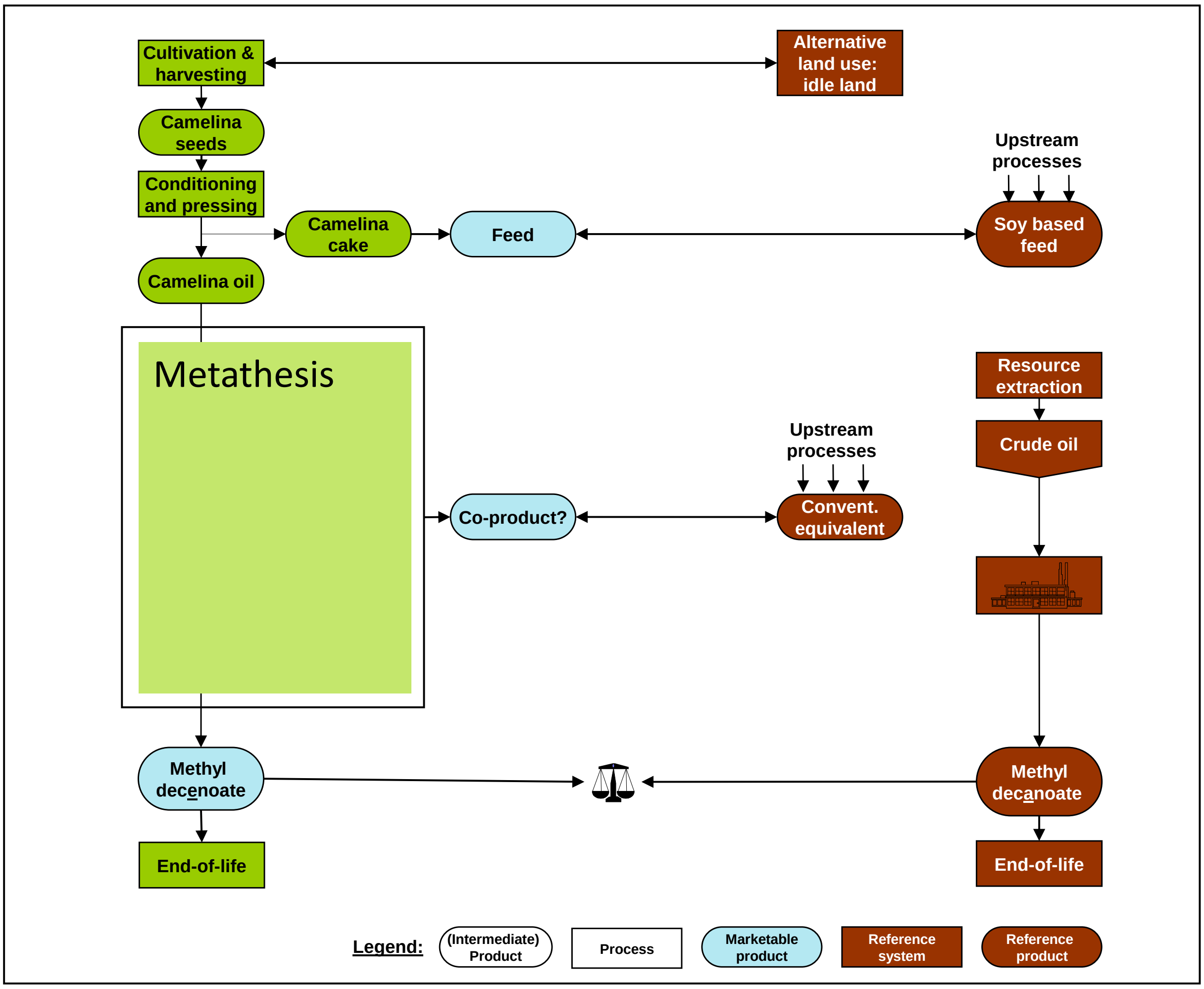

Figure 6: Life cycle comparison for VC 6: methyl decenoate from Camelina via metathesis.

In the following, for the time being only the provision of Camelina oil seeds is described.

Cultivation

Camelina is an annual oil crop which can be grown as a winter crop but in mild climates such as the Mediterranean area also as a spring crop. It belongs to the same family as rapeseed (Brassicaceae), has a short vegetation period (90-120 days) and is specifically tolerant to dry soils.

Minor establishment efforts are required (little seedbed preparation, low sowing depth, no herbicide application). Also, Camelina shows comparatively low nutritional requirements. Due to its drought and heat tolerance, little/no irrigation water has to be applied [Alexopoulou et al. 2018].

Due to its specifically short rotation period, Camelina is suitable for double cropping, i.e. it can be integrated into a crop rotation without displacement of other crops or decreases in production volumes thereof. To maintain comparability among investigated value chains, this scenario will be assessed as part of an excursus only.

Harvesting

Camelina can be harvested with conventional combines and is usually direct-combined standing but can be swathed and then combined with similar seed yields. The harvesting should start when 50-75% of the pods are dried [Pari & Scarfone 2018]. The harvested seeds have a moisture content of approximately 13%. Straw including leaves and Camelina pods remain on the field and are ploughed in. They maintain soil fertility and thus substitute for conventional mineral fertilisers. Seed yields range from 1-3 t/ha. A detailed table including all data used for the sustainability assessment will be given in MS6.3.

Logistics, pre-treatment, oil extraction and refining

Camelina seeds are transported to a processing/storage facility. There, a cleaning step is necessary to remove stalks, leaves and pods which are unintendedly among the seeds. The residues are set to be reapplied to agricultural fields to maintain soil fertility. In addition, pre-treatment encompasses technical drying of the seeds until they have a moisture content of approximately 9%.

Oil extraction is conducted by means of pressing, i.e. solvent extraction is not applied. Cake is obtained as a co-product from pressing. It is set to be used as animal feed, e.g. for cattle. Due to the anti-nutritional compounds, Camelina cake should represent only a minor fraction of the diet. It is set to substitute for soy-based conventional feed. After pressing, the oil is refined. It can then be stored or directly be transported to the conversion unit.

Interim appraisal of VC 6:

- The biomass conversion part of this value chain still needs to be defined.

2.7 VC 7: Diacids from castor oil (via several oleochemical processes)

This value chain describes the conversion of castor (*Ricinus communis* L.) to undecanedioic acid via several oleochemical processes (hydrogenation, dehydration and oxidative cleavage). This life cycle is compared to conventional ways of providing the same products or services (Figure 7).

