A global scenario on agricultural feedstock requirements in the bio-based industry for non-energy use

Master thesis within the Master programme
Agricultural and Food Economics

(H066 457)

at

University of Natural Resources and Life Sciences

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"Anyone who believes in infinite growth of anything physical on a physically finite planet is either a madman or an economist."

Kenneth Boulding

Abstract

The global consumption of non-renewable fossil resources is constantly increasing. Hence, transition from a fossil-based towards a bio-based form of economy is paramount. A closed carbon cycle has the potential to minimize greenhouse gas emissions in the production of energy and commodities. In this thesis, a global scenario on agricultural feedstock requirements is being developed in order to substitute fossil-based non-energy product groups in the bio-based industry. Four product groups are in focus: polymers, lubricants and hydraulic fluids, solvents and surface-active agents (= surfactants). Producing these products from starch, sugar or vegetable oil is a possible alternative to petroleum and other fossil based derivatives. This thesis will specifically answer the question how much biomass form agricultural crop production would be needed to achieve a 100% substitution level for these four product groups on a global scale. Therefore recent data of the agricultural production, recorded by FAO Stat (2017a) was compared with the actual demand of non-energy fossil resources published by IEA and OECD (2016). The calculations of the required agricultural biomass and arable land are based on the approach published by Schipfer et al. (2015). The results are showing that in 2014 about 271.4 Mt of fossil resources were consumed for the global production of the described product groups. To substitute this amount, 358.9 Mt of starch, 158.2 Mt of vegetable oil, and 10.6 Mt of sugar would be required. Globally, this would account for 22% of the arable land currently cultivated with starch crops, 3% with sugar crops, and 38% with oilseeds, which sums up to approximately 4 million km^2. Although it would be possible to manufacture these four products using agriculturally produced renewable raw materials on global scale, it is challenging and even impossible in some regions and countries. It should be considered that an increasing request for crops causes direct and indirect land use changes as well as economic and ecological impacts. Consistent framework conditions as well as a market-competitive production of bio-based products are subsequently paving the way for a transition to a bio-based economy.

Zusammenfassung

Der globale Verbrauch an nicht erneuerbaren fossilen Rohstoffen ist stetig steigend. Deshalb ist ein Übergang von einer fossil-basierten hin zu einer bio-basierten und erneuerbaren Form des Wirtschaftens notwendig. Durch einen geschlossenen Kohlenstoffkreislauf können die Treibhausgasemissionen bei der Bereitstellung von Energie und Gütern auf einem Minimum gehalten werden. Diese Masterarbeit entwickelt ein globales Szenario für den Bedarf an landwirtschaftlichen Primärprodukten, um Produkte auf fossiler Basis im nicht energetischen Bereich in einer bio-basierten Industrie zu substituieren. Vier Produktgruppen, die aktuell aus fossilen Ressourcen für nicht energetische Zwecke hergestellt werden, zeigen großes Potential durch biogene Ressourcen substituiert zu werden. Dabei handelt es sich um die Produktgruppen der Kunststoffe, Schmier- und Hydraulikflüssigkeiten, Lösungsmittel sowie der grenzflächenaktiven Stoffe/Tenside. Diese Produkte können auch aus Stärke, Zucker oder pflanzlichem Öl hergestellt werden. In dieser Masterarbeit wird die Frage beantwortet, wie viel Biomasse aus agrarischer Produktion notwendig wäre, um ein 100 prozentiges Substitutionsniveau auf globaler Ebene für ebendiese vier Produktgruppen zu erreichen und wie viel Agrarfläche dafür beansprucht werden würde. Dafür wurden aktuelle Daten der landwirtschaftlichen Produktion, von FAO Stat (2017a), mit jenen Daten von IEA und OECD (2016) verglichen. Letztere beinhalten die aktuelle Nachfrage an fossilen Ressourcen im nicht energetischen Bereich. Die Kalkulationen für die benötigte Biomasse und agrarische Fläche folgen dem Ansatz in Schipfer et al. (2015). Die Ergebnisse zeigen, dass 2014 für die globale Produktion der vier Produktgruppen ungefähr 277,5 Mt an fossilen Ressourcen verbraucht wurden. Um diese Menge zu substituieren, würden 358,9 Mt Stärke, 158,2 Mt pflanzliches Öl und 10,6 Mt Zucker gebraucht werden. Das würde global 22% der Agrarflächen beanspruchen, auf denen aktuell stärkehaltige Pflanzen angebaut werden, 3% von Zuckerpflanzenflächen, sowie 38% von Ölpflanzenflächen was in Summe etwa 4 Mio. km² entspricht. Unter dem Aspekt der Substitution betrachtet, wäre es möglich diese vier Produktgruppen mit agrarischen Rohstoffen auf globaler Ebene herzustellen, obwohl in manchen Ländern und Regionen die innerregionale Substitution nicht möglich ist. Es gilt zu bedenken, dass dieser zusätzliche Bedarf an landwirtschaftlichen Nutzpflanzen sowohl direkte und indirekte Landnutzungsänderungen als auch ökonomische und ökologische Auswirkungen verursacht. Einheitliche Rahmenbedingungen sowie eine wirtschaftliche und marktkompetitive Herstellung der biobasierten Produkte sind in weiterer Folge die Voraussetzung für einen Übergang zu einer Bioökonomie.

1 Introduction

The global demand for renewable and non-renewable resources is permanently increasing. Therefore, there are concerns and uncertainties about the availability of resources in the future (WEF, 2014). The increasing global population and anthropogenic climate change (UNFPA et IIED, 2009) are pushing our planet to its ecological limits (Global Footprint Network, 2014). One of the main driving forces behind climate change is the increase of greenhouse gas (GHG) emissions in the atmosphere. 78% of the total GHG emissions were generated by the combustion of non-renewable fossil resources to supply energy, fuels for transportation, or other products by the petroleum industry (IPCC, 2014). At the same time the global demand for crude oil is permanently increasing (OPEC, 2015), which will lead to an exhaustion of oil reserves, and the end of cheap oil supply (Tsoskounoglou et al., 2008). To sustain the current global welfare, it is necessary to achieve independency from non-renewable fossil resources in the energy sector as well as in other petroleum dependent industries.

GHG emissions are the driving factors of climate change, which in turn threatens livelihoods, ecosystems and mankind (IPCC, 2000). Therefore, it is important to set preventive actions against this development on a global scale. In 2015, the United Nations set up an agreement in Paris, which was signed by all member states of the United Nations on April 22nd 2016, to prevent a further increase of the average global temperature by reducing GHG emissions (UN, 2015).

It has been shown that bioeconomic approaches, that substitute non-renewable fossil resources have the possibility to emit less GHG than comparable products, if sustainable land use policies are applied and leakage is minimized (e.g. Hermann et al., 2007; Dornburg et al., 2006; Patel et al., 1999). The European Union (EC, 2012), the OECD (2009), and newly industrialized countries (BIOSTEP, 2016), formulated bioeconomic strategies as one measure to achieve GHG reduction goals and to foster independence from fossil resources. Most bioeconomic strategies and position papers are addressing ways to substitute oil as an energy resource as approximately 78% to 90% of the crude oil production is used for energy purposes (IEA et OECD, 2016; Ulber et al., 2011).

The supply of fossil energy, in particular oil and gas, depends on few countries. Domestic political unrests or disputes in foreign affairs can have a high impact on oil prices on a global scale. This is forcing governments – especially countries with high import rates on raw materials - to support alternative production technologies in order to gain autarky in economically relevant areas. From a political-economic point of view, it is seen as important strategy to support technologies that will allow achieving independency from the oil supplying countries and the ability to provide energy for domestic demand at low prices. Not only oil-independency, but also eco-political aims are on the political agenda of the bioeconomic strategies.

Besides decreasing GHG emissions, a realization of those strategies has the possibility to create new jobs and foster research and technological development which can result in an increase of economic growth and welfare (van Meijl et al., 2018; EC, 2010). A major advantage of bio-based materials is the possibility of cascading utilisation: depending on their field of usage, it is possible to adding value by recycle, compost, or combust them. Recycling and composting is reducing the amount of needed feedstock in production of new goods as well as closing the nutrient cycle to some extent. The combustion of disposed products for energy generation is the last opportunity for adding value. Therefore, the higher level of utilisation is a better opportunity than the direct combustion of biomass for energy purposes (Keegan et al., 2013).

10% to 22% of the global crude oil production goes into the industry for production of non-energy goods (IEA et OECD, 2016; Ulber et al., 2011). The usage of renewable raw materials in the chemical industry as substitute for crude oil has the potential to reduce GHG emissions depending on the produced bio-based bulk chemical (Hermann et al, 2007), it can also reduce environmental pollution (e.g. plastic in oceans (WEF, 2016)) by producing biodegradable polymers instead of common polymers with a long-lasting durability of several years until complete degradation. Usage of biodegradable lubricants in sensitive environmental areas (e.g. sylviculture, stream and maritime navigation, agriculture) can provide a reduction of water and soil pollution particularly in the case of an accident (e.g. burst of hydraulic systems). However, the ecological benefits of bio-based products depend not only in its utilisation and processing. The (agricultural) production of the feedstock as well as the correct disposal of the products has a major influence on its saving potential in GHG emissions. One fundamental challenge in the production of bio-based materials from agricultural crops is the trade-off between the utilisation either for food and feed or fuels and other bio-based products (Yates et Barlow, 2013). An increase in the amounts of agricultural products requested can cause direct and indirect land use change (e.g. transformation of land from forest to cropland) and other environmental externalities (e.g. intensification by nitrogen fertilisation) which at least can lead to higher global GHG emissions again (Prapaspongsa et Gheewala, 2015).

In this thesis, a global scenario on agricultural feedstock requirements is being developed in order to substitute fossil-based non-energy product groups in the bio-based industry.

The objectives of this thesis are to calculate:

(I) *the global agricultural production requirements of four specific product groups in order to substitute non-renewable feedstocks in the bio-based industry for non-energy use;*

(II) *the necessary global cropland requirements.*

The thesis is structured as follows: in the following chapter 2, a short overview over the importance of crude oil, the global aims of the bioeconomy, and the actual production schemes in the biorefinery is given. Further in chapter 2, land use changes and their environmental and socio-economic impacts are discussed. Chapters 3 and 4 describe four product groups and the bio-based raw material requirements. Chapter 5 and 6 outline the methods and results of the calculations on the global cropland requirements for producing bio-based materials. A discussion as well as a summary and conclusions are provided in chapters 7 and 8.

2 Bio-materials in the context of fossil fuel substitution

As described by BREW (2006), most of the organic compounds used in the industry are made from petrochemical feedstocks. To attain the aims outlined in the bio-economy strategy, the petrochemical feedstocks have to be substituted by carbohydrates like sucrose, starch, cellulose and hemicellulose, oils and proteins and by lignin. Through refining of biological feedstocks, the dependency on mineral oil and its negative side effects can be reduced in producing bio-based goods.

2.1 Fossil products in the current global production system

Mineral oil is one of the most important globally traded commodities. In 2014, 78% (≙ 5539.37 Mtoe) of the global demand in non-renewable fossil resources (= crude oil, coal and natural gas) were used for energy purposes (fuel for heating, transportation industry or energy production in general). 22% (≙ 1578.3 Mtoe) were used for non-energy purposes. These are, according to IEA et OECD (2016, p. 14), “fuels that are used as raw materials in the different sectors and are not consumed as a fuel or transformed into another fuel”.

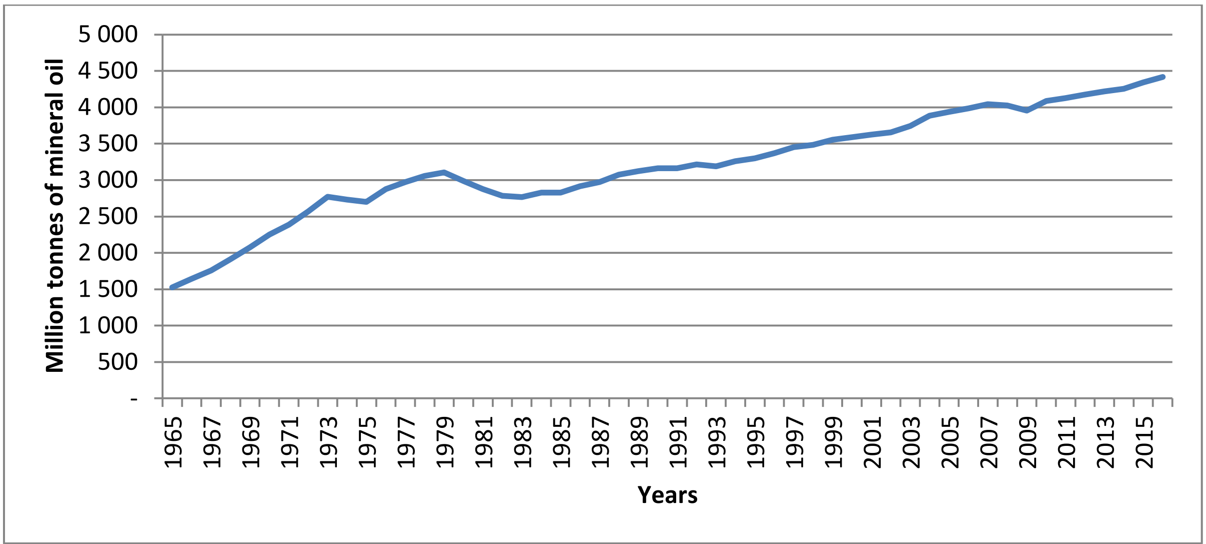


Figure 1: Annually global oil consumption in million tonnes between 1965 and 2016. Data taken from BP, 2017.

Since the first oil crisis in 1973, oil was seen as scarce resource. The demand for crude oil exists globally, while the places, where oil is extracted, are located in a few countries. The five countries with the highest supply for the global market, according to BP (2017), are Saudi Arabia (568.5 Mt/a), USA (567.2 Mt/a), Russia (540.7 Mt/a), Canada (215.5 Mt/a), and China (214.6 Mt/a). A view on the share of the oil sector in the GDP of the OPEC member countries shows their economic dependence on crude oil (The World Bank, 2016 [Data from 2014]).

Due mineral oil is a finite resource, Hubbert (1956) shaped the term “peak oil”. Today, even publications by the oil industry (BP, 2017; OPEC, 2015) are showing uncertainties about the remaining global oil reserves.

Basically mineral oil consists of hydrocarbon chains with different lengths and impurities which are removed during the refining process. Through physical and chemical treatment, crude oil gets separated in different fractions, basically depending on the size and length of the hydrocarbon molecules. The results of these separation processes are already final or intermediate mineral oil products. Depending on their specific field of application, further treatment may be necessary (Bukold, 2009; Leffler, 2010).

The discussions of finding substitutes for mineral oils are mostly concerning the energy sector (e.g. Mat Yasin et al., 2017; Höfer et Bigorra, 2008). Due to the current state of technology and the high production costs, bio-based non energy products are not particularly widespread (EC, 2010; BREW, 2006). Despite the Paris Agreement (UN, 2015) and the global aim of receiving a low-carbon economy, mineral oil will play a major role in the global economy in the short- and mid-term.

2.2 Bioeconomy

To break the dependency on fossil fuels, it is necessary to develop an economy which is based on renewable resources. Some countries, transnational institutions (OECD), and confederations (European Union) set up position papers on bioeconomic strategies for achieving the shift from a fossil based to a bio-based economy. Since there is no uniform definition of the term "bioeconomy", the range of interpretation goes along with assumed future needs of the countries. Summarizing the statements of all position papers one can say that the bioeconomy "encompasses biotechnological activities and processes that translate into economic outputs, particularly those with industrial application" (DST, 2013, p. 3).

