Towards Circular Bioeconomy in the Czech Republic

The identification of sustainable business cases for agricultural residues

Master's Thesis Internship - master Sustainable Business & Innovation

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Abstract

Biomass is projected to play an important role in accomplishing European Union's (EU) climate targets. Biomass sources are, however, limited and a resource efficient focus is needed. A novel concept of Circular Bioeconomy (CBE) has been put forward which aims at utilizing biomass residues in an effective manner. This thesis tests this concept on a national level in the Czech Republic. Material Flow Analysis (MFA) was employed in order to map the current state of play in the Czech agriculture as well as to measure the degree of circularity. Primary (straw), secondary (e.g. husk) and tertiary residues (food waste) along with conventional biomass types were estimated and visualized in a Sankey diagram. This was followed by analyzing barriers to mobilizing the available primary residues with a farmers' survey and an expert roundtable workshop. Finally, a literature review was employed in order to identify possible business cases utilizing the primary residues in the bio-based industries.

The level of circularity was assessed at 43 % with straw, manure and digestate as the most significant biomass flows in the Czech agriculture. The sustainable potential of primary residues was estimated at approximately 1.5 Mt_{dry} although its mobilization is substantially hindered by the lack of clarity regarding local sustainable removal rates and by the unwillingness of the farmers to supply the biomass. This underlines the necessity to include social dimension in the CBE concept and to take a more regional and bottom-up focus. This research indicates also untapped potential for the case of secondary and tertiary residues which were estimated at around 0.9 Mt_{dry} and 0.3 Mt_{dry}. Both the roundtable workshop and the literature review on business cases highlighted the biobased chemical sector as a promising end-use market for primary residues although other segments might be more promising from GHG mitigation perspective.

Executive Summary

Biomass will play an important role in curbing the greenhouse gas emissions (GHGs) and consequently in climate mitigation. The bio-based economy (BBE) which aims to develop and commercialize bio-based products or services as alternatives to fossil-based counterparts is therefore projected to increase on importance in the upcoming years. The potential of the BBE in the Czech Republic, which is the main scope of this research, is, however, under exploited. Currently, the turnover per person employed in the Czech bioeconomy is approximately 40 % lower than the EU average and at the EU level, the bio-based sectors are rapidly expanding with the highest value-added annual growth rate in bio-based chemicals (+26%), bioenergy (+15%) and bioplastics (+13%).

The BBE can, however, have negative impacts on the climate and on local ecosystems if the biomass stocks are overexploited. A resource-efficient focus which is emphasized by the Circular Economy (CE) is therefore needed. A novel concept of Circular Bioeconomy (CBE), which primarily focuses on biomass residues, has been proposed as an intersection between CE and BBE. This research sets out to explore the combination of the CE and BBE in the Czech Republic via the following research question:

''How can the bio-based economy and circular economy be aligned so that they contribute to climate-change mitigation while creating new high-value added business cases in the Czech Republic?''

To answer the research question, three work streams were followed. Firstly, the Material Flow Analysis (MFA), which is a predominantly a CE tool, was used to map and visualize the availability and uses of biomass and biogenic residues. All three types of residues including the primary (e.g. straw), secondary (e.g. husk) and tertiary (e.g. food waste) residues were estimated. The aim was also to measure the level of circularity in the Czech agriculture, i.e. the proportion of biomass which is annually returned back into the ecosystem to that annually extracted. Secondly, the barriers to mobilizing the identified biomass sources were assessed by a literature review, survey and an expert roundtable workshop. Thirdly, even if the identified residues would be mobilized an optimal end-markets needed to be prospected. This was done by a desk research with the combination of Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis.

The post-harvest residues were identified as the most abundant with an overall theoretical potential of 11 Mt_{dry} (million tonnes in dry matter). Considering competing uses, technical constraints and constant sustainable removal rate of 33 %, the sustainable potential of these residues is 1.5 to 2 Mt_{dry}. However, in order to identify the amount of crop residues that can be removed without truly compromising on soil quality, regionally tailored strategies that would consider the local conditions are needed. Moreover, the survey has enumerated the farmers' lack of clarity regarding sustainable removal rates of the primary residues thereby posing a large hurdle to the mobilization. Majority (85 %) of the generated straw is also used by the farmers and only a fraction (15 %) is being sold to a second party which indicates that straw is used right where it is produced. The importance of the farmers perception underlines the need to intensely focus on the social dimension in the CBE.

The theoretical availability of secondary residues were estimated at approximately 0.9 Mt_{dry} although their current uses need to be more investigated in order to identify their potential for mobilization. The tertiary residues mainly in the form of food waste were estimated at 0.3 of Mt_{dry} of which more than half ends up in landfills.

The level of circularity was calculated at 43 % with straw, manure and digestate as the main cycling streams. Especially straw covers approximately 70 % of the amount of biomass that is returned back into the soil. If all the

secondary and tertiary residues would be composted and returned back into the soil the circularity gap would rise to 51 %. Total annual circularity is not possible due to loss of carbon via human or animal metabolism, however, more research should be directed towards understanding more thoroughly the combination of MFA with carbon cycling.

The desk research on business cases revealed that majority of the high-value utilization pathways for straw are still technologically immature. Moreover, there exists a trade-off between the GHG related emission focus of biofuels and bioenergy where the objective is to simply replace fossil-based fuels without considering circularity aspects and the more material oriented biochemical or biocomposite sector where the more social, economic or circularity aspects are pronounced.

Overall, this research underlines the need to take a regional perspective when designing bioeconomy strategies as local bio-physical and socio-political conditions are crucial to determine the suitable intervention strategies. So far, however, there is not even a national bioeconomy strategy in the Czech Republic. The latter is therefore a necessary step in order to set clear guidelines on the desired development of the Czech bioeconomy in the upcoming decades where climate mitigation will be of the utmost importance.

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List of Abbreviations:

1G – 1st generation feedstock

2G – 2nd generation feedstock

APR - Aqueous Phase Reforming

BBE – Biobased Economy

CAGR – Compounded Annual Growth Rate

CBE – Circular Bioeconomy

CE – Circular Economy

CEE – Central and Eastern Europe

CENIA – Czech Environmental Information Agency

CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation

CSO – Czech Statistical Office

DSHC – Direct Sugars to Hydrocarbons

EC – European Commission

EEA – European Environment Agency

EMF – EllenMac Arthur

EOL – End of Life

EU – European Union

FCR – Feed Conversion Ratio

FRL – Fuel Readiness Level

FTS - Fischer Tropsch Synthesis

GHG – Greenhouse Gas

HDCJ - Hydrotreated Depolymerized Cellulosic Jet

HEFA – Hydroprocessed Esters and Fatty Acid

HS - Harmonized Commodity Description and Coding Systems

IATA – International Air Transport Association

ICAO – International Civil Aviation Organization

IEA – International Energy Agency

IPCC – Intergovernmental Panel on Climate Change

IRENA – International Renewable Agency

LCA – Life Cycle Assessment

MFA – Material Flow Analysis

MJSP – Minimum Jet-fuel Selling Price

MT$_{ar}$ – Megatonnes in as received values

Mt$_{dry}$- Megatonnes in dry matter

NFC – Natural Fiber Composite

PET – Polyethylene Terephthalate

PHA – Polyhydroxyalkanoates

PLA – Polylactic Acid

RED II – Renewable Energy Directive II

RJF – Renewable Jet Fuel

RPR – Residue Product Ratio

RRF – Renewable Road Fuel

SOC – Soil Organic Carbon

SWOT - Strengths-Weaknesses-opportunities-Threats

TRL – Technology Readiness Level

UCO – Used Cooking Oil

WPC – Wood-Plastic Composite

Content

1 Introduction

In order to keep the increase of global temperature below 2 °C while aiming for 1.5 °C compared to pre-industrial levels, the global net anthropogenic greenhouse gas (GHG) emissions need to reach net zero around 2050 (IPCC, 2018). The European Union (EU) is at the forefront of proclaiming climate neutrality by 2050 (European Commission (EC), 2018). Several ambitious EU policies and strategies have been put in place in order to curb the GHG emissions as well as to alleviate other environmental damages while ensuring the competitiveness of the EU economy. The Renewable Energy Directive (RED II), the Circular Economy Package and the Bioeconomy-related strategies are at the center of these efforts.

The Bio-based economy (BBE) - which aims to develop and commercialize bio-based products or services as alternatives to fossil-based counterparts thereby mitigating climate-change - will play an indispensable role in the accomplishment of the EU climate targets (Rogelj et al., 2018). Nevertheless, there are large differences in the potential and size of the BBE across the individual Member States (Piotrowski & Dammer, 2018). In fact, the EC has stressed that: ‘‘(…) low bioeconomy added value in the Central and Eastern European (CEE) countries is at odds with their high, and, compared to other European regions, yet underutilized biomass potential’’ (European Commission, 2018c, p.31).

The Czech Republic, which is the main scope of this research and which belongs to the CEE region, is no exception. Currently, the turnover per person employed in the Czech bioeconomy is approximately 40 % lower than the EU average (Ronzon & M’Barek, 2018). At the EU level, the bio-based sectors are rapidly expanding with the highest value-added annual growth rate in bio-based chemicals (+26%), bioenergy (+15%) and bioplastics (+13%) (European Commission, 2018). A well-functioning bio-based economy could thus help achieve climate-goals and increase economic returns.

In 2018, the revised Renewable Energy Directive (RED II) entered into force, establishing new collective renewable energy target for the EU of at least 32 % in 2030 (European Commission, 2018b). All EU countries must also achieve 10 % and 14 % shares of renewable transport fuels by 2020 and 2030 respectively. Conventional crop-based biofuels will be capped at 7 % from 2020 and advanced biofuels from agricultural wastes and residues should reach 0.5 % shares at 2021 and 3.5 % at 2030. Currently, more than 80 % of renewable energy in the Czech Republic is supplied from biomass and it is expected to increase with 40 % in 2030 (Ministry of Industry and Trade, 2015). A resource efficient focus is thus needed. Additionally, certain economy sectors such as the chemical industry or aviation, might rely on biomass feedstock in the future because of limited alternatives (Isikgor & Becker, 2015). Overall, large pull of biomass is expected (Philibert, 2017).

However, biomass resources are limited and their cultivation solely for bioenergy or for biofuels is often disputed on the grounds of insufficient environmental sustainability (Bicalho, Bessou, & Pacca, 2016). Utilization of unused or underutilized biomass sources such as agricultural residues or wastes are being, therefore, lately promoted. This is where Circular Economy (CE) – a concept which promotes resources efficiency, cascading and waste minimization – plays an important role (Korhonen, Honkasalo, & Seppälä, 2018). Several authors highlight the synergies between CE and BBE and call for their integration into a novel concept called Circular Bioeconomy (CBE) (Hetemäki et al., 2017; Mohan et al., 2016). The aim of this thesis is to combine the CE and BBE and hence explore a novel concept of CBE. The objective is also to identify synergies rather than conflicts (Stegmann, Londo, & Junginger, 2020) whilst facilitating new high-value added business cases that would lead to climate mitigation in the Czech Republic.

1.1 Problem Description

A precondition to a well-developed bio-based economy is sustainable, cost effective and reliable supply of biomass feedstocks. Forestry and agriculture are the main sectors of supply. Today's bioenergy supply is still largely covered from forests (70% in the EU), but further growth might be constraint (Calderón, Colla, Jossart, & Hemeleers, 2019). Lately, an emphasis has been put largely on residual biomass to avoid conflicts with food, feed and fiber production as well as to alleviate environmental impacts in terms of direct and indirect land-use change (Scarlat, N., Fahl, Lugato, Monforti-Ferrario, & Dallemand, 2019). The approach to utilize residuals in an effective manner is also aligned with CE principles (D'Amato et al., 2017a). This research follows this path and focuses on agricultural residues which were identified as a promising source of biomass in the Czech Republic[1] (Wietschel, Thorenz, & Tuma, 2019).

These agricultural residues can generally be distinguished into three main groups (Brosowski et al., 2016). Primary residues are the most abundant and they become available during harvest mainly in the form of a straw. Secondary residues include the generated waste from biomass processing for food, feed or from technical cycles (e.g. biofuel production). These can include, for example, cereal processing residues such as husk or bran or sugar beet pulp from sugar production. Finally, tertiary residues represent the post-consumption biogenic wastes such as food waste (van Stralen, Kraan, Uslu, Londo, & Mozaffarian, 2016) .

García-Condado et al. (2019) estimated the primary agricultural residue availability in the Czech Republic from cereals, oil crops and sugar crops to be 8.6, 3.6 and 0.4 Mt_{DM}/y (million tonnes of dry matter per year) respectively. Similar findings are reported in other studies (Camia et al., 2018; Gurría et al., 2017; Kanianska et al., 2011). These, however, do not consider competing uses (e.g. animal bedding), technical limitations such as the harvesting capability of the machinery and the necessity to keep part of this biomass on the field to avoid soil erosion. Other studies take these limitations into account and already provide estimates on the sustainable potential on a NUTS-3[2] level. The estimates on sustainable potential of agricultural residues range from 2.2 Mt_{DM}/y to 3.0 Mt_{DM}/y with wheat and rapeseed straw as the main contributors (Searle & Malins, 2016; Thorenz, Wietschel, Stindt, & Tuma, 2018; Wietschel et al., 2019). Searle & Malins, (2016), note that this amount of feedstock would allow to fulfill the 0.5 % target for advanced biofuels more than 10 times in the Czech Republic and could supply biomass to 2 to 7 new bio-refineries.

Although the availability of these biomass sources is theoretically high, this does not imply they are readily available on the market. There are several barriers still that limit the mobilization of these resources. Firstly, distribution of the biomass across regions implies that it needs to be collected, processed and transported to a biorefinery. For this, several stakeholders must cooperate, suiting infrastructure should be in place and economic feasibility must be ensured (Piotrowski & Dammer, 2018). Secondly, the primary agricultural residues play an important role in terms of maintaining the soil organic carbon (SOC) stocks which is directly linked to soil quality (Lal, Griffin, Apt, Lave, & Morgan, 2004). The sustainable removal rates of these residues are often region specific and are based on local characteristics such as soil type, climatic conditions or agricultural practices (Stella et al., 2019). This means that generic sustainable removal rates will not suffice to estimate the sustainable potential and residue management must be designed in an integrated and site-specific manner (Mouratiadou et al., 2020). Finally, the locally specific socio-political factors such as the existing policies or the (un)willingness of the biomass producers to supply the residues to second parties are crucial (Smith et al., 2017). Overall, many barriers exist to mobilizing the theoretically available biomass and to what extent this feedstock be directed to the Czech bio-based industries remains unknown.

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[1] Forest residues were part of a study made by the internship organization (Jonáš, 2019) and are not covered herein.

[2] NUTS-3 or the Nomenclatures of Territorial Units for Statistics is the smallest regional division in Eurostat's database.

Another issue is that the above-mentioned biomass availability studies capture mainly primary harvesting residues and not the secondary and tertiary residues. Identifying and utilizing the latter two is exactly where the CE and BBE could be in high synergy (Mohan et al., 2016). Moreover, analyzing the stocks and flows of the main agricultural crops from harvest to disposal, allows for a systemic analysis of the agricultural sector. This is crucial in order to receive a holistic picture of the current uses of biomass whilst identifying material inefficiencies in a system (Kalt, 2015). This can be combined with a quantification of the level of circularity of the agricultural sector. This is often employed with the so-called circularity gap analysis, which points to the ratio of materials cycled in the economy or a sector to those extracted (Jacobi, Haas, Wiedenhofer, & Mayer, 2018), although many other metrics assessing the circularity are being currently discussed (Corona, Shen, Reike, Carreón, & Worrell, 2019). No study with a similar focus exists in the Czech Republic.

Finally, even if some of the available biomass could be successfully mobilized, it remains unclear what are the suitable end-markets where biomass should be directed. Identifying the right utilization pathway is difficult as the intersection of CE and BBE is complex. For example, all products should according to CE follow a waste hierarchy with incineration as the second least option after landfilling. The use of biomass for material use is also preferred in economic and social terms as it can facilitate 5 to 10 times more jobs and 4 to 9 times more value added compared to the energy use of biomass (Carus, M., Dammer, & Essel, 2015). Today, only 15 % of biomass (including wood) is, however, used in materials (Carus, Michael & Dammer, 2018). On the other hand, bioenergy or advanced biofuels are an indispensable part of the EU climate strategy at least from a short term perspective (Hanssen et al., 2019).

The emphasis on biogenic side streams such as agricultural residues is relatively novel at the EU level (Cavallo & Gerussi, 2015) and even more so in the Czech context where limited attention to CE and BBE has been given. Receiving a clearer insight on the strategic use of biomass, on the current state of play and on the existing barriers towards biomass mobilization in the Czech Republic is thus the strived for societal contribution of this thesis. From a theoretical point of view, the objective of this report is to shed light on the novel concept of CBE, explore its strengths and weaknesses and eventually test its feasibility. The aim is to identify the synergies and conflicts in the CE and BBE on a practical national scale. This research also aims to contribute to the debate on circularity metrics in general (Corona et al., 2019; Parchomenko, Nelen, Gillabel, & Rechberger, 2019) .

1.2 Research questions

How can the bio-based economy and circular economy be aligned so that they contribute to climate-change mitigation while creating new high-value added business cases in the Czech Republic?

1. What is the current state of play in terms of size, utilization and processing of the agricultural biomass?
2. How large is the circularity gap in the agricultural sector and which interventions could reduce this gap?
3. What are the barriers that hinder the mobilization of regional biomass feedstock into high-value added bio-based industries and what strategies might help overcome these barriers?
4. What is an optimal utilization of residual biomass in the Czech Republic considering climate targets, economic feasibility and circularity?

2 Theoretical Framework

In the following chapter, the concepts of CE and BBE are more thoroughly explained together with their strengths and limitations. The CBE as an overarching concept is then presented. The sustainability tools of Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) are introduced in the later part. Finally, different biomass potentials are discussed in order to clarify the methodology used for biomass availability estimates.

2.1 Circular Economy & Bio-based Economy

The current economic system is resource-intensive and largely inefficient. In fact, only 8.6 % materials ever extracted are returned back into the economy (De Wit, Hoogzaad, Ramkumar, Friedl, & Douma, 2018). Because of the high material throughput of the current economic system, the global economy has been described as linear and from a long-term perspective unsustainable (Korhonen et al., 2018). The Circular Economy (CE) offers alternative model, which is based on high material efficiency, lower extraction rates and consequently on reducing waste production whilst allowing for global economic development (Ellen MacArthur Foundation, 2015). The current linear economy is not worrying only due to the high removal rate of mostly non-renewable materials on a finite planet, but it has also substantial implications on the GHG related emissions from material productions (Giampietro, 2019). According to the Ellen MacArthur Foundation (EMF), around 45 % of global GHG emissions are related to material productions (Morlet et al., 2019). By following CE principles, the negative climate impact can therefore be presumably reduced by longer retention of the value embedded in the materials as well as by other strategies the CE concept offers (Geissdoerfer et al., 2017). The EMF also posits the economic gains of CE and estimates the macro-economic potential of 1.8 trillion euros (MacArthur et al., 2015).

While broadly agreed upon interpretation of CE is still missing, the Kirchherr, Reike & Hekkter (2017) study conceptualizes the CE thoroughly after reviewing 114 different CE definitions. This report works with their definition of CE as: “an economic system that replaces the ‘end-of-life’ concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers” (Kirchherr et al., 2017, p.224)

The CE indeed offers several strategies as a way to rethink the current economic production system, ranging from better product design, smarter product use and manufacture via extending lifespan of products up until effective reutilization of materials at their end-of-life phase. Potting, Hekkert, Worrell, & Hanemaaijer (2017) identified 9 of the so-called R-strategies which point to a waste hierarchy ranging from refusing (R0) to remanufacturing (R6) up until recovery of energy from materials (R9). The R-strategies point to the circular material flows within a system which according to CE demands less resources and energy while being more economical (Korhonen et al., 2018). These recurring streams are often portrayed graphically in the separate technical and biological cycles (MacArthur, 2013). The CE also emphasizes the need to retain the embedded value of materials for longer periods than currently practiced (Asif, Lieder, & Rashid, 2016). This is related to another concept that the CE puts forward: cascading.

There are two main views on cascading, although many other exist (see figure 1) (Stegmann et al., 2020). The (i) first thinks of cascading as a "sequential use of resources for different purposes"(Olsson et al., 2018, p.1) . This is also accepted by the EC which defines it as: ''the efficient utilization of resources by using residues and recycled materials for material use to extend total biomass availability within a given system'' (European Commission, 2016, p.1). To ensure this type of cascading, the products should be (eco)designed so they can be kept in the separate technical and biological cycles as mixing these two often hinders further use other than energy recovery or landfilling (European Environment Agency (EEA), 2018). The (ii) second interpretation is based around the bio-based value pyramid where as high-value applications as possible are preferred (Bosman & Rotmans, 2014). This value is mostly determined by economic or social indicators such as added value or jobs produced, although the price-based indicators are critiqued (Olsson et al., 2018). These two interpretations differ considerably as for example utilizing a material into high-value added application (e.g. personal care product) without its possibility for subsequent use would be preferred by one definition (ii) but rejected by the other (i). There is still a confusion on the suitable perspective on cascading both in the academic and policy circles (Jarre, Petit-Boix, Priefer, Meyer, & Leipold, 2020).

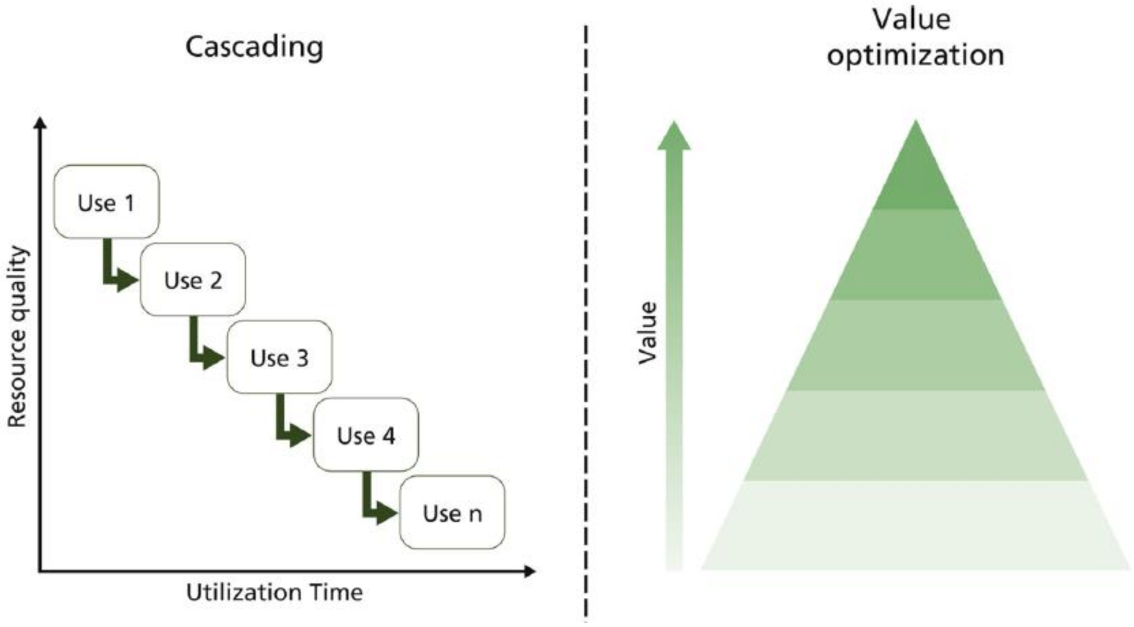


Figure 1: Cascading: Visualization of cascading as sequential use of materials (i, left) and in high value applications (ii, right). Extracted from Stegmann et al., (2020).

