LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
LUT School of Business and Management
Business Administration
Master's Degree Programme in Supply Management

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BIOFUELS - A CONTRIBUTION ASSESSMENT FOR THE GLOBAL ENERGY TRANSITION INTEGRATING ASPECTS OF TECHNOLOGY, RESOURCES, ECONOMICS, SUSTAINABILITY AND ALTERNATIVE OPTIONS

Master's Thesis, 2018

Examiners: Professor Veli Matti Virolainen
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ABSTRACT

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167 pages, 58 figures, 6 tables, 4 appendices

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Keywords: biofuel, sugarcane, corn, energy return on energy investment (EROI), greenhouse gas (GHG) emissions, levelized cost of fuel (LCOF), synthetic fuel, sustainable development, sustainability, global energy transition.

Burning of fossil fuels is one of the main drivers accelerating the climate change. COP21 agreement adopted at the United Nations Climate Change Conference has addressed the climate change. In order to comply with the targets the countries need to implement energy transition from fossil fuels towards renewable energy. Biofuels are one of the alternatives for fossil fuels in transportation. Though the constraints for their deployment include the low commercialization level, limited resource availability, uncertainty regarding cost competitiveness with fossil fuels, sustainability concerns and better alternatives in the future such as synthetic fuels. The objective of the thesis is to assess the biofuels contribution towards the global energy transition from the different perspectives such as technology, resources, economics, sustainability and alternative options. The work is based on secondary data, which was collected and analyzed. The cost calculations were done by means of levelized cost of fuel formula. The cost projections for biofuels were done based on the feedstock cost estimations for the future. The findings have shown that there are many types of biofuels but only conventional biofuels, which are generally associated with sustainability constraints, are commercially available. Nowadays the United States corn and Brazilian sugarcane ethanol are the major biofuels on the market. Sugarcane ethanol has excellent emission reduction, good energy return on energy investment as well as dramatically decreasing costs in the future. Whereas corn ethanol has average emission reduction performance and energy return on energy investment as well as its costs slightly grow in the future. Therefore it is clear that sugarcane ethanol will stay on the market long time in the future while corn ethanol will be extruded by a cheaper and more sustainable alternative. Biofuels cannot satisfy the global transportation demand alone so their contribution towards global energy transition is limited. Thus, there should be an energy mix of conventional and advanced biofuels, synthetic fuels and electrification of transport aimed at satisfying the demand of different transportation sectors.

ACKNOWLEDGEMENTS

This work would not be done without the help from my supervisors. Many thanks to Christian Breyer for being an extremely motivating person and providing me very helpful guidelines, ideas, information and advices. I am very thankful to Veli Matti Virolainen for helping me in planning, organizing the structure, narrowing the scope of my work and keeping it focused on economics part.

There are team members from Neo Carbon Energy group who helped me to proceed in my thesis work. I am very grateful to Mahdi Fasihi for reviewing with me LCOF calculation part as well as providing me with great numbers for synthetic fuels. I would also like to thank Michael Child for helping me in understanding LCOF and efficiency concepts. Great thanks to Larissa Noel for providing me with Brazil wholesale electricity numbers.

Many thanks to my beloved Simon Richter for being with me in good and bad times and for believing in me and supporting me no matter which unrealistic ambitions I have in my projects. I know that together we can move the mountains. Simon Richter would kindly laugh at that and immediately encourage me to climb on Gersfeld mountains with the bicycles: as a fair start. I am thankful to the universe that such a wonderful person as Simon Richter is going to travel through the life joys and sorrows side by side with me.

I am very grateful to my family, especially my parents, for supporting my talents and desire to learn. Thanks to my mom and dad I was studying in Finland: it made me a better, smarter and more open-minded person. Conversations via Face time with my sister, nephew, grandmother, mom and dad have been keeping me happy and not lonely through all the time I was in Finland. I am thankful to the universe for having such a lovely family.

I am also thankful to my friends for their support. Special thanks to Polina Fedorova and Elena Tomovska for being extremely strong personalities and inspiring me to strive for being strong as well.

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LIST OF SYMBOLS AND ABBREVIATIONS

BTL	Biomass-To-Liquid
CDO	Corn Distiller's Oil
CGF	Corn Gluten Feed
CGM	Corn Gluten Meal
CH_4	Methane
CKF	Corn Kernel Fiber
CO_2	Carbon dioxide
DDGS	Dried Distiller's Grains with Solubles
DH	District Heating
DME	Dimethyl Ether (DME)
EROI	Energy Return on Energy Investment
EU	European Union
FAME	Fatty Acid Methyl Esters
FAEE	Fatty Acid Ethyl Esters
FT	Fischer-Tropsch
GHG	Greenhouse Gas
H_2	Hydrogen
H_2S	Hydrogen sulphide
HVO	Hydrotreated Vegetable Oil
LNG	Liquified natural gas
MeOH	Methanol
MSW	Municipal Solid Waste
N_2	Nitrogen
NG	Natural gas
NH_3	Ammonia
NO_x	Nitrogen oxide
NO_2	Nitrogen dioxide
PtG	Power-to-Gas
PtL	Power-to-Liquid
PtX	Power-to-X
PV	Photovoltaic
R&D	Research & Development
RE	Renewable Electricity
SBH	Sugar-Based Hydrocarbons
SLF	Synthetic Liquid Fuels
SNG	Synthetic Natural Gas
SO_2	Sulphur dioxide
SRF	Solid Recovered Fuels
UN	United Nations
US	United States
WDGS	Wet Distiller's Grains with Solubles
WDG	Wet Distiller's Grains

1 INTRODUCTION

1.1 Background

Climate change has been happening through the Earth history, however, people's activities accelerate climate to change 170 times faster than forces of the nature (Davey 2017). Greenhouse gas (GHG) emissions such as carbon dioxide, methane, nitrous oxide and fluorinated gases are the main drivers of the climate change acceleration (EPA 2017). The main GHG causing activities include such as burning of fossil fuels, deforestation, increase in livestock farming, using of fertilizers containing nitrogen and fluorinated gases effect (EC 2017b). The consequences of climate change include more extreme natural disasters and weather-related events, melting of glaciers and rising of sea level leading to flooding of the coastal areas, landscape change, acidification of the oceans and many others (European Parliament 2015a, 6). In order to address climate change, the Paris Agreement also known as COP21 Agreement was adopted at the United Nations (UN) Climate Change Conference in Paris on 12 December 2015. The Agreement has a target of keeping global temperature increase well below 2°C and implementing actions for limiting the temperature increase to 1.5°C. (UN 2015) In order to comply with the COP21 agreement countries need to implement energy transition from fossil fuels towards renewable energy (European Parliament 2015a, 11, 19). Renewable energy resources include such sources as solar energy, wind energy, hydro energy, ocean energy, geothermal energy and biomass (Perez & Perez 2009, 5). Biomass is a great resource because it can replace fossil fuels in production of electricity, heat and transportation fuels (European Parliament 2015b, 1). However, the biomass resources are not sufficient enough to satisfy the global energy demand alone. They can play a role of contributor, while the main roles in 100% energy transition from fossil fuels towards renewables will be played by solar and wind energy. (Perez & Perez 2009, 5) There are several sustainability issues associated with biomass resources such as for instance direct and indirect land-use change and competition with food production (IEA Bioenergy 2010, 2; WRI 2015, 1). So biomass should be used carefully and rely on sustainable feedstock sources. The market for transport biofuels has been created primarily due to national and European Union (EU) policies, establishing targets related to renewable fuels and energy

(ECOFYS 2015, 4). Being demanded due to renewable energy targets biofuels might play a major role in mobility sector energy transition especially in marine and aviation transport as long as it is hard to electrify those sectors (Nylund 2016, 25; ETIP Bioenergy 2016a, 31). Biofuels have the competitive technology called power-to-X or synthetic fuels, which can replace biofuels in the future due to decrease in costs and higher efficiency. The problem with the determining of the biofuels role in global energy transition lies in too diverse opinions about biofuels contribution depending on the institution or scientist, lack of studies describing all the biofuel technologies at once and comparing them by different characteristics, sustainability issues associated with conventional biofuel feedstocks, varying efficiency values depending on the study, issues with measuring of GHG emissions of biofuels and potential future competition with the other technologies such as power-to-X. Therefore, current study will provide a comprehensive overview of biofuels from the perspective of technologies, resources, economics, sustainability and alternative options. The core of the study will be the biofuel cost modelling as well as the cost projections and comparison of biofuel costs to the costs of competitive technology. The main implications about biofuels contribution to the energy transition will be made based on their technical development status, benefits to the society, resource availability, positions on the market and cost projections.

1.2 Research problem, objectives and delimitation

The aim of the thesis is to assess the role of biofuels in the global energy transition. It is achieved through the overview and analysis of biofuels from various perspectives including technology, resources, economics, sustainability and alternative options. The limitations contain such as taking into account biofuels only for the mobility sector, because biofuels are one of not many options of fossil fuel replacement for transport. Due to this their role in this sector can be substantial. Also this limitation is made due to already comprehensive variety of transportation biofuels and further expansion of chosen sectors to heating, electricity and chemical industry would make the study too wide. The detailed resource overview, life cycle assessment, efficiency analysis and cost modeling and projections are made not for all biofuels described in the technology part, but only for the corn and sugarcane ethanol due to the time limitation of thesis work. These two biofuel types were chosen based on the fact that they have been and stay to be the most produced biofuel types globally. The other limitation is related to making of cost projections maximum for the next 2 decades due to the data availability constraints and too volatile cost situation on the feedstock market. It was also decided to include only power-to-X fuel technology as an alternative option to biofuels. Power-to-X fuels are more comparable with biofuels than for instance electrification. Moreover, electrification cannot offer fossil fuel replacement for aviation and marine transportation, while biofuels along with power-to-X fuels can.

The main research question of the study is:

- What is the contribution of biofuels to the global energy transition?

The sub-questions, which support the main research question, are:

- What is the main biofuel technology of today and of the future?
- Are biofuel resources sufficient enough to satisfy the transport energy demand and which countries can contribute the most?
- What are the sustainability constraints of biofuels and how could they be overcome?
- How the cost of biofuels will change in the future?
- When biofuels might lose their cost competitiveness?

1.3 Research methodology and data collection

The study conducted is descripto-explanatory as it contains descriptions that are furtherly followed by related explanations. The study aims to create a clear profile of biofuel as a contributor to the energy transition by means of collecting, evaluating and synthesizing the data about existing technologic, resource, economic and sustainability characteristics of biofuels as well as explaining the nature of particular relationships such as for instance relationship between feedstock cost and cost of the biofuel. The carried out research is longitudinal in a form of a trend study. The trends are tried to be found out for instance in resource availability and production of biofuels, as well as in cost modelling and cost change over time. The data across the years is widely compared in current study. The research is conducted in non-contrived settings because biofuels are observed and evaluated without interference with the researcher.

The approach of the study is inductive and the data collection is qualitative, whereas the data collected includes both qualitative and quantitative. The method utilized for the data collection is a single embedded case study of a product biofuel in a global context. The case study is embedded because it overviews and examines a number of biofuel types. The mixed method research is applied because the qualitative data is analyzed qualitatively and quantitative data is analyzed quantitatively. The quantitative data includes numerical data, namely interval, ratio and continuous data. The quantitative data analysis is non-statistical and includes comparative analysis as well as determining the trends and forecasting.

The study is based on a secondary data, namely documentary and multiple sources. The documentary data utilized includes written materials such as organizations' websites, international organizations' reports, scientific journal, magazine and newspaper articles and books. The multiple sources contain area- and time-based sources. The area-based multiple sources include governments' and European Union publications. The time-series based multiple sources contain industry statistics and reports.

Every chapter has its own methods applied. The technology chapter is based on the description of different technologies based on the secondary data. Also the comparison graphs were created. Commercialization graph was created on the basis of synthesis of data from several secondary sources. In case of GHG emission reduction the graph is based on the minimum and maximum values found in the secondary sources for every fuel from the graph. In case of EROI graph maximum and minimum values were found in secondary sources as well as the mean value was calculated in order to create an objective picture. The resources chapter implied the secondary data collection for global biomass scenarios and further comparison of the scenarios was done. Also the graphs for production, import and export of biofuels and biomass were created based on the dataset publically available. The global maps for corn and sugar production were created by means of Google online software with the data taken from publically available source. Biofuel economics in case of indicative cost trend description is based on the secondary sources. Cost model is partly done by means of descriptions from secondary sources, while the cost breakdown, cost calculation and sensitivity analysis are based on LCOF concept and formula. The data for the calculations was taken from secondary sources with some assumptions done as well. Cost projections are done based on the feedstock cost trend taken from the publically available source. All the calculations were done in Microsoft Office Excel. The cost projections for synthetic fuels were taken from private communication with the author of projections from the author's permission to use the data in current work. Life cycle assessment is done based on the data collection from secondary sources. Efficiency analysis is partly done by means of literature review and it contains calculations as well. The global energy transition chapter has comparison of different scenarios taken from the secondary sources.

1.4 Organization of the study

The conceptual framework of the Master's thesis is illustrated in figure 1 below.

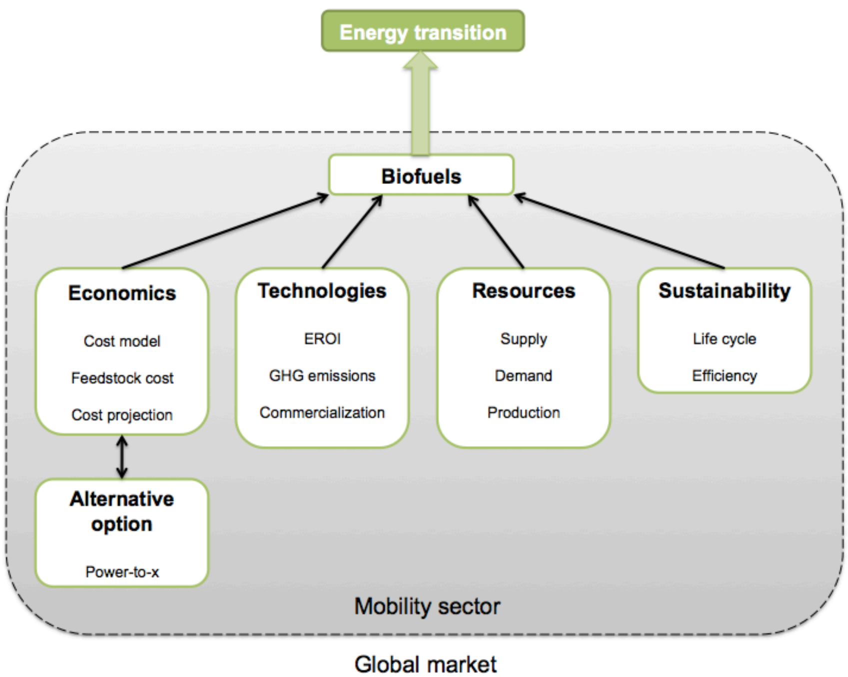


Figure 1 Conceptual framework (own artwork)

Conceptual framework shows that the study is made in the context of global market with focusing on mobility sector only. The goal of the study is to assess biofuel's contribution to the energy transition. It can be achieved via assessing biofuels from different perspectives, which include such as economics, technologies, resources, sustainability and alternative options. The main concepts in economics are cost model, feedstock cost as well as cost projection, which means that biofuels will be described and assessed on the basis of their cost structure and cost change in the future. The technology perspective has the main concepts of energy return on energy investment (EROI), greenhouse gas (GHG) emissions and commercialization status, which will be of help to show whether the technologies make sense to be used as conventional fuels' substitution. The resource part is observed in terms of supply and demand of biomass as well as the production trends. The sustainability's main concepts are life cycle and efficiency and the technologies are evaluated throughout it. Finally, the technologies are assessed from the perspective of comparison to alternative option namely power-to-X in terms of costs.

1.5 Definitions and key concepts

The key definitions and concepts of the study include such as biofuel, sustainable development, energy return on energy investment (EROI), greenhouse gas (GHG) emission and synthetic fuel, also known as power-to-X.

Biofuel is a liquid or gaseous fuel extracted from organic matter, which can play a major role in the transport sector in terms of emission reduction and reinforcing energy security (IEA 2011, 5).

Sustainable development is the development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN 1987).

Energy return on energy investment (EROI) is the method of determining the quality of various fuels by means of calculating the ratio between the energy output or energy delivered by a specific fuel and the energy input or energy invested in capturing and delivering of this energy (Hall et al 2014, 142).

Greenhouse gas (GHG) emission is the emission of gases, which catch heat in the atmosphere (EPA 2014).

Power-to-X is "renewable liquid and gaseous transport fuel of non-biological origin" (EC 2015).

2 BIOFUEL TECHNOLOGY DESCRIPTION

The chapter contains the descriptions of the conventional and advanced biofuel technologies, as well as the comparison of technologies in terms of commercializations statuses, EROI and GHG emission reductions.

2.1 Conventional biofuel technologies

Conventional biofuel technologies are commonly referred to as 1st generation biofuels, which are based on already well-known technologies and commercially deployed worldwide from the small to the large scales (IEA 2011, 8; ETSAP&IRENA 2013, 7; IRENA 2013, 27). Conventional biofuels include bioethanol, biodiesel and biogas, which primarily utilize energy crops as the feedstock for production. They are produced in order to replace gasoline, diesel or natural gas in the transportation sector (IEA 2011, 16). Conventional biofuels are not perfect in terms of efficiency, GHG emissions and costs and that is why they are continuously developing (ETSAP&IRENA 2013, 7). Bioethanol, biodiesel and biogas will be discussed in current subchapter from the perspectives of conversion technology, feedstock, co-products and blending characteristics.

2.1.1 Bioethanol

Conventional bioethanol is the most commonly produced biofuel (IRENA 2013, 27). Bioethanol can be produced from various feedstocks including sugarcane, sugar beet, sorghum, corn, wheat, potatoes and cassava (ETSAP&IRENA 2013, 7; Makkar 2012, 5).

Conventional bioethanol is produced via biochemical processes, which are a bit different for sugar-based and starch-based feedstocks. For the sugar-based crops the production process starts with heating of the raw feedstock from which the surcose is then subsequently mechanically pressed in a specialized roller. The collected juice is then purified by lime milk or calcium saccharate and after that the filtration takes place in order to remove debris from the sugar crop juice. Then the evaporation is applied to condense the juice to a sugar level suitable for the fermenting microorganisms. It is followed by the supplementation by nutrients of the concentrated syrup. Then the extracted surcose goes through the process of metabolisation through yeast cells, which are fermenting the hexose. Finally, the distillation to ethanol can be implemented. (IRENA 2013a, 27; Zabed et al 2017, 481, 483) Starch-based crops require an additional step namely hydrolysis into glucose. Therefore, the bioethanol produced from sugar crops is cheaper than starch-based bioethanol. However, the specific requirements towards soil and climatic conditions take place in case of growing sugar crops. Thus, starch based ethanol represents most part of global ethanol, namely around 60%, while sugar-based ethanol presents nearly 40%. In order to improve the process of starch-based ethanol production enzymatic hydrolysis can be used. It is followed by the same steps, which take place in the production of sugar-based ethanol. Due to the necessity of additional step implementation in case of starch the more energy is needed than the sugar-to-ethanol process, though the process is highly efficient. In overall, the environmental and economic efficiency of starch-based ethanol is achieved because of valuable co-products gained during the production. One of them is for instance dried distiller's grains with solubles (DDGS), which can be used as a livestock feed. (ETSAP&IRENA 2013, 7; IEA 2011, 13; IRENA 2013a, 27; Makkar 2012, 117; Zabed et al 2017, 481) Simplified schemes of sugar and stach-based bioethanol can be found in figure 2 below.

