TU Delft

The Controversies of Bioenergy

A Multi Criteria Decision Analysis of Bioenergy Feedstocks

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By

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Preface

Before you lies the thesis ”The Controversies of Bioenergy - A Multi Criteria Decision Analysis of Bioenergy Feedstocks”, which mainly concerns the ranking of 40 selected feedstocks using the MCDA method PROMETHEE II. This report is written in order to fulfill the requirements for the master program Sustainable Energy Technology (SET) at Delft University of Technology. I have been working on this research from June 2020 to March 2021.

After formulating the research question together with my first supervisor, Prof.dr. Kornelis Blok, I felt very motivated to start my research. The topic interested me greatly which resulted in true enjoyment during the project. I have learned a great deal about several aspects of bioenergy and the bioenergy debate which is a nice elaboration to the knowledge already gained during the courses followed within my degree. No large difficulties or obstacles were encountered during this study. However, some frustrations were present during the analysis of the controversies around bioenergy. Some of the reasoning of authors/researchers were not in line with how I was educated. To me this was hard to grasp because scientific research should not be interpreted in such a way that it will suit your case. Besides this, it was a great pleasure to look into the bioenergy debate more closely and to be able to generate satisfactory results.

I would like to thank my supervisors for their advice and guidance. When it was needed, it was possible to get a little nudge in the right direction, I really appreciate this. With their help I was able to stay on track and complete my research.

I hope you enjoy reading my thesis.

Jolien Wilbrink

Summary

Rising carbon dioxide concentrations in the air increase the global temperature since the industrial revolution. Today, there exists a great need to limit global warming, and an energy transition is vital to do so. With the upcoming changes in our energy system, bioenergy is widely discussed, resulting in a heated debate on including or excluding bioenergy in the energy transition. This study aims to identify the least controversial feedstocks out of 40 different ones and if they will help to resolve the controversies around bioenergy.

Before a feedstock is deemed controversial, a background of bioenergy was established to see what role bioenergy has in today's energy system and in the future. A literature analysis identifies the role of bioenergy today. Using the 'IAMC 1.5°C Scenario Explorer' hosted by IIASA the role in the future is identified. To determine the least controversial feedstocks, a multi-criteria decision analysis (MCDA) is performed. The PROMETHEE II method is used to perform the MCDA and the entropy weight method for weighting the criteria. The ranking and weighting make use of MATLAB. Since the aim is to classify feedstocks as the least controversial, the criteria are deduced from a literature analysis and represent the controversies of bioenergy.

The first part of the report indicates a significant role in today's renewable energy system and a shift towards more modern bioenergy implementations like biofuels and bio-electricity. According to the scenario analysis, for the five different shared socio-economic pathways, bioenergy will be used. For the SSPs with RCP 1.9, the increase of bioenergy TPES for 2020 to 2050 ranges from 61 EJ for SSP1 to 191 EJ for SSP5. For the SSPs with RCP 2.6, this was 29 EJ for SSP1 to 129 EJ for SSP5. Besides the identification of a clear use of bioenergy in the future energy system, the scenario analysis of TFE of bioenergy indicated a shift towards modern bioenergy use. It was observed that the solid biomass use reduced and a strong increase in liquid biofuels in the transport sector will happen. These findings are in line with the predictions made by the IPCC. Also, this is in accordance with the observed growth rates and development trends found for today and in the recent years. This all results in the conclusion that bioenergy is important for the energy transition. Due to the observed research and development into biofuels and bio-electricity, traditional bioenergy will be phased out and replaced by modern bioenergy types.

The next part of the report considers the controversies around bioenergy. The following controversies are identified and considered the most discussed ones: chain emissions, removal of carbon sinks, the carbon debt, land-use, competition with the food industry, and biodiversity. From these controversies, the following six criteria are derived: yield in ha/MJ energy (C1), generation type (C2), nitrogen fertilizer use in kg N/ha (C3), biodiversity impact (C4), carbon debt in days (C5), and marginal land use (C6). The controversy of removal of carbon sinks is not quantified in this research. Identification of the controversies and with that the criteria are necessary for the feedstock ranking. The MCDA ranking shows that residues and wastes feedstocks are the least controversial, followed by alfalfa. The top eight high-scoring crops are alfalfa, oil palm, kenaf, mustard, cotton seeds, prairie grasses, camelina, and hemp. For this top eight, an additional ranking that included water use is done. This ranking shows that incorporating such a detail does not significantly change the results. It was seen that the top four was kept constant except when the simplest form of an MCDA is applied. Cotton seeds drops two to three places in rank. Prairie grasses replace cotton seed at place five when water use is considered.

The most remarkable contradiction with literature is that oil palm ranks very high, and miscanthus is not present in the top eight. Oil palm is, in literature, considered a very controversial feedstock, and miscanthus shows promising features. These results indicate that either the data is not specific enough, or the criteria are not detailed enough. Another explanation is that the choice for an objective weighting method is not the best choice since it excludes opinions of the decision makers (the scientist participating in the debate). The debate is opinion and preference driven, which makes that a data based weighting method might not be ideal. Nevertheless, the rank of the waste streams is following the expectations.

The results indicate that waste streams are to be used as primary feedstocks when controversies need to be resolved. The PROMETHEE II ranking shows this solution, and a sensitivity analysis supports the results. Reflection of the data for the feedstocks and the controversies shows that the use of residues and waste feedstocks can resolve several controversies with a relatively high degree of certainty (controversy of land use and competition with food industry) and others with some degree of certainty (controversy of chain emissions and biodiversity). Due to the global scope and simplifications, the data used could be improved. Therefore, further research is necessary to back-up the findings. Nevertheless, this research gives insight into the controversiality of several feedstocks and takes a first step in tackling the bioenergy debate.

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List of Abbreviations

Abbreviation	**Meaning**
AIM/GCE	Asia-Pacific integrated assessment model/computable general equilibrium
bbl	Barrel
BDt	Bone dry ton
BECCS	Bioenergy and carbon capture and storge
CCS	Carbon capture and storage
CO_2	Carbon dioxide
DM	Decision matrix
EJ	Exa joule
EU	European Union
ET	Evapotranspiration
EWM	Entropy weighting method
EW	Equal weight
F-AHP	Analytical hierarchy process
Gaus	Gaussian
GCAM	Global change assessment model
GHG	Green house gas
GLOBIOM	Global biosphere management model
GIS	Geographic information systems
HDV	Heavy-duty vehicles
HEFA	Hydroprocessed esters and fatty acids
HVO	Hydrotreated vegetable oils
IAM	Integrated assesment model
IAMC	Integrated assessment modeling consortium
IEA	International energy agency
IIASA	International institute for applied systems analysis
iLUC	indirect land use change
IPCC	Intergovernmental panel on climate change
IRENA	International renewable energy agency
LCA	Life cycle analysis
LDV	Light-duty vehicles
LUC	Land use change
MAgPIE	Model of agricultural production and its impacts on the enviornment
MPB	Multi-period budgeting
MCDA	Multi criteria decision analysis
MESSAGE	Model for energy supply strategy alternatives
Mg	Mega gram
MJ	Mega joule
MSW	Municipal solid waste
Mtoe	Million tonne of oil equivalent
MWh	Mega watt hour
N	Nitrogen
N_2O	Nitrous oxide
PBL	Planbureau voor de leefomgeving
PJ	Peta joule
PV	Photovoltaic
REMIND	Regionalized model of investment and technological development
RCP	Representative concentration pathway
SRC	Short rotation coppice
SSP	Shared socioeconomic pathway
TFE	Total final energy
TFC	Total final consumption
TPES	Total primary energy supply
TWh	Terra watt hour
USA	United States of America
WITCH	World induced technological change hybrid
1G	First generation
2G	Second generation
3G	Third generation

1 Introduction

Global climate change is becoming a more frequent discussed topic. The need for a change is observed not only in the world of science, but also during your daily walk in the park. One of the main greenhouse gas (GHG) emitting sectors is energy. Looking only at fuel combustion, heat and electricity production was responsible for at least two thirds of the total CO_2 emissions in 2018 (IEA, 2020b). This means that it is of great importance to reduce the fossil fuel dependency of this sector, and with that decrease the GHG emissions. For many years, alternative energy sources have been developed. As an example, the solar cell was first constructed in 1883 and is today, due to its developments over the past 137 years, already quite widely applied (Chu & Taranzo, 2019). Many more low carbon emitting energy sources exists besides the photovoltaic (PV) principle. Windmills can convert wind to electricity, heat stored in the ground can be extracted by geothermal technologies, and organic matter can be processed to deliver several forms of energy. The latter is better known by the term bioenergy. Bioenergy is now the main sustainable energy source used, responsible for about half of the total renewable energy consumed in 2017 (quantified at the level of total final energy consumption (TFEC)) (IEA, 2018). Bioenergy is not just known to be the main sustainable energy source applied in the current energy system. It is also known to be the most discussed and debated one. Researchers around the world seem unable to come to an agreement whether bioenergy is a sustainable source that should or should not be included in the decarbonization of the energy sector. It is intriguing to observe that this energy source is the cause of an increasingly heated debate. The researchers are in discord and this is the cause of the creation of controversies around bioenergy. When new scientific papers and reports about bioenergy are published, other reports and papers are published with contradicting views (from now on referred to as counter reports). It is because of this scientific battle that the debate can keep on going.

An example of such a counter report is the one of (Searchinger & Tufts, 2020), they react to (Strengers, Bart; Elzenga, 2020). This type of interaction between scientists gives good insights into how the debate continues. Besides this example, the counter reports could also be used to identify problems around bioenergy. Therefore, it could be of use for further developments for bioenergy. However, this is not yet the case, indicating the presence of a knowledge gap. The counter reports and the debate itself could be used as a feedback loop. The debate is disconnected from research and development within the bioenergy sector, and therefore missing out on problem solving opportunities. When scientific research incorporates the controversies of bioenergy, the implementation of bioenergy can be performed in such a way that it is least controversial. This will add scientific value to the debate and eliminates possible missed opportunities in meeting energy transition related goals. The need for a transition to cleaner energy sources becomes more evident each year. The seriousness of the problem indicates that the wait cannot be stalled anymore. Especially when the aim is to limit global warming to 1.5 °C. The bioenergy debate creates a barrier for the implementation of bioenergy and thereby can effect the energy transition in a negative way. It is of great importance that the researches are aligned concerning bioenergy to decide whether or not to include bioenergy technology in the equation.

Aim and Research Questions

The aim of this study is to identify the least controversial feedstocks out of 40 selected, and if this feedstock can help resolve the controversies regarding bioenergy on a global level. This is done by using a multi criteria decision analysis (MCDA) ranking method, to rank the feedstock according to specified criteria.

This research is a contribution to solving the challenges that are observed with the implementation of bioenergy to decarbonize the energy sector. The contribution is made in a decision making manner. With the help of an MCDA and the bioenergy controversies as the decision criteria, feedstocks are ranked from least to most controversial. The use of a feedstock with a low degree of controversy should not encourage the debate but, due to its properties, overcome the challenges highlighted in the debate. In that way, this research creates a link between the bionenergy debate and scientific research in bioenergy. As described above, it was found that such a link was missing, so this research is a contribution to the existing knowledge in this field. Another reason why this research makes a contribution to the existing knowledge, is that it takes arguments from both sides of the debate into consideration while staying neutral whether to use bioenergy or not. The controversies are used as the problem solving criteria and not to provide information about benefits and challenges of bioenergy.

This research can be divided into three parts. The first part consist of information collection in order to understand to what extent bioenergy had a role in the energy sector in recent years, and to what extent it will play a role in the future. The method used to understand the role of bioenergy in the past was a literature analysis. For the role of bioenergy in the future, a scenario analysis using the shared socio-economic pathway (SSP) scenarios and the 'IAMC 1.5°C Scenario Explorer' hosted by IIASA was used. The second part shall contain the preparation for the MCDA. This consists of the description of the controversies of bioenergy, the selection of the feedstocks, collection of the data for the criteria and feedstocks, and the construction of the decision matrix. All data is collected by a literature search and not by experiment. The feedstocks are selected after a literature research for the type of bioenergy feedstocks. Once the four main categories were known, some more widely applied and some newer feedstocks were selected for the ranking. These were all feedstocks that are mentioned in literature. No specific selecting procedure was used. The last part considers am MCDA ranking by using the PROMETHEE II method, a sensitivity analysis, discussion of the results, and the conclusion. The analysis is based on the method of PROMETHEE II as described in (Ishizaka & Nemery, 2013; Kocmanová, Dočekalová, & Luňáček, 2013). The sensitivity analysis was performed by first changing the preference function of the PROMETHEE II method, then by changing the weights (from entropy weights to equal weights and fuzzy analytical hierarchy process weights) and lastly, applying the simplest form of an MCDA method. The discussion aims to look critically at the results to discuss the credibility and robustness of the research due to the choices and assumptions made.

The research consists of six sub-questions, each is answered in order to gather understanding of the situation and to perform the MCDA ranking of feedstocks. The following questions are answered:

1. What role has bioenergy in the current energy system, on a global level?
2. To what extent (amount) is bioenergy included in future scenarios to limit global warming to 1.5 °C or below 2.0 °C?
3. What are the global controversies that fuel the bioenergy debate?
4. Which feedstocks can be used for bioenergy, and what are some of their characteristics (not considering a specific region)?
5. Looking into the feedstocks, which ones can be identified as least controversial?
6. How can the less controversial feedstock help reduce the global controversies about bioenergy?

First, a literature review identifies what literature is already existing around this research's topic (chapter 2). Then literature research is performed in chapter 3 to quantify the use of bioenergy today and in the recent years, in order to get insight into the importance of bioenergy in the future, a SSPs scenario analysis is completed for bioenergy only. The analysis is introduced with a description of the different shared socioeconomic pathways (SSPs) narratives, explanation of the IAM models and the representative concentration pathways (RCPs), this can be found in chapters 4 and 5 respectively. Once the role of bioenergy in the energy transition is known, literature research is performed to identify the main controversies of bioenergy (chapter 6). The next step is to select feedstocks and to collect their characteristics, they are presented in a table (see chapter 7). When all characteristics are known, the criteria are formulated and the decision matrix is constructed. After that, the weights are determined. Next, the PROMETHEE ranking method is used, and the MCDA ranking is performed in MATLAB, using the code as designed by (Mukhametzyanov, 2020). This can be found in chapter 8. The ranking determines the least controversial feedstock. After presenting the results, they are discussed in detail (see chapter 9). A conclusion is drawn and recommendations for further research are given in chapter 10.

2 Literature Review

In this chapter, literature that already exists about the different aspects of this research is discussed. A literature analysis evaluates whether and why this research is an addition to the already existing information within this topic of study. The main focus will be the feedstock ranking and ways to resolve the controversies, since these topics are the primary goal of the report. In order to do so, the TU Delft online library, Google Scholar, and ScienceDirect were used to find reports and papers using searchterms like Bioenergy feedstock ranking, Solving bioenergy controversies, and Bioenergy feedstocks versus controversies.

Today, there exists quite some literature about assessing several aspects of the sustainability or optimization of bioenergy production. When looking at the research that has been done in bioenergy feedstock ranking, several cases are found. The research of (Samanlioglu, 2018), for example, ranked several feedstocks to determine which one was most suitable for the production of biodiesel. The criteria used for that specific research are quantitative and qualitative feedstock characteristics. These criteria are more focused on feedstock performance and its suitability within the chosen region. Some of the criteria considered in this ranking are price, suitability to the climate, suitability for processing technology, and yield. No connection to the controversies is made within the study of (Samanlioglu, 2018). The study of (Anwar, Rasul, & Ashwath, 2019) among others, performed a PROMETHEE ranking of second-generation biodiesel feedstocks. Six feedstocks were ranked and evaluated over 12 different criteria. These criteria were all physical and technical characteristics. It is clearly stated that any social aspects were left out. Some examples of the physio-chemical criteria used are density, flash point, oxidation stability, and acid value. Again, this research shows no direct connection to the controversies around bioenergy and makes no attempt to solve them with their research. Elaborating on the research done in bioenergy feedstocks, the study of (von Doderer & Kleynhans, 2014) assessed the sustainability of several lignocellulosic bioenergy feedstocks. Here, a case study for South-Africa is performed to see what effects electricity generation from lignocellulosic biomass has on the environment. It makes uses of several quantifying methods, such as LCA (life cycle assessment), GIS (geographic information systems), MPB (multi-period budgeting), etc. With the help of a MCDA it prioritizes the lignocellulosic feedstocks. The criteria were categorised in three groups: financial-economic, socio-economic, and environmental. Due to the incorporation of social acceptance, it is most likely that the controversies are to some extent incorporated in the sustainability assessment of (von Doderer & Kleynhans, 2014). It aims to assess sustainability and therefore indirectly contributes to resolving the bioenergy debate, because that aspect is often questioned. However, it can be concluded that again no direct link can be made between (von Doderer & Kleynhans, 2014) and the controversies.

Other rankings for bioenergy related aspects have been done in order to choose a most suitable or sustainable processing technology/production process. For example, the research of (Vannarath & Thalla, 2019) uses a MCDA to select a pretreatment method for the conversion of lignocellulosic biomass to biogas that will result in the highest gas yield. In order to see what bioenergy heating system is most suitable and sustainable, a sustainability assessment and MCDA methodologies were used by (Martín-Gamboa et al., 2019). Here, a combination of feedstock and technology ranking was performed. There are both social and economic aspects considered which indicates that some degree of the controversies are included. This means that although both studies again aim to ensure sustainable implementation of bioenergy, no direct links to the controversies are present and no bioenergy specific problems are aimed to be solved.

Several studies exists that optimize the bioenergy production processes or parts of it. This, for example, can be found in the studies of (W. Y. Liu, Lin, & Yeh, 2017; Castillo-Villar, Eksioglu, & Taherkhorsandi, 2017). Optimization is of great importance because it will result in the most efficient production process and system. An optimized system can have positive effects on the sustainability of it and has the potential to control negative impacts it might have. Looking from a bioenergy perspective, controversies can be partly solved by optimizing activities. For the example studies given above, however, the controversies are not taken into account specifically and no direct solutions for the debate are given.

It is seen that using MCDA tools for the assessment of bioenergy is widely applied and frequently used to evaluate or improve the sustainability of bioenergy production, or parts of it. Many studies focus on the optimization of processing technologies, increasing sustainability or perform MCDAs in order to make a ranking based on sustainability and/or efficiency. Although this is important for further development of bioenergy, it is not directly connected to the controversies and in that way, they are not resolving these issues. Some researches do take into account the controversies, however not directly or not as a means to indicate less controversial technique/feedstock/process. Also, no research was found that specifically focuses on resolving the bioenergy debate or its controversies.

So, it is seen that most of the feedstock rankings performed recently are mainly focused on performance, physio-chemical and technological characteristics. Rankings to determine which feedstock gives bioenergy with the highest degree of sustainability were also observed. No research has done feedstock rankings to determine a least controversial feedstock. Therefore, due to the choice of using the controversies as criteria for the feedstock ranking, this study is a new aspect and therefore an addition to the already existing literature.

3 Bioenergy Use Today

Biomass can be converted into a range of different energy carriers, ranging from electricity to liquid fuels and everything in between. The diverse nature of bioenergy makes it widely applicable in almost every sub-section of the energy sector. To understand the global role of bioenergy today, the recent and past developments of this energy source are considered.
In this chapter, first the distinction between modern and traditional bioenergy is made so to understand their differences. Second, the production and use of bioenergy over the years 2018 and 2019 are presented in section 3.2. This is followed by a short overview of the development of bioenergy in the years before 2018 (section 3.3). The development patterns and use of bioenergy that are presented in this chapter were extracted from the reports of REN21, IRENA, IEA, and World Bioenergy Association by performing a literature analysis.

3.1 Traditional and Modern Bioenergy

Traditional bioenergy is the use of biomass for fueling wood and cooking stoves with low efficiencies. Developing countries are the primary users of traditional bioenergy. This type of bioenergy produces heat. Modern bioenergy is produced using modern processing technologies to convert biomass into energy. Using such technologies results in more efficient production and results in fewer emissions than traditional bioenergy. Modern biomass processing results in energy in the form of liquid biofuels, biogas, wood pellets, bio-electricity, and more (World Bioenergy Association, 2019; REN21, 2020). The importance of this difference is that traditional bioenergy is not necessarily sustainable nor renewable. Nevertheless, it also classifies as renewable energy. Not all research papers make a clear distinction between the bioenergy types. The sustainability of traditional bioenergy is low, and today exceeds the use of modern bioenergy. Because of this, the share allocated to bioenergy of the total renewable energy produced worldwide is wrong. Figure 1 shows the share of modern bioenergy in the global energy supply.

3.2 Bioenergy of the Recent Years

Bioenergy production of the recent years (2018 and 2019) is summarized in this section. First, the overall trends are given, followed by some more detailed information per industry or energy type.

Figure 1 visualizes the use of bioenergy in different sectors. In 2018 the modern bioenergy use was 5.1% (19.3 EJ) of the total final energy consumption (TFEC) globally. With respect to world wide use of renewable energy the share of bioenergy was about 50%. Modern bioenergy was mostly used in the form of heat (72 % of the total bioenergy TFEC), about 20% of the total bioenergy supplied was used in the transport sector, and about 8% in the power sector (REN21, 2020). Growth of modern bioenergy was mainly observed in the electricity sector (6.7 %/yr), followed by modern bioenergy in the transport sector (4.4 %/yr), and the smallest growth rate was observed for bio-heat (1.1 %/yr).

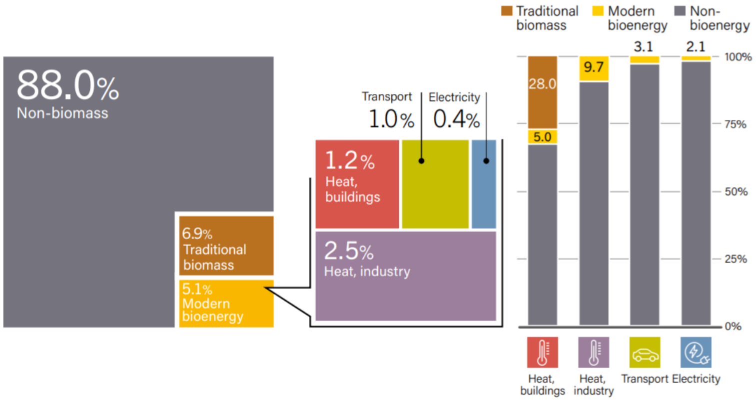

Figure 1: Overview of the division of the share of bioenergy in total final energy consumption. As well as for modern as for traditional and a more in depth per sector division of modern bioenergy for 2018 (REN21, 2020).

Bio-heat in Industry sector The use of Bio-heat in the industry and agricultural sectors increased with a 1.8 %/yr growth rate, which counted for 9.3% of the total heat demand in those sectors by End-Use. The growth over the years within this sector is visualized in Figure 2. The use of bioenergy in the industrial sector is mainly due to increased use in paper and board industry, sugar and other food industry, and wood industry. They use their own production of organic residues to generate energy (REN21, 2020).

Bio-heat in Residential & Commercial sector Of the total global heat demand in the buildings sector, 4.6% was supplied by modern bioenergy in 2018 by End-Use. The amount of bioenergy in this sector has been declining since 2013. A large share of bioenergy results from traditional bioenergy use. The emergence of new technologies and national regulations for traditional bioenergy use resulted in a trigger to reduce consumption of traditional bioenergy and slowly shift to the consumption of modern bioenergy in residential and commercial buildings. The use of bio-heat per sector is shown in Figure 2. The main producer of modern bioenergy in the residential and commercial sector for the year 2018 was the EU. It accounted for 47% of the global modern bio-heat production. The EU is mainly producing this heat by processing wood or wood residues. The use of wood pellets increased fast: a 5% increase was observed in 2018. This growth is promoted by policy measures in the EU that encourage the use of of low carbon emitting technologies in the heat industry (REN21, 2020).

The bio-heat in the residential and commercial sector as described above concerned the direct use of bio-heat. Bio-heat in the district heating system accounted for 0.7 EJ of total demand in 2018 of which 51% was reserved for industry and agricultural sectors. This bio-heat for district heating was 95% of the renewable energy used for these sectors in 2018. This was again centered in the EU (REN21, 2020).

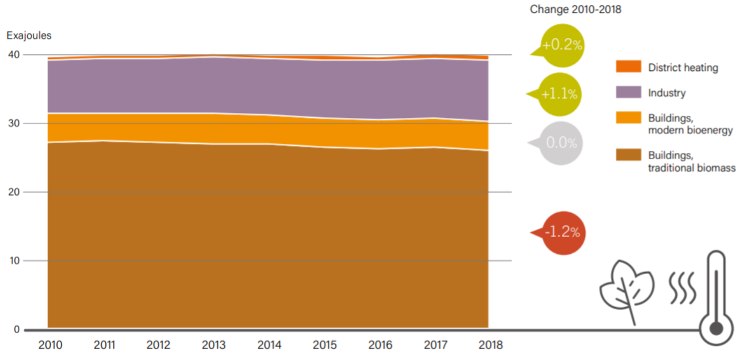

Figure 2: Division of the global use of bioenergy in the form of heat (by End-Use) in different sectors from 2010 to 2018 (REN21, 2020).

Biofuels Implementation of direct use of renewable energy in the transport sector proved to be challenging. The transport sector mainly makes use of energy in the form of fuels. This means that the only renewable energy that can be directly used are biofuels. Therefore, biofuel accounted for about 22 million bbl/d (0.13 EJ/d) of the total primary energy demand for the transport sector in 2018. Supporting policies for the use of biofuels in the transport sector were found in 45 countries. This number did not increase in 2018 but it was seen that some countries reinforced the policies that were already in place (IEA, 2019).

The global production of liquid biofuels saw an increase of 5% in 2019 with respect to 2018 by global production of the fuels, see Figure 3. The leading country in biofuel production is the USA with a share of 41%. However the production in the USA is slightly declining now. Next in line are Brazil (26%), Indonesia (4.5%), then China and Germany (respectively 2.9% and 2.8%). From the several fuels that biomass can produce, ethanol and biodiesel are the most popular. There is active research and development in the production of advanced fuels from biomass that might substitute diesel, like HVO and HEFA. The division of the shares (by global production) is the following: ethanol accounts for 59%, biodiesel for 35% and HVO/HEFA for 6%. Although ethanol held the largest share of biofuels in 2019, the growth rate of ethanol is becoming significantly lower than that of biodiesel and HVO/HEFA (2% vs 13% and 12%) (REN21, 2020).

Biomethane is mainly produced for the transport sector in the EU and USA. In the USA, starting 2015, there has been an increasing amount of methane in the transport sector. In the EU, biomethane use increased by about 20% or 8.2 PJ (by global production) in 2018 (REN21, 2020).

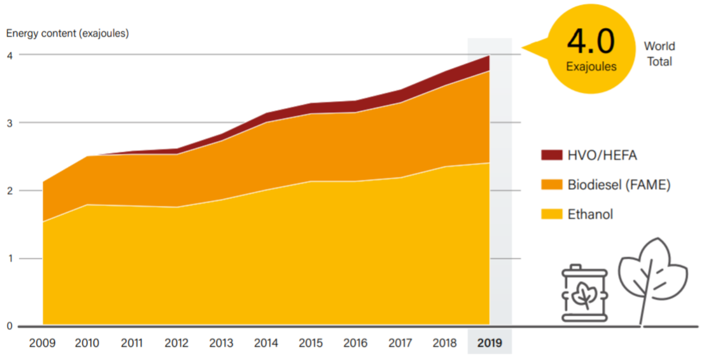

Figure 3: Division of the global production of bioenergy in the form of the different fuels from 2009 to 2019 by energy content (REN21, 2020).

Bio-electricity The amount of electricity generated from biomass worldwide increased by 9% between 2018 and 2019 (591 TWh of bio-electricity generated in 2019). The increase in production over the years is visualized in Figure 4. Asia held the highest share (17% of the world total bio-electricity production), followed by the EU (5% of the world total bio-electricity). The largest growth rates, however, occured in the EU and Asia (mainly China, Japan, Republic of Korea). North America showed a negative growth rate of 2%. The increased production in the EU is driven by a need to reach the goals of the Renewable Energy Directive, resulting in a total bio-electricity generation growth of 5% (or 200 TWh). The decrease of bio-electricity in the USA is due to the absence of policies to promote the use of low-carbon electricity sources and strong competition with cheaper electricity producers (REN21, 2020).

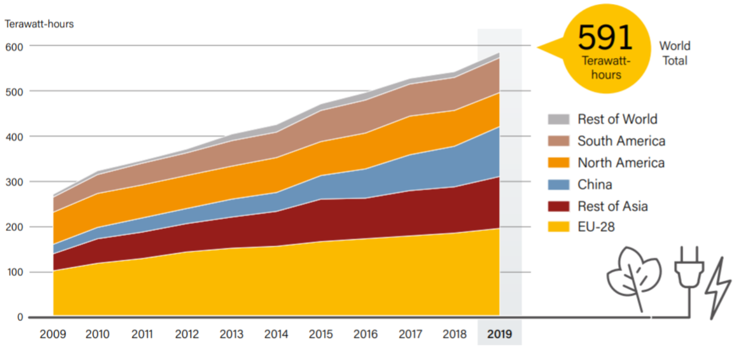

Figure 4: World wide production of bio-electricity and the shares per regions for 2009-2019 (REN21, 2020).