Most of the position papers were published by the G7 (Canada (BC Committee on Bio - Economy, 2011), France (Ministère du Redressement Productif, 2014), Germany (BMEL, 2014), Japan (MAFF, 2012), United Kingdom (BIS, 2013), USA (The White House, 2012)), BRICS (Brazil (Guverno Federal, 2007), Russia (Popov, 2011), India (DBT, 2014), South Africa (DST, 2013)), the European Union (EC, 2012), and the OECD (2009), as representative organ of 35 countries. Besides covering ideas how to support economies in deploying biological technologies some position papers face questions concerning bioenergy as well (e.g. Australia (RIRDC, 2011), Brazil (Rodrigurz et Accarini, 2004), India (DBT, 2012), United Kingdom (DECC, 2012), Ghana (Otu-Danquah, 2014), Mali (Fofana, 2009), Indonesia (Kusdiana, 2014)).

Most of the position papers are not describing specific aims, rather means what kind of framework would be necessary, to achieve steps towards a bio-based economy. Conclusively it can be said that:

- financial support in research and development on public and private level,
- development and reforms of regulations and reducing barriers,
- facilitate and accelerate market access,
- support education and trainings in all sectors with relation to bioeconomy, and
- encouragement of development of public-private-partnerships and pooling of resources, knowledge and expertise to learn from each other

are the most important points to receive a breakthrough (e.g. The White House, 2012; Popov, 2011; OECD, 2009).

The realization of these steps is generally taking place in the areas of agriculture, health, energy, industry and environment. Biotechnology and genetic engineering are often mentioned as key technologies in the bioeconomy. The application of biotechnology in agriculture should ensure food security, supply for the industry and job security in rural areas (e.g. DBT, 2014; DST, 2013; Popov, 2011). In the area of health, South Africa is particularly eager to enforce the application of biotechnology in the pharmaceutical sector.

In some papers (e.g. DST, 2013; EC, 2012) the shift to a low-carbon economy and a greater independence from imported mineral oil are described as additional aims. This should be, in addition to applying biotechnology, brought about through support in the production of bio-based fuels, materials and chemicals in combination with environmentally sustainable management systems in the industry like standardization of life cycle analysis, uniform standards, and certification as well as development of environmentally sustainable technologies in the production process. One necessary step to reach the aims is seeking the dialogue with society and industry on socio-economic and ethical implications, benefits, and requirements of biotechnologies to gain acceptance and a paved way to a bio-based economy. The production of bio-based goods needs, as fossil based ones, initially technical treatment of the raw materials which takes place in the biorefineries.

2.3 Biorefinery

The original idea to implement and foster biorefineries was mainly driven by the need for finding alternative ways of energy supply apart from fossil fuels. So the first purpose in developing biorefining technology was the conversion of biomass to useable fuels. Afterwards, technologies for material and chemical production have been developed (Clark et al., 2006). Refining processes of biomass, comparable to those in the mineral oil industry, are the technical key technology in a transition to a bio-based economy. The burning of organic matter should only be the last step in adding value in a process chain.

The modern objective of biorefineries is converting biomass into fuels, chemicals, and materials with an optimal utilization of resources and minimal waste with maximal benefits and profitability at the same time (WEF, 2010). Through a combination of processes and technologies, it is possible to transform biological inputs into platform chemicals or intermediate products. In terms of the idea of the circular economy "the main goal of a biorefinery is to produce high-value low-volume (HVLV) and low-value high-volume (LVHV) products […]" (Fernando et al., 2006, p. 1727), whereby the high-value products (e.g. bio-polymers) represent the main output of a biorefinery plant and the low value ones provide a source of energy (Fernando et al., 2006), which can be used to power the plant itself or even sell surplus energy.

Nowadays biorefinery plants can be divided into three types (Phase I-III), which describe the flexibility of a plant in the use of feedstock, in the conversion processes, and the final products: Phase I plants in general use grains as feedstock and have limited processing capabilities. A phase II plant uses grains as feedstock as well, but additionally has the ability of a higher processing flexibility and therefore varying final products. Phase III biorefinery plants are the technologically most advanced ones. They can use various feedstocks and provide a broad range of different products. These phase III biorefineries are subdivided into whole crop, green, and lignocellulose feedstock (LCF) biorefineries (Kamm et Kamm, 2004; Dyne et al., 1999).

<u>Whole crop refineries</u>: Here the whole crop will be consumed, in general starch containing grains. Initial mechanical separation is necessary for further treatment. The first intermediate product is syngas which can be processed to fuels or methanol by the Fischer-Tropsch-Synthesis.

<u>Green biorefineries</u>: The feedstock is untreated, natural wet biomass like grass or green plant material. The biomass will be separated into two phases: A dryer fibre rich press cake and a nutrient-rich liquid. The pressed cake is used for the production of chemicals and conversion to syngas.

<u>Lignocellulose feedstock (LCF) biorefineries:</u> The main input materials are cellulose, hemicellulose, and lignin from lumber and other non-edible plant material. In the first step, the cleaned raw feedstock will be separated into these three fractions. This happens through

chemical digestion or enzymatic hydrolysis. Cellulose and hemicellulose factions have several uses, Lignin can be processed to adhesives, binder, or as fuel for combustion.

Integrated biorefineries are the most cost-effective biorefineries. Through combination of several conversion technologies, the integrated biorefinery has a greater flexibility in product generation and input material, so the costs for the final products can be decreased compared to plants operating with only one conversion technology (Fernando et al., 2006).

While running the plant, it is necessary that clean and efficient technologies are applied, so that the idea of creating environmentally friendly products with reduced CO_2 emissions will not get distorted. One approach is adopting biorefinery plants and processes to locally available feedstocks. As with every industrial plant, common economically aspects must be taken into account: availability of resources, economies of scale, and at least the demand in final products (Kazmi et Clark, 2011). Usually the increase of the demand in agricultural products simultaneously leads to an increase of the therefore needed input. Depending on regional agricultural cropping systems this increase can lead to a higher demand in another finite resource: arable land. This higher demand in arable land can lead to land use changes with associated negative environmental externalities.

2.4 Land use changes

Arable land is a finite resource. The increase in demand for available resources affects land for arable use and construction. Nowadays, every piece of land has its purpose for humans, even seemingly unused areas like rain forests. A change of land use to new requirements may go along with negative externalities e.g. grassland and forests to agriculturally used land, either for production of food and feed or for industrial use, are contributing to an increase of GHG emissions by releasing of below (in soil) and above-ground (in plants) stored carbon (e.g. EC, 2017; Harris et al., 2015; Wise et al., 2009). A transition to a bio-based industry inevitably leads to an additional quantitative request in renewable biological resources, which also increases the demand for the limited resource of land. Especially grassland and forests have the ability of storing CO_2 as sink. A change into cropland for the e.g. biofuel production reduces that ability and the stored CO_2 will be, in the long term, set free in the atmosphere. In an ideal situation, the amounts of CO_2 emitted during production of bio-based products and along the whole value chain, are equal to the amounts of CO_2 stored in the plants to produce the bio-based products. The most important land use changes affecting greenhouse gas emissions (positively and negatively) are, in general changes in forest, grassland and other woody biomass stocks and their conversion, abandonment of croplands, pastures, plantation forests, or other managed lands that regrow into their prior conditions and changes in soil carbon (IPCC, s.a.).

Changes in land use can be subdivided into two types: change in competition between uses (e.g.: conversion from farmland to construction land) and in change in the quality of land (e.g.: conversion to intensive monoculture based agriculture from extensive agricultural production) (Baumann et Tillman, 2004). The impacts of land use changes can be measured by the quality of different ways of land usage: The functional approach measures the different natural functions of land like groundwater protection, habitat resource function or human resort function. Another classification of land use was derived from landscape ecology, where land can be graded stepwise from “natural systems” to “systems degraded by pollution and loss of soil and vegetation” (Brentrup et al., 2002), or the quality of land displayed by measuring impacts of land use change on biodiversity, biotic production potential, and ecological soil quality (Milà i Canals et al., 2007). Summarising the ways to classify land use changes, all are concerned with three dimensions: area, time of duration of occupation, and transformation process, and the land quality with a reference situation before and after the land use change (Schebek, 2011).

Regarding the effects of a higher production of energy crops on GHG emissions, it was observed that in general the substitution of fossil fuels through renewable ones can avoid GHG emissions from -2.2% (higher emissions compared to the use of fossil resources) to 164.8% in best cases, which mostly depends on the impact of land use changes, management practices and what kind of crops are used for the bio-based production (e.g. Lange, 2011, Walter et al., 2011, Brehmer et Sanders, 2009). Besides the used crops and the efficiency in the biorefineries, land use change plays a major role in the efficiency of GHG emission saving potential too.

As an example, due to the renewable energy act (EEG) in Germany, a massive increase of the cultivation of maize was observed (Appel et al., 2016). The aim of this law was to mitigate GHG emissions, which was achieved between 22 – 75% compared to the actual energy mix supplied in Germany (inclusive land use change) (Scholz et al., 2011), mostly depending on the agricultural management practices employed previous to land use change and the crop that is displaced through the land use change (Walter et al., 2011). In Germany, it was observed that an increase in the biogas production leads to a higher competition for land between farmers which further leads to high rental and purchase prices for arable land (Appel et al., 2016). The higher prices made it, with some exceptions (Guenther-Lübbers et al., 2016), impossible for smallholder farmers to stay competitive on the market (Appel et al., 2016). One possibility to avoid this competition and the increase in land prices and rents may be the usage of degraded land for industrial crop production, though the negative effects, that in degraded land the yields are lower and costs for restauration may occur (Lange, 2011). So even in the EU price changes for agricultural products may increase up to 3% and indirect land use change outside the EU may sum up to 1 Mio ha (Britz et Delzeit, 2013).

Concerns, that forests are converted into cropland were not confirmed for the case of Brazil (Walter et al., 2011), rather consisting cropland formally used for food production or pastures are used for the cultivation of energy crops (Lange, 2011, Walter et al., 2011). This leads inevitably to a competition between the food and feed sector and the production of crops for industrial use (Grundmann et Klauss, 2014) The conclusions of the examples of Germany and Brazil in the sector of producing bio-energy can be seen as examples for a development in the agricultural sector in a transition to a bio-based economy.

Generally (indirect) land use changes are connected to complex global land use dynamics (Lange, 2011) and therefore general statements should be avoided due to the heterogeneity of production conditions (Walter et al., 2011). The competition between food, feed and crops cultivated for industrial use in combination with a rising world population leads sooner or later to a tremendous scarcity of arable land on global scale (Lange, 2011). One promising step in reducing the competition of biological resources lies in a higher efficiency in the usage of renewable raw materials, like 2nd generation feedstocks (e.g. lignocellulose). Including the usage of 2nd generation feedstocks (especially non-edible biomass) to 1st generation ones (sugar, starch, oil), leads to the highest mitigation potential of GHG emissions per land unit (Brehmer et Sanders, 2009). Due to the high complexity in the requirements and environmental impacts in the fields of bio-based economy, highly specific assessments for each raw material and final product should always be conducted (Brehmer et Sanders, 2009).

3 Final product groups and process chains

To understand, how products of daily use can be made out of agricultural raw materials, contemplating the (bio)-chemical properties and structures of both, the final products and the raw materials, is necessary. The focus of the next subsection lies on the specification of these.

To substitute a fossil based product by a bio-based one, it is important that the substitute provides similar or even better properties to stay in line with market requirements. Based on current data, presented in the BIOCHEM report (EC, 2010), there already exist product groups where biomass may substitute non-renewable fossil resources in the production process: polymers, lubricants, solvents, and surfactants. Compared to the whole production of these four products, the market share of bio-based products currently lies between 4 – 6% in Europe; in the group of polymers even between 5 – 10% with a predicted share up to 70 – 100% in the mid-term by 2030 (EC, 2010). That means that bio-based polymers have the possibility to substitute fossil based ones at least in the next two decades. Besides the mentioned four product groups enzymes, pharmaceuticals, and other high-value-chemicals (HVCs) also show high potential to be produced by renewable raw materials (Ulber et al, 2011). In the following, details on these four groups, which are also the ones considered in this study, are given.

3.1 Lubricants

The performance of lubricants, which are made of crude oil, depends on the types of molecules in the refined base oils. After distillation and refining processes, additives in the base oils influence their chemical and physical properties (Bratz, 2010; Braun, 2007; Miller, 1993). The most important criteria for the quality of liquid lubricants are viscosity, density, flashpoint, aniline point, and toxicity (Bratz, 2010). Lubricants are in most cases base oils in tribological systems to reduce friction and wear in mobile machine parts. Additionally, lubricants have a function in cooling, corrosion protection, sealing, and disposing of contaminants. Common fields of application are engines, gears, compressors, hydraulic systems, and in metal processing. Non-lubricating applications are e.g. electrical isolation, tire manufacturing, food processing, pharmaceuticals etc. (Bratz, 2010; Leffler, 2010; Mang, 2007; Miller, 1993).

The idea of using vegetable oil as substitute for mineral oil is not a new one. Because of higher standards in mechanical engineering and the higher process ability of mineral oils, the usage of vegetable oil remains on marginal levels (Riedinger, 1949). Even if the market share of bio-based lubricants is on a low level of about 1% (Bremmer et Plonsker, 2008; Bratz, 1998), the growth rate is predicted at 3.6% per year in the European Union (EC, 2010). This can be traced back to the better applicability nowadays and the usage of bio-based lubricants in environmentally sensitive areas (e.g.: sylviculture, stream and maritime navigation, agriculture, food industry). The environmental damage is in most cases caused by wrong disposal of used lubricants (e.g. residual oil in cans, oil filters) as well as oil spills, leaks, drips from hydraulic couplings, or accidental release. Although there is an obvious negative environmental impact, only in a few countries the utilization of environmentally non-harming lubricants in ecologically sensitive areas is requested by law (Bratz, 1998). The most important objective criteria in evaluating the environmental compatibility of lubricants are biodegradability, water solubility, water pollution, ecological toxicity, and physiological safety.

3.2 Surfactants

Detergents, tensides, and surface active agents (= Surfactants) are substances whose molecules consist in general of two parts: one non-polar hydrophobic and one polar/ionic hydrophilic part. Unlike the hydrophobic part, the hydrophilic one has a strong interaction with water, which enables the surfactant to increase the solubility in water. The main function of surfactants is creating (micro-, nano-) emulsions, suspensions, and foams. This is necessary if the properties of one substance hinder the solubility in water (e.g.: oil).

The reduction of contact between the water and the (hydrophobic) hydrocarbon chain reduces the free energy in the system. As a result spherical micelles, cylinders or bilayers are formed and reach a dynamic, reversible equilibrium. The reducing of phase boundary (= reduced surface tension) leads to an increase of the wetting properties. A decrease of concentration can re-establish the surface tension (Butt et al., 2003; Tadros, 2005).

Surfactants produced from fossil resources are based on alkylbenzene (Petrochemicals Europe, s.a.), whereas plant oil can also be used as feedstock (Salimon et al. 2010). Like all other product groups, the field of application and the cost of production determine which feedstock will be used. Common fields of application are in detergents, paints, dyestuffs, paper coatings, inks, plastics and fibres, personal care products, agrochemicals, food processing or decontamination after oil spills and environmental bioremediation.

If surfactants are biodegradable (e.g. bio-tensides), they will be digested by bacteria in the soil. CO_2, water, oxides, and other elements are products of the decomposing process. This process can take from one or two hours up to several months – depending on the molecular structure of the surfactant as well as the concentration, pH, and temperature while decomposing. The length and amount of branches of the surfactant molecule is a determining factor for the duration of decomposing. In case that the surfactant is not biodegradable, it will persist in the soil (Lang et Trowitzsch-Kienast, 2002; Tadros, 2005).

To obtain surfactants out of renewable resources, the production of bulk chemicals is separated in the production of either the hydrophobic or hydrophilic part of the final product. In general fats and oils are the raw materials for the hydrophobic part, mostly taken from plants or animals (Svensson, 2010), for the hydrophilic part proteins and carbohydrates are used (Hill, 2010). Surface-active compounds, like resin, fatty acids or stabilizers for emulsions, can also be received by forest (wood) products (Holbom et al, 2010). The benefits of using bio-based surfactants are the better biodegradability and less environmentally toxic characteristics compared to ones out of crude oil.