The CE also promotes the use of renewable resources and it is often hailed as being ''regenerative by design'' (MacArthur, 2013). This is where it clearly overlaps with the bioeconomy which is defined as: "production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy" (Ciervo, 2018, p.9) Its subset, the bio-based economy, focuses mainly on the production of fossil-based substitutes from renewables such as biofuels, biopolymers or biobased chemicals. The main aim is contributing to mitigating climate change, substituting fossil fuels with renewable (''regenerative'') carbon source whilst allowing for new business opportunities (Carus & Dammer, 2018). The ambition of bioeconomy within the EU is high and goes further than providing only a renewable source of carbon. It aims to promote energy security, facilitate job employment, increase economic competitiveness and technological innovation (European Commission, 2018).

2.2 Limitations of CE and BBE: Towards Sustainable Circular Bioeconomy

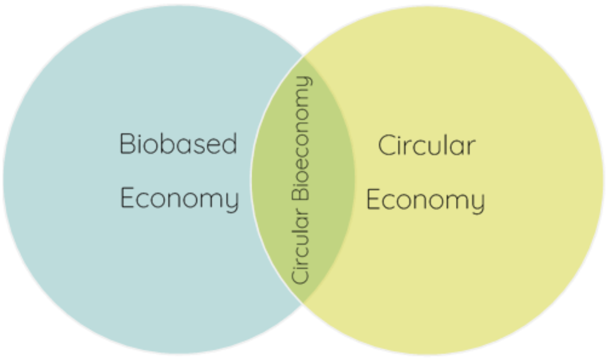
Notwithstanding the proliferation of these two concepts within business and policy circles, the scholarly debate has been rather critical. The CE is criticized for being too vague, scientifically unclear and with ambiguous scope (Kirchherr et al., 2017). This is illustrated by the plethora of existing definitions and by inconsistent metrics to measure the level of circularity (Corona et al., 2019). Many CE initiatives are also presented as more sustainable by simply being circular. This, however, is misleading and can lead to burden shifting as many interventions can be less environmentally sensible from a life-cycle perspective despite being more circular (Haupt & Zschokke, 2017). Many authors call for quantitative and holistic analysis of environmental impacts prior to a CE-related intervention (Carus et al., 2015). Similarly, CE emphasizes more the material use but is slightly less focused on other environmental impacts such as GHG emissions or land use (Korhonen et al., 2018).

The CE is also often criticized for omitting to some extent the social dimension of sustainability and is often portrayed as being too business centered (D'Amato et al., 2017; Geissdoerfer, Savaget, Bocken, & Hultink, 2017; Korhonen et al., 2018). The latter manifests itself by the overemphasis on economic growth and by the warm acceptance of CE in business circles . The focus of CE is also largely on urbanized and industrialized areas despite large material flows in rural regions (D'Amato et al., 2017). Overall, the CE is critiqued as not fully covering the triple bottom line of sustainability as defined by Elkington (2013).

Likewise, bio-based economy has in practice failed in its sustainability promises in the case of crop-based biofuels (Gawel, Pannicke, & Hagemann, 2019). Emphasis has been put on environmental assessment prior to any bio-based realization ever since. The highest concern is for actual climate-change mitigation and direct and indirect land use change (IRENA, 2019). The bio-based economy is also criticized for giving limited attention to eco-design (EEA, 2019), cascading (D'Amato et al., 2017) and for being too techno-centric (Giampietro, 2019).

The abovementioned scrutiny of BBE and CE led some authors to promote the concept of CBE as an intersection between the two (see figure 2). Hetemäki et al. (2017) warns that without the consideration of circularity aspects, the bio-based economy could risk becoming too much of a 'business-as-usual' scenario. Similarly, the EEA (2018) highlights the conceptual link between BBE and CE and calls for the conversion of the different policy agendas. Given the relative novelty of the concept there is a limited agreement on the definition of CBE, nevertheless Stegmann et al. (2020, p.5) provide widely encompassing and up to date conceptualization of the term:

''The circular bioeconomy focuses on the sustainable, resource-efficient valorization of biomass in integrated, multi-output production chains (e.g. biorefineries) while also making use of residues and wastes and optimizing the value of biomass over time via cascading. Such an optimization can focus on economic, environmental or social aspects and ideally considers all three pillars of sustainability. The cascading steps aim at retaining the resource quality by adhering to the bio-based value pyramid and the waste hierarchy where possible and adequate.''



- Bio-based products
- R-strategies
- Cascading use
- Utilization of organic waste streams
- Resource-efficient value chains
- Organic recycling, nutrient cycling

Figure 2: Synergies between CE and BBE (Carus & Dammer, 2018)

The synergies between these two concepts are high as many of the weaker points of one are covered by the other (see figure 2). For example, eco-design is principal to CE but is less so a priority in the BBE. Similarly, the lack of focus on rural areas or the over-emphasis on technical rather than biological cycle within CE can be alleviated by the scope of BBE. The CE is often viewed as a form of identifying the material flows, the leakages and ultimately resource inefficiencies in a system (D'Amato et al., 2017). It can offer novel business models, emphasis on cascading and eco-design and an overall systematic approach to system transition. The BBE on the other hand has large experience with transforming the identified under-utilized resources into higher-value added products and services such as biopolymers or biochemicals. It offers great variety of different technologies which are essential to climate reduction. Hetemäki et al. (2017) provides synthesis of the two concepts in a figure 3 where different aspect of CE such as cascading, or waste hierarchies are integrated into the different BBE sectors such as Biofuels or Biochemicals production. However, as already highlighted cascading and other principles of CE or BBE in themselves do not ensure environmental sustainability. In the next chapter the sustainability tools of MFA and LCA are presented.

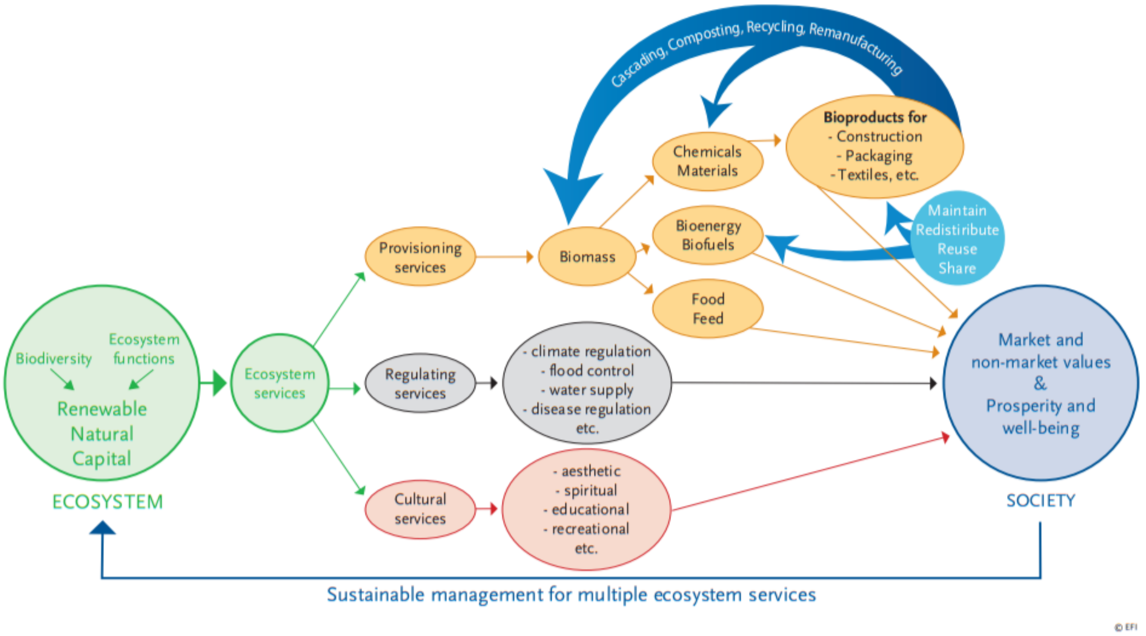


Figure 3: Visualizing the application of different R-strategies in different BBE sectors (Hetemäki et al., 2017)

2.3 Sustainability assessment tools & measuring circularity

The identification of wastes, leakages and inefficiencies in a given system is one of the main assets of using Material Flow Analysis (MFA) which is why it is one of the main tools within CE (Kaufman, 2012). The MFA is defined as the: ''systematic assessment of flows and stocks of materials within an arbitrarily complex system defined in space and time.'' (Cencic & Rechberger, 2008, p.440). There are four main procedures when conducting an MFA analysis namely the (i) system definition, (ii) process chain analysis, (iii) accounting and balancing and (iv) evaluation and reflection (Bringezu & Moriguchi, 2018). MFA has been used on a national level to map the level of circularity for the whole economy (Jacobi et al., 2018) as well as to map the biomass flows on a national level (Gurría et al., 2017; Kalt, 2015). The use of MFA for mapping flows and stocks of goods and/or substances on a regional (Barles, 2009) or urban level (Rosado, Niza, & Ferrão, 2014) is also common.

While the MFA is more about identifying material leakages in a given space and time, Life Cycle Assessment (LCA) can provide information on the actual environmental impact on that system before and after intervention (Goldstein & Rasmussen, 2018). The LCA evaluates the environmental impacts of a product or a service across the whole life cycle that is from primary extraction until the end-of-life phase (Guinée, 2002). The LCA is thus a comprehensive tool that allows decision makers to identify whether a planned intervention will eventually lead to environmental gains. Coupling the LCA and MFA is often proposed (Silvia et al., 2015)

Even though both the MFA and LCA can be used to measure the level of circularity, they are not the only tools. In fact, there are more than 300 indicators that could be hypothetically used for assessing circularity (EASAC, 2016). According to Corona et al. (2020) the well-established sustainability tools such as LCA or MFA are, however, one of the most fitting as they have been continuously improved over the years and they are more encompassing compared to single indicators. The LCA is perceived as one of the most comprehensive tools to measure circularity on all its three dimensions, however, it is mostly used on a product level (Hellweg & Canals, 2014). It is less suitable on a national or even global scale where on the other hand MFA is has its place.

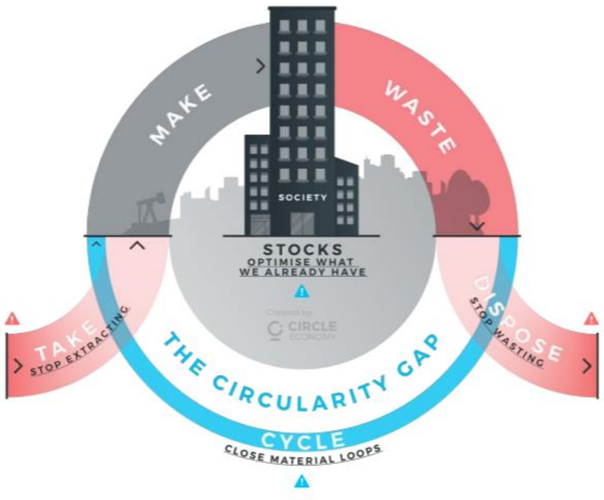


Figure 4: Graphical visualization of the 'take-make-waste-dispose' economy & the Circularity Gap (De Wit et al., 2018).

The choice of these tools is thereby predominantly based on the aim and scope of a research. As this research aims at receiving the current state of play in the Czech agriculture and at identifying the availability and flows of the agricultural crops and their residues, the MFA is suitable for this need and LCA would not be applicable to this scope. This report also aims to apply the MFA more in an informational and communicational manner where the circularity metrics using MFA can be beneficial (Corona et al., 2020). It is not aiming at an overall environmental impact assessment framework. De Wit et al., (2018) have measured the level of circularity based on the amount of materials extracted to those cycled on a global scale (see figure 4) .They distinguish between the different processes in the lifecycle of a product, i.e. ''take'', ''make'', ''waste'' and ''dispose''. A similar approach is used in this work.

2.4 Types of biomass potentials & lignocellulosic feedstock

The focus of CBE is on biogenic residues and wastes, and the potential of CBE is therefore dependent on the availability of these biomass types. The aim of this chapter is to clarify the different biomass potentials of mainly primary residues[3] as described in Vis & van den Berg, (2010). The primary or post-harvest agricultural residues are defined as the above ground part of a crop without considering the economic production (grain). The main primary residue in the Czech Republic is a cereal or a rapeseed straw. The availability of these residues is mostly derived from the experimentally determined residue-to-product (RPR) ratio which in the case of cereals would illustrate the ratio of the straw to the grain. Generally, 4 types of potentials can be differentiated:

- Theoretical potential which points to the maximum amount of residues available taking the biophysical conditions into account. It is mostly derived from the crop yields and RPRs.
- Technical potential which corresponds to the fraction of the theoretical potential whilst taking into account the type and efficiency of the machinery used for harvest as well as local field management practices (e.g. crop rotation, cutting height etc.)
- Sustainable potential is the fraction of technical potential take takes into account the allowable removal of residues in order to avoid negative impacts on soil quality.
- Implementation potential also considers the socio-political conditions in the respective area. These can include the existing policies on soil quality or the social impediments such as the unwillingness of the providers of the biomass to supply it.

Additionally, competing uses are a necessary component in order to fully comprehend the potential of primary residues. The main competing use of straw is animal bedding followed by less sizable applications such as feed, mushroom mulching or incineration (Scarlat et al., 2019). These competing uses are, generally, regionally specific, for example, on the number of livestock or whether a straw incineration plant exists in the region. Straw has gained a considerable attention in the past few years as it falls under the second generation feedstock (2G) which doesn't compete with food or feed production (IRENA, 2019). On the other hand, biofuels that could be used as food or feed are referred as conventional or 1st generation feedstocks (1G). Straw is one of the most promising residual biomass types which is also often grouped into the so-called lignocellulosic feedstock due to its specific physiochemical properties (Thorenz et al., 2018). The lignocellulosic feedstock together with organic wastes such as the secondary or tertiary residues are one of the main biomass materials for the production of advanced biofuels (IRENA, 2019).

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[3] This research also estimated the secondary and tertiary residues, however, these estimates are less developed and less complex and are not discuss in this chapter.

3 Methods

In this section the choice of methodologies for the proposed research questions are presented. This research combines qualitative and quantitative approach as either alone would provide less insights into the above presented problematics. This research is divided into three work streams (see figure 5). Firstly, the methodology of MFA has been employed in order to map the current state of play in agriculture and to identify and visualize the availability of primary, secondary and tertiary residues. The aim was also to measure the circularity gap. The first work stream therefore aims at answering the first two research (sub)questions. To answer the third research (sub)question, a short literature review on biomass mobilization barriers together with stakeholder survey and an expert roundtable workshop were employed. Thirdly, a literature review on suitable end-markets for the lignocellulosic feedstock was combined with SWOT analysis. Finally, the overall theoretical implications are covered by the main research question .

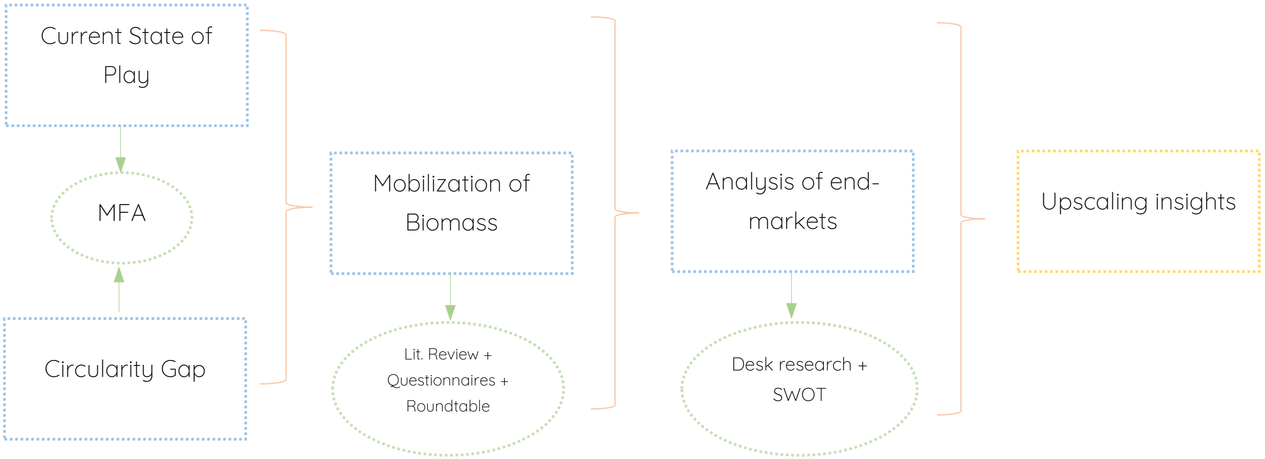

Figure 5: Research design: the blue dotted lines represent work streams, the green the methods and the yellow the theoretical implications.

3.1 MFA Methodology

The methodological framework of MFA was applied using the widely accepted guidelines provided by Brunner & Rechberger (2016). Large part of the case-specific methodology was, however, extracted from a similar case study on mapping biomass flows (agriculture & forestry) in Austria by Kalt (2015). The whole MFA was employed using a programme e!sankey (Ifu, 2018) with a combination of an Excel model. Prior to initiating any work on the MFA an expert consultation has been held. A production-based approach which uses physical inputs as opposed to monetary inputs (consumption-based approach) was employed (Jacobi et al., 2018). While the production-based approach is deemed as more precise as it does not use monetary units as a proxy to the material flows, some data on the physical inputs are limited and crude assumptions in a few cases using this approach must be made. To measure the circularity, the input) and output flows of the system were aggregated over the whole year and the total recovering streams were divided over the total output (De Wit et al., 2018). The circularity degree is then represented by a single indicator between 0 and 100 %. The 0 % would imply that no biomass extracted is returned into the ecosystem (soil) whereas 100 % would mean that all biomass extracted is returned to the ecosystem.

The specific methodological process for the MFA model which is based on Kalt (2015) was made in the following steps:

1. **Literature Research:** A background research was made in order to identify similar studies for biomass resource mapping. The study by Kalt (2015) uses MFA for mapping all biogenic sources including agricultural crops and wood on a national level. Given the large similarity of this publication with respect to its aim and scope, large part of its methodological framework was used for this thesis as well. The Gurría et al. (2017) study assesses EU-wide MFA based on economic production, however, given that it is based on monetary units, limited parts of the methodology were considered. Other studies on MFA that at least to an extent focus on biomass were taken into account (Courtonne, Alapetite, Longaretti, Dupré, & Prados, 2015; Jacobi et al., 2018).

2. **Definition of the preliminary system structure:** On the basis of the literature search and from the MFA consultation at the internship organization a preliminary structure of individual flows and processes was created in the e!sankey programme. This structure was then repeatedly revised in an iterative manner. The scope of the study was limited only to agricultural crops (no forest biomass) which constitute majority of the agricultural biomass. The temporal scope was narrowed to the year 2018 and the geographical scope to the Czech Republic while taking import and export into account.

3. **Identifying relevant data sources and data collection:** In order to receive a reliable picture of the biomass flows in the Czech Republic, robust and credible data sources were necessary. The Czech Statistical Office (CSO), the Czech Environment Information Agency (CENIA) and the information portal of the Ministry of Agriculture served as the main official databases. Mainly 2018 data were used where possible[4]. Additionally, Eurostat, scholarly articles and industry papers such as statistical reports published by Bioenergy Europe (Calderón, Colla, Hemeleers, & Martin, 2019) were often used. Finally, where limited data were available, own calculation of the author was performed or an estimation with an expert was made. Estimates on the availability of agricultural biomass, residues or on other biomass flows which were not found in the official databases were done following the ''Best Practices and Method Handbook'' by Vis & Van den Berg (2010). Data on imports and exports were extracted from the cross-border movements of goods statistics using the HS-4[5] codes from the CSO (2019). For all processes the trade statistics are considered (except consumption and waste phase). Given that biomass weight is dependent on its water content, all flows were reported in their moisture levels under normal conditions (as received) and subsequently also converted to dry weight. Majority of the moisture content was extracted from Kalt (2015) and if there unavailable, additional search was made. The CSO also provides some data on water content in the respective biomass types. The level of uncertainty of the data were assessed qualitatively in the following three levels: (++) data directly extracted from official databases or from credible scientific articles, (+) data from white papers or from more aggregated data, (0) own calculation and estimation of the authors. In all cases, the aim was to make the assumptions as transparent as possible. For more information on the specific data used and on the assumptions behind these, please, see the background chapter 4 on ''Data and Assumptions'' and the Annex 1.

4. **Filling in the preliminary structure with data:** Data from the abovementioned sources were used to fill in the preliminary structure. A suitable level of aggregation was performed in order to find the balance between complexity and comprehensibility.

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[4] While the temporal scope was set to 2018, some data were only available for other periods and these were used when no other source provided better figures. In order to have more robust results, average values over a longer period would provide more insights. This was, however, not the case herein due to limited time appropriated for the MFA.

[5] The Harmonized Commodity Description and Coding Systems (HS) is an international nomenclature for the classification of products. The HS-2 include the chapter the goods are classified in (cereals) whereas the HS-4 specifies the commodities (wheat) (UN, 2017) .

5. **Identification of redundant data and inconsistent flows:** After the step four, not all processes were consistent in their mass balances. Where possible the aim was to clarify the inconsistency in data and correct these. For all processes a relative error was set at 10 %, i.e. the mass balance was deemed as satisfactory as long as the difference between the input and output was lower than 10 %. The whole system in which biomass is utilized, however, is generally difficult to be in mass balance in all cases (Kalt, 2015). There are at least two reasons for this. Firstly, given that the mass of biomass is highly dependent upon water content which is often only crudely estimated and given that the moisture levels are changing in the respective process, it is difficult to estimate the exact water content for all commodities and thereby their actual mass values. Secondly, the biogenic systems are complex and some of the processes are - opposed to some technical cycles – more difficult to evaluate. For example, human consumption or animal and human metabolisms can only be crudely estimated in their processes and respective mass balances.
6. **Expert judgement & Interpretation and discussion:** The final draft of the MFA was verified with the internship organization as well as with an expert from agriculture. The MFA was then adjusted based on these comments. With the final MFA a discussion was held at the internship organization on the availability and uses of biomass in the Czech Republic.

3.2 Biomass mobilization

The following three methodologies were chosen to identify the Czech specific barriers to biomass mobilization: (i) Literature Review, (ii) Stakeholder Survey, (iii) Expert Roundtable Workshop. The latter activity also touched upon the strategic and appropriate use of biomass taking Czech context into account.