3.3 Bioenergy Use in the Past Years

This section describes the role of bioenergy in the past years. The application and growth for several types of bioenergy in different sectors from 2010 to 2017 is given. This will provide insights into the development patterns of bioenergy.

In 2010 bioenergy was used for heat production within the sector of residential and commercial buildings (consuming 62% of total bioenergy amount). This increased to 96% in 2017 (40 EJ), which is slightly lower than in 2015 (41.8 EJ) (IRENA, n.d.; IEA, 2019; World Bioenergy Association, 2018). Overall, it can be stated that over the past years, bioenergy is mainly used in the form of heat for the residential and commercial sector.

The share of biofuels in the transport sector increased from 2.7% (in 2010) to 3% in 2017 (55.6 EJ by End-Use). The major biofuels produced were bioethanol and biodiesel, where bioethanol held the larger share (about 65% of total biofuels produced in 2015). The Americas were by far the main producers of biofuels, followed by the continent of Europe and Asia (IRENA, n.d.; World Bioenergy Association, 2018, 2019).

Europe, USA and China accounted for 90% of the total amount of biogas produced (world total was 1.26 EJ). The larger share of biogas was used for electricity production in 2017, followed by biogas use in the residential and commercial sector. A small part was upgraded to biomethane for the gas network systems. The remainder was reserved for the direct use as transportation fuel in the transport sector (IEA, 2019).

Europe, Japan and USA are the leaders in bio-electricity production, but development and increased implementation of bio-electricity was happening in developing countries. The use of municipal solid waste (MSW) as a feedstock for electricity generation increased with 6% over the past decade and resulted in a total amount of 596 TWh bio-electricity in 2017 (IRENA, n.d.; World Bioenergy Association, 2019).

3.4 Conclusion

This chapter aimed to identify the role bioenergy had in the past decade. By performing a literature analysis of reports from institutions like the IEA and REN21, the use and development trends of bioenergy were found. From this it can be concluded that the role of bioenergy became more significant over the years. Bioenergy is responsible for more than half of the sustainable energy produced. The main form of energy is heat (more than 50% of total modern bioenergy consumed) and this heat is mainly supplied to the industry and residential and commercial sectors. However, the research and development is shifting its focus to the production of modern bioenergy. Due to this shift, the largest growth was observed in bio-electricity (6.7% by TFEC in 2018) and the transport sector (5% increase in 2019 of the global biofuel production). In the past years, traditional bioenergy made up a large part of the bioenergy produced. This share is phased out and replaced by modern bioenergy. Due to slower development and more complex implementation of modern bioenergy, a reduction in traditional bioenergy cannot be as easily compensated for by modern bioenergy which may result in some lower values of bioenergy use.

4 The Shared Socioeconomic Pathway Scenarios

A number of different scenarios are constructed to provide insights into what pathway to follow when an energy transition to a renewable-based system is required. These pathways present possible drivers and barriers that one might encounter with the implementation of sustainable technologies and policies. Within the scenarios, predictions for several aspects are made. Examples of these aspects are future energy mixes, the global trading market, sociological aspects, and many more. They can serve as a wake-up call, a warning, or as a guideline for policymaking to stimulate decarbonization of any sector. The scenarios are not necessarily based on reality and are often idealized versions of the future. This indicates that during the construction of scenarios, assumptions have been made about several factors and this effects the reality and reliability of the scenarios. Integrated assessment models (IAMs) generate the outcome of a future scenario. Often two or more different IAMs work together to produce results. In section 4.3 more information about IAMs is given.

To understand the future role of bioenergy on the global level, the Shared Socioeconomic Pathway scenarios (SSPs) in combination with Representative Concentration Pathways (RCPs) are analyzed for bioenergy use. The reason why the SSPs are chosen for this scenario analysis is that they represent five different pathways for societal development (as will be explained in the next sections). This allows for insight into the development and future use of bioenergy with five different underlying assumptions and five different pathways to sustainability. Besides, they represent important scenarios for the IPCC. This organisation used the SSP scenarios for the special report 1.5°C (IPCC, 2015). Because the IPCC values these scenarios and used them in their work, they have a certain degree of importance.

First, the concept of the SSP is explained, followed by the different narratives for each SSP which can be found in section 4.1. Then, section 4.2 explains the framework of the RCPs, and the two different RCPs used for the analysis are given in detail. Lastly, section 4.3 explains the working of IAMs, the IAMs used with the SSP scenarios, and how the different IAMs define bioenergy and which assumptions they make for bioenergy. The literature was found using the search engine of TU Delft online library, ScienceDirect, and GoogleScholar. The literature was found by using search terms like Shared Socioeconomic Pathway scenarios, SSP1/2/3/4/5 narrative, SSP scenario analysis, Integrated Assessment Models, The IAM X (where X is one of the six IAM discussed in this chapter), and The Representative Concentration Pathways.

4.1 The Shared Socioeconomic Pathways

The Shared Socioeconomic Pathways include five different possibilities for development of society in the future. They represent pathways for development of society and its ability to adapt and mitigate climate change. Each SSP represents a different possible development of society: it ranges from a focus on green growth to still largely fossil fueled in the future and all in between. They are without concerns about climate shifts and global warming and try to indicate patterns of development of socio-economic aspects. Although they do not incorporate specific concerns of global warming, they show how one of the five pathways can reach climate goals. The differences in view can be seen in figure 5. The main goal of the SSP scenarios is to show possible outcomes for choices made in each pathway. Each pathway has different underlying ideas and views, and analyzing the results gives insight into how they develop in the future and what might be a result of them. Therefore, the scenarios help to clarify and quantify some uncertainties in societal futures (Fricko et al., 2017; O'Neill et al., 2017).

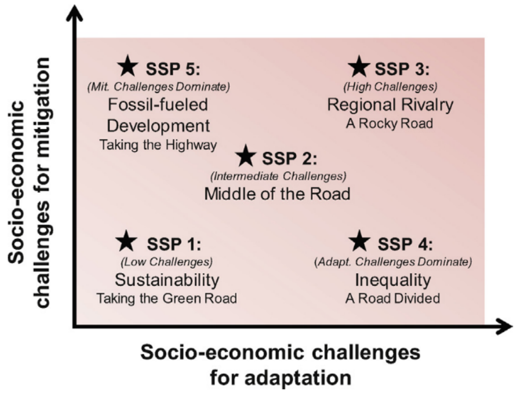

Figure 5: The five Shared Socioeconomic Pathways and their degree of challenges for adaptation and mitigation to climate change (O'Neill et al., 2017).

In the following subsections the five different SSPs are described by their vision and main assumptions.

4.1.1 SSP1

The SSP1 scenario has the main focus on sustainability. Within this scenario, the goal is "to take the green road". The changes are not drastic but gradual and the main goal is to move forward. However, at all times it should be done by respecting natural boundaries of earth. Extra attention is paid to include environmental degradation as a result of human actions and societal and cultural activities.

Another aspect, is that there exists good global and national cooperation. This results in a stimulating environment for technological development where investments are centered towards green technologies. Cooperation is not only worldwide, but also found in the private sector and civil society. The collaborative nature and focus on sustainable development results in a reduction of inequality within society, improved environmental well-being, and a strong increase in renewable energy systems. Economic growth is no longer paired with an increase in material, resource, and energy use. Due to the orientation towards low material growth and requirement that technologies and products should have a low environmental impact. This effect is enlarged as a result of a strong decrease in population growth (O'Neill et al., 2017).

SSP1 results in low mitigation and adaptation towards climate change (O'Neill et al., 2017). The role of bioenergy is in the form of modern bioenergy. Bioenergy combined with CCS is not in great need (Bauer et al., 2017).

4.1.2 SSP2

The SSP2 scenario represents the "The-Middle-of-the-Road" scenario. This scenario is following historical development trends. This means that societal and economic growth continues to be spread unevenly on a global and regional level. Historical trends do not continue in this scenario, but it uses the knowledge gained from previous development patterns. However, the future development is according to a middle-of-the-road pathway (Fricko et al., 2017).

Although a stable global political situation, the world trade market behaves imperfectly. There is a focus on development in sustainable energy and technologies to meet the climate goals. The progress of this is, however, slow. The primary goal of this scenario is not technological development. However, successes are observed, but no large breakthroughs are happening. Overall, some decline in resource use is present but is not enough to prevent degradation and depletion of the environment. Aversion towards fossil resources cannot be observed, but that does not avert a reduction in the use of fossil fuel dependency. Population growth is still positive, but the growth rate does decline (O'Neill et al., 2017).

A stable society is achieved and this hampers development and investments in green technologies. This results in medium challenges regarding mitigation and adaptation to climate change (O'Neill et al., 2017). SSP2 requires no large scale use of BECCs in its narrative. This is mainly because part of the carbon emissions is compensated with afforestation (Bauer et al., 2017).

4.1.3 SSP3

This scenario represents "A Rocky Road" scenario. The resurrection of nationalism characterizes this scenario. There is a disruption in peace due to concerns about competitiveness and overall security. Conflicts on a regional level are happening, and solving them is the main focus on a domestic and national level. The lack of global cooperation is enforcing this behavior. This all results in the establishment of policies that focus on national security rather than on worldwide trade. Therefore, it creates a barrier to global markets for agriculture and energy resources. No global cooperation exists that can tackle energy and food security issues, and there is a decrease in investment in matters such as technological development and education (O'Neill et al., 2017).

Consumption patterns are material-intensive and societal inequality and stratification worsens. The issues that arise from this contribute to the lack of urgency to address environmental issues. This leads to environmental degradation. Together with slow development, it all results in little to no sustainable progress in any sector (O'Neill et al., 2017).

Besides the problems mentioned above, a large difference in population growth is present. There exists strong population growth in the developing countries, and it is slow in the industrialized ones. This all results in high challenges regarding both mitigation and adaptation to climate change (O'Neill et al., 2017).

Due to the large income differences, not everyone can switch to cleaner energy sources. This means that continued reliability to conventional fuels is maintained, and therefore traditional bioenergy is still used. Not only is the usage of traditional bioenergy continued, but it also increases due to the increase in population in developing countries (Fricko et al., 2017).

4.1.4 SSP4

This scenario represents "A Road Divided". Within this scenario, inequality and societal division still exist and increases over time. This can be explained by increased separation, on an educational and economic basis between the highly educated (who have higher income) and low educated (who have lower income) regions worldwide. This all results in a rising tension within the society and the unity destabilizes. Little investment in alternative resources is present in the larger part of the world. Nevertheless, the energy system starts to show a mix of conventional energy sources and low-carbon sources.

On the one hand, there does exist some degree of development in sustainable energy sources, and education is high in several regions. On the other hand, the world is not globally connected. This results in small challenges to mitigation to climate change. Adaptation challenges, however, are high. A large share of the population is in the low-income region, together with increasing inequality within society does not stimulate the implementation of adaptation measures (O'Neill et al., 2017).

In SSP4, as already mentioned, inequality of income is still present. This gives rise to the continued use of traditional bioenergy for low-income regions. However, since the upper class is highly educated, technological development does happen, and therefore modern bioenergy plays a significant role. To offset carbon emissions bioenergy is combined with CCS, meaning that BECCS and traditional bioenergy are incorporated into the energy system for SSP4. A note to this is that the type of energy preferred from BECCS is fuel and not electricity (Bauer et al., 2017).

4.1.5 SSP5

The SSP5 represents the "Fossil-Fueled Development - Taking the Highway" scenario. For this scenario industrialization of the economy continues. Competitive markets are stimulated together with innovation.

Using the competitiveness and eagerness to innovate, rapid technological development is the key to sustainable development. The global market is of great importance. That means that effort is made to maintain competition and to remove possible barriers to trade so that all income groups can participate. Besides, means are spent to ensure coalescence of the global market. The push for an increase in human capital is made with an increase in fossil fuel use, together with an increase in resource and energy use. The narrative of SSP5 believes that social and ecological systems can be engineered and technological applications can tackle environmental issues. A strong increase in population is expected and stimulated by the positive outlook on the growing economy. SSP5 results in large mitigation challenges and small challenges to adaptation (O'Neill et al., 2017).

The need for technologies to reduce carbon emissions together with the increased energy demand - due to an increasing population - results in high demand for bioenergy (mainly biofuels). To further reduce the carbon emissions in the energy sector, BECCS is incorporated on a large scale in the energy mix (Bauer et al., 2017).

4.2 The Representative Concentration Pathways

The Representative Concentration Pathways (RCPs) describe, like the SSPs, possible pathways for the future until 2100. The RCPs focus mainly on GHG emissions and the resulting concentrations in the atmosphere, but they also include other polluting emissions and land-use (Pachauri & Meyer, 2015).

The RCPs do not represent new scenarios but are used to project certain developments in the future regarding the different components of radiative forcing. They can be used together with other climate or scenario models, such as the SSPs. The RCPs do not include direct effects on land use, policy, do not predict environmental boundaries, and thus do not project policy outcomes. Therefore, the RCP framework maps out a broad climate space.

There originally exists four different RCPs (2.6 W/m^2, 4.5 W/m^2, 6.0 W/m^2, and 8.5 W/m^2). The different RCPs are all unique. For this report, the RCPs considered are the ones that are in line with the limitation of global warming to 1.5 °C (van Vuuren et al., 2011).

When one combines RCPs with the SSPs, it creates scenarios that take emission pathways, atmospheric concentrations, and socio-economic factors into consideration. To form a matrix of climate forcing outcomes (RCPs) as the rows and socio-economic inputs (SSPs) as the columns, for good analysis overview, an arrangement of the frameworks of the RCPs and SSPs is necessary (Climate Scenarios, n.d.). The power of these scenarios is the identification of effects of climate policies and strategies for several aspects. These can be analyzed by comparison with the baseline scenarios, in which no climate policies and mitigation pathways are applied (Bauer et al., 2017). It can, in the end, help to ease the transition to a more sustainable society, and fewer challenges for adaptation and mitigation are expected.

Now that the idea behind the representative pathways is known, the two RCPs that will be combined with the SSPs for the scenario analysis will be explained. For this research, it is of interest to see the global bioenergy use in the future when the aim is to have maximum global warming of 1.5°C. Therefore, the RCPs of significance are 1.9 W/m^2 and 2.6 W/m^2.

4.2.1 RCP 1.9

The forcing target of 1.9 W/m^2 is not one of the four original developed RCPs. One of the conclusions from the Paris Agreement was that an additional concentration pathway was needed because none of them showed global warming limitation of 1.5°C or below. That is why they came up with RCP 1.9, which is an addition to the already existing RCPs. This pathway is characterized by a strong reduction in emissions over time and indicates little to no overshoot of the 1.5°C (Climate Scenarios, n.d.; IPCC, 2019).

4.2.2 RCP 2.6

This RCP indicates a forcing target of 2.6 W/m^2, and is also called 'Stringent Mitigation Scenario' (IPCC, 2015). This scenario, or forcing pathway, is defined as the 'Peak and Decline' pathway. This means that in the first half (the years 2000 to 2050) of the century, there exists an increase of radiative forcing and the GHG emissions concentration in the atmosphere, and the second half (2050-2100) a decline. The peak is to be at 3 W/m^2, and after it reaches this highest level the radiative forcing starts to decline towards 2.6 W/m^2. This pathway characterizes itself further by being a low greenhouse gas concentration pathway. A key factor for reaching the low GHG emissions concentration is that a reduction of the emissions over time will occur. This RCP will likely limit global warming below 2°C above industrial level around 2050 (Pachauri & Meyer, 2015).

4.3 Integrated Assessment Models

Integrated Assessment Models (IAMs) are designed to show the feasibility of implemented technologies and socioeconomic actions for meeting climate goals. They integrate different models, each specializing in a specific climate-related aspect, like an energy system technology model and a climate change model. The main limitation of the IAMs is that they cannot include rapid diffusion and development of technologies because the IAMs are designed to represent gradual changes in the systems (Hare, Brecha, & Schaeffer, 2018).

Within the IAMs, bioenergy is included but is seen as the main uncertainty. This uncertainty lies in the potential of bioenergy. A wide range of the potential exists and changes per research. Additional uncertainty exists about the land area available for the production of sustainable biomass within IAMs. This factor is of great importance for scenarios with strong population growth. Each IAM differs to some extent to another resulting in variation of bioenergy consideration. Because of these uncertainties for bioenergy, the results generated using IAMs do not give accurate conclusions for bioenergy use (Hare et al., 2018). Also, since most of the results generated by IAMs are based on many assumptions and often idealized situations, it should never be considered as the truth but just as guidelines.

The IAMs identify bioenergy in several forms: as a source for electricity production, in the form of biogas, and as a source to produce hydrogen. For the IAMs, bioenergy and the bioenergy technologies are seen as a tool to help to decarbonize the energy sector. IAMs also include BECCS, and depending on the type of energy produced from biomass, IAMs assume different capture rates for the CCS. A lower capture rate gets assigned to biofuel production than to the production of electricity and hydrogen. The way the IAMs decided to what extent bioenergy is incorporated is mainly from economic viewpoints. In other words, the cost of including any form of bioenergy should not exceed the carbon budget for a long-term climate goal. Bioenergy exists in many forms, and thus its implementation is diverse. Most of the time, high BECCS capture rates are favored if the amount of bioenergy used is small. If the amount of bioenergy is high, biofuels are often considered due to their capability to replace fossil fuels in the transport sector. If the technology for CO_2 capture is not available, the role of bioenergy in the energy sector remains unchanged or increases because bioenergy exists in many forms. It also means that when no BECCS is available, little to no change is observed for land-use impact and competition with food production, water, etc. (IPCC, 2019). The primary used feedstock in IAMs are from the second generation feedstock type. The assumptions for bioenergy land-use depends on the land-use models in the IAMs. In addition, it also depends on assumptions made for socioeconomic drivers, crop yield, agricultural technologies, efficiency, food demand, biodiversity, and carbon policies (IPCC, 2019).

The SSPs are modeled using IAMs. The scenarios use six different IAMs. The IAMs used to model the SSPs integrate economy, energy, land-use, and climate. This covers all GHGs and air pollutants (Bauer et al., 2017). Every SSP scenario has a specific marker IAM. The marker models are the models of which the underlying assumptions best match the story of the shared socioeconomic pathway (Bauer et al., 2017; Riahi et al., 2017). Although the markers are seen as the best representation of the SSP narrative, they do not represent an average or median estimate. It is, therefore, necessary to also run the SSPs in the non-marker IAMs to see the effect of different underlying assumptions on the outcomes of the scenarios (Riahi et al., 2017).

4.3.1 IMAGE

The integrated models for IMAGE describe the change of the global environment. It includes air pollution change, climate change, and land-use change (Scott, 2015). The model includes 26 worldwide regions and is mainly designed to allow the analysis of long-term and large-scale relations between human development and the environment. It allows for the formation of plans to overcome specific environmental changes and damages so that mitigation and adaptation to climate change are eased (van Vuuren et al., 2017).

IMAGE describes energy by demand, production, emissions, and air pollutants for primary and secondary energy. The model characterizes further by the description of land-use. It describes the emissions and effects of climate change from agricultural activities and what effects these activities may have on the natural vegetation. Land-use change can be calculated by taking into account several aspects that can result in land-use change and agricultural behavior (like bioenergy, food production for humans and cattle, grassland, etc.). The model is also able to estimate the productivity of the crops in the future. It uses this information for the allocation of cropland for several types of crops (Scott, 2015). The IMAGE IAM is the marker for the SSP1 scenario.

4.3.2 MESSAGE-GLOBIOM

The Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) is used for medium to long term planning of energy systems and policy analysis. It gives information about the use of domestic resources, energy flows (imports and exports), monetary flows from trade, investment requirements, selected technologies for conversion and production, emissions, and development pathways of primary, secondary and final energy. Emissions coming from agriculture are also quantified, which allows projections of climate change-induced by land-use. The economy is represented by the linkage of the MESSAGE model to the MACRO model. This model uses available labor, capital stock, and energy inputs as variables to determine the economy and its total output.

The MESSAGE model is complemented by the Global Biosphere Management Model (GLOBIOM). It represents land-use activities, and this also includes the bioenergy sector. The model bases the two-sided trade on cost competitiveness. GLOBIOM is often used for mitigation policies for land-use, biofuels, and agricultural markets (Scott, 2015). In this IAM, bioenergy is a renewable energy source with good potential, and it includes both bioenergy types (Fricko et al., 2017).
The MESSAGE-GLOBIOM model is the marker for SSP2.

4.3.3 AIM/GCE

AIM/GCE is short for Asia-Pacific Integrated assessment Model/Computable General Equilibrium. It is a dynamic general equilibrium model that covers the whole world. The model builds up out of three main models: an emission model (AIM/emission), a global climate change model (AIM/climate), and a climate change impact model (AIM/impact). The purpose of this model is to help assess different policy options that must guide smooth adaptation and mitigation for climate change and lower emissions of GHGs. The climate model is linked so that climate change and environmental impacts are quantified. The emissions resulting from the energy sector are assumed to be a result of fossil fuel use. The remaining emissions are considered to be the result of land-use changes and other industrial processes (Scott, 2015).

Bioenergy and land-use competition are dealt with by the vision that the agriculture sector and land-use are seen as important (Scott, 2015). The AIM/GCE model is the marker for SSP3.

4.3.4 GCAM

GCAM is short for the Global Change Assessment Model. It is a model that emphasizes human-earth systems. Those human-earth systems include interactions between world economic, energy, agriculture, land-use, and the technology system. Hector, an open-source coupled cycle-climate model, represents the climate and environment in the GCAM model (Scott, 2015). The energy sectors considered in this model are buildings, industry, and transport. One of the limiting factors of production is resource availability. Therefore, the model includes to some extend environmental boundaries (Scott, 2015).

The model treats bioenergy as a renewable energy source and sees it as a product of the agricultural sector. This, therefore, means that bioenergy is part of the Agricultural and land-use model (Scott, 2015). GCAM is the marker for SSP4.

4.3.5 REMIND-MAgPIE

The REMIND-MAgPIE model is a coupled IAM of the REMIND and MAgPIE models. REMIND is short for the Regionalized Model of Investment and Technological Development and is a globally integrated assessment model. REMIND consists of two models: top-down macroeconomic growth model and one climate model. The model not only includes a wide range of sustainable energy sources but does also incorporate fossil fuel use (Scott, 2015).

The other half of this IAM is the MAgPIE model. MAgPIE is short for the Model of Agricultural production and its Impacts on the Environment. The inputs are explicit biophysical ones. For example, this can be land, agricultural output, or the presence of water. The MAgPIE model aims to meet agricultural demand. This demand consists of food, feed, energy from biomass, agricultural materials, and seeds. With the help of technologies and methods that result in the lowest overall costs, the aim can be achieved (Kriegler et al., 2017). Therefore, this model gives insight into the intensification of land-use, the required land-use change, and relocation of production facilities (Scott, 2015). The two models are linked by the exchange of information on the price and quantity of the emissions of GHGs and bioenergy.

For this combined model, modern bioenergy production is incorporated, leaving traditional bioenergy out of the picture. Biomass processing to produce energy is combined with CCS (Scott, 2015; Bauer et al., 2017). This model is the marker for SSP5.

4.3.6 WITCH-GLOBIOM

WITCH is short for World Induced Technical Change Hybrid, and the model includes a medium representation of the energy sector. WITCH analyses policy settings and represents technological change. The model is global, grouping the world in 13 regions. It assumes that perfect foresight exists up until the end of the century (2100). This IAM quantifies technological change and development, with a focus on the development of energy technologies. It has several assumptions for future development and the effort that countries put into the innovation of energy technologies. WITCH places additional emphasis on the development and incorporation of energy technologies with little carbon emissions. The model links to the GLOBIOM model, and in that way, bioenergy is considered (Scott, 2015). This model does not function as a marker for one of the SSPs but is nevertheless used to model SSP scenarios.

5 Shared Socioeconomic Pathway Scenario Analysis

In this chapter, scenario analysis for bioenergy use in the five SSPs coupled with RCP 1.9 and 2.6 from 2020 to 2050 is performed. The SSPs and RCPs give insights into many aspects of the energy transition. However, the scope of this analysis is limited to bioenergy only. To see the bioenergy use in medium-term, the time scale is set to range from 2020 to 2050. One must know, the scenario analyses in sections 5.2 and 5.3 aim to identify if bioenergy plays a role in the future energy system. It is therefore not aimed to explain the differences in bioenergy use between the different SSPs. This scenario analysis used the 'IAMC 1.5°C Scenario Explorer' which is a property of the IIASA. It is a database of climate change mitigation pathways for global warming of 1.5°C, and the IPCC special report 1.5 supports this database. To visualize the predicted pathway for global bioenergy per SSP, plots were made using data obtained from the scenario analysis. The time scale applied was 2020 to 2050.

First, the SR 1.5 of the IPCC is analyzed for the SSPs scenarios (see section 5.1). Section 5.2 gives the results per SSP for every IAM model. Lastly, an analysis is done for the total final bioenergy for the SSPs with RCP 1.9 and 2.6 in their marker models and this can be found in section 5.3.

5.1 Bioenergy Prospects According to the IPCC SR1.5

Before a scenario analysis will be made, the future prospects of bioenergy according to the IPCC SR1.5 are considered. The IPCC is a panel that assesses the science related to climate change. Their main objective is to help the formation and development of climate policies by facilitating scientific information about climate change, climate impacts, future risks and provides options for mitigation and adaptation strategies. Because of this, when trying to identify the role of bioenergy in the future, it is important to consider what the IPCC has to say about the prospects of bioenergy.

In Figure 6 the primary energy supply and its changes over three time periods (2030, 2050, and 2100) for three of the SSP scenarios (SSP1, SSP2, and SSP5) are shown for the RCP of 1.9 W/m^2. From the figure, it becomes clear that, for all three scenarios, bioenergy plays a significant role in meeting energy demand in the future. It will be supplied in various types of energy like electricity or biofuels and various energy sub-sectors. Besides, for the scenarios where BECCS is applicable, the share of bioenergy use increases over the years as well. Both for high and for low overshoot, 1.5 °C and below 1.5 °C pathways, the growth factor of biomass contribution to the primary energy supply is 1.7% in the years between 2020-2050 (IPCC, 2019).

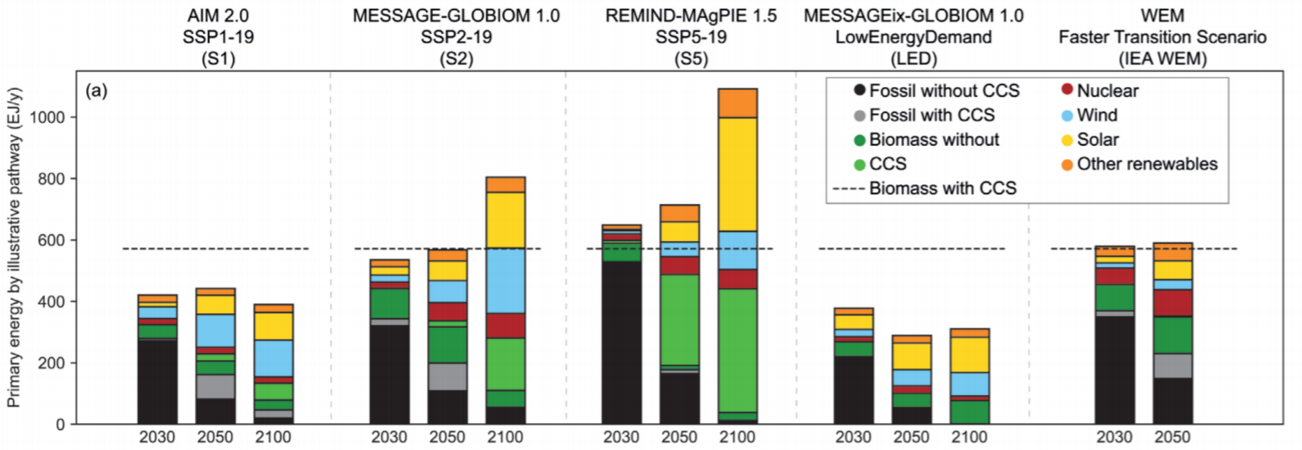

Figure 6: Primary energy supply (EJ/yr) division for different energy sources for SSP1, SSP2 and SSP5 for the years 2030, 2050, and 2100. (IPCC, 2019).

Electricity from biomass The contribution of bioenergy in the form of electricity will increase over the years together with other renewable sources like wind and solar. The global electricity generation from bioenergy shows growth between the years 2020 and 2050 with a factor of 6.4% (corresponding to a share of 8.8% in 2050) for below 1.5 °C and 1.5 °C with low overshoot pathways. This growth is 7.9% (corresponding to a share of 3.8% in 2050) for 1.5 °C with high overshoot pathways (IPCC, 2019).