3.3 Solvents

A solvent is a compound, in general a liquid, which dissolves solutes without changing them chemically. The aim in using solvents is gaining a solution by mixing liquid, solid or gaseous substances with liquids into a homogenous product, where the liquid is always the solvent to process, apply, clean or separate materials. Nowadays, most solvents are used in paints, coatings, pharmaceuticals, adhesives, and cosmetic products (ESIG, 2010). Good properties in the volatility of solvents are necessary to achieve fast evaporation and leave the dissolved substances at the place of application rapidly. Plasticizers can be regarded as solvents too, whereas the technical requirements for plasticizers differ from those of solvents. According to the field of application based on its molecular structure and other physical and chemical properties, several types of solvents are in use (Stoye et Ortelt, 1998). With exception of alcohol, all solvents are made out of Aromatics (Benzene, Toluene) and Oleofins (Propylene, Ethylene) (Petrochemicals Europe, s.a.).

Due to the high volatility of organic solvents and their threatening potential, solvents underlie, for example, regulations in usage and production to reduce air pollution and further health related issues in the USA (EPA, 2016) and Europe (EC, 1999). Volatile organic compounds (VOCs) are forming ground level ozone which is harmful to all living creatures, whereas the effects depend on the nature of the VOC as well as on the level and length of the exposure (NLM, 2015). The range of effects on human health goes from irritation in the respiratory system or eyes to damages of the liver, kidneys and the central nervous system. According to the U.S. National Toxicology Program (2016), ingredients in VOCs are "reasonably anticipated to be human carcinogens".

One advantage in the usage of bio-based solvents is that the majority do not emit those harmful VOCs. Currently the production of bio-based solvents is not as cost effective as the production of solvents by crude oil (EC, 2010). A broad industrial application in the future will only be possible if the production costs will be similar or lower compared to traditional produced solvents and a constant high quality can be provided (FNR, 2000). Nevertheless bio-based solvents are in use in the printing industry for paints and cleaning supplies, e.g. Soy oil based ink in newspaper printing (ÖKL, 1998).

Due to the broad functions of solvents, it is necessary to know the field of application of the solvent as well as the performance of the final product with regard to health, safety and environmental issues (American Solvents Council, 2005).

3.4 Polymers

Polymers are materials composed of molecules with high molecular weight (Macromolecules). Based on the material properties and the versatility of processing methods, polymers are the most sought after materials today. The combination of low density, the ability to be shaped at low temperatures, and low production costs compared to traditional products like wood, metal, ceramics or glass, makes polymers the preferred material in production processes.

The first polymer used by humans was natural rubber from the rubber tree (*caotchouc*) used by South American indigenous peoples, which was brought to Europe in the 1740s. Until the beginning of the 20th century, natural rubber was the only source for polymer production (Seymour et al., 1989). In the middle of the 20th century, especially during World War II, and the post-war years, the development of polymer products like polyvinylchloride (PVC), polyethylene (PE), polypropylene (PP), polyacetal (POM), polyethylene terephtalare (PET) or polycarbonate (PC) accelerated. This rapid development goes along with the developments in the oil refining industry in that time. Since the 1960s the global polymer production has been steadily increasing (Osswald, 2011).

According to the definition of polymers, they are high polymeric materials, which are partly or as a whole synthetically produced and show in general a chemically organic structure. These materials can occur in solid or liquid states. This definition includes amongst others synthetic fibres, glues, varnishes and plastics (Schwarz et al., 2007). In this thesis, the main focus of polymers is on multiple forms of plastics.

Ethylene is the basic precursor for most polymer chemicals and is produced during the cracking in the refinery process. Through polymerization processes it is possible to form polymers (poly ethylene, poly styrene, polyvinyl chloride, etc.) out of monomers. Through further processing steps (polyaddition, vulcanization, etc.) and additives, plastics can be formed (Schwarz et al. 2007; Keim, 2006). Plastics are differentiated in two groups: thermoplasts (one-dimensionally built macro molecules) and thermosets and elastomers (interconnected, three-dimensional). The way bigger group of polymers are the thermoplasts. They do have a melting point, and so are able to take on any shape. After cooling them, they keep their shape. This process is reversible. Thermosets are not able to melt, and it is not possible to form them into another shape after the end of the production process (Keim, 2006; Osswald, 2001).

There are two different forms of biodegradable polymers, based on their feedstock: Ones from synthesis of organic feedstock (e.g. microorganisms, lactic acid monomers produced by fermentation of carbohydrate feedstock), the other from plant resources (e.g. starch, cellulose, proteins). A treatment of starch, for example, with acid and glucose produces lactic acid and finally results in polylactic acid (PLA), which physical properties are similar to those of polyethylen. First uses of bio-plastics made of polylactic acid are in biomedical applications like tissue engineering, medical sutures, and drug delivery vehicles (Schwarz et al., 2007; Sisson et al., 2011).

Non degradable plastics persist in the environment and are harming wildlife, especially water-bound animals, which are not able to distinguish plastic particles from food and ingest them by mistake (e.g.: de Stephanis et al, 2013; Tankana et al, 2013; Holland et al, 2016).The main benefit in using bio-based polymers is the nontoxicity and, if biodegradable, the decomposition into harmless, natural substances. The feedstock for producing those polymers is based on carbohydrates (sugar cane, corn, potato, wheat, beets) or vegetable oil (soybean, sunflower, palm, etc.) (Ienczak et Falcão de Aragão, 2011).

The fabrication of the product groups out of renewable raw materials needs product specific raw materials. For example, it is only possible to produce bio-based lubricants out of plant oils (Heikal et al., 2017). The basic plant materials necessary to produce all presented product groups are starch, sugar and plant oil.

4 Agricultural feedstocks in bio-refineries

The genuine purpose of agricultural crops is to ensure nutrition for living beings. The technical applications of agricultural crops are, besides the usage as source of energy, several fields of biotechnology like in medical applications, for industrial use or for the production of goods. The content and composition of the nutrients determine the quality and usability of the harvested goods.

Most agricultural crops are, according to how they assimilate CO_2, either C_3 or C_4 crops. C_3 crops (e.g. wheat, rye, rice) underlie a specific disadvantage in comparison to C_4 crops (e.g. maize, sugar cane, millet): in general C_4 plants do have the ability to maintain photosynthesis at higher temperatures (> 30°C) without high photo-respiratory losses. This implies the particular advantage for the group of C_4 plants: rising global temperatures can lead to a displacement of C_3 crops by C_4 crops. In the long term, the cultivation areas of e.g. maize, sugar cane and sorghum are therefore expected to increase in the future (Lieberei et Reisdorff, 2012).

Agricultural crops can be, due to their main nutrient content, categorized into starch, oil, sugar, or protein crops (exl. horticultural crops, fruits, etc.). Some crops have plural utilisation possibilities like soy (protein and oil), maize (starch and oil), or rice (starch and oil). This thesis focuses on the substitution with renewable raw materials for the production of the above presented four specific product groups. The group of protein crops is therefore not regarded.

4.1 Carbohydrates

The main purpose of carbohydrates in plants is providing energy stored plant-specific either in the vacuoles in form of sucrose or in semi-crystalline granules in form of starch. The vacuoles and the semi-crystalline granules are located in the cells of storage organs of the plants (beets, tubers, leaves etc.) after ripening. Most of the stored energy is needed for sprouting after hibernation. Another important role of sugars in plants in particular is maintaining the osmotic pressure inside the vessels and plant cells.

4.1.1 Sugar

In the process of photosynthesis, atmospheric CO_2 gets converted into hexoses (six carbon atoms in the molecule), in general fructose, and further into glucose. The both types of sugars (fructose and glucose) represent the group of monosaccharides, which are the basic compounds of all carbohydrates. Plants store and transport sugars in the form of disaccharides, like sucrose, which are an aggregation of two monosaccharides like fructose and glucose. The most common form of sugars for nutrition is the extracted sucrose from sugar beet and sugar cane (Lieberei et Reisdorff, 2012).

4.1.2 Starch

Starch is a polymer formed out of coupled glucose molecules. It can be found in crops like wheat, rice, maize, potatoes and other tuber or cereal crops (See Annex 3). It is, like the synthesis of sugar, a product of the assimilation of CO_2. The occurrence of starch is divided in two forms: Amylose and Amylopectin. Amylose contains between 200 and 1000 glucose molecules and has a share of 20-30% in the starch. It consists of six C- atoms, generally lined up in a helix-like structure chain. . The second, more abundant form, in which starch with a share about 70-80% occurs, is amylopectin. It contains 2000 to 10000 glucose molecules. The more branched and complex structure of amylopectin leads to multiple linkages between the molecules (AGRANA, 2017). The synthesis and storage of starch happens in the amyloplasts and independently from photosynthesis unlike the synthesis of sugars.

One significant difference between sugar and starch is the insolubility of starch in water and therefore no osmotic effect in the plant cells. The storage of energy in the form of starch needs less water and the compound can be stored more compactly than sugar. The release of the energy happens in the amyloplasts and needs enzymes (amylase and isoamylase) to convert the starch back into the suitable form of glucose that is available for plants.

To extract starch from plants, the starch containing plant parts first gets destroyed mechanically. Then the starch granules are powerfully flushed out and sieved in multiple steps. The extraction concludes in refining, cleaning and drying the starch (ISI, 2006).

Commonly processed starch occurs in tree forms:

> native starch: powder that is used as thickening agent and stabilizer.
> modified starch: used in the production of foodstuffs and for technical purposes, derived from native starch by physical, chemical or enzymatic processes in which the primal properties of native starch can be changed according to their field of application.
> Starch saccharification: cracking of starch molecules into sugar molecules, used for sweetener in the food industry (AGRANA, 2017).

Carbohydrates do also have a function as scaffold and component in the cell structures. Other carbohydrates not mentioned before are fructan, cellulose, pectin, other oligosaccharides and carrageen, agar, and alginic acid. The last three can be found in algae which are also discussed as resource for the bio-based industry (Lieberei et Reisdorff, 2012), but, not considered in this thesis.

4.2 Fats and Oils

The main characteristic of fats is the higher energy value compared to carbohydrates: 1 g of fat has 38.1 – 38.94 kJ; 1 g of carbohydrates only 16.7 kJ. Further they are formed by carbo acids and fatty acids, which are synthesised in plastids and partially in the cytoplasm. Both types of organic acids are built through an esterification with glycerine natural fats, which are then stored in oleosomes in the plant cells. Fats and oils are generally one of the main contents of seeds. They provide a compact and lightweight first source of nutrients in the endosperm and the embryo while sprouting. The content and composition of fatty acids and triglycerides determines the melting point and other properties of fats. Fats and oils can be divided into oils with saturated and unsaturated fatty acids. The composition and amount of saturated and unsaturated fatty acids in fats and oils do not only play a major role in the human diet, they are also important for their technical applicability. Fats with a high content of unsaturated fatty acids are applicable for paints and varnishes, and lubricants. For hydraulic oils fats with a high content of saturated fatty acids are used (Lieberei et Reisdorff, 2012).

5 Methods and Data

Agricultural crops play a major role as possible substitute for fossil fuels in the petrochemical based industries. Promising products are already being made from plant oil, starch, and sugar crops. Recent technologies make it possible to refine cellulose, hemicellulose, and lignin as well (eg. Kawaguchi et al., 2017; Ghaffar et al., 2015; Gupta et Verma, 2015). Of course there are many factors that will determine the potential of agricultural crops in the bio-based industry now and in future. To narrow down the surveyed field, following system boundaries were set up in this model. The development of prices of fossil or agricultural resources and the consequences for trade are not assessed. Forestry will not be in the scope of this thesis, although lignin and cellulosic production plays a major role in the bio-based chemical industry nowadays (e.g. BREW, 2006, IEA, 2012). Agricultural by-products (e.g. straw, mill dust, husks…) and by-products by the food and feed industry will not be assessed as well. To answer the research questions, this thesis focuses only on agricultural oil, starch, and sugar crops. Therefore all crops listened under FAO Stat (2017a) and cultivated for the production of starch, oil, or sugar were taken into account for further calculations (Annex 3).

The calculation of land-resources necessary to substitute the fossil based materials by 100%, following assumptions are made:

- the crop areas do not change relatively to each other, and

- the amounts in terms of percentage of the investigated product groups remain at the same level.

These assumptions are the basis of the following land-allocation approach, which was first published by Schipfer et al. (2015).

Table 1: List of symbols used in the calculations with short description

Symbols	Description
$\boldsymbol{\alpha}$	Fossil based non energy feedstock [kt]
$\boldsymbol{\beta}$	Relative amounts of fossil based product groups [%]
$\boldsymbol{\gamma}$	Absolute amount of fossil based product groups [kt]
$\boldsymbol{\delta}$	Raw material to bio-based products conversion factor
$\boldsymbol{\varepsilon}$	Demand for bio-based raw material [kt]
$\boldsymbol{\lambda}$	Cultivated area [ha]
$\boldsymbol{\mu}$	Conversion factor yield to bio-based raw material
$\boldsymbol{\pi}$	Needed raw material [kt]
$\boldsymbol{\sigma}$	Average yield per hectare (2010-2014) [t/ha]
$\boldsymbol{\rho}$	Needed yield (=biomass) [kt]
$\boldsymbol{\varphi}$	Needed arable land [ha]

Table 2: List of indices used in the calculations with short description

Indices	Description
EU-27	Countries in the EU-27 in 2008
C	Country
P	Product Group (Polymer, Solvent, Surfactant, Lubricant)
L	Agricultural crop (e.g. Maize, Wheat, Sunflower…)
R	Raw Material (Oil, Sugar, Starch)

First, it is necessary to understand the amount of non-energy demand compared to the energy based demand in fossil resources. For that purpose, the cumulative share of the whole crude oil consumption per country listened in the report by IEA et OECD (2016) (providing latest data from 2014) under the definition "Non-Energy Use" is derived. The different fossil based stocks (oil, coke, gas) are mentioned separately but summed up and regarded as equivalent fossil raw materials in this thesis. According to IEA et OECD (2016, p. I.14) "non-energy use covers those fuels that are used as raw materials in the different sectors and are not consumed as a fuel or transformed into another fuel." The country wise amounts can be seen in Annex 1, spreadsheet: "Non Energy Demand 2014".

5.1 Classification of geographical regions

In the report, 201 countries are represented. Some countries are not mentioned separately, but summarized under the terms "other Asia", "other Africa" and "other Non-OECD Americas". A few countries are not mentioned in the report by IEA et OECD (2016) at all. On the other hand, some countries considered in that report are not mentioned in FAO Stat (2017a). Due to simplification of the available data, some countries mentioned individually or regions that underlie a special administration are grouped together with countries that have close bearings to those countries and regions (USA and China) (Table 4).

Table 3: List of countries and regions conglomerated under the terms “Other Asia”, “Other Africa”, “Other non-OECD Americas”, USA and China as well as countries that are not mentioned in the reports by IEA et OECD (2016) or FAO Stat (2017a).