3.2.1 Literature Review

A Literature Review was performed in order to identify scholarly articles and relevant books that dealt with mobilization barriers of the lignocellulosic feedstock. The aim was to get an overview of existing barriers as reported in the literature. Terms as ''biomass mobilization'', ''lignocellulosic biomass mobilization'', ''cereal straw mobilization'' and similar were used via the Google Scholar engine search or through the Knowledge Center for Bioeconomy at the EU Joint Research Center. Possible books or articles were also provided to the author by the supervisor. The following publications were identified as highly suitable and relevant in order to receive a solid overview of the mobilizing potential of biomass and on the barriers: (Lamers, Searcy, Hess, & Stichnothe, 2016; Sikkema et al., 2014; Smith et al., 2017; Uslu, Detz, & Mozaffarian, 2018)

3.2.2 Stakeholder Survey

The literature review presented diverse set of barriers and validating all of them ranging from societal, technical to economic hurdles would be outside of the scope of this thesis. Few studies were also found as a result of the literature search that already present the relevance of barriers in a quantitative manner (Uslu, Detz, & Mozaffarian, 2018). Those hurdles that were transferrable into the Czech context from an EU-wide studies such as technological readiness or economic competitiveness of a technology processing lignocellulosic feedstock were perceived as applicable to the Czech Republic and did not need acute further insight. However, certain barriers were identified as Czech specific. Mainly the focus on the providers of the biomass, that is on the farmers, was identified as highly contextual and was thereby chosen as a relevant group for further scrutiny. A methodology of survey was identified as suitable in order to identify the farmers' willingness to provide the biomass as well as on their perception of the importance of straw or on their agricultural practices (e.g. how much straw should be ploughed back to the field to maintain soil nutrient levels). The scope of the questionnaire was predominantly on cereal straw as the most abundant residual biomass.

The questionnaire was designed according to the guidelines as described in Krosnick (2018). The questionnaire consisted of more than 20 questions out which 7 were of general nature (e.g. size of a farm) in order to understand the sample group and 11 additional questions were covering the straw theme specifically. Part of the questionnaire (6 questions) was of a more explorative nature where the aim was to identify other residual materials that are possibly at the disposal of the farmers and that are in their perception viewed as an unutilized resource[6] (see the questionnaire in Annex 2).

Mainly closed questions were used on a mostly 4-point scale in order to avoid satisficing (Krosnick, 2018). Where necessary open questions were used and coded in order to receive more quantitative figures. Final draft of the questionnaire was consulted with an expert from agriculture in order to receive a relevant feedback prior to its final distribution. The main Czech agricultural associations were identified as a suitable channel to reach a representative

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[6] While this is less focused on the mobilization barriers, it is line with the theme of this thesis, i.e. identify underutilized sources of biomass according to CE principles. The results are presented in the Annex

sample and majority of them were contacted prior to distributing the questionnaire. Using Google forms the questionnaire was sent to the following agricultural organizations:

- Agrarian Chamber
- Association of Private Farming of the Czech Republic
- Agricultural Association of the Czech Republic
- The Young Agrarians’ Society of the Czech Republic
- Association of Local Food Initiatives

More than 360 responses to the questionnaire were recorded within a three-week period mainly from the Association of Private Farming of the Czech Republic. The responses were then evaluated and translated from Czech to English. The fact that mainly one association responded to the questionnaire slightly diminishes the overall possible generalization. For that reason, the characteristics of the sample group are presented in the section 5.2.

3.2.3 Expert Roundtable Workshop

The questionnaires illustrated the complexity of using residual biomass in the bio-based industries as well as controversies about its correct utilization pathways (e.g. soil protection vs. bioenergy). Moreover, the main sample group from the questionnaire were a single interest party (the farmers) and it thus only captured a partial view of the barriers. In order to hear and discuss the views of other stakeholder, an expert roundtable workshop with diverse actors was organized. The aim of this workshop was to initiate a debate on biomass mobilization as well as on the outcomes from the questionnaire. The objective was also to hold a more strategy-oriented debate on the suitable handling of biomass in light of the climate targets, soil quality and circularity goals in the Czech context. This part therefore slightly overlaps with the workstream on business cases for using straw.

Representatives from different sectors ranging from biofuel producers to an NGO representative were invited. Prior to the workshop, the participants were given thematic circles around which the discussion will be held. The farmers’ position was represented by the results from the questionnaire and hence did not need participation.

The following stakeholders were invited:

- Renewable energy specialist, Alliance of Energy Reliability
- Director of the Biofuel platform of the Czech Republic
- Sustainability specialist, Glopolis - think tank on the environment and energy provision
- Food security specialist, the Institute of Circular Economy

The process of the workshop was following:

- General overview into high-level climate goals (e.g. RED II advanced biofuels and energy targets) and on the potential of biomass to fulfill some of these goals was presented by the author.
- This was followed by a presentation of the preliminary MFA model showing the availability and use of biomass in the Czech Republic as well as by the questionnaires that illustrated the perception of the farmers towards providing biomass. The potential barriers to biomass mobilization were also introduced.
- Every participant than had a dedicated time to express their opinion on the role of biomass in the Czech context as well as on their view on mobilizing biomass.

- Afterwards approximately hour and a half discussion was being held which was finalized with a consensus in several points on the strategic advice of using biomass. Several drivers to overcome some of the biomass mobilization barriers were also identified.

3.3 Literature review on business cases for lignocellulosic biomass

The following work stream focused on providing insights for using lignocellulosic biomass - of which cereal straw is the main representative – in the different bio-based sectors. This was realized in the form of literature review on a high-level case study by assuming the different end-markets for lignocellulosic feedstock (straw). Case study is defined as an ‘’intensive study of a (…) unit, which is aimed to generalize over several units’’ (Gustafsson, 2017, p.2). Another aim was to receive an overview of the strategic use of lignocellulosic biomass in the Czech Republic as to which sectors seem promising in the upcoming years. To do so, a market research using Strenghts-Weaknesses-Threats-Opportunities (SWOT) method for each sector was employed. Generally, scholarly articles or detailed and robust technical and market reports from credible organizations focusing on bio-based economy such as the German Nova-Institute (Panchaksharam et al., 2019) or British E4tech (2019) were used. The SWOT factors were assessed mainly in terms of the sectors' economic aspects (competitiveness with a fossil-based sector, market share, value-added etc.), environmental performance (mainly GHG emissions) and circularity aspects (see below) and in regards to general threats and opportunities (e.g. existing policy guidelines). Corona et al. (2020) proposes 8 validity requirements in order to identify what constitutes progress on CE terms in all three dimensions of sustainability:

1. Reducing input of resources, especially scarce ones
2. Reducing emission levels (pollutants and GHG emissions)
3. Reducing material losses/waste
4. Increasing input of renewable and recycled resources
5. Maximizing the utility and durability of products
6. Creating local jobs at all skill level
7. Value added creation and distribution
8. Increase social wellbeing

Given that that the points 1, 3 and 4 are intrinsically linked to the CBE agenda and adequately fulfilled by considering a residual and renewable feedstock, they are not elaborated upon in the literature review. Similarly, the increase in social wellbeing is difficult to capture from a sole desk research. The literature review therefore primarily focused on (2) reducing emission levels, (5) maximizing the utility and durability of products (cascading), (6) job creation and (7) value added.

The following end-markets were chosen as suitable for the review:

- Renewable Jet Fuels (RJFs)
- Renewable Road Fuels (RRFs)
- Biobased chemicals such as cosmetics, man-made fibers or platform chemicals
- Biocomposites & construction materials

The choice of these end-uses of biomass was partly based on the waste hierarchy (Potting et al., 2017) and due to the following reasons. Firstly, one of the focus of this thesis are the high-value added bio-based industries and therefore more conventional uses of biomass such as BG plants or composting were excluded. Secondly, there was a consensus at the expert roundtable workshop around not using biomass in bioenergy due to low CE performance and due to low added value. Hence bioenergy was also excluded. The inclusion of Renewable Road Transport Fuels (RRFs) was based mainly on the emphasis on advanced biofuels in the RED II directive where lignocellulosic feedstock will play a major role. The Czech Republic also has to fulfill the 3.5 % target for advanced biofuel and the lignocellulosic feedstock is projected to play an important role. The aviation sector was chosen mainly for its rapidly increasing GHG emissions and due to the limited substitutes for RJFs other than from biomass. These two categories represent the lower-end in the waste hierarchy which is the closest to energy use (R9). The bio-based chemicals sector is perceived as one of the most value-added economic sectors in bioeconomy and there was a consensus at the roundtable workshop on using biomass mainly in the high-value markets. Similarly to RJFs, limited substitutes for fossil-based chemicals other than biomass will exist. The biocomposite and construction sector were chosen as a growing sector with lower complexity opposed to the other segments as well as due to its interesting CE aspects.

3.4 Background visits

Next to the literature review, questionnaires and roundtable diverse set of meetings were held with stakeholders identified as relevant (table 1). Meetings with these stakeholders gave a context to the author and provided a highly valuable insights into the problematics from different perspectives. The following events or personal meetings were held:

Table 1: Stakeholder consultation and events related to bioeconomy visited

Date	Place	Person met / Event attended / Short description
4.12.2019	Prague	Action group on Circular Economy at the City of Prague on tertiary residues (biogenic waste)
5.12.2019	Choťovice	Farmer - visit at the farm and a semi-structured interview on straw and on biomass use in agriculture
5.12.2019	Kněžice	Mayor of a village Kněžice - visit at the local waste biogas plant and a small straw biomass incineration plant
19.12.2019	Brno	Lead author of the Bioeconomy report for the Czech Republic - debate on the different biomass potentials in agriculture
29.1.2020	Kutná Hora	Supply chain director of a straw incineration plant EC Kutná Hora - visit at the straw incineration plant and a semi-structured interview on straw supply chains and sustainability guidelines
29.1.2020	Přelouč	Director of a company Ekopanely - visit at a company manufacturing construction desks from straw and a semi-structured interview on straw supply chains
28.1.2020	Prague	Director of the Czech Technological Platform for Biofuels – discussion on the Restep project that analyzed the potential of bioeconomy in the Czech Republic
26.9.2019	Prague	Event: Best practices in bioeconomy. Organized by the Czech University of Life Sciences
17.10.2019	Prague	Event: Conference on biodiversity and agriculture under the Czech Ministry of Environment
3.11.2019	Brno	Event: "Break through the droughts" Conference organized by the Czech parliamentary group on droughts and the impact on agriculture
13.12.2019	Prague	Event: Seminar in the Czech parliament organized by the Institutue of Circular Economy on the Circular Economy legislative package from the European Commission
16.12.2019	Prague	Event: Seminar on bioeconomy organized by the Insitute of Circular Economy

4 Background Chapter on Data and Assumptions behind the MFA model

In the following part detailed description of the data sources and necessary assumptions behind the MFA model are described in more detail. The MFA was divided into four main phases of biomass transformation, i.e. Harvest (*take*), Production (*make*), Use (*consume*) and End-of-life (*disposal*) phase. The sources and sinks of the individual flows, the exact values and the reliability of the data were recorded using an excel sheet which then served as the basis for the visualization using e!sankey programme (see Annex 1).

The Harvest phase is the ''take'' part of the whole biomass lifecycle and it represents the total domestic extraction of raw agricultural biomass while considering imports and exports of the raw biomass. The CSO served as the main source of data in order to identify crop yields of cereals, sugar crops, oil seeds, green-silage maize, fruits and vegetables, arable fodder crops and permanent grasslands. These crops represent majority (> 95 %) of the overall agricultural production in the Czech Republic (CSO, 2019). Generally, two biomass yields were distinguished: economic (e.g. grain) and residue (e.g. straw). The economic yield per crop are reported by the CSO and were directly extracted. The economic production was then assumed to flow into the respective production processes, i.e. plant and animal food & feed production or technical processes (more detail below). The exports and imports of raw biomass were also accounted for.

Table 2: Economic yields in the Czech Republic as extracted from the CSO & Residue yields as calculated from Garciá-Condado et al. (2019).

Crop	*Area [ha]*	*Economic Yield [t/ha]*	*Economic Yield [Mt]*	*Residue Yield [t/ha]*	*Residue Yield [Mt]*
Wheat	819690	5.4	4.4	5.9	4.9
Rye	25355	4.7	0.1	4.7	0.1
Barley	324724	5.0	1.6	4.0	1.3
Oat	42821	3.6	0.2	4.1	0.2
Triticale	37851	4.6	0.2	5.2	0.2
Grain Maize	81851	6.0	0.5	8.9	0.7
Potatoes	22889	26.0	0.6	2.2	0.1
Sugar Beet	64760	58.0	3.7	5.5	0.4
Rapeseed	411802	3.4	1.4	8.6	3.5
Green & Silage Maize	224105	30.0	6.7	0	0
Perennial Fodder Crops	193199	5.5	1.1	0	0
Arable Fodder Crops	468604	8.5	4.0	0	0
Permanent Grassland	971791	2.5	2.5	0	0
Sum	2768952		22.9		11.3

Identifying the residue yields is more complex as it is dependent on several factors such as climate, location, specific crop type or interannual variability and it is therefore less accurate than economic yield (Scarlat et al., 2019). García-Condado et al. (2019) published one of the most detailed and up-to date analyses for this. They provide average residue yields (dry ton per hectare) for all EU member states for each crop and the theoretical residue availability can thus be estimated based on their database[7] (see table 2). For fodder crops, silage maize and grasslands no residue yields were considered as the production of by-products in their use is marginal.

The total residue yield estimates represented the theoretical potential of primary residues (see section 2.4) of which cereal and rapeseed straw represented the majority (> 95 %). The technical potential was extracted from (Scarlat et al., 2019) and was assumed uniform to all the EU countries (approximately 60 %). Sustainable removal rates were set at a constant value of 33 % of the theoretical availability[8] (Scarlat et al., 2010, Thorenz et al., 2018). The uses of straw were then considered including animal bedding, animal feed, fertilizing (ploughing the straw into the soil) and technical use (mainly bioenergy). The animal bedding part was extracted from a study that already assessed this thoroughly for majority of the EU countries and is based on the number of livestock and specific stabling practices (Scarlat, Nicolae, Martinov, & Dallemand, 2010). This value was then cross-checked with (Kalt, 2015) who also publishes the use of straw in animal bedding in Austria and his numbers were recalculated to a Czech context[9]. The use of straw in technical cycles is not reported by the statistical offices. An estimate on the use of straw in technical cycles was made during a visit at the straw incineration plant in the city of Kutná Hora. This was done together with the supply chain director of the plant and based on the amount of large incineration plants and pellet mills. The estimate on the amount of straw that has been left on the field or ploughed back was calculated from mass balances based on the competing uses and on the farming practices retrieved from the questionnaires.

The Production or ''make'' part of the whole system covers the production of food from animal and non-animal sources and the manufacturing of technical products (mainly biofuels).

The *Animal feed & food production* included the consumption of raw or partly processed biomass for feeding the livestock as well as the use of residual biomass as an animal bedding (described above). Meat, milk and egg production was considered as part of the animal food production. Meat production was extracted from the CSO. Beef, pork and poultry meat were only assumed as they cover more than 95 % of the overall production. The value for carcass weight is lower as it covers the part of animal for human consumption. Live weight is the weight of an animal after it has been slayed. The difference between these two values are assumed as the animal secondary residues from meat production. Additionally, milk and egg production and their processing residues were considered and retrieved from the CSO.

In order to assess feed consumption for animal products, the feed conversion ratio (FCR) was applied. This metric measures the amount of dry feed needed to produce a kg of a meat product. Specific FCRs were extracted from (Lesschen, Van den Berg, Westhoek, Witzke, & Oenema, 2011) and the meat production from CSO (table 3). Even though the feed consumption can be estimated based on FCRs, it is still difficult to estimate which crop type has been

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[7] Generally, there are large uncertainties around the exact production of lignocellulosic biomass and these values are hence still relatively uncertain (see the uncertainties range in García-Condado et al. (2019)

[8] Limitations of the constant removal rates are presented in the discussion section

[9] The use in animal bedding in the Czech Republic was adjusted to the number and composition of the livestock.

used for the feed. This metric was only reported for wheat and sugar beet by the Ministry of Agriculture (Kust & Záruba, 2018). It is then assumed that all grassland flows, and half of the plant secondary residues are fed to animals.

Table 3: Estimates on feed demands based on the Feed to Conversion Ratio (FCR).

Animal product	Production in carcass weight[10] [t]	Production in live weight [t]	FCR [$t_{feed}/t_{product}$]	Feed Estimate [Mt]
Cow's Milk	3078000	3078000	1.20	3.69
Beef	71181	136667	19.80	1.41
Pork	210910	288076	4.10	0.86
Poultry	164261	260084	3.30	0.54

The manure production was estimated based on the number of livestock and on the average manure production per head as already assessed in Foged et al. (Foged et al., 2012). Manure application on the field is reported by the CSO. The resulting manure is then assumed as administered towards biogas production in agricultural biogas plants.

The *Plant food production* was considered for cereals, sugar crops (sugar beet, potatoes), oil crops (rapeseed) and for fruits and vegetables. The latter two are marginal in the overall agriculture production (less than 5 %) but are relevant in the consumption phase and in the import and export balances. The CSO provides figures on the consumption of given commodities. From mass balances and from the import flows, the amount of raw biomass flowing from *Harvest* to *Plant food production* was calculated. Secondary residues from plant food processing were assumed for cereals, potatoes, sugar beet, oil crops and fruits and vegetables. The official statistics were insufficient to receive a picture of the overall secondary residues production. The European Agrimax project gives estimates on the plant processing residues for potatoes, wheat and sugar beet (Montanati, Cigognini, & Cifarelli, 2015). The main residues from cereal processing were considered as husk and bran with the production of residues of about 20-25 % from the whole grain. For potatoes and sugar beet the generated waste in their processing is approximately 20 % with potato peels and sugar beet pulp as the main residue types (Montanati et al., 2015). For other biomass types additional search for the average generation of processing residues was made. Large uncertainties exist for these data points and further investigation should be made in order to increase the reliability.

The *Technical production* covers the use of biomass for bioenergy (heat and electricity provision) in biomass incineration plants and as a feedstock to produce biofuels (biodiesel and bioethanol). No second-generation biofuels refinery using residual biomass exists in the Czech Republic and thus only economic biomass production is used as a feedstock for biofuels production. Mainly oilseeds for the production of biodiesel, and sugar beet and corn for ethanol production are included. Additionally, a screening on other potential uses of crops or their residues in the technical use has been made. Small pellet mills for straw, using straw in construction materials and as an insulation were also identified as relevant and an estimate was made. No other processes are herein considered. From agriculture only baled and pelleted straw were assumed as a feedstock into large incineration plants. Official statistics, however, do not report on this. An estimate on the use of straw in technical cycles was made during a visit at the straw incineration

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[10] The separation into carcass and live weight does not apply for milk production.

plant in Kutná Hora (see explanation above). Biofuels production and consumption was extracted from the Ministry of Industry and Trade (Ministry of Industry and Trade, 2019). The amount of rapeseed needed to produce biodiesel was calculated based on the efficiency for oil extraction and for the biofuel production efficiency from the oil (Ayuk, Umunakwe, & Ejele, 2011). Secondary residues were also considered as a waste from the oil extraction. The Ministry of Agriculture also reports on the amount of rapeseed and sugar beet used for biodiesel and bioethanol production respectively (Froněk, 2019). Similarly, to the plant food production, secondary residues from biofuel production are based on a crude estimate and more insights must be made to retrieve more reliable data.

In the *Consumption* phase the food consumption, and biofuels and straw consumption (loss of mass into carbon dioxide) were considered. Data on the food consumption are reported by the CSO on per capita basis for different commodities. These were differentiated into Animal and non-Animal sources so that flows from respective processes (*Animal feed & food Production* and *Plant food production*) could have been differentiated. Human metabolism was calculated from the daily energy consumption per capita (FAO, 2001) and converted to mass by assuming a fully carbohydrate-based diet (17 kJ/g). In the consumption phase no import or export is considered as the movement of goods is covered in the production part. The tertiary residues (human & food waste) are being produced in the consumption phase. The total food waste was calculated on per capita basis and extracted from (Eurostat, 2016). The human waste was calculated on per capita basis as published in (Rose, Parker, Jefferson, & Cartmell, 2015).

The secondary residues from *Plant food production*, *Technical production* and *Animal feed & food production* were together with tertiary residues and manure directed towards a node named ‘‘*Total Secondary & Tertiary Residues*’’. This was done for two reasons: Firstly, to highlight the amount of residues from agriculture and thus visualize the potentially underutilized biomass. Secondly, to make the MFA understandable and unnecessarily complex.

The *Disposal* or *End-of-life (EOL)* part included the final processing of the waste materials and included the following process: anaerobic digestion in biogas (BG) plants, composting, incineration, wastewater treatment plants and landfilling. Overall there are 554 BG plants of which 383 are agricultural (energy crops + manure as feedstock) and only 17 are biowaste (Calderón, Colla, & Jossart, 2019). Only the agricultural BG plants which account for 80 % of the total BG infrastructure were considered. The feedstock into these BG plants is not reported by any official statistics. The input was thus calculated based on the heat and electricity generated from these BG plants (ERÚ, 2018) and from the amount of biogas needed for such production. The energy and biogas values were then considered as 80 % of the total in order to adjust only for the agricultural BG plants. Given that the biogas potential of different feedstocks is diverse (e.g. maize vs. manure) additional estimates based on the proportion of the different feedstocks as an input were consulted with an expert (Novotný, personal communication, January 24, 2020). The annual production of biogas was then converted to mass assuming a weight of a 1.15 kg/m^3 (Jørgensen, 2009)

Digestate production was extracted from Jeřábková & Dufková (Jeřábková & Duffková, 2019) and all is assumed to be returned to the soil. The sludge produced in the wastewater treatment plants and the amount of sludge that is applied to the soil was extracted from (Wanner, 2019). The amount of waste composted is reported by CENIA, however, this figure includes also other biodegradable materials such as wood or textile which are outside of the scope. It was therefore adjusted to food and processing waste only. All compost produced is assumed as going back to the field. Biogenic waste that is landfilled or incinerated was derived from the share of total waste incinerated or landfilled (CENIA, 2018).

5 Literature Review and stakeholder consultation

In this section the findings from the work stream on biomass mobilization are presented. Firstly, an overview of the main barriers identified during the literature search is introduced. Then the results from the questionnaire on farmers use of straw and on their willingness to provide it is set out. Finally, main takeaways from the expert roundtable workshop are enumerated. The aim of this work stream is answering the following (sub)research question:

''What are the barriers that hinder the mobilization of regional biomass feedstock into high-value added bio-based industries and what strategies might help overcome these barriers?''