Bioenergy in the End-Use Sectors One of the more intensive energy-using sectors is that of industry. The role of bioenergy in the decarbonization of this sector is diverse. As mentioned, bioenergy can also supply energy in the form of electricity, and in that way contribute to the decarbonization of the industry sector. A larger role for bioenergy, however, is observed to be in the form of biofuel and bio-heat. The industry consumes heat in large quantities. Today, fossil fuels mainly provide this heat. The primary energy form of bioenergy is in the form of heat. This heat allows supplying sustainable warmth to the industry. Biomass may function as a sustainable source for carbon and hydrogen for (chemical) production, and with this, it makes an additional contribution to the decarbonization of the industry (IPCC, 2019). The transport sector requires a reduction of 60% of CO_2 emissions to limit global warming. The IPCC indicates a share of biofuels in this sector of 36%. However, due to an observed increase in EV production and use, this share might decrease. The estimated amount for biofuel use in the transport sector is set to 24 EJ (by final consumption) in 2060. From this, 17% is allocated for light-duty vehicles (LDV), 35% for heavy-duty vehicles (HDV), 28% for aviation, and 21% for shipping. These transport modes are also known as difficult to decarbonize. Especially in short-term perspective, biofuels play a big role in the decarbonization of the transport sector (IPCC, 2019).

5.2 Analysis per SSP

This section presents the results of the scenario analysis for the different SSPs for all IAM models. The analysis includes the generation of two graphs per SSP. The first plots show the SSP for the different IAMs with RCP 1.9, and the second graph the SSP for the different IAMs with RCP 2.6. On the y-axis, the plot shows the total primary supply of bioenergy, and the x-axis represents the years. The region chosen is 'World', the data selected was 'Primary Energy— Bioenergy (Total)', and the time scale ranges from 2020 to 2050. There is no distinction made between the different types or forms of bioenergy. Each SSP scenario deals with bioenergy in its own way, as explained in the previous chapter. From Figures 7, 8, 9, 10, 11, and 12 a difference between the models or SSPs at the year 2010 is observed. This year is in the past, and thus the TPES and final energy values should be known and thus the same. That the figures show a difference in their values for 2010 is strange. It might be that the base year of this data base is even before 2010, and thus the values for 2010 are also predictions. However, the reason for it is out of scope for this research and will therefore not be explained. The SSP3 scenario did not give results for both RCP 1.9 and RCP 2.6. The database held no information for these scenarios.

SSP1 The REMIND-MAgPIE IAM did show the strongest increase and the highest TPES for RCP 1.9. This model focuses on agricultural yields, managing intensification, technological development, land-use change, and production relocation for the world. It does incorporate bioenergy conversion technologies with CCS, meaning that the model includes improvement of BECCS, and thus, over time, technology and its efficiency improve. This technology development will reduce costs. The way the model incorporates bioenergy creates an opportunity for strong growth of the primary supply of bioenergy. Use of bioenergy is considered because a reduction in carbon emissions is desired. On average, the increase for SSP1 with RCP 1.9 was 61 EJ over the years 2020 to 2050. All scenarios except for the MESSAGE-GLOBIOM and REMIND-MAgPIE did show an increase in TPES of bioenergy each year. For MESSAGE-GLOBIOM and REMIND-MAgPIE, bioenergy use dropped between 2020 and 2030. After 2030 its use increases again.

For RCP 2.6, differences concerning RCP 1.9 were observed. Firstly, the model with the highest TPES of bioenergy in 2050 was AIM/GCE. Secondly, the AIM/GCE model, now together with MESSAGE-GLOBIOM and REMIND-MAgPIE, did show a reduction in TPES bioenergy between 2020 and 2030. For the REMIND-MAgPIE model, the decrease continued to 2040. After 2040 it increased of similar magnitude as the other models.
The average increase in TPES of bioenergy over the years 2020 to 2050 was 29 EJ. This amount was significantly lower than that was observed for RCP 1.9. The higher maximum global warming temperature for RCP 2.6 explains the differences in bioenergy use between the two RCPs. For RCP 1.9, this temperature is lower than for RCP 2.6. Therefore more bioenergy might be needed to achieve this goal.

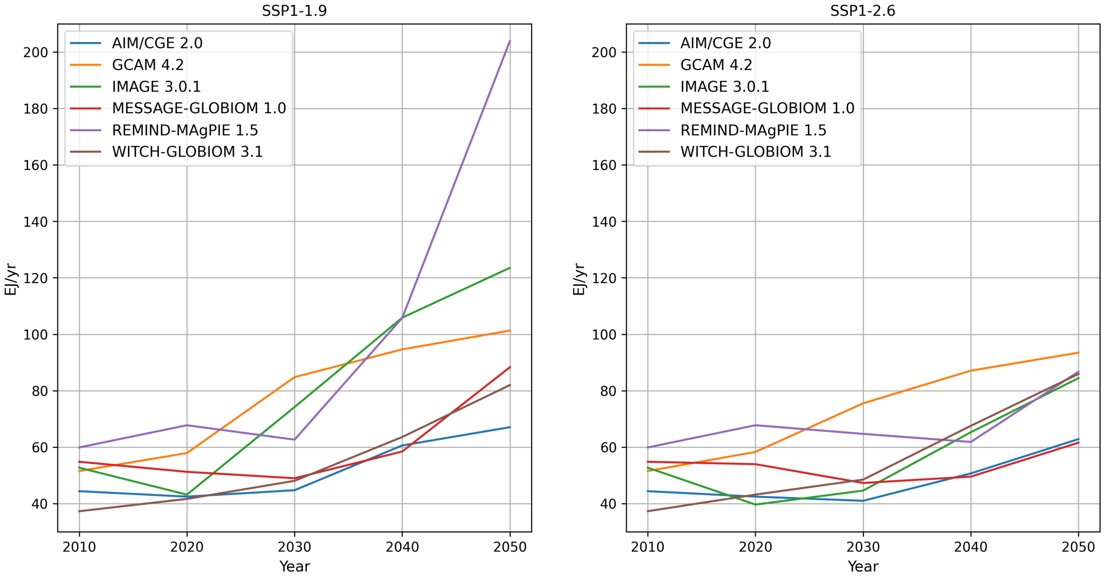

Figure 7: TPES of bioenergy for the SSP1 with RCP 1.9 (left) and RCP 2.6 (right) scenarios for the different IAM models. With on the y-axis the TPES (EJ/yr) and on the x-axis the decades of interest.

SSP2 SSP2-1.9 was not able to generate results for the models IMAGE and WITCH-GLOBIOM. For these models no data of TPES bioenergy was available. For the models that gave results, the REMIND-MAgPIE had the largest TPES in 2050, just like for SSP1-1.9. Every model did show an increase in bioenergy between all the years. The average overall increase in TPES of bioenergy between the years 2020 and 2050 was 75 EJ.

SSP2-2.6 was able to generate results for all six IAM models. This scenario has the largest TPES of bioenergy in 2050 when run using the GCAM model. The model REMIND-MAgPIE did show a decrease between the years 2020 and 2030, but after 2030 the TPES of bioenergy was increasing again. A reduction in use for the model IMAGE was observed between the years 2040 and 2050. All the other models showed a continuous increase in bioenergy use within the chosen time scope. The average overall increase in TPES of bioenergy between the years 2020 and 2050 was 63.5 EJ. This value was, like for the SSP1 scenario, lower than that for the RCP 1.9 case. Again, the difference in global warming targets might explain this difference.

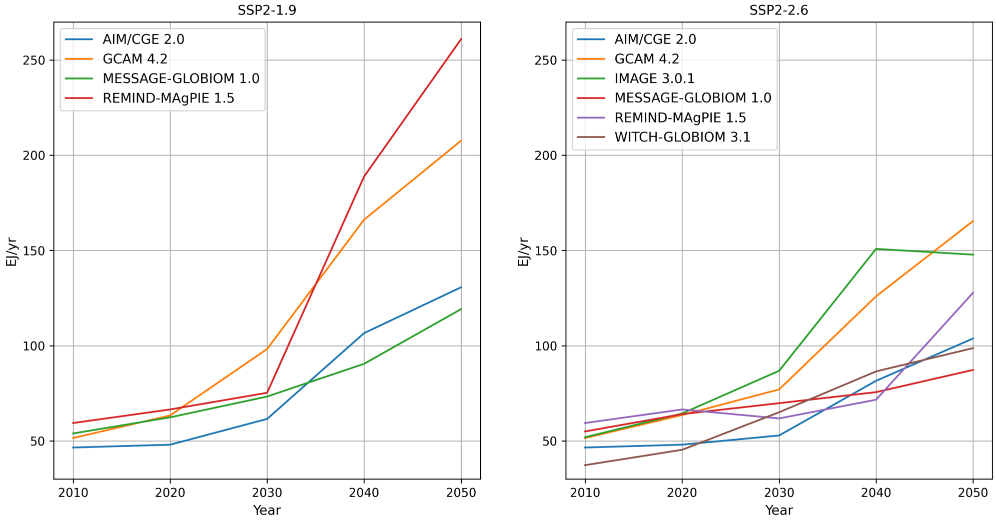

Figure 8: TPES of bioenergy for the SSP2 with RCP 1.9 (left) and RCP 2.6 (right) scenarios for the different IAM models. With on the y-axis the TPES (EJ/yr) and on the x-axis the decades of interest.

SSP4 WITCH-GLOBIOM was the only model that could produce results for SSP4-1.9. This model did show a constant increase of bioenergy TPES during the years 2020 to 2050. One observation is that specifically from 2040 to 2050, this increase was very strong. The overall increase for TPES of bioenergy between 2020 to 2050 was according to this scenario 43 EJ.

For the SSP4-2.6 scenario, the models AIM/GCE, GCAM, IMAGE, and WITCH-GLOBIOM were able to generate results. The IMAGE model gave the highest TPES in 2050 with 186 EJ/yr. No model showed a decrease in output after 2020. However, the IMAGE model declined in slope after 2040.
The average increase in TPES of bioenergy over the years 2020 to 2050 was 100 EJ.

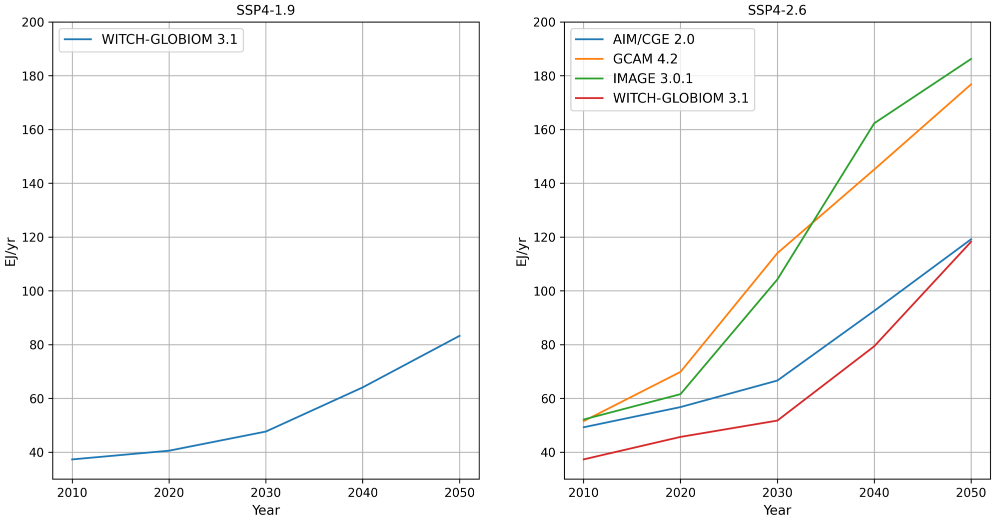

Figure 9: TPES of bioenergy for the SSP4 with RCP 1.9 (left) and RCP 2.6 (right) scenarios for the different IAM models. With on the y-axis the TPES (EJ/yr) and on the x-axis the decades of interest.

SSP5 For SSP5-1.9, the GCAM and REMIND-MAgPIE were able to produce results. From these two models, REMIND-MAgPIE gave the highest TPES of bioenergy for 2050 (310 EJ/yr). For this model, it was seen that after 2040 significant growth was observed. Although GCAM did show a continued increase in bioenergy supply, it did not make an as large increase after 2040 as the REMIND-MAgPIE model did. For GCAM, however, it was observed that the rate of growth decreased after 2040. The average increase of TPES of bioenergy for SSP5-19 between 2020 and 2050 was 191 EJ.

The models AIM/GCE, GCAM, and REMIND-MAgPIE gave results for the scenario SSP5-2.6. From these models, the largest bioenergy supply in 2050 came with the use of the AIM/GCE model. The model resulted in a TPES of 204 EJ/yr in 2050. The REMIND-MAgPIE did show a decrease in bioenergy supply between 2020 and 2030. After 2030, there was again an increase in supply. The other two models showed an increase in TPES every decade. However, for both models, the growth rate decreased significantly after 2040. The average increase for the TPES of bioenergy for SSP5-2.6 for 2020 to 2050 was 129 EJ.

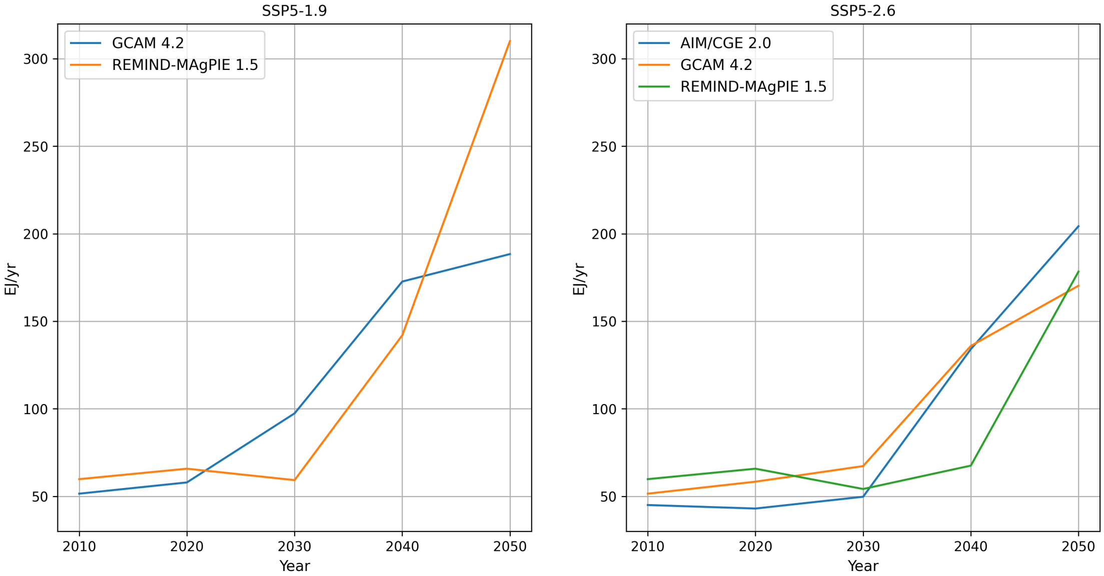

Figure 10: TPES of bioenergy for the SSP5 with RCP 1.9 (left) and RCP 2.6 (right) scenarios for the different IAM models. With on the y-axis the TPES (EJ/yr) and on the x-axis the decades of interest.

Summary This section aimed to see the development and use of the worldwide TPES of bioenergy over 2020 to 2050. This was done by producing plots for each SSP, coupled to either one of the RCPs, for the different IAMs. The IAMC 1.5°C scenario explorer generated the graphs. The settings for the scenario explorer were the following: the region chosen is "World", data selected was "Primary Energy Bioenergy (Total)", the range was 2020 to 2050, and the scenarios were the different SSP scenarios with RCP 1.9 and 2.6.

No attempt was made to understand the differences in bioenergy use between the SSPs and IAMs. The intend was purely to identify the future role of bioenergy, according to the five SSPs pathways. Differences in bioenergy use between the different SSPs can be observed. Each SSP has a different narrative which explains their differences in need for bioenergy. For example. SSP1 is a scenario that has low energy demand, also in the baseline, whereas SSP5 includes strongest growth of energy demand. It is therefore not unexpected that SSP5 has a higher bioenergy TPES in 2050 than SSP1. Looking at how the TPES develops, the main differences between the scenarios are in the first years. At some point in time, their bioenergy use will increase with similar trends. This indicates that in the end the SSPs are to some extend in agreement with each other about bioenergy use. The use of bioenergy, according to the SSP scenarios, in 2030 and 2050 are shown in Table 1. These values are found by averaging the TPES for each IAM that gave results. Comparing these values to the total global TPES in 2017 (which was about 585 EJ (IEA, 2019)), it shows that bioenergy most likely will produce a significant share in the future especially for SSP5, according to the SSP scenarios.

Table 1: Overview of the average TPES of bioenergy (EJ) for each SSP and RCPs used for 2030 and 2050.

	SSP1-1.9	SSP1-2.6	SSP2-1.9	SSP2-2.6	SSP4-1.9	SSP4-2.6	SSP5-1.9	SSP5-2.6
2030	60.6	53.6	77.1	68.9	47.66	84.15	78.3	57.09
2050	111.0	79.2	179.6	121.8	83.3	150.1	249.3	184.3

To summarize, the SSP with the RCP 2.6 pathway always results in a lower amount of bioenergy in the future. Table 2 gives an overview of the total average increase of bioenergy use between 2020 and 2050 for each scenario. In this table, it becomes clear that RCP 2.6 results in lower bioenergy use. The only exception to this is for SSP4. An explanation for this is that the maximum global warming temperature is higher than that for RCP 1.9. A higher maximum global warming temperature asks for less drastic measures. Therefore, the need for bioenergy might be less. Also, with each SSP scenario, the amount of TPES of bioenergy increased. Again, an exception to this is for SSP4. Population growth is only seriously slowed down for SSP1. With every next SSP, the measures taken to reduce population growth are weakened. So, the fact that a larger population requires more energy explains this observed increase. Overall, it can be concluded that regardless of the pathway, bioenergy is part of the energy transition. Therefore, in the future, bioenergy plays a role in the energy sector, and thus in the energy transition. The amount of bioenergy increases for every scenario from 2020 to 2050. It indicates that it gets assigned an increasingly significant role in the future energy system, up until at least 2050. All SSPs have a focus on modern bioenergy use. This indicates that modern bioenergy use will grow and traditional use will be faced out.

Table 2: Overview of the total average increases of TPES of bioenergy (EJ) for each SSP for the different RCPs used.

	SSP1	SSP2	SSP3	SSP4	SSP5
RCP 1.9	61	75	-	43	191
RCP 2.6	29	63.5	-	100	129

5.3 Marker Analysis - Final Energy

To get some insight into which sectors the bioenergy will be used, the IAMC 1.5 °C scenario explorer is used to produce plots for the Final Energy use of bioenergy. It turned out that the scenario explorer only provides information about solid biomass within no specific sector and liquid biofuels in the transport sector when considering Final Energy. This scenario analysis is similar to that performed in the previous chapter. By analyzing the SSPs in their marker models, the final energy use of bioenergy in the transport sector becomes known. The time scale considered is 2020 to 2050, and the region selected is 'World'. This resulted in two plots for solid biomass and two plots for liquid biofuels. First, the amount of solid biomass final energy for the different SSPs coupled to the two RCPs is discussed, followed by a per scenario discussion of the results for the final energy use of liquid biofuels in the transport sector.

Solid Biomass Final Energy For RCP 1.9, the scenario explorer generated results for the SSP1, SSP2, and SSP5 scenarios. For SSP1, the use of solid biomass first reduced from 2020 to 2030. After 2030 slow increase did happen, which resulted in a minimal overall increase in the final energy of solid biomass in 2050. Between the years 2020 and 2030, an increase in solid biomass use was observed for SSP2. After 2030, this amount decreased throughout the years, which resulted in an overall decrease of about 1.5 EJ in 2050. SSP5 did show a strong decrease in solid biomass by final energy from 2020 to 2050. This analysis shows that SSP1 is the only scenario that shows an increase in solid biomass use. The other two scenarios do not increase their solid biomass energy. SSP5 has a focus on technological development and therefore will most likely only use high quality bioenergy like biofuels or biogas, which explains the strong decrease of solid biomass for SSP5. Overall, the decrease was of a magnitude of 37 EJ. For the SSPs with RCP 1.9, an overall average reduction for solid biomass final energy of 12 EJ in 2050 was observed.

Results for the SSPs with RCP 2.6 showed that all but SSP3 were able to give results. For SSP1, solid biomass final energy decreased between the years 2020 and 2030. After 2030, the TFE of solid biomass increased again, ending in an overall increase between 2020 and 2050. SSP2 also gave similar results as observed for the RCP 1.9 scenario. The TFE of solid biomass first increased until 2030. After 2030, the TFE decreased and resulted in a slight increase in the TFE use of solid biomass from 2020 to 2050. The results of SSP4 indicated an increase in the period 2020 to 2030 and a decrease in the period of 2030 to 2050. Overall, this scenario decreased the solid biomass TFE by about 1 EJ. A strong decreasing trend is, again, observed for SSP5. From 2020 to 2050, the amount of TFE solid biomass decreased. This resulted in a decrease of about 35 EJ. Again, the only SSP that shows an increase of solid biomass use is SSP1. The other SSPs reduce their energy from solid biomass. The main goal of SSP1 is to eliminate fossil fuel use completely, and thus their need for alternative sources is bigger than for the other SSPs. For the other SSPs the need to eliminate fossil fuels is less strong and thus their need for sustainable sources is limited compared to SSP1. For the SSPs with RCP 2.6 in their markers, an overall average decrease in the final energy use of solid biomass of about 6 EJ in 2050 was the result.

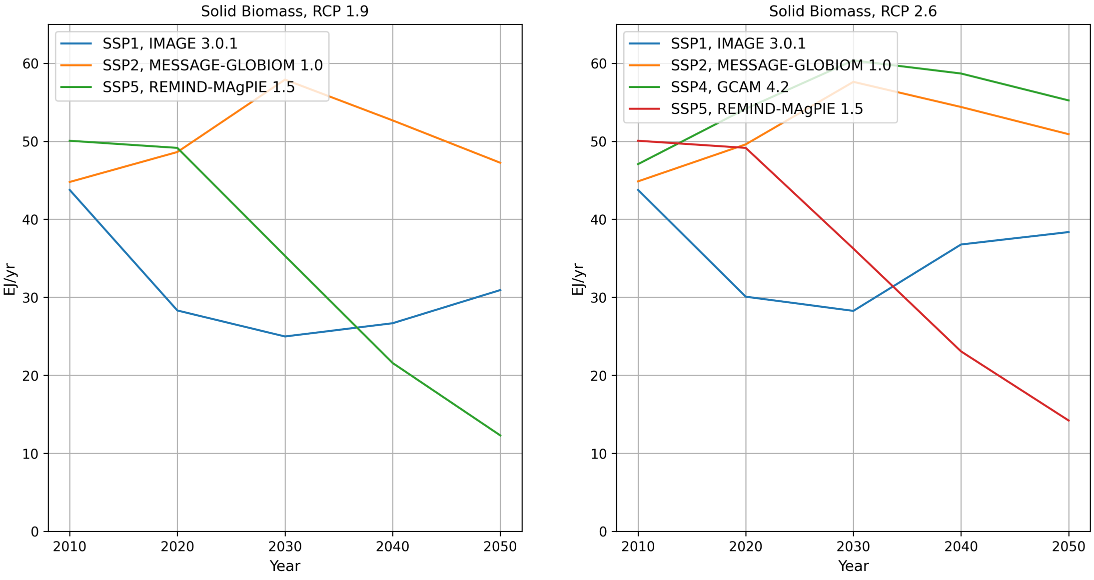

Figure 11: TFE for solid biomass for the different SSPs scenarios combined with RCP 1.9 (left) and RCP 2.6 (right) within their marker IAM. On the y-axis the TPES (EJ/yr) and on the x-axis the decades of interest.

Liquid Biofuels Final Energy For the SSPs with RCP 1.9, it was possible to get results for SSP1, SSP2, and SSP5, and the results are discussed below. The amount of liquid biofuel in the transport sector for SSP1 increased from 2020 to 2040. After 2040, this amount decreased. However, the decrease was not of such a magnitude that it resulted in an overall reduction in biofuel use. The scenarios resulted in a total increase of about 7 EJ in the selected period. The SSP2 scenario decreased in TFE of biofuels from 2020 to 2030. A strong increase after 2030 made up for the loss between 2020 and 2030. The surge continued to 2050. This resulted in an overall gain in TFE use of biofuels in the period 2020-2050. The amount of energy from biofuels for SSP5 started with a slight increase between 2020 and 2030. After 2030, it continued to expand with a large growth rate. Overall, the increase of TFE of biofuels was about 51 EJ. Up until now, this was by far the largest gain for all the SSPs. Looking at the narrative of SSP5, its strong population growth, and focus on technological solutions to climate change (see section 4.1.5), this makes sense. The SSPs with RCP 1.9 in their markers resulted in an overall average increase of 19.5 EJ in biofuels TFE for the transport sector. Looking at the SSPs with RCP 2.6, the following becomes clear. For the SSP1 scenario, the amount of liquid biofuel in the transport sector increased from 2020 to 2050. Concerning the results for RCP 1.9, the overall increase between 2020-2050 was more significant. The SSP2 scenario with RCP 2.6 indicated a decrease of final biofuel use in the transport sector in the years 2020 to 2040. After 2040 a slight increase was seen, but this was for an overall increase between 2020 and 2050. This continued decrease was not similar as was observed for SSP2 with RCP 1.9. The SSP5-2.6 scenario decreased in biofuel energy in the transport sector. After 2030, however, it started to increase. Especially after 2040, this increase became very strong. The increase resulted in a boost of biofuel use in the transport sector for SSP5.
For the SSPs with RCP 2.6, an overall average decrease in the final energy use of biofuels in the transport sector of 15 EJ between the period 2020-2050 was observed. This amount is slightly less than for the SSPs with RCP 1.9.

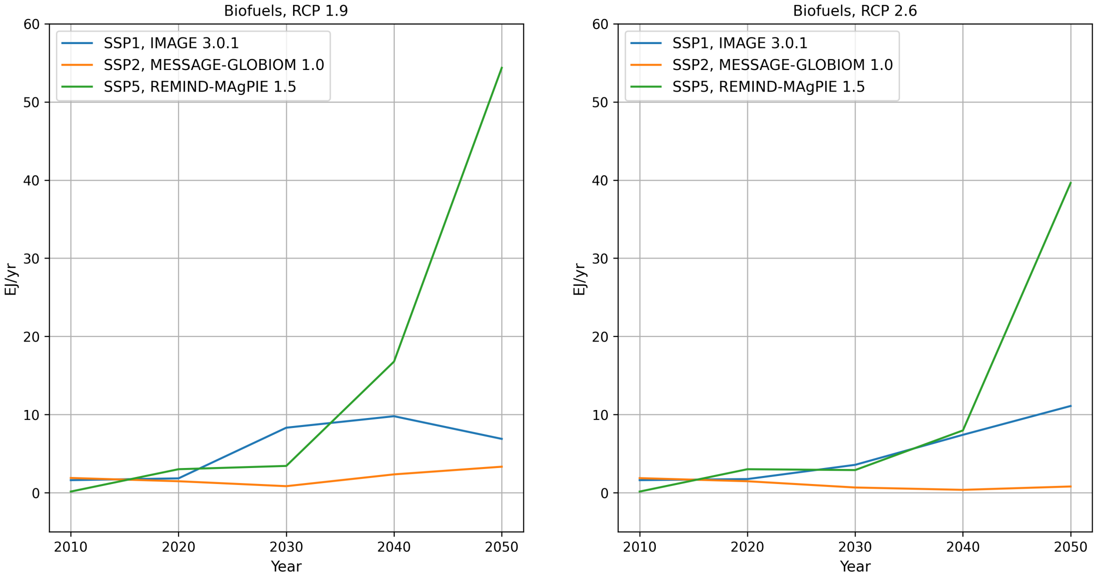

Figure 12: TFE for biofuels for the different SSPs scenarios combined with RCP 1.9 (left) and RCP 2.6 (right) within their marker IAM. On the y-axis the TPES (EJ/yr) and on the x-axis the decades of interest.

Summary For this section, the goal was to predict the future behavior in the total final energy of solid biomass, and biofuels in the transport sector. The period considered was 2020 to 2050. The scenarios considered were the SSPs with the RCPs 1.9 and 2.6. This analysis gave additional information for the role of bioenergy in the future energy system as described in 5.2. Again, plots were produced for these specific scenarios for the two types of TFE using the IAMC 1.5°C scenario explorer.

From this section, the conclusion that the TFE of solid biomass is expected to decrease over the years for most scenarios can be drawn. Given the average overall decrease between TFE in 2020 and 2050, the TFE of solid biomass is less in 2050 than in 2020. The only scenario in which the TFE of solid biomass increased was SSP1. This increase was for both RCP 1.9 and RCP 2.6. The goal of SSP1 is a serious reduction in fossil fuel use. Therefore, many alternatives are needed, and this might explain the overall increase in solid biomass use. For the transport sector, the conclusion is that its biofuel final energy share will increase between the years 2020 and 2050. The largest increase was for SSP5, both for the RCP 1.9 and RCP 2.6 cases. Since the SSP5 scenario continues to rely on fossil fuels, facilitates population growth, focuses on technological developments and technical solutions to limit global warming (see section 4.1.5), the surge becomes clear. The decrease for

SSP1 with RCP 1.9 between 2040 and 2050 is unexpected. It is not clear what causes this decline. It can represent an increase in electric cars. The need for fuels in this sector is therefore lower. There is an important difference between SSP1 and SSP5 when looking at the transport sector. For SSP1, increase in the use of electric and hydrogen cars happens, and thus the dependency on fuels for this sector decreases strongly. For SSP5, the opposite is true. This scenario stays very depended on fuels, which will remain the primary energy source for transport (Bauer et al., 2017). Important is that for this analysis, only two types of final bioenergy were available. When looking at the scenario analysis in section 5.2 the increases in TPES of bioenergy are observed. This increase does not necessarily match with the scenario analysis performed here. However, since not all final energy types are considered, the difference can be explained. Overall, modern bioenergy will replace traditional bioenergy in the coming years.