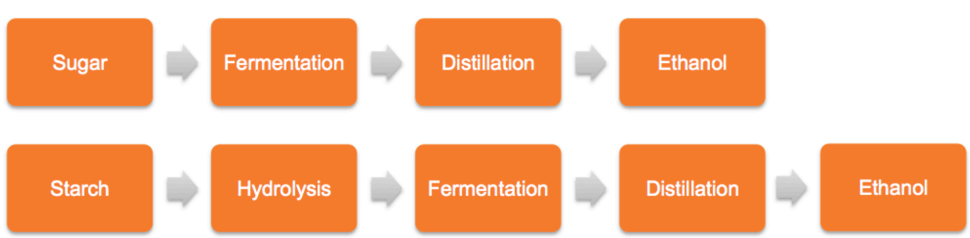


Figure 2 Sugar and starch-based bioethanol conversion processes (own artwork based on ETSAP & IRENA 2013, 11)

The other co-products, which can be generated during the production process, include for instance bagasse from sugarcane, which can be used in the operating of the sugar mill, namely as a fuel source to generate steam and electricity. In a small scale bagasse is also utilized as an ingredient for cattle feed. (ETSAP&IRENA 2013, 23; IEA 2011, 27; Makkar 2012, 4) Sugar beet creates beet pulp as a co-product in the ethanol production, though the amount is insignificant and it presents to be component of feed concentrates in low quality (ETSAP&IRENA 2013, 14; IEA 2011, 27; Makkar 2012, 5; Popp et al 2016, 10-11). Sorghum brings DDGS and wet distiller's grains with solubles (WDGS) as co-products, which are used for livestock feed (Makkar 2012, 117). Co-products from corn-based ethanol contain DDGS, wet distiller's grains (WDG) and corn gluten feed (CGF) as feed for the livestock, corn distiller's oil (CDO) as feed ingredient or feedstock for biodiesel, corn gluten meal (CGM) as feed for livestock or herbicide replacement and corn kernel fiber (CKF) as a source for the production of cellulosic ethanol (ETSAP&IRENA 2013, 14; IEA 2011, 27; Arodudu et al 2016, 10; Popp et al 2016, 11-12). Wheat creates DDGS, while potatoes-to-ethanol have such co-products as roots, aerial vines, culls and alcohol distillery waste water from anaerobic digestion enabling electricity or heat production in integrated biorefinery (Popp et al 2016, 10, Henly n/a, 22; Mussoline & Wilkie 2015, 113). The last but not the least feedstock is cassava, also known as tapioca, which includes such co-product from ethanol production as root fibre utilized as a boiler fuel source (Makkar 2012, 5). Therefore, in overall co-products from conventional bioethanol production include feed for livestock, source for electricity and heat generation and products for chemical industry.

Bioethanol can be blended with gasoline and depending on the amount it can be used in either conventional or flex-fuel vehicles (IRENA 2013, 27). Flex-fuel vehicles identify the fuel composition due to the oxygen sensors in the exhaust system, which adjust the ratio of fuel and air and ensure optimal combustion. The blending characteristics are typically low and blends vary from 10% to 15% of ethanol in conventional gasoline vehicles, while for instance in Brazil the blend can reach 25%. For flexible-fuel or ethanol vehicles the blending can be 85-100%. The blends have the names such as for instance E10, E15, E25 and E85. The blend E10 is 10% ethanol and 90% gasoline. (IEA 2011, 47; IRENA 2013, 28-29)

2.1.2 Biodiesel

Conventional biodiesel can be produced via transesterification of various feedstocks through the methanol, biomethanol or some other alcohols and catalysts addition. The feedstocks include rapeseed, soy seed, palm seed, sunflowers, castor beans, jatropha and animal waste and oils. Production of biodiesel from waste oils and animal fats is more efficient and cheaper, though the feedstock is limited. (ETSAP&IRENA 2013, 7, 14; Popp et al 2016, 5) In case of dealing with oil seeds or waste fats the oil and fats have to be firstly extracted or refined either mechanically or chemically. After that the fatty acids are separated from the glycerine molecule to which they are attached by means of esterification process of liquid oils and refined fats. Then the fatty acids are re-attached to the alcohol, which is normally ethanol or methanol. As an example during the production process roughly 100 pounds of oil or fat react with 10 pounds of alcohol in order to form 100 pounds of biodiesel and 10 pounds of glycerin. Addition of catalysts such as for instance sodium or potassium hydroxide makes the reaction much faster and less energy requiring. Moreover, catalysts offer further advantages as catalyst reuse, product separation and preferred conditions of reaction. The results of the reaction are FAME or FAEE biodiesel and glycerine. (IRENA 2013a, 43; AFDC 2017d; Martins et al 2013, 817) The schematic illustration of biodiesel production process can be found in figure 3 below.

Figure 3 Biodiesel production process (own artwork based on ETSAP&IRENA 2013, 11; IRENA 2013a, 43)

All types of biodiesel feedstocks enable generation of fatty acids and glycerine co-products (ETSAP&IRENA 2013, 14; IEA 2011, 27; Makkar 2012, 7). Though there are other co-products, which can be generated. For instance, rapeseed, soy seed and sunflowers create meal, which is used as livestock feed (Popp et al 2016, 12; Carter 2013). Palm seed creates kernel cake pulp, though the amount is insignificant and it presents to be low quality component of feed concentrates (Popp et al 2016, 10-11). Castor beans and jatropha create castor and jatropha cakes, which can be used as fertilizers or animal feed, but only after good quality elimination or inactivation of toxic compounds (Lago 2009, 241, 244). Biodiesel can be blended in amounts of up to B20 in conventional diesel engines (IEA 2011, 47).

2.1.3 Biogas

Conventional biogas can be produced through anaerobic digestion from dedicated energy crops such as maize, crop wheat and grass or from waste including organic waste, sewage sludge waste and animal manure (IEA 2011, 13, 28). Anaerobic digestion is a continuous process, which requires steady supply of feedstock with high moisture content. The feedstock needs a rigorous control and normally demands a pre-treatment in order to maximise methane production as well as minimise the probability of natural digestion process disruption. The common practice is to co-digest multiple feedstocks in order to reach the best balance of biogas yield and stability of the process. (IRENA 2013, 55) In case of waste feedstock in anaerobic digestion process the organic waste goes through the hydrolysis and acidification when the breaking of the large molecules and the formation of organic acids happens. After that acetogenesis and methanization occur where microbes generate methane. In overall the anaerobic digestion process includes such steps as hydrolysis, acidogenesis, acetogenesis and methanogenesis. (Greene 2014, 3) The co-products from anaerobic digestion allow replace nitrogen (N), phosphate (P) and potassium (K) fertilizers (IEA 2011, 28; Arodudu et al 2016, 5). Conversion process of biogas is schematically illustrated in figure 4 below.

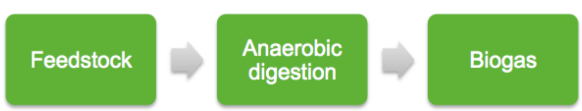


Figure 4 Conversion process of biogas (own artwork based on ETSAP&IRENA 2013, 11)

The composition of biogas is mostly methane (CH_4) and carbon dioxide (CO_2), with minor constituents such as nitrogen (N_2), hydrogen (H_2), ammonia (NH_3), sulphur dioxide (SO_2) and hydrogen sulphide (H_2S). In order to be used in transportation biogas is cleaned, upgraded and compressed. After being upgraded biogas is fully compatible with flex-fuel or dedicated natural or biogas vehicles. (IRENA 2013, 55-56; IEA 2011, 47)

2.2 Advanced biofuel technologies

Advanced biofuel technologies include 2nd and 3rd generation biofuels (IEA 2011, 8). One of the main features of advanced biofuel technologies is that they focus on non-food feedstocks, such as for instance agricultural and forest residues, genetically modified crops and perennial grasses, which are grown on non-arable land, short-rotation forestry and waste. The majority of the feedstock utilized presents to be ligno-cellulosic biomass. (ETSAP&IRENA 2013, 7) Advanced biofuels will be described and discussed in terms of conversion technology, feedstock, co-products and blending characteristics in current chapter.

2.2.1 Cellulosic ethanol

Cellulosic ethanol is produced from lignocellulosic biomass primarily forest and agricultural residues in order to replace gasoline (IEA 2011, 13, 16; IRENA 2016, 6). Agricultural residues can include for instance stalks, husks, straw, bagasse, cobs and so on. The plants which residues are suitable for the cellulosic ethanol production are cotton, canola, wheat, rice, sugarcane, corn, sorghum and many others. (Gonçalves et al 2013, 625-626) There are several ways of how the feedstocks can be converted into cellulosic ethanol. For example, biochemical process is similar to the one of conventional ethanol production. Due to acidic or enzymatic hydrolysis cellulose and hemicellulose can be converted into sugars and then subsequent fermentation and distillation to ethanol takes place. The problem with cellulosic feedstock lies in lignin content, which must be removed due to its properties of impedding hydrolysis. Enzymatic hydrolysis is cheaper than acidic though due to the need of feedstock pre-treatment the overall process is rather expensive. (ETSAP & IRENA 2013, 8; IEA 2011, 13) The other conversion process is thermochemical. It implies gasification and subsequent mixed alcohol synthesis. (IRENA 2016, 114) Besides biochemical and thermochemical processes cellulosic ethanol can be also produced by means of hybrid process, which includes gasification and syngas fermentation steps (IRENA 2016, 113). The conversion process steps are shown in figure 5 below.

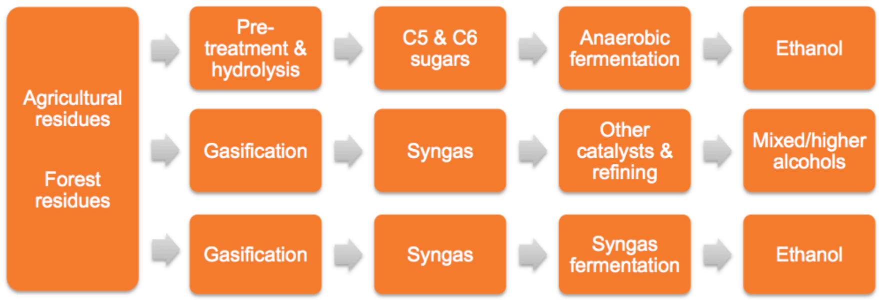


Figure 5 Conversion processes of cellulosic ethanol (own artwork based on IRENA 2016, 33, 46, 50)

Among the co-products generated during conversion processes of cellulosic ethanol are lignin, gases, fuels, organic acids, alcohols, aromatic compounds, macromolecules and other products. The co-products can be used in various processes such as for instance fuel production, industrial processes, pharmaceuticals, in chemical industry and so on. (ETSAP & IRENA 2013, 14; IEA 2011, 27; Patton n/a, 6)

Cellulosic ethanol can be blended in amounts same as sugar-based ethanol, namely in amount of 10-15% in conventional gasoline vehicles with the exception of Brazil, where ethanol can be blended in amounts of 25%. In flexible-fuel or ethanol vehicles the amount of ethanol can reach 85-100%. (IEA 2011, 47)

2.2.2 Advanced biodiesel

Advanced biodiesel is produced in order to replace diesel and jet fuels (IEA 2011, 16, 47; Milbrandt et al 2013, 3; ETIP Bioenergy 2016b). There are several pathways of how advanced biodiesel can be produced as well as the feedstocks utilized are very different. One of advanced biodiesel technologies is called biomass-to-liquid (BTL). It is a thermochemical process, which starts with biomass pre-treatment and followed by gasification to produce syngas, which is rich in hydrogen and carbon monoxide. Syngas is subsequently cleaned-up and further catalytical conversion through Fischer-Tropsch (FT) synthesis takes place. (ETSAP & IRENA 2013, 8; IEA 2011, 13) The feedstocks which are suitable for BTL are mainly forest residues, though it can be also waste and almost any type of biomass (IRENA 2016, 116; ETIP Bioenergy 2016a; ETIP Bioenergy 2016b). The other technology for advanced biodiesel production is called hydrotreated vegetable oil (HVO), which involves such process steps as catalytic hydrogenation of vegetable oils and fats and subsequent cracking. (ETSAP & IRENA 2013, 9; IEA 2011, 13) The feedstocks, which are suitable for the process, are rape, palm or jatropha oil, non-food grade vegetable oil fractions as well as waste and residue fat fractions from food, fish and slaughterhouse industries. (Arvidsson et al 2011, 129; Neste 2016, 3). Advanced biodiesel can be also produced via oil extraction and transesterification. The feedstock, which is needed for it is micro-algae and the final product, is FAME. The other technology implies hydrolysis and aqueous phase reforming of sugars as well as hydro-treatment and refining. The feedstock suitable for the technology is agricultural residues. (IRENA 2016, 6, 45, 118) All the advanced biodiesel technologies are schematichally illustrated in figure 6 below.

Figure 6 Conversion processes of advanced biodiesel (own artwork based on IRENA 2016, 45, 48, 52; ETSAP & IRENA 2013, 9; IEA 2011, 13)

There are various co-products, which can be generated due to the production of advanced biodiesel. There are low-temperature heat, pure CO_2 from the production of BTL, glycerine, naphtha and propane from HVO, oil, protein, carbohydrates from FAME and lignin with acetate from sugar-based hydrocarbons (SBH) (ETSAP & IRENA 2013, 14; IEA 2011, 28; Casas et al n/a, 7; Darzins et al 2010, 2; Davis et al 2013, 2).

Concerning blending characteristics, all of the advanced biodiesel types have full compatibility with the existing infrastructure of vehicles and distribution, except only FAME, which needs hydro treating before it can be blended with conventional diesel (IEA 2011, 47).

2.2.3 Bio-synthetic gas

Bio-synthetic gas or also known as bio-SNG (bio-synthetic natural gas) is biomethane produced from various biomass feedstocks including virgin (woody) biomass and waste biomass such as municipal solid waste (MSW), sludge and solid recovered fuels (SRF). Though basically it can be any biomass feedstock, which cannot be broken down in traditional plants of anaerobic digestion. (IEA 2011, 14; CNG Services 2011, 1; Vitasari et al 2011, 3825) Bio-SNG is produced via thermal processes, which start with gasification of the biomass into flammable gas. Then it is followed by the purification of so-called synthesis gas and upgrading to methane in a methanation plant. (IEA 2011, 14; Göteborg Energi n/a) Conversion process of bio-SNG is illustrated in figure 7 below.

The co-products of the bio-SNG production are pure CO_2 and heat, which can be used in district heating (DH) (IEA 2011, 28; Ahrenfeldt et al 2010, 44). Concerning its blending characteristics, bio-SNG can be used in natural gas and flex-fuel vehicles as well as it is compatible with fueling infrastructure but after cleaning and upgrading of biomethane (IEA 2011, 14, 47; IRENA 2013, 55).

Figure 7 Conversion process of bio-SNG (own artwork based on ETSAP & IRENA 2013, 11)

2.2.4 Hydrogen

Hydrogen is an energy carrier and secondary form of energy that can be produced from various primary energy sources as well as via many production technologies (Balat & Kırtay 2010, 7416). Among the production pathways for the hydrogen there are for instance laboratory methods, electrolysis of water using surplus of renewable electricity, solar direct conversion of hydrogen, production of hydrogen from biomass, biological methods and many others (Press et al 2009, 195-209). According to REN21 (2017, 58) electrolysis is considered to be the dominant production way of hydrogen in all sectors. Though production of hydrogen from the biomass also exists and deserves a short overview.

The biomass feedstocks for hydrogen production include dedicated bioenergy crops, lignocellulosic biomass such as agricultural waste and wood residues, and MSW (Singh et al 2015, 13062; Balat & Kırtay 2010, 7418; Press et al 2009, 204). The methods for the hydrogen production from biomass contain themochemical and biological. The thermochemical conversion paths include such processes as gasification and steam gasification, supercritical water gasification, pyrolysis, steam reforming of bio-oils, partial oxidation and cracking. The biological methods include direct and indirect biophotolysis of water using microalgae and cyanobacteria, high-yield dark-fermentation utilizing fermentative bacteria, photo-fermentation using purple bacteria and microalgae, water gas shift reaction, two-phase H_2 + CH_4 fermentations, steam reforming of bioethanol or methanol and many others. (Singh et al 2015, 13064; Balat & Kırtay 2010, 7418; Reith et al 2003, 12; Milne et al 2002, 3) The production of hydrogen from biomass creates various co-products, such as for instance carbon monoxide, carbon dioxide, methane, acetylene, ethylene, benzene, toluene, xylene, light tars, heavy tars, ammonia, water, solvents, acide, electricity, heat, FT diesel, SNG and so on (Balat & Kırtay 2010, 7421).

One of the thermochemical ways of hydrogen production from biomass is the process when the biomass is converted into a gas consisting of mainly CH_4, H_2 and CO followed by steam introduction in order to reform CH_4 to H_2 and CO. Afterwards water shift reaction is applied for CO to attain a higher level of H_2. The process has a by-product CO_2, which does not increase the carbon dioxide concentration in the atmosphere and that is why the GHG emissions are considered to be neutral from the process. (Press et al 2009, 204; IEA 2011, 12; ETSAP & IRENA 2013, 10, 12) One of the biological pathways, which can be highlighted, is the steam reforming of bioethanol or methanol. The reforming process happens easily with the help of catalysts such as copper, cobalt and nickel for ethanol and copper, chronium, manganese and silicon for methanol. (Milne et al 2002, 19-23; IEA 2011, 12; ETSAP & IRENA 2013, 10, 12)

2.2.5 Other novel fuels

There are also many other biofuels, which deserve attention, such as for instance biomethanol, biobutanol, bio dimethyl ether (DME) and pyrolysis-based biofuels.

Biomethanol is the biofuel, which can replace gasoline, diesel and petro-chemical methanol, ethylene and propylene. It can be produced from biomass, waste, biogas from landfill, sewage and solid waste treatment, from glycerin and black liquor. The production process starts with pre-treatment, and after that the feedstock's gasification to syngas takes place. Syngas contains carbon monoxide, hydrogen, carbon dioxide, water and some other hydrocarbons. After that goes the step of removing of impurities and contaminants. According to Specht & Bandi (1999) the purpose of it lies in attempt to produce syngas that has minimum twice as much molecules of hydrogen as carbon monoxide molecules (as cited in IRENA 2013b, 7). It can be achieved via various processes such as for instance water gas-shift reaction. Then after conditioning the syngas is converted into methanol by catalytic process followed by distillation. The potential co-products from the production process are electricity, heat, hydrogen, bioethanol and urea. (IRENA 2013b, 5, 6-8, 11, 16) Concerning blending characteristics, biomethanol can achieve 10%-20% blends in gasoline and up to 85% in flexible-fuel vehicles (IEA 2011, 47).

Biobutanol is the biofuel, which can replace gasoline or diesel and can be produced via biological and chemical conversion of sugars into alkanes (Niemistö et al 2013, 61; IEA 2011, 16; ETSAP & IRENA 2013, 10). The feedstocks suitable for biobutanol production include such as wood-based biomass, agricultural residues, crop and non-food crop biomass, biodegradable municipal waste and industrial by-products (Niemistö et al 2013, 61). The potential co-products from the production process contain acetone, solvents, coatings, DDGS, fibers, hydrogen, ethanol and fatty acids (AFDC 2017a; Wu et al 2007, 22). Biobutanol can be blended with gasoline or diesel in amounts of 85% without the need for retrofitting of vehicle (Niemistö et al 2013, 59; IEA 2011, 47).

Bio-dimethyl ether (DME) can replace diesel and can be used in diesel engines, as well as in liquified petroleum gas infrastructure (ETSAP & IRENA 2013, 10; IEA 2011, 47; AFDC 2017b). It is produced from forest residues and it has electricity as a co-product from the conversion process (IRENA 2016, 115; Tan et al 2015, 44). Bio-DME can be produced via conversion of biogas into methanol, which is furtherly distilled and dehydrated by means of zeolite catalysts (ETSAP & IRENA 2013, 10).

Pyrolysis-based fuels are good in a sense that they can replace gasoline, diesel, as well as a jet fuel (ETSAP & IRENA 2013, 9; Han et al 2011, 1; Milbrandt et al 2013, 6). The fuels can be produced from forest biomass via fast pyrolysis. The process implies gasification in the absence of oxygen and in a low temperature, which continues with the quick cooling to get condensed oil. (ETSAP & IRENA 2013, 9) The co-products of the conversion process are excess solids, fuel gas and steam (Han et al 2011, 6, 25). Concerning the blending characteristics of the pyrolysis-based fuels, to assess the blend limits more data concerning the composition of these fuels is required, though for widespread application pyrolysis based biodiesel blending is limited to 20% volume (Milbrandt et al 2013, 30).

2.3 Summary

The overall summary about biofuels can be found in appendix 1. It has the information about conversion technologies, feedstocks, co-products, blending characteristics, fossil fuel replacement, EROI, GHG emission reduction, commercialization status and indicative cost trend. Since EROI, GHG emissions and commercialization status can be compared the comparison graphs were made. The graph about commercialization status (figure 8), GHG emissions (figure 9) and EROI (figure 10), as well as the analyses of the graphs can be found below.

There are 5 groups of biofuels and 4 commercialization statuses presented in figure 8. Among the biofuel groups are bioethanol, diesel-type fuels, biomethane, hydrogen and other fuels. The commercialization statuses include such as R&D, demo, pre-commercial and commercial. Only several biofuels have reached pre-commercial and commercial stages. Among those are conventional bioethanol from energy crops, cellulosic ethanol produced by means of biochemical conversion, conventional biodiesel produced via transesterification, advanced biodiesel HVO, conventional biogas made via anaerobic digestion, biomethanol and bio-DME.