Other Asia	Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Lao People’s Democratic Republic, Macau-China, the Maldives, New Caledonia, Plau, Papua New Guinea, Samoa, the Solomon Islands, Timor-Leste, Tonga, Vanuatu
Other Africa	Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comors, Djibouti, Equatorial Guinea, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauretania, Réunion, Rwanda, Sao Tome and Principe, thy Seychelles, Sierra Leone, Somalia, Swaziland, Uganda
Other non-OECD Americas	Antigua and Barbuda, Aruba, the Bahamas, Barbados, Belize, Bermuda, Bonaire, the British Virgin Islands, the Cayman Islands, Dominica, the Falkland Islands (Malvinas), French Guiana, Grenade, Guadeloupe, Guyana, Mratinique, Montserrat, Saba, Saint Eustatius, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Sint Maarten, Turks and Caicos Islands
China	Province of Taiwan, Hong Kong, People’s Republic of China
USA	Guam, Puerto Rico, United States Virgin Islands, United States of America
Not mentioned in IEA et OECD (2016)	American Samoa, the Faroe Islands, the Marshall Islands, the Federated States of Micronesia, Nauru, Niue, the Occupied Palestinian Territory, Tokelau, Tuvalu, the Wallis and Futuna Islands, Western Sahara
Not mentioned in FAO Stat (2017a)	Gibraltar, Curaçao

For a better global comparability, beside the global and country wise results, all countries were grouped in sixteen geographic regions after UNSD (2017) (Table 5). The country wise results of one geographical region were pooled. The tree conglomerates of countries “Other Africa”, “Other Asia” and “Other non-OECD Americas” were counted to the geographical region where most of the included countries are located. So “Other Africa” is attached to Sub Saharan Africa, “Other non-OECD Americas” to the Caribbean region and “Other Asia” to the region of Oceania.

Table 4: All investigated countries pooled in the geographical regions after UNSD (2017).

Eastern Europe	Belarus, Bulgaria, Czech Republic, Hungary, Poland, Republic of Moldova, Romania, Russian Federation, Slovakia, Ukraine
Northern Europe	Denmark, Estonia, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden, United Kingdom
Southern Europe	Albania, Bosnia and Herzegovina, Croatia, Greece, Italy, Malta, Montenegro, Portugal, Serbia (incl. Kosovo), Slovenia, Spain, The former Yugoslav Republic of Macedonia
Western Europe	Austria, Belgium, France, Germany, Luxembourg, Netherlands, Switzerland
Sub Saharan Africa	Angola, Benin, Botswana, Cameroon, Côte d'Ivoire, Congo, Democratic Republic of the Congo, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, Togo, United Republic of Tanzania, Zambia, Zimbabwe, Other Africa
Northern Africa	Algeria, Egypt, Libya, Morocco, Sudan, Tunisia
Central Asia	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan
Eastern Asia	China, Democratic People's Republic of Korea, Japan, Mongolia, Republic of Korea
South Asia	Bangladesh, India, Iran (Islamic Republic of), Nepal, Pakistan, Sri Lanka
South-Eastern Asia	Brunei Darussalam, Cambodia, Indonesia, Malaysia, Myanmar, Philippines, Singapore, Thailand, Viet Nam
Western Asia	Armenia, Azerbaijan, Bahrein, Cyprus, Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Turkey, United Arab Emirates, Yemen
Oceania	Australia, New Zealand, Other Asia
Southern America	Argentina, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Suriname, Uruguay, Venezuela (Bolivarian Republic of)
Northern America	Canada, United States of America
Central America	Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama
Caribbean	Cuba, Dominican, Haiti, Jamaica, Trinidad and Tobago, Other non-OECD Americas

5.2 Global requirement scenario for the four product groups

The relative amounts of the mentioned fossil based product groups in the whole non-energy sector were taken from a global analysis in Daioglou et al. (2014), and from EC (2010), displayed European database.

5% of the global non-energy fossil based production goes into the methanol production, where it is used primarily for the production of various chemicals (e.g. formaldehyde) or where it is directly used as a solvent. Due to this direct usability of methanol as solvent it can be assumed, that the amount of methanol production equals the amount of the global solvent production (Daioglou, 2014).

In Daioglou et al. (2014) polymers are summed up in the category "HVC – high value chemicals". The amount of HVCs on a global scale is declared with 41% of global non-energy fossil based production, thereof 50% specifically in polymer production. This results in an amount of 20.5% fossil based polymer production.

Since Daioglou et al. (2014) did not describe further data concerning the global demand in lubricants and surfactants, the relative amounts are derived from available data from the European market (EC, 2010). The presented data comprises the absolute sum of the production of the four product groups in the EU-27 countries from 2008. Therefore, the non-energy demand of fossil fuels of the EU-27 in 2008 ($\boldsymbol{\alpha_{EU27}}$) was calculated with data taken from IEA (2010a, 2010b). It has to be mentioned that the measuring unit of natural gas is expressed in *terra Joules* (TJ). To unify the data, the figures from natural gas were converted in *kilo tonnes of oil equivalent* (ktoe) with the conversion factor 1TJ ≙ 0.024 ktoe (according to IEA, 2017). The results of the comparison between the absolute amounts of the four fossil based product groups of the EU-27 countries in 2008 with the non-energy demand at the same time leads to the relative amounts of the product groups: Lubricants: 4.406%, Surfactants: 1.029%, Polymers: 41.76%, Solvents 3.813% ($\boldsymbol{\beta_P}$) (Annex 2). The differences in the amounts of the products described in Daioglou et al. (2014) and EC (2010) may be explainable by the fact that in the EU-27 countries in 2008 more polymers were produced compared to the global average. The relative amounts given in Daioglou et al. (2014) for the two product groups of polymers and solvent and the derived amounts of lubricants and surfactants from EC (2010) (underlined parts above) were taken into account for the further calculations, as displayed in table 6. A major part of the consumption of non-energy fossil resources is not taken in account. Half of the HVCs (20.5%), the whole group of ammonia production (25%) and the share of the group of refinery products (25%) which account for 70% of the consumption of non-energy fossil resources are not regarded in this thesis (Figure 4).

Table 5: Relative requirements of the four investigated product groups for the non-energy use.

Product groups	Relative amount in non-energy demand (%) ($\boldsymbol{\beta_P}$)	Source
Solvents	5.00	Daioglou et al. (2014)
Surfactants	1.03	Derived after EC (2010)
Lubricants	4.41	Derived after EC (2010)
Polymers	20.50	Derived after Daioglou et al. (2014)

5.3 Formulas and conversion factors

After calculating the whole non-energy demand for fossil resources for every country ($\boldsymbol{\alpha_C}$), the results are multiplied by the relative amount of the four product groups described ($\boldsymbol{\beta_P}$, ($\boldsymbol{I}$)). The results shows the consumption (in this context equal to demand) of fossil resources needed for the production of the product groups per country ($\boldsymbol{\gamma_{C,P}}$) (Annex 1, spreadsheet: "Demand in n-f based Products").

$$(\boldsymbol{I}) \quad \boldsymbol{\gamma_{C,P}} = \boldsymbol{\alpha_C} \times \boldsymbol{\beta_P}$$

In the next step, the amounts of necessary primary crop products (= bio-based raw materials) were determined. The data is listed according to country, crops cultivated there and complying with the mentioned criteria, their individual yields, and cultivated arable areas. For this calculation the mean over the last five years of registered agricultural production (2010 – 2014) for each crop and country were taken in account. It has to be mentioned that FAO Stat (2017a) only reports agricultural crops whose primary usage is for food and feed purposes. Thus plants with better applicability for the bio-based industries like *miscanthus sinensis* or other crops, are not listed (Annex 3).

The content of raw material (starch, sugar and oil) in the investigated plants are presented in literature (e.g. FAO 2009; Champagne et al., 2004; Wäsche, 2002) in a specific range. For example, Rapeseeds contain between 72% and 85% technically usable oil (Wäsche, 2002). Different amounts can be explained with different results due to the investigation of varieties from one crop species or extrinsic factors (e.g. water stress, amount of nutrients accessibly for plants, pests…). To unify the conversion factors for the following calculations, the mean of the range reported in literature was determined and used in the further analysis (Annex 3).

Due to losses in the production chain, the final products do not occur in the same quantity as the raw materials used for input material. So the amount of input is generally higher than the amount of output. In cases where this is the other way round or the output equals the amount of input, the final product consists only partially of bio-based materials. Table 7 shows how much bio-based raw material mass units are necessary to provide one mass unit for a certain bio-based product group. The detailed list can be found in Annex 4. As mentioned in IfBB (2016), there are several types of bioplastics like Bio-PET, PLA, Bio-PA or Bio-PE. To simplify the further calculations, all different types of bioplastics are unified under the term "polymers". All of those types of bio-plastics need different amounts of input material (starch, sugar or oil).

Table 6: Conversion factors "raw material to bio-based product" ($\boldsymbol{\delta_{P,R}}$). Example: To produce one mass unit of bio-based Solvents, 1.587 mass units of starch would be needed.

Raw Material (***R***) / Product Groups (***P***)	Oil	Starch	Sugar	Source
Solvents		1.59	1.61	Derived after Schindler, 1997
Surfactants	2.17			Derived after Salimon et al., 2010
Lubricants	1.02			Derived after Heikal et al., 2017
Polymers	1.37	2.81	2.40	Derived after IfBB, 2016

It should be noted that natural products cannot be regarded as a homogenous substance. There are, for example, major differences in the structure and fatty acid composition of common plant oils (Montero de Espinosa et Meier, 2011). Considering these specific differences in the bio-based raw materials would go beyond this thesis. Therefore, although different sources are considered, the bio-based raw materials are regarded homogeneously. For example, the oil gained from castor is treated as if it had the same characteristics and properties as oil gained from sunflower.

The following formulas were set up to receive a global, regional and country wise picture of the global quantitative amounts requested for bio-based raw materials, therefore produced biomass and arable land would be necessary to receive a 100% substitution level for the four product groups discussed. So it is assumed that the consumption of fossil based products equals the consumption of bio-based ones.

To determine the product specific amount for raw materials, equations ($\boldsymbol{IIa-c}$) are used. The conversion factor "raw material to bio-based product"($\boldsymbol{\delta_{P,R}}$) is taken times each country's absolute demand of fossil based product groups ($\boldsymbol{\gamma_{C,P}}$) (Annex 1, spreadsheet: "Product specific demand"). This applies only to the groups of surfactants and lubricants ($\boldsymbol{IIa}$), as the bio-based production of those product groups is only based on oil crops because only one raw material (oil) is needed for substitution. For the groups of polymers and solvents the results get multiplied with the country wise relative amounts of arable land used for oil, starch and/or sugar crop production in relation to the whole arable land used for actual production of the specific crop groups - three for polymers ($\boldsymbol{IIb}$) or two (starch and sugar) for solvents ($\boldsymbol{IIc}$) ($\frac{\boldsymbol{\lambda_{R,C}}}{\sum_{R}\boldsymbol{\lambda_{R,C}}}$). Consequently, it can be identified how much bio-based raw material (oil, starch and sugar) would be needed per country and product group ($\boldsymbol{\varepsilon_{C,P,R}}$).

$$(\boldsymbol{IIa}) \quad \boldsymbol{\varepsilon_{C,P,R}} = \boldsymbol{\delta_{P,R}} * \boldsymbol{\gamma_{C,P}},$$

$$under\ conditions\ \ R \in \{Oil\}, \qquad P \in \{Surfactants, Lubricants\}$$

$$(\boldsymbol{IIb}) \quad \boldsymbol{\varepsilon_{C,P,R}} = \boldsymbol{\delta_{P,R}} * \boldsymbol{\gamma_{C,P}} * \frac{\boldsymbol{\lambda_{R,C}}}{\sum_{R}\boldsymbol{\lambda_{R,C}}},$$

$$under\ conditions\ \ R \in \{Oil, Starch, Sugar\}, \qquad P \in \{Polymers\}$$

$$(\boldsymbol{IIc}) \quad \boldsymbol{\varepsilon_{C,P,R}} = \boldsymbol{\delta_{P,R}} * \boldsymbol{\gamma_{C,P}} * \frac{\boldsymbol{\lambda_{R,C}}}{\sum_{R}\boldsymbol{\lambda_{R,C}}},$$

$$under\ conditions\ R \in \{Starch, Sugar\}, \qquad P \in \{Solvents\}$$

To derive the necessary raw material, in the next step, each $\boldsymbol{\varepsilon_{C,P,R}}$ will be multiplied with the relative amounts of each cumulative areas cultivated with starch, sugar and oil crops (rice and maize were calculated twice: once as oil, once as starch crop) ($\boldsymbol{\lambda_{L,C}}/\boldsymbol{\lambda_{R,C}}$). This step results in a realistic picture of country level plant distribution and raw material composition, because not every plant is cultivatable in every region. The amount of product group specific raw material quantitative amount for each plant per country ($\boldsymbol{\pi_{L,C,P}}$) thus can be determined by:

$$(\boldsymbol{III}) \quad \boldsymbol{\pi_{L,C,P}} = \sum_{\boldsymbol{R}} \boldsymbol{\varepsilon_{C,P,R}} \times \frac{\boldsymbol{\lambda_{L,C}}}{\sum_{L}\boldsymbol{\lambda_{L,C}}}$$

The needed quantitative amount in raw materials ($\boldsymbol{\pi_{L,C,P}}$) is taken times the conversion factor "yield to bio-based raw material" (Annex 3) ($\boldsymbol{\mu_L}$). This shows the quantitative amount of required yield (=biomass) for each country, plant and product group ($\boldsymbol{\rho_{L,C,P}}$).

$$(\boldsymbol{IV}) \quad \boldsymbol{\rho_{L,C,P}} = \boldsymbol{\pi_{L,C,P}} \times \boldsymbol{\mu_L}$$

In the last step, the required quantity of crop biomass $(\boldsymbol{\rho_{C,L,P}})$ divided by the product and country wise average yield per hectare and per plant ($\boldsymbol{\sigma_{C,L,P}}$) (Annex 1, spreadsheet: "Rel amounts of arable land") results in the amount of arable land needed per agricultural crop, country and product ($\boldsymbol{\varphi_{C,L,P}}$):

$$(\boldsymbol{V}) \quad \boldsymbol{\varphi_{L,C,P}} = \frac{\boldsymbol{\rho_{L,C,P}}}{\boldsymbol{\sigma_{L,C,P}}}$$

The results of these calculations allow drawing a picture of how much biomass and arable land would be needed to receive a 100% substitution level under current circumstances. An accumulation of all interim results shows the global picture.

A balance comparison between the received results and the actual amount of arable land used for the investigated crops shows the needed amount of the actual production at current status per country or rather the amount of arable land that would be needed additionally (Annex 1, spreadsheet "Delta (L,P,C)").

6 Results

6.1 Demand for non-energy fossil resources

The data from IEA et OECD (2016) shows that only a few countries use the majority of fossil-based resources for non-energy purposes. China (Mainland inclusive Taiwan and Hong Kong) stands out with a demand of about 24% of the whole global demand (Figure 2). About half (51%) of the global demand is, besides China, requested by only three more countries: the Unites States of America (inclusive Puerto Rico, Guam and United States Virgin Islands) (13%), the Russian Federation (9%) and the Republic of Korea (5%). More than three quarters of the global demand is declared by only 10 more countries (Sum = 14 countries): India (5%), Japan (4%), Saudi Arabia (3%), Canada (3%), Islamic Republic of Iran (3%), Germany (3%), Thailand (2%), Brazil (2%), France (2%), and the Netherlands (2%). The countries summarized in “Other Asia” do also have a comparably big demand of about 2%.

The other 182 of the 195 observed countries have a cumulative demand of 22% of the global demand of fossil based resources for non-energy purposes.