5.4 Conclusion

This chapter aimed to identify the role of bioenergy in the future. This was done by short literature research of IPCC special report 1.5 (IPCC, 2019), an SSP scenario analysis for the TPES of bioenergy run with different IAMs, and the TFE of solid biomass and bioenergy transport fuels run for the SSPs in their marker models. The scenario analysis used the 'IAMC 1.5°C Scenario Explorer' and is a property of the IIASA. The SSP scenarios are chosen because they are of value to the IPCC and this assigns importance to them.

The analysis of the IPCC report indicated a clear decrease in traditional bioenergy use, it predicted a shift towards modern production of biomass energy. This observation is a result of an expected increase in biofuels for the transport sector and electricity production. The transition towards electricity and fuels does not eliminate bio-heat. Biomass to produce heat is necessary for decarbonizing the industry. However, the largest predicted increase is for electricity and biofuels, indicating modern bioenergy products. These observations made it clear that modern bioenergy will play a role in the future energy system. The two scenario analyses support these findings. The TPES analysis showed a clear increasing trend for bioenergy because each SSP resulted in an overall increase in 2050. The final amounts differ per SSP, but this is explained by the differences in underlying narratives for each SSP. Whether the bioenergy produced in the future is modern or traditional depends on the narrative of the SSP. For example, SSP1 only considers modern bioenergy, whereas SSP4 still includes both types due to large income differences. However, the conclusion remains that all the SSPs focus on modern bioenergy use, and that will be the main form in the future. The TFE analysis further visualizes the replacement of traditional biomass use. A strong reduction of solid biomass for all but SSP1 is observed. Also, the transport biofuels show a strong increase, and this indicates a clear preference for modern bioenergy up until at least 2050. The decrease in transport fuels for SSP1 is due to electric vehicles.

In the next decades, bioenergy will still play an important role in the energy system. Bioenergy use today is more traditional orientated, but it will shift towards more modern energy forms like biofuels and electricity. Such a change towards high-quality applications was already seen in chapter 3 and the results from this chapter add to it. So, up until at least 2050, the use of bioenergy increases. The increase is observed for each of the different narratives of the SSPs, with an exception for SSP3 because for that narrative global warming cannot be limited to 1.5 °C. Energy from biomass will therefore be incorporated in future energy systems and play a significant role in the energy transition.

Whilst the scenario analyses clearly indicate that bioenergy is important, an intriguing debate is present about its implementation. The conclusions made here are important for the next chapter (chapter 6) where the controversies around bioenergy are presented.

6 Controversies Regarding Bioenergy

"For its supporters, it represents a relatively cheap and flexible way of supplying renewable energy, with benefits to the global climate and forests industries. To its critics, it can release more greenhouse gas emissions into the atmosphere than the fossil fuels it replaces and threatens the maintenance of natural forests, and the biodiversity that depends on them" (Brack et al., 2017, p:2) (Brack, 2017). This statement made by Brack et al. (2017) summarizes the bioenergy debate that is currently going on. According to the critics, it is impossible to produce bioenergy sustainably, and the advocates come with arguments that indicate the complete opposite. The result is the existence of several controversies for bioenergy. Within these extremes, there exist nuances from both sides about the different controversies. For this research, the extreme side of the debate is chosen to be the main focus because the controversies are more evident there.

The controversies listed in this chapter will be used in the analysis to identify the least controversial feedstocks and if these feedstocks can help resolve them. This section aims to identify the controversies, which is done by performing literature research. To obtain knowledge about the controversies, papers that aim to identify the challenges and prospects of bioenergy were searched. With every controversy identified, further literature for it was gathered. Search engines like that of TU Delft online library, ScienceDirect, and Google Scholar were used. Insight into the debate is obtained from analyzing papers that explicitly react to each other (from now on referred to as counter-papers). Therefore, a special focus was to look for counter-papers. This resulted in a total of two such papers found which were used in the analysis. These counter reports were the main sources used to identify the controversies. The other papers were analysed to see if they were in agreement with what was found in the counter-report, and to provide additional information about a controversy when necessary. The other documents consulted were mostly reports about the future of bioenergy, the prospects for bioenergy, and the challenges bioenergy is facing today. The counter-reports used were the response of Searchinger et al. (2020) (Searchinger & Tufts, 2020) to the PBL report of 2020 (Strengers, Bart; Elzenga, 2020), and one was the report of Cowie et al. (2017) (Cowie, Berndes, Junginger, & Ximenes, 2017) that reacted to the Chatham House written by Brack et al. (2017) (Brack, 2017). These all are scientifc papers written by scientist. This makes the bioenergy debate a scientific one. The institute PBL cannot be named a bioenergy advocate, but their report of 2020 did show positive results for bioenergy use. Because Searchinger et al. countered these positive outcomes, makes this set of counter papers useful for the analysis. Those reports especially gave insight into the different viewpoints for bioenergy of the opposing parties. The controversies that are considered most important are explained using the findings from the consulted literature. No own opinions or viewpoints are included. The arguments used from both sides are therefore carefully extracted from the documents consulted. This means that some arguments used by one of the parties might be contradictory with modern science and what one might say to be a measurable factor. The order in which the controversies are explained in the upcoming sections also indicates the importance as reported by the consulted literature. The first controversy is the main discussed one, and the last is the least one. The rank is necessary for the sensitivity analysis that will be performed with the results in chapter 8.

First the controversies concerning chain emissions, carbon debt and the removal of carbon sinks are explained in section 6.1, followed by the controversy about land use in section 6.2, the third section (6.3) discusses the controversy concerning the biodiversity. The explanation of the controversies is followed by deriving the criteria from them (section 6.4). The chapter ends with a conclusion (section 6.5).

6.1 Chain Emissions, Removal of Carbon Sinks, and Carbon Debt

The feedstock for bioenergy is a carbon-based source. Therefore, the production of bioenergy results in the release of GHG emissions. Bioenergy is considered carbon neutral since the feedstock can regrow, and during this regrowth absorb the emitted CO_2. This fact, together with the production chain of bioenergy, results in three concerns: chain emissions, removal of carbon sinks, and the carbon debt. This section first explains these problems before the arguments from the critics and the advocates are presented. From literature, a lot was debated about these topics. However, they were not as specifically mentioned as formulated here. It was a more confusing and unclear part of the debate. Hence, after careful analysis of the collected arguments, these three problems were identified.

The first problem results from the production chain of bioenergy. This includes the very first stages of land cultivation to the end use of energy. The production chain results in all sorts of emissions: greenhouse and non-greenhouse, carbon dioxide or non-carbon dioxide, and all (i)LUC emissions. It is no surprise or unknown fact that production results in emissions. However, the problem with bioenergy emissions is that not all are allocated to the energy sector. Today, experts are not in agreement about where to allocate the emissions resulting from bioenergy production and if bioenergy can be considered carbon neutral. The IPCC created a system in which the non-carbon dioxide emissions are registered and counted where they are generated. For example, the agricultural sector counts the emissions as a result of the cultivation of biomass and not the energy sector. Looking at CO_2, it is a bit more complicated. When land that is constantly cultivated and has a healthy ecosystem is used to produce biomass for energy, the plants and trees on this land compensate for the emitted CO_2. This is an addition to the recapture of the new growing feedstock. The compensation results in the production of energy to which no CO_2 is assigned. So, whether the CO_2 counts for bioenergy depends on the type of land the biomass is grown on together with the land management present. The critics doubt if the system from the IPCC is an accurate one. They question if this cycle is indeed closed due to the chain emissions of bioenergy. When considering all emissions (including all (i)LUC, CO_2 and non-CO_2, and greenhouse and non-greenhouse emissions) is the cycle really closed (Brack, 2017; Searchinger, Beringer, & Strong, 2017)?

The second problem is concerning the removal of carbon sinks. For most trees it takes several years to become of significant size. During the years, CO_2 is absorbed and stored in the wood. The trees thus function as a carbon sink by capturing and storing the carbon while growing. As long as the tree shall live it will continue to grow and capture CO_2. When the tree is used to produce bioenergy, its ability to continue to capture CO_2 is removed. This introduces the problem of removal of carbon sinks (Brack, 2017; Searchinger et al., 2017; Searchinger & Tufts, 2020).

The last problem is that of carbon debt. As known, bioenergy makes use of the carbon cycle. This process indicates that by burning biomass, stored carbon is released. Newly growing biomass recaptures the carbon dioxide and closes the loop. New planted trees and crops need some time to grow and mature. Before they reach the harvesting state some time will pass. The CO_2 released by the use of bioenergy is recaptured as a whole when the "new" biomass reaches this state of maturity. Hence, no direct recapture of the carbon dioxide exits. There is a time gap between emission and recapture, this time gap is also called the carbon debt. The carbon debt does not indicate that the carbon cycle is not closed, but merely that there is a time difference. Although the CO_2 is eventually recaptured, it does not eliminate the global warming from these carbon dioxide molecules. Once emitted, it acts like a greenhouse gas and influences global warming. The longer time gap, the longer the GHG is in the air, and thus it has a larger influence on global warming. The arguments used for the removal of carbon debt and carbon sinks do have some overlap. With the removal of carbon sinks additional emissions are released and this enlarges the carbon debt. Therefore, these arguments are presented together.

The problem with these controversies is that the arguments, either pro as against, are based on "what if" scenarios. This is due to concerns about damages of bioenergy production today that come to light in the future and the complexity of counting all emissions. These effects are difficult to quantify, and therefore uncertain.

The Critics In the literature, it was found that the classification of biomass as carbon-neutral derives from either one of two assumptions. The first is that biomass emissions are part of a natural cycle in which, over time, forest growth balances the carbon emitted by burning wood for energy. The second assumption derives from IPCC reporting rules intended to avoid the double-counting of carbon emissions. This system results in the accounting of the emissions from bioenergy in the land-use sector. The allocation problem (the second assumption) results in more questions than just where to allocate the emissions. For example, it is questioned how the iLUC emissions should be counted and will it affect the carbon counting for bioenergy or not? With this, the critics express their criticism on the IPCC rules for emission allocation. They indicate that the production of biomass results in several emissions and impacts that, due to the rules of the IPCC, are now excluded for bioenergy. Allocating those emissions to the agricultural and forestry sector assigns a wrong level of sustainability to bioenergy. Total emissions differ per feedstock. Depending on the use of the waste residues, using it for energy production might cause a release of additional emissions. When the destination of the residue is to form long-lasting products, carbon captured in those products will not be released. When that residue instead is used to produce bioenergy, the carbon will be emitted. The actual emissions, therefore, depend on the original use of the feedstock and the alternative end-uses (Brack, 2017). Besides this, the critics argue that the original or alternative use of the feedstock, decay times (if applicable), harvesting/transport/processing of the organic material, and forgone future absorption of carbon emissions should be considered (Brack, 2017; Reid, Ali, & Field, 2020). With the removal of forest residues, the carbon storage in the ground decreases along with the concentration of nutrients. When the carbon and nutrients concentrations diminish, the fertility and quality of the soil declines. In the long term, this results in reduced carbon storage in woody biomass. Restoring the soil requires fertilizer use and this results in the release of emissions and thus creates a chain effect of bioenergy production from forest residues. A final reason for whether bioenergy can be said to be carbon neutral or not is that it is not always clear how the LCAs for GHG emissions of bioenergy compare, and how they compare to other energy sources (Searchinger et al., 2017; Brack, 2017; ANTARES GROUP, 2011).

The removal of carbon sinks and the carbon debt can be linked to the first assumption mentioned above. Critics counter this assumption because one should not consider bioenergy to be carbon neutral just because plant growth off setts the released carbon emissions resulting from bioenergy. That is because plants will take up CO_2 from the air regardless of the final use of those plants. When the plants are harvested and combusted, it results in a higher overall CO_2 concentration. In addition, the critics say that although new plant growth recaptures the CO_2 emitted by combustion, the carbon that could be stored when the plant or tree is not harvested for energy production is not compensated. This exclusion indicates that bioenergy actually results in the release of more CO_2 emissions than now considered because the removal of those carbon sinks is not included. When sustainable forest management repays the carbon debts, it indicates that, compared to fossil fuels, no increase in emissions is happening. Generating a decrease in emissions with bioenergy from woody biomass compared to fossil fuels will take many years. The only way bioenergy might reduce GHG concentration in the air is when the total plant growth/forest area worldwide increases and releases of stored carbon are counted (Searchinger & Tufts, 2020). But this is not yet the case. A slow decay rate of residual biomass results in a larger net increase in emissions when these residues are used to produce energy in the short- and medium-term. The carbon is released more immediately by combustion than by the decay process. Over time the net impact declines during the years due to the rotting process, which coincides with the release of carbon emissions (Brack, 2017). The balanced system created by the carbon cycle does not make that part of bioenergy production carbon-neutral because it excludes loss of captured carbon due to the harvesting of trees. The trees would have captured more carbon over the years when not harvested. With harvesting, the overall uptake of CO_2 falls and thus the carbon debt becomes bigger or might not be repaid (Brack, 2017; Searchinger et al., 2017).

The Advocates The literature indicates that carbon neutrality for bioenergy is achieved if the production of the feedstock makes use of sustainable land management. This means that the biomass harvested must in equal amounts regrow to balance the emissions (Cowie et al., 2017; Giuntoli & Searle, 2019). The advocates clearly state that the type of feedstock strongly influences the amount of CO_2 emissions, likewise for the processing technology chosen. There exist a lot of factors (such as feedstock type and processing technology) that influence the total emissions of bioenergy. When no distinction for these factors is made, the total emissions of bioenergy cannot be quantified precisely. Also, due to the wide availability of quantifying methods, objectivity and reliability are reduced by this diversity. However, all bioenergy systems deliver GHG savings if they replace fossil-based energy and if the bioenergy production emissions are kept low (Popp, Lakner, Harangi-Rákos, & Fári, 2014). According to the IEA, biofuels are allowed to have higher CO_2 emissions than fossil fuels due to the difference in energy density (bioenergy has a lower energy density than fossil fuels) and should only be considered when no sustainable forest and land management is applied. When bioenergy is produced with good land and forest management, no emissions are allocated to it since the carbon cycle results in net-zero emissions. In other words, the carbon cycle creates a balanced system between photosynthesis and biomass combustion (Brack, 2017). It does not question the carbon neutrality of bioenergy but indicates that the amount of emissions may differ per feedstock and processing technology. The same applies to the carbon payback time, when no distinction in the feedstock is made the carbon payback time cannot be rightly determined. The production region should also be considered, thus making it a context- and feedstock-specific problem.

For the carbon sinks and carbon debt, the advocates say the following. The carbon dioxide from the combustion of biomass is a result of atmospheric carbon stored in the biomass. This carbon was in the air not long ago and is part of a biogenic cycle. By burning biomass, carbon emissions are released that were not long ago in the air. Therefore, bioenergy becomes a better option than fossil fuel use. The carbon released by burning fossil fuels was stored for a very long time. With their release, extra carbon that is not part of today's biogenic cycle enters the atmosphere. Hence, by replacing fossil fuels with bioenergy, the carbon debt can be repaid in a shorter period (Cowie et al., 2017). If the forest for the production of high-quality logs is maintained, the low-quality wood is removed. The removal promotes the growth of high-quality trees. When such maintenance is not present, the forest is not as productive, resulting in less carbon uptake by the trees. In the end, the use of such low-quality logs for bioenergy production results in more CO_2 uptake. With the right policies and governance for sustainable forest management, the carbon balance is maintained, and the carbon debt is not affected on landscape-level (Cowie et al., 2017). Bioenergy contributes to an enhanced carbon cycle, more and possible faster recapture, if soil carbon increases due to the crops planted for bioenergy. Depending on the crop and original plantation of the area, the soil carbon may increase (Mendes Souza, Vioctoria, Joly, Carlos A., & Verdade, 2015).

Summary The controversy of chain emissions has to do with that the critics consider it wrong that only the end-of-pipe emissions are counted and not the whole process from plant or tree growth to energy. This can result in falsely calling bioenergy a low carbon-emitting energy source. The advocates counter the concern by stating that carbon neutrality is achieved if several important factors are considered during production of bioenergy. Besides, some feedstocks or processing technologies result in a more robust carbon-neutral bioenergy system than others.

For the removal of carbon sinks and carbon debt, the critics say that the recapture time is longer than as predicted because harvest removes carbon sinks, and today this is not considered in the calculation. Fewer carbon sinks available will create a larger time gap between CO_2 emitted and fully resorption. But, as the advocates indicate, the use of biomass for energy will at all times have a lower carbon debt than fossil fuels. Biomass is part of a relatively short biogenic cycle, and fossil energy sources are not. This makes bioenergy already a better and more sustainable source than fossil fuels.

6.2 The Land Use Controversy

The amount of land on earth is set. Therefore, the available land is a scarce commodity. There exists the expectation that the population will grow even larger than today in the coming years. An expanding population results in more mouths to feed, and thus food production must increase. Such an expansion of food production will result in an intensification of the agricultural sector. With the introduction of bioenergy, land for food might have to make room for land for biomass. This possible competition for arable land between food and bioenergy causes concerns and this results in the formation of the land-use controversy. Not only is there a discussion about the availability of land for bioenergy, but also what the effect will be on food prices when competition between food and bioenergy happens.

The Critics When bioenergy is only produced from feedstocks that are land-intensive, it will not meet the predicted future demands. Land is scarce, and the land required for bioenergy using such feedstocks will be too large. Thus, causing problems to meet food demands for the growing population. Scenarios that claim the difference base their arguments on optimistic assumptions that probably cannot be justified. That is even when increased crop yield and efficiency in the agricultural sector are achieved (Reid et al., 2020; Popp et al., 2014). When food crops are also used for bioenergy production, additional competition between energy and food may occur. A result can be a price increase in the food and energy sectors (ANTARES GROUP, 2011). Switching to energy crops and waste streams for energy can partly overcome price increase but issue with available land continues to exists. Besides, energy crops most possible require irrigation, therefore stressing water demand in the agricultural sector (Pulighe et al., 2019). Bioenergy interlinks with the water-energy-food system. This gives rise to several concerns which are mainly about whether this will affect meeting the food demand in the future. Waste and marginal land show opportunities for the production of bioenergy. Crops for bioenergy can grow on land that is not suitable for the production of food. In that way, it avoids competition with the food industry. The problem is that most of the wastelands are forests, woody savannas, and pastureland. Those types of lands can also be of use for the production of crops. Another problem with converting marginal land to produce bioenergy feedstocks is that this is not carbon-free due to direct and indirect land-use changes. The recapture time of such carbon emissions is longer than one might think. The question arises if converting marginal land for the production of bioenergy feedstock is beneficial and whether such lands can then still be considered as marginal (Searchinger et al., 2017).

The Advocates The advocates argue that the demand for land for bioenergy will not be as large. There are large amounts of organic waste streams that can be used to produce energy. To limit the need for land for biomass even further, increasing efficiency in the agricultural sector and an increased crop yield can reduce the required land (Popp et al., 2014; IEA, 2015). The amount of arable land that bioenergy will occupy in the future can reduce even further when using marginal lands. Upgraded wastelands can then become available for the agricultural sector. Growing bioenergy crops on these lands helps to avoid abandonment of agricultural land and further degradation. Bioenergy can stimulate improved management of soils, forests, and croplands. Technological development in the agricultural sector has good potential to use marginal land for the production of specific crops. With the help of genome editing, wild germplasm (living genetic resources of wild plant species, used in scientific resource or preservation purposes, etc.), flex crops (crops that have multiple purposes and can interchange easily), and orphan crops (underutilized/lost/neglected crops) the agricultural sector can be made more efficient and agroecological approaches can be promoted (Pulighe et al., 2019; Axelsson et al., 2012; IEA, 2015). The IEA has identified two more ways to limit the competition for land. The first method is that of so-called contract farming. Contract farming means that farmers sign a contract to diversify their land in such a way that a share of what they produce can be used in bioenergy production, resulting in additional income for those farmers. The second method identified is in the form of integrated production systems. This can help create systems that meet the demand for food, energy, and other agricultural processes. By using crop rotations, flexible crops, intercropping, and agroforestry approaches it is possible to construct such systems (IEA, 2015).

Summary The land available for the production of food, feed, and energy is scarce. With a rising world population, the critics question whether it is sensible to implement bioenergy on a large scale if this will reduce the amount of land for food production. The advocates counter this by stating that there are many suitable organic waste streams, and thus land for energy can be limited. There exists the possibility that feedstocks are grown on marginal lands that are not suitable for food production. The downside of using marginal land is the possible extra (i)LUC emissions. The advocates state that the IEA has proposed contract farming and integrated production systems to limit land for bioenergy use. However, the critics do not show good faith in such methods. They stress the biases on over-optimistic assumptions for future predictions for land use allocation, and those cannot be justified in the future.

6.3 The Biodiversity Controversy

The health and biodiversity of an ecosystem are well connected. In the past decades, a lot of ecosystems have disappeared together with several species. Today, an effort is made to preserve the species that are left on earth. The debate is going on whether bioenergy contributes to an increased or decreased biodiversity. If bioenergy reduces biodiversity, it would have severe consequences to its implementation (Brachet et al., 2018; Strengers, Bart; Elzenga, 2020). The debate around biodiversity and bioenergy gives rise to the question to what extent a possible biodiversity loss weights up to a biodiversity loss due to climate change.

The Critics Harvesting and collecting of biomass is a cause for the loss of biodiversity in the ecosystems. Not only these actions impact biodiversity, but also growing biomass, especially when cultivated as a monoculture. The risk is primarily observed in the industry of sustainable forestry and wood pellet production. When biomass is extracted from ecosystems it removes the protection and living spaces of several species, in that way it affects well-established ecosystems. The destabilization can result in the migration of species to another ecosystem, or they might not survive due to reduced living quality. When biomass grows on land that was a forest (or another type of ecosystem), it has the most severe effects on biodiversity (Strengers, Bart; Elzenga, 2020; Pulighe et al., 2019).

The Advocates Bioenergy advocates, however, argue that growing bioenergy feedstocks on marginal and wastelands increases biodiversity. Second-generation feedstocks create more diversify landscapes and contribute to an improved connection between such lands and natural habitats. With the existence of energy crop farming on marginal land, buffer zones are created. These buffer zones protect other more vulnerable areas that, on their own, protect other ecosystems. Besides, it can also help to protect coastal and near river banks (Pulighe et al., 2019). With this, bioenergy can considered to be beneficial for biodiversity.

Summary The debate around biodiversity and bioenergy gives rise to the question if bioenergy impacts biodiversity or not. According to the critics, harvest of biomass results in habitat loss and thus increases risk for biodiversity loss. This is disputed by the advocates by the fact that second-generation feedstock have the ability to create connections to other ecosystems and thus providing shelter. This is especially possible for perennial energy crops. The advocates indicate that there exists options to limit possible biodiversity risks.

6.4 Quantification of the Criteria

As mentioned the controversies are necessary to identify the criteria of interest and the method of quantification. When basing the criteria on the controversies it becomes clear that the following should be quantified: yield per land area, generation type of feedstock, fertilizer use, biodiversity impact, growth time of feedstock, and marginal land use. These characteristics connected in the following way to the controversies:

- The yield connects to the controversies of land use and the competition with the food industry.
- Generation type connects to the controversy of competition with the food industry.
- The fertilizer use connects to the controversy of chain emissions.
- The biodiversity impact connects to the controversy of biodiversity
- The growth time of the feedstock connects to the carbon debt controversy.
- The marginal land use connects to the controversies of land use and of biodiversity.

The explanation and justification of the criteria to controversy connections are explained in the following paragraphs.

Generation Type Bioenergy feedstocks are distinguished into three different generation types. A first-generation (1G) feedstock is a food crop (such as corn, soybean, rice, etc.) and a part of the (human) food industry. Second-generation (2G) feedstocks are crops that are not part of the food industry (such as Miscanthus, Palm Oil, and grasses) and every type of waste stream. The third generation type (3G) are micro-and macro-algae (Lee & Lavoie, 2013). This research chose to consider human food sources only as 1G feedstocks. This links in a more direct way to the controversy of competition with the food industry. However, animal feed crops can also be considered 1G because they, indirectly, function as a human food source. For this research, animal feed is not seen as 1G.

There exist concerns about the possible competition between the food industry and bioenergy production. The worries are about available land for food production and the availability of the food crops. Therefore, it is of value to take the generation type of the feedstocks into account. The controversy about competition with food is further quantified by the yield and this characteristic can also be linked to the controversy of land use. When the crop is a 1G feedstock, it competes with the food industry since it is a food crop. This is unfavorable when looking at the controversy. The problems around the competition with food indicate that non-food crops are more favorable than food crops, and thus 2G and 3G feedstocks are preferred. Therefore, a higher degree of generation is preferred.

Yield per Land Area To indicate the required land for biomass cultivation, quantification of yield (MJ/ha) is done. The yield indicates how much useful energy, the amount of energy it produces when in the final form, from that specific feedstock can be produced using 1 hectare of land. To elaborate, it is the energy delivered to the end user. What happens after that is not considered. The energy represents the lower calorific value. This value means that the yield might be higher than now indicated. The reason for this choice is that for this research, no processing details will be considered, and thus it is not specified whether it is possible to use condensation energy.

The more useful megajoules a feedstock can produce on one hectare, the less problematic this feedstock might be. The use of a feedstock with a high yield, reduces, compared to low yield biomass, the amount of land needed to meet bioenergy demand. Looking at the bioenergy debate, this is an essential factor for selecting the right feedstock.

To give the residues and wastes feedstocks a value for this criteria, the choice is made to invert the land area values (so from MJ/ha to ha/MJ). With this, the criterion should be minimized. The residues and wastes streams do not directly require land for bioenergy. Therefore, their values are close to zero (0.0001). The ranking and weighting methods do not allow zeros in the decision matrix because division by zero is not possible. Hence, a value close to zero is given and not zero itself.

Fertilizer Use Processing crops and land cultivation are responsible for several emissions. One of the most well-known emissions resulting from the agricultural industry are the ones from fertilizer use. For this research, the decision was made to not quantify end-of-pipe CO_2 emissions. Both sides of the debate indicate that, under the right circumstances, the recapture of these emissions is possible. However, the main controversy is about emissions not resulting from direct energy use. The emissions of interest are the non-carbon dioxide emissions, because they are said to be neglected or wrongly allocated. This makes fertilizer use a good indicator for the controversy. It is a non-CO_2 emission which is the result of a part of the processing chain. Besides, it is not an end-of-pipe emission. This all makes it a suitable quantification of the chain emissions controversy. By considering this emission, only a small part of the total chain emissions are considered. Although this does give some insight into the impact on the controversiality of the feedstock, one must keep this limitation in mind when interpreting the results.

Nitrogen fertilizer gives rise to N_2O, NO_x, and ammonia emissions. N_2O has a high CO_2 equivalent value and is therefore important when considering environmental impact (Chai et al., 2019). The more nitrogen fertilizer the feedstock requires, the higher the emissions and the less favorable that feedstock is. Therefore, the criterion must be minimized.

Biodiversity As explained in section 6.3, there exists the possibility that bioenergy cultivation impacts biodiversity. Identifying the risk per feedstocks is therefore important for the ranking. A value between zero and one without a unit is used for quantification. The value is based on several impacts on biodiversity as a result of cultivating that feedstock for bioenergy. The impact can be on micro- or on ecosystem level, and all in between. The type of impact differs per feedstock. The impact of the feedstocks are not quantified on the same level, and the number of levels considered may differ as well. These limitations are important to know when interpreting the results. To quantify the impact, the review paper of (Immerzeel, Verweij, van der Hilst, & Faaij, 2014) was used. Upon deciding to use this review paper, several others were considered to see if there is agreement on biodiversity impact due to bioenergy feedstock cultivation. The papers of (Wu et al., 2018), (Elshout, van Zelm, van der Velde, Steinmann, & Huijbregts, 2019), (De Jong & Dahlberg, 2016), (Y. Liu, Xu, Zhang, Yun, & Shen, 2014), (Haughton et al., 2016), (Milner et al., 2016) and (Mohr & Raman, 2013) all showed similar conclusions that are in agreement with the conclusion made in the paper of Immerzeel et al. (2014). These papers agree on the complexity of biodiversity impact measurements, that 1G feedstocks have an overall larger impact than 2G and 3G, that the impact is feedstock and location depending, and that there exists great uncertainty about the actual impact of bioenergy production on biodiversity. Some of the papers are, like that of Immerzeel et al., a review paper, and others are performing original research. Not all methods used are similar, as for the level of interest (on a micro-level or ecosystem level). In the end, they observe several degrees of impact on biodiversity.