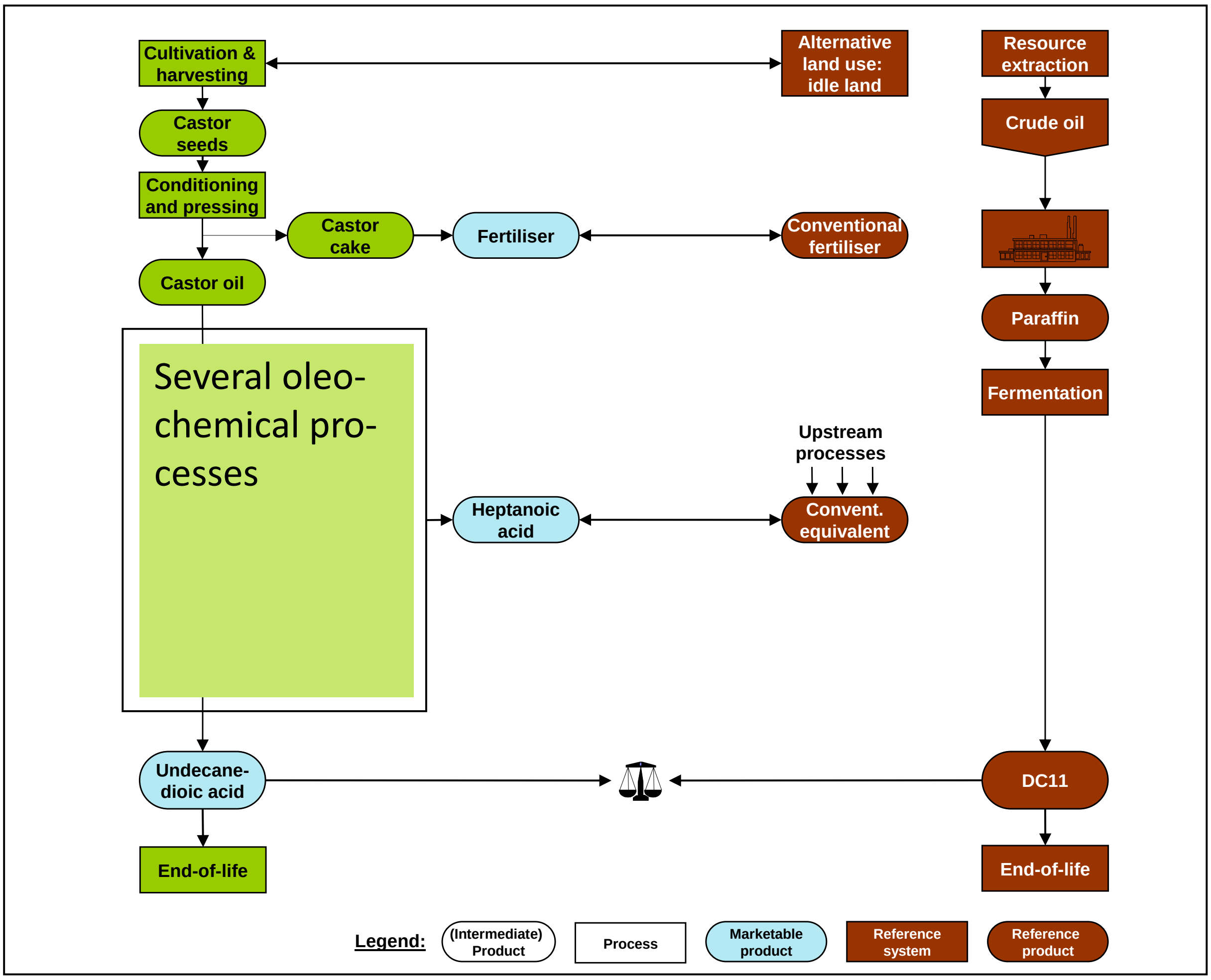

Figure 7: Life cycle comparison for VC 7: diacids from castor oil.

In the following, for the time being only the provision of castor bean is described.

Cultivation

Castor belongs to the spurge family (Euphorbiaceae) that is cultivated both as an annual and perennial crop. The crop varies greatly in its growth (80 cm to 3 m high) and appearance (shape, colour). The annual growing cycle depends on the cultivation site and can be up to 180 days when it is grown in India and between 120 and 150 days in the Mediterranean region. The crop is quit tolerant to marginal conditions, both in terms of climate (it is quite drought-tolerant) and soil (moderately fertile soils are preferred). However, a frost free climate is mandatory for the crop [Alexopoulou et al. 2018].

Harvesting

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The harvesting mechanisation of castor oil is still an unresolved problem. The problem is mainly related to the fact that the traditional varieties are very tall, have several racemes, and capsules ripening over a period of 2 months, which makes 2-3 manual harvesting per season necessary. Breeders worldwide are developing new varieties with characteristics that permit the introduction of harvesting mechanisation. Once this is achieved, either conventional combines equipped with a modified maize header (to prevent seed losses) or purpose-built castor headers (as announced by Evofuel Ltd. in 2018) could be used. However, since castor beans are very susceptible to cracking and splitting during harvest, adjustment of the combine (e.g. cylinder speed and cylinder-concave clearance) is very important [Pari & Scarfone 2018].

Logistics, pre-treatment, oil extraction and refining

Castor beans are transported to a processing/storage facility. In case of manual harvest, a de-hulling step is necessary. The empty capsules (~1/3 of the harvested biomass) are briquetted and used for bioenergy purposes. In case of mechanical harvest (using a combine), the empty capsules remain on the field and are ploughed in. They maintain soil fertility and thus substitute for conventional mineral fertilisers. Mechanical oil extraction is conducted and yields 30% of oil. The protein-rich press cake cannot be used as animal feed since it contains several toxic compounds. Therefore, it is used as fertiliser.

Interim appraisal of VC 7:

- This value chain still needs to be defined.

2.8 VC 8: Insulation material from hemp

This value chain describes the production of an insulation material from industrial hemp (*Cannabis sativa* L.). This life cycle is compared to conventional ways of providing the same products or services (Figure 8).
Industrial hemp (*Cannabis sativa* L.) is an interesting multipurpose crop with a multitude of applications for the fibres, the by-products shives and dust as well as the seeds (for food or bird feed) and pharmaceuticals (CBD and THC).