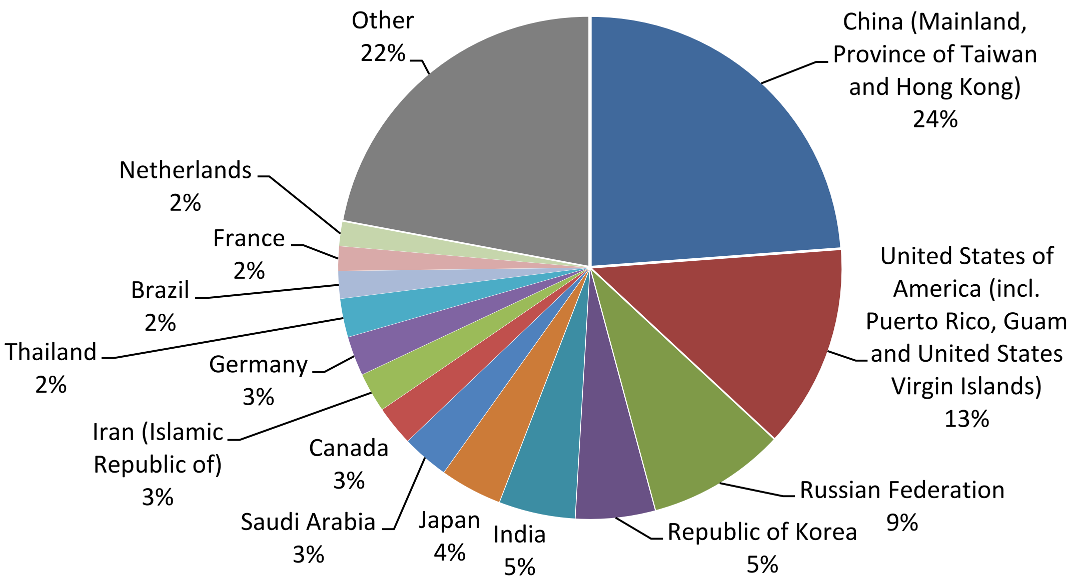


Figure 2: Country wise global demand of non-energy fossil resources in percent. Data derived from IEA et OECD (2016).

On a regional level approximately half (49%) of the demand of non-energy fossil resources is requested by only two regions: Eastern Asia (33%) and Northern America (16%). Eastern Europe (11%), Western Europe (7%) and Southern Asia (8%) represent, together with Eastern Asia and Northern America, 75% of the global demand. The region with the lowest demand is Central Asia with less than 1%.

On continent level, Africa has the lowest demands (Sub-Saharan Africa and Northern Africa) with 2%, and Southern America and Oceania with 3% each. Europe (Northern -, Southern -, Western -, and Eastern Europe) demands 22%, Asia (Eastern -, Southern -, Western -, South-Eastern -, and Central Asia) more than half of the global demand (52%). Northern -, Central America and the Caribbean Region have a demand of 18% of the demand of non-energy fossil resources, whereas Central America and the Caribbean Region demand only 1% each. (Figure 3).

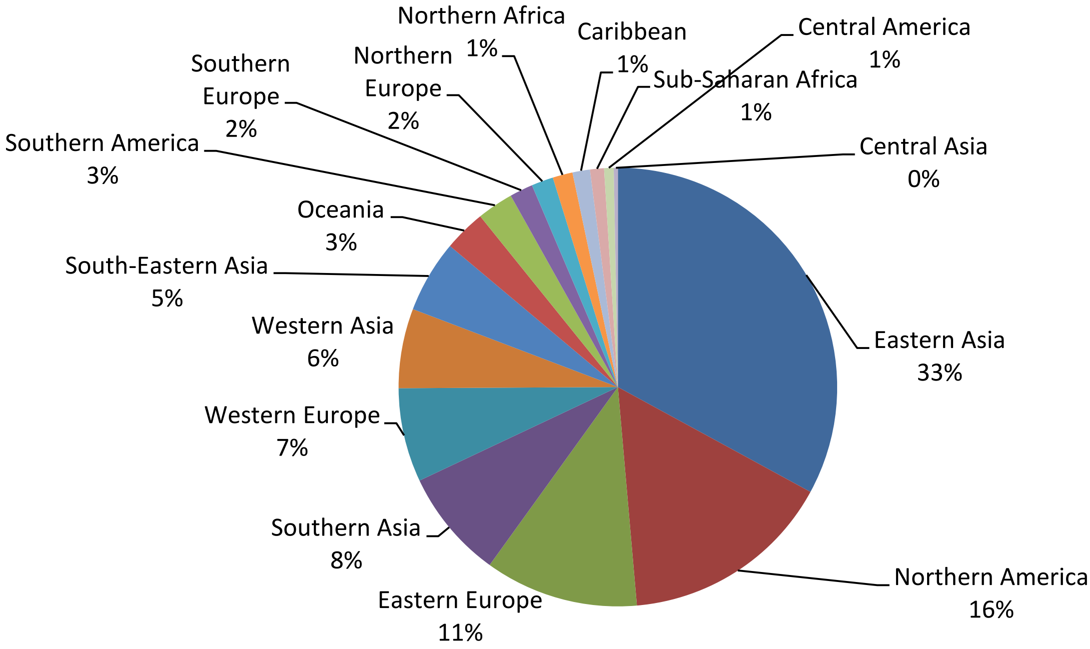


Figure 3: Global demand, split up in the geographical regions, for non-energy fossil resources in percent. Data derived from IEA and OECD (2016).

Regarding the requirements of the four described product groups, compared to the demand of non-energy fossil resources in total, it becomes evident that the greatest amount with approximately 69% is not considered in this thesis. Polymers, solvents, lubricants, and surfactants form only about 31% of the total fossil non-energy resource-demand, whereby the distribution for each product group is like described in Table 4 in chapter “Methods and Data”. Figure 4 shows that polymers make up the biggest percentage (179 826.6 kt; 21%) of the four product groups. Regarding the demand in non-energy fossil resources of the four product groups individually, polymers represent approximately two thirds (Figure 5).

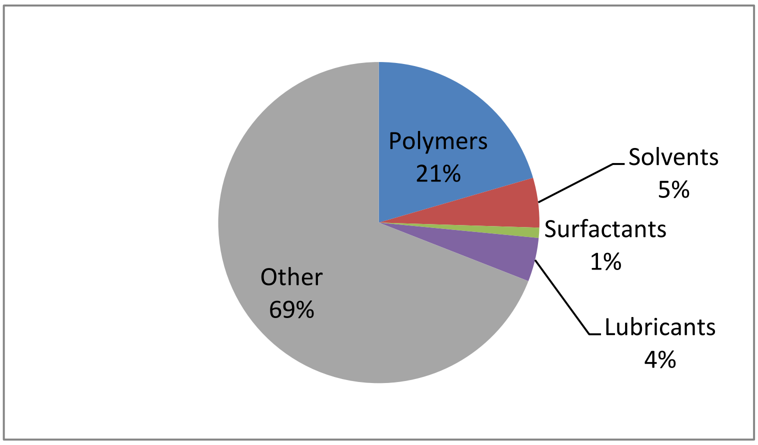


Figure 4: Relative amounts of fossil based non-energy products, with detailed amounts of the four investigated product groups. Displayed in percent related to the global non-energy demand in non renewable fossil resources.

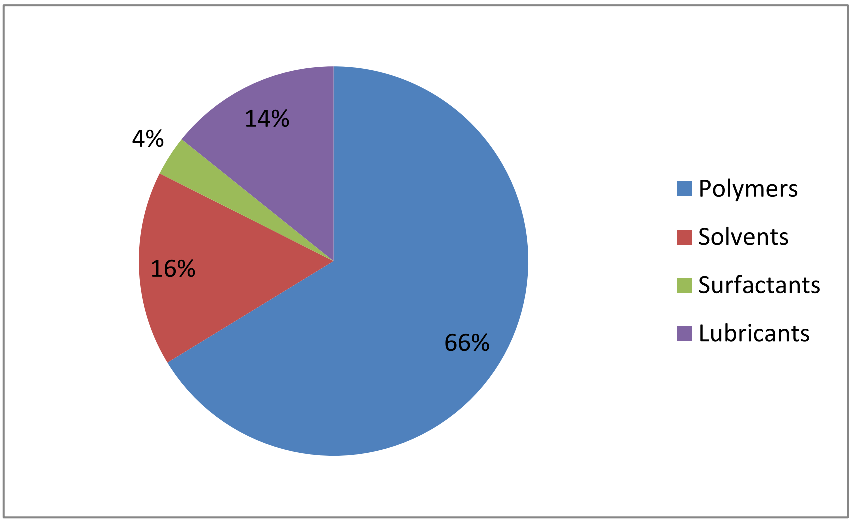
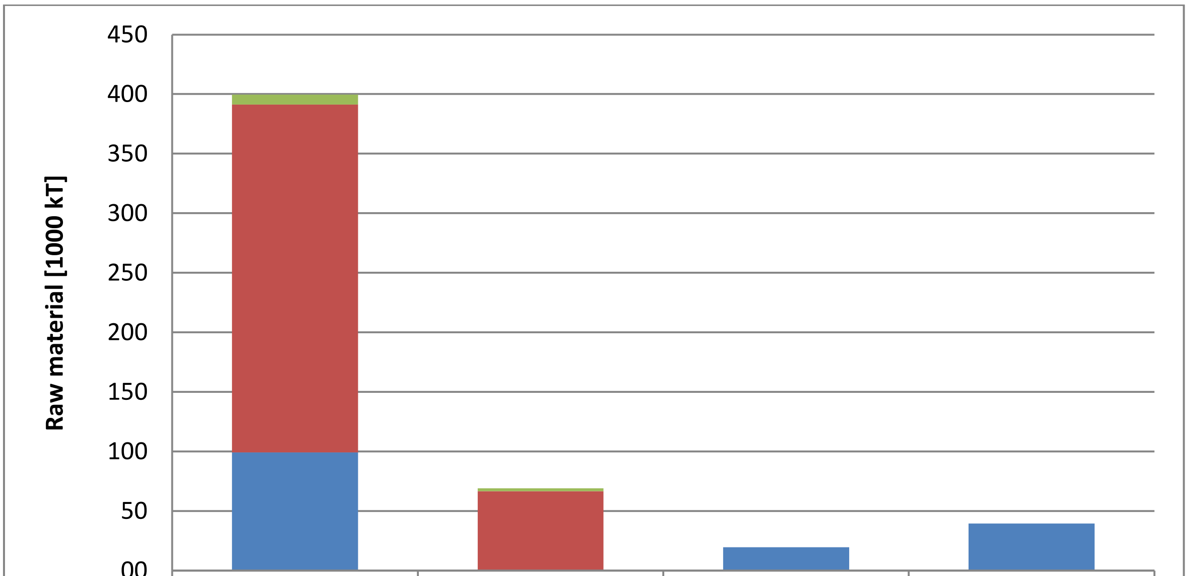


Figure 5: Distribution of the investigated non-energy fossil products, displayed in percent.

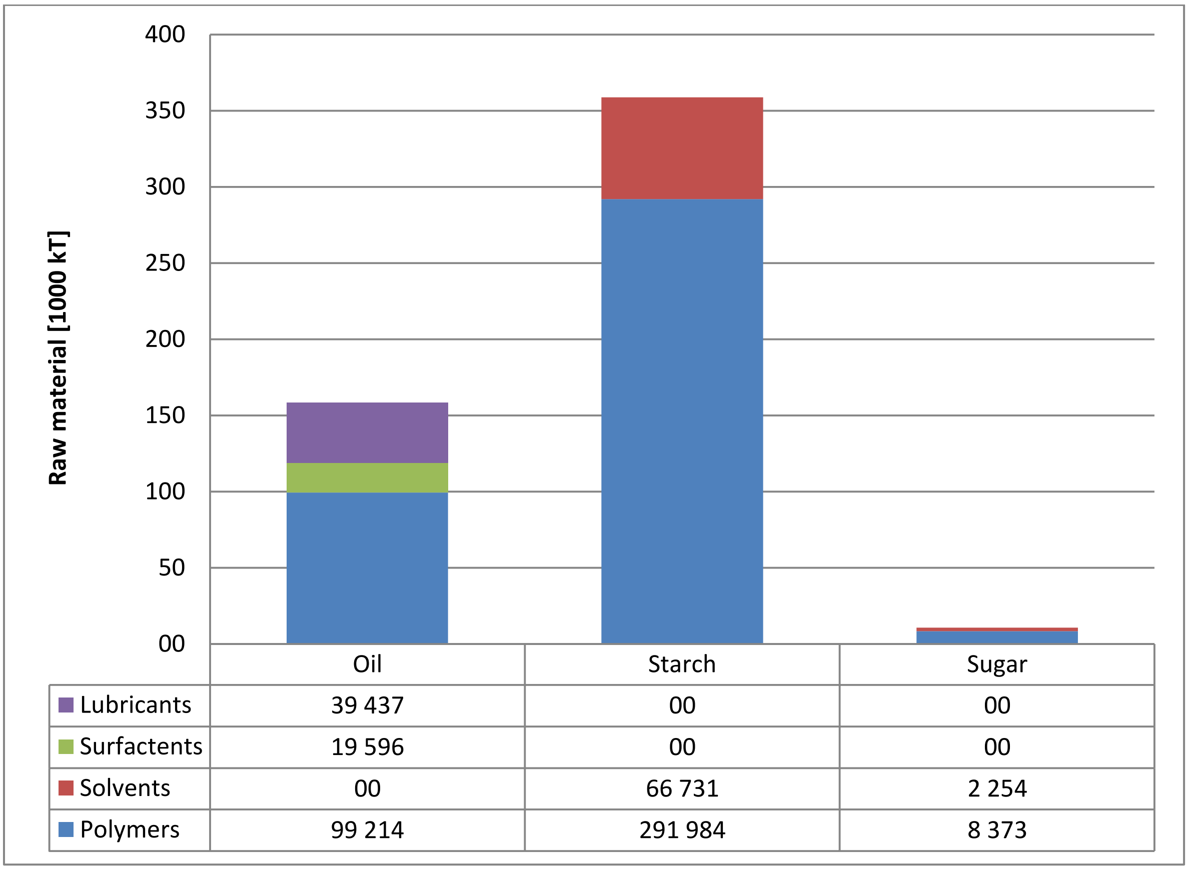
6.2 Quantity of raw materials required for substitution

In the next step, the quantity of raw materials required for each product group is identified. The biggest part of raw materials is needed for the substitution of polymers which requires about 399 571.03 kt of raw material. Regarding the raw materials, the highest required quantity lies in starch, followed by oil. The requirement of sugar is comparably low with only 10626.98 kt and like starch, only applicable for the production of polymers (8 372.96 kt) and solvents (2 254.01 kt). Plant oil is needed by three products (lubricants, surfactants and polymers), whereas polymers have the highest requirement (99 214.31 kt), followed by lubricants (39 436.93 kt) and surfactants (19 595.82 kt) (Figure 6, Figure 7).



	Polymers	Solvents	Surfactans	Lubricants
Sugar	8 373	2 254	00	00
Starch	291 984	66 731	00	00
Oil	99 214	00	19 596	39 437

Figure 6: Cumulative quantitative requirements for bio-based raw materials for each product group, displayed in 1000 kilotonnes, related to the product wise global harvested area of starch, sugar and oil crops.



	Oil	Starch	Sugar
Lubricants	39 437	00	00
Surfactents	19 596	00	00
Solvents	00	66 731	2 254
Polymers	99 214	291 984	8 373

Figure 7: Quantitative requirements for raw materials displayed cumulative for all product groups in 1000 kilotonnes, product wise related to the global harvested area of starch, sugar and oil crops.

To substitute 271 355.28 kt of fossil resources, in sum 527 742.62 kt of renewable raw materials would be needed. Referring to each country's relative amounts of arable land in the product groups, the requirements for 313 kt for a bio-based solvent production in Singapore and the whole bio-based substitution for Gibraltar (4.92 kt for polymer, 1.2 kt for solvent, 0.25 kt for surfactant and 1.05 kt for lubricant substitution) cannot be regarded, because no cultivation of therefore needed crops in both countries are recorded in FAO Stat (2017a), though a demand in fossil resources is described in IEA et OECD (2016). This reflects in a negligible inaccuracy in the results.

6.3 Agricultural production of starch, sugar and oil crops

A look at the inner distribution of the three groups of renewable raw materials shows that wheat, maize and rice are globally the most harvested starch crops (Figure 8). The countries with the highest amounts of harvested area of starch crops are India (1 018 433.2 km²), China (1 009 378.1 km²), the USA (587 837.8 km²), the Russian Federation (395 633.3 km²), "Other Africa"(256 366.0 km²) and Nigeria (229 039.5 km²). On a regional scale, the highest harvested areas of starch crops are located in Southern Asia (1 419 400.1 km²), Sub-Saharan Africa (1 056 575.8km²) and Eastern Asia (1 056 559.1 km²). (Annex 1, spreandsheet: "Rel amounts of arable land").