The impact is more often negative than positive. Therefore, it can be justified to use this review paper as the source for quantifying the biodiversity impact from bioenergy production. The quantification of biodiversity impact used Table 1 from Immerzeel et al. (Immerzeel et al., 2014). For every feedstock selected, the negative, positive, and positive/negative impacts were tallied. Some feedstocks were mentioned in the table, but most were not. However, the table gave information about first- and second-generation crops. These parts of the table allowed the quantification of those not mentioned. The third-generation feedstocks used information from (Correa, Beyer, Possingham, Thomas-Hall, & Schenk, 2017) to appraise their biodiversity impact. The positive impacts were multiplied with -1 for each feedstock, the neutral impacts with zero (since they have no negative or positive impact), and the negative impact with +1. Adding the scores for each impact for each feedstock formed the total impact on biodiversity. Immerzeel et al. did not use an equal number of studies to quantify the impact for each feedstock. Therefore, the total impact of the feedstock was divided by the number of studies used to quantify the impact of that specific feedstock. The higher the sum of impacts, the higher the impact is. Therefore, the criterion should be minimized.
No information was found about the impact on the biodiversity of the feedstock type residues and wastes streams. This type is a waste stream and therefore not directly produced for bioenergy. It is, therefore, assumed that no (direct) impact exists for this type of feedstock. To give it a value for the decision matrix their impact is set close to zero (0.0001). Again, because the ranking and weighting methods do not allow a zero in the decision matrix, a value close to zero was assigned for the residues and waste stream feedstocks.

Carbon Debt The growth time in the table is in days and indicates the time it takes the crop to grow to maturity from the moment of sowing. For palm oil, the oil-bearing source is the bushels. Therefore, the analysis considers the days it takes to regrow a bushel of oilseeds for the carbon debt. The growth time of each crop represents the time gap for recapturing the CO_2 emissions. This regrowth evaluates the controversy of carbon debt, and the time difference may be an indicator for this. With the help of a literature search, the growth cycles were quantified. ScienceDirect, TU Delft online library, and Google Scholar were used to look for the required information using search terms like Growth time of X and Growth cycle of X (X indicating a feedstock). Again, for the feedstock type residues and wastes streams, no growth times were available. This absence is because they are not consistent with one specific crop or not a crop at all. Their values equal the most favorite growth time found for the crops. This data assignment is necessary for them to be considered in the analyses. The decision matrix may not have an entry that equals zero. Since a shorter growth cycle indicates faster re-absorption of CO_2, this criterion must be minimized. Due to this minimization, the best-observed growth cycle belongs to palm oil, and thus the residues and waste stream cycles equal that of palm oil.

Marginal Land Use Although the use of marginal land for bioenergy feedstock production is connected to the land use and biodiversity controversy, it is decided to use it as a separate criterion. When trying to incorporate the marginal land use into the connecting criteria, it became rather complicated. Therefore, it is considered an individual criterion. The possibility to grow the crop on marginal land does not take the land-use and biodiversity controversy into account. When used as a separate benchmark, this characteristic is more rightfully considered. As is seen from Table 25 in Appendix C, the marginal land is quantified with a "yes" or a "no". To convert this to a numerical value, a "no" scores a 1, and a "yes" scores a 10. The advocates indicated that marginal land has, or most likely has, a positive impact on biodiversity and reduces the pressure on arable land. Therefore, this criterion is to be maximized.

6.5 Conclusion

The purpose of this section was to identify the most important controversies for bioenergy and the main points of discussion in the bioenergy debate. The controversies are required for the comparative analysis for the identification of the least controversial feedstock. The identification will be done with the help of an MCDA. The controversies form the basis for the formulation of the criteria.

The literature analysis gave insight into the main controversies: chain emissions, removal of carbon sinks, the carbon debt, land use, the possible competition with food production, and if bioenergy increases or decreases the biodiversity. It was observed in the literature that some of the controversies were more extensively discussed than others due to the larger number of information found about these controversies. The order of importance is the following: chain emissions, removal of the carbon sink, the carbon debt, land-use, competition of food industry, and biodiversity.

To identify the least controversial feedstock and to what extent its implementation can help stop the ongoing debate, it is necessary to rank the feedstock according to their performance for each controversy. Therefore, the choice to use the controversies in the formation of the criteria is justified. This chapter functioned as the identification of the in literature most discussed controversies about bioenergy. With the help of the information given above, the following criteria are formulated for the MCDA:

1. Generation type of feedstock (1, 2 or 3)
2. Land use (ha arable land/MJ energy)
3. Chain emissions (kg N/ha)
4. Biodiversity impact (value between 0 and 1)
5. Carbon debt (days to regrowth of feedstock)
6. Marginal land use (yes or no)

The type of generation of the feedstock indicates whether it is a food crop or not and thus refers to the controversy of competition with the food industry. The criterion land use gives insight into feedstock efficiency, and thus the amount of land it requires to meet certain energy demands. For the chain emissions of bioenergy, it was chosen to quantify this in terms of nitrogen fertilizer. It does not refer to end-of-pipe emissions and in a way quantifies the emissions resulting from an agricultural process of biomass production. These fertilizer emissions are only a part of the total chain emissions of bioenergy production. This quantification therefore not completely covers this controversy. The choice to only quantify this controversy is due to simplicity reasons. The choice and simplification are justified by the fact that it is an important and well-known chain emission. The biodiversity impact is quantified using the review paper of Immerzeel et al.. It was chosen to quantify the carbon debt controversy by the time it takes for the feedstock to regrow and recapture the end of pipe emissions of bioenergy for that feedstock. The last criterion is that of marginal land use. The marginal land criterion quantifies with "yes" or a "no" to see if it can or cannot be grown on marginal land. The use of marginal land refers to the land-use controversy and also partly to the controversy of biodiversity. These criteria show that the only controversy not included is that of the removal of carbon sinks. No simple method was identified to quantify this controversy. However, it closely relates to the chain emissions and carbon debt controversy which both will be quantified for the analysis. Also, for this research the controversies are quantified in a broad sense and thus no details were incorporated. Some controversies span more than one factor, like the chain emissions. This will result in a ranking that considers the controversies in a broad and global sense.

Now that the controversies and the corresponding criteria are known they need to be quantified and scored for each feedstock. Once this is done, the identification of the least controversial feedstock can take place. The quantification will be done in the next chapter (chapter 7), and in chapter 8 the least controversial feedstocks will be identified.

7 Bioenergy Feedstocks

This chapter includes selecting 40 feedstocks and collecting their characteristics (like yield and fertilizer use). Table 25 represents the data obtained for the characteristics. The table is presented in Appendix C. This Appendix also contains the sources used to fill the table, and they are found in Table 26. They are put in a separate table in the Appendix to enhance legibility.

The collection of several different feedstocks is necessary to make the analysis that will indicate the least controversial feedstocks. The feedstocks selection was performed by searching for literature that considers the available feedstocks of bioenergy. The search engines of TU Delft online library, ScienceDirect, and Google Scholar were consulted to find suitable literature. Using search terms like Bioenergy feedstocks, Types of bioenergy feedstocks, and Available bioenergy feedstocks, it was found that roughly four bioenergy categories exist. Entering these categories separately as search terms enabled the selection of several feedstocks per bioenergy feedstock category. The 40 used in this research are just a fraction of the available feedstocks. The production of energy can make use of many crops and waste and residues streams. As an example, there exist over 350 oil crops for biodiesel production (Anwar et al., 2019). The number of biomass types suitable for energy is way too large to incorporate them all in the analysis. Therefore, based on in literature mentioned biomass, both the more frequently applied as some upcoming feedstocks were selected. There was no specific selection method used. Care was taken to incorporate several feedstocks for four different biomass types (sugar and starch crops, oil crops, lignocellulosic crops, and residues and waste streams). Upon completion of feedstock selection, data for the criteria are collected. The criteria are defined and described in chapter 6.

After selection of the feedstocks, data had to be found to quantify the criteria. With the help of a literature search the required data was collected. The literature consulted were mainly research papers or books. To find the desired information for each feedstock, search terms like Yield of X, Fertilizer use X, LCA of X, Bioenergy from X, and Biodiesel/bioethanol from X, where X indicates one of the 40 feedstocks. The search showed that not all characteristics were available for all 40 feedstocks. However, it was made sure that there was at least enough data to compare them for the ranking. Important to know is that, although some crops can be produced on marginal lands, the yields indicated in the tables are based on crop growth on non-marginal lands.

First, the chapter discusses the sugar and starch crops (section 7.1), followed by the oil crops (section 7.2), then the lignocellulosic crops (section 7.3), and lastly residues and wastes (section 7.4). The chapter ends with a conclusion.

7.1 Sugar and Starch Crops

This type of feedstock has either a high starch or sugar content. Typical crops of this type are corn, sugar cane, sugar beet, and potatoes. Today, the primarily used sugar and starch products are corn (mainly in the USA) and sugar beet and sugar cane (Brazil). These crops are used in several sectors and have the largest share in the food industry (Bassam, 2015; Pennington, 2020). The high sugar and starch content make these crops suitable for ethanol production. Due to the suitability for ethanol production, the ethanol yields are considered. By fermenting the sugars in the crop ethanol is produced. The higher the sugar content, the higher the ethanol yield.

Table 3 shows the results for the data collection for the criteria for the sugar and starch crops. Appendix C includes Table 26 which contains the sources that have been consulted for the quantification of the criteria. According to Table 3, sugar and starch crops are mainly first-generation feedstocks. This means that it is also a food crop, and therefore competes with the food industry. Another interesting finding is that the only crops with the option to produce on marginal land are sweet sorghum and cassava. This feature indicates that their competition for food production is slightly lowered. Looking at fertilizer use, sugar cane and sorghum require the lowest amount (when considering the lower range) whereas, potatoes and cassava demand the most (when considering the upper value). The highest energy yield is found for sorghum, sugar cane, and sugar beet. Biodiversity impact is lowest for maize but the lowest carbon debt is for sugar beet.

Table 3: The feedstock table for the sugar and starch type feedstocks for the production of ethanol. The table indicates several characteristics of seven sugar and starch crops with their ethanol yields and fertilizer use.

Feedstock	**Generation (-)**	**Biodiversity (-)**	**Yield ($*10^3$ L ethanol/ha**	**Fertilizer use (kg N/ha)**	**Marginal Land Use (-)**	**Carbon Debt (days)**
Maize/Corn	1	0.5	5.3	157	1	150
Wheat	1	0.6	2.2	150	1	175
Sugar beet	1	0.6	5.2 - 6.5	120	1	80
Sugar cane	1	0.67	5.0	34 - 123	1	330
Potatoes	1	0.67	1.6	168 - 224	1	105
Sorghum	1	0.67	10.5	60 - 120	10	125
Cassava	1	0.67	2.8	180 - 250	10	390

7.2 Oil Crops

This feedstock type includes crops that produce seeds that are high in oil content. The oil in the seeds is suitable for vegetable oil production. This vegetable oil is part of the food industry, can be directly used as a fuel, or converts via a transesterification reaction into biodiesel. Besides these applications, there are many more sectors in which they play a role (like the cosmetic sector). As mentioned, there are a considerable number of oil crops available for the production of biodiesel. No plant has the same chemical structure and nutrient content. This difference in composition influences the calorific value of the diesel. Not only the calorific value is affected, but also the quality of the diesel may differ due to structural differences of the plants (Pennington, 2020; Bassam, 2015).

In Table 4, eleven oil crops are presented. For flax, it was not possible to find the yield per land area. Appendix C includes Table 26 which contains the sources that have been consulted for the quantification of the criteria. Jatropha, palm oil, and cotton seeds are not used in the food industry and are thus a second-generation feedstock. Algae is also included as an oil crop and is of the third-generation feedstock type. The algae considered here are grown in water tanks placed on land. Algae is still a feedstock under investigation, meaning that the yields are potentials rather than real data. This side note might also explain why algae give such a high oil yield per area. The criterion yield shows that algae, palm oil, and jatropha are the most efficient. Maize grain oil is severely underperforming compared to the other oils. A reason for this bad performance can be that it is primarily a sugar and starch crop and not an oil crop. The oil content of a maize grain may therefore be lower, and thus the yield is lower. Algae require the largest amount of fertilizer, followed by palm oil, mustard, and sunflower, which will result in significant emissions compared to the other crops. The option to use marginal land is available to all oil crops except for soybean, rapeseed, and maize grain oil, which is unfavorable for these crops since they are also first-generation feedstocks. Being a 1G crop and unable to grow on marginal land make that their competition with the food industry is enlarged. Also, these characteristics make them unfavourable when looking at land use.

Table 4: The feedstock table for the oil type feedstocks for the production of biodiesel. The table indicates several characteristics and biodiesel yields of ten oil crops and one microorganism.

Feedstock	**Generation Type (-)**	**Biodiversity (-)**	**Yield ($*10^3$ L biodiesel/ha)**	**Fertilizer use (kg N/ha)**	**Marginal Land Use (-)**	**Carbon Debt (days)**
Soybean	1	0.56	*0.6*	22 - 45	1	157
Jatropha	2	0.50	*1.8*	140	10	108.5
Oil Palm	2	0.81	3.7-6.1	34	10	14
Rapeseed/Canola	1	0.43	0.8	80	1	103
Camelina	1	0.67	0.6	50-120	10	92.5
Maize Grain oil	1	0.50	0.2	157	1	150
Sunflower	1	0.60	0.7 - 1.0	114	10	119
Mustard	1	0.67	0.6 - 1.3	66	10	87.5
Flax/Linseed	1	0.67	?	80	10	100
Cotton Seeds	2	0.50	0.3 - 0.4	66	10	109.5
Algae	3	0.2	45.0 - 137.0	*867*	10	24.5

Italic: self calculated value

7.3 Lignocellulosic Crops

Lignocellulosic crops have high cellulose content. This type of feedstock generally produces a range of bioenergy products. It produces heat and electricity by combustion or liquid biofuels like ethanol by several chemical processes. The lignocellulosic crops are often also known as energy crops. There exist two types of cellulosic crops, namely annual and perennial crops. Annual crops are crops that last for one year and must be replanted after harvest. Perennial crops have the advantage that when harvested, the root system is left intact, and they can regrow for another harvest cycle. The elimination of additional sowing cycles reduces the (i)LUC emissions. When regrowth is possible, it facilitates a more constant habitat for species due to more constant land covering. This continued cultivation is favorable for biodiversity. The roots of perennial crops are left in the ground after harvest. When the harvest is at the right moment (depending on the crop), the plants' nutrients are stored around or in the root system and thus remain in the ground. When the soil keeps its nutrients the soil quality is maintained, and the required fertilizer reduces. Such a harvest strategy and the fact that good yields can be obtained with limited amounts of water makes that perennial crops show good potential to be grown on marginal land (Pennington, 2020; Smith, Current, Schulman, & Easter, 2018; Hikmah et al., 2016).

Table 5 gives the results of the literature data search for the criteria for the lignocellulosic feedstocks. Appendix C includes Table 26 which contains the sources that have been consulted for the quantification of the criteria. In total, fifteen lignocellulosic feedstocks are considered. Of these fifteen, only one (kenaf) is a first-generation feedstock. The crop that generates the most energy per land area is hemp, followed by kenaf. It was not possible to find ethanol yield for all species. However, for the species that did give ethanol yields, it is observed that cereal straw gives the highest value. Significant ethanol production is observed for the eucalyptus tree, miscanthus, and hemp. They are to some extent akin to the yields for the sugar and starch crops. Maize stover, rice straw and husk, and cereal straw cannot be grown on marginal land. These feedstocks can also be considered as a waste stream from the production of maize, rice, and cereal. This aspect indicates that their use does not directly require land. The results show that several feedstocks do not require any application of nitrogen fertilizer. Low fertilizer use is in favor of the controversy of emissions. The highest fertilizer demand is for rice straw and husk, however as already explained above, it is a waste stream of another sector. The right allocation of the amount of fertilizer will determine the actual fertilizer requirement for this feedstock. For now, however, the amount of fertilizer and land use is similar to that of rice, straw and maize production. The lowest biodiversity impact is for miscanthus, followed by switchgrass, prairie grasses, poplar, and reed canary grass. The smallest time gap for CO_2 recapture is observed for alfalfa. This value is by far the lowest of the lignocellulosic crops considered.

Table 5: The feedstock table for the lignocellulosic type feedstocks for the production of power, heat and ethanol. The table indicates several characteristics of fifteen lignocellulosic crops, including ethanol yields (L/tonne and L/ha) and heat, power and LHV yields.

Feedstock	**Generation Type (-)**	**Biodiversity (-)**	**Yield (GJ/ha)**	**Yield ($*10^3$ L ethanol/ha)**	**Fertilizer use (kg N/ha)**	**Marginal Land Use (-)**	**Carbon Debt (days)**
Switchgrass	2	0.31	25.3[2]	3.7	112	10	365
Prairie Grasses	2	0.33	*313.7*[2]	1.1	70	10	105
Miscanthus	2	0.17	*147.2*[2]	5.2	- [7]	10	365
Sugarcane Bagasse	2	0.67	69.2 - 72.7	-	-	1	330
Rice Straw and husk	2	0.50	84.8[2]	*1.3*	250	1	115
Maize Stover	2	0.50	-	1.4	-	1	150
Willow	2	0.08	*74.2*[5], *174.0*[2]	*3.1*	112	10	1080
Poplar	2	0.33	78.2[2]	*0.9*	56	10	5475
Cereal Straw	2	0.67	48.4[2]	*10.9*	-	1	175
Eucalyptus	2	0.62	461.8[2]	*8.5*	30 - 60	10	1350
Alder	2	0.60	728.1[2]	-	93	10	1095
Alfalfa	2	0.50	69.4[2]	1.3	-	10	34
Reed Canary Grass	2	0.33	133.8[2]	-	84	10	273.5
Hemp	2	0.50	*339.4*[2]	*4.3 - 5.2*	60-100	10	110
Kenaf	1	0.60	268.5[2]	*4.5*	20 - 60	10	150

[2] Lower heating value dry matter
[5] Power
[7] Only on very low N holding soils fertilizer is required
Italic: self calculated value

7.4 Residues and Wastes

Like mentioned before, bioenergy uses organic resources. The food and agricultural industries generate several organic wastes. This waste often has some function in other sectors (like cattle feed or animal bedding) but can also be used for energy generation. With an expected increase in food demand, organic wastes will most probably also increase. The use of organic wastes for bioenergy can function as a means of waste management. By producing energy from waste, the production process improves. This feedstock type can produce bioenergy in the form of heat, electricity, or biofuels.

Table 6 shows the gathered characteristics for the waste and residues feedstock type. Appendix C includes Table 26 which contains the sources that have been consulted for the quantification of the criteria. Within this feedstock type, land use and fertilizer are left out of consideration. On a side note, the food industry wastes and the olive oil cake indirectly require fertilizer use since it is plant-based waste (the same holds for some of the cooking oils). However, for simplicity, no fertilizer and land use are allocated. The same reasoning is used for the biodiversity impact and the carbon cycle since there is no direct production of crops for these feedstocks no biodiversity impact and no growth cycle are assigned. Two waste streams produce biodiesel, namely that of waste cooking oils and that of animal fats. The lower heating value (LHV) of the corresponding biodiesels show a minimal difference to each other. However, animal fats give higher LHV. Looking at the LHV (the MJ/Mg) of the other waste streams, wood residues have the highest value, followed by the olive press cake. The highest ethanol yield is observed for chicken manure, followed by organic municipal solid waste (MSW) and wood residues. These lower calorific values represent the energy resulting from burning one megatonne of dry feedstock. Wood residues can be considered to be a type of lignocellulosic feedstock. When comparing the yield for wood residues to that of lignocellulosic, it is seen that wood residues produce significantly more ethanol per land area. The higher heating value of woody residues does not differ so much from that of the lignocellulosic feedstocks.

Table 6: The feedstock table for the residues and waste type feedstocks. The table indicates several characteristics of seven residues or waste streams.

Feedstock	**Generation Type**	**Yield (GJ/Mg)**	**Yield (GJ/ha)**	**Yield ($*10^3$ L ethanol/ha)**
Wood Residues	Second	18.4[2]	*1.2*[3]	184000[2]
Industrial Food Waste	Second	16.8[2]	-	-
Municipal Solid Waste	Second	17970[2]	-	-
Chicken Manure	Second	5.5[5,6]; 12.6[2]	-	-
Waste Cooking oils	Second	37.8[1]; 36.6[2]	-	-
Agro-industry wastes (olive cake)	Second	18.0[2]	-	-
Animal Fats	Second	37.9[1]	-	-

[1] Lower Heating Value of the biodiesel made from corresponding vegetable oil
[2] Lower heating value dry matter
[3] Sum of ethanol yields of sawdust and savings, early thinning, tops and branches and hog fuel
[5] Power
[6] Heat
Italic: self calculated value

7.5 Conclusion

This chapter introduced the different types of feedstocks, quantified the criteria, discussed the data shortly, and compared the feedstocks within their feedstock type. It can be concluded that most of the sugar and starch, and some of the oil crops, function as food crops, and production on marginal land is infeasible. These factors are not in favor of land use, competition with food, and biodiversity controversy. No Fertilizer requirements exist for most of the lignocellulosic crops and are not included for the residues and waste streams. A lower fertilizer use results in lower (i)LUC emissions, and thus the lignocellulosic crops are in favor considering the controversy of emissions. The highest ethanol yield is to be for wood residues. The oil crop that produces the most biodiesel per land area is algae. However, energy from this species is still undergoing technological developments and is not yet widely applied. When considering 2G crops only, the highest biodiesel yield per land area is palm oil. The more efficient the crop is, the less land is required to meet energy demand by that feedstock. The feedstocks that score high for the criterion yield are scoring well for the controversy of land use.

From this chapter, it becomes already clear that the residues and waste feedstocks will be scoring high. Residues and wastes streams do not have direct requirements for land and fertilizer, are no first-generation feedstocks, have no direct impact on biodiversity, and their yields are not low. These factors indicate that their ranking will be higher than some other feedstocks considered. However, if this is the case will be made known in the next chapter. In chapter 8, the theory behind the ranking will be given, together with the execution of the MCDA.

8 Feedstock Ranking

In this chapter, the aim is to perform a ranking of the feedstocks to determine which feedstocks are the least controversial. This is done by performing a multi-criteria decision analysis (MCDA). Before executing the ranking, establishing a basic understanding of the concepts and aspects of an MCDA is necessary. This background further gives information about existing MCDA methods and which weighting methods exist. Using this information, a suitable method for this research can be selected. No prior knowledge about performing such decision making was present. Consulting literature about MCDA supplied the necessary information. With the help of the search engines of TU Delft online library, ScienceDirect, and Google Scholar, information about MCDAs was obtained. The search terms used were Multi-criteria decision analysis, MCDA ranking methods, Choosing the right MCDA method, and Bioenergy feedstock ranking. This literature search resulted in the choice to use the outranking MCDA method PROMETHEE II and the Entropy weighting method for the primary ranking. The concepts of an MCDA are explained in section 8.1. Within this section, the weighting method and outranking method are also chosen and explained. Section 8.2 presents the methods for the sensitivity analysis, and section 8.3 explains how the decision matrix (DM) is constructed. Lastly, in section 8.4 the results of the base case and the sensitivity analysis are presented.

8.1 Multi Criteria Decision Analysis

An MCDA is a tool that helps select the best option for a decision-maker. It takes several criteria for different options into account. By using input from the decision-makers it results in the best option suiting their preferences or according to the data. MCDA differentiates two decision-making problems: continuous (linear) decision problems or discrete decision problems (outranking). A continuous MCDA is quite similar to a linear programming problem and therefore represents simple decision making problems. The discrete problem is based on the input data and makes use of preferences of one alternative over another. The priority can be related to defined thresholds that identify uncertainty (Wątróbski, Jankowski, Ziemba, Karczmarczyk, & Zioło, 2019).

Another aspect in which MCDA methods can differ is the type of data used. Within an MCDA it is possible to use both qualitative and quantitative data. The data can also vary in scale: cardinal or ordinal scale, where the cardinal scale can be of the type interval, or it can be relative. This scale difference is important for identifying the data as certain (deterministic) or uncertain (non-deterministic). This data classification is necessary for choosing the method to use. With the introduction of fuzzy sets, it is possible to express non-deterministic data and therefore use them in MCDA (Wątróbski et al., 2019).

The MCDA requires firstly to identify the objective for the decision. This research is to find the least controversial feedstocks. The next step is to identify the criteria. The criteria used for this ranking are given in chapter 6. After defining the criteria and finding data for each alternative, the criteria can be weighted. When the weighting is done, the MCDA can be performed. The last two steps involve interpreting the results and making a decision or recommendation (Wątróbski et al., 2019). For this case, the aim is to identify the least controversial feedstocks using the results. Now that the basics of an MCDA are explained, the selected weighting method and the MCDA method will be discussed.

8.1.1 Entropy Weighting Method

For this analysis, the entropy weighting method (EWM) applies. This method will assign different weights for each criterion. The entropy method is chosen because it is an objective method. Most of the weighting methods for an MCDA are based on the weights assigned by decision-makers. Therefore, they classify as subjective weightings. However, for this method, no decision-makers are present. It was, therefore, chosen to use an objective weighting method. Since the EWM is one of the most widely applied objective methods, and it was used in another bioenergy feedstock ranking research, it is a logical choice (Lotfi & Fallahnejad, 2010; Anwar et al., 2019).

Entropy is a measure for the amount of information that the criterion holds. Using the EWM, the criteria are valued and weighted by calculating the dispersion between the six criteria. Dispersion indicates scatter of data. When the data is widely spread (for example 1, 20, 50, 100) it has a large dispersion. When the data is closely spread (for example 1, 2, 3, 4) is has a small dispersion. When the dispersion is large, the differentiation between the criteria is also large, and the result is a higher weight for this criterion. A high dispersion indicates a data set with a lot of information and thus a higher weight is assigned. This working principle indicates that the weighting is purely data-based. This principle makes it an objective method (Zhu, Tian, & Yan, 2020; X. Li et al., 2011; Vajapeyam, 2014). The entropy method is useful in decision making without decision-makers, since it can measure differences that occur between the data of the criteria and in that way clarifies the inner information of the data (Hafezalkotob & Hafezalkotob, 2015).

The entropy weights can be calculated in the following steps (Anwar et al., 2019):

- Normalization of DM using:

$$r_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}} \tag{1}$$

Where X_{ij} is the value of j$^{\text{th}}$ criterion for the i$^{\text{th}}$ feedstock, and m is the number of feedstocks.

- Entropy calculation using:

$$E_j = -\frac{1}{ln(m)} \sum_{i=1}^{m} r_{ij} * ln(r_{ij}) \tag{2}$$

Where E_j indicates the entropy of the j$^{\text{th}}$ criterion, n is the number of criteria and $j = 1, 2, .., n$, and m the number of feedstocks.

- Lastly, the weight calculation using:

$$w_j = \frac{1 - E_j}{\sum_{j=1}^{n}(1 - E_j)} \tag{3}$$

Where w_j indicates the weight for criterion j, $j = 1, 2, ..., n$.

So, the entropy method outputs weights for the criteria derived directly from mutual differences and dispersion of the data for the criteria. Therefore, no more subjectivity, ineptitude, or absence of decision-makers problems are present (Anwar et al., 2019).

8.1.2 PROMETHEE II Ranking Method

The two main outranking methods that exist within the MCDA are that of PROMETHEE and ELECTRE. For this analysis, the ranking will be performed using the PROMETHEE method, mainly because it is a more simple model to apply than ELECTRE.

The PROMETHEE method is a useful method for ranking a large number of alternatives. There exist several versions of PROMETHEE and for this research, the decision is made to use PROMETHEE II since this method performs a complete ranking of the alternatives, whereas PROMETHEE I only performs partly rankings. This method ranks the feedstocks by performing a pairwise comparison in which one feedstock can outrank the other one according to the values for one criterion. By doing this, the alternative or feedstock gets a preference degree that ranges between 0 and 1, and a net flow gives the final ranking from best to worst feedstock (Safari, Sadat Fagheyi, Sadat Ahangari, & Reza Fathi, 2012; Cinelli, Coles, & Kirwan, 2014). The method of PROMETHEE consists of three main steps: first, it calculates the preference degree for every pair of alternatives for every criterion, then the flows are calculated, and third, it uses the overall flows to rank the feedstocks (Ishizaka & Nemery, 2013).

The preference degree indicates how, or to what degree, the alternative is preferred over another based on the data for the criteria. The preference is expressed by values between 0 and 1. When there is a total preference of one alternative over another, the preference gets a value of 1. A value of 0 indicates no preference for the feedstock. Values between 0 and 1 indicate that some degree of preference exists for either one of the alternatives. The preference can be determined using a linear or a Gaussian function, see Figure 13. For the linear function, there exists a gradual increase where the variable is the difference in preference for that criterion. The Gaussian function has an exponential increase. As can be seen from Figure 13 the linear function requires an indifference threshold q and a preference threshold p. The Gaussian function only requires the inflection point s. A value of zero preference is assigned when the difference between the alternatives is smaller than the indifference point, if this difference is higher than the preference a value of 1 is assigned (Ishizaka & Nemery, 2013).