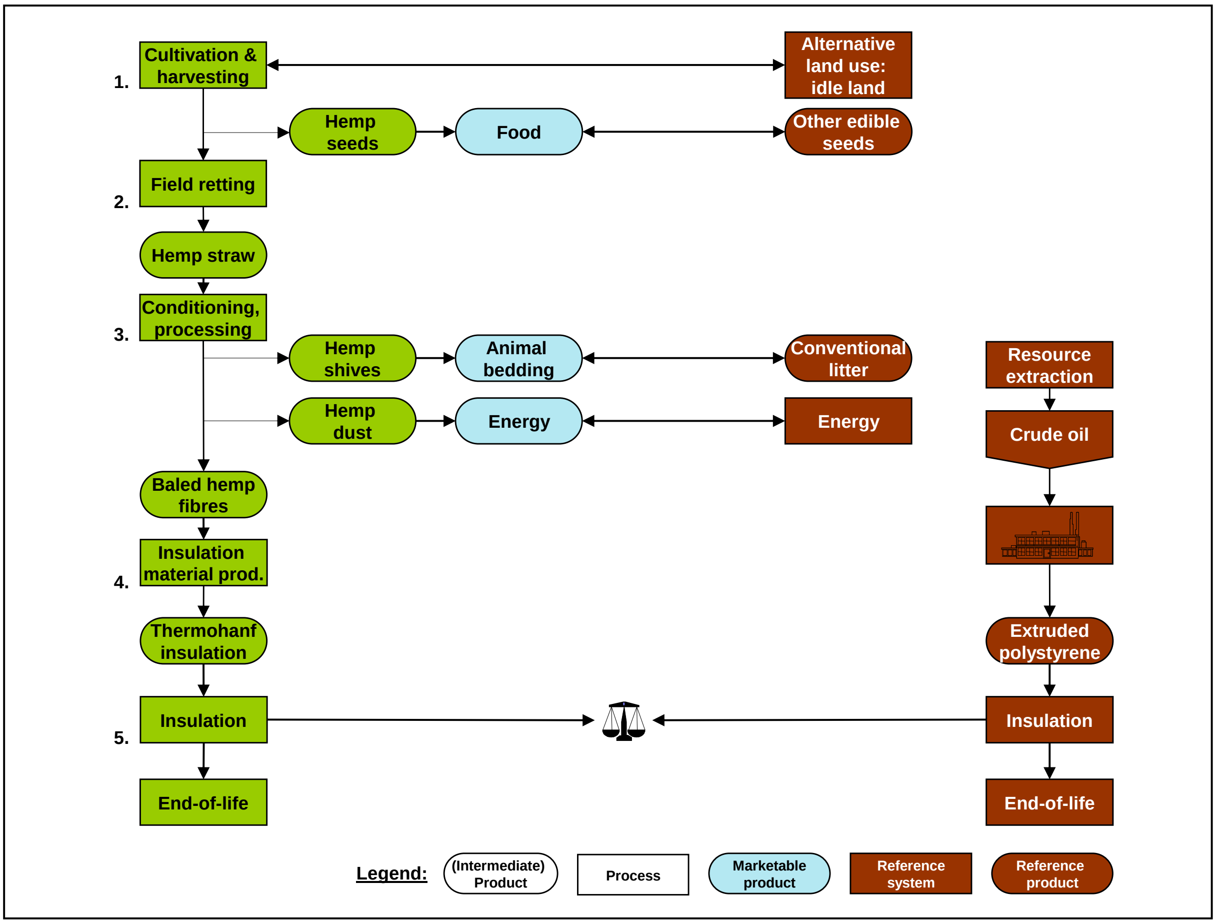

Figure 8: Life cycle comparison for VC 8: insulation material from industrial hemp.

Insulation accounts for about 25% of fibre applications. One of the major commercially available hemp insulation materials is THERMO HANF®, produced by the company Thermo Natur, in Nördlingen, Germany. This product is a commercially available hemp-based insulation roll which provides thermal, acoustic, impact and fire resistance (www.thermo-natur.de). Production volumes amounted to 100,000 m^3 in 2007 (newer data is likely available but need to be researched).
This specific type of insulation material is most suitable for the project because a lot of data exist from different studies, including LCA inventory data [Bos 2010; Spirinchx et al. 2013]. In the frame of the MultiHemp project (FP7-311849), nova-Institute performed an environmental hotspot analysis between THERMO HANF® and an innovative hemp blow-in insulation material [de Beus & Piotrowski 2017].

The life cycle comparison for the hemp value chain is displayed in Figure 8. It is assumed that hemp is cultivated for the dual use of the straw for fibres and the seeds for food or feed. Additional, separated harvest of the leaves for extraction of pharmaceuticals or selling as tea is feasible but not representative for hemp cultivation in Europe.

After the hemp cultivation and harvest (1), the hemp straw is left on the field for retting (2), which separates the bast fibres from the shives. This step is essential and unique in the hemp value chain. The processing of hemp straw to obtain hemp fibres (3) is typically done in Europe in the so-called Total Fibre Line, which produces as by-products hemp shives and dust.

The shives as a by-product of the fibre production can be 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. Since animal bedding is still the largest market for the shives with more than 60%, this application is shown in Figure 8. The remaining fine particles (dust) after the separation of fibres and shives are mainly pressed into briquettes and used for incineration.

The hemp fibres are then baled and transported to the insulation material production site. The production process for THERMO HANF® (4) consists of mixing long hemp fibres with BICO-PES fibres, layering this mix in a carding and cross-laying machine and bonding it in a thermobonding oven.

The conventional reference product for this product could be glass or rock wool insulation material or alternatively an insulation material from Expanded polystyrene (EPS), Extruded polystyrene (XPS) or Polyurethane (PUR).

Interim appraisal of VC 8:

- The biomass conversion part of this value chain is fully defined.

2.9 VC 9: Biogas/biomethane from sorghum

This value chain describes the production of biogas from sorghum (*Sorghum bicolor* (L.) MOENCH) as a substrate. This life cycle is compared to conventional ways of providing the same products or services (Figure 9).

Sorghum bicolor, also known as great millet, durra or milo, but commonly called sorghum is a grass species, which is native to Africa and is now widely cultivated in tropical and subtropical regions. The whole crop can be processed and converted into biogas after harvesting.