5.1 Literature review on barriers to biomass mobilization

From the literature review three main publications served as a suitable overview to the biomass mobilization barriers. Lamers, Searcy, Hess, & Stichnothe, (2016), Smith et al., (2017) and Uslu et al., (2018) all provide similarly detailed analysis of the potential barriers that constrain the effective use of biomass (see figure 6). They mostly distinguish between economic, institutional, social and technical barriers illustrating the diversity of hurdles. Investigating all these barriers would be outside of the scope of this thesis, however, some of them can already be estimated by having an insight into the Czech agriculture from the discussions with diverse stakeholders (see stakeholder consultation in table 1). With no bioeconomy strategy in place, many of the institutional barriers apply to the Czech Republic. This has been highlighted by several stakeholders during the different discussion or events attended as well as by (Piotrowski & Dammer, 2018). There are limited sustainability guidelines, and a long-term and coherent bioeconomy strategy that would be coordinated among the different ministries is missing.

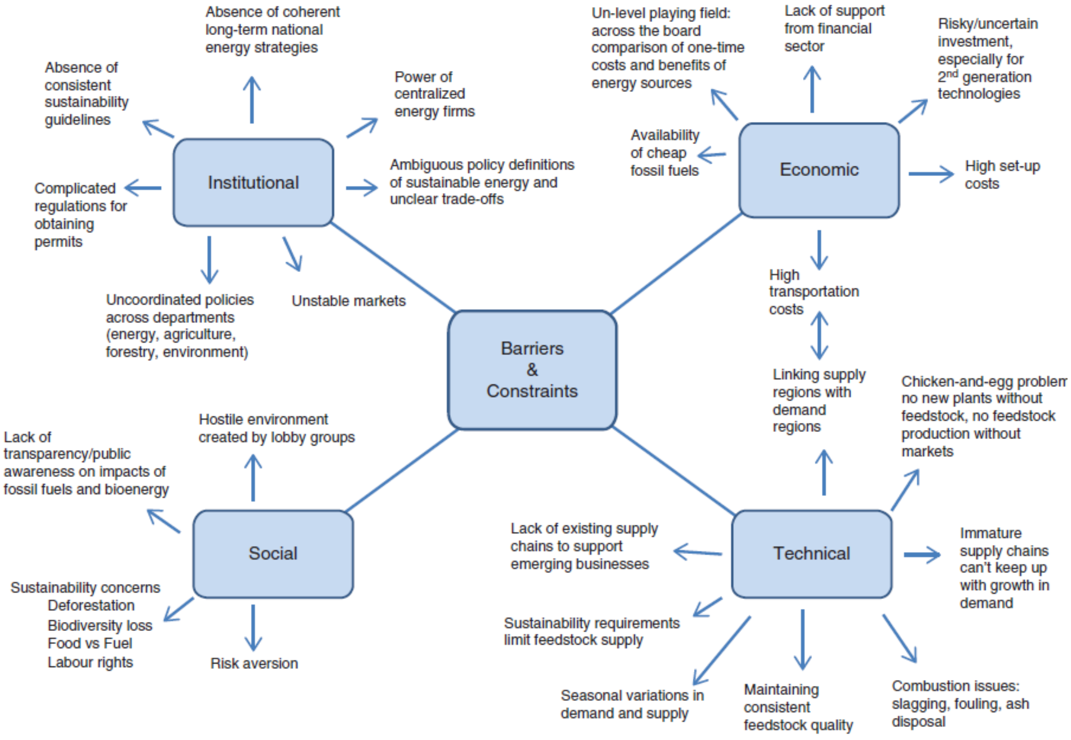

Figure 6: Overview of barriers to mobilizing biomass (Smith et al., 2017).

The economic barriers are, to a large extent, transferrable and can be applied to the context of the Czech Republic, especially when it comes to the risks and costs of the specific technologies utilizing residual biomass (e.g. advanced biofuels). The uncertainty around the reliability and feasibility of these technologies makes the mobilization risky thus potentially discouraging private investors. High set-up costs and transportation costs were also highlighted during the expert roundtable workshop. The economic barriers are, nevertheless, based on a specific technology which is more elaborated upon in the literature review on lignocellulosic business cases.

Generally, the lignocellulosic materials are bulky, and their pre-treatment, storing or transport is costly which makes the feedstock less competitive. Indeed, the dispersed nature of straw and its interannual variability is often cited as one of the greatest barriers to its use (Camia et al., 2018; IRENA, 2019; Johnsson & Papadokonstantakis, 2018; Uslu, 2018). From the personal visit at the straw incineration plant in Kutná Hora and at the company Ekopanely, the logistic infrastructure of these facilities is rather simple and there are limited measures that would balance feedstock quality and/or the seasonal variations in demand and supply. The need for advanced feedstock designs systems that would stabilize the interannual variability in yields, quality and price is thus potential driver for overcoming these barriers (Lamers et al., 2016).

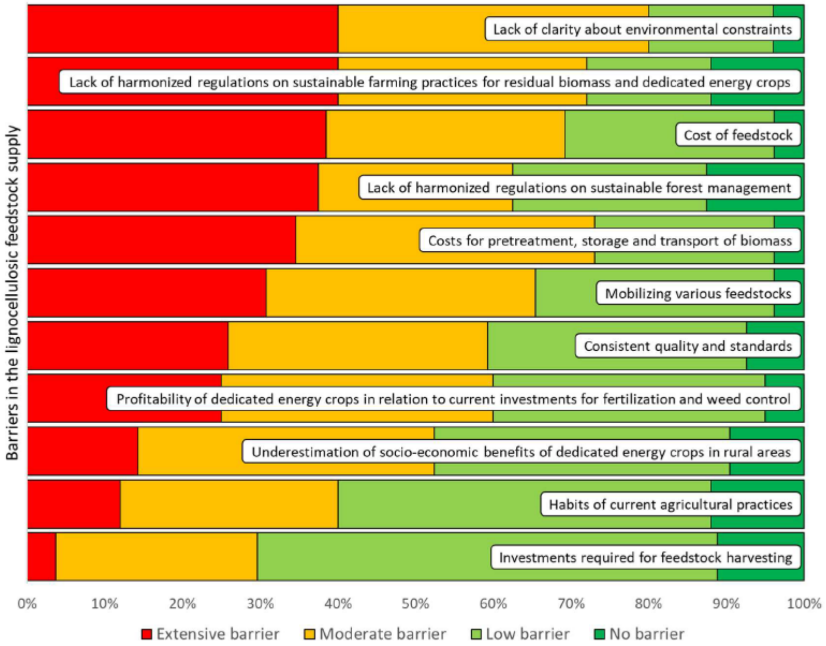

Figure 7:Barriers in the lignocellulosic supply (Uslu et al., 2018)

Uslu et al., (2018) provided also the quantification of the individual barriers by surveying stakeholders from diverse groups on the EU level ranging from academia through industry to policy makers (figure 7). Mainly the institutional and social barriers such as the lack of clarity about environmental constraints and lack of harmonized regulations on suitable farming practices for residual biomass were identified as most pressing. They therefore confirm the necessity to understand the context specific group of farmers and their perception on providing (residual) biomass to logistic companies or to the bio-based industries directly. What was therefore deemed as highly Czech specific and at the time of reviewing the literature yet unanswered were the social barriers and the position of the providers of the residual biomass. This is investigated in the following chapter by a survey.

5.2 Questionnaire

The questionnaire provided a valuable insight into the farmers' willingness to provide lignocellulosic material (straw) as well as on their farming practices. Overall 361 responses were recorded mainly by the Association of Private Farming (91 %) and only a few responses were recorded by the Agrarian Association (5 %) and the Agrarian Council (2 %) (figure 8a). Other contacted association did not participate. The respondents represented mainly medium sized farms (50 – 250 ha) (48 %) and small sized farmers (0 – 50 ha) represented 35 % of the answers (figure 8c)[11]. More than 85 % of the respondents were running a farm for more than 10 years illustrating the importance of established farming practices (figure 8b).

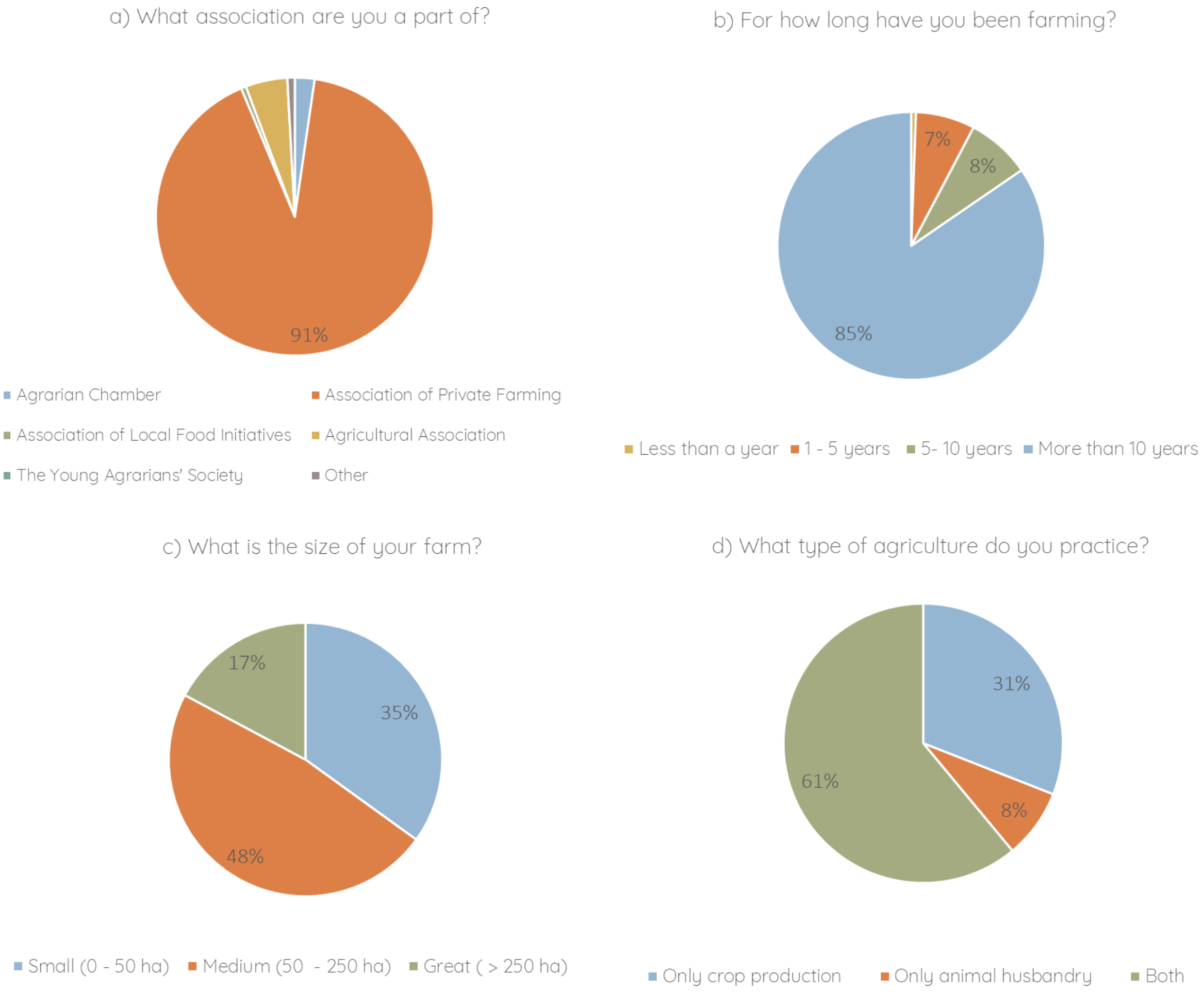

Figure 8: Questionnaire results illustrating the characteristic of the sample group: a) The respondents' affiliation to an agricultural association; b) Length of operating the farm; c) Size of respondents' farm; d) Type of agricultural practices;

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[11] The Czech Republic has the highest average utilized area per holding in the whole EU. The average value is around 130 ha per holding whereas for the EU it is less than 20 ha per holding (Eurostat, 2018).

Only 7 % were operating an agricultural business for less than 5 years. More than half of the farmers practice crop production and animal husbandry jointly (61 %) (mixed farming) and only 8 % had an animal husbandry business (figure 8d). Around 31 % do only crop harvesting. Majority of the respondents practice a conventional agriculture (77 %) and just a handful (17 %) practice ecological farming with a license (figure 9a). Only 15 % farm on privately owned soil which is a typical characteristic of the Czech agriculture.[12] The majority (84 %) farm on partly leased and partly owned soil (figure 9b). Overall, the sample is relatively close to the typical Czech agricultural holding (see Eurostat, 2018).

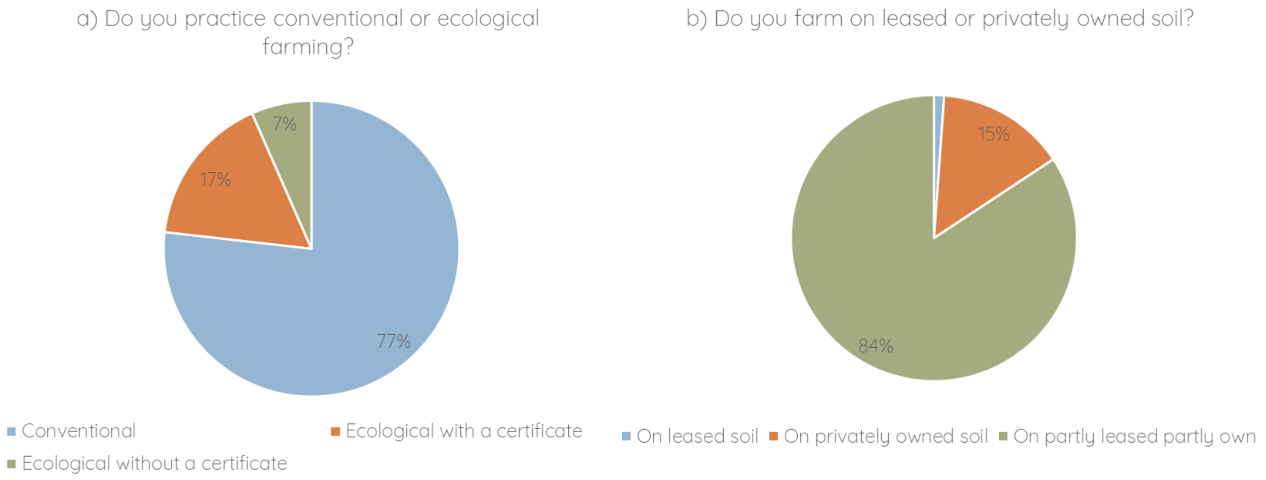

Figure 9: Questionnaire results illustrating the characteristic of the sample group: a) Number of farmers practicing ecological farming (b) and the proportion of farmers on leased or privately owned soil.

Most respondents (85 %) indeed produce post-harvest residues such as straw as part of their farming practices (figure 10b). More importantly, 88 % of these producers perceive straw as a highly valuable commodity and only a minority (around 4 %) does not view straw as valuable (figure 10a).

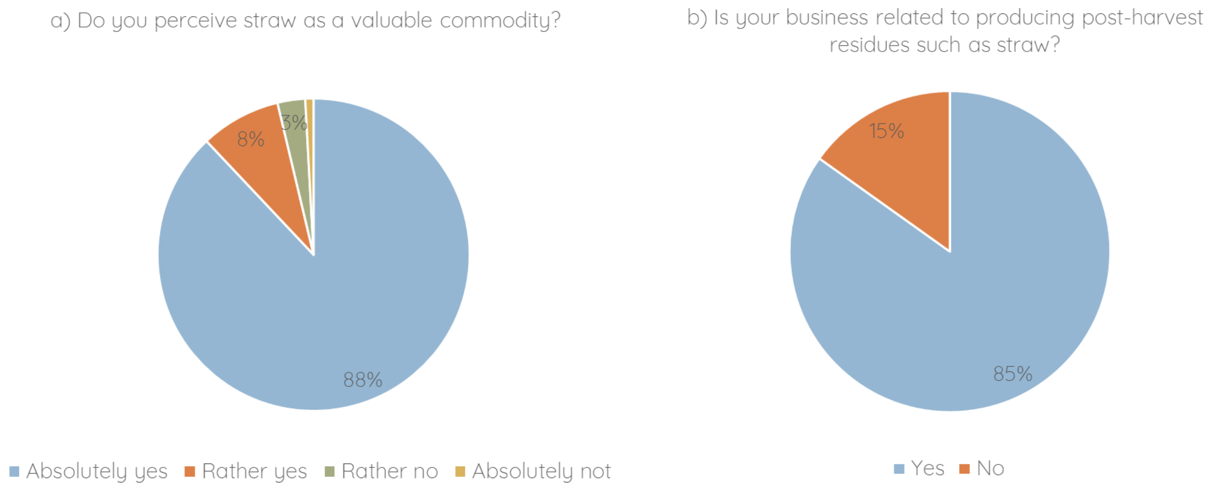

Figure 10: (a) Importance of straw and (b) the proportion of respondents that produce post-harvest residues

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[12] In the Czech Republic more than 74 % of the soil is rented to an individual or a legal entity (Trnka, 2018).

An important finding is that 84 % use the straw only for their own purposes and only 15 % partly sell it (figure 11a). This signifies the relevance of straw in agricultural businesses. Out of those that use the straw solely for their own means, 26 % only plough the straw back to the soil, 33 % use it as animal bedding and 38 % use it in a combination (part is ploughed back part is used as animal bedding (figure 11b). Only 2 % use the straw for other purposes such as mulch in mushroom production or as a feed. Some of them trade the straw for manure[13]. This shows that animal bedding and fertilizing are the major uses of straw in agriculture. No respondent reported that they sell all the straw that they produce.

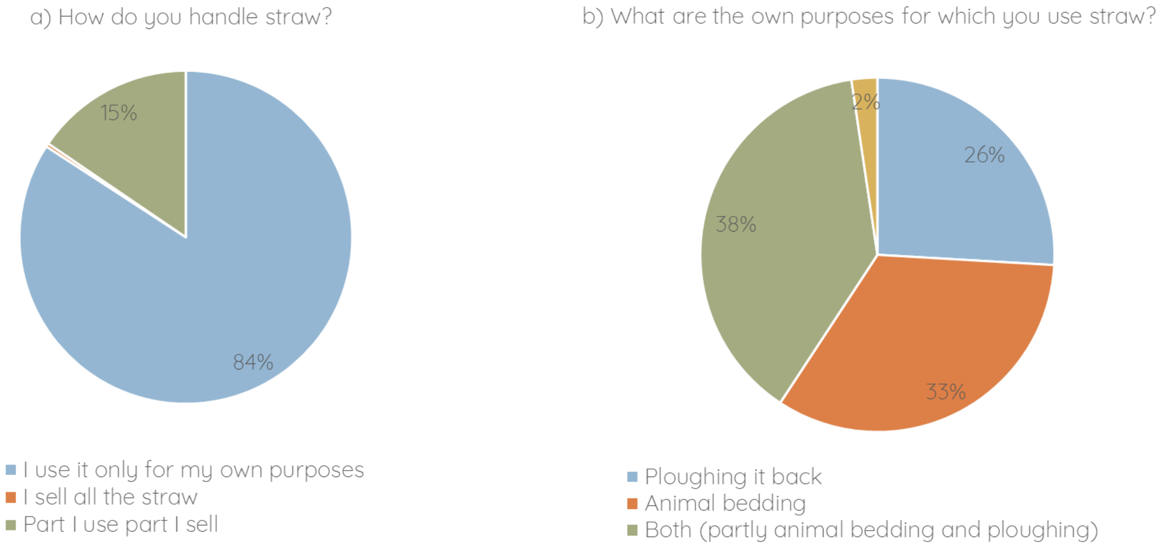

Figure 11: a) Handling of straw for own or other purposes; b) Specific use of straw for own means

Those respondents that sell at least part of the straw (only 15 %) report that mainly the price and partly the subsequent use of the straw is their decisive factor (34 %) (figure 12). For only 11 % the price solely is the decisive factor prior to sale and 9 % report that the subsequent use of straw is their priority. Relatively large amount of respondent (26 %) report other factors that are decisive for them in an open question. These are mainly their obligation towards a signed contract, demand from those lacking the straw and a trade for manure.

Around 49 % are highly concerned about what is the use of straw after the sale and 30 % are moderately concerned illustrating the value of straw for the farmers (figure 13). Only 20 % are either totally or moderately unconcerned. This signifies the importance of reputation of the bio-based industries in general. From the authors' own experience and from the rather negative media coverage of food-based biofuels, the notion about using crops in technical cycles is generally perceived negatively.

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[13] The use of straw other than an animal bedding or as a fertilizer was recorded using an open question.

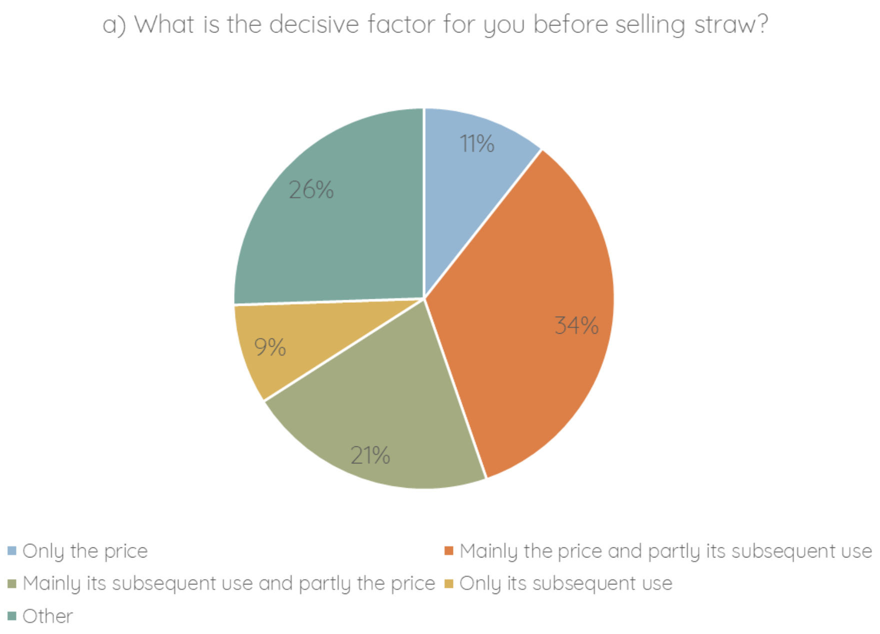

Figure 12: Decisive factor for the farmers to sell the straw

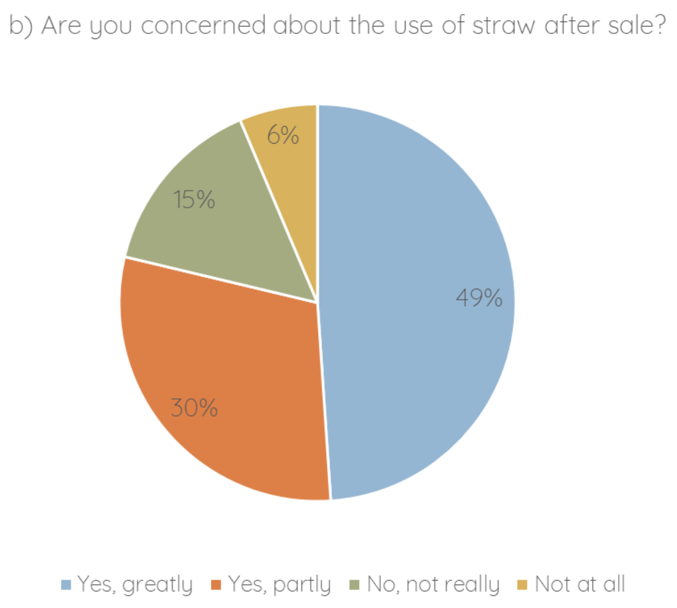

Figure 13: Level of concern regarding the after sale use of straw

When sold, majority of the biomass is directed to animal bedding (55 %), 21 % is used as a feed and 16 % as a feedstock to incineration plants[14] (figure 14). Other post-sale uses such as feedstock into BG plants, material use, or export of the straw are marginal.