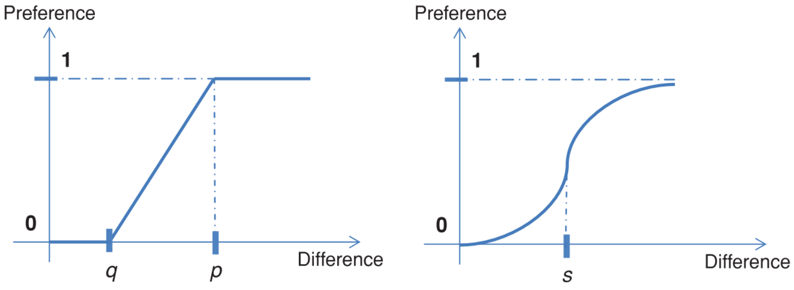

Figure 13: Graphical representation of the linear preference function (left) and Gaussian preference function (right) for the PROMETHEE outranking method (Ishizaka & Nemery, 2013).

When all preferences are determined, they are summarized in three types of flows: positive, negative, and net flows. The flows indicate the preference of one feedstock over all other feedstocks. The higher the positive flow, the more preferred the feedstock is. A negative flow indicates an average behavior, and the net flows take both negative and positive flows into account. Thus, the flows are based on the calculated preferences. The preferred feedstock gets a positive flow, and the non-preferred a negative one. Once the preferences are given a negative or positive flow, the net flows are calculated. This is the summation of positive and negative flows for each feedstock for that criterion. After applying the weights for each criterion, global flows can be established to rank the feedstocks. The global flow is the sum of the net flows of each criterion for the feedstock (Ishizaka & Nemery, 2013).

The PROMETHEE method can also be described using the following formulas (Kocmanová et al., 2013):

- Preference degree:
$$P(a_i, a_j) = P|f(a_i) - f(a_j)| = P(d), P(d) \in (0, 1) \tag{4}$$
Where $P(d)$ is the preference of $f(a_i)$ over $f(a_j)$, and $f(a)$ is the value of the feedstock i or j for one criterion.

- Preferential strength or aggregated preference calculation:
$$\pi(a_i, a_j) = \sum_{h=1}^{k} w_c * P_h(a_i, a_j) \tag{5}$$
Where w_c is the weight for criterion c, and c = 1, 2, .., n.

- Positive and negative flow calculation:
$$F'^{+}(a_i) = \sum_{a_j \in A} \pi(a_i, a_j) \tag{6}$$
$$F^{-}(a_i) = \sum_{a_j \in A} \pi(a_j, a_i) \tag{7}$$
Where $F^{+}(a_i)$ is the positive flow, and $F'^{-}(a_i)$ the negative flow.

- Net flow calculation:
$$F(a_i) = F^{+}(a_i) - F^{-}(a_i) \tag{8}$$

8.2 Sensitivity Analysis

To check the robustness of the ranking of the base case, a sensitivity analysis is performed. Such an additional analysis changes one parameter or one aspect of the method to see how the results change. For this research, slight alterations in method and weightings are made. In total, four sensitivity analysis are performed. These are all deviating on one point from the base case. This section explains how each sensitivity analysis differs from the base case. To be able to understand the changes made, the base case is first explained. All analysis use the decision matrix as will be given below. No changes in the decision matrix are made.

The MATLAB codes for these methods require the following inputs: a decision matrix, weights of the criteria according to decision maker, criteria sign (minimization or maximization of the criteria), the choice for preference function (linear, Gaussian, etc), and the weight for each criterion. The entropy method and the PROMETHEE II ranking used the decision matrix as given in Table 8. For the entropy calculation, the other input necessary was the weights of attributes according to the decision makers, this is set to 1 for each criterion since no initial importance is present.

The base case makes use of entropy weights and the PROMETHEE II ranking method. The inputs for the entropy weights are described above. For the PROMETHEE II method, the criteria sign and the choice of preference function has to be defined. The criteria signs are the following: C1: -1, C2: 1, C3: -1, C4: -1, C5: -1, and C6: 1. This corresponds with what is given in section 6.4. The preference function is defined by a number between 1 to 6 and can differ per criterion. For this ranking, the choice is made to keep the same preference function for each criterion. The base case is further defined by a linear preference function and corresponds to the number 5. So, these methods and the matching inputs characterize the base case.

The first robustness check changes the preference function of PROMETHEE II. No longer a linear preference is applied but a Gaussian one. The differences between these functions is shown in Figure 13. A change in preference function asks for a change in input for this parameter. Now, this input changes from 5 to 6 for each criterion, because a Gaussian preference function is defined by the number 6. All other parameters and inputs are unchanged and thus similar to the base case.

As a second check, the weights of the criteria were changed to equal weights. This indicates that, with respect to the base case, the method of weight determination changes. The entropy weights are now not used. Another weighting method, the equal weights method, is now applied to assign a level of importance to a criterion. The calculation that now applies is the following (Anwar et al., 2019):

$$EW = \frac{Total\,weight}{Total\,criteria} * 100\% = \frac{1}{6} * 100\% = 16.7\% \tag{9}$$

Equal weights thus indicate that each criterion is considered equally important. The total of weight is 1 or 100%. To assign equal weights 1 or 100% is divided by the total number of criteria, which is six for this analysis. Again, only the weights are changed for this sensitivity analysis and thus this is the only input that changes. All other inputs are kept identical to the base case.

For the next analysis, the weights changed. Since the base case makes use of objective weights, it is interesting to see how the results vary when subjective weights are applied. One problem: there are no decision makers for this research. To be able to apply subjective weights, decision makers need to be present. However, the criteria are based on the controversies. Using the literature consulted for the identification of the controversies, some degree of preference for the criteria can be deduced. The method for subjective weights is the one of Fuzzy Analytical Hierarchy Process (F-AHP). This method assesses the criteria by pairwise comparison. Criteria are plotted against each other and the decision maker gives per criterion a value of importance with respect to another criterion. When the same criteria (for example C1 vs C1) are compared it gets the value 1 which indicates equal importance. The following meaning per score exists (Samanlioglu, 2018):

- 1 - Represents equal importance.
- 3 - Represents moderate importance.
- 5 - Represents strong importance.
- 7 - Represents very strong importance.
- 9 - Represents extremely importance.

For clarification: if C1 has strong importance over C3, the row C1 and column C3 gets the value 5. To assign the level of importance of C3 vs C1, for this example, the value gets the reciprocal of the preference assigned for C1 vs C3. That is, C3 cannot be equally or more important than C1 because it was previous defined that C1 was strongly more important than C3. Once the level of importance is assigned, a number of calculations occur and it results in a single value for each criterion which represents the subjective weights (Samanlioglu, 2018). No detailed calculations are given in this report because they are performed by using the MATLAB function made by Ferhat Ogzur Catak (Catak, 2020). This code required the comparison matrix as input and the one used here is give in Appendix D in Table 28.

The last ranking used the most simple form of an MCDA: only applying the entropy weights. For this method, no pairwise comparisons are made between the feedstocks. The only factor that influences the data is the weights. Due to the weights, different levels of importance are applied to the criteria and thus the data. After applying the weights, the criteria signs are applied. The criteria signs are similar to as defined for the base case. it results in negative values for C1, C3, C4, and C5. For C2 and C6, the criteria sign results in positive values. Then, for each feedstock the scores for every criteria are summed. This results in one value for each feedstock. Based on this value, the ranking is performed. A higher value indicates a higher rank and vice versa.

The weights used for each analysis are given in the table below. From the table the division of the entropy weights is shown. When applying the entropy method, the criterion considered most important is that of land use, followed by the carbon debt, and chain emissions. A lowest importance is assigned to marginal land use and biodiversity. The equal weighs, as explained, show equal importance for each criterion, and thus the same weight is applied to every criterion. When a subjective weighting method is applied, the criterion with highest importance is again land use, followed by competition with food industry, and chain emissions. The least important is marginal land use and the biodiversity.

Table 7: The weights used in the feedstock rankings (%). Where C1 refers to land use, C2 to competition with food industry, C3 to chain emissions, C4 to biodiversity, C5 to carbon debt, and C6 to marginal land use.

Analysis	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Base Case	61	0.9	9.8	4.2	20	4.0
Gaussian	61	0.9	9.8	4.2	20	4.0
Equal Weights	16.7	16.7	16.7	16.7	16.7	16.7
Fuzzy Weights	30.2	26.6	26.3	5.2	11.0	0.7
No MCDA	61	0.9	9.8	4.2	20	4.0

8.3 Decision Matrix

To construct the decision matrix, first, the decision criteria must be defined. Since this research aims to identify the least controversial feedstocks the controversies indicated in chapter 6 are used. As explained in chapter 6, the following criteria are derived:

1. Land use (C1)
2. Competition with food industry (C2)
3. Emissions (C3)
4. Biodiversity impact (C4)
5. Carbon debt (C5)
6. Marginal land use (C6)

Although C6 is not specifically mentioned as a controversy in chapter 6, it plays a role in some controversies and is an important factor in the bioenergy debate. Because it is a part of two criteria (land use and biodiversity), it was decided to make it a separate criterion as explained in the previous chapter.

For C1 (land use), some of the values as presented in Table 25 are converted from L/ha to MJ/ha. The calculation was done by using the following formula:

$$Land\,area = fuel\,yield\,(L/ha) * \rho_{Fuel}\,(kg/L) * LHV_{fuel}\,(MJ/kg) \tag{10}$$

The residues and waste streams do not have a value for C1. To include this criterion for them values for land use are inverted to give ha/MJ data. Due to this conversion, maximization is no longer the aim, but minimizing is. The more MJ one hectare of feedstock produces, the less land is needed to meet the bioenergy demand. The criteria for which the residues and waste streams do not have a value, a zero is indicated. However, for the ranking itself a value close to zero (0.0001) is filled in. That is, as explained in previous chapter, because MATLAB does not allow zeros in the decision matrix. The decision matrix and the data used in the ranking are presented in table 8.

Knowing the theory behind the entropy weighting method and considering the data in the decision matrix, the weights as presented in Table 7 can be explained. The EWM makes use of dispersion between the data for a criterion. The larger the dispersion, the more information the data set contains and thus the higher the weight. Here, the land use criterion has the highest weights and marginal land use the lowest. For the criterion of land use, the data ranges from 0 to $170*10^{-6}$ without gradual increases. This indicates a high dispersion. The data for marginal land is either 1 or 10. Values between 1 and 10 are not present and the dispersion is thus low. Likewise, the data for the competition with food criterion have the value 1, 2, or 3 and thus have a low dispersion. This high dispersion for criterion C1, and low dispersion for criteria C2 and C6 correspond to their entropy weights: C1 has highest weight, C2 and C6 lowest weights. The criterion of carbon debt (C5) also shows large dispersion: it ranges between 14 and 5475 days with no stepwise increase. This dispersion is - due to the high carbon debts for eucalyptus, Alder, poplar and willow - larger than observed for the criterion of chain emissions (C3) and thus criterion C5 has a higher weight than criterion C3.
This way of dividing importance among the criteria, clearly shows that it is completely data based.

Table 8: The decision matrix as it will be used in the MCDA. Where C1 refers to land use ($*10^{-6}$ ha/MJ), C2 to competition with food industry (-), C3 to chain emissions (kg N/ha), C4 to biodiversity (-), C5 to carbon debt (days), and C6 to marginal land use (-).

Feedstock	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Maize/Corn	9.4	1	157	0.50	150	1
Wheat	23	1	150	0.60	175	1
Sugar beet	8.6	1	120	0.60	80	1
Sugar cane	10	1	78.5	0.67	330	1
Potatoes	31	1	196	0.67	105	1
Sorghum	4.8	1	90	0.67	125	1
Cassava	18	1	215	0.67	390	10
Soybean	50	1	33.5	0.56	157	1
Jatropha	17	2	140	0.50	108.5	10
Oil Palm	6.2	2	34	0.81	14	10
Rapeseed/Canola	41	1	80	0.43	103	1
Camelina	52	1	85	0.67	92.5	10
Maize Grain oil	170	1	157	0.50	150	1
Sunflower	36	1	114	0.60	119	10
Mustard	33	1	66	0.67	87.5	10
Flax/Linseed	100	1	80	0.67	100	10
Cotton Seeds	82	2	66	0.50	109.5	10
Algea	0.34	3	867	0.20	24.5	10
Switchgrass	13	2	112	0.31	365	10
Prairie Grasses	45	2	70	0.33	105	10
Miscanthus	9.6	2	0	0.17	365	10
Sugarcane Bagasse	14	2	78.5	0.67	330	1
Rice Straw and husk	39	2	250	0.50	115	1
Maize Stover	35	2	157	0.50	150	1
Willow	16	2	112	0.08	1080	10
Poplar	53	2	56	0.33	5475	10
Cereal Straw	4.6	2	150	0.67	175	1
Eucalyptus	5.9	2	45	0.62	1350	10
Alder	1.4	2	93	0.60	1095	10
Alfalfa	39	2	0	0.50	34	10
Reed Canary Grass	7.5	2	84	0.33	273.5	10
Hemp	11	1	80	0.50	110	10
Kenaf	11	2	40	0.60	150	10
Wood Residues	4.1	2	0	0	14	10
Industrial Food Waste	0	2	0	0	14	10
Municipal Solid Waste	0	2	0	0	14	10
Chicken Manure	0	2	0	0	14	10
Waste Cooking oils	0	2	0	0	14	10
Agro-industry wastes (olive cake)	0	2	0	0	14	10
Animal Fats	0	2	0	0	14	10

8.4 Results

In this section, the results from the PROMETHEE II ranking are presented. The results of the base case are firstly given, followed by the sensitivity analysis. To produce results, MATLAB (R2020b) was used. In MATLAB the weights and the PROMETHEE ranking were performed. The sensitivity analysis that performed the most simple MCDA method was performed in Microsoft Excel. The base case and the four different sensitivity analysis made use of the methods as described in the previous sections, and the weights for each ranking is presented in Table 7. The functions for the weighting and the ranking methods were retrieved from MATLAB Central File Exchange. The file exchange is found on the official webpage of MATLAB. Irik Mukhametzyanov (2020) (Mukhametzyanov, 2020) created the specific functions for the entropy weighting and PROMETHEE II ranking.

First, a base case was constructed and evaluated. The second step included performing the sensitivity analysis to test the robustness of the results. The sensitivity analysis entails that one parameter is changed, whereas the rest stays as defined in the base case. Lastly, from the results of the base case and the sensitivity analysis, a comparison of the ten least controversial crops resulted in a list of eight least controversial crops.

Table 9: Results of the MCDA analysis (Base Case) and the sensitivity analysis. Where Gaussian indicates a Gaussian preference function, EW stands for Equal Weights, F-AHP stands for Fuzzy AHP weighting and Simplest MCDA refers to the case where the simplest form of MCDA is used. The rank of 1 represents the least controversial feedstock and thus the best one, and a rank of 40 represents the worse feedstock.

Feedstock	**Base Case**	**Gaussian**	**EW**	**F-AHP**	**Simplest MCDA**
Maize/Corn	26	26	32	33	24
Wheat	32	30	37	36	29
Sugar beet	22	23	30	27	14
Sugar cane	35	34	**38**	25	33
Potatoes	29	28	**39**	**38**	23
Sorghum	20	21	26	21	19
Cassava	**40**	**38**	34	**40**	36
Soybean	17	16	22	12	22
Jatropha	21	20	21	30	21
Oil Palm	**9**	**9**	**9**	**9**	**8**
Rapeseed/Canola	19	18	25	18	16
Camelina	16	14	16	19	11
Maize Grain oil	26	27	32	33	24
Sunflower	18	17	18	26	20
Mustard	11	11	12	14	10
Flax/Linseed	14	**40**	14	16	12
Cotton Seeds	12	12	11	13	15
Algea	23	22	19	29	35
Switchgrass	36	33	28	32	34
Prairie Grasses	13	13	13	15	13
Miscanthus	24	19	17	10	31
Sugarcane Bagasse	34	32	36	24	32
Rice Straw and husk	30	31	**40**	**39**	27
Maize Stover	25	25	31	31	24
Willow	**39**	**39**	29	37	37
Poplar	37	36	24	23	**40**
Cereal Straw	31	29	35	35	28
Eucalyptus	33	35	23	20	**39**
Alder	**38**	37	27	28	**38**
Alfalfa	**8**	**8**	**8**	**8**	**9**
Reed Canary Grass	28	24	20	22	30
Hemp	15	15	15	17	17
Kenaf	10	10	10	11	18
Wood Residues	**1**	**1**	**1**	**1**	**1**
Industrial Food Waste	**1**	**1**	**1**	**1**	**1**
Municipal Solid Waste	**1**	**1**	**1**	**1**	**1**
Chicken Manure	**1**	**1**	**1**	**1**	**1**
Waste Cooking oils	**1**	**1**	**1**	**1**	**1**
Agro-industry wastes (olive cake)	**1**	**1**	**1**	**1**	**1**
Animal Fats	**1**	**1**	**1**	**1**	**1**

8.4.1 Ranking of the Base Case

The base case characterizes by the following inputs: the decision matrix as given in table 8, by the criteria signs: minimization or maximization of the criteria as explained in section 6.4 (C1: -1, C2: 1, C3: -1, C4: -1, C5: -1, C6: 1), and a linear preference function for all criteria. This resulted in the ranking as observed in table 9. The feedstocks with the highest ranks are that of the type residues and wastes streams. All of these feedstocks score equally high and therefore rank number one. The least controversial crop is alfalfa, which is a lignocellulosic non-food crop. After alfalfa, palm oil ranks 9^{th}. The feedstock ranked lowest is cassava. This crop is a sugar and starch crop used for ethanol production. Willow and alder rank just above cassava. Both are woody-SRC and thus lignocellulosic crops. Looking at the energy crops miscanthus and switchgrass, they both score below 20, where Switchgrass scores even below rank 30.

8.4.2 Sensitivity Analysis

To see how the ranking changes when changing the input parameters, a sensitivity analysis is performed. When the preference function changes from a linear function to a Gaussian one, the residues and waste streams are still the least controversial feedstocks. It also shows that alfalfa is again the least controversial crop, and palm oil is again ranked 9^{th}. With a Gaussian preference function, the most controversial feedstock is flax/linseed, which scored relatively high in the base case and is, therefore, a significant deviation. Cassava is now ranked 38^{th} which is not as big of a difference as in the base case. The feedstock on place number 39 is again willow.

When equal weights are assigned to each criterion, they have equal importance. When this is the case, the least controversial feedstocks are again the residues and wastes feedstocks and alfalfa. Palm oil is still ranked 9^{th}. The most controversial feedstock for this analysis turns out to be rice straw and husk. This feedstock is followed by two sugar and starch crops, namely potatoes and sugar cane. These rankings are a large difference from observed for the base case. However, sugar cane is ranked bottom five in both the base case and the Gaussian preference function case. Cassava and the woody-SRC are likewise ranked low.

According to the theory, subjective weights, such as Fuzzy AHP, are constructed using decision-makers. No decision-makers are present for this study. Therefore, the bioenergy debate and the literature consulted during the literature analysis for chapter 6 are used to establish the Fuzzy AHP weights. Appendix D shows the input for the weight calculation. Using subjective weights resulted in the ranking as presented in table 9. From these results, the same feedstocks as for the base case and the other two cases are ranked as least controversial, namely: the residues and wastes streams and alfalfa. The 9^{th} place is for palm oil. Miscanthus is now in place 10. This rank is 14 places higher than in the base case. The feedstock with the lowest rank is the same as for the base case, namely cassava. Rice straw and husk (place 39) and potatoes (place 38) are also considered controversial when using Fuzzy AHP weights. The SRC such as poplar and willow are ranked similarly low with fuzzy weights as with the entropy weights. An exception is for eucalyptus, which scores a lot better than in the base case.

For the last sensitivity analysis, the simplest form of an MCDA was performed: applying weights only. It means that no comparisons between the feedstocks are made to identify their preference over one another. This ranking resulted in that the residues and wastes streams feedstocks are again ranked number one. Alfalfa is now ranked 9th because the 8th place is for palm oil. Poplar is ranked last and therefore considered to be most controversial. Other feedstocks identified as controversial are eucalyptus and alder. The low scoring biomass are all woody-SRC.

Overall, the results show that when having controversies as the criteria, the residues and waste streams are scoring best and ranking the highest. Leaving this feedstock type out results in alfalfa ranking highest, often followed by palm oil, kenaf, and mustard.

8.5 Least Controversial Crops

From all the different rankings performed above, it became clear that the residues and waste streams are the least controversial feedstocks. This type of feedstocks are of a specific type and differ in many ways from crop or plant-based biomass. Therefore, it was chosen to zoom in on the top ten highest ranking crops for each analysis (see Table 10). Hence, for now, neglecting the residues and waste streams. With the help of this top ten, the eight least controversial crop-based feedstocks are identified. The eight crops were selected by placing the ten highest-ranking crops for each ranking next to each other. The crops that scored highest and were present in (almost) all rankings were placed higher in the top eight than the crops that scored lower or were present in fewer rankings. Table 11 gives the eight least controversial plant-based feedstocks. This table shows that alfalfa is the least controversial plant-based feedstock, followed by oil palm. This information is not new and is similar to the results in table 9.

Table 10: The top ten least controversial plant based feedstocks for bioenergy production according to the five rankings. Where Gaus stands for Gaussian preference function, EW stands for Equal Weights, F-AHP stands for Fuzzy AHP weighting and Simplest MCDA refers to the case where the simplest form of an MCDA is applied.

Rank	Base Case	Gaus	EW	F-AHP	No MCDA
1	Alfalfa	Alfalfa	Alfalfa	Alfalfa	Oil palm
2	Oil Palm	Oil Palm	Oil Palm	Oil Palm	Alfalfa
3	Kenaf	Kenaf	Kenaf	Miscanthus	Mustard
4	Mustard	Mustard	Cotton seeds	Kenaf	Camelina
5	Cotton seeds	Cotton seeds	Mustard	Soybean	Flax/Linseed
6	Prairie grasses	Prairie grasses	Prairie grasses	Cotton seeds	Prairie grasses
7	Flax/Linseed	Camelina	Flax/Linseed	Mustard	Sugar beet
8	Hemp	Hemp	Hemp	Prairie grasses	Cotton seeds
9	Camelina	Soybean	Camelina	Flax/Linseed	Rapeseed/Canola
10	Soybean	Sunflower	Miscanthus	Hemp	Hemp

Table 11: The top eight least controversial plant based feedstocks for bioenergy production according to top tens of each ranking performed.

Rank	Crop
1	Alfalfa
2	Oil Palm
3	Kenaf
4	Mustard
5	Cotton seeds
6	Prairie grasses
7	Camelina
8	Hemp

Water Use Up until now, the water use of the crops was neglected. To see how the top eight changes according to their water use, the crop evapotranspiration (ET) is added as an additional criterion. Water use is a critical factor. Water scarcity becomes more evident with time, and climate change makes it a more serious concern for the agricultural sector. ET indicates the amount of water evaporation from both the soil the crop grows on and the transpiration of the crop itself. This value is linked to the irrigation requirements since it refers to the water loss by a cultivated piece of land. The value for ET depends on location since the temperature and climate affect water evaporation. Besides, type of crop, soil management, planting density, and many more factors influence the ET. For alfalfa, an ET value of 800 - 1600 mm per growing season was found. Considering the growth cycle found for criterion C5, the daily water use for alfalfa is on average 2.2 - 4.4 mm/day, based on a growing season of 365 days since alfalfa can be harvested all year round with harvest cycles of 34 days (FAO, n.d.-a). For oil palm, an ET value of 3.0 - 3.7 mm/day was found (Safitri et al., 2018). With an ET value of 765 mm as an average of two years, kenaf has a daily ET of 2.1 mm/day (Perniola, Tarantine, Rivelli, & Disciglio, 2000). Mustard, ranked fourth, has a water requirement of 328 - 373 mm/growing season (Khavse, Singh, Manikandan, Chandrawanshi, & Chaudhary, 2014). Converting this to daily use results in 3.7 - 4.3 mm/day. The water requirement of cotton is 700 - 1300 mm/growing season (FAO, n.d.-b), this corresponds to an ET of 6.4 - 11.9 mm/day. An average ET for the growing season of prairie grasses is 519 mm. Using the growth cycle given in Table 8 prairie grasses have an ET of 4.9 mm/day. Next, camelina has an evapotranspiration value of 332 - 371 mm per growing season or 3.6 - 4.0 mm/day (Hunsaker, French, Clarke, & El-Shikha, 2011). Lastly, the ET of Hemp is 4.3 mm/day (Pejic et al., 2018). These values form the input for the seventh criterion, and a new DM is constructed for the eight crops only. The ranking is performed for the base case scenario and the four sensitivity analysis rankings. The DM is given in Appendix D and the results in Table 12.

Table 12 shows that the addition of the water use criterion does not significantly influence the ranking. The top four (alfalfa, oil palm, kenaf, and mustard) also form the top four with this additional criterion. This compliance is observed for the base case, Gaussian function, equal weights, and fuzzy weights. Before the inclusion of water use, the fifth least controversial crop was cotton seed. With the addition of C7, cottonseed lowers in rank. When no MCDA is applied, there is some deviation observed. Kenaf ranks 6th instead of third, and cottonseeds now have the same rank as in Table 11. The last observation is for the higher rank of prairie grasses, which is one higher for all but when no MCDA is applied. Without an MCDA, prairie grasses are in the top four of the least controversial crops.

Table 12: Results for the ranking of the crops top eight with the extra criterion for water use (C7). Where Gaus stands for Gaussian preference function, EW stands for Equal Weights, F-AHP stands for Fuzzy AHP weighting and Simplest MCDA refers to the case where the simplest form of an MCDA is applied.

Feedstock	**Base case**	**Gaus**	**EW**	**F-AHP**	**Simplest MCDA**
Alfalfa	1	1	1	1	1
Oil palm	2	2	2	2	2
Kenaf	3	3	3	3	6
Mustard	4	4	4	4	3
Cotton Seeds	7	8	8	8	5
Prairie grasses	5	5	5	5	4
Camelina	8	6	6	7	7
Hemp	6	7	7	6	8

9 Discussion

This chapter aims to provide a critical look at the results obtained in chapter 8. The discussion divides into roughly three parts: how robust are the results and the data used, how does it compare with the literature, and what effects have the results on this field of study. After discussing the results, the availability of the lesser controversial feedstock is discussed shortly. Part of the aim of this research is to answer the question if the least controversial feedstocks can solve (some of the) controversies around bioenergy. This is discussed in section 9.4. The discussion is required in order to draw conclusions from the results, the conclusions will be stated in chapter 10.

9.1 Robustness of Results and Data

This section includes a discussion of the results obtained for the base case and the sensitivity analysis. The latter one checks the robustness of the results from the base case. Before discussing the observations themselves, the data used in the ranking (as explained in chapter 7) is debated.

9.1.1 Discussion of the Data

This study aimed to assess the worldwide bioenergy use and thus identify the least controversial feedstocks on a global scale. The data gathered for the ranking has as global values as possible. However, the criteria quantified depend on the climate of a specific location, and thus global data was not always possible. It is critical to understand that the rankings may differ when performing the study on a regional scale and using region-specific data. The impact on biodiversity also depends on the type of land the feedstock is produced on and what the previous function of the land was. Here, these factors are all aggregated, which made it possible to approximate a global scale. If it was possible to get a global value, it was most often an average. The problem with average values is that it does not make the ranking always, for specific regions, valid. For example, the yield of a crop may be higher when grown in tropical climate than in a temperate one. Using the same value for different climates for this criterion will eventually result in different degrees of sustainability, and controversiality. To clarify: the rank a feedstock gets in this research may differ when the ranking is performed on regional scale. This change in rank is because most of the criteria are climate depending. The result of this dependency is that a crop that is less controversial in one region might be more controversial in another one. When regional data is known it can be easily checked, but this is out of scope for this research. Besides affecting the yield, it also interferes with the criteria of emissions, carbon debt, and biodiversity. The use of fertilizer further depends, besides the region's climate, on the type of soil. This fact adds another dimension to the right quantification of fertilizer use. The biodiversity impact, among others, depends solely on the review paper of Immerzeel et al. (Immerzeel et al., 2014). The justification was partly that their work reviewed many papers (about 50). It was further justified by checking whether other studies around this topic came to similar conclusions. However, the impact is not just region-specific but also very complex. The impact can happen on several levels of the ecosystem. A complete impact can, therefore, only be assessed by taking into account all these levels. The absence of such studies today makes the data used for criterion C5 of this research incomplete.

The global view of this research is not ideal. It causes the data unspecific and may create misalignment within the data. Some crops had a global or average value, and some did not. The criteria are region, climate, and soil depending. These factors are not incorporated in this research, and therefore the data may improve with a regional or climate specific scope. Nevertheless, it is unknown to what extent these factors will lead to different values than now used. This study made use of suitable sources, and the findings were checked with the help of others. Also, the information applied in the ranking is feedstock specific (region depending or not), and thus the differences between feedstocks are visualized. The data used is sufficient to give a first and a global ranking of bioenergy feedstocks to identify the least controversial ones.