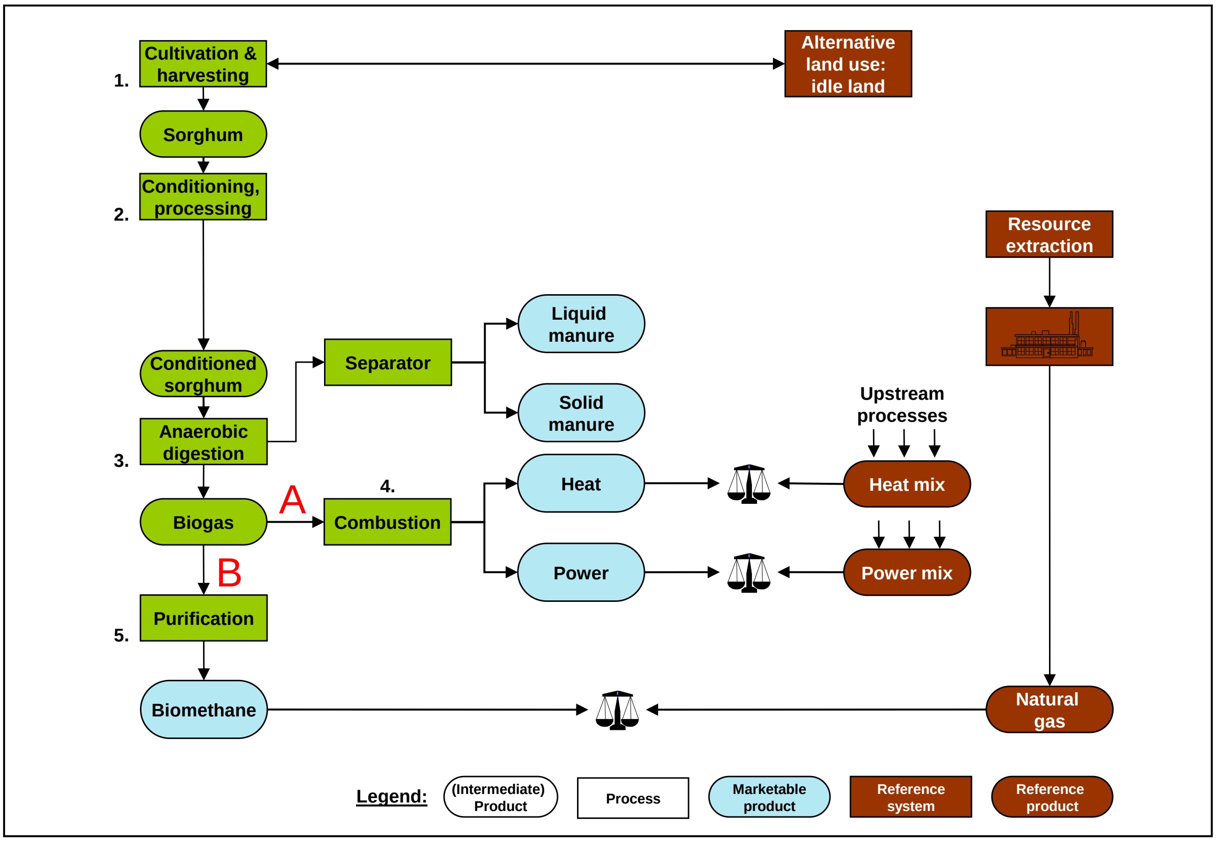

Figure 9: Life cycle comparison for VC 9: biogas/biomethane from sorghum.

Most commonly sorghum is grown for its grain, which is used for food, animal feed and ethanol production. As a whole crop it can be used as substrate for biogas/methane production and achieves comparable yields to the conventional substrates e.g. maize [Herrmann et al. 2016; Mursec et al. 2009; Stolzenburg & Monkos 2012]. Crops such as maize, wheat and sorghum are excellent raw materials for the production of biogas and valuable by-products. The dry matter yield of sorghum is dependent on cultivar and environment and ranges between 10 – 25 t/ha [Zeise & Fritz 2011].

The crop can be harvested with a standard forage harvester, which makes it easy to include it into an existing maize production system. The transportation from field to plant does therefore not pose a problem due to the available machines (1) [Stolzenburg & Monkos 2012].

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After harvesting and chopping, the pre-treatment with water and beneficial microorganisms is conducted (2). The whole mixture is then pumped into the fermenter where the anaerobic digestion takes place. In the fermenter a great number of bacteria decompose the organic matter. The process happens at the absence of oxygen and in temperature-controlled environment to achieve the optimal activity of the microorganisms resulting in maximum output. Products of the process are biogas, heat, and digestate as natural fertiliser.

Anaerobic digestion is a complex process that takes place in four biological and chemical stages i.e. hydrolysis, acidogenesis, acetogenesis and methanogenesis. The individual degradation steps are carried out by different consortia of microorganisms, which partly stand in syntrophic interrelation and place different requirements on the environment. Most of the bacteria are strict anaerobes [Raja & Wazir 2017].

Anaerobic digestion is most commonly used to convert organic material into biogas and is carried out all over the world. The environment of the fermenter needs to be strictly controlled to result in maximum gas output. Mostly, it is dependent on oxygen, temperature, pH level, nutrients and toxic materials [FNR 2016; Raja & Wazir 2017].

After releasing the gas out of the fermenter, it can either be used directly to produce electricity and heat (4.) or be further purified to biomethane, which resembles conventional natural gas and can thus be fed into the natural gas grid (5.).

Due to the high investments, upgrading of biogas to methane only becomes profitable at a methane production of 2-4 mln m^3 annually [own calculation based on Daniel-Gromke et al. 2017]. Based on a crop yield of 15 t/ha dry matter, as stated in most studies, around 670 ha of sorghum would be required to gain a profitable methane yield of 3 mln m^3. Higher yields due to an accurate choice of the cultivar and the optimal adaption to the location are possible and already documented [Stolzenburg & Monkos 2012]. Based on the assumption to grow sorghum on marginal lands it can also substitute parts of the existing supply chain or act as extension for the present production system.

Interim appraisal of VC 9:

- The biomass conversion part of this value chain is fully defined.

2.10 VC 10: Adhesives from lupin

This value chain describes the conversion of Andean lupin (*Lupinus mutabilis* SWEET) to micellar lupin protein (MLP), which can be used as a food packaging adhesive. This life cycle is compared to conventional ways of providing the same products or services (Figure 10).