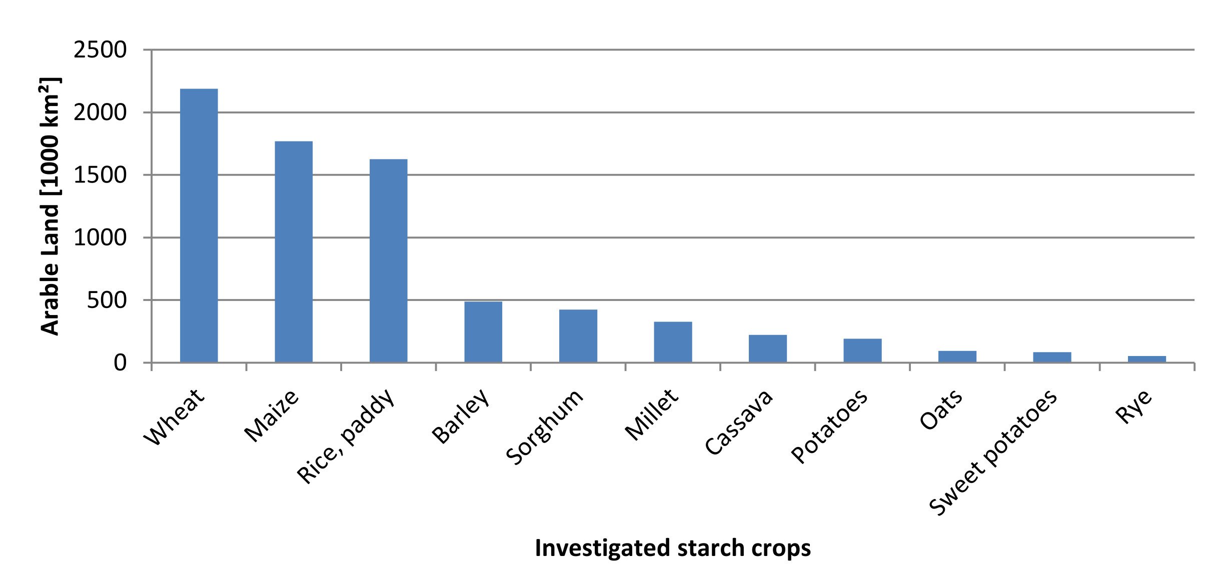


Figure 8: Cumulative harvested area in 1000 km² of the investigated starch crops on global scale.

If maize and rice are regarded as oil crops, both crops and soybeans are globally by far the oil crops with the highest amounts of harvested area (Figure 9). India (928 783.1km²), China (919 722.2 km²), the USA (723 428.7 km²), Brazil (446 524.0 km²), Indonesia (283 793.3 km²) and Agrnetinia (254 856.1 km²) are, respectively, the countries with the highest amounts of harvested area of oil crops. The three geographical regions with the highest amounts of harvested area of oil crops are Southern Asia (1 175 599.4 km²), Eastern Asia (960 777.5 km²) and Northern America (837 676.7 km²) respectively. The Caribbean region is the region with the smallest area used for harvesting oil crops with only 14 278.7 km² (Annex 1, spreadsheet “Rel amounts of arable land”).

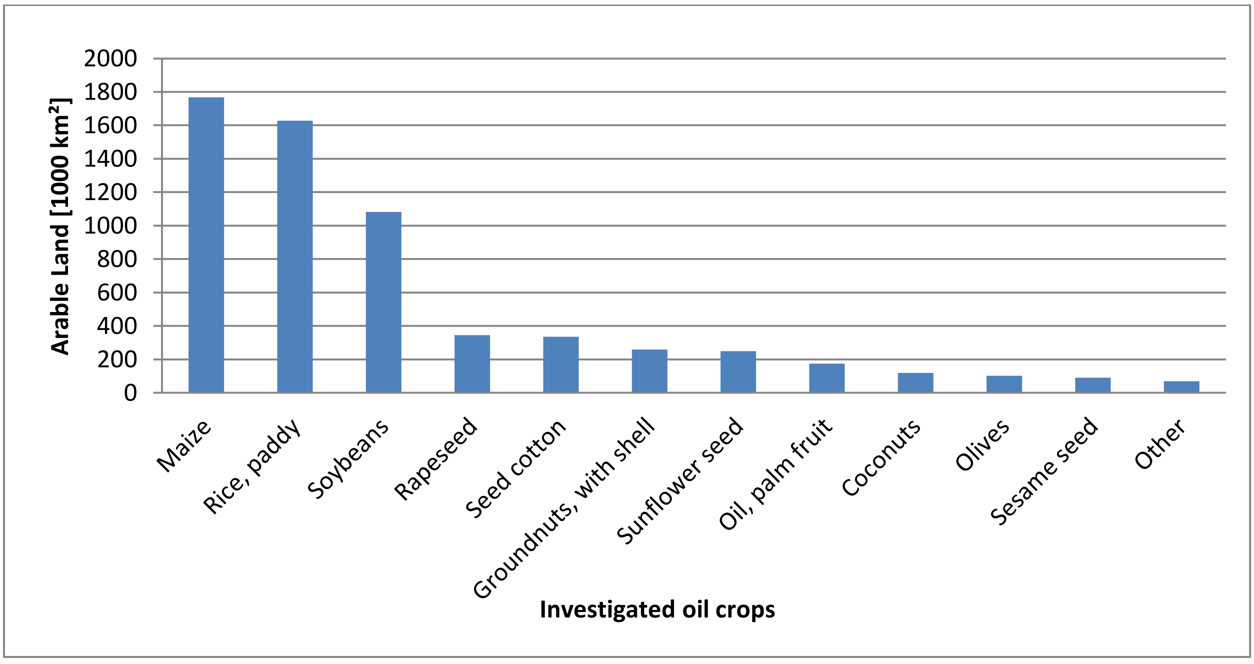


Figure 9: Cumulative cultivated area in 1000 km² of the investigated oil crops on global scale. “Other” includes Linseed, Castor oil seed, Safflower seed, Mustard seed, Karite Nuts (shea nuts), Tallowtree seeds, Kapok fruit, Tung nuts, Poppy seeds, Hempseeds and Jojoba seeds.

Although sugar beet (47 073.3 km² annually harvested area) has a great importance in the northern hemisphere, the global cultivated area of sugar crops is dominated by sugar cane with 85% (259 139.5 km²) (Figure 10). Globally the area of harvested sugar cane is approximately five times higher than the area of harvested sugar beet. The biggest producers of sugar crops are Brazil (97 996.5 km²), followed by India (48 562.0 km²), and China (19 648.9 km²). On a regional level, Southern America (110 893.5 km²) provides the highest area cultivated with sugar crops, followed by Southern Asia (62 819.4 km²) and South-Eastern Asia (25 897.2 km²).

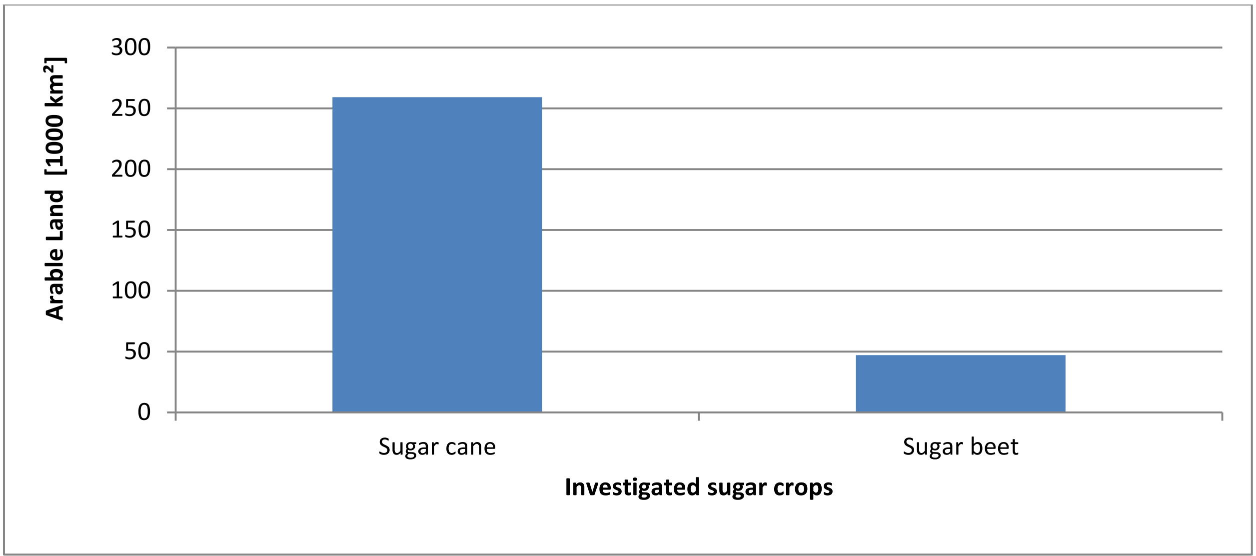


Figure 10: Cumulative harvested area in 1000 km² on global scale of the investigated sugar crops.

Countries with the highest amounts of harvested areas in all three raw material categories are India (1 995 778.3 km²), China (1 948 749.2 km²), the USA (1 319 607.7 km²), Brazil (762 466.4 km²) and the Russian Federation (518 880.6 km²) respectively. Together, these countries contribute 45 % of the cultivated area of the investigated crops worldwide. After breaking down the product specific demands into the relative amounts of arable land per country and product group, the crop wise quantitative amount requested for raw material in kilo tonnes [kt] can be derived (= $\pi_{L,C,P}$; see Annex 1, spreadsheet “L,C,P specific demand”).

6.4 Biomass requirement

The results of (IV), the potential quantitative requirements for each product group, plant and country ($\rho_{L,C,P}$), leads to the answer to the first research question. They show that the global requirements in kilotonnes biomass (=yield) of oil crops (956 679.3 kt) is higher than the requirements in starch crops (569 969.6 kt), although the product specific requirements displays the reciprocal picture (Figures 6 and 7). The requirements in sugar remains comparatively small with “only” 65 006.1 kt (Figure 11). The country wise distribution of the necessary amount of biomass shows parallels to the demand in non-energy fossil fuels.

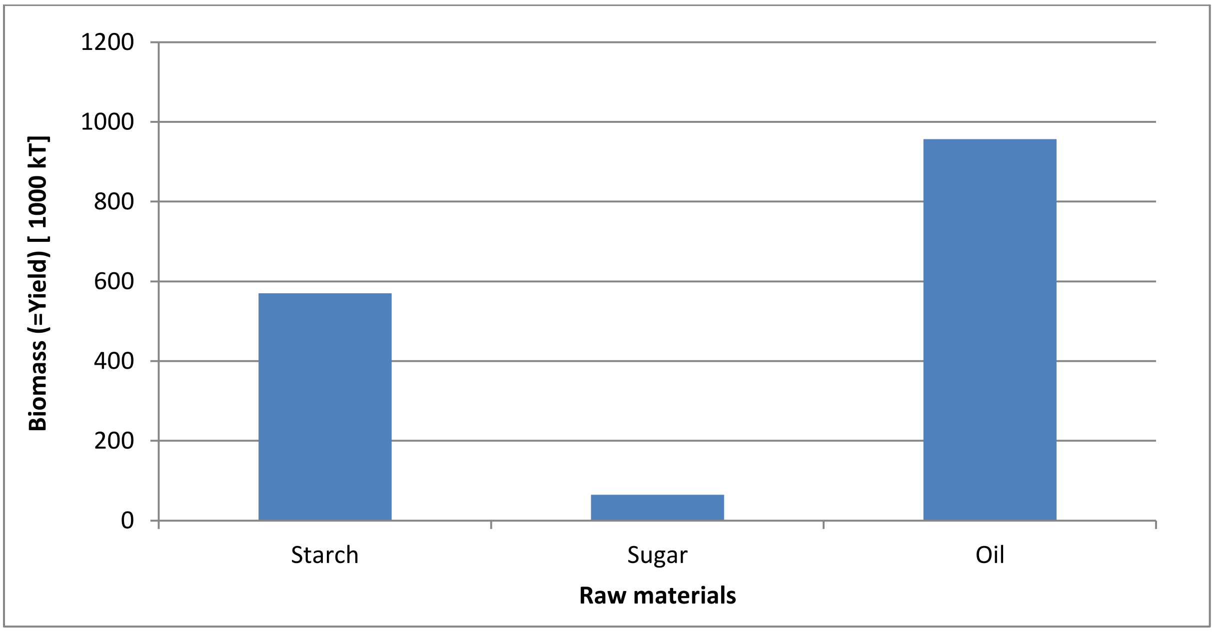


Figure 11: Cumulative, global requirements for raw materials in 1000 kt at a 100% substitution level of the four investigated product groups.

The distribution of the requirements in biomass among the geographical regions are showing that, similar to the requirements in non-energy fossil resources, the highest requirements are lying in Eastern Asia (596 787.6 kt), Northern America (290 063.8 kt), Eastern Europe (161 416.2 kt), and Western Europe (128 151.3 kt) respectively (Figure 12), whereas the allocation of the raw materials in the regions differs from the global distribution. Western Europe would have the highest requirements in sugar with 15 114.6 kt, followed by Eastern Asia (11 752.7 kt), Southern America (9 961.4 kt) and South Asia (6 517.2 kt). The quantitative requirements in oil crops are the highest in Eastern Asia (360 571.5 kt) followed by Northern America (208 414.4 kt), Southern Asia (60 972.5 kt) and Eastern Europe (59 903.9 kt), the requirements in starch crops are the highest in Eastern Asia (224 463.4 kt), Eastern Europe (94 989.6 kt), Northern America (78 677.1 kt) and Western Europe (70 517.7 kt) (Figure 12).

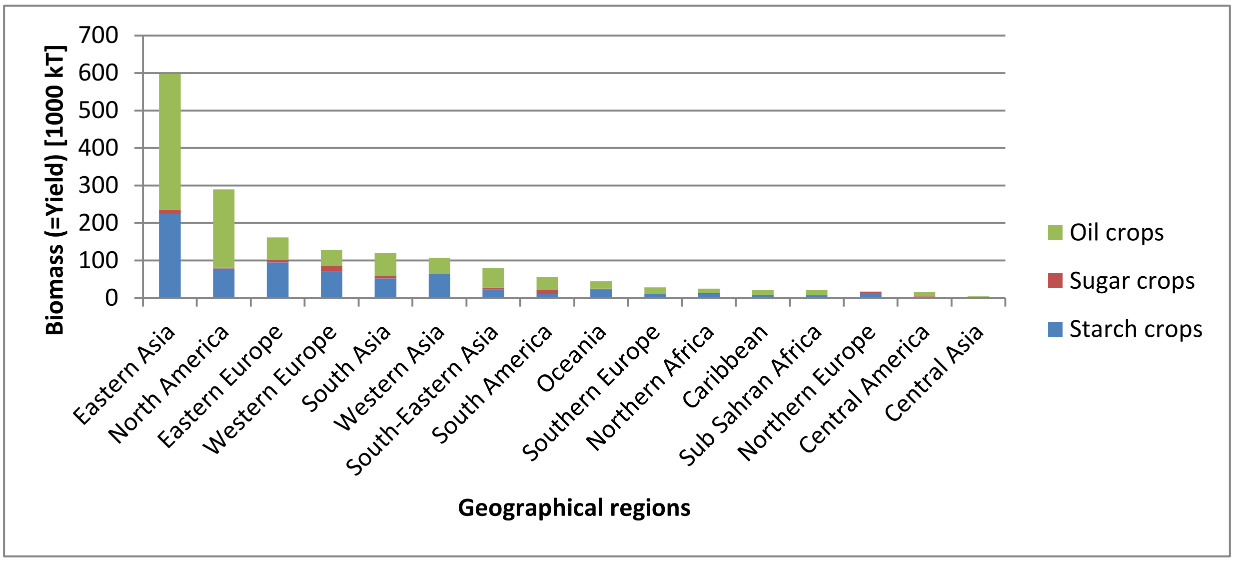


Figure 12: Regional quantitative requirements for raw materials in 1000 kt at a 100% substitution level of the four investigated product groups. Bars split up in the relative needed amount of three raw material groups.