Besides, it is good to note that the criteria, and thus the controversies, are considered in the broadest sense possible. The criterion of emissions quantifies by the fertilizer use of each crop. This quantification refers to the N_2O emissions from the fertilizer. However, several other emissions are also urgent, like end-of-pipe, transport, and other (i)LUC emissions. For the land use criterion, only the actual land per megajoule is considered. It has no inclusion of side effects of bioenergy production on land use, no land degradation, and no water use. A similar lack of detail incorporation can be mentioned for the other criteria. However, no intentions exist to perform an in-detail study for those factors. The ranking of the eight least controversial crops included water use. This showed that the rank of these crops did not cause large deviations from the primarily obtained results. The choices made for the quantification of the data are in awareness of the exclusion of several other factors. This lack of detail is partly because the bioenergy debate primarily leads this research in which several elements are also often not mentioned.

Nevertheless, despite some room for improvement within the data and the exclusion of some details, the results provide adequate information to consider the results of this study likely and to be able to learn from it in a broad and global sense.

9.1.2 Base Case

The high rank of oil palm is an unexpected result. Most times, this feedstock is seen as very controversial and has several negative side effects. The main benefit of oil palm is the relatively high oil yield, so it has good productivity. Looking at the decision matrix (see Table 8), this is also reflected in C1. A further look into oil palm reveals that its nitrogen fertilizer use is also relatively low. Its biodiversity impact is the highest for all crops considered, but the growth cycle is the lowest. To understand the high rank of oil palm the weighting is determinative. From Table 7 it is seen that the three criteria considered most important are yield, carbon debt, and emissions. These three criteria are also the ones for which oil palm show beneficial scores. Oil palm scores very badly on biodiversity. This criterion only has fourth importance according to the weighting. Because the weights assign lesser importance to biodiversity, its impact on the ranking is low. The criteria where oil palm has a good score have high importance, and therefore oil palm ranks higher than expected. As mentioned in chapter 6, not all controversies are incorporated in full detail due to simplicity. To add to this, the weights assigned are objective and data based. The use of objective weights may not be suitable considering the controversies. The intensity of the discussion about a controversy depends on the importance the scientists assigned to it. This makes that the bioenergy debate is not completely data based and objective weights are not ideal. The exclusion of several factors of (i)LUC and the objective weights give an unexpected high rank for oil palm. Further research and weights determined by decision makers (the scientist from the debate) may result in a different ranking where the rank of oil palm is according to expectations.

It was also not necessarily expected for alfalfa to score that high since it is an unknown crop. However, it is a secondary feedstock that can grow on marginal land and does not require fertilizer. This all makes it an attractive resource. Also, the growth cycle is short, only 34 days. The biodiversity impact from alfalfa is relatively low, and its land to energy ratio is in the middle range. Although alfalfa scores high due to its low carbon debt, its positive result is also facilitated by the fact that it has no "bad score" for any of the criteria.

The feedstock ranked lowest is cassava. This crop is a sugar and starch feedstock used for ethanol production. Cassava is followed by willow and alder, both being woody-SRC and thus lignocellulosic crops. The one thing these feedstocks have in common is their long growth times. As mentioned above, this criterion has the second-highest weight. The high importance of these criteria explains the low scores of these feedstocks. Besides their long growth cycles, they also have a relatively high biodiversity impact. However, this effect will be less significant due to the low weight of C4. The score for the energy crops was not expected due to the promising features often mentioned by the bioenergy advocates. Especially the low rank for miscanthus was unanticipated. A place of 24 is relatively low for this promising feedstock. According to the decision matrix, Table 8, the data seems positive. It has a low land to energy ratio, is a 2G feedstock, requires little to no nitrogen fertilizer, has the lowest biodiversity impact, and can use marginal land. That it can grow on marginal land or that it is a 2G feedstock is, compared to the other feedstocks, not the main benefit. The low impact on biodiversity and the low land requirement are. The cause for the low rank must therefore be the result of the large carbon debt. The value for this criterion is relatively high concerning the other growth cycles. Together with the division of the weights makes that miscanthus ranks low. Besides the division of the weights, a similar explanation as used for oil palm applies. The choice for the weighting method is not necessarily the best one since the debate is not data driven. The choice for the EWM therefore can be the result of the unexpected low rank for miscanthus. Assigning a higher weight to biodiversity will result in an overall higher rank for miscanthus. This is seen in Appendix D.2, where Table 31 shows the top ten crops when biodiversity and land use have the highest importance and thus highest weights. In addition, the controversies are quantified in a global and simplified manner. Leaving out details may cause an unexpected rank for miscanthus.

The unforeseen ranks for oil palm and miscanthus represent points for improvement in the data used and methods selected. Not only the data may cause this, but also the choice of weighting method and the division of the weights. However, real data for the feedstocks are used and the entropy method is correctly applied. Hence, the results give insight into the degree of controversy of the feedstock and least controversial feedstocks can be identified.

9.1.3 Sensitivity Analysis

First, the preference function of the ranking method changed. The main difference between the linear and Gaussian preference function is that the Gaussian one has an exponential increase of preference and no longer a gradual one. With the Gaussian function, only one point, the inflection point, is being considered. Once the preference passes the inflection point, the increase of preference enlarges exponentially. Although deviations from the base case are observed, the feedstocks ranked as least controversial are similar or close. One observation is that the scores for miscanthus and other perennial crops are slightly higher. When the preference function is exponential rather than linear, the comparison may become more accurate. Because the ranking is similar, it supports the results of the base case and thus the robustness of the method used.

Second, the weights were equalized so that all criteria become equally important. When this is the case, the sugar and starch crops are ranked less favorable. These crops are often first-generation, require fertilizer, have a high biodiversity impact, and their growth cycles are long. Now that the weights are equal, the more criteria

the feedstocks score low, the lower the rank. This change in assessment reflects in the score of miscanthus, which is now seven places higher than in the base case. This robustness check shows a shift in results for the most controversial feedstocks. The lowest ranks are still equal to the base case. The middle ranks have slight deviations as well but are of less importance than the lower ranks. This check, therefore, adds robustness to the results for the least controversial feedstocks.
Third, subjective weights are assigned to the criteria. The literature suggests that miscanthus is a promising feedstock. The tenth place for miscanthus now corresponds with the expectations. Although the change in rank for miscanthus is significant, the remaining rankings do not show large differences. The less and most controversial feedstocks are similar as observed before, and thus enforce the results of the base case.
Lastly, the simplest form of an MCDA method was applied: application of weights only. This change results, again, in low rankings for the woody short rotation coppice. Also, good rankings for the waste streams, alfalfa, and oil palm are obtained. This correspondence to the base case adds credibility to the used method. The main change in results is for kenaf (eight down), sugar beet (eight up), and algae (eight down). Without a ranking method used, no preference between the feedstocks is measured, and thus the ranking is purely data-based. This might explain the observed differences and the similarities with the base case. Interesting to note is the observation that there are no real differences between the rankings with and without the use of an MCDA ranking method. This similarity questions the usefulness of an MCDA method.

9.2 Results Compared to the Literature

A comparison of the results with existing literature about the topic gives additional insight into the credibility. Firstly, considering the debate around bioenergy, energy crops such as miscanthus and switchgrass are often discussed as feedstocks with good potential for sustainable bioenergy production (Pulighe et al., 2019; Gatete & Dabat, 2017; Popp et al., 2014). The advocates are more convinced about these crops than the critics. But one might consider these as less controversial. According to the results, the rank of these crops is not coinciding with the advocates' view, except for the ranking done with subjective weights. Prairie grasses, however, score relatively high and are also a perennial lignocellulosic energy crop. A similar oddity about the results is that oil palm scores very high in every ranking, as mentioned above. This result does not align with the literature since oil palm is one of today's most controversial feedstocks (Meijaard et al., 2020). The high rank is therefore not in correspondence with the literature. As explained, the criteria used here are considered in the broadest and global sense. The lack of depth and specification, and the choice for weighting method reflects in the results, and especially for miscanthus and oil palm. However, the residues and waste streams do score high, and this is following the consulted literature. This result indicates that the method used is correct, but a lack of detail causes deviations from expectations.
For the top eight, not all feedstocks are actively discussed in literature. Alfalfa is a not as widely used for bioenergy production, but some research to its potential is done. From this literature it is seen that alfalfa shows good sustainability features and has the potential to produce bioenergy with a relative low carbon footprint (Parajuli et al., 2017). For kenaf, ranking third, positive words were already spoken in literature (Saba et al., 2014). Sustainable production of camelina is not self-evident. The potential of camelina, however, is promising and once a sustainable production chain is present it is a good bioenergy feedstock (Chen, Bekkerman, Afshar, & Neill, 2015). Research for the potential and sustainability of hemp showed that it is a good energy crop that has potential to be produced in a sustainable way (Das et al., 2017; Parvez, Lewis, & Afzal, 2021). For the other crops no clear identification of its sustainability or controversy was found. The above shows that the results of the ranking are in accordance with the found information about the least controversial crops. They are all identified as a promising feedstock for low environmental impact bioenergy.

The results of bioenergy feedstock rankings in the studies mentioned in chapter 2 show to some extend similarities in their work to this one. However, a good comparison cannot be made due to the large differences in the criteria used. One note to make: in the study of (Anwar et al., 2019) the use of waste cooking oils as a biodiesel feedstock scores lowest according to the physio-chemical and fatty acid composition criteria. According to their ranking waste cooking oils are one of the least suitable feedstocks, and thus this is a big difference in results.

9.3 Consequences for Field of Study

The results of this research affect the field of study by making a start in using the bioenergy debate as a problem-solving resource to eliminate discrepancy and actively move forward with sustainable implementation of bioenergy. Although the criteria and data require some more attention, the method proves to be useful for selecting less controversial feedstocks. This study adds value to the debate, and can therefore have consequences for implementing biomass energy and the energy transition.

The next section (9.4) answers the question if the use of a less controversial feedstock can help to resolve the controversies. When such a feedstock can resolve the debate, it could lift the negativity around bioenergy.

However, since it will not make bioenergy a perfect energy source, it is most expected that the critics will find other points to debate. With further improvements of this research, solving future issues should be more easy. In that way, there will be a more consistent development of the technique and less opposition to its use. With the help of this research, the debate might become scientifically useful and move forward.

This research treated the debate and the controversies around bioenergy as a problem indicating tool - as a feedback loop - to see if the implementation of bioenergy without opposition is possible. Using it in this way may have consequences for the debate itself but also the development of bioenergy.

9.4 Possibility of Solving the Controversies by Least Controvesial Feedstocks

The characteristics that residues and waste streams do not directly require land and fertilizer to grow, do not directly impact biodiversity by its production and are not used to feed to the human population directly, already solve some controversies. Without using land, there is no need for the land for food or land for energy debate. One of the waste streams is from the food industry. Food not consumed and other food wastes can be converted to energy. This conversion not only eliminates competition with the food industry but also reduces waste streams from this industry. These two characteristics of residues and waste stream already eliminate controversies. Whether this type of feedstock also eliminates the controversies of chain emissions, biodiversity, and the carbon debt is more complicated. Considering the chain emissions, it might be that no other emissions can be allocated to this feedstock besides the end of pipe emissions. That is, the formation of a waste stream is not the aim of production. However, since waste is generated by that specific process and the waste is measurable, emissions to that waste stream can be allocated. Hence, more emissions than only the end of pipe emissions can be assigned to a waste stream. Due to simplification, and since this research chose to quantify the emissions by fertilizer use, no chain emissions were quantified to the waste streams. Nevertheless, the emissions will be lower for waste steams than for crops cultivated with agricultural techniques. Hence, the conclusion is that waste streams can partly resolve the controversy of chain emissions. Similar reasoning as mentioned above exists for the biodiversity impact resulting from waste streams for bioenergy. The waste streams result from some agricultural process, meaning that, at some point, the primary source of the waste stream impacts biodiversity. Since the waste stream is only a part of the whole process, this impact should not fully assign to it but at least a fair share. This again will lead to a lower impact than the crops chosen for this research. Thus waste and residues streams will partly overcome the controversy of biodiversity. The controversy of the carbon debt is the only controversy where there exists great uncertainty if it can be resolved with the wastes and residues streams. When the waste stream is plant-based, the CO_2 recaptured by that plant cannot be allocated completely for the end of pipe emissions resulting from bioenergy production. Again, the waste stream is only a part of the whole process of that industry. A right allocation will determine what part of the recapture capability of the plants assigns to the waste stream. In theory, this allocated amount should be sufficient to recapture the end of pipe emissions. However, whether this is the case should be proven in further research. It is therefore uncertain if these feedstocks resolve the carbon debt controversy. For the not plant-based waste streams (like chicken manure and animal fats), no carbon cycle exists. Animals do not capture CO_2. Therefore, the carbon cycle is lacking. In the ranking, these waste streams got assigned the same carbon debt as the other waste streams. This quantification is not completely correct and thus makes this type of waste stream slightly more controversial. Also, these waste streams will not resolve the carbon debt controversy, since the end of pipe emissions are not recaptured by new growing plants.

9.5 Availability of the Feedstocks

To see if the least controversial feedstocks will meet bioenergy demand, this section discusses the availability and potential of some waste streams and alfalfa. The potentials represent the amount of biomass available today and what this might be in the future.

Residues and Waste Streams About 5% of the total crop and residues is used in the bioenergy industry. This 5% corresponds to about 11 EJ. Another 24 EJ can be added if the now burned residues and crop residues would be made available for bioenergy applications. This potential is already excluding the amount of biomass needed for fertilizer use and land management. Waste streams from non-agricultural industries can add about 21 EJ to the bioenergy potential from agriculture. The paper and pulp industry and woody residues used in 2014 for energy production were about 17 EJ (Van Den Born, Van Minnen, Olivier, & Ros, 2014). However, the potential of wood residues might be way more. Production of woody residues (sawdust, bark, and shavings) in Canada was in 2004 21,228,536 BDt (bone dry ton). A part of this total is processed, but the remaining 2,737,805 BDt is still available. To put this in energy units: 1 BDt produces 10,000 lb of steam, which on its own can produce 1 MWh of energy. This woody residue production could add significantly to the potential of bioenergy from this waste stream (BW McCloy & Associates Inc., 2006).
The expectation that the world population will expand over the next few years is sincere, so there exists

the expectation that the yearly food production will rise. With an increased output of this industry, the corresponding waste stream will also enlarge. It is estimated that the amount of global food waste increases by 5.4% from 2020 to 2027. Since the amounts of food wasted today already reached 1.6 billion tons, significant potential exists for using food waste as a bioenergy feedstock for waste management purposes. The primary destination of food waste is animal feed. However, expectations are that the use of food waste to produce biofuels grows with 6.6% per year (GVR, 2020). The IPCC made an estimation about the technical global potential of sustainable bioenergy produced from the residues an waste streams. They proposed a range of 40 to 170 EJ/yr in 2050 from these feedstocks. The mean was said to be 100 EJ/yr. This includes sustainable produced bioenergy only. An additional 60 - 100 EJ/yr can be added by surpluses from the forestry sector (Chum et al., 2011).

Energy Crops Alfalfa is a worldwide produced animal feed crop. The global trade of this crop reached 8.3 million metric tons in 2017, and the production of alfalfa is expected to grow (Basigalup, Spada, Odorizzi, & Arolfo, 2018). In 2010 the USA produced 68 Mtons alfalfa on about 8 million hectares. The application of alfalfa as a source to produce biofuels is not yet widely applied. A proposal of a feed and fuel synergy stands. The crop has more nutritious and less nutritious parts, which allows for synergy. The nutritious parts function as feed, whereas the less nutritious parts play a role in the production of bioenergy. The main downside is that the use of alfalfa for cattle feed production has more economic value than for energy production, which lowers the chance of application (Bhattaraim, Brummer, & Monteros, 2013). However, today's alfalfa production is already significant, and with the possibility of feed and energy cooperation as explained above, some potential for alfalfa bioenergy is present. To put this in numbers: the global trade of alfalfa has an energy content (based on LHV) of 140 PJ (or 0.14 EJ). Looking at Table 1, this is not enough to meet the demands for 2030 and 2050. To meet the demand in 2050 for SSP5-1.9 (250 EJ), the production of alfalfa must increase by at least 1786 times. The chance that alfalfa will be the only producer of bioenergy in the future is therefore not likely. Considering the energy crops in general, the IPCC estimates its potential on surplus agricultural lands to be 120 EJ/yr by 2050. To this amount, an additional 70 EJ/yr can be added by energy crops produced on marginal lands. It is further estimated that the improvement of efficiency of agricultural methods and its technology could add another 140 EJ/yr, coming to a total of about 500 EJ/yr from energy crops only. This, like for the residues and waste streams, includes sustainable bioenergy production only (Chum et al., 2011). It must be noted that, both for the energy crops as for the residues and waste streams, these values represent technical potentials.

When one compares the potentials here with the predicted amounts for TPES of bioenergy, it is seen that the technical potentials are enough to supply these TPES for each SSP. The largest bioenergy demand was observed for SSP5-1.9, but this amount is just under 50% of the total technical potential for energy crops alone. This indicates that bioenergy can be produced without stressing its resources in the future.

9.6 Summary

In this section, the MCDA outranking results were discussed, and the four different sensitivity analyses checked the robustness of the results. From the results and the sensitivity analysis, it was observed that the feedstocks of the type residues and wastes streams were always ranked as number one, often followed by alfalfa. The feedstocks ranked lowest or low were mainly cassava, woody-SRC like poplar, and straw feedstocks (cereal and rice straw).

It was interesting to see that miscanthus and switchgrass scored mediocre or low since, in literature, these crops were considered promising and classify as energy crops. Besides, oil palm scored not as low as expected, which is a widely (negatively) discussed biodiesel source. Looking at the ranks that several crops obtained, the oil crops have the highest overall rank, followed by the lignocellulosic crops, and the sugar and starch crops. The residues and wastes feedstocks can produce a range of bioenergy products, depending on the waste stream, which means that no specific bioenergy product is less controversial. Considering the runner-ups of these rankings, ethanol from sugar and starch crops is more controversial than ethanol production from lignocellulosic crops and waste streams.

According to the result of the additional ranking for the top eight, water use does not significantly change the results. Hence, water use did not affect this decision-making analysis. Besides the global scope, this research lacked detail incorporation. Due to the top eight ranking it is not sure to what extent additional details will change the ranking.

When evaluating if the least controversial feedstocks (the residues an waste streams) can resolve the controversies, it is seen that the plant based waste streams show a better potential than non-plant based. This is due to the ability to recapture possible emissions from bioenergy production, which are not present, or less evident, for the non-plant based waste streams. In addition, the land use and competition with food industry controversy can be solved with some degree of certainty, whereas more detailed research is needed to say if they can resolve the controversies of chain emissions, carbon debt and biodiversity impact. The controversy of removal of carbon sinks is not assessed.

Although the method proved to give sufficient enough results, an improvement would be to incorporate more detailed criteria to represent the controversies. Now, only one aspect of the controversy was considered. Including more factors per controversy may change the rankings as observed here. One way to do this is to reduce the number of feedstocks and make it a region or climate specific research. In that way, it is more easy to incorporate good data and add criteria. Besides, a more detailed study into MCDAs would also result in an improved method. Although the PROMETHEE II method is a common one, there exits a great number of decision methods. There might be one that is more suitable for this type of research than used now. This would be especially valuable because no prior knowledge and experience was present about these topics and methods. Nevertheless, still some good results are generated from which conclusions can be drawn.

10 Conclusion and Recommendations

This report aimed to identify the least controversial feedstocks and how these feedstocks resolve the controversies. To answer the research question, the subquestions as stated in the introduction were answered. Bioenergy use today and in the future gives background information about the situation of bioenergy and what role bioenergy gets assigned in the future. The collection of the controversies were necessary because they formed the criteria for the MCDA and to get insight into the bioenergy debate. Using the outranking method PROMETHEE II and the entropy weighting method, a complete ranking of 40 feedstocks was achieved.

First, this chapter will shortly repeat the conclusions that were made in the chapters 3, 5, and 6. The subquestions mentioned in the introduction (chapter 1) will be answered in the corresponding conclusions. Next, the conclusion of the research question will be made. The chapter ends with recommendations for the application of the method and further research.

10.1 Bioenergy use Today and Scenario Analysis

Over the past several years, bioenergy use increased. The main form of bioenergy is in the form of heat, and the residential and industrial sectors are the primary users of this energy. Most research, and therefore increased implementation, happens for the development of biofuels for the transport sector. Bioenergy is the major sustainable energy technology applied today, and development towards more modern forms is the main focus. From the scenario analysis this shift towards more modern forms of bioenergy is also observed. Especially a growth of biofuels for the coming years is seen. A society that focuses more on green growth shows less bioenergy use than one that keeps relying on fossil fuels. When energy demand increases, so will the demand for bioenergy. According to the literature and the SSPs analysis, it became clear that bioenergy already plays a role today and will have a role in the future. The use in the coming decades will be primarily in the form of modern bioenergy.

10.2 The Controversies of Bioenergy

The literature research to identify the controversies resulted in five main discrepancies. The first three controversies are that of the chain emissions resulting from bioenergy, removal of carbon sinks, and the carbon debt. The fourth one is that of land use and is about the fact that land is a scarce resource. With the predicted population growth, a debate exists about whether it is sensible to use the available land for the production of bioenergy feedstocks or not. The fifth controversy is that of the competition with the food industry.

The sixth is the impact on biodiversity due to bioenergy production. These six controversies were the most discussed in the literature and fuel the current debate. From these controversies, six criteria (land use, competition with food industry, fertilizer use, biodiversity impact, carbon debt, and marginal land use) were formulated. The only controversy where no criterion was found for was that removal of carbon sinks.

10.3 Answer to the Research Question

The combination of the entropy weighting and the PROMETHEE II outranking method showed that the most controversial feedstocks are cassava and the woody-SRC (like poplar, eucalyptus, and willow). The least controversial feedstocks are the residue and waste streams. These feedstocks all ranked one for the base case as well as for each sensitivity analysis. They rank first because of good scores for the criteria to the other feedstocks considered. The waste and residues streams are not produced for energy, eliminating land use, fertilizer use, and short carbon cycle requirements. When no land for bioenergy is required, there is no direct impact on biodiversity. Also, the waste and residues streams are no food source for the human population. This characteristic is in favor of their ranking and is also a crucial factor for resolving controversies. The feedstock considered the least controversial after the residue and waste streams is alfalfa. Since the residue and waste streams are no crop, it can be concluded that alfalfa is the least controversial crop, and it is a lignocellulosic crop. Alfalfa is ranked high since it is no food crop, has no fertilizer requirements, can be produced on marginal land, has a relatively low biodiversity impact, and a short carbon debt. The top eight least controversial crops turned out to be alfalfa, oil palm, kenaf, mustard seed, cotton seed, prairie grasses, camelina, and hemp. Including water use for this top eight did not change their ranking significantly. This might indicate that with the incorporation of additional details no significant changes in the rankings will happen. However, further research should prove this. The high rank of oil palm and the absence of miscanthus in this top eight concludes that the criteria could be more detailed (due to global and simplified quantification of the controversies), the data could be more specific, and the choice for the weighting method could be improved. The high rank of the waste streams and most of the top eight is backed-up by the positive potentials found in literature.

The least controversial feedstocks are of the residues and waste streams, where the plant-based waste streams will be slightly less controversial than the non-plant-based waste streams. The plant-based wastes can recapture the end of pipe CO_2 emissions by the new growing feedstocks for the primary process, which is not possible or less evident for non-plant-based waste streams. Bioenergy produced from these feedstocks can resolve at least two of the six controversies with relative certainty and two of the six with a higher degree of uncertainty due to the indirectness of impacts. These two controversies are land use and competition with the food industry. For the carbon debt controversy, there exists too much uncertainty to determine if plant-based waste streams can resolve it, but non-plant-based feedstock cannot resolve this controversy. No conclusions can be drawn about solving the controversy of the removal of carbon sinks, because this controversy was not assessed.

10.4 Recommendations

As mentioned, this research has a global perspective for ranking from least to most controversial. However, the development of several characteristics of crops depends on the location. Therefore, the results for this research might not be similar when using regional-specific data for the crops. When one wants to implement bioenergy systems with the least controversial feedstocks, it is recommended to apply the concept of this study on a regional scale. This regional application will make it possible to select a feedstock for bioenergy production, aiming to avoid controversies as much as possible for the chosen region.

A recommendation for further research will be to elaborate more on the controversies themselves. When the ranking uses more details for each controversy and the criteria, a more in-depth analysis can be performed. This more detailed ranking will give more accurate results. Several critical factors of the controversies are left out. For further research, these should be included. It would add to this research to see how the results are changed considering details.

This study aimed to identify the least controversial feedstocks out of 40 randomly selected ones. From the results, a mere guess about the degree of the controversy of the energy form or bioenergy product was made. As an elaboration of this research, it is interesting to use the method as formulated here and aim to identify if either heat, electricity, biodiesel, bioethanol, or biogas is the least controversial energy form using the least controversial feedstocks. Also, it would be interesting to see what processing technique will result in a reduction in controversy. This itself could be follow-up research after the identification of the least controversial energy form. The two elaborations result in a more robust solving of the controversies around bioenergy.

A last recommendation for further research is about ways to reduce the controversiality. It would be interesting to see how a specific agricultural or production method could reduce the degree of controversiality of that feedstock. The IEA already proposed some ideas about land use efficiency which might already reduce the problems around land use (see chapter 6). When such methods are elaborated and found for other controversies, it would severely help with sustainable implementation of bioenergy.

This research made a start in connecting the research and development of bioenergy with the bioenergy debate to ensure sustainable implementation of bioenergy that contributes to the energy transition. Although the global and broad scope, the results already show that some great differences in the controversiality of feedstocks exist. Such research helps temper the bioenergy debate when implementation is connected to the research and development of bioenergy to add value to the controversies.

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A Scenario Analysis Tables

A.1 SSP1

Table 13: This table gives the world TPES of bioenergy for the years 2010 to 2050 in EJ/yr, that is according to the SSP1 scenarios coupled with RCP 1.9 for different integrated assessment models.

Model	**Unit**	**Year**				
		2010	**2020**	**2030**	**2040**	**2050**
AIM/CGE 2.0	EJ/yr	44.94	42.47	44.74	60.60	67.07
GCAM 4.2	EJ/yr	51.53	57.91	84.80	94.64	101.30
IMAGE 3.0.1	EJ/yr	52.72	43.17	74.21	105.87	123.54
MESSAGE-GLOBIOM 1.0	EJ/yr	54.82	51.25	48.99	58.46	88.33
REMIND-MAgPIE 1.5	EJ/yr	59.90	67.76	62.66	105.80	203.90
WITCH-GLOBIOM 3.1	EJ/yr	37.30	41.66	48.07	63.69	82.00

Table 14: This table gives the world TPES of bioenergy for the years 2010 to 2050 in EJ/yr, that is according to the SSP1 scenarios coupled with RCP 2.6 for different integrated assessment models.

Model	**Unit**	**Year**				
		2010	**2020**	**2030**	**2040**	**2050**
AIM/CGE 2.0	EJ/yr	44.94	42.46	40.99	50.70	62.85
GCAM 4.2	EJ/yr	51.53	58.30	75.52	87.09	93.47
IMAGE 3.0.1	EJ/yr	52.72	39.65	44.60	65.27	84.47
MESSAGE-GLOBIOM 1.0	EJ/yr	54.82	53.97	47.30	49.55	61.59
REMIND-MAgPIE 1.5	EJ/yr	59.90	67.76	64.70	61.84	86.75
WITCH-GLOBIOM 3.1	EJ/yr	37.31	43.19	48.50	67.55	85.93

A.2 SSP2

Table 15: This table gives the world TPES of bioenergy for the years 2005 to 2050 in EJ/yr, that is according to the SSP2 scenarios coupled with RCP 1.9 for different integrated assessment models.

Model	**Unit**	**Year**				
		2010	**2020**	**2030**	**2040**	**2050**
AIM/CGE 2.0	EJ/yr	46.55	48.03	61.56	106.60	130.67
GCAM 4.2	EJ/yr	51.53	63.39	98.27	166.14	207.60
MESSAGE-GLOBIOM 1.0	EJ/yr	53.94	62.39	73.31	90.49	119.19
REMIND-MAgPIE 1.5	EJ/yr	59.41	66.53	75.28	188.80	260.90

Table 16: This table gives the world TPES of bioenergy for the years 2005 to 2050 in EJ/yr, that is according to the SSP2 scenarios coupled with RCP 2.6 for different integrated assessment models.

Model	**Unit**	**Year**				
		2010	**2020**	**2030**	**2040**	**2050**
AIM/CGE 2.0	EJ/yr	46.55	48.04	52.87	81.57	103.79
GCAM 4.2	EJ/yr	51.53	63.60	77.04	125.92	165.45
IMAGE 3.0.1	EJ/yr	51.97	64.43	86.82	150.82	147.80
MESSAGE-GLOBIOM 1.0	EJ/yr	54.99	64.07	69.83	75.62	87.28
REMIND-MAgPIE 1.5	EJ/yr	59.41	66.53	61.82	71.64	127.80
WITCH-GLOBIOM 3.1	EJ/yr	37.30	45.36	65.06	86.50	98.73

A.3 SSP4

Table 17: This table gives the world TPES of bioenergy for the years 2005 to 2050 in EJ/yr, that is according to the SSP4 scenarios coupled with RCP 1.9 for different integrated assessment models.