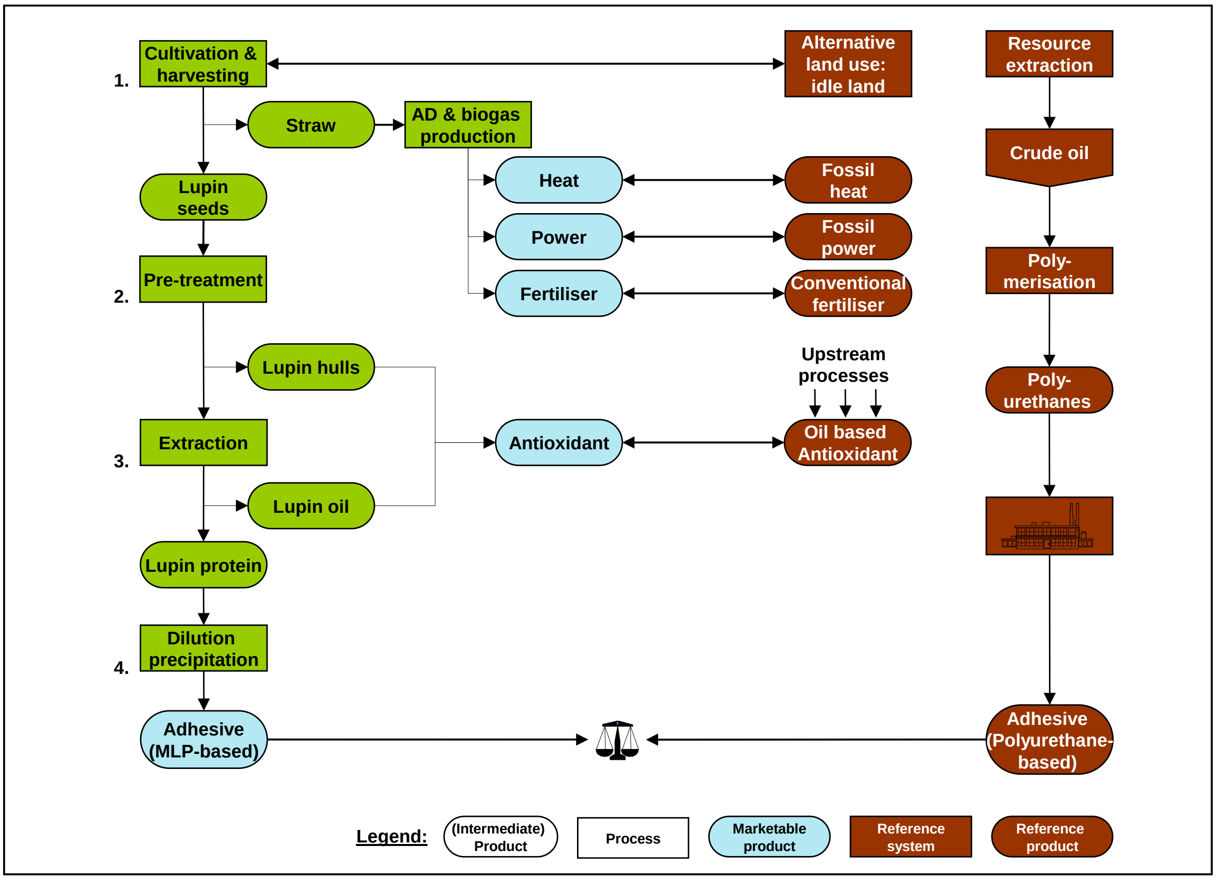

Figure 10: Life cycle comparison for VC 10: adhesives from lupin.

The lupin adhesive stands out as a promising alternative to petrol-based adhesives [Eibl et al. 2018]. In fact, micellar lupin protein (MLP) showed a great potential as functional laminating adhesive due to its high adhesion and oxygen-barrier features. Formulations of MLP are used as laminating adhesive between various elements (e.g. high-density polyethylene foil and paper, coating for PET foil), being a valid alternative to the commonly used polyurethane-based adhesives [Eibl et al. 2018], whose raw materials are in most of the cases petroleum-based [Zia et al. 2007]. A detailed value chain description is shown in Figure 10.

From the cultivation of lupin on marginal lands (1), biomass is fed to the process. First of all, lupin seeds have to be separated from the vegetative part (mainly straw) of the harvested biomass. Lupin straw can be used as a as a valuable source for anaerobic digestion and therefore power and heat (from CHP) and fertiliser (from digestate) production [Corré & Conijn 2016; Dubrovskis et al. 2011; Kintl et al. 2019].

Prior to further proceed with the protein extraction step (3), lupin seeds have to be pre-treated (2). The pre-treatment phase is crucial to remove lupin hulls, via cracking, and to create extruded flakes, via extrusion. According to Lampart-Szczapa et al. [2003], lupin hulls showed interesting antioxidant properties, that might qualify this by-products as high value side stream components. Similar antioxidant properties have also been found for lupin oils, by-product of the protein extraction step (3).

Various techniques can be carried out in the extraction phase (3), such as solvent, aqueous and dry extraction. However, because of the low oil content in the seed (e.g. compared to soybean), solvent extraction of lupin is not economically advantageous. Thus, aqueous extraction processing (AEP), allowing simultaneous extraction of the oil and protein from oilseeds, could be an appropriate alternative [Jung 2009]. According to the same study, the adoption of enzyme-assisted AEP (EAEP) yield considerable amounts of oil, protein and cream + free oil yields. Alternatively, dry extraction can be implemented. This technique involves dry fractionation by combining milling and air classification [Pelgrom et al. 2014] or electrostatic separation [Wang et al. 2016], consuming no water and low energy and producing functional protein enriched fractions.

Last, micellar lupin protein (MLP) isolate, the laminating adhesive, is obtained by dilution precipitation (4). Dissociation reactions occur after abrupt dilution, leading to the orientation of hydrophilic groups to the protein surface. This change in protein structure results in globular, micelle-like protein with a smooth and fat like, but very sticky texture. As mentioned, due to their polarity proteins in general exhibit excellent barrier properties against oxygen [Eibl et al. 2018].

Interim appraisal of VC 10:

- The biomass conversion part of this value chain is fully defined.

3 Conclusions

This ‘Report on system description of selected value chains’ (Deliverable D 6.2) contains detailed qualitative system descriptions of those ten value chains that were selected for in-depth analysis within the sustainability assessment performed under WP 6. It lays an important foundation for the further work in tasks 6.2 to 6.6 and will be complemented by the full quantitative system description (in the form of mass & energy balances) in M36.

It is important to note that this report represents the status as of 31 January 2019. It is not fully completed yet and therefore still has to be regarded as a living document because i) some of the value chains could not be completed yet and ii) more questions might arise and create a need for adaptations once the LCA and TEA are under way. We therefore expect this report to be updated by March 2020.

4 Abbreviations

CBD	Cannabidiol
CHP	Combined heat and power
D X.Y	Deliverable
DFB	dual fluidised bed
dLUC	Direct land use change
EoL	End-of-life
EPS	Expanded polystyrene
GHG	Greenhouse gas
HMF	Hydroxymethylfurfural
iLUC	Indirect land use change
LCA	Life cycle assessment
MLP	Micellar lupin protein
PET	Polyethylene terephthalate
PUR	Polyurethane
SNG	Synthetic/substitute natural gas
THC	Tetrahydrocannabinol
TRL	Technology readiness level
VC	Value chain
WGSR	Water gas shift reactor
WP	Work package
XPS	Extruded polystyrene

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7 Annex

7.1 Details on biomass provision

7.1.1 Camelina

Camelina [*Camelina sativa* (L.) CRANTZ], Brassicaceae family] is an annual winter and/or spring oilseed crop with plant height varying from 30 to 120 cm. In general, the crop is best adapted to cool temperate and semi-arid climates. It grows very well on well-drained light (sandy), medium (loamy) and heavy (clay) soils. Compared to other oilseed crops, like rapeseed and sunflower, camelina shows better performance in semi-arid regions due to its drought and frost tolerance. Camelina can survive conditions of dry soil, low rainfall and frost due to its short growing season (90 to 120 days). It can be grown well in nutritionally poor soil.

It was studied in detail in the view of COSMOS project (H2020, completed on 31st of August 2019) as an important oilseed crop for Europe. In Figure 11 the cultivation of camelina on large scale field trials in Poland is presented.