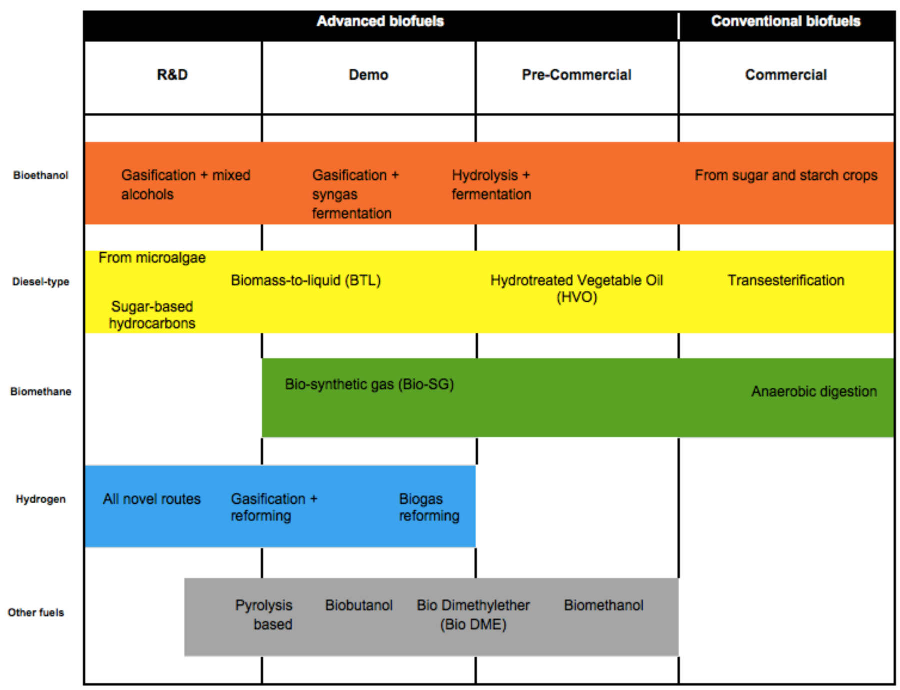
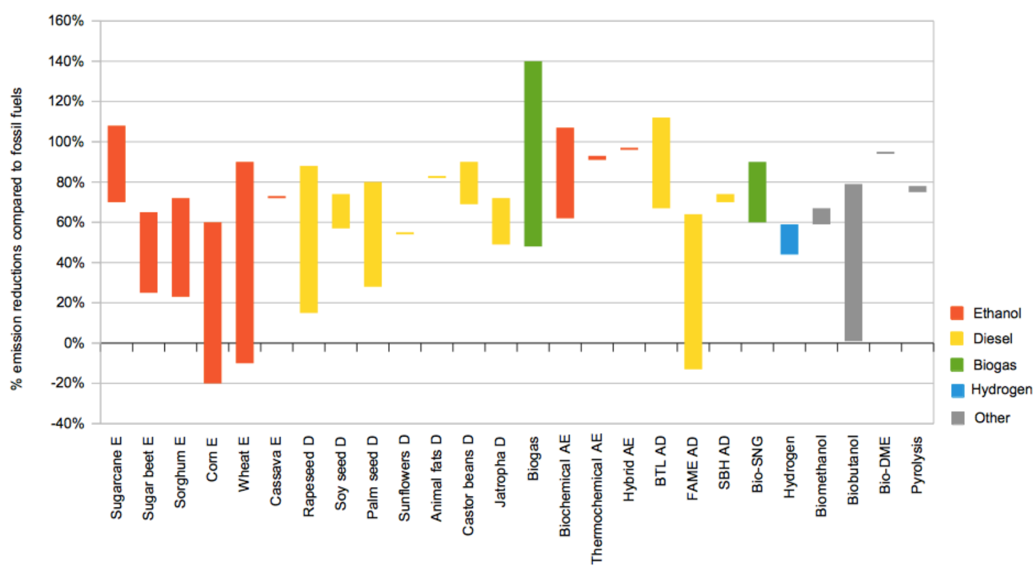


Figure 8 Commercialisation status of biofuel technologies (own artwork based on ETSAP&IRENA 2013, 12; IEA 2011, 12; IRENA 2016, 5)

The demonstration stage has been achieved by such biofuels as cellulosic ethanol produced via hybrid method, advanced biodiesel BTL, advanced bio-SNG, hydrogen produced via gasification with reforming and via steam reforming from ethanol and methanol, as well as pyrolysis-based fuels and biobutanol. Some of the biofuels are just at the R&D stage. Among them are thermochemical cellulosic ethanol, biodiesel from microalgae FAME and sugar-based hydrocarbons.

The GHG emission reduction graph, which is presented in figure 9, has various biofuels on the x axis and on y axis it has a percentage of emission reduction offered by biofuel compared to the fossil fuel analogue.



Note: E – conventional bioethanol, D – conventional biodiesel, AE – advanced bioethanol, AD – advanced biodiesel, BTL – biomass-to-liquid, FAME - fatty acid methyl ester, SBH – sugar-based hydrocarbons, DME – dimethyl ether

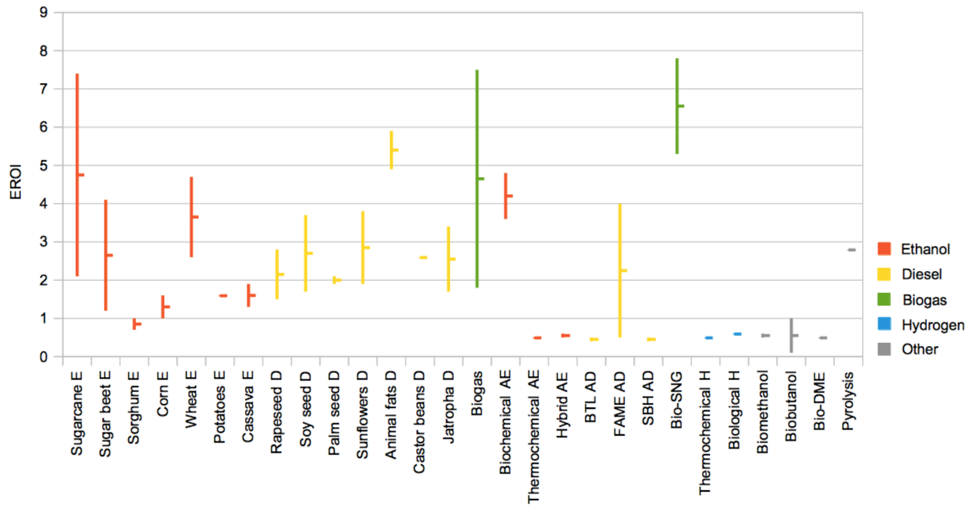
Figure 9 Biofuels' emission reductions compared to fossil fuels (own artwork)

The GHG emission reduction varies from one biofuel to another. From the literature review results presented in figure 9 it can be seen that conventional biofuels basically have much wider ranges of possible emission reduction percentages than advanced biofuels, which are more predictable. The highest GHG emission reduction is offered by conventional biogas, which can reach up to 140% reduction. The biofuels which emission reductions can reach 80% compared to fossil fuels are sugarcane ethanol, diesel from animal fats and waste oils, diesel from castor beans, advanced ethanol, BTL advanced biodiesel, bio-SNG and bio-DME.

Conventional bioethanol from wheat, biodiesel from rapeseed and palm seed can also achieve emission reductions of 80%, but these biofuels are controversial, because in some cases they also offer too low emission reductions. For instance, wheat bioethanol can even have higher GHG emissions than gasoline.

The graph about EROI can be found in figure 10 and it has biofuel names on x axis and EROI level on y axis. The ranges for EROI published about the same biofuel are sometimes quite big and can reach a difference between the minimum and maximum values of up to 5. Therefore, the mean values of biofuels' EROI will be compared to have a better overview. According to Atlason & Unnthorsson (2014, 241) and Hall et al (2014, 144) the EROI values above 3 are required for the fuel to be useful for the society at least on a minimum level. The EROI levels above 3 are offered by conventional and advanced biogas, biodiesel from animal fats and waste oils, conventional sugarcane and wheat ethanol and cellulosic biochemical ethanol. The EROI levels of advanced biofuels are too low at the moment, below 1, except bio-SNG and FAME biodiesel. It is clear from the graph that there is a significant difference between EROI of conventional and advanced biofuel types when conventional biofuels show better performance than advanced biofuels. Firstly, it might be related to the fact that conventional biofuels are commercialized and that is why the conversion process is better optimized than the conversion processes of advanced biofuels, which are at R&D or demonstration stage. Secondly, it might be also related to the lack of variety of literature about advanced biofuels. Several sources related to EROI of each conventional biofuel type were used, while the advanced biofuels' EROI are built mostly based on single literature sources, which might make the results slightly biased. Moreover, the calculation method of EROI might be different from one literature source to another and include more or less parameters to the calculation, which also makes it different to compare EROI of biofuels. Nevertheless, the graph shows the generalized overview of the biofuels' EROI published in recent literature.

The technological overview has also shown that conventional biofuels are more road transportation oriented, whereas advanced biofuels can replace shipping and aviation fuels as well as they can be applied at chemical industry as a substitution of oil products. Also it is worth mentioning that co-products play substantial role in biofuel profile because they can increase EROI, mitigate GHG emissions and decrease production costs of biofuels.



Note: E – conventional bioethanol, D – conventional biodiesel, AE – advanced bioethanol, AD – advanced biodiesel, BTL – biomass-to-liquid, FAME - fatty acid methyl ester, SBH – sugar-based hydrocarbons, H – hydrogen, DME – dimethyl ether

Figure 10 EROI of biofuels (own artwork)

3 BIOFUEL RESOURCES

The chapter contains the detailed information about biomass supply and demand. Also the description of the biofuel production is done with the emphasis on biodiesel and bioethanol production, import and export trends. Moreover, corn and sugarcane production, import and export trends are observed in details.

3.1 Biomass supply and demand

Biofuel resources, which are primarily utilized for biofuel production, can be divided into 4 clusters based on the feedstock type. The clusters are energy crops, forestry products, agricultural products and waste. Energy crops were separated from the agricultural products because they already present a very substantial group alone. The schematic illustration of biofuel feedstock clusters can be seen in figure 11 below. Energy crops present to be the major group for today as energy crops are widely utilized for the conventional biofuel production. Energy crops can be divided into food crops and non-food crops. Food crops contain sugarcane, sugar beet, sorghum, corn, wheat, potatoes, cassava, rape seed, soy seed, palm seed and sunflower, whereas non-food crops group is not that substantial and includes only castor beans and jatropha.

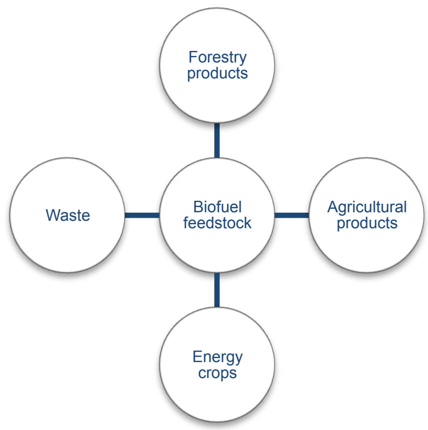


Figure 11 Biofuel feedstock clusters (own artwork)

Any type of woody biomass can be utilized, though it is not very widespread to use woody biomass for transportation biofuels production except forest residues. Only several fuels are produced from virgin wood, but they have not reached commercialization stage yet. Agricultural products are a very diverse group. It can include agricultural residues, animal fats and animal manure. The waste category includes MSW, waste oils, sewage sludge, organic waste and industrial by-products. Algae-based biofuels are still at R&D or demonstration stages and algae are very rarely utilized at the moment so they were not included to the clustering.

Global total final energy consumption in 2013 was 381.8 EJ. Around 28% (106.6 EJ) of global energy use falls on transportation where biofuels represent not a very big share nowadays: in 2013 the transport fuels, which came from biofuels, were 3%. (IEA 2015, 584; IEA 2017) According to IRENA (2014a, 33) the biomass demand for transportation sector in 2010 was 5

EJ/yr, whereas according to IEA (2012, as cited in IRENA 2014b, 110) the utilization of biomass in transportation has reached just 2 EJ/yr. The demand of biomass in transportation is about to substantially grow by 2030 and reach 31 EJ/yr. (IRENA 2014a, 33). The main driver of the biomass demand in transportation has been the deployment of blending mandates in major economies as well as the sustained fuel use globally (OECD-FAO 2016b, 116). Total biomass demand for all energy sectors in 2010 was 53 EJ/yr, while total biomass supply exceeded this number and was 56 EJ/yr, which shows that current supply of biomass is sufficient globally. Biomass demand for all sectors in 2030 is forecasted to be 108 EJ/yr, while supply is estimated to be 96-148 EJ/yr. (IRENA 2014a, 33)

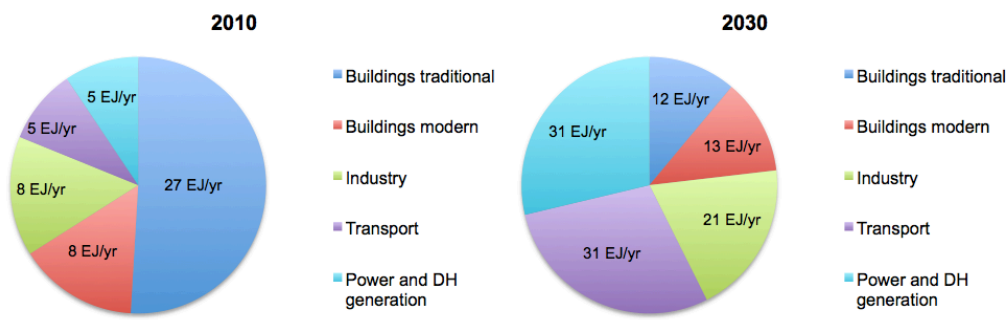
The global transportation energy use in 2010 was 99 EJ/yr, which is forecasted to grow and reach 123-132 EJ/yr by 2030 (IEA 2012, as cited in IRENA 2014b, 110). Theoretically biomass potential for 2030, which presents to be 96-148 EJ/yr, could be almost sufficient to satisfy transportation energy demand alone (IRENA 2014a, 33). Though it should be taken into consideration that biomass originating from the forest or agricultural systems can have a negative environmental, social or economic impacts, also known as sustainability concerns. For instance, some of such constraints can include competition of the biomass with food production or land-use change impacts. To be utilized for biofuels production, it should be demonstrated that the advantages of biomass usage exceed the cost of potential damage it might cause. (Ladanai & Vinterbäck 2009, 18) Therefore, practically the sustainable potential of biomass is lower than theoretical. So biomass cannot satisfy the transportation energy demand alone, it should be used along with the other fuels or electricity.

There are different estimations for 2030 and 2050 years concerning the total biomass supply potential and biomass potential according to the origin of biomass such as for instance energy crops or residues. The current global biomass supply and different estimations for 2030 and 2050 are presented in table 1 below.

Table 1 Current global biomass supply and global biomass potential for 2030 and 2050

Cluster	Feedstock type	EJ/yr	%
Global biomass supply in 2010 (IPCC as cited in WBA 2014, 15)			
Forestry products	Fuel wood	36.3	67
	Charcoal	3.80	7
	Forest residues	0.54	1
	Black liquor	0.54	1
	Wood industry residues	2.71	5
	Recovered wood	3.25	6
Agricultural products	Animal by-products	1.63	3
	Agricultural by-products	2.17	4
Energy crops	Energy crops	1.63	3
Waste	MSW and landfill gas	1.63	3
	Total	54.2	100
Global biomass potential for 2030 (IRENA 2014a, 27)			
Energy crops	Energy crops	33-39 (36)	30
Agricultural products and waste	Agricultural residue	19-48 (33.5)	27
	Animal and household waste	18	15
Forestry products	Fuel wood	5-19 (12)	10
	Forest residues	21-24 (22.5)	18
	Total	96-148 (122)	100
Global biomass potential for 2030 (WBA as cited in IRENA 2014a, 28)			
Energy crops	Energy crops	18	12
Agricultural products and waste	Agricultural residue and food waste	62	62
Forestry products	Forestry products	70	57
	Total	150	100
Global biomass potential for 2050 (IIASA 2012)			
Energy crops	Energy crops	44-133 (88.5)	41
Agricultural products	Agricultural residue	49	23
	Animal waste	39	18
Waste	MSW	11	5
Forest products	Forest residues	19-35 (27)	13
	Total	162-267 (214.5)	100

According to IPCC (as cited in WBA 2014, 15) in 2010 global biomass supply was fulfilled primarily by forestry products such as fuel wood, charcoal, recovered wood and wood industry residues. This is so because in 2010 more than a half of energy demand was caused by traditional buildings, which implies energy demand for cooking and heating by the use of wood. Whereas in 2030 the situation is going to change, and the demand will be caused mainly by transport, power and DH generation. (IRENA 2014a, 33) The split of the demand depending on the energy sector in 2010 and 2030 as well as the comparison are illustrated in figure 12 below.



Notes: Total biomass demand in 2010 is 53 EJ/yr; in 2030 – 108 EJ/yr.

Figure 12 Biomass demand by sectors in 2010 and 2030 (own artwork based on IRENA 2014, 33)

There are two scenarios of the biomass potential for 2030 provided by IRENA and WBA. According to IRENA (2014a, 27) biomass potential in 2030 will be primarily presented by energy crops, agricultural residues and forest residues. Whereas WBA (as cited in IRENA 2014a, 28) claims that the 2030 biomass potential is going to be provided by agricultural residues, food waste and forestry products. In their scenario energy crops are not going to play substantial role. Concerning 2050, IIASA (2012) affirms that energy crops will present almost half of the biomass potential with agricultural products namely agricultural residues and animal waste playing secondary roles.

3.2 Biofuel production trends

The global biofuel production takes place primarily in the United States (US), Brazil and EU. The US is the leader in biofuel production since 2007 and until now, whereas from 1990 till 2004 Brazil was the leading biofuel producing country. The other countries entered the market in 1990s but the share of biofuel produced by them has been too small till the middle of 2000s. The US produces almost half of the global biofuel, while the EU, Brazil and other countries share the market almost equally with the predominance of Brazil. (World Bank 2017a, 11) According to IEA 2010a (as cited in IEA 2011, 12) the US and Brazil specialize on ethanol, while OECD countries are known on the biofuel market for the biodiesel they produce. The most substantial roles on the global biofuel market are played by the ethanol produced in the US and Brazil. When taken together they represent roughly three fourth of the global biofuel production in 2010. According to World Bank (2017a, 11) in the future production of biofuel is going to increase with the shares of contribution of the countries staying almost equal to nowadays. The only forecasted significant change would be the increase of the contribution to the biofuel production by other players than the US, Brazil and OECD countries. Figure 13 shows global biofuel production depending on the producing area as well as the fuel type typical for the country or area.

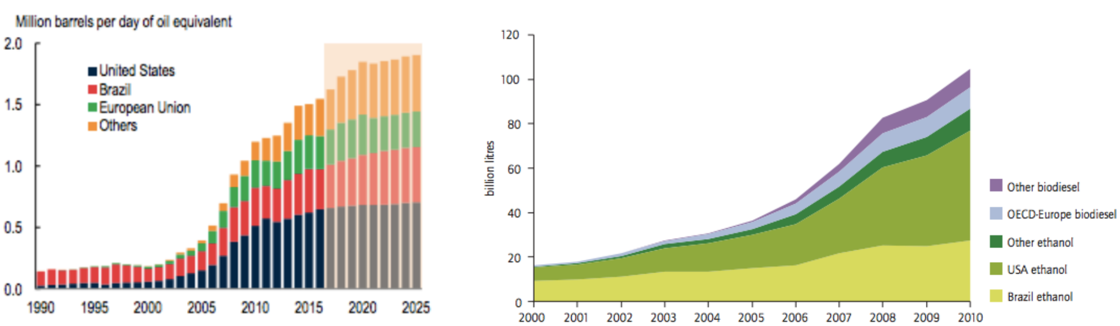


Figure 13 Global biofuel production (World Bank 2017a, 11; IEA 2010a as cited in IEA 2011, 12)

Concerning the distribution of biofuel types depending on the feedstock, nowadays the majority of produced biofuel falls on corn ethanol, which represents 41% of all global biofuel production. Sugarcane ethanol is the second most produced biofuel globally with the share of 19%. Almost the equal share (18%) has biodiesel produced from vegetable oils. Ethanol produced from the other not specified feedstocks represents 15% of global biofuel. Biofuel produced from waste has no significant contribution to the market as it represents only 2% share for ethanol as well as for biodiesel. (OECD-FAO 2016a) Concerning the future changes, ethanol and biodiesel production is going to increase though advanced biofuels will not take off by 2025 (OECD-FAO 2016b, 116). The shares of different bioethanol and biodiesel types in global biofuel production in 2014 are shown in figure 14 below.