Model	**Unit**	**Year**				
		2010	**2020**	**2030**	**2040**	**2050**
WITCH-GLOBIOM 3.1	EJ/yr	37.30	40.54	47.66	64.09	83.27

Table 18: This table gives the world TPES of bioenergy for the years 2005 to 2050 in EJ/yr, that is according to the SSP4 scenarios coupled with RCP 2.6 for different integrated assessment models.

Model	**Unit**	**Year**				
		2010	**2020**	**2030**	**2040**	**2050**
AIM/CGE 2.0	EJ/yr	49.25	56.76	66,62	92.54	119.17
GCAM 4.2	EJ/yr	51.53	69.84	114	145.1	176.78
IMAGE 3.0.1	EJ/yr	52.14	61.57	104.23	162.29	186.22
WITCH-GLOBIOM 3.1	EJ/yr	37.31	45.67	51.74	79.37	118.24

A.4 SSP5

Table 19: This table gives the world TPES of bioenergy for the years 2005 to 2050 in EJ/yr, that is according to the SSP5 scenarios coupled with RCP 1.9 for different integrated assessment models.

Model	**Unit**	**Year**				
		2010	**2020**	**2030**	**2040**	**2050**
GCAM 4.2	EJ/yr	51.53	57.95	97.41	172.71	188.41
REMIND-MAgPIE 1.5	EJ/yr	59.83	65.8	59.27	142	310.1

Table 20: This table gives the world TPES of bioenergy for the years 2005 to 2050 in EJ/yr, that is according to the SSP5 scenarios coupled with RCP 2.6 for different integrated assessment models.

Model	**Unit**	**Year**				
		2010	**2020**	**2030**	**2040**	**2050**
AIM/CGE 2.0	EJ/yr	45.04	43.04	49.78	134.11	204.32
GCAM 4.2	EJ/yr	51.53	58.38	67.29	135.92	170.31
REMIND-MAgPIE 1.5	EJ/yr	59.83	65.8	54.2	67.55	178.4

A.5 Solid Biomass

Table 21: This table gives the world TFE of solid biomass for the years 2010 to 2050 in EJ/yr for the different SSPs scenarios with RCP 1.9 in their marker model.

Model	**Scenario**	**Variable**	**Unit**	**Year**				
				2010	**2020**	**2030**	**2040**	**2050**
IMAGE 3.0.1	SSP1	Solids—Biomass	EJ/yr	43.76	28.31	24.98	26.68	30.93
MESSAGE-GLOBIOM 1.0	SSP2	Solids—Biomass	EJ/yr	44.78	48.62	57.90	52.67	47.24
REMIND-MAgPIE 1.5	SSP5	Solids—Biomass	EJ/yr	50.06	49.15	35.31	21.58	12.30

Table 22: This table gives the world TFE of solid biomass for the years 2010 to 2050 in EJ/yr for the different SSPs scenarios with RCP 2.6 in their marker model.

Model	**Scenario**	**Variable**	**Unit**	**Year**				
				2010	**2020**	**2030**	**2040**	**2050**
IMAGE 3.0.1	SSP1-26	Solids—Biomass	EJ/yr	43.76	30.08	28.26	36.77	38.36
MESSAGE-GLOBIOM 1.0	SSP2-26	Solids—Biomass	EJ/yr	44.86	49.60	57.61	54.39	50.91
GCAM 4.2	SSP4-26	Solids—Biomass	EJ/yr	47.07	54.16	60.36	58.68	55.23
REMIND-MAgPIE 1.5	SSP5-26	Solids—Biomass	EJ/yr	50.06	49.15	36.24	23.07	14.21

A.6 Liquid Biofuels

Table 23: This table gives the world TFE of liquid biofuels in the transport sector for the years 2010 to 2050 in EJ/yr for the different SSPs scenarios with RCP 1.9 in their marker model.

Model	**Scenario**	**Variable**	**Unit**	**Year**				
				2010	**2020**	**2030**	**2040**	**2050**
IMAGE 3.0.1	SSP1	Biofuels	EJ/yr	1.61	1.84	8,32	9.79	6.89
MESSAGE-GLOBIOM 1.0	SSP2	Biofuels	EJ/yr	1.89	1.47	0.84	2.35	3.33
REMIND-MAgPIE 1.5	SSP5	Biofuels	EJ/yr	0.15	3.01	3.43	16.78	54.36

Table 24: This table gives the world TFE of liquid biofuels in the transport sector for the years 2010 to 2050 in EJ/yr for the different SSPs scenarios with RCP 2.6 in their marker model.

Model	**Scenario**	**Variable**	**Unit**	**Year**				
				2010	**2020**	**2030**	**2040**	**2050**
IMAGE 3.0.1	SSP1	Biofuels	EJ/yr	1.61	1.75	3.57	7.41	11.10
MESSAGE-GLOBIOM 1.0	SSP2	Biofuels	EJ/yr	1.87	1.47	0.67	0.37	0.80
REMIND-MAgPIE 1.5	SSP5	Biofuels	EJ/yr	0.15	3.01	2.90	7.97	39.63

B A Reaction to the Debate

After reading and analyzing several papers and reports published over a range of 10 years, it stands out that the whole bioenergy debate has not changed in this period. Over the years, the critics and advocates use the same arguments and are often at odds with each other. Both parties claim to have significant scientific research to back-up their statements, and the debate is creating nothing but confusion. The bioenergy debate is tunnel-visioned from both sides. Instead of solving the problems to improve the current bioenergy technology, they are debated, argued, and spread, leaving the development of bioenergy nearly absent and counteracting the energy transition.

Both parties use many 'ifs and buts' to make their statements. Searchinger et al. (2017, 2020) and Reid et al. (2020) use the reasoning that bioenergy should be excluded, because there exist better options, like wind and solar energy. Those are not yet widely applied because several complementary technologies still have to reach maturity. However, they state that **if** these technologies reach that stage and **if** the price of those technologies lower, they are way better than bioenergy. An example: "If and by the time storage limitations do become truly limiting, the large research investments in storage **may** have found solutions. Policymakers should not commit to any far poorer approaches until that time, let alone bioenergy approaches that will increase emissions for decades" (Searchinger et al., 2017, p.439) (Searchinger et al., 2017). This statement gives the impression that we should not start the energy transition until adequate technologies are ready to shift towards a solar and wind-based energy system. Although better solutions will appear in the future, this will always be the case. Technology is not static but constantly evolving. Within several years there would be an improved version of the technology known today. The argument of Searchinger to not use something because "better options might develop" is therefore inadequate. Similar arguments are made for the use of biofuels in the transportation sector. Electric vehicles have more potential than biofuel vehicles because electricity generation is more efficient and can be completely carbon neutral. Such is a fair argument, but one must not forget that only 1% of the global car stock was EV in 2019 (IEA, 2020a), and thus by far, the majority of cars are still running on fuels. So, the argument not to use biofuels for the energy transition according to the current situation is invalid. By not using biofuels to start decarbonization in the transport sector, they waste a chance. It is more challenging to decarbonize these sectors, and it asks for a more gradual transition.

On the opposite side of the debate, bioenergy advocates often say that bioenergy should be used because its production can be sustainable. That is: **if** the feedstock production is sustainably managed, **if** there exists adequate policies and governance to control the sustainability, and **if** only specific feedstocks are used or only specific parts of biomass are used (like woody residues and not whole trees).

These "ifs" make it that one can say that the statement "If ifs and buts were candies and nuts, we'd all have a merry Christmas" applies to the bioenergy debate.

Comparison of bioenergy with other sustainable energy sources is often made. Searchinger et al. even mentioned that it is wrong to compare bioenergy with fossil fuel energy since it should represent a renewable source (Searchinger et al., 2017). But is this fair? Today the energy transition is still just taking off. The energy sector is still mostly based on fossil fuels. The whole idea of the energy transition is moving away from fossil resources to decarbonize the energy system, reduce emissions of GHGs, and limit global warming. Bioenergy can produce energy with lower emission of GHGs to fossil fuels, which both the advocates as the critics confirm. This fact indicates that for the *transition*, bioenergy does contribute to decarbonization and thus is a better option than fossil fuels to produce energy. When you compare sustainably produced bioenergy with fossil fuels, it makes sense to apply it in the energy transition. When comparing it to wind and solar energy, it does to a lesser extent. The carbon emissions over the whole life cycle show that bioenergy is not so attractive concerning wind and solar energy. However, they are not the primary energy sources today and are not the reason the energy transition is needed. Hence, at the start of the energy transition, it is not logical to compare bioenergy with other sustainable sources. The energy transition is a process, meaning that step by step decarbonization is achieved. The use of bioenergy can make a step in the right direction since it has (under the right circumstances) lower emissions than fossil fuels, produces primarily heat, produce fuels, uses similar techniques as today, and can be readily applied (IEA, 2015). With the implementation of bioenergy, solar and wind energy, and storage techniques can be more developed. This allows for a slow transition to a more electricity-based energy system. Leaving out bioenergy asks for more rigorous actions and a society that is more open to bigger and more direct changes. This does not mean that, in the far future, bioenergy will still play a large role in the energy system. Due to better options, as (Searchinger et al., 2017), (Reid et al., 2020) and (Brack, 2017) state, bioenergy will not likely play a big role in the energy system further down the road of the transition. However, it shows good potential to provide a renewable source for carbon in the industry sector and to produce sustainable fuel.

Two other findings stood out. Firstly, in the paper of Reid et al. (2020), it is mentioned that the production of bioenergy threatens biodiversity since it will overtake several ecosystems for the feedstock production (Reid et al., 2020). The question then arises how they can justify using this argument against bioenergy when those

ecosystems will most likely disappear due to food production or human habitat creation when not used for bioenergy production. It seems very strange and almost hypocritical that, within the same document, biodiversity loss is justified for food production and the building of houses but not for bioenergy production. Especially because climate change has a chance to result in the extinction of several more species and bioenergy also has scientific proof that it may improve biodiversity and not limit it.
Secondly, there are problems with the interpretation of LCA results. The LCAs performed to assess the sustainability of bioenergy often contains many flaws. These flaws mainly exist in the fact that limitations of the research and user data are excluded. Most of the time, no sensitivity analysis is present. This problem, together with lack of identification and framing the issues and subjective choices correctly, leads to misleading results of the LCAs and results in wrong interpretation. Problems related to the use of the results and the method chosen to perform the LCA also exist. Most of the studies use attributional modeling, which is often used for eco-design or for identifying hot spots of emissions or other sustainability issues to improve the supply chain. This research could be of great value for the development of more sustainable bioenergy, but the attributional modeling results are used for the making of policies, and therefore not used correctly. This again leads to the wrong interpretation of results. If policy development is the goal, LCAs must use the consequential modeling method and not the attributional one. Choosing the wrong method is already a problem because limitations of the main assumptions made to perform the LCAs are often not mentioned, causing the production of misleading and incomplete results. From these results, no conclusions should be drawn, and those results should not function as valid arguments in the bioenergy debate. Nevertheless, this is happening nowadays (Agostini, Giuntoli, Marelli, & Amaducci, 2020). "The lack of limitations reporting makes most of the studies potentially misleading, as the key issues and subjective choices are neither identified nor properly framed through sensitivity analyses and, most importantly not communicated to the readers. In our opinion, these flaws in the interpretation phase play a significant role in fuelling the debate around the governance of sustainability of bioenergy" (Agostini et al., 2020, p.30) (Agostini et al., 2020).

As said the debate is going on for some time now. Sustainable energy, climate, and environmental scientist all try to defend their case whether to use bioenergy or not. The debate is getting more worked up; advocates and critics whose views are perpendicular to each other are getting frustrated, and it shows. When reading the reaction articles of Searchinger et al. (2020) (Searchinger & Tufts, 2020) on the recent PBL report (Strengers, Bart; Elzenga, 2020) and Cowie et al. (2017) (Cowie et al., 2017) on the Chatham House report (Brack, 2017), one gets the idea that they feel personally attacked by these works. With this, emotions are introduced into the debate, and therefore scientific credibility is reduced. The debate should not be affected by scientists that are stepped on their toes because someone presents a report that is not in line with yours. It should not be a debate to prove you are right. The debate and controversies should result in points to be improved to make bioenergy more sustainable to help the energy transition. With the right intentions of the involved researchers, the debate must result in the sustainable production of bioenergy and an implementation plan to help move the technology further, not drag it down or stagnate it.

C Feedstocks

Table 25: Table with all the feedstocks and their found characteristics together.

Feedstock	Generation	Yield (MJ/ha)	Yield (L/ha)	Fertilizer use (kg N/ha)	Growth time (days)	Marginal Land Use	Biodiversity
Maize/Corn	First	-	5332	157	100-200	No	0.50
Wheat	First	-	2200	150	100-250	No	0.60
Sugar beet	First	-	5200 - 6500	120	70-90	No	0.60
Sugar cane	First	-	5000	34-123	300-360	No	0.67
Potatoes	First	-	1600	168 - 224	100-110	No	0.67
Sorghum	First	-	10476	60 - 120	120-130	yes	0.67
Cassava	First	-	2750	180 - 250	240-540	Yes	0.67
Soybean	First	-	*617*	22 - 45	157	No	0.56
Jatropha	Second	-	*1750*	140	93-124	Yes	0.50
Oil Palm	Second	-	3742 - 6080	34	14	Yes	0.81
Rapeseed/Canola	First	-	748	80	66-140	No	0.43
Camelina	First	-	561 - 608	50-120	85-100	Yes	0.67
Maize Grain oil	First	-	168 - 187	157	100-200	No	0.50
Sunflower	First	-	702 - 982	?	119	Yes	0.60
Mustard	First	-	561 - 1310	66	80-95	Yes	0.67
Flax/Linseed	First	-	?	80	90-110	Yes	0.67
Cotton Seeds	Second	-	327 - 421	66	91-128	Yes	0.50
Algea	Third	-	45000 - 137000	*867*	14-35	Yes	0.20
Switchgrass	Second	25312^1	3742	112	365	Yes	0.31
Prairie Grasses	Second	*313664*^{2}	1125	70	42-168	Yes	0.33
Miscanthus	Second	*147167*^{1}	5238	-^{7}	365	Yes	0.17
Sugarcane Bagasse	Second	69247 - 72674	-	-	300-360	No	0.67
Rice Straw and husk	Second	84842^2	*1285*	250	100-130	No	0.50
Maize Stover	Second	-	1422	-	100-200	No	0.50
Willow	Second	*Power: 74238; 173987*^{2}	*3064*	112	1080	Yes	0.08
Poplar	Second	78217^2	*946*	56	5475	Yes	0.33
Cereal Straw	Second	48367^2	*10850*	-	100-250	No	0.67
Eucalyptus	Second	461825^2	8516	30-60	900-1800	Yes	0.62
Alder	Second	728073^2	-	93	1095	Yes	0.60
Alfalfa	Second	69372^2	1281	-	28-40	Yes	0.50
Reed Canary Grass	Second	133760^2	-	84	182-365	Yes	0.33
Hemp	Second	*339400*^{2}	*4335 - 5160*	60-100	100-120	Yes	0.50
Kenaf	First	268460^2	*4449*	20 - 60	150	Yes	0.60
Wood Residues	Second	*12300*^{3}	-	-	-	-	
Industrial Food Waste	Second	-	-	-	-	-	-
Municipal Solid Waste	Second	-	-	-	-	-	-
Chicken Manure	Second	-	-	-	-	-	-
Waste Cooking oils	Second	-	-	-	-	-	-
Agro-industry wastes (olive cake)	Second	-	-	-	-	-	-
Animal Fats	Second	-	-	-	-	-	-

[1] Lower Heating Value of the biodiesel made

[2] Lower heating value dry matter

[3] Sum of ethanol yields of sawdust and savings, early thinning, tops and branches and hog fuel

[4] Sum of KOW, GOW and PCW for London case study

[5] Power

[6] Heat

[7] Only on very low N holding soils fertilizer is required

Italic: self calculated value

C.1 Sources for Feedstock table

Table 26: The sources used to construct the feedstock table per feedstock.

Feedstock	Sources
Maize/Corn	(Pennington, 2020); (Muñoz et al., 2013); (Mueller et al., 2015)
Wheat	(Pennington, 2020); (Muñoz et al., 2013); (Mueller et al., 2015)
Sugar beet	(Pennington, 2020); (Foteinis, Kouloumpis, & Tsoutsos, 2011); (Cattanach, Dexter, & Oplinger, n.d.).
Sugar cane	(Pennington, 2020); (Mccray, Morgan, & Baucum, 2019); (Karlen, 2014)
Potatoes	(Koçar & Civaş, 2013), University of Arizona (n.d.); (Tantowijoyo & v.d. Fliert, 2006).
Sorghum	(Pennington, 2020); (Olugbemi, 2017); (Karlen, 2014).
Cassava	(Kaweewong, Kongkeawa, Tawornprek, Yampracha, & Yost, 2013); (Moore, 2003) .
Soybean	(Bassam, 2015); (Schmidt, n.d.), (Hay, n.d.); (Oliveira & Da Silva, 2013); (v. Benthem, 2013)
Jatropha	(Bassam, 2015); (NRG, n.d.); (Oliveira & Da Silva, 2013); (Silip, Tambunan, Hambali, Sutrisno, & Surahman, 2010).
Oil Palm	(Bassam, 2015); (Bin & Ghazali, n.d.), (Koçar & Civaş, 2013); (Oliveira & Da Silva, 2013); (Mohammadi Ashnani, Johari, Hashim, & Hasani, 2014); (Verheye, n.d.).
Rapeseed	(Bassam, 2015); (Pennington, 2020); (Mehta & Anand, 2009); (Opslinger, Hardman, Gritton, Doll, & Kelling, n.d.)
Camelina	(Bassam, 2015); (Koçar & Civaş, 2013); (Chaturvedi, Bhattacharya, Khare, & Kaushik, 2013); (H. Li et al., 2019); (Fleenor, 2011)
Maize oil	(Bassam, 2015); (Koçar & Civaş, 2013)
Sunflower	(Bassam, 2015); (Koçar & Civaş, 2013); (Mehta & Anand, 2009); (Spinelli, Jez, & Basosi, 2012); (Berglund, 2007)
Mustard	(Bassam, 2015); (Koçar & Civaş, 2013); (Sanjid, Masjuki, Kalam, Abedin, & Rahman, 2014);(McKenzie & Carcamo, 2010); (Wysocki & Corp, 2002)
Flaxseed	(Bassam, 2015); (Mehta & Anand, 2009); (Mohammadi Ashnani et al., 2014); (Opslinger, Oelke, Doll, Bundy, & Schuler, 1997)
Cotton Seeds	(Bassam, 2015); (Koçar & Civaş, 2013); (Mehta & Anand, 2009); (Murphy et al., 2010); (Chaudhry & Guitchounts, 2003)
Switchgrass	(Pennington, 2020); (Cherney, Cherney, & Paddock, 2018); (Karlen, 2014)
Prairie Grasses	(Yang, Tilman, Lehman, & Trost, 2018); (Jungers, Fargione, Sheaffer, Wyse, & Lehman, 2013); (Bedoić et al., 2019); (Karikalan, Chandrasekaran, & Sudhagar, 2014)
Miscanthus	(Pennington, 2020); (Varnero, Urrutia, & Ibaceta, 2018); (Danielewicz, Surma-Ślusarska, Żurek, & Martyniak, 2015);(Karikalan et al., 2014)
Bagasse	fao.org/faostat/en/#data/QC; (Rabelo, Carrere, Maciel Filho, & Costa, 2011); (Cardona, Quintero, & Paz, 2010)
Rice husk	(Lim, Abdul Manan, Wan Alwi, & Hashim, 2012); (Sietske Boschma, Kees, & Kwant, 2013); (Chitawo & Chimphango, 2017); (by Shahida Sarker Parul, 2017)
Maize Stover	(Pennington, 2020); fao.org/faostat/en/#data/QC
Willow	(Pennington, 2020); (Budsberg et al., 2012); (Penn State Extension, 2014); (Karlen, 2014)
Poplar	(Pennington, 2020); (W. Y. Liu et al., 2017); (Dillen, Djomo, Al Afas, Vanbeveren, & Ceulemans, 2013); (Haughton et al., 2016)
Cereal Straw	(Lantz, Prade, Ahlgren, & Björnsson, 2018);
Eucalyptus	(Viera, Fernández, & Rodríguez-Soalleiro, 2016); (González-García & Bacenetti, 2019)
Alder	(Hytönen & Saarsalmi, 2014); (Glaessens, Oosterbaan, Savill, & Rondeux, 2010)
Alfalfa	(Befekadu & Yunus, 2015); (VOA, 2007); (Hatfield, 2015); (Undersander et al., 2011)
RCG	(Bosworth, 2020); (Pahkala et al., 2007); (Reinhart & Galatowitsch, 2004)
Hemp	(Bassam, 2015); (Rehman, Rashid, Saif, Mahmood, & Han, 2013); (Das et al., 2017); (Government of Alberta, n.d.)
Kenaf	(Bassam, 2015); (Das et al., 2017); (Webber & Bledsoe, 2002)
Wood Residues	(Frankó, Galbe, & Wallberg, 2016); (van Vuuren et al., 2017)
IFW	(Chae, Kim, Lee, Joo, & Ohm, 2020); (S. Li & Yang, 2016)
MSW	(A. Li & Khraisheh, 2009); (Johari et al., 2012)
Chicken Manure	(Gomaa & Abed, 2017); (Tańczuk, Junga, Kolasa-Więcek, & Niemiec, 2019)
WCO	(Sheinbaum-Pardo, Calderón-Irazoque, & Ramírez-Suá Rez, 2013); (Tesfa, Gu, Mishra, & Ball, 2013); (Karikalan et al., 2014)
olive cake	(Hytönen & Saarsalmi, 2014)
Animal Fats	(Toldrá-Reig, Mora, & Toldrá, 2020); (Tesfa et al., 2013)
Algea	(Bassam, 2015); (Satputaley, Chawane, & Deshpande, 2012); (Schlagermann, Göttlicher, Dillschneider, Rosello-Sastre, & Posten, 2012); (Foteinis, Antoniadis-Gavriil, & Tsoutsos, 2018); (Bawiec, Garbowski, Pawęska, & Pulikowski, 2019)

D Feedstock Ranking

Table 27: The global flows of the PROMETHEE II ranking. For the No MCDA there were no flows so in the there the final sum of each criteria per alternative is given.

Feedstock	**Base Case**	**Gaus**	**EW**	**F-AHP**	**Simplest MCDA**
Maize/Corn	-1.91	-2.56	-741.22	-6.32	-45.54
Wheat	-2.86	-2.93	-823.71	-6.59	-49.89
Sugar beet	-0.70	-0.28	-576.04	-2.94	-27.59
Sugar cane	-5.70	-3.99	-835.07	-2.52	-74.11
Potatoes	-2.49	-2.70	-840.38	-7.21	-40.31
Sorghum	0.44	-0.03	-293.79	-0.21	-33.96
Cassava	-8.05	-6.60	-757.89	-8.89	-99.20
Soybean	2.08	1.94	-21.30	5.18	-34.87
Jatropha	0.11	0.11	-13.96	-5.02	-35.16
Oil Palm	5.60	5.99	902.56	9.36	-5.76
Rapeseed/Canola	0.97	0.54	-280.61	1.08	-28.54
Camelina	2.49	2.52	370.92	0.80	-26.57
Maize Grain oil	-1.91	-2.70	-757.89	-6.36	-45.55
Sunflower	2.08	1.45	301.85	-2.79	-34.74
Mustard	3.78	3.02	430.34	2.02	-23.70
Flax/Linseed	2.63	-7.13	407.60	1.64	-27.59
Cotton Seeds	2.82	2.63	622.02	4.84	-28.12
Algea	-0.70	-0.23	114.49	-4.88	-89.36
Switchgrass	-5.70	-3.89	-427.86	-6.09	-84.07
Prairie Grasses	2.75	2.54	420.22	1.79	-27.59
Miscanthus	-1.05	0.45	348.35	5.77	-73.10
Sugarcane Bagasse	-5.53	-3.14	-818.40	-1.79	-74.11
Rice Straw and husk	-2.49	-3.05	-874.13	-8.35	-47.59
Maize Stover	-1.66	-1.15	-577.89	-5.11	-45.54
Willow	-6.79	-6.81	-440.90	-6.85	-228.05
Poplar	-6.02	-5.28	-161.14	-1.50	-1107.71
Cereal Straw	-2.81	-2.80	-800.16	-6.36	-49.89
Eucalyptus	-2.86	-4.03	-58.61	0.67	-275.89
Alder	-6.44	-6.17	-368.87	-3.74	-229.24
Alfalfa	5.76	6.51	916.25	9.45	-6.45
Reed Canary Grass	-1.91	-0.77	-8.63	-0.33	-62.90
Hemp	2.53	1.96	373.90	1.10	-29.60
Kenaf	4.39	5.10	682.87	5.39	-33.73
Wood Residues	5.76	6.51	916.25	9.45	-2.40
Industrial Food Waste	5.76	6.51	916.25	9.45	-2.40
Municipal Solid Waste	5.76	6.51	916.25	9.45	-2.40
Chicken Manure	5.76	6.51	916.25	9.45	-2.40
Waste Cooking oils	5.76	6.51	916.25	9.45	-2.40
Agro-industry wastes (olive cake)	5.76	6.51	916.25	9.45	-2.40
Animal Fats	5.76	6.51	916.25	9.45	-2.40

Table 28: The input matrix for the F-AHP weights.

	C1	C2	C3	C4	C5	C6
C1	1	3	3	5	5	7
C2	1/3	1	1	5	3	7
C3	1/3	1	1	5	1	7
C4	1/5	1/5	1/5	1	1/3	3
C5	1/5	1/3	1	3	1	3
C6	1/7	1/7	1/7	1/3	1/3	1

D.1 Top Eight ranking Including Water Use

Table 29: Decision matrix for the additional ranking of eight less controversial feedstocks with the additional criterion of water use. Where C1 refers to land use, C2 to food competition, C3 to emissions, C4 to biodiversity, C5 to carbon debt, C6 to marginal land use, and C7 to water use.

Crop	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
Alfalfa	3.9E-05	2	0.0001	0.50	34	10	2.3
Oil Palm	6.2E-06	2	34	0.81	14	10	3.35
Kenaf	1.1E-05	2	40	0.60	150	10	2.1
Mustard	3.3E-05	1	66	0.67	87.5	10	4
Cotton seeds	8.2E-05	2	66	0.50	109.5	10	9.15
Prairie grasses	4.5E-05	2	70	0.33	105	10	4.9
Camelina	5.2E-05	1	85	0.67	92.5	10	3.8
Hemp	1.1E-05	1	80	0.50	110	10	4.3

Table 30: The global flows for the additional ranking of eight crops with the extra criterion of water use.

Crop	**Base Case**	**Gaus**	**EW**	**F-AHP**	**Simplest MCDA**
Alfalfa	3.2887	3.2435	2.1027	2.8846	-6.4
Oil palm	2.3063	2.3601	1.4598	1.6354	-11.1
Kenaf	0.3598	0.2581	0.2312	1.3915	-37.2
Mustard	-0.279	-0.4777	-0.1598	-0.3518	-32.3
Cotton seeds	-1.594	-1.6451	-1.2455	-2.0268	-37
Prairie grasses	-0.9057	-0.9399	-0.5902	-0.8837	-36.5
Camelina	-1.6196	-1.2901	-0.8786	-1.3372	-37.7
Hemp	-1.5564	-1.5088	-0.9196	-1.3119	-39.8

D.2 Additional Ranking: Higher Weights for Biodiversity

The table below gives the results of an additional ranking in which biodiversity has a higher weight than in the original rankings of the base case, Gaussian preference function, and with the simplest form of an MCDA. The original division of the entropy weights was the following: C1: 61%, C2: 0.9%, C3: 9.8%, C4: 4.2%, C5: 20%, and C6: 4%. For this new ranking, the weights were changed so that biodiversity has the highest weight and land use the second highest one. This resulted in the following weights for each criterion: C1: 20%, C2: 0.09%, C3: 9.8%, C4: 61%, C5: 4.2%, and C6: 4%. Interchanging these entropy weights is in theory not allowed. However, the reason this was done was to see how the ranking will change if biodiversity and land use become the criteria of greatest importance. Besides, this ranking was used to clarify the effects of weights on the results, as mentioned in the discussion.

Table 31: Additional ranking to see the effect of a higher weight for biodiversity. Where HWBD stands for higher weight biodiversity.

Rank	**HWBD Base Case**	**HWBD Gaussian**	**HWBD Simplest MCDA**
1	Alfalfa	Miscanthus	Alfalfa
2	Oil palm	Alfalfa	Oil palm
3	Miscanthus	Prairie grasses	Mustard
4	Kenaf	Kenaf	Soybean
5	Mustard	Cotton seeds	Kenaf
6	Cotton seeds	Oil palm	Cotton seeds
7	Prairie grasses	Reed canary grass	Prairie grasses
8	Flax/linseed	Hemp	Flax/linseed
9	Hemp	Poplar	Camelina
10	Soybean	Willow	Hemp