Figure 11: View of camelina trial in Poland (Source: UWM; COSMOS project)

It should be pointed out the camelina had been tested on large field trials in several sites in Spain started from 2012 in the view of ITAKA project. For the period 2012-2018, a total area of 20.000 ha has been cultivated on several dry sites in Spain by Camelina Company.

For its sowing a minimal seedbed preparation is needed. There is no registered herbicide for camelina. It is recommended 4 to 6 kg/ha seeds to be applied at sowing (400-500 seeds/m^2) and the soil depth to be between 6 and 13 mm. When it is grown in South Europe (Figure 12) it can be cultivated both as winter or spring crop, while when it is grown in central/north Europe it is recommended to be grown as spring crop. Regarding the nitrogen fertilization 75 kg N/ha are needed to cover the crops needs.

Figure 12: View of camelina field ready to be harvested (Source: CRES, COSMOS project)

The seed yields in COSMOS project varied from 1 to 3 t/ha (mean yields of 2 t/ha) and with oil content from 38 to 42%. 90% of the camelina oil contains unsaturated fatty acids, including a 30-40% fraction of alpha linolenic acid, another 15-25% fraction of linoleic acid, about a 15% fraction of oleic acid and around 15% eicosenoic acid.
Camelina can be harvested with unmodified combines and is usually direct-combined standing but can be swathed and then combined with similar seed yields. The harvesting should start when 75% of silicles are dried. Mature pods are dark tan or brown. The combine settings should be similar to those used for canola or alfalfa seed, but the combine fan speed should be reduced to minimize seed losses. Small-opening combine screens designed for alfalfa seed are effective in separating camelina seed and hulls. Unlike other members of the mustard family, camelina pods hold their seeds tightly, and seed shattering is not generally a problem. Most camelina cultivars are resistant to shattering.

7.1.2 Castor

Castor (*Ricinus communis* L., Euphorbiaceae family) is a valuable annual spring oilseed crop (around 80 cm high) with a growing cycle between 120 and 150 days when it is grown in the Mediterranean region. Its panicles are racemes up 40 cm long that produce 80 to 120 capsules each (3 seeds per capsule). In Figure 13 castor is presented at several stages of growth (source: CRES).

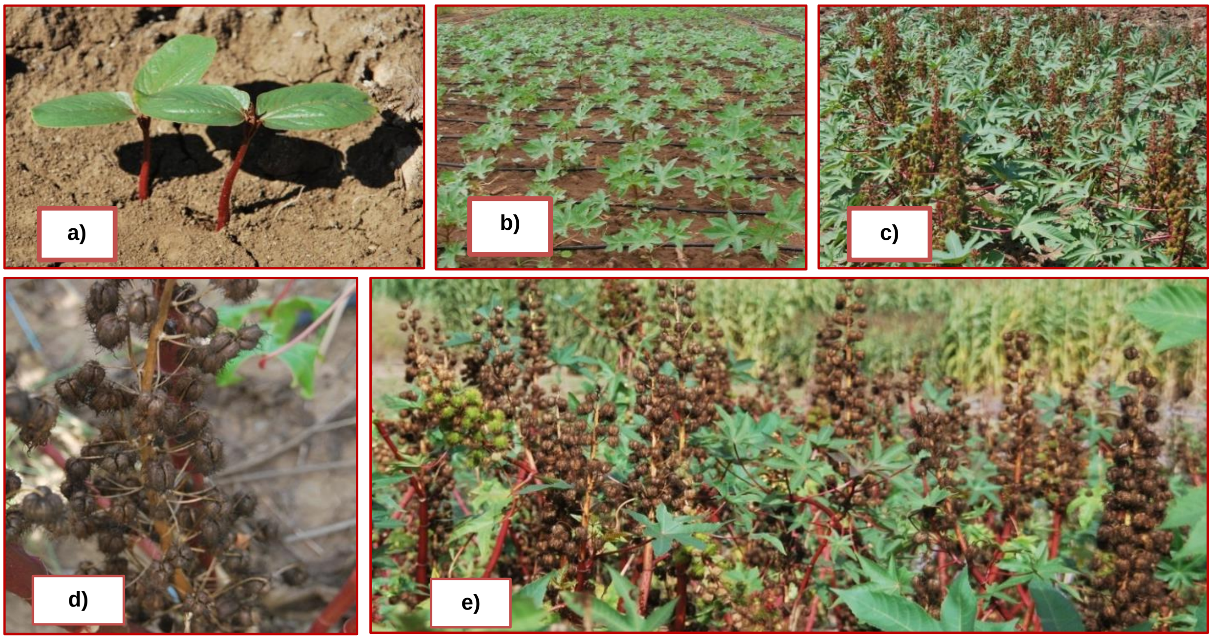

Figure 13: View of castor at: a) emergence, b) early stages of growth, c) full flowering, d, e) mature racemes (Source: CRES, Greece)

Castor is being reported as a crop with tolerance to insects and diseases, nematodes, drought and heat, high and low pH, poor soil and slope. It is commercially grown in India, China, and Brazil. Currently, more than 3 million hectares of land is planted with castor around the world. Although the crop can be cultivated in the Mediterranean region, it is found only on experimental and demonstrative fields. It should be pointed out that Europe is one of the main importers of castor oil.

The crop can be grown on low rainfall and fertility conditions and it is considered appropriate for drying farming. Castor is a hardy crop and can be grown in a wide range of climates of warm regions with a rainfall of 250-750 mm. It performs best in moderate temperature (20-26 °C) with low relative humidity and clear sunny days throughout the crop season. Areas with temperature higher than 40 °C or lower than15 °C are not conducive for castor cultivation. A frost free climate is mandatory for the crop. It is a drought resistant crop due to its tap root and due to light reflecting characteristics of its stems and leaves that reduce heat load and improve survival under moisture stress. The crop can be grown successfully on most of the soils apart from heavy clay and poorly drained soils. Moreover, soils with low water holding capacity like the sandy soils are also not appropriate for castor cultivation. Soils with pH > 9.0 or < 4.0 should be avoided. Moderately fertile soils are preferred as high fertility induces excess vegetative growth, prolonged flowering and delay the maturity, leading finally to poor yields.

The last years a number of hybrids have been developed that are short with increased yields (up to 5 t/ha seeds, usually vary from 2 to 5 t/ha seeds and oil content 48 to 50%), uniform seed maturity, increased tolerance to pests and diseases and increased performance to mechanical harvest.

A deep ploughing is necessary, for weed control and conserving moisture followed by harrowing. It has been recommended to sow in rows with 1 m distance between the rows and 25 cm within the rows; 15 kg seeds/ha for sowing. In general, it can be said that the distances between the rows should be large varying from 60 to 100 cm, while within the rows should be between 15 and 60 cm (12-15 kg seeds per ha). The soil depth at sowing varies according to the soil type from 6 to 10 cm. Shallow soil depth at sowing (6 to 8 cm) is recommended in heavy soils. The soil temperature at sowing should be higher than 12 °C.