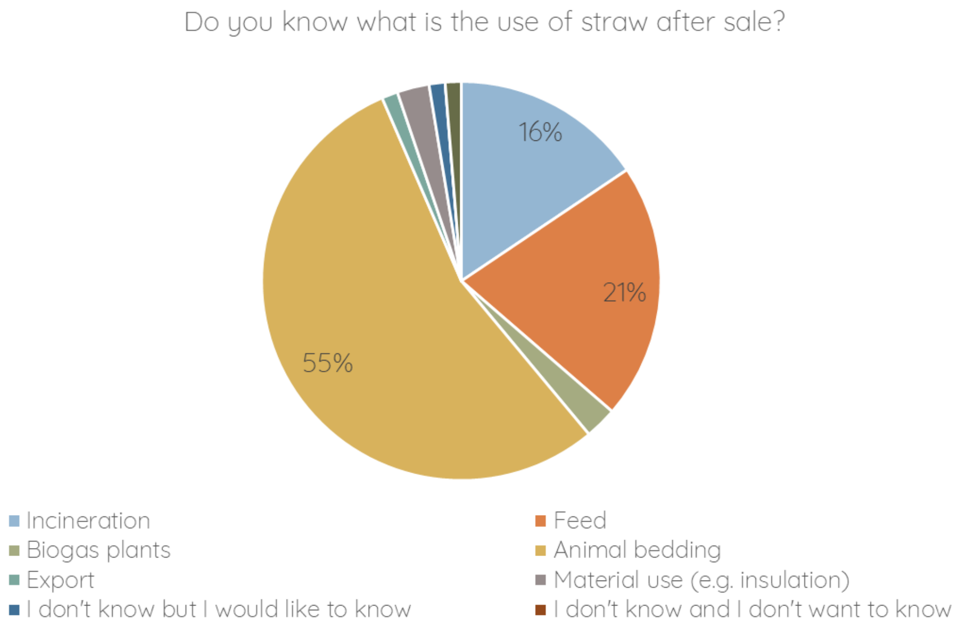

Figure 14: Use of straw after sale

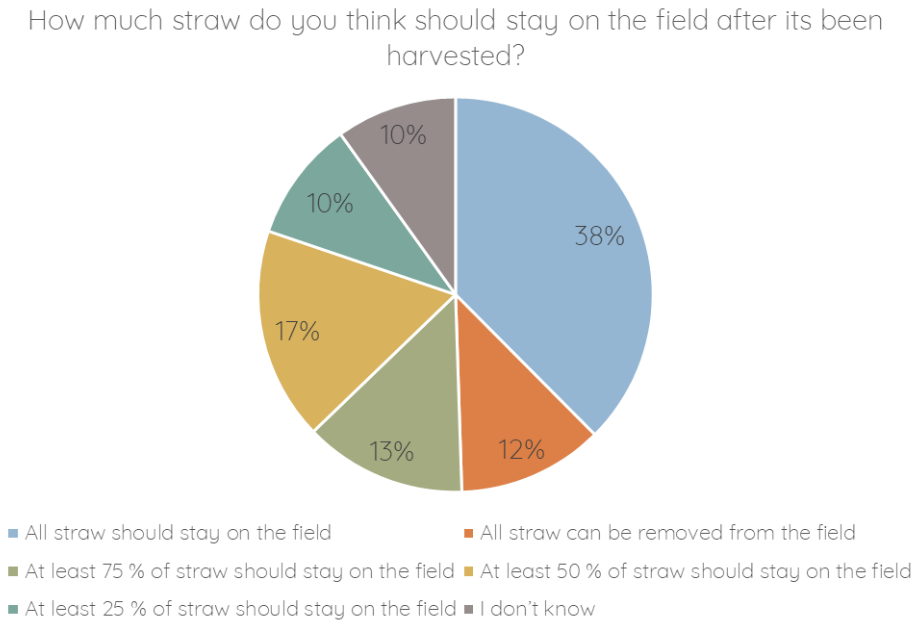

Figure 15: Agricultural practices in terms of the amount of straw that should be ploughed back into the soil

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[14] From this response the use of straw in the MFA is partially deducted together with international estimates on the straw use.

More importantly, there is a confusion around the proper use of straw to remain the SOC balance and the respondents showed large diversity when answering the amount of straw that should be left on the field (figure 15). Approximately 38 % responded that all straw should be left on the field and 13 % that at least 75 % of the straw annually produced should be ploughed back. Around 17 % and 10 % responded that less than 50 % and 25 % respectively should be left on the field. Only 12 % think that all straw can be removed. Resulting 10 % don’t know what is the right amount of straw that should be ploughed back. While more than half of the farmers think that at least 75 % of straw should be left on the field, there is by no means a consensus around its proper use. This confirms the most pressing barrier by Uslu et al., (2018) namely the ‘’lack of clarity about environmental constraints’’ and ‘’lack of harmonized regulations on sustainable farming practices for residual biomass’’.

The aim of the questionnaire was also to explore whether other materials that are perceived by the farmers as waste could be identified and subsequently utilized as accordance to CE principles. However, only 7 % of the respondents reported that they produce a material that they view as a waste and that they no longer use (see Annex 3). More than 64 % don’t produce any waste and 29 % produce a material that they perceive as waste, however, which they utilize afterwards. Majority of the specified waste was manure (60 %) followed by processing residues such as chaff or washing waste (22 %). Others reported a plastic or packaging waste (9 %) as part of the bailing of straw or from other unspecified processes. This illustrates that there are limited underutilized biomass types other than the primary residues.

Overall, the questionnaire highlights the importance of straw to the farmers and the fact that it is mostly used where it is produced (only 15 % is sold). For majority of the respondents’ price is not the only decisive factor. Animal bedding and ploughing straw to the soil are the main competing uses for bio-based utilization pathways and these largely limit the mobilization. For majority of the farmers straw is a highly valuable commodity. There is a confusion among the farmers on the proper farming practices when it comes to post-harvest use of the residues, however, leaving more than 75 % of the straw on the field is supported by the majority. There seem to be no other materials at the hands of farmers that shows a significant potential other than manure and waste from washing the crops. The potential drivers to overcome the barriers are presented in the discussions section and as a result from the Expert Roundtable Workshop.

5.3 Expert Roundtable Workshop

The literature review and the survey allowed for a valuable insight into both the EU-wide barriers to mobilizing biomass as well as to the Czech specific societal barriers on the farmers level. The expert roundtable workshop was held in order to receive more holistic picture of using residual biomass in the Czech Republic. Generally, the participants at the expert roundtable workshop were rather critical on the use of biomass in the bio-based industries. There are several reasons for this. Firstly, the first-generation biofuels have created a negative perception both in the public eye and in a more professional circles on the use of biomass for other than food-related uses. While the new policies focus on advanced feedstock such as residuals, these biomass types are still viewed as important part of the carbon cycle. Secondly, the soil quality in the Czech Republic has been rapidly decreasing also as part of the severe droughts that took place in the years 2017 and 2018 (Kukla & Kourková, 2019). Any additional removal of biomass (carbon) is thus often viewed as controversial. The Czech agricultural landscape is already relatively intensified with the highest utilized area per holding and any further intensification is viewed as controversial (Eurostat, 2018). In light of these contextual factors, the participants came to the following consensus on biomass mobilization and on the strategic use of biomass in the Czech Republic:

- Prior to mobilizing biomass, a coherent national strategy on the suitable end-uses should be established in order to avoid the institutional barriers existing.
- Extracting additional carbon from the soil in the form of biomass other than for food purposes should be based on regional climatic conditions, soil structures and other regionally related variables. The biomass mobilization should thus be regionally based, and these areas should be supported in creating their own bioeconomy strategy.
- Retaining or increasing the soil quality should be priority in all instances when extracting biomass. This is extremely important taking the droughts and worsening soil quality in the Czech Republic.
- Generally, mobilizing agricultural residual biomass directly into bioenergy facilities shouldn't be supported due to the direct loss of value (against CE principles), low added value and due to the negatively exacerbating effect on soil quality levels[15]. Other forms of providing energy such as solar and wind should be supported instead of biomass.
- Most 2nd generation biofuels are yet not competitive with conventional biofuels and other forms of providing renewable transport fuels should be explored (e.g. Power-to-X, biomethane, hydrogen) irrespective of the emphasis on advanced biofuels by the European Commission. Otherwise, the RED II transport targets might be difficult to achieve.
- In case the sustainability constraints allow it, biomass, be it residual or crop, should be directed primarily towards bio-based industries with very high value-added utilizations (e.g. biochemicals such as cosmetics or man-made fibers).
- In these instances, suitable supply chains should be set up that can ensure sustainability guidelines in order to avoid the technical barriers in biomass mobilization.
- Focus on cascading should be stressed. Mainly the economic valuation of cascading was pronounced, i.e. using biomass in high-value added business, rather than the sequential use of biomass (see section 2.1).
- There is a large difference between primary, secondary and tertiary residues as only the latter and partly the secondary residues can be viewed as a waste. Primary residues should not be viewed as waste as their current use plays an important role.
- Clear intersection between forestry and agriculture in the bioeconomy strategy should be made.[16]
- An investigation into potentially unused lands should be made in order to reevaluate the potential of biomass in the Czech Republic
- Biodiversity should be an important element in designing any bioeconomy strategy.

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[15] The reason for this is also the fact that the two large incineration plants of straw which are located around the cities of Kutná Hora and Jindřichův Hradce have made a negative impression in the professional's circle as well as in the eyes of the farmers. The reason for this is mainly the inadequate supply chain that is vertically integrated and where the need for ensuring sustainable removal rates have been rather ignored. There are no bio-based hubs that would support the interannual variability and ensure sustainable practices.

[16] From 2017 onwards the Czech forests were seriously hit by the beetle bug creating an oversupply of biomass.

5.4 Literature review on sustainable business cases

The following section is based on a short literature review that compares the different pathways for utilizing lignocellulosic biomass (straw) for the case of the Czech Republic. Firstly, a context for each sector is given and the implicit SWOT factors are introduced. The bottlenecks and drivers for each end-market are presented. The aim is not to give an exhaustive review of each of these categories but rather to present the more general SWOT factors as well as to pinpoint the circularity aspects of each segment. Firstly, the advanced biofuels are presented. This is differentiated into Renewable Jet Fuels (RJFs) and Renewable Road Fuels (RRFs). This is followed by a section on the bio-based chemicals. Finally, analysis of the biocomposite and construction sector is given. The final SWOT analysis is presented in the results section.

5.4.1 Advanced biofuels in transport and aviation:

In 2017, around 27 % of the total EU greenhouse gas emissions came from the transport sector (EEA, 2019). Road transport is the most significant contributor to the total GHG emissions (72 %), followed by aviation (14 %) and maritime shipping (13 %). Advanced biofuels that are on average reducing the GHG footprint by 60 – 95 % (IRENA, 2019) are thus a necessary component of the climate package towards climate neutrality by 2050. Cereal straw is one of the main feedstocks for the advanced biofuels. Especially renewable jet fuels (RJFs) in aviation will have limited substitutes other than those derived from biomass (Staples, Malina, Suresh, Hileman, & Barrett, 2018a). The RED II directive set a clear target for the share of renewable fuels in the final energy consumption at 3.5 %[17] by 2030 and lignocellulosic pathways are supposed to play an important role in fulfilling these objectives. There are, however, several barriers and weakness points that did not propel the take up of the lignocellulosic advanced biofuels yet. This is especially connected to the specific properties of the lignocellulosic feedstock which is generally difficult to handle. First, the Renewable Jet Fuel market will be presented followed by the Renewable Road Transport Fuels.

5.4.1.1 Renewable Jet Fuels

Aviation is an enticing economic sector which is expected to grow substantially in the upcoming years. In fact, the International Air Transport Association predicts double passenger numbers by 2037 (IATA, 2018). Unfortunately, such growth corresponds to substantial increase in GHG emissions and aviation is projected to consume around third of the global carbon budget by 2050 under a business-as-usual scenario (Graver, Zhang, & Rutherford, 2019). Finding alternatives for current fossil-based kerosene is therefore a necessity.

Decarbonization in the aviation sector is opposed to road transport or heavy industry operating on a fully global scale making it difficult to set binding and collective targets. The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) organized under the International Civil Aviation Organization (ICAO) should alter this situation. This initiative which aims at reducing the GHG emissions by direct decarbonization (different fuels) and by offering effective offsetting schemes will be applicable from 2021 onwards on an international level. Compliance will be voluntary until 2027, however, afterwards provisions of such measure will be binding (Scheelhaase, Maertens,

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[17] 0.2% required in 2022, 1.0% required in 2025, 3.5% required in 2030. Fuels may be double-counted to achieve this target, which implies that the targets are only 0.1%, 0.5% and 1.75%

Grimme, & Jung, 2018). The existence of CORSIA is relevant from the perspective of stable policy and market guidelines that can create a more solid grounds for investments.

The aviation sector will probably rely to a large extent on biomass as a feedstock to produce renewable kerosene like fuels (Graver et al., 2019). There exist several pathways of converting raw biomass into RJFs. The Hydroprocessed Esters and Fatty Acid (HEFA) is the most developed pathway which is technically matured and already commercialized (Fuel Readiness level[18] 6-8) (Mawhood, Gazis, de Jong, Hoefnagels, & Slade, 2016). In fact, almost all flights to this date that blend biofuels use HEFA based RJFs (Mawhood et al., 2016). The HEFA pathway uses vegetable oils, animal fats and used cooking oil (UCO) as a feedstock. This type of feedstock, however, substantially limits the scaling potential of HEFA and is thus posing a barrier towards higher uptake (Le Feuvre, 2019). Furthermore, environmental concerns about using pure vegetable oils for RJFs are often pronounced (Tao, Milbrandt, Zhang, & Wang, 2017). The UCOs are also limited in their supply as they are mostly already used in biodiesel production in the EU (Spöttle et al., 2013). The HEFA production is also limited economically by a high price (the price of vegetable oil is almost the same as petrol made kerosene) (Bann et al., 2017).

In light of the above, other pathways which are cost-effective and more in line with sustainability principles are therefore being prospected. The lignocellulosic biomass is in fact perceived as a low-cost feedstock that additionally does not compete with food and feed demands. It is relatively abundant and there are technological options for producing RJFs from straw or other lignocellulosic materials (Johnsson & Papadokonstantakis, 2018) . Moreover, other feedstocks such as starch or sugar often collide with food and feed principle making the lignocellulosic pathway even more attractive. Additionally, agricultural and forest residuals are projected to remain relatively stable in terms of their price which cannot be said for oil crops or sugar crops (IRENA, 2019). From this perspective, straw is expected to become an important material.

There are extensive reviews on the specific lignocellulosic pathways, their processes and technical or non-technical barriers towards commercialization (E4tech, 2017; Johnsson & Papadokonstantakis, 2018; Mawhood et al., 2016; Wei et al., 2019), however naming all of them would be outside of the scope of this report. Generally, it can be said that these pathways are not in a fully commercial scale yet with relatively low technical maturity. Gasification and Fischer Tropsch Synthesis (FTS) at FRL 7-8, Aqueous phase reforming (APR) at FRL 6 and Hydrotreated depolymerized cellulosic jet (HDCJ) at FRL 6 are one of the most promising pathways, however, the E4tech, (2017) study identified around 15 promising pathways illustrating the uncertainty which direction will be taken. Wei et al., (2019) also provide minimum jet fuel selling prices[19] for FTS (6.23 – 7.57 USD/gallon), HDCJ (5.23 – 7.15 USD/gallon) and APR (7.30 – 7.82 USD/gallon). Given the current prices of gasoline the lignocellulosic fuels are approximately 2 to 6 times pricier than conventional jet fuels.

Generally, low price of the conventional fuels and conversely high costs of the RJFs pose a large barrier towards scale up. High capital and operational costs go hand in hand with insufficient technical maturity and more R&D is still necessary. Sufficient policy support such as subsidies, R&D funding, binding blending targets and stricter regulatory environment (carbon tax) are often cited as necessary in order to propel the RJFs (Staples, Malina, Suresh, Hileman, & Barrett, 2018b). These support mechanisms are especially important as developing RJFs is arguably more

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[18] The Fuel Readiness Level (FRL) is a similar measure to Technology Readiness Level only specified towards fuel characteristic for aviation engines with respect to the fuel's chemistry and compatibility with the infrastructure (Mawhood et al., 2016)

[19] The Minimum Jet-Fuel Selling Prices (MJSP) is the minimum price to obtain a net present value of zero for a 10 % internal rate of return (Wei et al., 2019)

difficult than RRFs due to higher complexity of the engine and safety requirements (Mawhood et al., 2016). Technical maturation is especially needed for lignocellulosic plants where straw could be used as a feedstock. Moreover, the advanced fuels for aviation compete with road transport fuels and biochemical markets. Given the relatively equal price of diesel and kerosene and the more expensive processing to produce RJFs, the aviation sector will have trouble competing with these markets. Similarly, the biochemical markets are processing often the same feedstock as RJFs, however, the former can ask for premium price in areas closer to the consumer such as cosmetics or man-made fibers.

Another reason for the slow uptake of the lignocellulosic RJFs is the complexity of handling the dispersed and bulky straw into centralized locations. This is exacerbated by the fact that the RJFs are often based on large scale plants for economies of scale which demands robust and well-planned supply chains that, however, often ramp up the price. Quality and seasonal variability are other factors that need to be balanced and where uncertainty exist. This, however, is common for all large scale lignocellulosic uses.

So far only demonstration plants exist and given that overcoming one FRL takes around 3-4 years (Mawhood et al., 2016) the use of lignocellulosic straw in the Czech Republic for these purposes on a commercial scale is rather improbable. The use of biomass for RJFs is also debatable from circularity perspective as they are rather bulky, with lower value added and with no possibility for further use. They are therefore relatively low on the cascading spectrum (applies both for sequential or value based cascading, see figure 1). The production of biofuels also generates less jobs than biomaterials or biochemicals (Carus & Dammer, 2018) thus performing weaker on the social dimension. From an environmental and GHG related perspective the use of biomass for RJFs might, however, be more impactful than in other areas (Stegmann et al., 2020). Moreover, even though the RJFs compete with other bio-based industries such as biochemicals, there exist limited substitutes for fossil-based kerosene making it more probable that this sector will be prioritized over others.

5.4.1.2 Advanced biofuels in Transport

Several climate scenarios indicate that large amounts of renewable fuels in the form of advanced biofuels will be necessary to fulfill the climate targets as set in the Paris Agreement (IEA, 2019). According to the EEA (2019), 8.1 % of the energy consumed in transport in 2018 was renewable and approximately 20 % from this number can be reported as advanced biofuels mostly made from UCO or animal fats. Moreover, crop-based biofuels are capped at 7 % incentivizing the use of advanced feedstocks which are reported in the Annex IX of the RED II directive. The agricultural residues currently, however, cover only around 1 % of the total biofuel production (Calderon, Gauthier, & Jossart, 2017). Similarly, to the RJFs production, lignocellulosic pathways will be, at least from a short-term perspective, crucial to achieve emission cuts in the transport sector (IRENA, 2019).

Renewable Road Fuels (RRF) share the same feedstocks as RJF pathways and technologically the conversion is very similar to RJFs. While the RRFs and RJFs are similar in terms of the feedstock used and technological conversion pathways, the market performances are slightly different. The RJFs require additional processing steps in order to increase the energy content of the fuel, making the RJFs often pricier. This is exacerbated by the fact that diesel and kerosene prices are fairly alike (Uslu, 2018). This generally makes the RRFs more competitive. In the EU the 3.5 % by 2030 binding target on advanced biofuels also creates a market stimulus and a clear guidance for the upcoming decade. This creates much more solid policy ground than in the aviation sector where limited guidelines are applicable. Moreover, the innovative capacity needed within RJFs production is much higher than the RRFs given the more complex engine structure and stricter safety standards. Finally, the lignocellulosic pathways for advanced biofuels are technologically more advanced and closer to its market penetration.

Enzymatic hydrolysis and fermentation pathway (or the Direct sugars to hydrocarbons (DSHC)) is one of the most promising pathways for utilizing straw into transport biofuel which has reached commercialization (see figure 16). The process is based on separating the main fractions of lignocellulose into lignin and a mixture of cellulose and hemicellulose which are then enzymatically converted to C5 and C6 sugars into ethanol or butanol. Lignocellulosic ethanol production is at the TRL 8. While the ethanol can be used in the road transport engines, for jet fuels additional conversion processes are needed putting this technology only at FRL 5-7 (Mawhood et al., 2016). Several companies have built demonstration plants for this technology to produce ethanol, however, with confusing success (see E4tech, 2019). The current production capacity in the EU is very low (15 ktons/year) compared to the worldwide production (293 ktons/years) (Hassan, Williams, & Jaiswal, 2019). Nevertheless, the production capacity is projected at 250 ktons/year by 2030 with two plants currently being built in Slovakia and a plant in Romania.

While the RRFs are probably more promising than the RJFs they are still not competitive to fossil-based fuels as they are approximately twice as pricier. IRENA states that oil prices need to exceed 100 USD per barrel so that the more technologically developed routes (lignocellulosic fermentation, syngas fermentation and gasification) can be competitive.