6.5 Requirements of arable land

The results of the last step ($\boldsymbol{V}$) provide the answer to the second research question. They show the amount of arable land each country needs per product group and crop to reach the 100% substitution level. The results of the distribution of arable land per country shows expectable similarities to the country wise demand in non-energy fossil resources. A substitution of all four fossil resources based product groups with bio-based raw materials would lead to the following requirements in arable land: China has the highest land requirements with 805 541.6 km², followed by the Russian Federation with 550 043.2 km², the USA with 484 633.7 km², India with 310 184.1 km², the Islamic Republic of Iran with 154 566.1 km² and the Republic of Korea 143 298.1 km² (Figure 13).

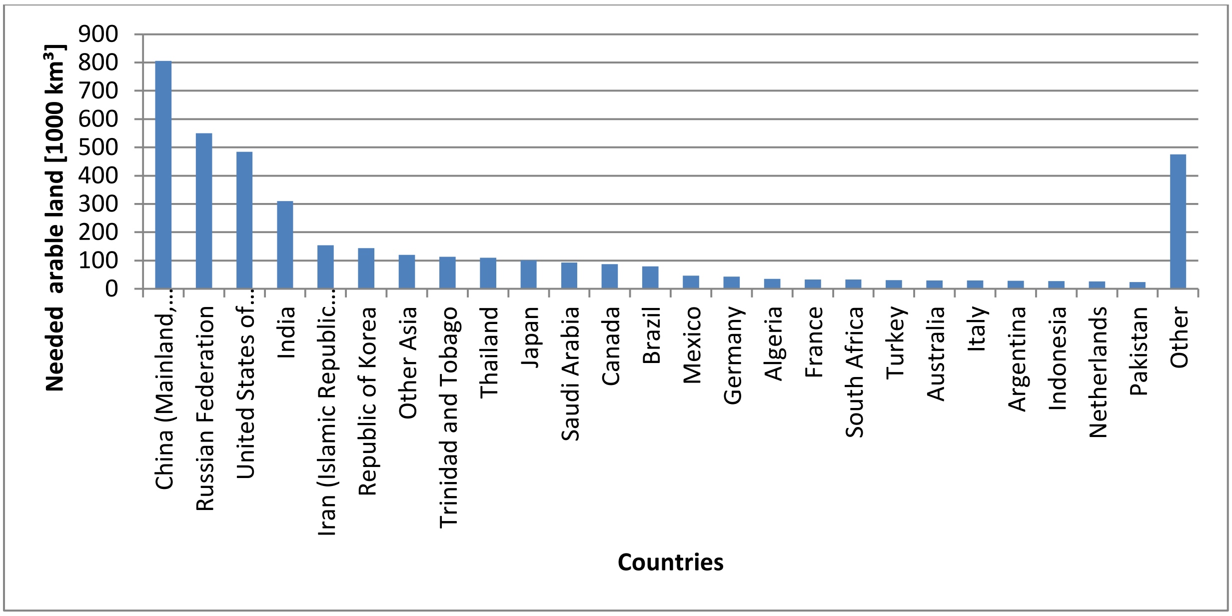


Figure 13: Countries (24 + other Asia) with the highest requirements of arable land needed to attain a 100% substitution level in 1000 km². Whole list can be seen in Annex 1, spreadsheet "Demand in arable land".

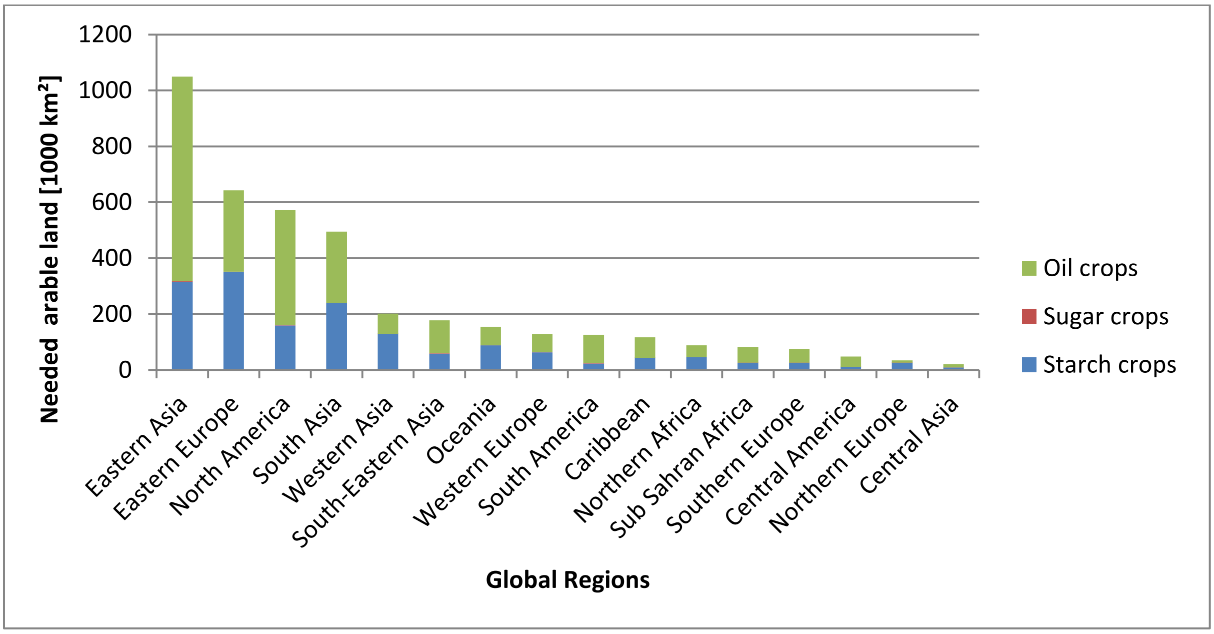


Figure 14: Regional requirements in arable land in 1000 km² at 100% substitution level. Bars split up in the relative needed amount of three raw material groups.

6.6 Summary of results

Similar to figure 10, the area required for sugar crops, compared to the requirements of areas for oil and sugar crops, is relatively low. The absolute values show that in Western Europe the area required for sugar crops is 1 913.5 km², followed by Eastern Asia (1 847.3 km²), Eastern Europe (1 648.7 km²), and Southern America (1 326.5 km²). The lowest requirement in arable land for sugar crops is in in Central Asia with only 1.7 km² to attain a full substitution. Globally 10 140.1 km² of sugar crops would be needed (Table 10).

The highest requirement in arable land is requested for oil crops. Globally 2 388 913.3 km² cultivated with the investigated oil crops would be needed to substitute the actual demand of non-energy fossil resources (Table 10). Eastern Asia has the highest potential request in arable land for oil crops with 733 030.7 km², Northern Europe the lowest with 8 109.5 km². In the case of starch plants Eastern Europe would have the highest potential requirement with 349 930.0 km², while Central Asia would have the lowest again with 9 488.1 km². The global potential requirement of arable land for starch plants would be 1 612 637.3 km² (Table 10). This leads to a cumulative global potential requirement of arable land for all three crop groups of about 4 011 690.7 km² to realize the production of raw materials at full substitution of all product groups (Figure 14, Table 10).

A comparison between the actual amounts of arable land and the potential required land to receive the 100% substitution level shows in which countries the circumstances would allow substitution based on actual data. With actual agricultural production, regarding the investigated crops only, 34 countries and the group of countries conglomerated in “Other Asia” would not be able to accomplish the substitution. The arable land needed for at least one of the raw material groups would overshoot the level of actually cultivated land by more than 100% (Table 8, Annex 1, spreadsheet “Delta cumulative”).

Due to the impossibility of using the majority of the agricultural production and area for industrial purposes, a limit of 10% of the actual production was set for each group of raw material providing plants. Regarding countries under this aspect, only 36 countries and

“Other Africa” provide the agricultural possibilities to substitute their domestic quantitative requirements for fossil based products by bio-based ones (Table 9, Annex 1, spreadsheet “Delta cumulative”). The highest potential lies in countries with a low demand in fossil based resources and a high agricultural production. The detailed list of countries with all results can be seen in Annex 1, spreadsheet “Demand in arable land”. On regional level, Sub Sahara Africa is the only region with the potential of domestic substitution of non-energy fossil-based products by bio-based ones by 100%. In western Asia, Oceania and the Caribbean region the requirement of arable land would be higher than the amounts of actually cultivated land (Table 10, Annex 1, spreadsheet “Delta cumulative”).

Table 7: List of all countries in which a domestic substitution is not possible as one crop group has a requirement higher than 100% of the actual production. The columns are differentiated by the actual production, cumulative quantitative requirement, and the difference between the actual production and the cumulative quantitative requirement in km². The last three columns are showing how much percent of the actual production would be needed to satisfy the requested amount for a 100% substitution level.

	Actual Production [km²]			Cumulative quant. requirement [km²]			Delta [km²]				Delta (percentage)		
Country	Starchcr.	Sugarcr.	Oilcrops	Starchcr.	Sugarcr.	Oilcrops	Starchcr.	Sugarcr.	Oilcr.	Sum	Starchcr.	Sugarcr.	Oilcr.
Algeria	28865	0	3495	23817	0	11800	5048	0	-8304	-3256	83%		338%
Armenia	1926	32	31	100	1	37	1826	31	-6	1851	5%	3%	120%
Azerbaijan	10584	61	787	2945	4	1738	7693	57	-951	6745	28%	6%	221%
Bahrein	0	0	0	4936	0	0	-4936	0	0	-4936	14518161%		
Belarus	22747	992	5721	9307	90	8702	13267	902	-2981	11188	42%	9%	152%
Belgium	4023	603	909	6809	358	12306	-2786	245	-11397	-13938	169%	59%	1354%
Botswana	1278	0	821	530	0	1716	758	0	-895	-147	41%		209%
Brunei Darussalam	18	0	18	3723	0	6299	-3705	0	-6281	-9986	20424%		34788%
Cyprus	371	0	110	120	0	110	251	0	0	251	32%		100%
Finland	10505	132	804	3114	10	950	7391	122	-147	7366	30%	8%	118%
Georgia	2146	0	1408	1207	0	2970	939	0	-1562	-623	56%		211%
Iceland	6	0	0	39	0	0	-34	0	0	-34	692%		
Iran (Islamic Republic of)	92798	1746	12978	120514	236	33816	-27167	1510	-20838	-47044	130%	14%	261%
Israel	987	00	459	5606	0	4637	-4620	0	-4179	-8798	568%		1011%
Japan	19815	823	17338	36982	506	63377	-17167	317	-46038	-62889	187%	61%	366%
Jordan	587	0	632	612	0	469	-25	0	162	137	104%		74%
Kuwait	36	0	11	3599	0	1945	-3563	0	-1934	-5497	10125%		17492%
Libya	4466	0	2775	7451	0	7389	-2990	0	-4614	-7604	167%		266%
Malta	42	0	0	9	0	12	34	0	-12	22	21%		18214%
Mauritius	13	547	10	1	13	19	12	535	-8	538	11%	2%	177%
Montenegro	107	0	36	77	0	114	30	0	-78	-48	72%		315%
Netherlands	3555	728	204	12345	866	12623	-8789	-158	-12419	-21366	347%	122%	6177%
New Zealand	1497	0	222	2292	0	1975	-795	0	-1752	-2547	153%		888%

Norway	3055	0	48	6770	0	1188	-3715	0	-1140	-4855	222%		2457%
Oman	199	0	17	9840	9	3315	-9641	-8	-3298	-12947	4942%	1837%	19866%
Portugal	3025	4	4986	3045	1	8907	-20	3	-3920	-3938	101%	22%	179%
Qatar	3	0	1	12707	0	2612	-12704	0	-2611	-15315	431330%		387533%
Republic of Korea	9522	0	9733	45249	0	98049	-35727	0	-88316	-124042	475%		1007%
Russian Federation	395633	10074	113174	306159	1349	242535	89475	8724	-129362	-31163	77%	13%	214%
Saudi Arabia	2465	0	183	55212	0	37189	-52747	0	-37006	-89753	2240%		20292%
Singapore	0	0	0	0	0	4561	0	0	-4561	-4561			2682759%
Switzerland	1481	195	433	632	20	521	849	175	-88	936	43%	10%	120%
Trinidad and Tobago	47	0	65	42721	0	70340	-42673	0	-70276	-112949	90071%		108463%
United Arab Emirates	19	0	2	605	0	652	-586	0	-650	-1236	3251%		37913%
Other Asia	45889	774	24361	62093	204	57735	-16204	569	-33374	-49008	135%	26%	237%

Table 8: List of all countries in which a domestic substitution is possible as all three crop groups have a quantitative requirement lower than 10% of the actual production. The columns are differentiated by the actual production, cumulative quantitative requirement, and the difference between the actual production and the cumulative quantitative requirement in km². The last three columns are showing how much percent of the actual production would be needed to satisfy the requested amount for a 100% substitution level.

	Actual Production [km²]			Cumulative qunant. Requirement [km²]			Delta [km²]				Delta (percentage)		
Country	Starchcr.	Sugarcr.	Oilcr.	Starchcr.	Sugarcr.	Oilcr.	Starchcr.	Sugarcr.	Oilcr.	Sum	Starchcr.	Sugarcr.	Oilcr.
Argentina	104222	3333	254856	4709	36	24047	99513	3297	230809	333619	5%	1%	9%
Bangladesh	125343	1116	120970	2186	7	3596	123157	1108	117374	241638	2%	1%	3%
Bolivia (Plurinational State of)	12961	1515	21116	131	2	395	12829	1513	20721	35063	1%	0%	2%
Côte d'Ivoire	15141	255	16841	151	0	338	14990	255	16503	31747	1%	0%	2%
Cambodia	34247	239	32650	22	0	42	34224	239	32607	67070	0%	0%	0%
Cameroon	23514	1333	18259	118	4	226	23396	1329	18033	42758	1%	0%	1%
Democratic Republic of the Congo	38916	451	27013	27	0	87	38888	451	26926	66265	0%	0%	0%
Denmark	14888	392	1701	403	3	130	14485	389	1571	16445	3%	1%	8%
El Salvador	3838	723	3047	46	1	125	3792	722	2921	7435	1%	0%	4%
Eritrea	4349	0	487	34	0	20	4314	0	466	4781	1%		4%
Ethiopia	70451	254	27601	299	0	440	70153	254	27161	97568	0%	0%	2%
Ghana	25804	59	19977	545	0	1166	25259	58	18812	44129	2%	1%	6%
Guatemala	9131	2525	10018	88	2	322	9043	2523	9696	21262	1%	0%	3%
Haiti	7603	228	5087	26	0	74	7577	228	5014	12819	0%	0%	1%
Indonesia	187819	4516	283793	7922	58	18804	179897	4458	264989	449344	4%	1%	7%
Kenya	29267	788	22840	429	1	1234	28837	787	21606	51230	1%	0%	5%
Latvia	5617	52	1139	258	1	65	5359	51	1075	6485	5%	1%	6%
Mongolia	3064	0	48	7	0	0	3058	0	48	3105	0%		1%
Myanmar	82649	1598	107358	444	2	1151	82205	1596	106207	190008	1%	0%	1%
Nepal	36170	637	25902	25	0	51	36145	637	25851	62633	0%	0%	0%
Nicaragua	4934	645	4776	117	1	388	4817	644	4387	9849	2%	0%	8%
Niger	105052	46	9368	174	0	30	104878	46	9337	114262	0%	0%	0%

Nigeria	229040	555	156595	7050	5	10358	221990	550	146237	368776	3%	1%	7%
Paraguay	17603	1106	42827	37	1	177	17566	1106	42651	61323	0%	0%	0%
Philippines	75016	4194	108070	653	6	1564	74363	4187	106506	185057	1%	0%	1%
Republic of Moldova	9141	274	8210	122	1	290	9019	273	7920	17212	1%	0%	4%
Senegal	12440	65	12258	402	0	345	12038	65	11913	24016	3%	0%	3%
Sri Lanka	11580	163	15499	84	0	152	11496	162	15347	27005	1%	0%	1%
Sudan	98099	658	43260	3346	0	1972	94754	658	41288	136699	3%	0%	5%
Tajikistan	4532	0	2235	46	0	69	4487	0	2166	6652	1%		3%
Togo	12588	0	9174	16	0	44	12572	0	9130	21702	0%		0%
United Republic of Tanzania	76418	551	84167	178	0	467	76240	551	83700	160491	0%	0%	1%
Uruguay	9351	71	13046	112	0	350	9240	71	12696	22006	1%	0%	3%
Viet Nam	95838	2936	94337	3237	30	6636	92600	2907	87701	183208	3%	1%	7%
Zambia	14625	366	16440	177	0	601	14449	366	15839	30653	1%	0%	4%
Zimbabwe	21574	453	20596	243	0	506	21331	453	20090	41874	1%	0%	2%
Other Africa	256366	3226	176276	5545	5	7641	250821	3221	168635	422677	2%	0%	4%

Table 9: List of global regions showing the potential of a substitution on regional level. In the last raw, the cumulative data for all regions (= world data) is shown in bold. The columns are differentiated by the actual production, cumulative quantitative requirement, and the difference between the actual production and the cumulative quantitative requirement in km². The last three columns are showing how much percent of the actual production would be needed to satisfy the requested amount for a 100% substitution level.