Castor exhausts the soil quickly. It has been estimated that for the production of 2000 kg seeds/ha is removed from the soil: 80 kg/ha N, 18 kg/ha P_2O_5, 32 kg/ha of K_2O, 13 kg/ha CaO, and 10 kg/ha of MgO.

In South Europe a period of 120 -150 days is needed for the crop to reach maturity (first half of September). The harvesting should be done when the capsules turn to yellow-brown. The seeds do not mature at the same time and in most of the cases the plantations should be sprayed in order the growth to be stopped and the harvesting to be scheduled. Castor seeds are very susceptible to cracking and splitting at the maturity stage. Thus, adjustment to the combine cylinder speed and cylinder-concave clearance is very important. Usually, a low cylinder speed and wide cylinder concave clearance are recommended. Combine operators should frequently inspect harvested beans for breakage. At the harvest seed losses up to 30% have been recorded. The harvesting of castor is an issue that needs further investigation.

7.2 Details on biomass conversion

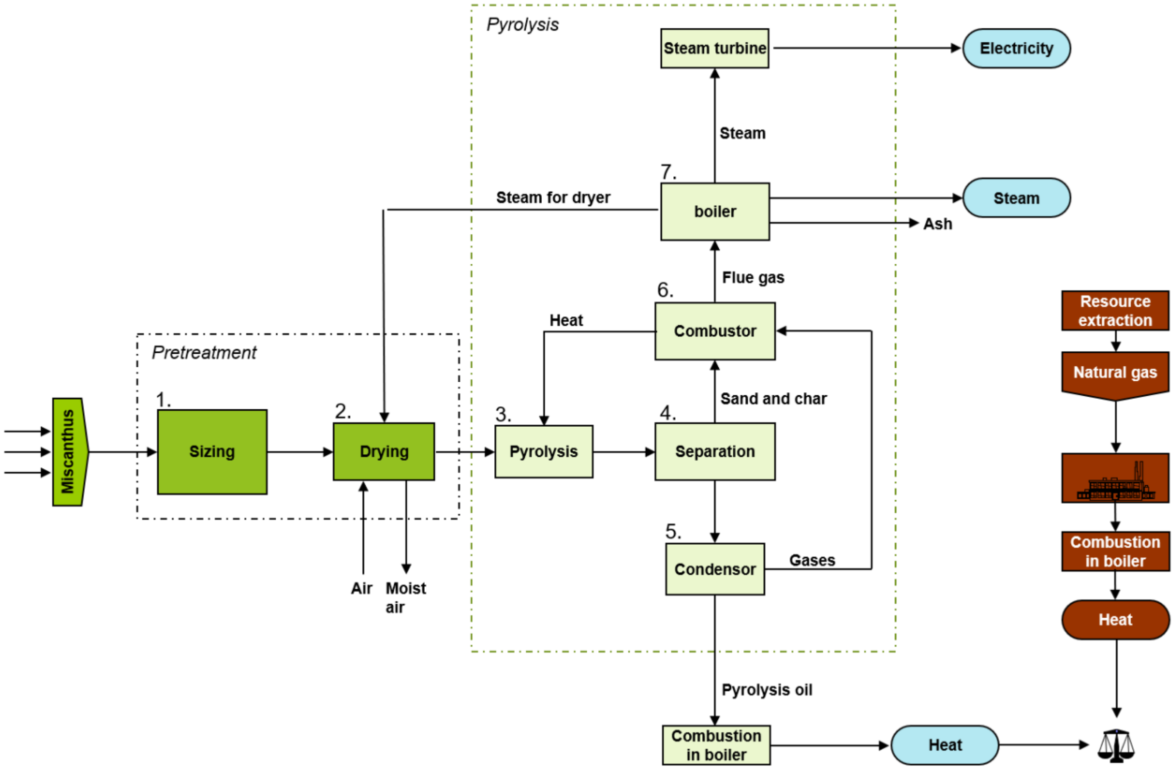

Figure 14: Detailed life cycle comparison for VC 1: industrial heat from Miscanthus via pyrolysis.

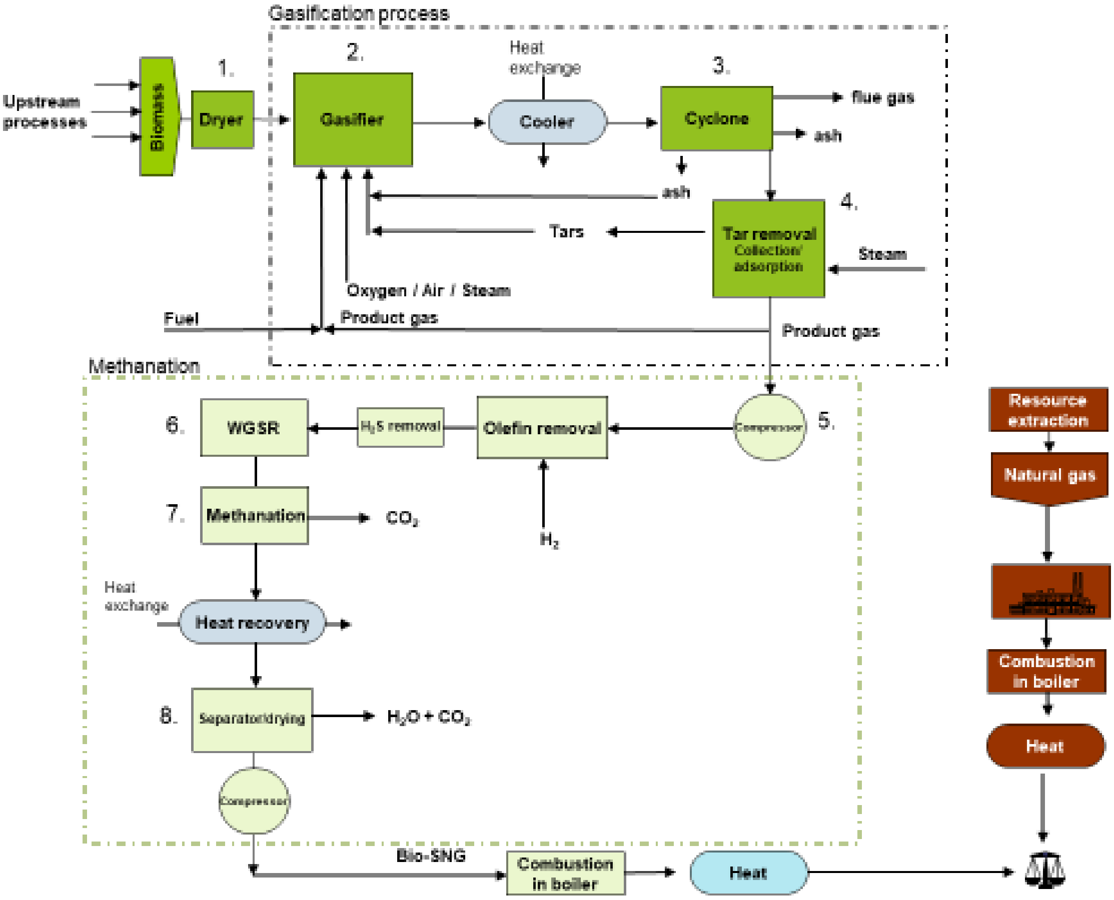

Figure 15: Detailed life cycle comparison for VC 2: Synthetic natural gas from poplar via gasification.