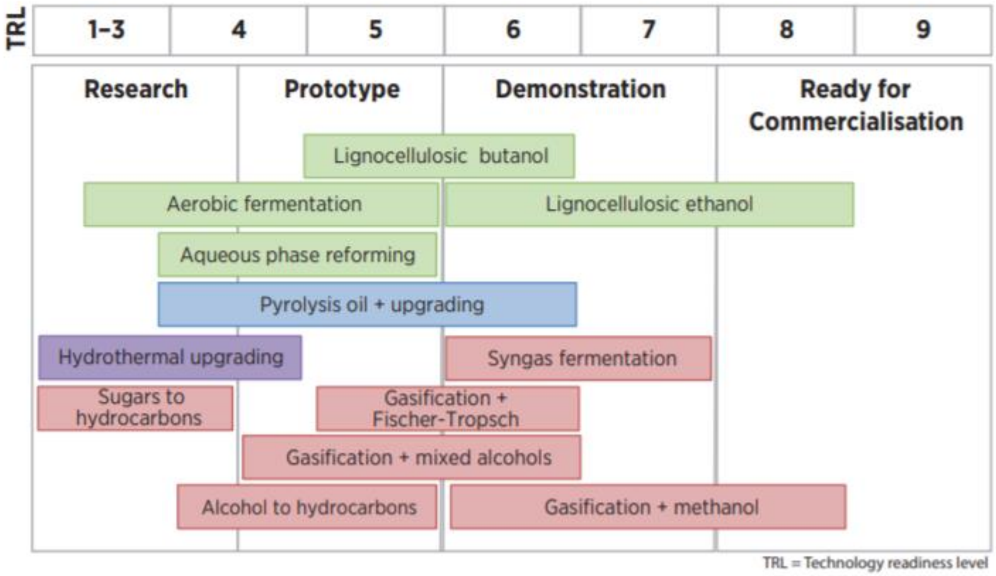

Figure 16: Technological readiness of the different conversion pathways of advanced biofuels

Moreover, the 3.5 % target can be fulfilled in other ways than those from lignocellulose such as compressing biomethane into bioCNG or by producing hydrogen from water via electrolysis run on renewable sources (power to gas). This creates a threat whether the lignocellulosic pathways using straw will materialize as the competitive one in the future. Mainly the feedstock quality and mobilization difficulties pose a large barrier. In fact, feedstock costs are approximately 40 – 70 % of the price fuel signifying the role of reliable and efficient supply chains (IRENA, 2019).

Generally stable and ambitious policy environment is necessary for the successful uptake of advanced biofuels. This can ensure project financing which is necessary to test and develop the yet technically immature conversion pathways. On the supply side, efficient and effective logistics and possibly alternative business models will be needed to ensure stable supply. Similarly, to RJFs the RRFs compete with more high-value based products such as chemicals creating a threat in terms of competitiveness.

The Czech Republic is bound to fulfilling the 3.5 % target, however, it is not yet clear whether the lignocellulosic pathway will be the main pathway to fulfill this. The advanced biofuels targets are also double counted making the total blending requirements rather small. Given the relatively large BG plants network the use of BioCNG might be preferred over lignocellulosic biofuels. From a circularity perspective, the same points as for the RJFs and the RRFs apply as being very close to the energy recovery spectrum of using materials without the possibility for further use. Both the sequential and value-base cascading is thus not possible.

5.4.2 Biochemicals:

The biochemicals market is a diverse economic sector that will largely rely on biomass sources as limited substitutes exist. The Road-To-Bio EU project created a roadmap with the aim to increase the proportion of bio-based chemicals to 25 % in the total production volume by 2030 (Panchaksharam et al., 2019). The same project lists more than 350 bio-based chemicals out of which 208 are on a TRL higher than 8. Notwithstanding the high pallet of options, the bio-based market is still very small both in the EU and worldwide and most of the bio-based chemicals developed are pricier than fossils-based chemicals. The average share of bio-based products in the overall fossil market is only 3 % and the average growth of bio-based chemicals is approximately 4 % (Spekreijse, Lammens, Parisi, Ronzon, & Vis, 2018).

The biochemicals segment can be distinguished into 9 main groups, namely: adhesives, agrochemicals, cosmetics, lubricants, man-made fibers, paints and coatings, plastics/polymers, solvents and surfactants. For, comprehensive review of the individual chemical groups, please, see (Londo, van Stralen, Uslu, Mozaffarian, & Kraan, 2018; Panchaksharam et al., 2019; Spekreijse et al., 2018). These groups can be roughly distinguished into solid and liquid chemicals. This partition is relevant when considering the circularity aspects of the individual chemical groups as well as the bulkier nature of liquids and thus their often lower price per mass (Spekreijse et al., 2018). The solid bio-based chemicals include man-made fibers, biopolymers and partially cosmetics. The liquid bio-based chemicals include solvents, platform chemicals, paints and coatings. In some instances, such as for adhesives or lubricants the partition is less clear as these are often denser and their price per kg is also higher.

The circularity aspects of the liquid and solid phase are largely different. The liquid-based chemicals mostly cannot be reused or cascaded after their intended use (e.g. paints and coatings, adhesives or lubricants). The recyclability of solid phase chemicals is mostly reliant on whether the technical and biological cycles were mixed or not. For example, biodegradable plastics such as PLA or PHA can be degraded and returned to a soil as compost. This is, however, not true for drop-in plastics which are mixed with conventional petrochemicals and their end-of-life phase is essentially same as PET (EEA, 2019). Currently more than half of the bioplastics are non-biodegradable (EEA, 2019). Similarly, in the production of bio-based man-made fibers, the technical and biological cycles are often mixed yielding a difficult-to-recycle material.

Generally, platform chemicals, polymers for plastics and paints and coatings cover slightly less than 85 % in terms of the total chemical production (incl. fossil based) in mass in the EU (table 4). In terms of bio-based production share, surfactants cover 50 % from the total and personal care products and man-made fibers cover 44 % and 13 %

respectively. Other fields are almost completely reliant on fossil-based materials such as platform chemicals (0.3 %), polymers for plastics (1.5 %) or lubricants (3.5 %).

In terms of price, bulky liquid materials such as solvents or platform chemicals are generally much cheaper compared to more specialized products such as cosmetics or man-made fibers. Products closer to the end consumer such as cosmetics or man-made fibers can generally ask for higher price and their relatively large production volumes increases their total turnover. The willingness to pay a premium by the consumers is an important element in the biochemical industry as most of these chemicals are still not competitive to fossil-based ones. The most promising sectors in terms of turnover, maturity and production are surfactants, personal care products and man-made fibers. Future projections also predict relatively high compound annual growth rate (CAGR)[20] for bioplastics. Platform chemical and adhesives are expected to grow intensely by 10 % although this projection is slightly skewed due to their current low production volumes.

Table 4: Market characteristics of the different chemical groups. Values extracted from (Spekreijse et al., 2018).

Product category	EU bio-based production (kt/a)	Total EU production (kt/a)	EU bio-based production share (%)	Price (EUR/kg)	Turnover (EUR million/a)	CAGR (%)	Maturity level
Platform chemicals	181	60791	0.3	1.48	268	10	Low
Solvents	75	5000	1.5	1.01	76	1	Low
Polymers for plastics	268	60000	0.4	2.98	799	4	Medium
Paints, coatings, inks & dyes	1002	10340	12.5	1.62	1623	2	Low
Surfactants	1500	3000	50	1.65	2475	4	High
Personal care products	558	1263	44	2.07	1155	3	High
Adhesives	237	2680	9	1.65	391	10	Medium
Lubricants	237	6765	3.5	2.33	552	1	High
Plasticizers	67	1300	9	3.6	241	3	Low
Man-made Fibers	600	4500	13	2.65	1590	3	Medium
Total	4725	155639	3	1.94	9167	2	-

While there are already competitive options for biochemicals and some of them are even better performing than their fossil counterparts, the lignocellulosic production pathways are still at a rather low TRL level (Chandel et al., 2018). In fact, most of the feedstocks for currently competitive biochemicals are the first-generation feedstocks (1G) and second-generation feedstock (2G) including straw or other residual biomass sources are still much less used. The reason for this is that the lignocellulosic structure is rather robust and special pre-treatment processes need to occur in order to release individual chemical compounds (e.g. lignin, cellulose). This is often costly and the technological process to disintegrate these structures are still not fully developed (Kumari & Singh, 2018). On the other hand, the 1G feedstock is in a relatively available structure as simple sugars or starches making it easy to process. One of the most

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[20] which describes the mean annual growth rate of production dispersed over a period longer than a year.

promising pathways for building bio-based chemicals from cereal straw and other lignocellulosic materials is the production of ethanol as a basic chemical building block via hydrolysis and fermentation. The same technology is applied for the production of biofuels for road transport and few plants are in operation in the EU. This pathway is, however, still questionable in terms of its reliability and economic competitiveness (Chandel et al., 2018). Additionally, several EU Horizon 2020 programs are currently prospecting the lignocellulosic biochemicals pathways by building demonstration plants (for overview of projects see (Hassan et al., 2019).

The advantage of the biochemicals market is that it can mostly produce higher added value than for example biofuels or bioenergy markets. The biochemicals market is often closer to the consumer (e.g. cosmetics) than other bio-based sectors. This can be both an advantage or disadvantage based on the general perception and public awareness of bio-based products. A possible threat is also prioritization of other bioeconomy fields such as bioenergy or biofuels which is already mirrored in the RED II directive where clear policy guidelines and incentives are given for biofuels and bioenergy but not for material productions. This is often criticized as the use of biomass in material use can produce 4-9 more value added and 5-10 times more employment (Carus et al., 2011). Generally, it is viewed that the bio-based materials are disadvantaged even though their value is generally higher (Carus & Dammer, 2018). Market pull in either direct support via subsidies, loans or indirect support by carbon tax or effective labelling are often cited as a way to make a more balanced playing field (Gross, 2019). Additionally, bio-chemicals must undergo time consuming process as part of the registration of the chemical in the REACH process. This often disincentive especially SMEs that cannot afford to cover this process.

5.4.3 Biocomposites and construction materials

The categories of biocomposites and construction materials were chosen as an example of a highly promising sectors yet with questionable characteristics in terms of their recyclability. The biocomposites are mostly differentiated into wood-plastic composites (WPC) and natural fiber composites (NFP) (EEA, 2019). The main characteristics of biocomposites is that they combine two materials of which one is a plastic based and the other one naturally based. The european biocomposite production reached 410 ktons in 2017 and it displays an approximate 3 % CAGR (Carus & Dammer, 2010). Biocomposite are mainly used in the construction area as decking and siding or in the automotive sector. Furniture or other consumer goods covers the rest of the production. Next to this, packaging is becoming an attractive field for biocomposite materials (Korhonen, 2020). The Nova Institute predicts that the market for biocomposites will double by 2030 (Partanen & Carus, 2019). The advantages of biocomposites are clear due to their potential biodegradability, lower carbon footprint and minimizing the use of non-renewable fossil based plastics. Ita-Nage et al. (2020) report approximately 60 % reduction in the GHG emissions compared to fully fossil-based composite material. Similarly, the bio-based construction materials can play a major role in the climate reduction in a highly GHG intensive sector such as the construction which is responsible for approximately 7 % of the global GHG (Akan et al., 2017). Not only does the bio-based material displaces the energy intensive cement or steel production, it also fixes carbon and can in this term act as a carbon capture and storage technique. The visit at the Czech company Ekopanely also proved the higher demand for these materials and an overall very high functionality characteristic. The construction materials that the Ekopanely company is manufacturing from straw are also certified for its biodegradability.

One of the biggest culprits of biocomposite is their actual recyclability and thus the performance on circularity. The EEA (2019) has published that around 80 % of the current composites are not recyclable due to the impossibility of separating the technical part (the fossil based plastic) from the natural part (e.g. straw). While there are opportunities to combine bio-based plastics with biodegradable opportunities (e.g. PLA or PHA) these options are often not used due to low performance and high costs (Gil-Castell et al., 2016). The bio composites are mostly fulfilling a supportive function where durability is a necessary component. Similarly, to biochemicals the use of biomass into biomaterials is preferred on both social and economic grounds.

6 Results

6.1 Defining the circularity gap in Agriculture

This section presents the results of the MFA model concerning the main agricultural crops and other biomass types and it thus aims to answer the following research (sub)questions:

''What is the current state of play in terms of size, utilization and processing of the agricultural biomass feedstock?''

''How large is the circularity gap in the agricultural sector and which interventions could reduce this gap?''

Both flows of agricultural crops and their residues in dry matter and in a standard water content are presented in figures 18 and 19. Both the dry and water-based MFA's serve slightly different purposes in terms of the illustration capabilities of the MFA model. While the dry weight serves well in order to calculate the mass balances more precisely and subsequently measure the circularity gap, the water-based flows on the other hand represent more realistic flows occurring in the bioeconomy which can be relevant when considering potential transport of biomass. The water and dry-based figures differ substantially in the respective figures as water content determines the weight of the flows greatly. This underlines the need to measure the circularity gap in dry weight. Generally, all the secondary and tertiary residues and part of the manure are directed towards a node named ''Total Secondary and Tertiary residues''. This is mainly in order to make the whole MFA easily understandable as multiple streams would disturb the overall picture. From this node the use of these residues is then estimated in the end-of-life phase. On a dry mass basis, the mass balance threshold of 10 % (see methodology) was exceeded only as part of the node ''Total secondary and tertiary residues''. As a result, there is a gap of knowledge surrounding the actual uses and respective flows of the secondary residues. Mainly a dry mass basis will be described and where appropriate also the wet version will be discussed.

Overall around 26 Mt of biomass on dry mass basis (Mt_{dry}) is harvested annually in the Czech Republic of which 15.0 Mt_{dry} is economic yield and 10.9 Mt_{dry} the primary residual yield. The economic yield on a wet mass basis (as received, Mt_{ar}) mainly comprises cereals (7.0 Mt_{ar}), green and sillage maize (6.7 Mt_{ar}), arable fodder crops (3.4 Mt_{ar}) and sugar beet (3.7 Mt_{ar}). These four crop groups cover around 85 % of the overall economic harvest (applicable for both dry and wet version). Fruits and vegetables are marginal in the total harvest, however, they are significant in the consumption phase where they cover approximately 40 % of the plant food consumption on a wet mass basis. This is due to the high import of these commodities which represent approximately 0.65 Mt_{ar} and 0.75 Mt_{ar} for vegetables and fruits respectively.

The theoretical primary residue yield is comprising mainly of lignocellulosic biomass in the form of cereal and rapeseed straw. Post-harvest residues from sugar beet or potatoes are less relevant as they cover only around 5 % from the total primary residue yield. The total theoretical cereal and rapeseed straw potential is estimated on 7.4 Mt_{dry} and 3.5 Mt_{dry} respectively. While the cereal harvest is 4.5 times higher than the rapeseed straw yields, the latter produces around half the straw due to high residue yields per hectare (García-Condado et al., 2019). The theoretical potential of the lignocellulosic biomass covers approximately 40 % of the total biomass supply in dry matter in the Czech Republic. Nevertheless, the majority of this biomass is not removed from the ecosystem and out of the total theoretical residue yield (10.9 Mt_{dry}) more than 80 % (around 9.0 Mt_{dry}) is not removed. The technical residue potential is estimated at 60 % of the theoretical potential, thus theoretically allowing to harvest 6.5 Mt_{dry} without yet taking sustainability and competing uses constraints into account. The current uses cover roughly 1.5 Mt_{dry} of straw. Animal bedding represents the largest consumption of biomass with around 1 Mt_{dry}. The amount of straw annually incinerated was estimated on 0.25 Mt$_{dry}$. The rest is assumed as used in other fields such as insulation or in pellet mills. Taking into account the large uncertainty surrounding the estimates on the actual uses of primary residues, a conservative estimate on the uses is close to 2 Mt$_{dry}$. This leaves around 4.5 Mt$_{dry}$ and which is assumed to be returned to the soil. This is in line with the questionnaires where 85 % of respondents cite that they use straw for their own purposes as either fertilizer (ploughing into the soil) or as animal bedding (which is mostly returned back to soil in the form of manure). The potential of additional straw removal will be regionally based mainly on the local conditions of the soil. Nevertheless, when using a constant sustainable removal rate of 33 %, the sustainable potential is estimated at around 1.5 - 2 Mt$_{dry}$.

Animal food & feed production is the largest sink of biomass with the feed demands estimated on 6.5 Mt$_{dry}$, representing 41 % of the total economic biomass production (figure 17). Mainly arable fodder crops and silage maize are used as a feed. In wet mass this figure is much higher (around 13 Mt$_{ar}$) due to high water content of fodder crops. In order to get a more accurate picture, the import of meat and the associated feed demands should be considered. Approximately 0.5 Mt$_{ar}$ of pig meat is annually imported which is according to Camia et al., (2018a) associated with additional 5 Mt$_{dry}$ of feed. Pastures are rather small contributor to the overall feed demands in dry matter 0.4 Mt$_{dry}$, however, in wet version they represent more than 2.4 Mt$_{dry}$.

Plant food processing or direct raw biomass consumption accounts for 21 % with 3.3 Mt$_{dry}$. A relatively large amount of biomass is exported (17 %) mainly in the form of cereals. In absolute terms, slightly less than 2.7 Mt$_{dry}$ is exported indicating still relatively large potential of food crops. Biogas plants and the production of biofuels then represents around 8 % and 6 % of biomass sinks respectively. Silage maize was assumed as the main crop commodity used as a feedstock in biogas plants with an estimated material use of 1.2 Mt$_{dry}$. The flows of silage maize on a wet mass basis are approximately 3 times higher. Sugar beet and oilseeds are the main feedstocks used for the production of biofuels.

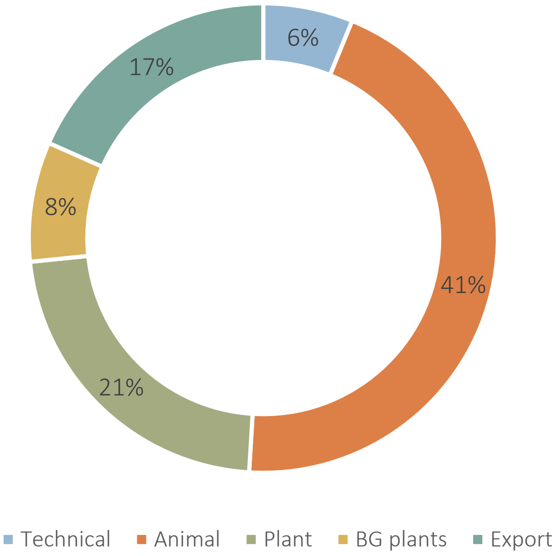

Figure 17: Uses of biomass in the Czech agriculture adjusted to imports which were added to the total supply. Differentiated into technical production, animal food & feed production, plant food production, biogas plants and export.

In the Animal food & feed production, milk represents the highest flow with 2.4 $\mathrm{Mt_{ar}}$ annually produced. Moreover, milk is also a highly significant exporting commodity with more than 1.1 $\mathrm{Mt_{ar}}$ exported. Meat production accounted for approximately 0.8 $\mathrm{Mt_{ar}}$and the dependency on meat imports is sizable (see above).

The Manure production was estimated on 2.11 $\mathrm{Mt_{dry}}$. While this figure is relatively small in dry mass, in wet mass it is one of the largest flows of the whole MFA with 21.1 $\mathrm{Mt_{ar}}$ due to high moisture content. Around 65 % is applied into the soil and the rest is used as a feedstock in biogas plants. The secondary residues from the animal food production are around 0.3 Mt.

The secondary residues from the plant food processing represent approximately 0.9 $\mathrm{Mt_{dry}}$ thus theoretically indicating relatively large and untapped potential. While official statistics report much lower numbers (around 0.25 $\mathrm{Mt_{dry}}$) these are probably highly underestimated as the processing residues are directly used as a feed and thus unreported. According to a study by the Institue of Circular Economy (2019) in the Czech Republic, large part also ends up in mixed municipal wastes or in wastewater treatment plants (mainly oils and fats). The secondary residues are mainly in the form of husk, chaff or other processing wastes from sugar, oil or other relevant food productions. Oil wastes are also a relevant source. Additional secondary residues are produced in the technical cycles mainly when converting the seed into oil in the biodiesel production or in other adjacent processes to produce biofuels. Approximately 0.5 $\mathrm{Mt_{dry}}$ were estimated from the mass balance. Reporting on these values is fairly incomplete and relatively large uncertainties thus remain on the exact number of secondary residues as well as on their current use and more insights must be made into these materials.

Overall, in wet mass around 11 % of food produced is annually wasted, which in absolute terms, represents 0.85 $\mathrm{Mt_{ar}}$ (0.3 $\mathrm{Mt_{dry}}$) of food waste. The treatment of this food waste is diverse ranging from composting to anaerobic digestion. However, still around half of this waste forming approximately 400 - 500 $\mathrm{ktons_{ar}}$ ends up in landfills and around 100 $\mathrm{ktons_{ar}}$ is incinerated.

At the End-of-life phase the biogas plants are a significant sink of biomass. The digestate production on a wet mass basis is relatively large with silage maize and manure as the main feedstock. All digestate as a form of waste from the anaerobic process is then assumed to go back to the soil. The digestate is to a large extent connected to the water content and there is a substantial difference between the wet and dry MFA. While on the dry mass basis digestate forms 0.6 $\mathrm{Mt_{dry}}$ on wet mass basis, it is approximately 7.5 $\mathrm{Mt_{ar}}$. Finally, the use of waste from food processing or from households is partly composted. The estimated compost that is returned to the soil is approximately 250 $\mathrm{ktons_{ar}}$ (less than 100 $\mathrm{ktons_{dry}}$) .

Out of the total biomass supply and from the aggregated recycling flows, the level of circularity was calculated. Overall, 11.2 $\mathrm{Mt_{dry}}$ of biomass is returned back to the ecosystem which corresponds to the level of circularity of 43 %. In the wet-based figure the level of circularity is largely skewed due to the high water content and the theoretical level of circularity is more than 85 % illustrating the role of mapping the flows in dry mass. The most significant flows that are recycled are manure, post-harvest residues such as straw and digestate. Especially in the dry version the role of straw in improving the SOC levels can be observed (figure 18). The estimated amount of straw that is left on the field either by incomplete machinery harvest or by directly ploughing the straw into the soil is around 9 $\mathrm{Mt_{dry}}$. Manure and digestate contribute by approximately 1.3 and 0.6 $\mathrm{Mt_{dry}}$ respectively. Other recycling flows such as compost or wastewater sludge are relatively small in the overall balance. This shows that straw is indeed an important element in the carbon cycle.

The MFA model also showed that highest recycling streams such manure and straw influence significantly the overall level of circularity and if the desire would be to increase the amount of biomass returned to the ecosystem, these flows represent the highest potential. Hypothetically if all the tertiary and secondary residues would be composted and returned back to the soil the circularity would still increase only by 8.4 % to slightly more than 51 % circularity. Additional loss of carbon is made in the biogas plants where manure and energy crops are fermented, and the biogas is then burned to generate heat and electricity. If all the generated manure would return directly to soil and the energy crops would not have been harvested for the production of biogas the circularity gap would increase from the initial 43 % to 48 %. The relatively low increase is balanced by the application of digestate. Generally, the limited increase in circularity is capped by the carbon lost in either human or animal metabolism. While the figure for metabolism was only very crudely calculated in mass it represents around 6 to 8 Mt_{dry}.