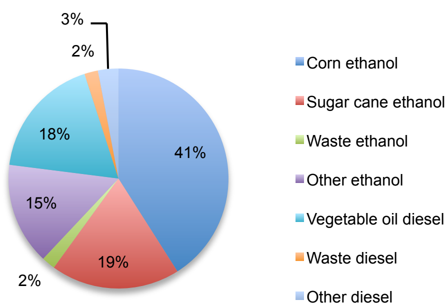
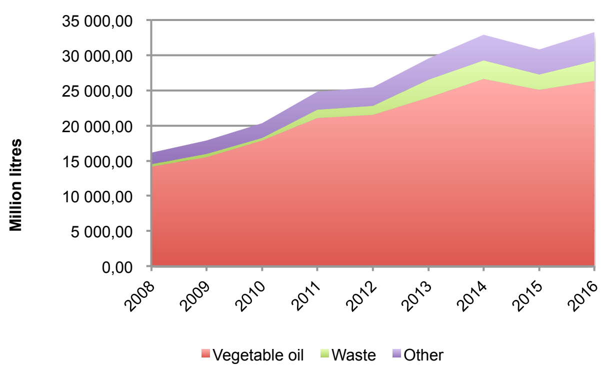


Figure 14 Shares of bioethanol and biodiesel types from different feedstock in global biofuel production in 2014 (own artwork based on dataset OECD-FAO 2016a)

There are various mandates and directives concerning biofuels, which can affect the production or export and import behavior in the future. For instance the EU has progressively increasing obligation on European transport fuel from 1.5% in 2021 to 6.8% in 2030. Current obligation is made on the utilization of renewable electricity, renewable transport fuels which have non-biological origin, advanced biofuels and waste-based fuels. At the same time the EU tries to mitigate the indirect land use change (ILUC) influence and therefore there is a cap on the food-based fuels' contribution to the renewable energy target beginning from 7% in 2021 and progressively decreasing to 3.8% by 2030. (EC 2016, 2) The US for instance has so called blend wall which is “a creation of the oil companies’ failure to respond appropriately to the very clear market signal given upon passage of the Energy Independence and Security Act of 2007” (RFA 2017a). The oil companies refused to invest in E15 and higher ethanol infrastructure and that is why it was prognosed that it might me a constraint towards the growth of ethanol production at the US (RFA 2017a; OECD-FAO 2016b, 116). Though in 2016 the US overcame the limit of 10% ethanol blend and the US Energy Information Administration (EIA) has claimed that the blend wall is not a real constraint for the future (RFA 2017b). In India there are the new policies aimed at encouraging sugar mills to have higher sugar prices. Thus, the ethanol production in India will be implemented from molasses (OECD-FAO 2016b, 116).

3.2.1 Biodiesel production trends

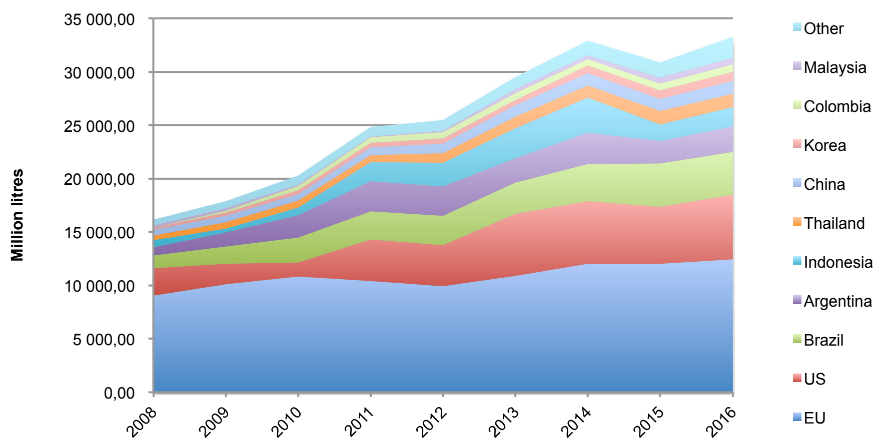
Biodiesel produced from vegetable oil plays the major role in global biodiesel production and represents 26604 million litres, while only 2662 million litres were produced from waste in 2014. In total there were 32891 million litres of biodiesel produced in 2014. Compared to 2008 the biodiesel production has doubled by 2014. Vegetable oil biodiesel has been and stayed the leader, while waste biodiesel and other types of biodiesel together represent roughly only 20% of the production nowadays. Though there was a substantial progress of the biodiesel production from waste: the production has grown by 801% since 2008. (OECD-FAO 2016a) Figure 15 below illustrates the biodiesel production based on the feedstock type in 2008-2016.



Notes: Data for 2015 and 2016 is based on forecast

Figure 15 Global biodiesel production from various feedstock 2008-2016 (own artwork based on dataset OECD-FAO 2016a)

Concerning the production areas of biodiesel the EU has been and stays the leader since 2008. In 2014 it produced 12028 million litres of biodiesel, which is 37% of the global biodiesel production. The US and Brazil are following with the production amounts of 5891 and 3419 million litres respectively. The other producing countries are Argentina, Indonesia, Thailand, China, Korea, Colombia, Malaysia and others. (OECD-FAO 2016a) Figure 16 below shows the biodiesel production trends based on the producing area in 2008-2016.

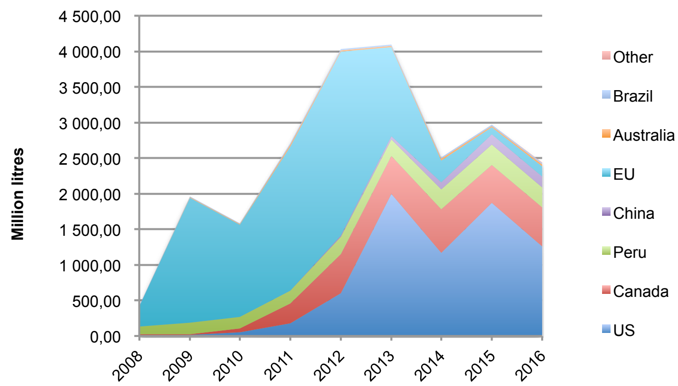


Notes: Data for 2015 and 2016 is based on forecast

Figure 16 Global biodiesel production by 10 biggest producers 2008-2016 (own artwork based on dataset OECD-FAO 2016a)

There is expected to be the expansion in production of biodiesel due to the policies in such countries as the US, Brazil, Argentina, Indonesia and in a lower extent in the EU due to RED target. The production amount is forecasted to increase from 31000 million litres in 2015 to 41400 million litres in 2025. (OECD-FAO 2016b, 116)

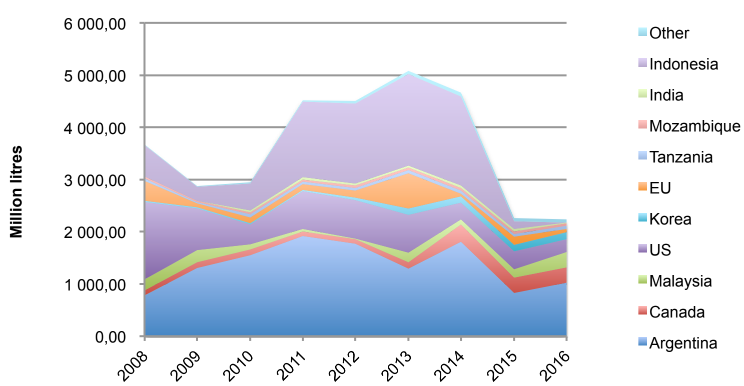
The global import of biodiesel is mainly implemented by the US, Canada and Peru. The other areas include China, the EU, Australia, Brazil and other countries. The US was the biggest importer in 2014 when it imported 1166 million litres of biodiesel, which is 46% of the global import. The import situation on the market had substantial changes within 2012-2014 years because the US increased significantly biodiesel import from 599 million litres in 2012 to 1998 million litres in 2013, whereas the EU decreased its biodiesel import dramatically from 1248 million litres in 2013 to 304 million litres in 2014. There was a huge breakdown of global biodiesel import in an amount of almost 40% if compare 2014 to 2013 years. Though in overall global biodiesel import grew by 490% from 426 million litres in 2008 to 2512 million litres in 2014. (OECD-FAO 2016a) Figure 17 below shows the global biodiesel import by its biggest importers.



Notes: Data for 2015 and 2016 is based on forecast

Figure 17 Global biodiesel import by 10 biggest importers 2008-2016 (own artwork based on dataset OECD-FAO 2016a)

The graph showing global biodiesel export by the main players is illustrated in figure 18 below.



Notes: Data for 2015 and 2016 is based on forecast

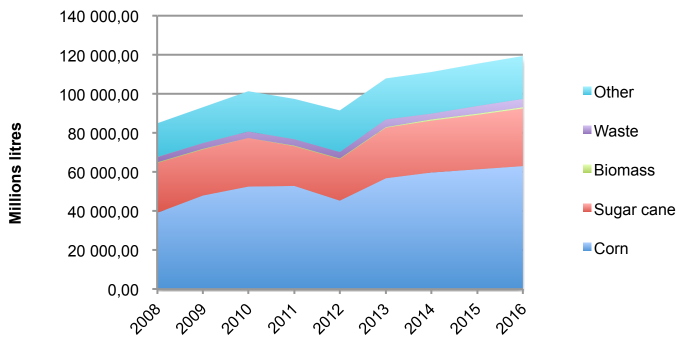
Figure 18 Global biodiesel export by 10 biggest exporters 2008-2016 (own artwork based on dataset OECD-FAO 2016a)

The main long-term biodiesel exporting country is Argentina. In 2014 it exported 1815 million litres of biodiesel, which is 39% of the global export that year. Indonesia was one of the leaders from 2010 till 2014 as well and the export of biodiesel implemented by the country constituted up to 1700 million litres, which is 36% of the global export in 2014. The countries, which contribute to the biodiesel export a bit lower, include the US, the EU, Canada and Malaysia. The rest of the countries are Korea, Tanzania, Mozambique and India. The situation on the market underwent changes within 2013-2014 period. If in 2013 there was a significant growth of biodiesel export from the EU, Argentina reduced its export, whereas in 2014 the EU almost cuts its biodiesel export and Argentina starts exporting more than in 2013. Global biodiesel export was 3668 million litres in 2008 and by 2014 it grew till 4662 million litres, which shows 27% growth. (OECD-FAO 2016a)

3.2.2 Bioethanol production trends

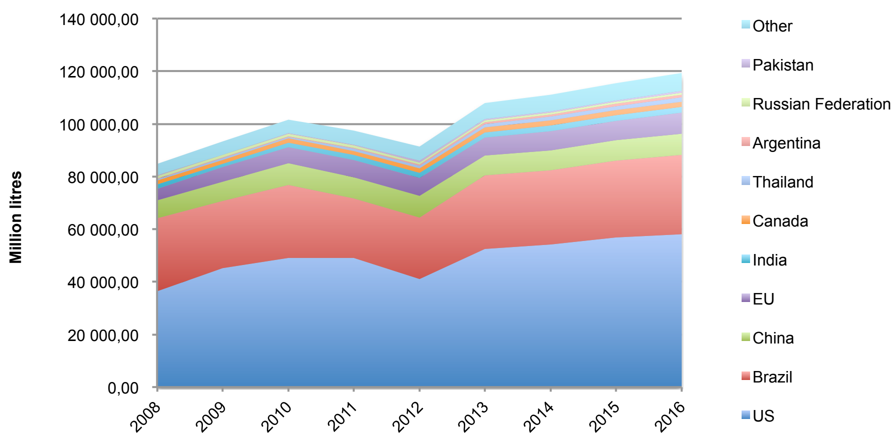
There are several feedstock, which are primarily utilized for the production of ethanol. They substantially include corn and sugarcane, other not specified feedstock and a very small insignificant amount of waste and biomass. In 2014 bioethanol produced from corn reached the amount of 59687 million litres, which is 54% of the global production. Sugarcane ethanol was produced in an amount of 26756 million litres and contributed by 24% to the global bioethanol production in 2014. Roughly one fourth of the total bioethanol production was implemented by means of other feedstock, which are not specified. In total global bioethanol production in 2014 was 111067 million litres, which shows the growth of 31% compared to 2008 when the production was 84942 million litres. (OECD-FAO 2016a) Figure 19 illustrates the production of bioethanol based on various feedstock.

Concerning the country based production the steady leading position is occupied by the US and then Brazil. The US produced 54184 million litres, which is almost a half of the global bioethanol production in 2014. Brazil in its turn contributed to the global production in an amount of 28246 million litres, which is 25% from the global production. The followers are China, the EU, India, Canada, Thailand, Argentina, Russian Federation and Pakistan. The production trend would have seemed to be steady if not a decrease of production in 2012 and then increase in 2013. (OECD-FAO 2016a) Concerning the future trends, the forecasting states that the global ethanol production will grow from 116000 million litres in 2015 to 128400 million litres in 2025. Half of the growth is predicted to originate from Brazil. (OECD-FAO 2016b) Figure 20 illustrates global bioethanol production.



Notes: Data for 2015 and 2016 is based on forecast

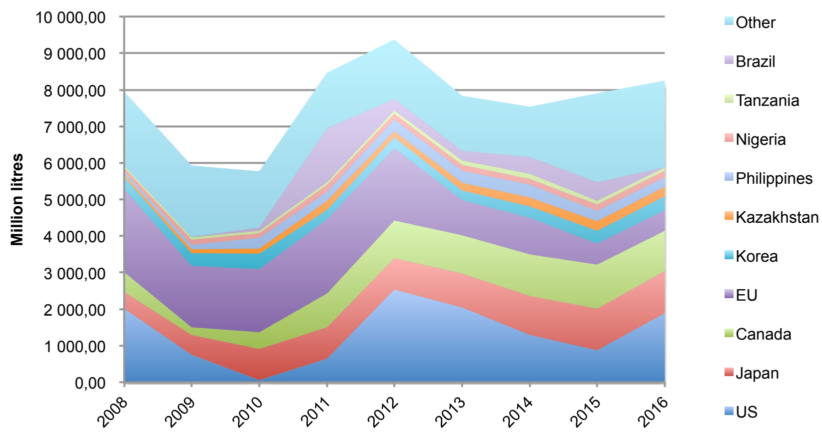
Figure 19 Global bioethanol production from various feedstock 2008-2016 (own artwork based on dataset OECD-FAO 2016a)



Notes: Data for 2015 and 2016 is based on forecast

Figure 20 Global bioethanol production by 10 biggest producers 2008-2016 (own artwork based on dataset OECD-FAO 2016a)

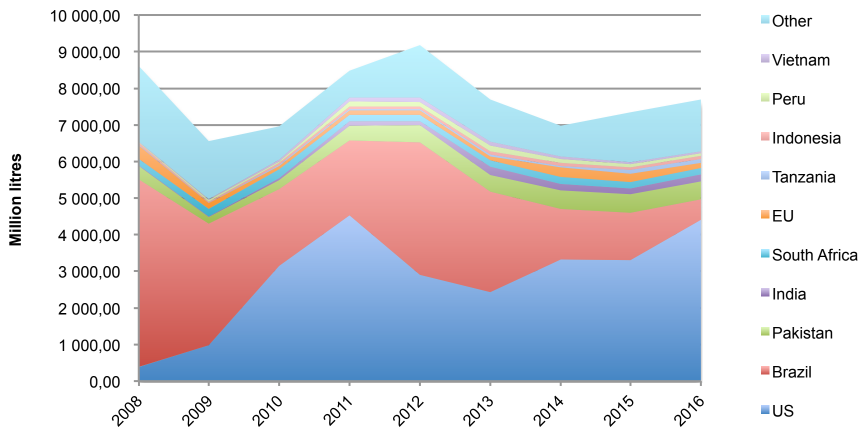
The main bioethanol importer is the US with Japan, Canada and the EU following. If taken together they contribute to more than a half of the global import. In 2014 the US imported 1291 million litres, Japan – 1072 million litres, Canada – 1130 million litres and the EU – 1001 million litres. The other bioethanol importers include such countries as Korea, Kazakhstan, Philippines, Nigeria, Tanzania and Brazil. Global bioethanol import situation underwent a substantial decrease within 2009-2010 years. At those times global import fell by more than 25%. In 2012 there was a peak of import, which reached 9366 million litres. If compared 2008 and 2014, in 2008 the global bioethanol import was higher and constituted 7944 million litres, while in 2014 it was 7535 million litres. (OECD-FAO 2016a) Figure 21 below illustrates global bioethanol import situation.



Notes: Data for 2015 and 2016 is based on forecast

Figure 21 Global bioethanol import by 10 biggest importers 2008-2016 (own artwork based on dataset OECD-FAO 2016a)

Concerning bioethanol export the biggest exporters are the US and Brazil. Brazil has been the biggest bioethanol exporter, while since 2010 the US started exporting more. In 2014 the US exported 3316 miilion litres, which is 48% of the global export. Brazil in its turn exported 1387 million litres, which is 20% of global export operations. The other bioethanol exporters are Pakistan, India, South Africa, the EU, Tanzania, Indonesia, Peru and Vietnam. There were ups and downs in global bioethanol export: so, in 2009 there was a decline while bioethanol export started growing again since 2010 and reached its peak by 2012 when it constituted up to 9186 million litres. Though in 2013 the global bioethanol export started growing again. If compared 2008 and 2014 the global bioethanol export declined from 8603 million litres in 2008 to 6981 million litres in 2014. (OECD-FAO 2016a) Figure 22 below illustrates the global bioethanol export.



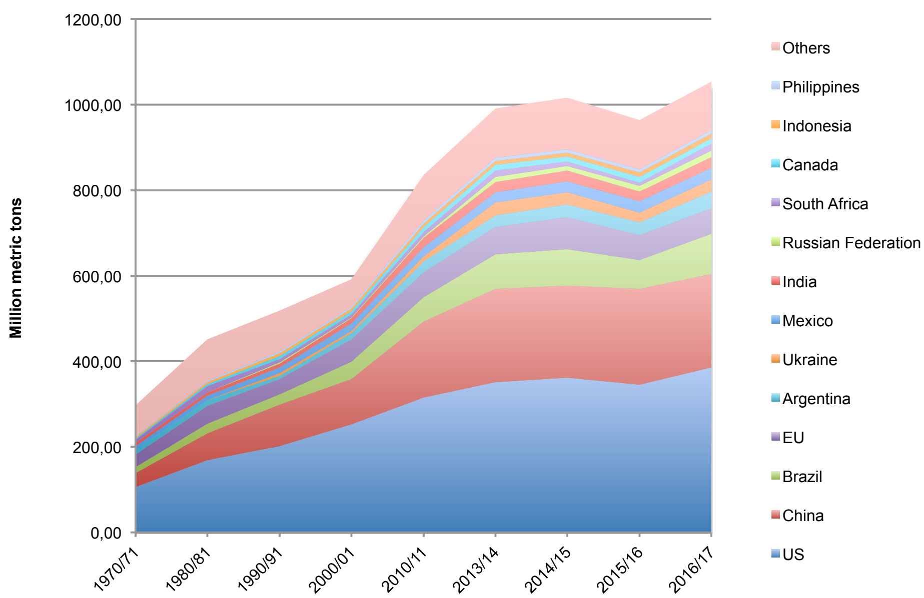
Notes: Data for 2015 and 2016 is based on forecast

Figure 22 Global bioethanol export by 10 biggest exporters 2008-2016 (own artwork based on dataset OECD-FAO 2016a)

According to OECD-FAO dataset (2016a) corn and sugarcane ethanol together contributed by 60% to the global biofuel production in 2014, where corn ethanol contributed by 41% and sugarcane ethanol – by 19%. They present to be the most utilized biofuels nowadays and known to be produced primarily at the US and Brazil respectively (IEA 2010a as cited in IEA 2011, 12). These two biofuels will be observed in detail in further two subchapters from the perspectives of production, import and export of the energy crop.