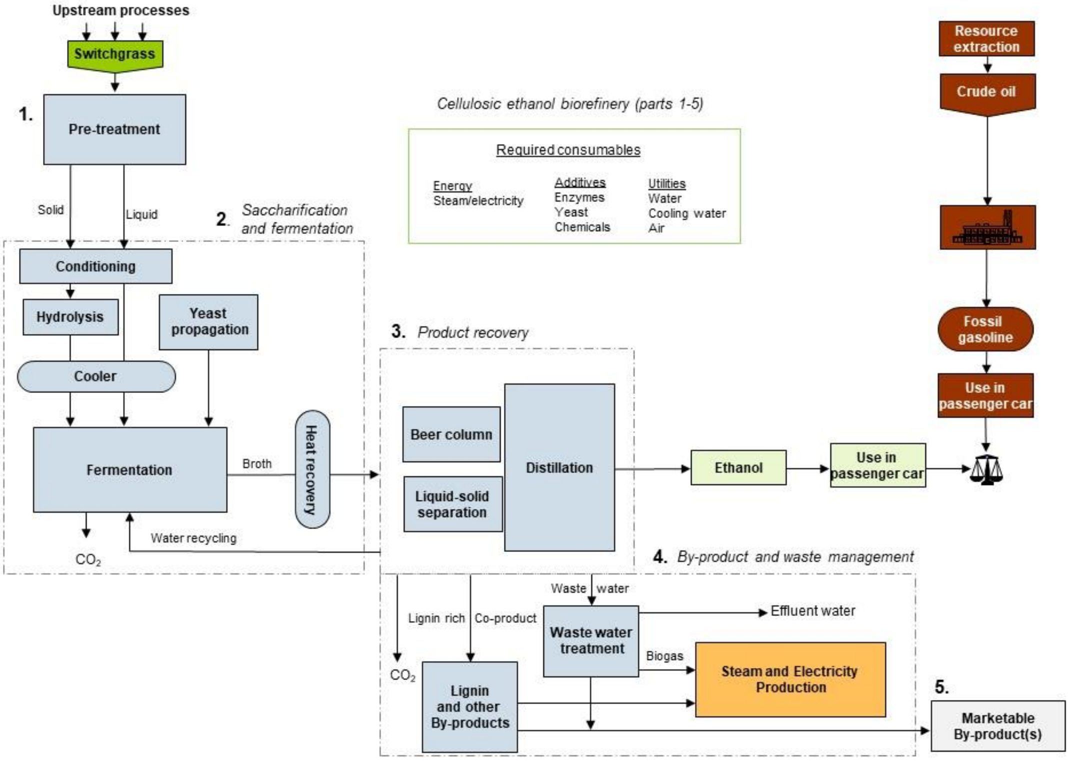

Figure 16: Detailed life cycle comparison for VC 3: ethanol from switchgrass via hydrolysis & fermentation.

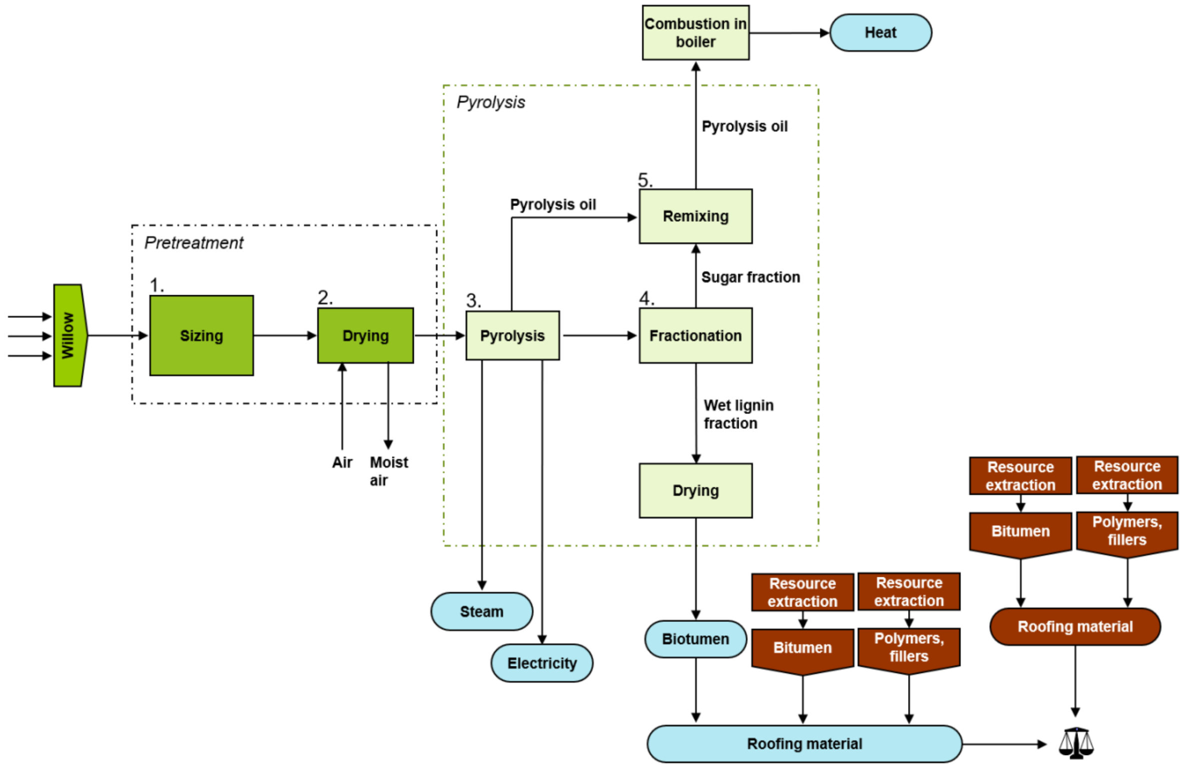

Figure 17: Detailed life cycle comparison for VC 4: biotumen from willow via pyrolysis. A more detailed scheme for the pyrolysis section can be found in Figure 14.