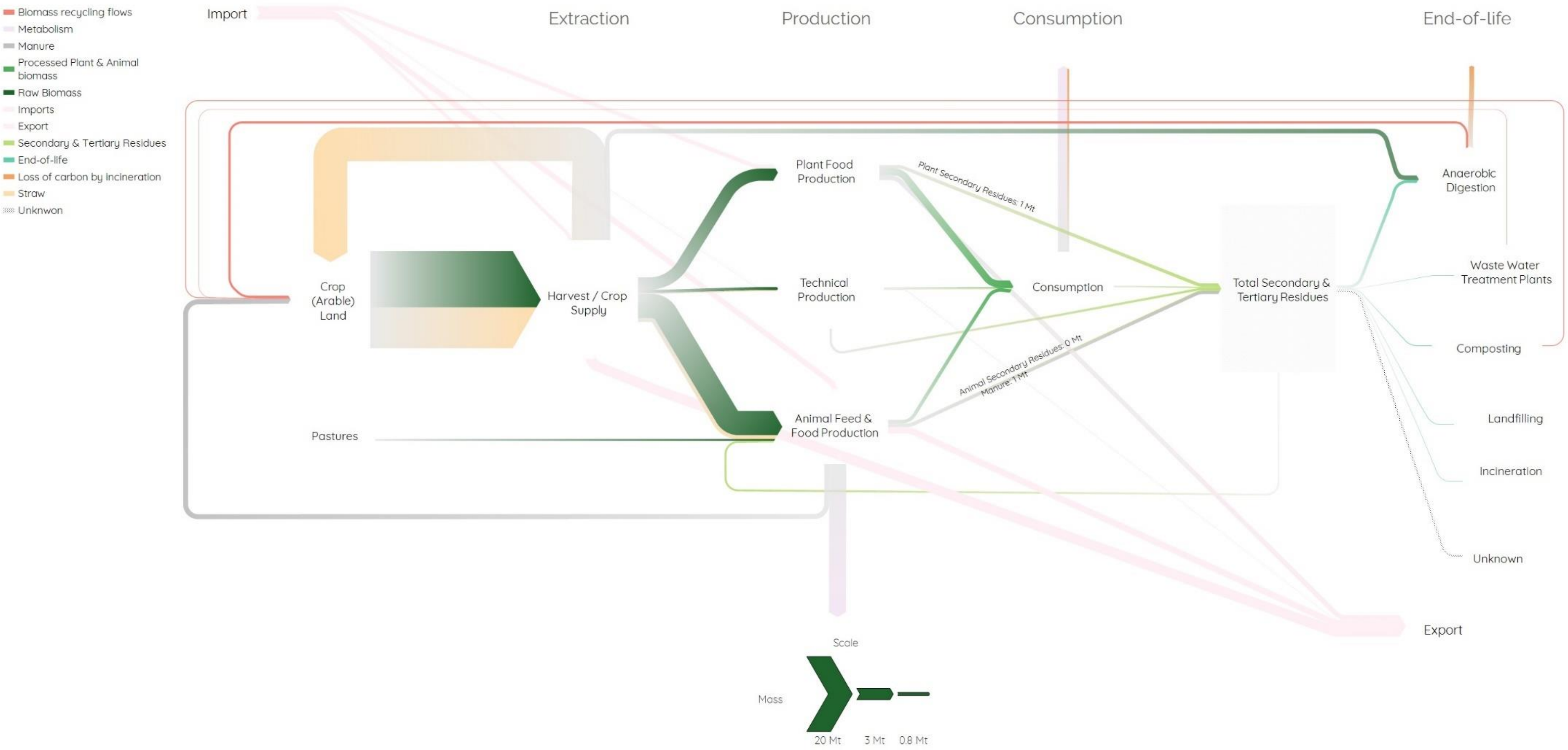

Figure 18: MFA in a dry-based diagram: for concrete values of the flows see Annex 1

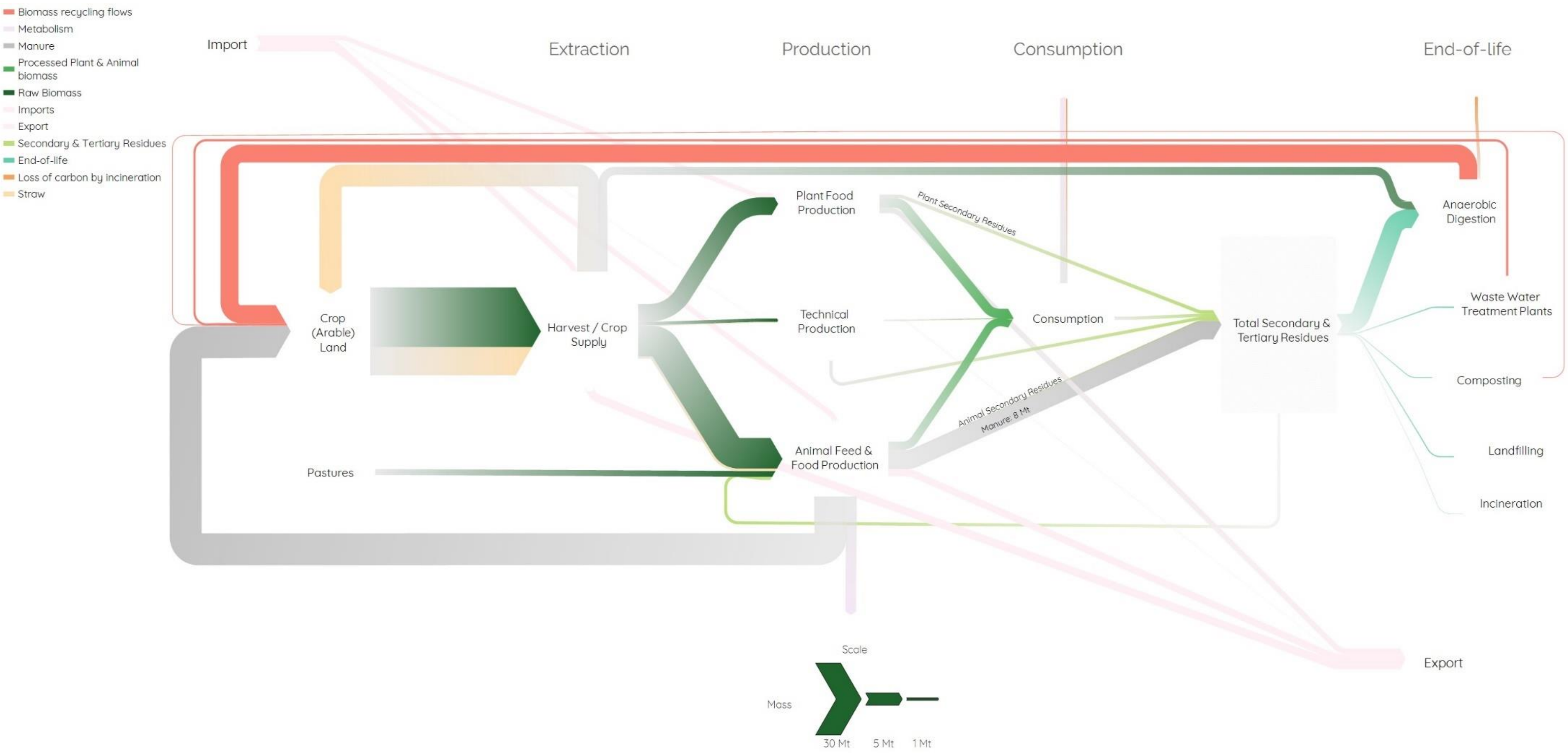

Figure 19: MFA in a water-based diagram. For concrete values of the flows see Annex 1

6.2 Identification of suitable end-markets for lignocellulosic biomass

This section provides the synthesis of the literature review on possible end-markets for straw. A market analysis using the SWOT technique is presented in the table 5. This section aims at answering question on:

(4) ''What is an optimal utilization of lignocellulosic biomass (e.g. wheat straw) in the Czech Republic considering climate targets, economic feasibility and circularity?''

The literature review showed that majority of the high-value added uses of straw be it in the biochemicals or biofuel sector are still rather immature. This is also confirmed by Stegmann et al. (2020) which reports that the bioeconomy clusters in the EU are still struggling with using the 2G feedstock. Most of the end-markets that are already competitive are therefore based on the 1G feedstock. The biggest hurdles for competitiveness of the bio-based sectors in general are the low price of oil, limited taxation of carbon emissions, insufficient technological maturity of the bio-based technologies and consequently higher costs. Dynamic policy and market development create an uncertainty around which sectors will be prioritized thereby becoming more economical. There is a need for substantial technological advancement for the lignocellulosic feedstock as well as for a wide-spread policy support.

Nevertheless, some sectors at this point seem more promising than others. The literature review confirms the findings from the expert roundtable workshop that using biomass in high-value added applications is gaining traction. The biochemicals are also sensible from an economic, social and to some extent circularity perspective compared to biofuels or bioenergy or even biocomposites. The solid-phase biochemicals such as biodegradable polymers (PLA) or man-made fibers can be cascaded and hypothetically even returned back to the soil after use. This could potentially reduce the circularity gap. The bulky, liquid and difficult to recycle chemicals (surfactants, adhesives, platform chemicals), however, are much less suited to reuse or recycling and thus perform worse on circularity.

Other circularity strategies such as cascading, value-retention and better performance on social (more jobs produced) and economic indicators (higher value added) are linked to the biochemical sector (mainly solid-phase biochemicals) and these are one of its main strengths. Partly similar conclusions could be made for the biocomposite and construction sector, although these sectors are of lower value and the end-of-life treatment is debatable as around 80 % of biocomposites are currently unrecyclable (EEA, 2019).

The weaknesses of the biochemical sector on the other hand are the high development cost and legal and safety burdens associated with testing the chemicals (REACH regulation). Also, the presumed better environmental performance of some of the biochemicals is still debatable (Singh & Narayan, 2018) which could pose a threat to its future development. Given that the bio-based sectors compete for similar feedstock, one of the biggest threats to the biobased chemical sector or biocomposite industry is the larger policy support for RRFs, RJFs or for bioenergy in order to prioritize these more GHG intensive sectors. Daioglou et al. (2014) for example identified that use of biomass in bioenergy or biofuels is more effective in reducing GHG emissions than in biochemicals.

The advanced biofuels both for RRFs and for RJFs are still technologically insufficient to compete with fossil-based fuels. These materials are also bulkier demanding larger feedstock supply, more robust supply chains and are consequently more costly. The RJFs are even more complex and pricier than RRFs which is exacerbated by similar prices of the final product (diesel vs. kerosene). The circularity aspects of these fuels are also relatively low at least compared to biochemicals or biocomposites where more value and more jobs is produced, not to mention the impossibility of sequential use of biomass. Potential opportunities for the advanced biofuels are carbon tax, higher oil prices, high policy support or a technological breakthrough. The threats on the other hand are mainly applicable for the RRFs where competing technologies (electric vehicles, bioCNG) might make the advanced biofuels less competitive.

Overall, there exists a trade-off between the GHG related emission focus of biofuels and bioenergy where the objective is to simply replace fossil-based fuels without considering circularity aspects and the more material oriented biochemical or biocomposite sector where more social, economic or circularity aspects are pronounced. From a GHG perspective the biofuel and bioenergy market might be more preferable (Daioglou et al. 2014) and if the desire would be to solely focus on GHG emissions these end-markets would be suitable. In case economic and circularity aspects would be prioritized the biochemicals (mainly in the solid form) are closer to the optimum

Table 5: SWOT analysis for the different lignocellulosic end-markets

	Renewable Jet Fuels	Renewable Road Transport Fuels	Biochemicals	Biocomposites & construction
Strengths	Lower carbon footprint Low competition from Other than biomass-based RJFs High growth industry	Lower carbon footprint Policy support (RED II targets) Large biofuel know-how within the EU Experience with 1G Biorefineries in the Czech Republic More competitive than RJFs	Lower carbon footprint High value added Higher employment Higher circularity performance (especially for solid materials)	Lower carbon footprint Relatively simple technologies compared to fuels or biochemicals Already competitive
Weaknesses	Low technical maturity High production costs Low price premium compared to biochemicals or RRFs Big-scaled plants needed Lack of aviation fuel standards and of international coordination No target set for blending Very costly R&D	Higher competition from non-biomass fuels (BioCNG, E-fuels) High production costs although lower than RJFs Technically still immature (TRL less than 8) Low reputation of biofuels Dynamic policy and market development	Limited policy support (bioenergy over chemicals) Higher production costs Low TRL (especially for lignocellulosic pathways) High development costs Often lower performance than fossils Applying for REACH regulation is costly	Lower value Often unrecycled (mixed cycles) Often lower performance For lignocellulose still limited uptake Limited attention to biocomposites
Opportunities	High carbon tax High policy support that would incentivize R&D and faster commercialization High oil prices Establishment of a common and stable policy for aviation Cost reductions & technological development	Technological breakthrough Establishment of a cost-effective and reliable technology (e.g. cellulosic ethanol) High oil prices Even More stringent targets by the EU Carbon tax on fuels	Future changes in regulation that would support biobased chemicals Market pull (tax credits, binding targets, procurement) CO2 tax EU policy and guidelines Higher demand from consumers (e.g. cosmetics)	Higher importance of biocomposites Shortage of construction materials Market pull (tax credits, binding targets, procurement) EU policy and guidelines
Threats	Competition from high value added markets (biochemicals) Worsening perception on biofuels Risk aversion of investors due to unsuccessful commercialization Non-biobased alternative	Competition from other renewable fuels (BioCNG. EV) Worsening perception of biofuel Biomass will be prioritized to jet fuels or to biochemicals due to limited substitutes	Low public perception / awareness Prioritization to biofuels, bioenergy, jet fuels Higher stringency of REACH regulation Environmental benefits will be lower than expected	Low public perception / awareness Prioritization to biofuels, bioenergy, jet fuels Limited progress in recyclability

7 Discussion

7.1 Towards Circular Bioeconomy in the Czech Republic & Research Limitations

This research allowed for a synthesis of CE and BBE into a novel concept of CBE at the national level. The MFA methodology was applied in order to identify the level of circularity (CE focus) within the Czech agricultural sector (BBE focus) as well as to map the current state of play of biomass use. The MFA analysis proved to be insightful from this perspective in terms of receiving a holistic overview of biomass flows and stocks at the national level. It clearly showed the untapped potential of secondary and tertiary residues from agriculture and it identified the most relevant streams which influence the degree of circularity. It also helped to identify the largest sinks of biomass, the role of international trade, and allowed for analyzing potential intervention points in order to increase the effectiveness of biomass use in the Czech Republic. From this perspective, the application of MFA which is predominantly used in technical cycles and which is primarily applied in urban rather than rural areas (D'Amato et al., 2017), proved its usefulness on biogenic systems as well. This approach also allows for identification of organic waste streams and underutilized materials which is the main focus of CBE (Stegmann et al., 2020; Giampietro, 2020). In these terms, there exists a clear and practical synergy between CE and BBE.

Nevertheless, the use of MFA on biological systems has demonstrated to be more complex than on technical cycles (Kalt, 2015). Firstly, some of the processes within MFA such as human or animal metabolism are difficult to evaluate in terms of their actual inputs and outputs. Similarly, this research has showed that dry-weights should be used to analyze the circularity. The conversion of wet-mass to dry-mass is, however, based on the moisture contents which are changing throughout the processes and which are generally difficult to obtain from official databases because they are rarely reported. This would support the general critique of MFA that it relies on data that are often difficult to retrieve eventually leading to rather crude estimates (Lutter, Giljum & Bruckner, 2016) (see background section). The MFA model also neglects alternative agricultural practices such as intercropping or tillage practices which are essential in the overall carbon cycling (Zhang et al., 2017). Future research should therefore focus on understanding the complexity of these biological systems when using MFA in order to receive more accurate picture of the bioeconomy and the associated climate impacts. Overall, given the complexity of the biological systems, the difficulty to retrieve robust data and the time consuming process of creating the MFA model, other methods might be more effective and suitable in measuring progress in sustainability in agriculture.

This research also calls for cautiousness when measuring and interpreting the level of circularity as a proxy to sustainability performance (Corona et al., 2020). For example, if the goal would be to primarily increase the level of circularity, increasing the number of livestock in order to produce more manure might be proposed. This can indeed increase the overall level of circularity as more manure is applied to the soil. Nevertheless, the GHG related impacts in terms of producing more feed or in terms of the imported biomass are crucial, yet they would not be included into the MFA analysis. Therefore, the requirements of any circularity metric should be coupled with the reduction of GHG emissions or with the studied environmental impact in order to avoid burden shifting.

While the MFA has several limitations, it should be highlighted that it still has a high informative and communicational power. By visualizing the processes and flows in a rather simple diagram, even a complex system can be relatively easily communicated. Overall, the MFA model applied on biological systems should thus be viewed more as an informative tool and possibly as an aid for early recognition of potential measures to increase the material efficiency (Hendriks et al., 2000) rather than an environmental impact assessment tool.

The CBE attracts for its sustainability promises as opposed to conventional first generation feedstocks which compete with food and feed production. This can, however, be misleading since the primary residues play a major role in maintaining the right SOC levels (Lal et al., 2004). This is also visible from the MFA model on a dry-mass basis. Moreover, according to Stella et al. (2019), returning all crop residues into the soil is in many cases a necessary measure to maintain the SOC pools although even that might not be sufficient. Agricultural practices, local climatic conditions, soil type and initial SOC content in the soil play a major role in determining the local sustainable removal rates (Gollany et al., 2011; Zhao et al., 2013). For example, light soils with initial high SOC content are more prone to degrading soil quality with higher removal rates as opposed to heavy soils with low initial SOC pools (Stella et al., 2019). The decreasing SOC levels might not solely mirror in lower quality of the soil and in the additional negative effects associated with such degradation (soil erosion) but also in higher GHG emissions due to higher mineralization of the carbon stocks (Mouratiadou et al., 2020). In this respect using generic and constant sustainable removal rates will not suffice to retrieve reliable sustainable potentials. More regional, bottom-up and integrated approach towards the use of primary residues is therefore needed (Mouratiadou et al., 2020, Gawel et al., 2019). Similarly, some of the secondary residues already have a use mainly as feed and redirecting them to high-value applications might induce increased production of the feed which can impact the overall GHG emissions negatively. The secondary residues thus also need to be considered with regards to their current uses.

This report also identified the significance of societal barriers in mobilizing the residual biomass into high-value added applications. Mainly, the farmers' lack of clarity about environmental constraints and their general unwillingness to provide it in light of the concerns on soil quality and recurring droughts were identified as pertinent. Similar findings are reported in different regions as well (Mouratiadou et al., 2019; Tyndall, Berg & Colleti, 2011, Uslu et al., 2018). This would underline the fact that the CBE, similarly as CE, should significantly focus on social aspects (Stegmann, 2020; D'amato, 2017) as otherwise the critique of CE that it omits the social dimension will prove true again in CBE (Bocken, De Pauw, Bakker, & van der Grinten, 2016; Geissdoerfer, Savaget, Bocken, & Hultink, 2017b; Korhonen et al., 2018). Moreover, in light of these barriers existing on the side of the biomass providers, the EU wide studies that assess the availability of primary residues (Camia et al., 2018; Scarlat et al., 2019; Searle & Malins, 2016; Thorenz et al., 2018) should be read cautiously as local socio-political conditions, which can be only crudely considered in these high-level studies, might play a crucial role.

Similarly, this research proves that strategies of CE such as cascading, recyclability or using a material in as high value applications as possible are penetrating into the debate on effective biomass use and into the BBE as a whole. This has been proved at the expert roundtable workshop, from the literature review as well as by the discussions held with diverse stakeholders. The higher uptake of the CBE concepts among professionals is also confirmed by Stegmann et al., (2020). Overall there is a confusion on the exact definition of cascading, which is currently more skewed into the economic narrative (Olsson et al., 2018), i.e. the biomass should be used in as high value applications as possible. This could, however, lead to overemphasis on the competitiveness and economic aspects of using biomass as opposed to the environmental impacts (Dewulf, Meester & Alvarenga, 2015). The definition of cascading as a "sequential use of resources for different purposes"(Olsson et al., 2018, p.1) might therefore be more suitable for assessing the environmental impacts.

The literature review also indicated the insufficient maturity of the lignocellulosic utilization pathways. This is also confirmed by Stegmann et al. (2020) who state that the bioeconomy clusters are struggling in practice with utilizing the lignocellulosic feedstock. Most projects are still on the level of feasibility studies and research and development. However, the IEA predicts a large increase of advanced biofuels from 2023 and additional technological development in other BBE fields can be expected (Bahar, 2017). Overall, the biochemical market seems as promising, from the economic and social perspective as well as by performing better on some of the circularity aspects (e.g. cascading). The GHG related focus is, however, crucial. Daioglou et al. (2014) identifies that the use of biomass in bioenergy or biofuels is more effective in reducing GHG emissions in a short-term than in manufacturing biochemicals. From a short-term perspective it might therefore be more preferable to support bioenergy or biofuels despite their low circularity or economic performance.

8 Conclusion

This thesis explored the novel concept of CBE as an intersection between CE and BBE. The overarching research question that it aimed to answer was:

''How can the bio-based economy and circular economy be aligned so that they contribute to climate-change mitigation while creating new high-value added business cases in the Czech Republic?''

This research has shown that the application of Material Flow Analysis, which is a predominantly CE tool, can be insightful when applied on a biological system. This is applicable both for receiving an overview of majority of the biomass flows as well as for identifying the underutilized biogenic materials on a national level. The synergy between CE and BBE is in this respect apparent. The MFA also allows for measuring the level of circularity as a crude indicator to the amount of biomass that is returned back into the soil. The level of circularity in the Czech agricultural sector was estimated at 43 % with manure and straw as the most important streams. Absolute circularity in agriculture is impossible because large part of the biomass is lost via human or animal metabolism or incinerated. The circularity level should, however, be taken cautiously and merely as an informative measure. Otherwise burden shifting from one environmental impact to another can occur.

The theoretical availability of primary residues was estimated at around 11 Mt_{dry}. Considering competing uses, technical constraints and constant sustainable removal rate of 33 %, the potential is 1.5 to 2 Mt_{dry}. However, in order to identify the amount of crop residues that can be removed without truly compromising on soil quality, regionally tailored strategies that would consider the local conditions are needed. This research also confirms that there is a lack of clarity among the farmers in identifying the sustainable removal rates and a general unwillingness to provide the crop residues. This signifies the role of social aspects in the CBE and it also poses a large barrier for mobilizing additional biomass in a sustainable manner. The estimates on primary residues provided at the EU level should therefore be interpreted critically and in order to receive a more accurate picture, the local socio-political factors need to be considered. The secondary residues were estimated at approximately 0.9 Mt_{dry}, however, further research is needed to identify their current uses to determine the amount of biomass that can be used without burden shifting. More than 11 % of food is annually wasted resulting in approximately 500 $ktons_{ar}$ of tertiary residues ending up in landfills and hence unused. Additionally, more than 2 Mt_{dry} of raw biomass are annually exported.

Large part of the current lignocellulosic utilization pathways are still rather immature and more technological advancements are needed in order to propel the use of this feedstock in the bio-based industries. The bio-based chemical sector has been identified as one of the most promising in terms of its economic and social aspects as well as by partly including circularity strategies such as cascading. Nevertheless, other sectors such as biofuels or bioenergy might be prioritized over biochemicals due to GHG mitigation efforts.