3.2.2.1 Corn production trends

Corn is the most widely utilized feedstock for biofuels in the world. The global corn production has been growing from 1971 till 2015. There was a slight decline in corn production in 2016, though by 2017 it is expected to grow again. The most substantial growth has been observed within 2001 and 2014 years. If compare 1971 and 2016, the global corn production has grown by 223% from 298 million metric tons in 1971 to 963 million metric tons in 2016. The biggest corn producers in the world are the US and China. The US produced 346 million metric tons of corn in 2016, which is 36% of the global corn production, and China produced 225 million metric tons of corn, which constitutes up to 23% of the global production. The following countries with less production are Brazil and the EU. The rest of the producing countries include Argentina, Ukraine, Mexico, India, Russian Federation, South Africa, Canada, Indonesia, Philippines and the others. (World Bank 2017a, 41) The global corn bioethanol production is presented in figure 23 below. The respective map in figure 24 shows the main corn producing areas in the world.

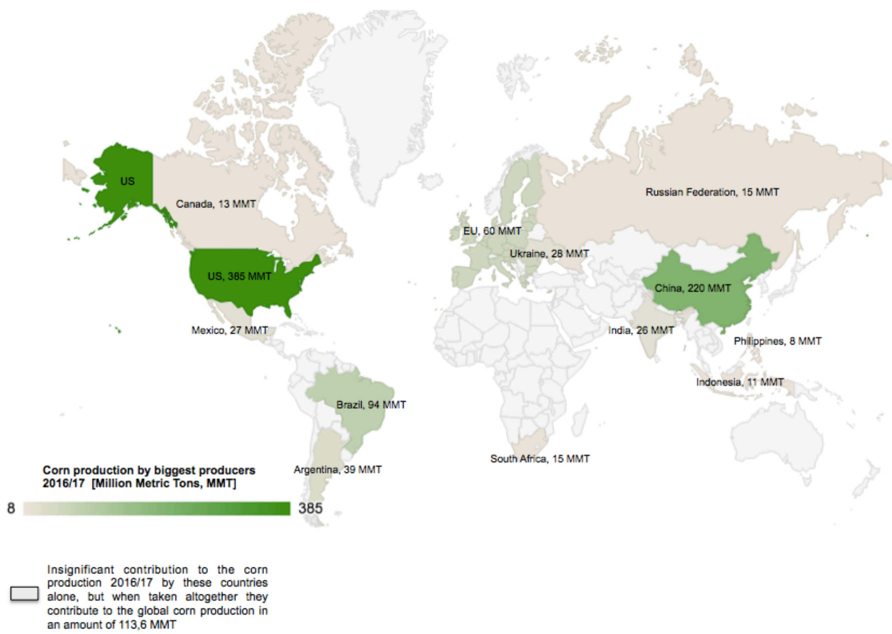


Notes: Data for 2016/17 is based on forecast.
The trade year is January-December of the later year of the split. For instance, 1970/71 refers to calendar year 1971.

Figure 23 Corn producing countries, 1971-2017 (own artwork based on World Bank 2017a, 41)

As long as the US is the biggest producer of corn worldwide representing 36% of global corn production in 2016, it is worth presenting the map of the US showing the allocation of corn production among the states (World Bank 2017a, 41). Figure 25 shows the map of corn production at the US. As it can be seen from the figure, the production is concentrated in the center of the US and in the Northern East part of the country, which together account for 75%

of the national production. The most contributing states are Iowa (17%), Illinois (15%), Nebraska (12%), Minnesota (10%), Indiana (7%) and South Dakota (5%). (USDA 2014a)



Notes: Data for 2016/17 is based on forecast.
The trade year is January-December of the later year of the split. For instance, 1970/71 refers to calendar year 1971.

Figure 24 Global corn production 2016/17 (own artwork based on World Bank 2017a, 41)

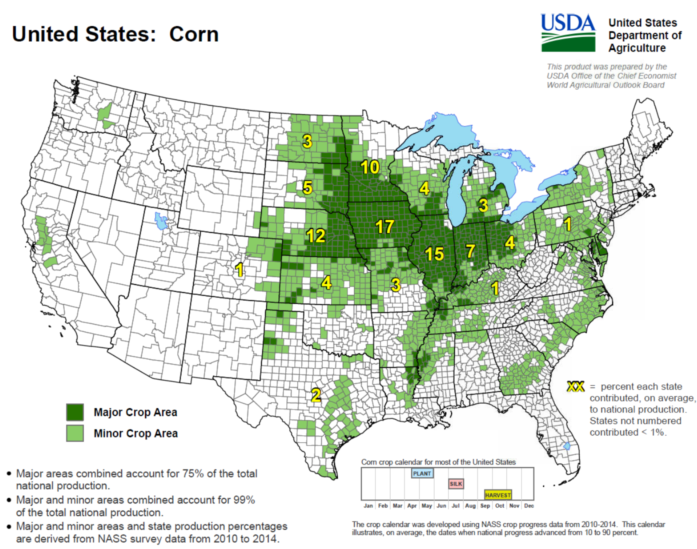
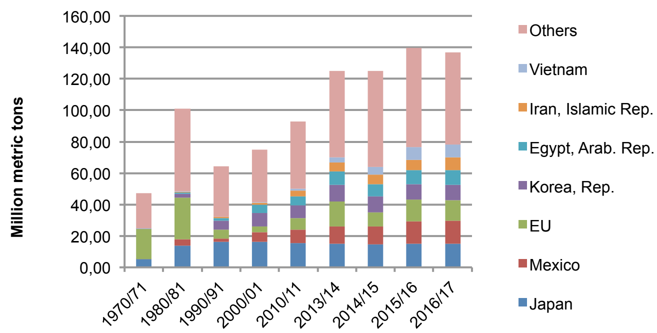


Figure 25 The main corn production states at the US 2010-2014 (USDA 2014a)

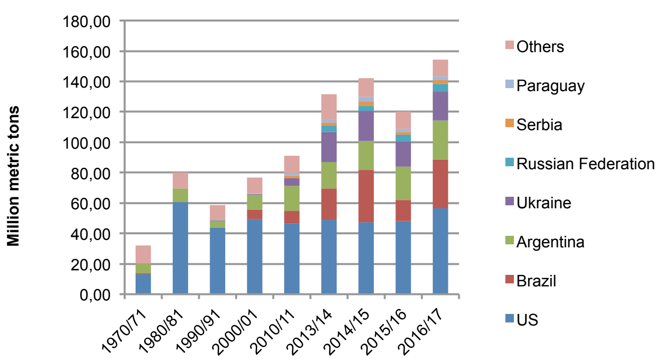
Corn import has grown since 1971 till 2016 by 195% from 47 million metric tons to 140 million metric tons in 2016. In 1970s there has been a substantial growth in global import, though in 1980s import has declined again and in 1990s it stabilized its growth. The main corn importers are Japan, Mexico and the EU. So, in 2016 Japan imported 11%, Mexico – 10% and EU – 10% as well from the global corn import. The rest of importers include Korea, Egypt, Iran, Vietnam and others. By 2017 the global corn import is expected to slightly decline. (World Bank 2017a, 41) Figure 26 below illustrates the global corn import.



Notes: Data for 2016/17 is based on forecast.
The trade year is January-December of the later year of the split. For instance, 1970/71 refers to calendar year 1971.

Figure 26 Corn importing countries,1971-2017 (own artwork based on World Bank 2017a, 41)

Figure 27 below shows the global corn export.



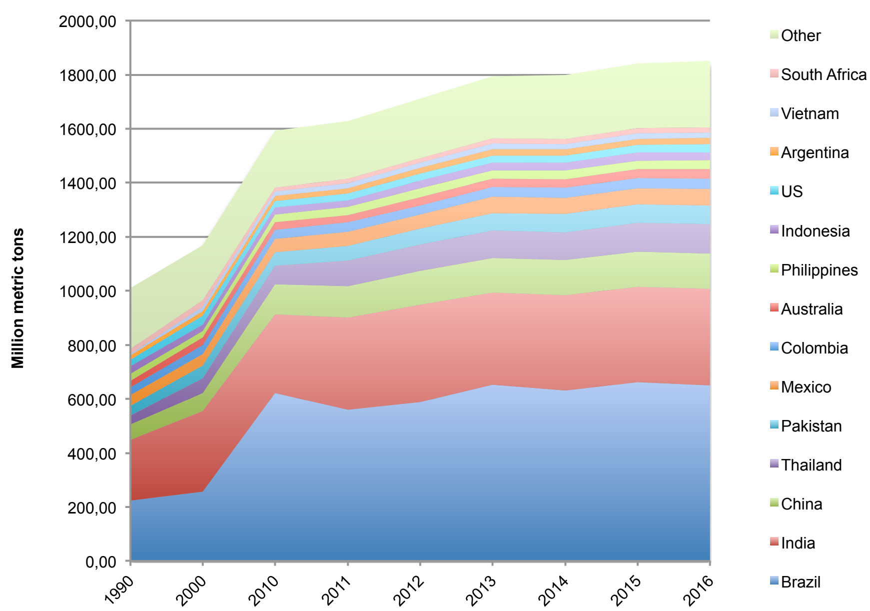
Notes: Data for 2016/17 is based on forecast.
The trade year is January-December of the later year of the split. For instance, 1970/71 refers to calendar year 1971.

Figure 27 Corn exporting countries, 1971-2017 (own artwork based on World Bank 2017a, 41)

The global corn export had its ups and downs within 1971 and 2016 years. In overall global corn export has grown by 273% from 32 million metric tons in 1971 to 120 million metric tons in 2016. The main corn exporters are the US, Brazil, Argentina and Ukraine. So, in 2016 the US exported 40% from the global export, Brazil – 12%, Argentina – 18% and Ukraine – 14%. The rest of the exporters include Russian Federation, Serbia, Paraguay and the others. By 2017 the global corn export is expected to grow substantially. (World Bank 2017a, 41)

3.2.2.2 Sugarcane production trends

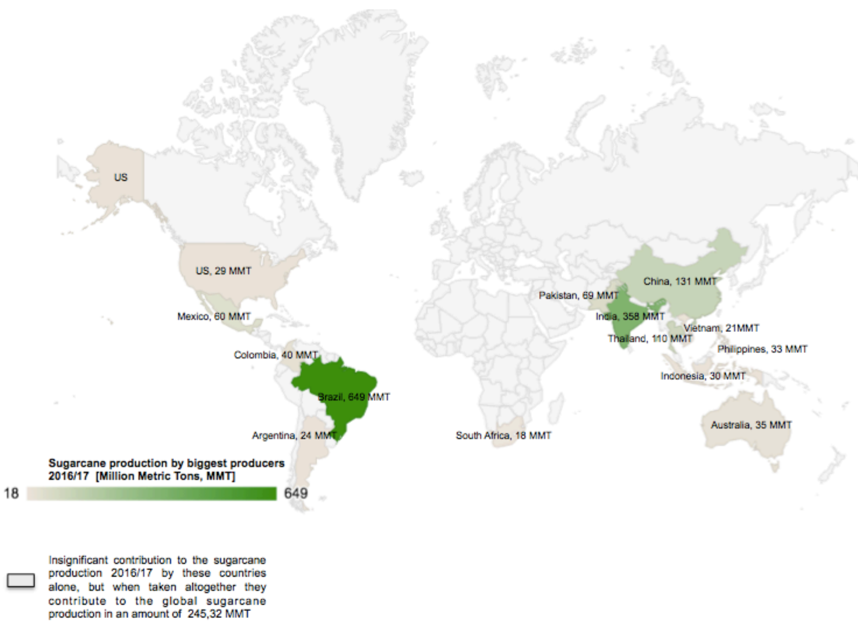
Sugarcane production has been growing since 1990 and the growth reached 78% by 2014. In 1990 the global production amount was 1010 million metric tons, while in 2014 it was 1799 million metric tons. Figure 28 below illustrates global sugarcane production trend, while figure 29 shows the main sugarcane producing areas on the global map.



Notes: Data for 2015 and 2016 is based on forecast

Figure 28 Global sugarcane production 1990-2016 (own artwork based on dataset OECD-FAO 2016a)

The main sugarcane production leader since 2000s is Brazil, though in 1990s Brazil and India were producing almost equal amount of sugarcane. In 2014 Brazil produced 35% of the global sugarcane, namely 632 million metric tons, while India produced 20% of the global sugarcane, namely 352 million metric tons. The other sugarcane producers in the world contain such countries as China, Thailand, Pakistan, Mexico, Colombia, Australia, Philippines, Indonesia, the US, Argentina, Vietnam, South Africa and the others. (OECD-FAO 2016a)



Notes: Data for 2016 is based on forecast

Figure 29 Global sugarcane production in 2016 (own artwork based on dataset OECD-FAO 2016a)

In 2014 Brazil produced 35% of the global sugarcane so it is worth representing the more detailed picture of the production situation of sugarcane in Brazil (OECD-FAO 2016a). Figure 30 below illustrates allocation of sugarcane production in Brazilian states. Sugarcane production in Brazil is concentrated in the South of the country. Sao Paulo has the highest sugarcane production among the whole country and contributes by 60% to the national production. The other most contributing states are Parana (8%), Minas Gerais (7%), Goias (5%) and Alagoas (5%). (USDA 2009)

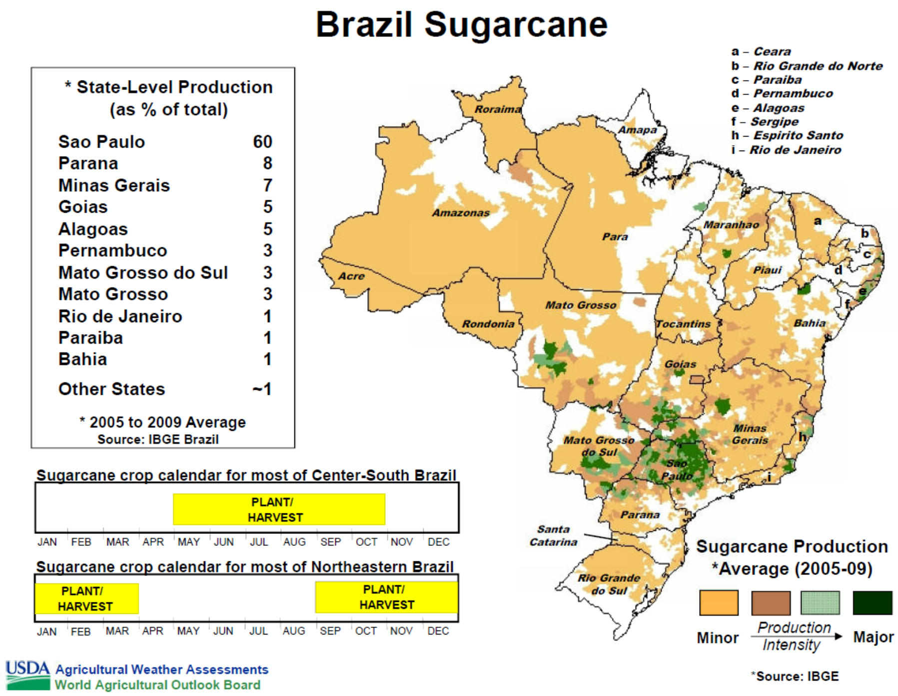
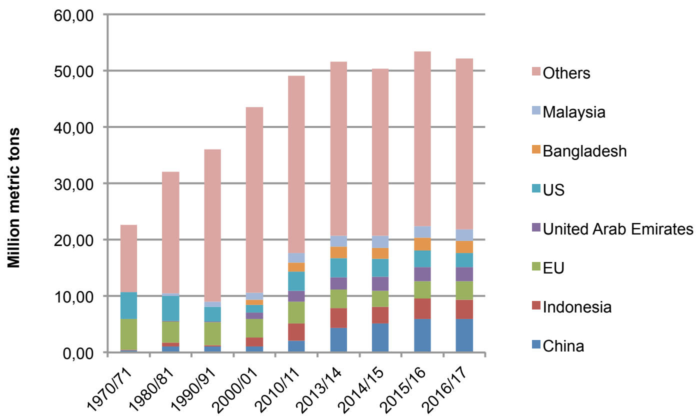


Figure 30 The main sugarcane production states at Brazil 2005-2009 (USDA 2009)

The only data available concerning import and export is referred to sugar, not sugarcane. Therefore, the import and export amounts do not show the real situation at the sugarcane market. Though the graphs 31 and 32 below can be used to show the trend as well as the main market players. The global sugar import has been growing from 1971 till 2014 with a slight decline in 2015. In 2016 import grew again, but it is expected to decline by 2017. The main market player is China with Indonesia, the EU, United Arab Emirates, the US, Bangladesh, Malaysia and the other countries following. (World Bank 2017a, 50) The global sugar import is illustrated in figure 31.

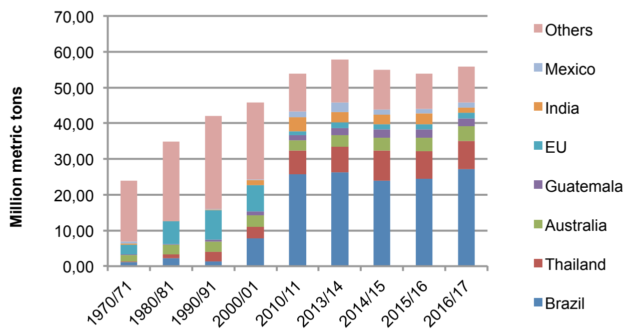
Global sugar export has been growing from 1971 till 2014 with a decline in 2015 and 2016. Though it is expected to grow slightly by 2017. The primary player in sugar exporting is Brazil with Thailand, Australia, Guatemala, the EU, India, Mexico and the other countries following.

(World Bank 2017a, 50) The global sugar export is illustrated in figure 32.



Notes: Data for 2016/17 is based on forecast.
The trade year is January-December of the later year of the split. For instance, 1970/71 refers to calendar year 1971.

Figure 31 Sugar importing countries, 1971-2017 (own artwork based on World Bank 2017a, 50)



Notes: Data for 2016/17 is based on forecast.
The trade year is January-December of the later year of the split. For instance, 1970/71 refers to calendar year 1971.

Figure 32 Sugar exporting countries, 1971-2017 (own artwork based on World Bank 2017a, 50)

3.3 Summary

Biomass resources used for biofuel production can be roughly divided into 4 groups, which are energy crops, forestry products, agricultural products and waste. Energy crops include food-based and non food-based crops. Forestry products include virgin wood and forest residues. Agricultural products contain agricultural residues, animal fats and animal manure. The waste category includes MSW, waste oils, sewage sludge, organic waste and industrial by-products. In the future energy crops along with agricultural products might play the most substantial roles in fulfilling biomass demand. Current biomass supply for global biomass demand is sufficient, though it is going to grow by 2030. If today the global biomass demand is mainly caused by traditional buildings, by 2030 the biomass demand is going to switch to transportation, power and DH generation. Biomass supply potential for 2030 could almost satisfy the transportation energy demand alone. Though it should be taken into consideration that sustainable potential is lower than theoretical because for instance the utilization of the biomass, which has competition with food production or has land-use change constraints is not sustainable. Therefore, biofuels cannot satisfy transportation energy demand alone.

The main players on the biofuel market are the United States, Brazil and European Union. Biodiesel produced from vegetable oil has been and stays the major type of biodiesel produced globally. The main producer of the biodiesel is the EU. Global biodiesel production is expected to grow by 2025 due to the policies in the producing countries like the US, Brazil, Argentina and Indonesia. The US is the main biodiesel importer, while Argentina – exporter. The most widely produced ethanol types are corn and sugarcane ethanol. The US is well known for its corn ethanol, whereas Brazil – for sugarcane ethanol. Corn ethanol has the highest production share in the global bioethanol production. The global bioethanol production is expected to grow by 2025. The main bioethanol importers are the US, Japan and Canada, whereas the major exporters are the US and Brazil.

The main corn producers are the US and China. The global corn production is expected to grow by 2017. The main corn importers are Japan, Mexico and the EU. By 2017 the global corn import is expected to slightly decline. The main corn exporters are the US, Brazil, Argentina and Ukraine. By 2017 the global corn export is expected to grow substantially. The main sugarcane producers are Brazil and India. The main sugar importer is China, while exporter – Brazil.

4 BIOFUEL ECONOMICS

The chapter contains the observations regarding indicative cost trend of biofuels, has the description and creation of the cost models of corn and sugarcane ehanol, as well as it has the projections of corn and sugarcane ethanol costs for the future and comparison of biofuel costs with the costs of fossil and synthetic fuels.