	Actual Production [km²]			Cumulative quant. requirement [km²]			Delta [km²]				Delta (percentage)		
Global region	Starchcr.	Sugarcr.	Oilcr.	Starchcr.	Sugarcr.	Oilcr.	Starchcr.	Sugarcr.	Oilcr.	Sum	Starchcr.	Sugarcr.	Oilcr.
Eastern Europe	764919	18698	336989	349930	1648	290666	414989	17049	46322	478361	46%	9%	86%
Northern Europe	92004	2292	15772	26053	150	8109	65951	2142	7663	75756	28%	7%	51%
Southern Europe	140971	1921	107868	26041	66	48912	114930	1855	58955	175739	18%	3%	45%
Western Europe	172995	9739	64899	62702	1913	63805	110293	7825	1094	119212	36%	20%	98%
Sub Sahran Africa	1056576	13080	720954	26336	214	55741	1030240	12865	665213	1708318	2%	2%	8%
Northern Africa	228945	4307	97541	45916	215	41935	183028	4091	55606	242725	20%	5%	43%
Central Asia	189519	356	45611	9488	2	11561	180031	354	34050	214435	5%	0%	25%
Eastern Asia	1056559	20472	960778	314834	1847	733031	741725	18625	227747	988097	30%	9%	76%
South Asia	1419400	62819	1175599	238841	1017	254824	1180559	61802	920775	2163136	17%	2%	22%
South-Eastern Asia	623212	25897	815628	58292	631	118285	564921	25266	697344	1287530	9%	2%	15%
Western Asia	201630	3259	44968	128908	92	72555	72722	3168	-27587	48303	64%	3%	161%
Oceania	233581	4286	55986	88195	245	65879	145387	4041	-9892	139536	38%	6%	118%
South America	418424	110894	826296	22573	1326	102381	395851	109567	723915	1229333	5%	1%	12%
North America	728867	8442	837677	159301	441	411753	569566	8001	425923	1003490	22%	5%	49%
Central America	121855	12980	102454	11493	156	36681	110362	12823	65773	188958	9%	1%	36%
Caribbean	17012	6771	14279	43734	172	72792	-26722	6599	-58514	-78637	257%	3%	510%
World	**7466470**	**306213**	**6223300**	**1612637**	**10140**	**2388913**	**5881812**	**296073**	**3834387**	**9984292**	**22%**	**3%**	**38%**

7 Discussion

Although the presented results are coherent and draw a consistent picture on agricultural feedstock requirements in substituting fossil-based non-energy products, there are some methodological shortcomings and uncertainties. The only sources of data are IEA et OECD (2016) and FAO Stat (2017a). The data is requiring information from each country. So it depends first on the willingness of each administrative authority to participate in the global statistical collection of data and second to provide sound data (IEA et OECD, 2016; FAO Stat, 2017a). Unfortunately, there is no other official source (free of charge) with comparable and coherent data on global scale.

It has to be mentioned that the demand for fossil resources does not represent the true, country wise demand in fossil-based goods. In the report by IEA and OECD (2016), the amounts of consumption are given in different forms of fossil resources (coal, gas, oil, etc.) and not in the form of final products. For example, many goods are produced in eastern and south-eastern Asia (e.g. China, Korea, Japan, Bangladesh, Indonesia) whereas the products are consumed globally (e.g. electronic devices, single use products, etc.) (IDE-JETRO et WTO, 2011). So, it can be said that the consumption of non-energy fossil based resources does not reflect exactly the same demand in the final products. The values of “consumption” and “production” were used equally throughout the thesis.

Despite the uncertainties, it has to be mentioned that an increase in the agricultural output mainly leads to a domestic output increase, especially in countries where market distribution effects in the primary sector are positive (Asada et Stern, 2018), because cost competitiveness is a key factor between the usage of bio-based or fossil based materials (Kircher, 2014). Technological development in utilization of bio-based raw materials in general and further development in the bio-based technology are main keys in a transition to a bio-based industry (e.g. Hermann et al., 2007; Dornburg et al., 2006; Patel et al., 1999) with the potential to receive macro-economic benefits in future (van Meijl et al. 2018). Furthermore, the actual state of technology in the bio-based industry is that a great potential lies in the usage of cellulose, hemicellulose and lignin as well as the cascading use of residues from the food and feed producing industries (ÖVAF et BIOS Science Austria, 2013, Keegan et al., 2013).

The assumptions on conversion factors for ”Biomass to raw material” and “Raw material to bio-based product” are based on recent literature, which is not primarily aimed at the industrial use of crops. Further, the values for the conversion factors are the average of a rather large range. The conversion factor “raw material to bio-based product” is based on averages of each sub-product group as well. As seen in Annex 4, the group of polymers encounters different types of “plastics” with product specific quantitative requested amount in renewable raw materials. To receive more detailed results, it would be necessary to split up each of the four product groups in its sub products with its particular product requirements specialized for their field of application. The actual cumulative requested amount for biomass to attain the calculated amounts of renewable raw materials showing a higher requirement of oil crops than of starch crops.

The conversion factors “biomass to raw material” (Annex 3) are for starch crops on average lower (2.792 : 1) than for oil crops (3.566 : 1). The “worst” conversion factors have sugar plants. It needs about 6.1 mass-units of biomass to produce 1 mass-unit of usable sugar.

Another determining factor is the yield of biomass per area unit, whereby a higher yield per hectare does not necessarily imply a higher yield in raw materials. For example, the yield of olives (Australia: Ø 2.17 t/ha) have compared to sunflower (Australia: Ø 1.34 t/ha) a higher yield per hectare, but the conversion factors from yield to raw material for olives are 4.44:1 and for sunflower 2.67:1. It means that the produced oil per area unit from both crops are similar to each other (ca. 0.5 t/ha). Therefore, a unit like “raw material per hectare” in mass units may be a more meaningful. Nevertheless, a look at the necessary required amount of arable land for each country shows an obvious picture: countries with a comparable high agricultural production and a low quantitative requirement for non-energy fossil resources have a great potential to substitute their domestic requirements by renewable resources.

For many polymer products (e.g. Polylactic acid, Polyhydroxybutyrat, Polyethylene terephthalate), sugar and starch are the substitutive building blocks, whereby it is possible to achieve the same output with less amount of sugar than with starch (IfBB, 2016). A higher efficiency in the usage of crops for industrial use could decrease the requirements for bio-based raw materials and in addition decrease the requirements in arable land. Similarities can be observed for the production of solvents (Schindler, 1997). Further studies dealing with the whole value chains of the products would be needed to optimize the agricultural production and increasing the efficiency in resource utilization for industrial products.

Important factors for mitigating GHG emissions are, besides the effects of land use change, the way renewable raw materials are produced. The higher the application of technical aids in agricultural production, the higher is the potential for greenhouse gas emissions (Gomiero et al., 2008). Another determining factor is the target market (e.g. subsistence, regional market, global market) and the ongoing usage of the harvested crops: food, feed or industrial use. Further, a higher production of agricultural goods can lead, besides the threats of land use changes, to a higher grade of monoculture on farms with consequential negative effects, for example a reduction of the biodiversity on farms (e.g. Gevers et al., 2011).

Although agricultural crops do have a great potential for industrial use, it has to be mentioned that globally the main task of agriculture is supplying food for humans. Unfortunately, even in the 21st century undernourishment and famine are persistent issues for humankind. A global and sustainable transition to a bio-based economy can only be achieved, if no one is suffering from these threats. The imbalance in food supply on global scale leads to the inevitable discussion if agricultural crops should not be used for industry purposes as long as people are suffering from starvation and undernourishment in several regions in the world. Nevertheless, it is necessary to gain coherent information of potential agricultural crops as feedstock for the chemical industry, especially if the dependency on crude oil should phase out. The development in world population predicts by 2050 an increase in the demand of food by up to 70% from now (EC, 2012) what constitutes an additional challenge in the availability of arable land on the long term.

An arbitrary boundary of 10% of the actual arable land used for sugar crops, starch crops and oil crops production was used to show that some countries have the availability to substitute their domestic quantitative requirements (Table 9) and still using more or equal to 90% of the produced crops for other purposes – like food or feed. Particularly outstanding are countries in which the share of agricultural production in the GDP of agricultural production is higher than the global average (The World Bank, 2017) and the demand in non-energy fossil resources is comparably low. For countries, where the climatic circumstances (e.g. Qatar, Oman, Iceland) or the availability of arable land is limited (e.g. Japan, Malta, Israel), it seems impossible to substitute their domestic requirements by the actual agricultural production. A global substitution of the four investigated fossil based product groups can be achieved with 21% of the area used for the cultivation of starch crops, 3% of sugar crops, and 38% of the global area used for oil crop production.

As some countries are not able to domestically produce their requirements to attain the 100% substitution level, equivalent to crude oil, trade of the needed commodities may be an option in attaining that goal. Independent from the country wise needs, a globally higher need in agricultural products leads inevitably to a higher need in arable land which likely results in potentially environmentally harmful impacts and dependencies. Using additively (non-edible) second generation feedstocks from other economic sectors dealing with biomass (e.g. forestry, food industry) may have the potential to reduce the discussed negative socio-ecological effects.

8 Summary & Conclusions

The consumption of non-renewable fossil resources for the non-energy sector has, compared to the consumption in the energy sector, a minor share. According to the data from IEA and OECD (2016), 89% of the fossil resources are consumed for energy, and 11% for non-energy purposes. The four investigated product groups are sharing an amount of approximately 4% of the global fossil resource consumption. On global scale, this may seem to be a small number but nevertheless the investigated amounts represent 271 355 kt of fossil resources consumption, which may be substituted by renewable raw materials. To achieve a 100% substitution, the results in this thesis are showing that 527 742 kt of raw materials (sugar, starch and plant oil) would be necessary. To produce that amount of raw material, about 1 720 784 kt of biomass, harvested on 4 011 690 km^2, which equals 22% of the global area cultivated with starch crops, 3% with sugar crops and 38% with oil crops, would be necessary.

Through an optimization of the whole supply chain, it may be possible for some countries to substitute their domestic requirements. A possible approach may be an increase in the yield through intensification of the currently used arable land or product based cultivation of the crops only for industrial purposes. An optimization in the production chains, like in biorefineries, plays also an important role in generating competitive goods.

Consumption habits demand a high amount of resources and energy. Even in high developed countries, the losses of food in the supply chain from the acre to the plate lies at approximately one third of the whole food production (FAO, 2011). The losses mutually influenced by (wrong) consumer habits and an idealistic idea of food in the supplying industries in general can only be reduced by the willingness to change by both players. In fact, political measures, like in France (prohibit of wasting food by super markets (Al Jazeera Media Network, 2015) and outlawing of single-use plastic bags (France 24, 2014) do have the ability to accelerate the progress in reducing the consumption of resources. The more efficient usage of produced food and the reduction of food waste can decrease the needed arable land in future as well as the demand in energy and resources in general.

Another aspect playing a major role to the mentioned transition is affecting the dietary habits. Again economically richer countries do have a high consumption rate in meat (e.g. OECD et FAO, 2017). The production of meat needs in addition to energy and resources agricultural land for the production of feed. Globally, 1.5 billion ha arable land are used for agricultural production (FAO Stat, 2017b), with a constantly increasing demand. A targeted change of the consumption of food, especially animal products, can reduce the increasing demand in arable land (Wirsenius et al., 2010) and provides more area for either food and/or even industrial use.

This thesis can be regarded as basis for further studies, which picks up the topic of potential substitutions of non-energy fossil resources, especially in countries where the ideas of a bio-based industry is not far advanced or even known.

9 Declaration of authorship

This master thesis was written according to the official guidelines to guarantee good scientific practice at the University of Natural Resources and Life Sciences, Vienna (BOKU, 2009).

After assessment with the program docoloc, it is certified that this thesis constitutes no plagiarism.

I, Viktor Schwabl, hereby declare that the work presented here is, to the best of my knowledge and belief, original and the results of my own investigation, except as acknowledged, and has not been submitted, either in part or whole, for a degree at this or any other university.

Location, Date	Signature
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10 Acknowledgements

Writing this thesis required me a lot of time, energy and motivation. Hereby I would like to gratefully acknowledge all persons, who helped and supported me finally achieving my graduation from university.

First I want to thank my parents *Bogusława* and *Dipl.-Ing. Dr. Wolfgang Schwabl*, who made it possible for me to study and supported me in with all I needed for my studies at university.

Especially I want to thank my thesis co-supervisor *Ass.Prof. Dipl.-Ing. Dr. Johannes Schmidt* for his patience, support and good advices during the time of writing this thesis and was available every time if problems occurred.

Further I want to thank my thesis supervisor *Univ.Prof. Dipl-Ing. Dr. Erwin Schmid* for giving advices and ensured a critical review of my thesis.

I also want to thank *Mag. Dr. Fabian Schipfer* for giving me precious tips concerning the methodology and *Julia Herrele BA* for proofreading.

Finally, I also want to thank my girlfriend *Amy* and all my close friends for motivating and believing in me.

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11.2 List of abbreviations

Abbreviation	Meaning
GHG	Greenhouse gas emissions
km²	Square kilometres
kt	Kilotonnes / thousand tonnes
Mt	Megatonnes / million tonnes
Mtoe	Megatonnes of oil equivalent
Mt/a	Megatonnes per year
TJ	Terra Joules

11.3 Figures and Tables

11.3.1 Figures

11.3.2 Tables

11.4 Annex

All Annexes are available for download at: https://homepage.boku.ac.at/jschmidt/schwabl/

Annex 1: Excel sheet with all presented calculations and results, except those stated below.

Annex 2: Non-energy fossil resource consumption in the European Union in 2008 including the calculation for the relative amounts of lubricants and surfactants.

Annex 3: List of all surveyed crops inclusive raw material content and resource.

Annex 4: List and calculations for the factors “raw material to bio-based product”.