This research has showed that in order to align the CE and BBE in a sustainable manner, the future CBE concept should intensely focus on social dimension and it should strive for a more bottom-up regional approach. This is crucial in order not to overshoot the biophysical limit of the local ecosystems. More regional focus would therefore leverage the resource efficiency focus of CE and the biomass focus of BBE, whilst allowing for staying within the ecological limits.

9 Acknowledgments

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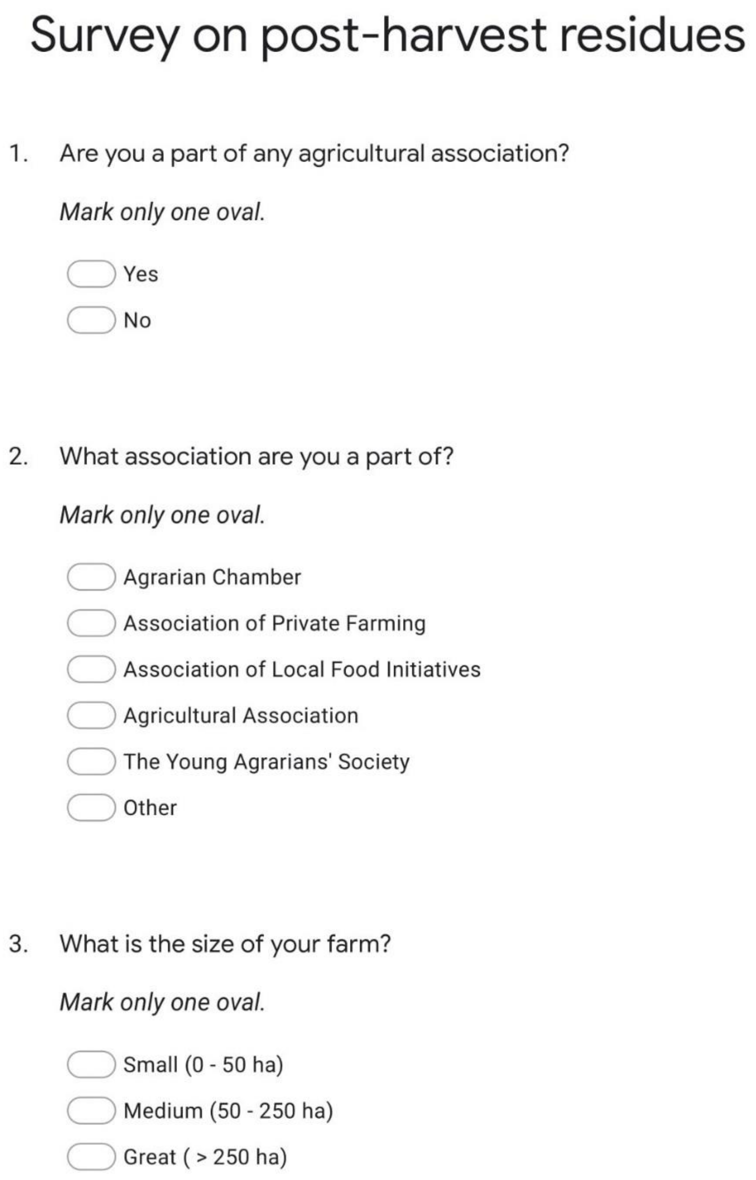
10 Annexe

10.1 Annex 1: Data used for the MFA model

Source of flow	Sink of flow	Commodity / Biomass type	Flow quantity		Water Content	Reliability of data
			Mt (dry)	Mt (wet)		
Crop Arable Land	Harvest Crop Supply	Cereal Grains	6.062	6.968	0.13	++
Crop Arable Land	Harvest Crop Supply	Straw (theoretical)	10.897	11.768	8%	+
Crop Arable Land	Harvest Crop Supply	Oilseeds	1.283	1.410	9%	++
Crop Arable Land	Harvest Crop Supply	Sugar Beet	0.818	3.720	78%	++
Crop Arable Land	Harvest Crop Supply	Potatoes	0.156	0.710	78%	++
Crop Arable Land	Harvest Crop Supply	Vegetables	0.025	0.250	90%	++
Crop Arable Land	Harvest Crop Supply	Fruits	0.030	0.200	85%	++
Crop Arable Land	Harvest Crop Supply	Green and Silage maize	2.342	6.690	65%	++
Crop Arable Land	Harvest Crop Supply	Arable fodder crops	3.372	3.967	15%	++
Crop Arable Land	Harvest Crop Supply	Perennial Fodder crops	0.901	1.060	15%	++
Crop Arable Land	Harvest Crop Supply	Total	25.89	36.74	-	-
Imports	Harvest Crop Supply	Cereal Grains	0.365	0.420	13%	++
Imports	Harvest Crop Supply	Oilseeds	0.262	0.288	9%	++
Imports	Harvest Crop Supply	Sugar Beet	0.020	0.090	78%	++
Imports	Harvest Crop Supply	Potatoes	0.040	0.182	78%	++
Imports	Harvest Crop Supply	Vegetables	0.065	0.648	90%	++
Imports	Harvest Crop Supply	Fruit	0.111	0.740	85%	++
Imports	Harvest Crop Supply	Total	0.86	2.37	-	-
Harvest / Crop Supply	Plant Food Production	Cereal Grains	1.784	2.050	13%	+
Harvest / Crop Supply	Plant Food Production	Oilseeds	0.469	0.510	8%	+
Harvest / Crop Supply	Plant Food Production	Sugar Beet	0.814	3.700	78%	+
Harvest / Crop Supply	Plant Food Production	Potatoes	0.141	0.640	78%	+
Harvest / Crop Supply	Plant Food Production	Vegetables	0.025	0.250	90%	+
Harvest / Crop Supply	Plant Food Production	Fruit	0.030	0.200	85%	+
Harvest / Crop Supply	Plant Food Production	Total	3.26	7.35	44%	
Import	Plant Food Products	Miscellaneous plant products	1.05	1.9	45%	+
Plant Food Products	Export	Miscellaneous plant products	1.23	2.25	45%	+
Plant Food Products	Secondary Residues	Cereal Grains (wheat bran)	0.446	0.513	13%	0
Plant Food Products	Secondary Residues	Oilseeds	0.188	0.255	8%	0
Plant Food Products	Secondary Residues	Sugar Beet	0.204	0.555	78%	0
Plant Food Products	Secondary Residues	Potatoes	0.028	0.096	78%	0
Plant Food Products	Secondary Residues	Vegetables	0.001	0.013	90%	0
Plant Food Products	Secondary Residues	Fruit	0.002	0.010	85%	0
Plant Food Products	Secondary Residues	Total	0.87	1.44	-	
Harvest / Crop Supply	Technical Production (biofuels)	Cereal Grains	0.187	0.215	13%	++
Harvest / Crop Supply	Technical Production (biofuels)	Oilseeds (for biofuels)	0.382	0.420	9%	++
Harvest / Crop Supply	Technical Production (biofuels)	Maize	0.131	0.150	13%	++
Harvest / Crop Supply	Technical Production (biofuels)	Sugar Beet	0.134	0.610	78%	++
Harvest / Crop Supply	Technical Production	Total	0.83	1.40		
Harvest / Crop Supply	Technical Production (incineration)	Straw	0.26	0.30	14%	0
Imports	Technical Production	Biofuels	0.19	0.19	0%	++
Technical Production	Export	Biofuels	0.12	0.12	0%	++
Technical Production	Consumption	Biofuels	0.23	0.23	0%	++
Pastures / Grassland	Animal Feed & Food Production	Grass and Grass sillage	0.44	2.45	82%	++
Total Secondary & Tert. R.	Animal Feed & Food Production	Secondary residues used as feed	0.50	1.26	-	0
Harvest / Crop Supply	Animal Feed & Food Production	Total	6.07	13.49	55%	0
Animal food production	Crop (Arable) Land	Manure	1.33	13.34	90%	++
Animal food production	Biogas Plants (via total residues)	Manure	0.78	7.76	90%	+
Animal food production		Total Manure	2.11	21.1	90%	+
Import	Animal Food Production	Live Animals	0.004	0.015	70%	++

Import	Animal Food Production	Meat & Meat products	0.126	0.504	75%	++
Import	Animal Food Production	Fish	0.015	0.049	70%	++
Import	Animal Food Production	Milk & milk products, eggs	0.062	0.309	80%	++
Import	Animal Food Production	Animal fats	0.188	0.188	0%	++
Import	Animal Food Production	Animal feed	0.990	1.100	10%	++
Import	Animal Food Production	Total	1.39	2.166	-	++
Animal Food Production	Export	Live Animals	0.054	0.180	70%	++
Animal Food Production	Export	Meat & Meat products	0.019	0.075	75%	++
Animal Food Production	Export	Fish	0.008	0.028	70%	++
Animal Food Production	Export	Milk & milk products, eggs	0.229	1.143	80%	++
Animal Food Production	Export	Animal fats	0.209	0.209	0%	++
Animal Food Production	Export	Miscellaneous animal products	0.036	0.071	50%	++
Animal Food Production	Export	Animal feed & residues	1.080	1.200	10%	++
Animal Food Production	Export	Total	1.63	2.91	-	++
Harvest / Crop Supply	Crop (Arable) Land	Straw (left on field)				
Harvest / Crop Supply	Anaerobic Digestion	Green Maize	1.20	3.43	65%	0
Plant food production	Consumption	Cereal Grains	0.987	1.135	13%	++
Plant food production	Consumption	Plant oils	0.180	0.2	0%	++
Plant food production	Consumption	Sugar Beet (crystal sugar)	0.350	0.4	0%	++
Plant food production	Consumption	Potatoes	0.145	0.7	78%	++
Plant food production	Consumption	Vegetables	0.087	0.9	90%	++
Plant food production	Consumption	Fruit	0.123	0.8	85%	++
Plant food production	Consumption	Total	1.87	4.02	-	-
Animal Food Production	Consumption	Meat in carcass weight	0.200	0.800	75%	++
Animal Food Production	Consumption	Milk products in milk weight	0.600	2.400	75%	++
Animal Food Production	Consumption	Animal fats	0.090	0.100	10%	++
Animal Food Production	Consumption	Eggs	0.020	0.100	80%	++
Animal Food Production	Consumption	Total	0.91	3.40	-	-
Harvest / Crop Supply	Export	Cereal Grains	2.323	2.670	13%	++
Harvest / Crop Supply	Export	Oilseeds	0.298	0.328	9%	++
Harvest / Crop Supply	Export	Sugar Beet	0.022	0.100	78%	++
Harvest / Crop Supply	Export	Potatoes	0.007	0.030	78%	++
Harvest / Crop Supply	Export	Vegetables	0.010	0.100	90%	++
Harvest / Crop Supply	Export	Fruit	0.015	0.100	85%	++
Harvest / Crop Supply	Export	Total	2.67	3.33	-	-
Consumption	Total Secondary & Tert. R.	Food Waste	0.26	0.85	70%	+
Consumption	Total Secondary & Tert. R.	Human Waste	0.11	0.47	77%	0
Plant food production	Total Secondary & Tert. R.	Plant secondary residues	0.87	1.44	60%	0
Technical Production	Total Secondary & Tert. R.	Oilseed meal, Sugar beet pulp	0.67	1.34	50%	0
Animal food production	Total Secondary & Tert. R.	Animal secondary residues	0.23	0.33	30%	0
Consumption	Human Metabolism	Human metabolism	2.50	2.50	0%	0
Total Secondary & Tert. R.	Waste Water Treatment Plants	Human waste	0.11	0.47	77%	0
Total Secondary & Tert. R.	Compost	Biogenic waste	0.10	0.34	70%	0
Total Secondary & Tert. R.	Landfil	Biogenic waste	0.13	0.43	70%	0
Total Secondary & Tert. R.	Incineration	Biogenic waste	0.03	0.10	70%	0
Total Secondary & Tert. R.	Total Secondary & Tert. R.	Total	2.83	-	-	0
Total Secondary & Tert. R.	Unknown	Unknown	1.29	-	-	0
Waste Water Treatment Plants	Arable (Crop) Land	Sludge	0.09	0.90	90%	+
Anaerobic digestion	Arable (Crop) Land	Digestate	0.56	7.50	93%	+
Anaerobic digestion	Air	CO2 emission from biogas	1.26	1.26	0	0
Composting	Arable (Crop) Land	Compost	0.10	0.26	60%	0

10.2 Annex 2: Questionnaire (translated from Czech to English)



Survey on post-harvest residues

1. Are you a part of any agricultural association?

Mark only one oval.

○ Yes
○ No

2. What association are you a part of?

Mark only one oval.

○ Agrarian Chamber
○ Association of Private Farming
○ Association of Local Food Initiatives
○ Agricultural Association
○ The Young Agrarians' Society
○ Other

3. What is the size of your farm?

Mark only one oval.

○ Small (0 - 50 ha)
○ Medium (50 - 250 ha)
○ Great (> 250 ha)

4. For how long have you been farming?

Mark only one oval.

○ Less than a year
○ 1 - 5 years
○ 5- 10 years
○ More than 10 years

5. What type of agriculture do you practice?

Mark only one oval.

○ Only crop production
○ Only animal husbandry
○ Both

6. Do you practic conventional or ecological farming?

Mark only one oval.

○ Conventional
○ Ecological with a certificate
○ Ecological without a certificate

7. Do you farm on leased or privately owned the soil?

Mark only one oval.

○ On leased soil
○ On privately owned soil
○ On partly leased partly own

8. Is your business related to producing post-harvest residues such as straw?

Mark only one oval.

○ Yes
○ No

9. Do you perceive straw as a vauable commodity?

Mark only one oval.

○ Absolutely yes
○ Rather yes
○ Rather no
○ Absolutely not

10. How do you use straw?

Mark only one oval.

○ I use it only for my own purposes
○ I sell all the straw
○ Part I use part I sell

11. Do you know what is the use of straw after sale?

Mark only one oval.

- ○ Incineration
- ○ Feed
- ○ Biogas plants
- ○ Animal bedding
- ○ Export
- ○ Material use (e.g. insulation)
- ○ I don't know but I would like to know
- ○ I don't know and I don't want to know
- ○ Other

12. Are you concerned about the use of straw after sale?

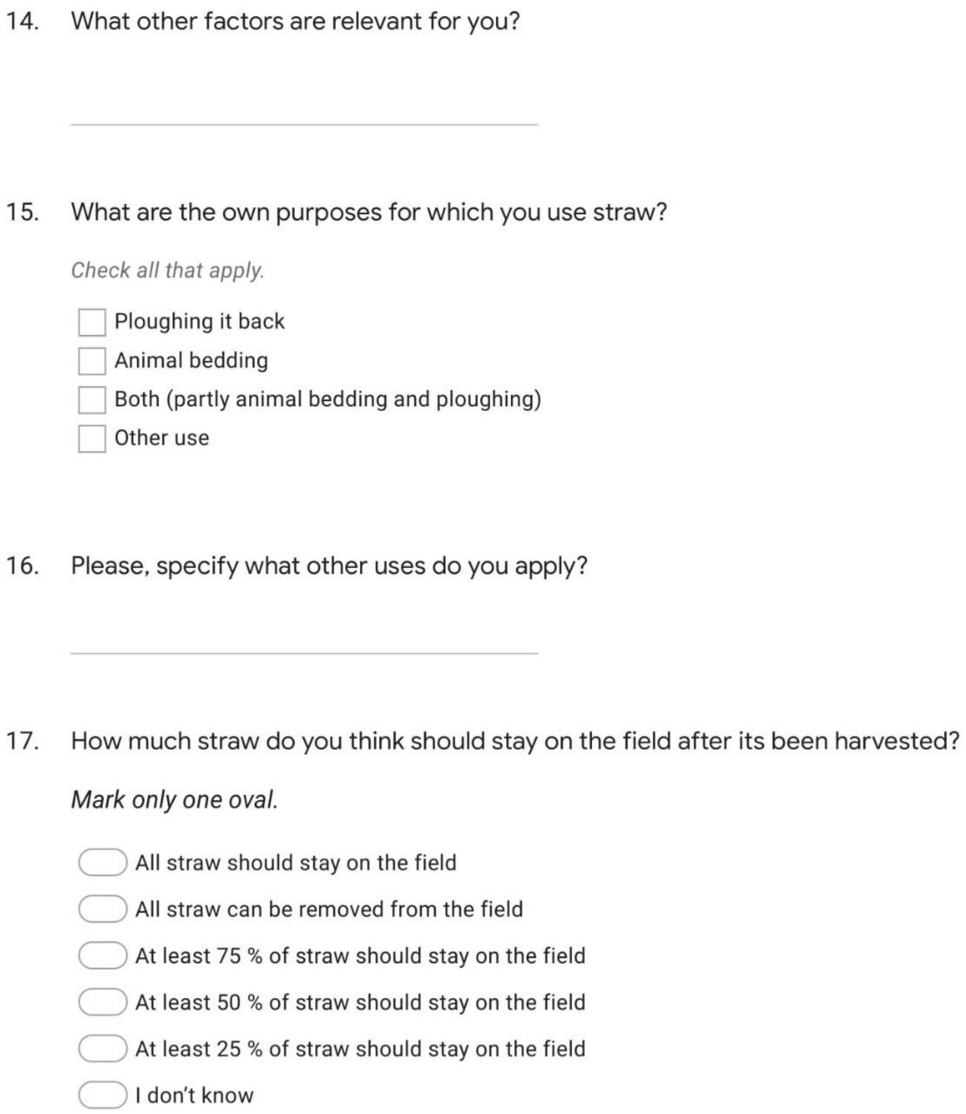
Mark only one oval.

- ○ Yes, greatly
- ○ Yes, partly
- ○ No, not really
- ○ Not at all

13. What is the decisive factor for you before selling straw?

Mark only one oval.

- ○ Only the price
- ○ Mainly the price and partly its subsequent use
- ○ Mainly its subsequent use and partly the price
- ○ Only its subsequent use
- ○ Other



14. What other factors are relevant for you?

15. What are the own purposes for which you use straw?

Check all that apply.

☐ Ploughing it back
☐ Animal bedding
☐ Both (partly animal bedding and ploughing)
☐ Other use

16. Please, specify what other uses do you apply?

17. How much straw do you think should stay on the field after its been harvested?

Mark only one oval.

○ All straw should stay on the field
○ All straw can be removed from the field
○ At least 75 % of straw should stay on the field
○ At least 50 % of straw should stay on the field
○ At least 25 % of straw should stay on the field
○ I don’t know

18. Do you produce a material during your business that you view as a waste?

Mark only one oval.

○ Yes, I am producing waste that I nolonger use
○ Yes, I am producing waste that I use
○ No, I don't produce any waste

19. Please, specify what type of commodity (waste) do you produce?

Mark only one oval.

○ open
○ Manure
○ Plant processing residues (chaff, husk, leaves, waste from washingú
○ Plastic and packaging material
○ Other

20. How do you use this commodity?

Mark only one oval.

○ I don't use it
○ I use it for my own purposes
○ I sell it

21. Would you be willing to sell this commodity or transform it into more valuabe product?

Mark only one oval.

○ Yes, absolutely
○ Rather yes
○ Rather no
○ Absolutely not

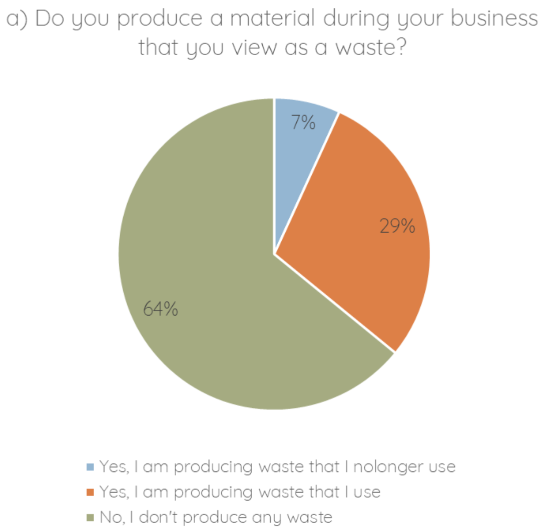
22. Is this commodity (waste) a financial burden or a financial gain for you?

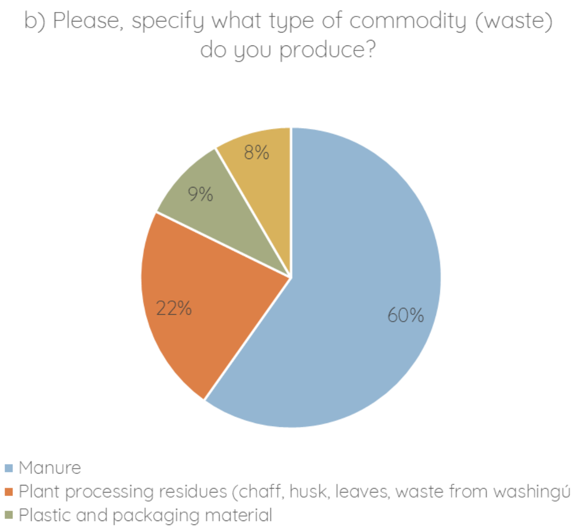
Mark only one oval.

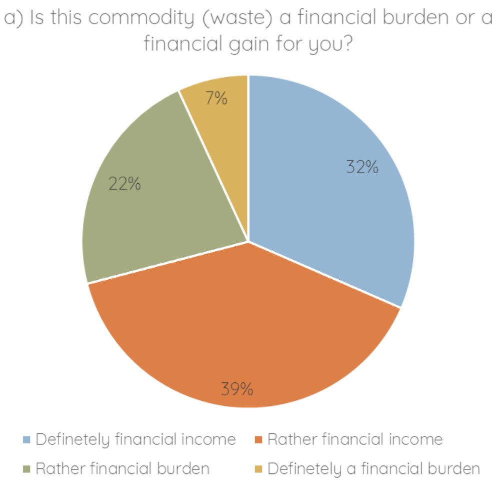
○ Definetely financial income
○ Rather financial income
○ Rather financial burden
○ Definetely a financial burden

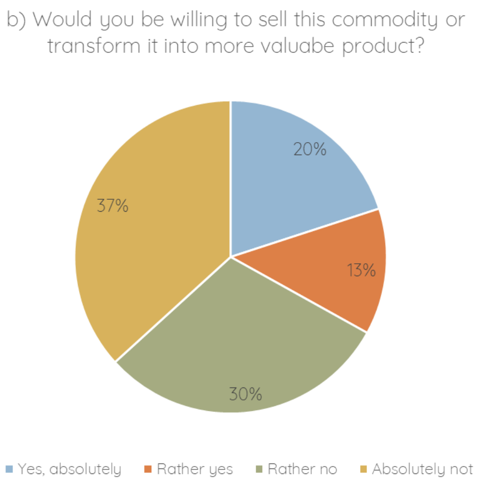
23. Do you have any other comments connected to straw harvest, its use or to any other residual products in agriculture?

10.3 Annex 3: Part of questionnaire on possible farmers' unutilized materials


a) Do you produce a material during your business that you view as a waste?


b) Please, specify what type of commodity (waste) do you produce?


a) Is this commodity (waste) a financial burden or a financial gain for you?


b) Would you be willing to sell this commodity or transform it into more valuabe product?

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