4.1 Indicative cost trend of biofuels

In order to understand the economics of biofuels it is good to start with the indicative cost trend observed in the secondary sources. Figure 33 shows the production costs estimated by IRENA (2013a) for some of the conventional and advanced bioethanol and biodiesel types. The presented costs are for 2012 and 2020 years. The ranges for costs can be compared to the average 2012 ex-refinery fossil fuel prices in the US to see if the biofuel is competitive enough to the fossil fuel. According to the graph, in 2012 biofuel types which in favorable situation could be competitive to the fossil fuels in terms of costs include such as sugarcane ethanol, biochemical advanced ethanol, biodiesel from jatropha and advanced biodiesel produced via pyrolysis. According to the graph mostly production costs for the biofuels are about to grow by 2020 and only advanced ethanol shows the decline of costs by 2020. The cost growth for sugarcane ethanol, advanced ethanol, jatropha biodiesel and FT advanced biodiesel happens on the level when the competitiveness of the biofuels with fossil fuels remains. According to the graph conventional ethanol produced from grains and conventional biodiesel produced from soy, rapeseed and palm do not show the competitiveness neither in 2012 nor in 2020.

According to IRENA (2013a, 5) in case of expansion of policy support the costs of advanced biofuels for transport could be competitive with the options of fossil fuels by 2020. Concerning conventional biofuels, being derived primarily from food-based feedstock, their costs are too dependent on the food prices. (IRENA 2013a, 5)

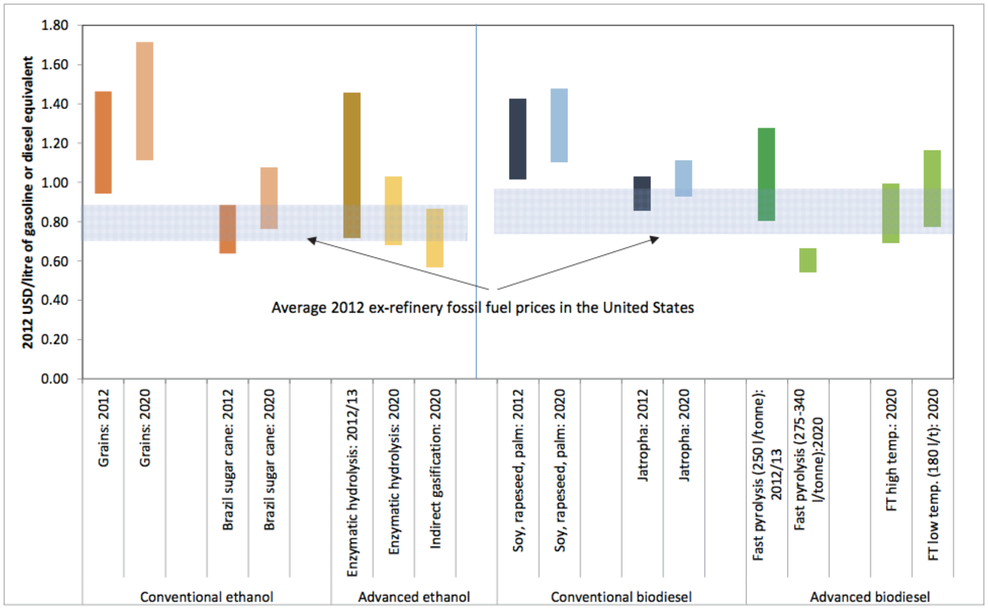
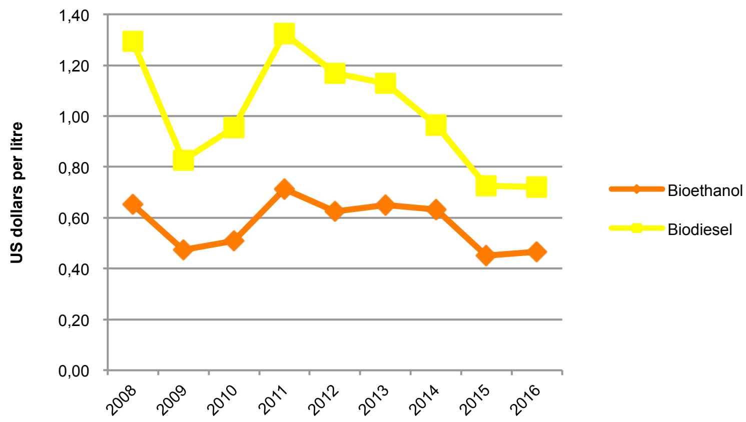


Figure 33 Conventional and advanced biofuel production costs, 2012 and 2020 (IRENA 2013a, 6)

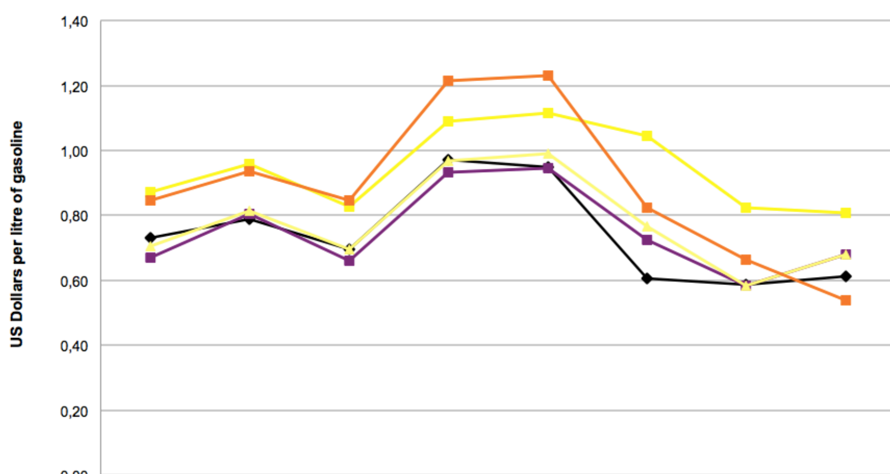
Figure 34 below shows the indicative trend of bioethanol and biodiesel world prices from 2008 till 2014 with the forecasted data for 2015 and 2016 years. According to the graph, bioethanol has been cheaper than biodiesel by 0.25-0.64 USD dollars per litre within 2008-2016 years. The highest difference between the world prices of bioethanol and biodiesel has been observed in 2008, while the lowest – in 2016. Both bioethanol and biodiesel prices declined in 2009 and came back to 2008 level and even slightly higher by 2011. After 2011 the prices started and continued declining in nominal terms till 2015 because of weak prices of crude oil and low biofuel feedstock prices (OECD-FAO 2016b, 116). For biodiesel the price stabilized in 2015-2016 years, while for bioethanol the price started slightly increasing again in 2016. Bioethanol world price in 2016 was 0.47 USD dollars per litre, whereas for biodiesel it was 0.72 USD dollars per litre. Concerning the future trends, according to OECD-FAO (2016b, 116) bioethanol and biodiesel world prices are forecasted to recover in nominal terms within the period until 2025 year due to the crude oil markets developments and the recovery of biofuel feedstock prices.



Notes: data for 2015 and 2016 is based on forecast

Figure 34 Bioethanol and biodiesel world prices 2008-2016 (own artwork based on dataset OECD-FAO 2016a)

For the comparison it could be also good to look at the graph illustrated in figure 35.



	2005	2008	2009	2011	2013	2015	2016	2017
Gasoline	0,73	0,79	0,70	0,97	0,95	0,61	0,59	0,61
Diesel	0,67	0,80	0,66	0,93	0,94	0,73	0,58	0,68
Biodiesel (B20)	0,70	0,81	0,69	0,97	0,99	0,77	0,58	0,68
Biodiesel (B99-B100)	0,87	0,96	0,83	1,09	1,12	1,04	0,82	0,81
Bioethanol (E85)	0,85	0,94	0,85	1,21	1,23	0,82	0,66	0,54

Figure 35 Average retail fuel prices in the US 2005-2017 (own artwork based on AFDC 2017c; The Calculator Site 2017)

Figure 35 shows the average retail fuel prices at the US in some years from 2005 till 2017. In 2017 the cheapest fuel at the US is considered to be bioethanol (E85), it outruns even conventional fuels gasoline and diesel. The interesting thing is that bioethanol was the second most expensive fuel in 2005 and the most expensive one in 2011 and 2013. After 2013 the prices for bioethanol started rapidly declining. The most expensive fuel in almost all the years is biodiesel (B99-B100). When biodiesel is presented in an amount of 20% with 80% of conventional diesel in the mix, this fuel is more competitive and on average is sold at the same price as conventional diesel.

4.2 Cost model of corn and sugarcane ethanol

Installed capital costs, operation and maintenance costs, feedstock costs and efficiency define conventional bioethanol production costs. Though feedstock costs, which present to be a function of productivity, farming costs and market supply and demand, dominate in total bioethanol production cost breakdown. Fluctuations in the local and global feedstock market influence the economics of conventional bioethanol production quite heavily. Feedstock needs conversion process, which unfortunately has only little efficiency improvement possibilities, and therefore the opportunities for cost reduction of conventional bioethanol are limited. (IRENA 2013a, 29, 30)

In order to understand which day-to-day costs of the corn and sugarcane production affect the final feedstock costs the most the breakdowns of operating costs for corn and sugarcane farming will be overviewed. The pictures of the cost breakdowns are illustrated in figure 36 below. From the figure it can be seen that the dominating costs in cultivation of corn are costs for fertilizers and seeds. Chemicals, fuel, lube, electricity and repairs costs are following and representing almost equal parts. The lower part is presented by custom operations costs, which include the costs of custom operations, technical services and commercial drying. The labor is one of the least cost components of corn production operating costs. Purchased irrigation water cost represents very small amount, which is less than 1% in corn production operating costs. The breakdown of sugarcane production operating costs does not include the seed cost component. The dominating cost components are fertilizers, chemicals and cane haulage from field. They are followed by harvesting costs, labor costs and maintenance costs. The least cost components are energy and water. It is assumed that harvesting and cane haulage from field cost components are related to the utilization of fuel for agricultural machinery. Therefore, it can be concluded that sugarcane production operating costs are dominated by fuel costs and costs of fertilizers and chemicals. Both corn and sugarcane production operating costs are influenced very much by the costs of fertilizers.

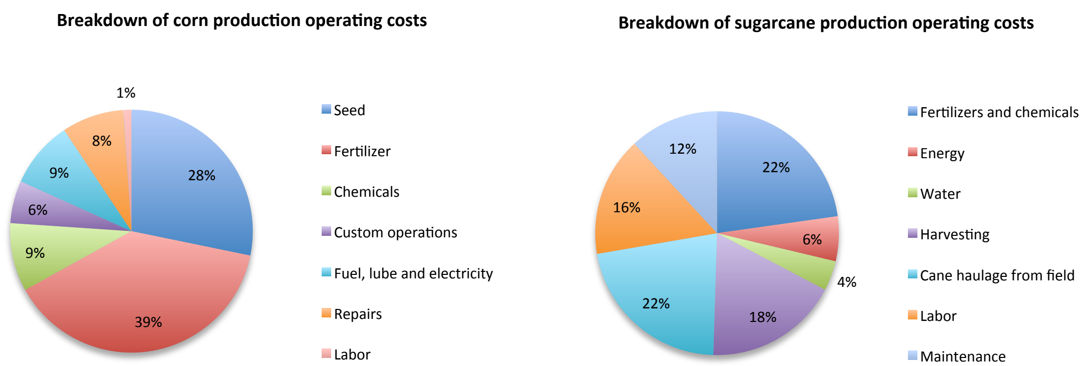


Figure 36. Breakdown of corn and sugarcane production operating costs (own artwork based on USDA 2016c, 17; Netafim 2014, 13)

Installed capital costs of biofuels have various cost categories in which equipment costs are dominating. They include for instance costs for liquefaction and saccharification, ethanol processing, grain handling and milling, fermentation, co-product processing and common support systems in case of corn ethanol production. The other costs which are included in installed capital costs are working capital, start-up costs, loan fees and interest, construction contingency, development, engineering and construction management costs, land and site preparation costs. (Iowa State University 2013; Kwiatkowski et al. 2006 as cited in IRENA 2013a, 30) Figure 37 shows the breakdown of installed capital costs for typical corn ethanol plant.

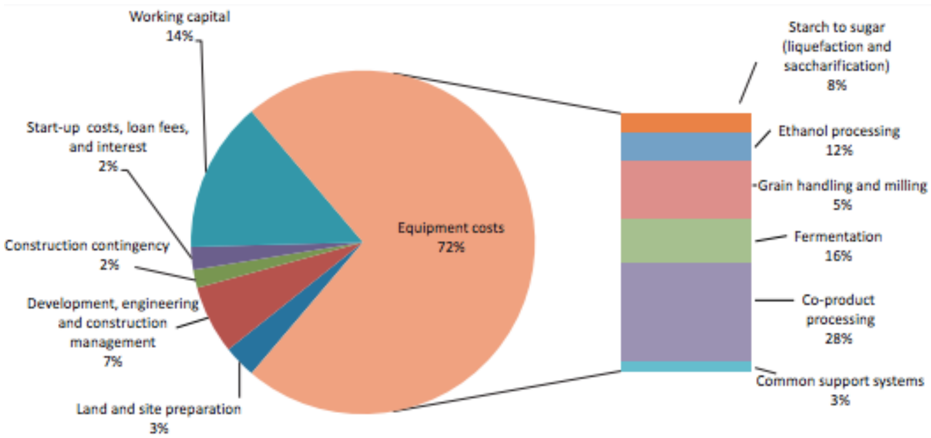


Figure 37 Total installed capital cost breakdown for a typical dry mill corn ethanol plant in the United States (Iowa State University 2013; Kwiatkowski et al. 2006 as cited in IRENA 2013a, 30)

Figure 38 below shows the breakdown of operating costs for the US corn ethanol production and Brazilian sugarcane ethanol production.

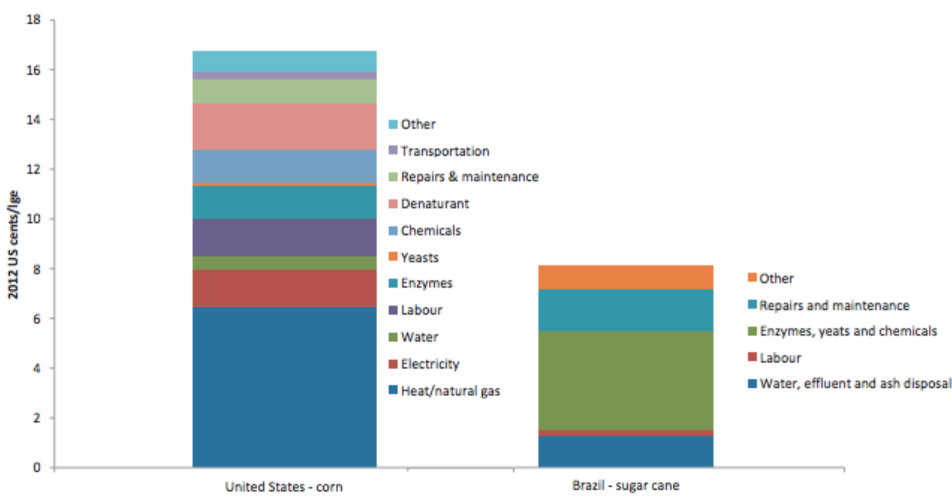
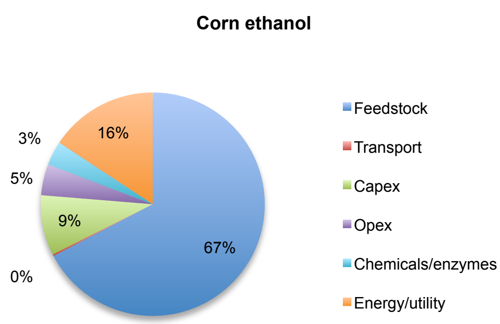
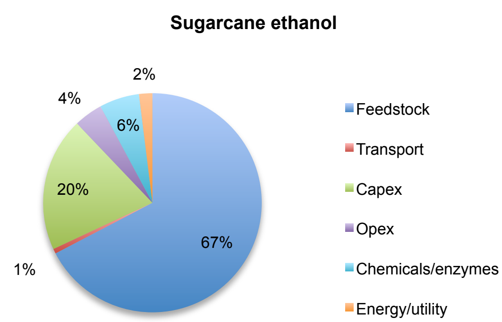


Figure 38 Other operating costs for ethanol production from corn in the United States and sugarcane in Brazil (APEC 2010; Iowa State University 2013 as cited in IRENA 2013a, 33)

The operating costs contain various categories for corn and sugarcane ethanol. Ethanol production from corn at the US requires such operating costs as heat and natural gas, electricity, water, labour, enzymes, yeasts, chemicals, denaturant, repairs and maintenance, transportation and others. The dominating cost sector is heat and natural gas, which can represent from 35% to 45% of the non-feedstock operating costs in the US depending on the prices of natural gas. In case of Brazilian sugarcane ethanol production the operating costs contain costs for water, effluent and disposal, labour, enzymes, yeasts and chemicals, repairs and maintenance and others with the cost for enzymes, yeasts and chemicals dominating. (APEC 2010; Iowa State University 2013 as cited in IRENA 2013a, 33)

Due to being quite developed process, corn ethanol production has low capital and operational costs, whereas sugarcane ethanol has higher capital costs (APEC 2010, 26, 32). This is so due to the fact that sugarcane feedstock handling equipment is more expensive than the one, which is used for corn. Nevertheless, the total installed capital costs can be influenced significantly by local costs. Therefore, because of lower local cost component in Brazil the capital costs may be similar with the ones from the US. The operating costs are lower for Brazilian sugarcane ethanol due to the fact that the heat and electricity for the process needs are provided not by natural gas like in case of the US corn ethanol but by combusting the bagasse in combined heat and power (CHP) plants. The bagasse comes as the residues from ethanol production and its amount is much higher than the process heat and electricity demand. Therefore, considerable amount of electricity can be transferred to the grid and by this means the production economics can be improved. (IRENA 2013a, 30, 33) It should be noted that the costs of chemicals and enzymes are higher for sugarcane ethanol than for corn ethanol because of high procurement and transportation costs of ammonia and limestone involved in the sugarcane ethanol production process. Both corn and sugarcane ethanol have the feedstock cost contributing the most to the total production costs, however, in case of sugarcane ethanol feedstock cost is more dominating in the overall picture. (APEC 2010, 26, 32) As it can be seen, the production cost breakdowns for corn and sugarcane ethanol are similar but not equal due to different capital requirements, energy demand for the production process, costs for chemicals and feedstock costs. The cost breakdown for sugarcane and corn ethanol based on own LCOF calculations is presented in figure 39 below. The formula for LCOF, which was used, is presented in equation (1) with the contributing formulas (2)-(8). In absolute values the contributions of different cost components of LCOF were calculated in the way described furtherly. Feedstock cost contribution towards total production expenses was calculated by means of dividing the feedstock cost at harvest by conversion efficiency. Transport cost contribution was calculated as a division of transport cost by the conversion efficiency. Capex contribution towards the total production expenses was calculated as a multiplication of capital recovery factor (crf) with the Capex value. Opex contribution is equal to the value of $Opex_{fix}$. Chemicals/enzymes and energy/utility contributions are equal to the values of Cost of chemicals and enzymes and Cost of energy and utility respectively. In order to find the contribution of different cost components in percentages the contribution of each component in absolute value was divided by total production expenses in absolute value.





Notes: **Corn ethanol, € per liter**: feedstock – 0.315, transport – 0.001, Capex – 0.041, Opex – 0.021, Chemicals/enzymes – 0.016, energy/utility – 0.073, total production expenses – 0.467. **Corn ethanol, € per MWh th fuel**: feedstock – 48.771, transport – 0.175, Capex – 6.320, Opex – 3.259, chemicals/enzymes – 2.529, energy/utility – 11.380, total production expenses – 72.435. **Sugarcane ethanol, € per liter**: feedstock – 0.278, transport – 0.003, Capex – 0.082, Opex – 0.018, chemicals/enzymes – 0.025, energy/utility – 0.008, total production expenses – 0.413. **Sugarcane ethanol, € per MWh th fuel**: feedstock – 43.170, transport – 0.457, Capex – 12.697, Opex – 2.713, chemicals/enzymes – 3.794, energy/utility – 1.265, total production expenses – 64.094.

Figure 39 US corn ethanol and Brazilian sugarcane ethanol production cost breakdown (own artwork based on LCOF calculations)

The cost breakdown presented by APEC (2010, 26,32) and the one based on own calculations are similar but have some insignificant differences. Cost breakdown from APEC for sugarcane ethanol shows 68% of feedstock, 20% of Capex, 4% of Opex, 6% of chemicals/enzymes and 2% of energy/utility. Whereas in own calculations feedstock is broken down into 2 categories: feedstock cost at field (67%) and transport cost from field to production plant (1%). For corn ethanol the differences between APEC calculations and own are a little bit more significant than for sugarcane ethanol. In the cost breakdown of APEC feedstock is 65%, Capex is 11%, Opex is 5%, chemicals/enzymes are 3% and energy/utility are 16%. While in own calculations there are 67% for feedstock, 9% for Capex, 5% for Opex, 3% for chemicals/enzymes and 16% for energy/utility.

The equation (1) below was used in order to calculate the LCOF (Levelized cost of fuel) of Brazilian sugarcane ethanol and the US corn ethanol.

$$LCOF\ [€/MWh,th,fuel] = Capex\ [€/(MWh,th*a)] \cdot crf + Opex_{fix}[€/(MWh,th*a)] + \frac{Feedstock\ cost\ at\ plant\ [€/MWh,th,feedstock]}{\eta\ [\%]} + Additional\ costs\ and\ benefits\ [€/MWh,th,fuel] \quad (1)$$

where
Capex - capital expenditures, € /(MWh,th*a)
$Opex_{fix}$ – operation and maintenance expenditures, €/(MWh,th*a)
Feedstock cost – feedstock cost at plant, €/MWh,th,feedstock
η – conversion efficiency from feedstock to fuel, %
Additional costs and benefits – costs of chemicals, enzymes, energy, utility and coproduct benefits, €/MWh,th,fuel.

The formulas (2)-(8) below contain the more detailed calculations of LCOF cost components such as Capex, crf, $Opex_{fix}$, Feedstock cost, η and Additional costs and benefits.

$$Capex\ [€/(MWh,th*a)] = \frac{Capex\ total\ [€]}{Annual\ capacity\ [MWh,th/a] \cdot Flh\ [hours]/Hours\ in\ year\ [hours]} \quad (2)$$

where
Capex-capital expenditures, € /(MWh,th*a)
Capex total – total capital expenditures, €
Annual capacity - amount of fuel which plant can produce if operates full year, MWh,th/a
FLh - full load hours, hours

Hours in year - amount of hours in one year, hours.

$$crf = \frac{WACC\ [\%] \cdot (1 + WACC\ [\%])^{N\ [years]}}{(1 + WACC\ [\%])^{N\ [years]} - 1} \tag{3}$$

where

crf - capital recovery factor

WACC - weighted average cost of capital, %

N - lifetime, years.

$$Opex_{fix}[€/(MWh, th * a)] = \frac{Opex_{fix} annual\ [\%\ of\ Capex\ total]}{Annual\ capacity\ [MWh, th/a] \cdot Flh\ [hours]/Hours\ in\ year\ [hours]} \tag{4}$$

where

$Opex_{fix}$ – operation and maintenance expenditures, €/(MWh,th*a)

$Opex_{fix}$ annual - operation and maintenance expenditures, €

Annual capacity - amount of fuel which plant can produce if operates full year, MWh,th/a

FLh - full load hours, hours

Hours in year - amount of hours in one year, hours

$$Feedstock\ cost\ at\ plant\ [€/MWh, th, feedstock] = Feedstock\ cost\ at\ harvest\ [€/MWh, th, feedstock] + Transportation\ cost\ [€/MWh, th, feedstock] \tag{5}$$

where

Feedstock cost at plant – feedstock cost at plant, €/MWh,th,feedstock

Feedstock cost at harvest - feedstock cost at harvest, €/MWh,th,feedstock

Transportation cost - cost of transporting biomass from field to plant, €/MWh,th,feedstock

$$\eta\ [\%] = yield\ [MWh, th, fuel/MWh, th, feedstock] \tag{6}$$

where

η – conversion efficiency from feedstock to fuel, %

Yield - amount of output energy of ethanol extracted from energy input of feedstock, MWh,th,fuel/MWh,th,feedstock

$$Additional\ costs\ and\ benefits\ [€/MWh, th, fuel] = Cost\ of\ chemicals\ and\ enzymes\ \left[\%\ of\ Opex_{fix}\right] + Cost\ of\ energy\ and\ utility\ [€/MWh, th, fuel] + Coproduct\ credit\ [€/MWh, th, fuel] \quad (7)$$

where

Additional costs and benefits – costs of chemicals, enzymes, energy, utility and coproduct benefits, €/MWh,th,fuel

Cost of chemicals and enzymes - cost of chemicals and enzymes used at production plant, % of $Opex_{fix}$

Cost of energy and utility - cost of energy and utility at production plant, €/MWh,th,fuel

Coproduct credit - profit from generation of co-product, €/MWh,th,fuel

$$Coproduct\ credit\ (sugarcane\ ethanol)[€/MWh, th, fuel] = \frac{Electricity\ available\ for\ sale\ [MWh, el]}{Annual\ capacity\ [MWh, th/a] \cdot Flh[hours]/Hours\ in\ year\ [hours]} \cdot Wholesale\ electricity\ price\ [€/MWh, el] \quad (8)$$

where

Coproduct credit - profit from generation of co-product, €/MWh,th,fuel

Electricity available for sale – surplus of electricity generated from bagasse, €/MWh,el

Annual capacity - amount of fuel which plant can produce if operates full year, MWh,th/a

FLh - full load hours, hours

Hours in year - amount of hours in one year, hours

Wholesale electricity price – price for which electricity can be sold to power market in Brazil, €/MWh,el

Table 2 below contains the values from the secondary sources for LCOF calculation. The table 3 complements the table 2 with the values converted into the specific units as well as with the values, which were assumed. The values from table 3 were used in formulas (1)-(8).

Table 2 Initial values of parameters data for LCOF calculation for corn and sugarcane ethanol taken from the secondary sources

Fuel type	**Corn ethanol in the US**	**Sugarcane ethanol in Brazil**
Capex total	91 386 000 USD 2010 (APEC 2010, 6)	73 972 000 USD 2010 (APEC 2010, 6)
Annual $opex_{fix}$	4 449 000 USD 2010 (APEC 2010, 25)	2 116 000 USD 2010 (APEC 2010, 32)
Annual capacity	189 million liters per year (APEC 2010, 10)	108 million liters per year (APEC 2010, 10)
Feedstock cost at harvest	3.29 USD 2016 per bushel (USDA 2016a)	77.83 R$ 2017 per ton (USDA Foreign Agricultural Service 2017, 7)
Yield	410 liter per ton (APEC 2010, 23)	77 liter per ton (APEC 2010, 23)

<table>
<tr><td>Cost of chemicals/enzymes</td><td>0.02 USD 2010 per liter (APEC 2010, 25)</td><td colspan="2">0.03 USD 2010 per liter (APEC 2010, 31)</td></tr>
<tr><td>Cost of energy/utility</td><td>0.09 USD 2010 per liter (APEC 2010, 25)</td><td colspan="2">0.01 USD 2010 per liter (APEC 2010, 31)</td></tr>
<tr><td rowspan="2">Co-product credit</td><td rowspan="2">-0.13 USD 2010 per liter (APEC 2010, 25)</td><td>electricity available for sale</td><td>173 000 MWh per year (APEC 2010, 30)</td></tr>
<tr><td>wholesale electricity price</td><td>75.7959 € 2016 per MWh (own calculation based on CCEE 2017 data)</td></tr>
</table>

Table 3 Specific initial data for LCOF calculation for corn and sugarcane ethanol

Fuel type	Corn ethanol in the US	Sugarcane ethanol in Brazil
Capex total, €	74 533 802.034	60 331 061.695
Capex, €/(MWh,th*a)	66.949	94.836
$Opex_{fix}$ annual, % of Capex total	4.868	2.861
Opex, €/(MWh,th*a)	3.259	2.713
Annual capacity, MWh,th/a	1 219 050	696 600
Flh, hours	8 000	8 000
Hours in year, hours	8 760	8 760
Feedstock cost at harvest, €/MWh,th,feedstock	31.593	11.496
Transportation cost, €/MWh,th,feedstock	0.113	0.122
Feedstock cost at plant, €/MWh,th,feedstock	31.707	11.618
η, %	64.779	26.630
Cost of chemicals/enzymes, % of $Opex_{fix}$	77.592	139.835
Cost of energy/utility, €/MWh,th,fuel	11.380	1.265
Co-product credit, €/MWh,th,fuel	-16.438	-20.612
Additional costs and benefits, €/MWh,th,fuel	-2.529	-15.554
WACC, %	7	12
N, years	20	20

crf	0.094	0.134

Notes: 1 liter of ethanol = 0.00645 MWh,th,fuel (Hofstrand 2007; IEA 2017); 1 bushel of corn = 0.025 tonne of corn (Rayglen Commodities 2017); 1 US ton = 0,907 metric tonne (Convert Units 2017); 1 ton of corn = 4.082 MWh,th,feedstock (Ontario Ministry of Agriculture, Food and Rural Affairs 1993; IEA 2017); 1 ton of sugarcane = 1.865 MWh,th,feedstock (Leal et al 2012; Leal 2014; IEA 2017); 1 USD (2016) = 0.903 euro (2016) (X-rates 2016a); 1 euro (2010) = 1.328 USD (2010) (X-rates 2010); 1 R$ (2017) = 0.281 euro (2017); CPI 2010 = 100; CPI 2016 = 108.270; CPI 2017 = 110.441 (OECD 2017i); 1 mile = 1.6 km (Unit Converter 2017).

All the cost components were used in euro. In cases when the data was found not in euro but in other currency the necessary conversions were done. All the financial data in euro not for 2016 year was transformed into 2016 euro values with accordance to the inflation rates from OECD 2017i. In order to implement such calculations the equation (9) was used. The formula is based on consumer price index (CPI), which shows “the change in the prices of a basket of goods and services that are typically purchased by specific groups of households” (OECD 2017i).

$$\text{2016 EUR value} = \frac{\text{CPI in year 2016}}{\text{CPI in year X}} \cdot \text{price in year X} \tag{9}$$

The data sources, which were used in calculations as well as the explanations of how the calculations were done, are presented below. First the focus is done on corn ethanol and after that on sugarcane ethanol production cost calculations.

The data collection for corn ethanol calculations was done in blocks which are as follows: feedstock cost (including cost at harvest and transportation cost), capex total, Opex_{fix} annual, annual capacity, full load hours, hours in year, WACC and crf, lifetime, yield, additional costs and benefits including chemicals/enzymes and energy/utility costs as well as co-product credit (DDGS). In cases when necessary currency exchanges were done the following sources were used: X-rates 2010 and X-rates 2016a. For conversion of units such sources were used as: Rayglen Commodities 2017, Convert Units 2017, Unit Converter 2017, The Calculator Site 2017, Hofstrand (2007, 4), IEA 2017, Metric Conversions 2017.

Calculation of corn feedstock cost implied addition to feedstock cost at harvest the transportation cost from farm to production facility. It was assumed that the distance between the field and the mill is 80 kilometers and the cargo is transported by Volvo truck with 40 foot container running on diesel fuel which costs 0.58 USD (0.52 euro) per liter and fuel consumption of 32 liter per 100 kilometers (USDA 2014b, 9; Sea Plus n/a; Volvotrucks 2014, 3; AFDC 2017c; Unit Converter 2017; The Calculator Site 2017; X-rates 2016a).

The LCOF was calculated in euro per MWh. Firstly it was calculated without taking into account additional costs and benefits and then with taking them into account. The data for additional costs and benefits was taken from APEC (2010, 25).

For sugarcane ethanol calculations the data collection was done also in blocks the same as for corn ethanol. In cases when necessary currency exchanges were done the following sources were used: X-rates 2010 and X-rates 2017. For conversion of units such sources were used as: Hofstrand (2007, 4), IEA 2017 and Metric Conversions 2017.

Calculation of sugarcane feedstock cost implied addition to feedstock cost at harvest the transportation cost from farm to production facility. It was assumed that the distance between the field and the mill is 24 kilometers and the cargo is transported by Volvo truck with 40 foot container running on diesel fuel which costs 3.1 R$ (0.87 euro) per liter and fuel consumption of 32 liter per 100 kilometers (Gonzales et al 2010; Sea Plus n/a; Volvotrucks 2014, 3; Global Petrol Prices 2017; X-rates 2017).

The LCOF was calculated in euro per MWh. Firstly it was calculated without taking into account additional costs and benefits and then with taking them into account. The data for additional costs and benefits was taken from APEC (2010, 31). Though in case of sugarcane the calculation of co-product credit was more complicated than for corn ethanol. The co-product is electricity generated from bagasse. The amount of electricity available for sale at the plant was taken from APEC (2010, 30). But wholesale electricity price was calculated based on the source CCEE 2017 where the weekly price for every year and for all electricity regions is available. The price was calculated based on 7 years average: from 2010 till 2016. First the average price for every month of every year was calculated with the subsequent conversion from Brazilian R$ to euro. After that the average price for every year in euro was calculated and transformed to 2016 euro by means of CPI formula (9). Afterwards, the average price for 7 years was found and it constitutes up to 75.8 euro per MWh (appendix 2). The initial data for the wholesale electricity prices for every week of every month from 2010-2016 years, calculated values of average wholesale electricity prices for every month of the years 2010-2016, the average price for every year and CPI related to every year from 2010 until 2016 are presented in appendix 2.

Figure 40 below shows the results of LCOF calculations for 2016 for corn and sugarcane ethanol.

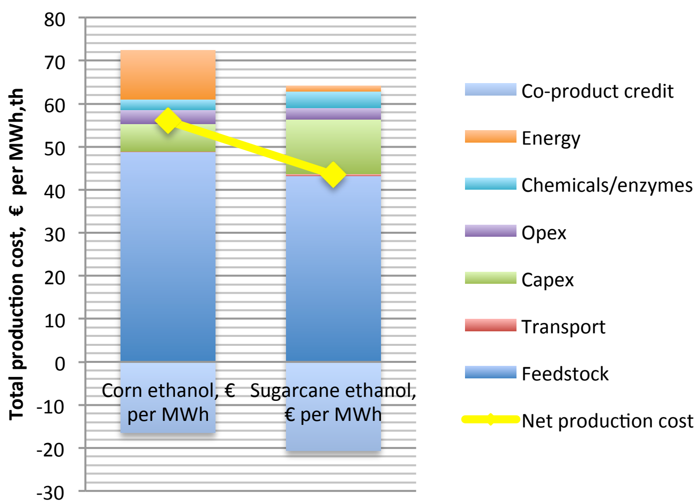


Figure 40 LCOF for corn ethanol produced at the US and sugarcane ethanol produced in Brazil in 2016 (own artwork based on LCOF calculations)

Table 4 below in its turn contains the data used for cost model graph in figure 40.

Table 4 Corn and sugarcane ethanol cost model components (based on LCOF calculations)

	Corn ethanol, € per liter	Corn ethanol, € per MWh,th	Sugarcane ethanol, € per liter	Sugarcane ethanol, € per MWh,th
Feedstock	0.315	48.771	0.278	43.170
Transport	0.001	0.175	0.003	0.457
Capex	0.041	6.320	0.082	12.697
Opex	0.021	3.259	0.018	2.713
Chemicals/enzymes	0.016	2.529	0.025	3.794
Energy	0.073	11.380	0.008	1.265
Co-product credit	-0.106	-16.438	-0.133	-20.612
Net production cost	0.361	55.996	0.281	43.482
Production cost w/o co-product credit	0.467	72.435	0.413	64.094

Corn ethanol LCOF without taking into consideration aditional costs and benefits such as chemicals/enzymes and energy/utility costs and DDGS co-product credits is 0.378 € per liter or 58.525 € per MWh. When additional costs and benefits are taken into account then LCOF for corn ethanol is 0.361 € per liter or 55.996 € per MWh.

Sugarcane ethanol LCOF without taking into consideration aditional costs and benefits such as chemicals/enzymes and energy/utility costs and electricity co-product credits is 0.381 € per liter or 59.036 € per MWh. When additional costs and benefits are taken into account then LCOF for sugarcane ethanol is 0.281 € per liter or 43.482 € per MWh.

As it can be seen from the table 4 production costs of corn ethanol without taking into account co-product credit but with taking into account all the additional costs for energy/utility and chemicals/enzymes is 0.467 € per liter or 72.435 € per MWh, whereas production costs of sugarcane ethanol are 0.413 € per liter or 64.094 € per MWh. In such a case sugarcane ethanol is 0.054 € per liter or 8.341 € per MWh cheaper than corn ethanol. The net production costs of corn ethanol with taking into account all additional costs and benefits is 0.361 € per liter or 55.996 € per MWh, whereas sugarcane ethanol net production costs are 0.281 € per liter or 43.482 € per MWh. In this case sugarcane ethanol is 0.080 € per liter or 12.514 € per MWh cheaper than corn ethanol.

In the base scenario LCOF for the US corn ethanol was calculated with a WACC value of 7%, while for Brazilian sugarcane ethanol WACC was assumed to be 12%. In case if WACC was assumed to be 7% for sugarcane ethanol then LCOF with taking into account all additional costs and benefits would be 0.256 € per liter or 39.738 € per MWh. It is 0.025 € per liter or 3.744 € per MWh cheaper than the base case scenario with a WACC of 12%.

The key results which are used for the sensitivity analysis and further cost projections are LCOF of corn ethanol in an amount of 55.996 € per MWh and LCOF for sugarcane ethanol in an amount of 43.482 € per MWh.

4.3 Sensitivity analysis

There was the sensitivity analysis done in order to see which LCOF calculation components play insignificant and which - significact roles in their influence towards the final result. Figure 41 shows the sensitivity analysis of WACC and capex total for LCOF calculation of corn ethanol.

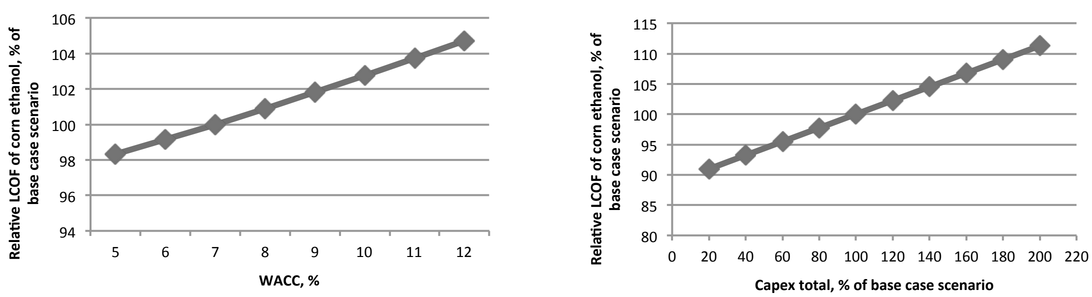


Figure 41 Sensitivity analysis for corn ethanol LCOF based on WACC and capex total (own artwork)

In base case scenario WACC was taken in an amount of 7% for the US corn ethanol plant. WACC amount depends on riskyness of the investment: the higher the WACC the more risky investment it is considered to be. When for instance corn ethanol plant was assumed as more risky investment with WACC of 12% then still the result of LCOF would not change much. It would rise by 5% compared to the base case scenario. Capex total is one of the main components of LCOF formula and yet changes in it are relatively influencing the result. When only 20% of capex total of the base case scenario were taken then LCOF result would fall just by 9%. In case if capex total increased by the factor of 2 then LCOF result would rise by 11%.

In the base case scenario $Opex_{fix}$ annual is roughly 5% of capex total. If for instance it was 2% then LCOF would decrease by 3% compared to base case scenario. In case if $Opex_{fix}$ annual was 8% of capex total then LCOF would increase by 4%. Feedstock cost fluctuations in their turn influence the final result a lot. In case if feedstock cost became by 40% cheaper than in base case scenario then LCOF would decrease by 52%. In case if feedstock cost increased by a factor of 2 then LCOF would increase by 87%. The results of sensitivity analyses are illustrated in figure 42.

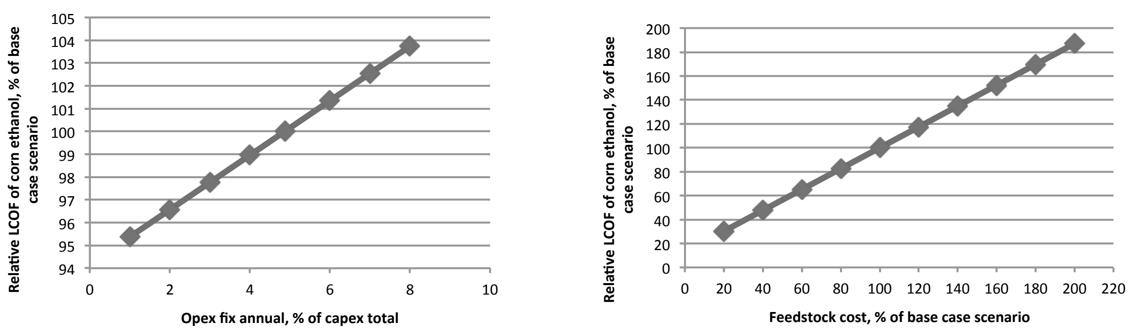


Figure 42 Sensitivity analysis for corn ethanol LCOF based on $Opex_{fix}$ annual and feedstock cost (own artwork)

Chemicals/enzymes, energy/utility and co-product credit are additional costs and benefits to LCOF calculation and sensitivity analyses of them are presented in figures 43 and 44. Chemicals/enzymes are the least influencing cost components when compared to other additional costs and benefits. If the expenditures for chemicals and enzymes increased by a factor of 2 then LCOF result would increase by 5%. While if cost of energy used at production plant doubled then LCOF would rise by 20%. Fluctuations in co-product credit are pretty much influencing the final results. In case if co-product credit was increased by a factor of 2 then LCOF would decrease by 29%. Also because co-product credit is a component reducing LCOF the relationship between of it with LCOF is inverse contrary to the situation with the most of the other cost components which have direct relationship with LCOF. There is also sensitivity analysis of conversion efficiency influence towards LCOF. It is a very influencing component of LCOF formula and it is presented in figure 44. In case if conversion efficiency was 45% instead of base case scenario 65% then LCOF would grow by 38%.

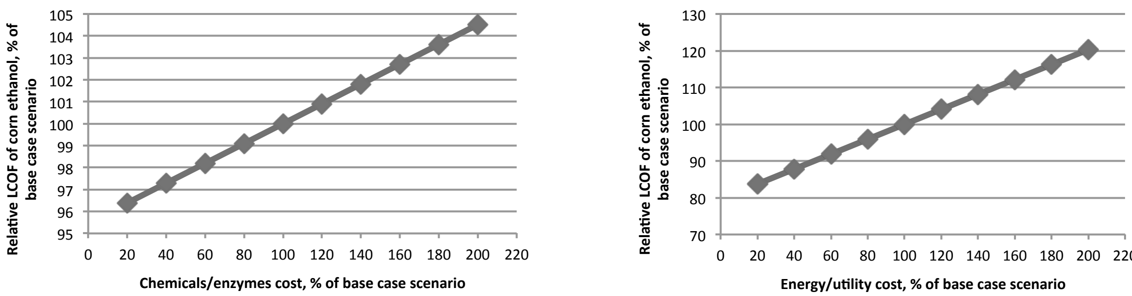


Figure 43 Sensitivity analysis for corn ethanol LCOF based on chemicals/enzymes and energy/utility cost (own artwork)

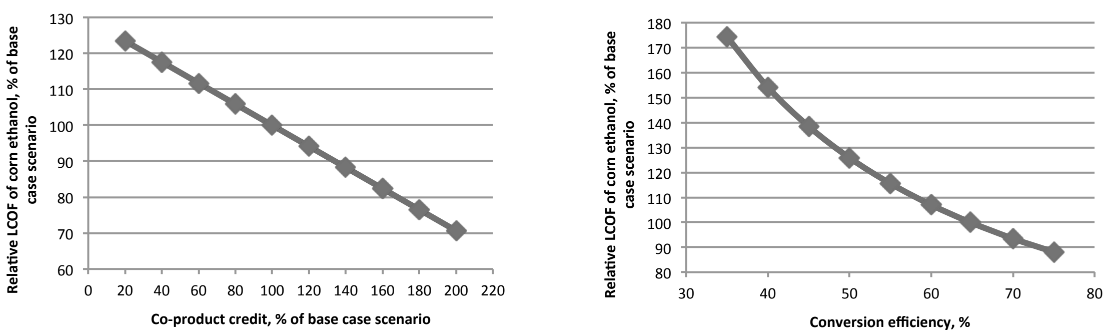


Figure 44 Sensitivity analysis for corn ethanol LCOF based on co-product credit and conversion efficiency (own artwork)

As it can be seen from all sensitivity analyses for corn ethanol the most influencing cost components are feedstock cost, conversion efficiency and co-product credit followed by energy expenditures at production facility.

In case of sugarcane ethanol produced in Brazil WACC equal to 12% was taken. If it was 14% then LCOF would grow by 4% compared to the base case scenario. In case if WACC was 7% then LCOF would be decreased by 9% in comparison to the basic result. LCOF result in case of sugarcane ethanol is more sensitive to the fluctuations in capex total than corn ethanol. For instance, if capex total doubled then LCOF would rise by 29%. If capex total was decreased by 80% then LCOF would fall by 23%. The graphs illustrating the dependence of LCOF from WACC and capex total can be found in figure 45.

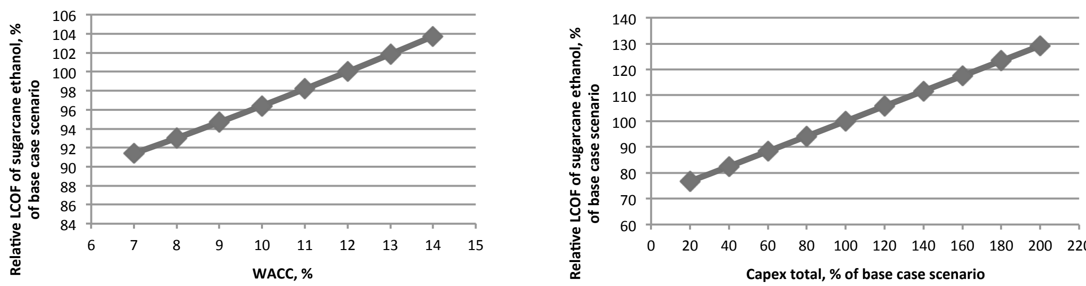


Figure 45 Sensitivity analysis for sugarcane ethanol LCOF based on WACC and capex total (own artwork)

Figure 46 below shows sensitivity analyses of $Opex_{fix}$ annual and feedstock cost. In base case $Opex_{fix}$ was considered to be roughly 3% from capex total. But if it was changed to 5% for example then LCOF would rise by 5%. LCOF of sugarcane ethanol is extremely dependent on feedstock cost fluctuations. In case if feedstock costs doubled in price then LCOF would react by doubling as well. If feedstock cost was reduced by 40% then LCOF would fall by 40% as well. So it means that there is a direct proportional relationship between feedstock cost of sugarcane and LCOF of sugarcane ethanol.

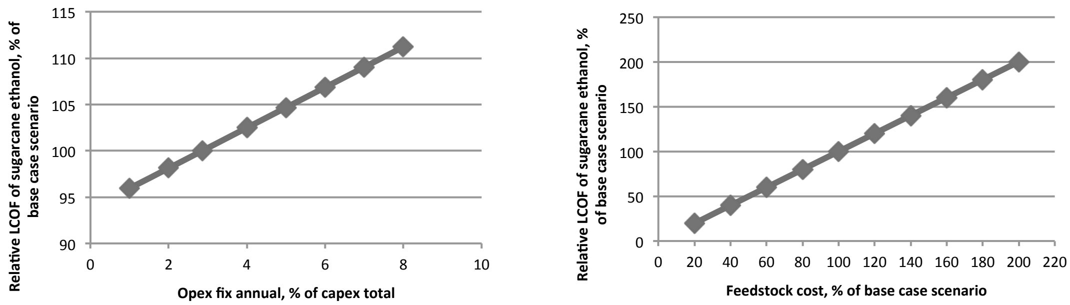


Figure 46 Sensitivity analysis for sugarcane ethanol LCOF based on $Opex_{fix}$ annual and feedstock cost (own artwork)

Chemicals/enzymes, energy cost and co-product credit influence of which on LCOF of sugarcane ethanol is examined and presented in figures 47 and 48 are related to additional costs and benefits of LCOF calculation.

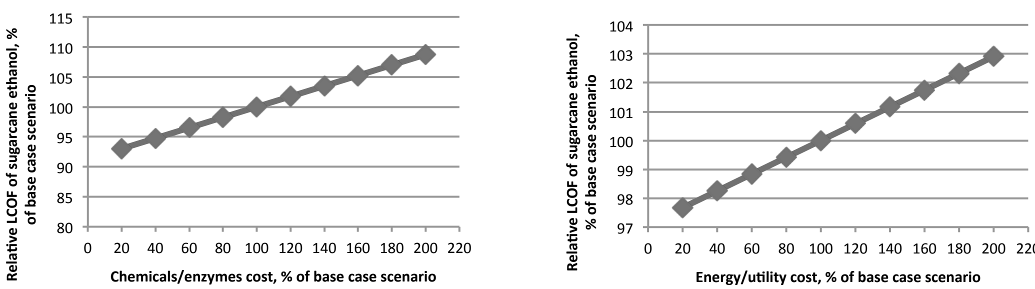


Figure 47 Sensitivity analysis for sugarcane ethanol LCOF based on chemicals/enzymes and energy/utility cost (own artwork)

Chemicals/enzymes are influencing the final result not that much because even in case if the prices for chemicals and enzymes doubled LCOF would grow just by 9%. Energy costs influence LCOF of sugarcane ethanol even less because when they double LCOF grows only by 3%. Sugarcane ethanol production is energy self-sufficient process due to co-generation of electricity. And therefore it is almost not dependent on energy costs but on co-product credit. Surplus electricity can be sold to the power market, which very much improves the economics of sugarcane ethanol. When co-product credit doubles for example due to the rising wholesale electricity prices in Brazil the LCOF decreases by 47%, so almost twice. There is also sensitivity analysis of conversion efficiency influence towards LCOF. It is a very influencing component of LCOF formula and it is presented in figure 48. In case if conversion efficiency was 40% instead of base case scenario 27% then LCOF would fall by 34%.

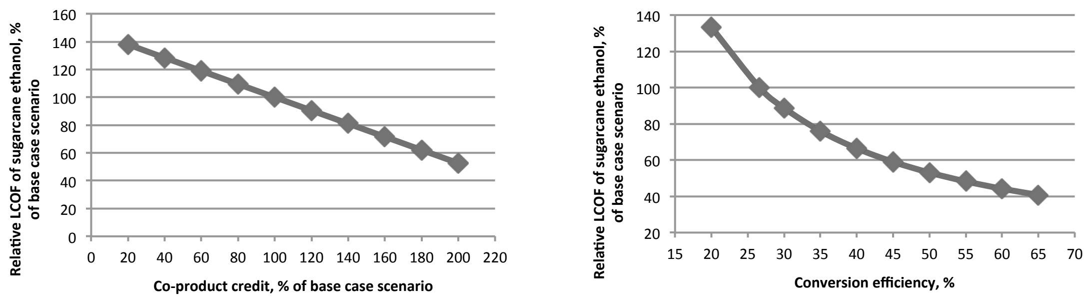


Figure 48 Sensitivity analysis for sugarcane ethanol LCOF based on co-product credit (own artwork)

As it can be seen from all sensitivity analyses for sugarcane ethanol the most influencing cost components are feedstock cost, conversion efficiency, co-product credit and capex total.

4.4 Projections of future costs

The projections of production costs were done based on feedstock cost forecasts from World Bank report published in October 2017. The utilized data was the one for global feedstock cost in constant (2010=100) USD. It was used only to calculate the percentages of feedstock cost growth globally. Later the global growth percentages were applied to the feedstock costs of 2016 which were used at LCOF calculations in order to find out how feedstock cost would approximately change in the US and Brazil by 2030 and 2040. First of all annual global feedstock cost growth in percentages was calculated up to 2025. Then the average growth by % for 5 years namely from 2020 to 2025 was calculated. Then the average growth by % for the next 5 years was calculated namely for 2025-2030 years. After that the average percentage of feedstock cost change for 5 years was found as a mean between price change of 2020-2025 and 2025-2030 years. Then the annual percentage growth from World Bank data from 2016 till 2025 was applied to feedstock costs of 2016 for the US and Brazil which were initially used at LCOF calculations. To find out the feedstock cost growth from 2025 till 2030 at the US and Brazil the global average growth by % for 2025-2030 years was applied. And then to find out the feedstock costs at the US and Brazil in 2035 and 2040 the mean percentage value between global feedstock cost change of 2020-2025 and 2025-2030 was applied. The initial data and the results of the projections are presented in appendix 3 for corn ethanol and in appendix 4 for sugarcane ethanol.

The data for feedstock cost forecasts at the US and Brazil for 2030 and 2040 was not found in secondary sources. The data for Brazilian sugarcane feedstock cost projections was not found at all. The only more or less relative data for corn feedstock is USDA (2017) projections but they are only up to 2026 and in nominal USD. The World Bank report which was finally used for calculations of cost forecasts along with projections in constant USD has also projections in nominal USD for corn and sugar globally. It was decided not to use the data with nominal USD because the inflation rates forecasts used by USDA and World Bank were different. Also in case if use projections of feedstock costs in nominal USD all the cost components of LCOF like capex total, $Opex_{fix}$ annual, transportation costs and additional costs and benefits have to be deflated with the same inflation rates as the ones used in calculations of nominal feedstock cost forecasts done by World Bank and USDA. But in case of World Bank it was not clear how they calculated their nominal cost projections and with which inflation rates forecasts. So in order to avoid calculation mistakes it was decided to use only projections in constant currency. Therefore the projections show how the biofuel prices would change without inflation influence. Figure 49 below shows the biofuel production cost changes in 2030 and 2040.

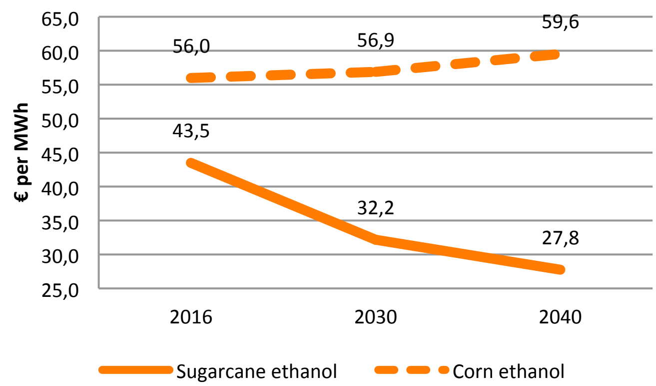
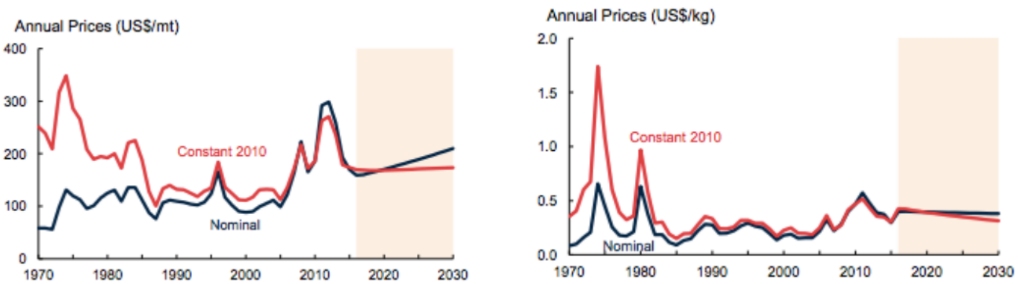


Figure 49 Sugarcane and corn ethanol production cost projections for 2030 and 2040 in constant 2016 € (own artwork)

As it can be seen from the graph production costs of corn ethanol slightly grow from 56 € per MWh or 0.361 € per liter in 2016 to 56.9 € per MWh or 0.367 € per liter by 2030 and 59.6 € per MWh or 0.384 € per liter by 2040. While production costs of sugarcane ethanol fall quite dramatically from 43.5 € per MWh or 0.281 € per liter in 2016 to 32.2 € per MWh or 0.208 € per liter by 2030 and 27.8 € per MWh or 0.179 € per liter by 2040. As it has been already concluded from sensitivity analysis, feedstock cost fluctuations influence corn and sugarcane ethanol production costs a lot. It is the most influencing component of LCOF formula in cases of corn and sugarcane ethanol along with conversion efficiency. This is why for example if the data for feedstock costs was calculated not in constant currency but in nominal then the situation with production costs would be different. Figure 50 below shows how the corn and sugar prices would change by 2030 in nominal and constant USD globally. When feedstock costs are projected in nominal USD the inflation makes projections being higher in cost by 2030. It can be seen that constant USD prices for corn grow just slightly, and its influence can be observed on production cost forecasts from figure 49 above: production costs grow not much. Though if corn cost projections in nominal USD were used then due to the inflation influence production costs of corn ethanol would grow more sharply by 2030 and 2040 following the dynamics of corn feedstock growth. In case of sugarcane ethanol if feedstock cost forecasts were used in nominal USD then production costs of sugarcane ethanol would be just slightly falling by 2030 and 2040.



Notes: data for 2017-2030 is based on forecast

Figure 50 Corn and sugar prices 1970-2030 (World Bank 2017a, 41, 50)

The fact that LCOF of biofuels depends so much on feedstock cost fluctuations makes the situation with projection calculations from one hand quite complicated. The feedstock cost projections data is not easy to get from secondary sources. Also the projections, which were finally found from the World Bank report are changing in every report update. So it is possible that after some years the projections of feedstock costs might change dramatically depending on the market situations. Though from the other hand when feedstock costs influence so much LCOF of biofuels then the model for projections of LCOF can be roughly updated just by changing the old feedstock cost forecasts with the new ones. And in case if after some years the more exact data related directly to the US corn costs and Brazilian sugarcane costs was published by some organization then it would be better to update the model with these more relative costs.

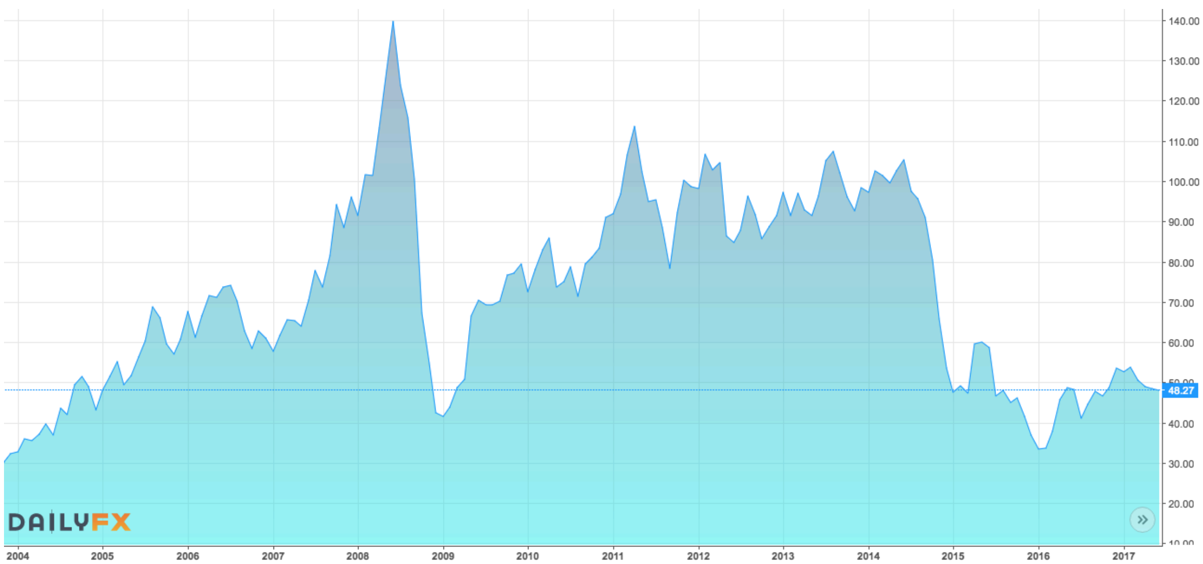
4.5 Comparison to fossil and synthetic fuels

There are several problems associated with the usage of fossil fuels in transportation. First of all, fossil fuel resources are limited while transportation demand is continuously growing. Secondly, the planet is facing a problem of climate change and growing carbon dioxide emissions present to be a considerable constraint for using fossil fuels in the long-term. (IEA 2015; EWG 2013; IPCC 2014; Carbon Tracker 2013; Carbon Tracker 2015 as cited in Fasihi et al 2016b, 243-244) Therefore, it is crucial to find the alternatives for fossil fuels in transportation sector. Synthetic fuels, biofuels and electrification of transport might play major roles in energy transition of mobility from fossil fuels to renewable energy in the future. There are some transport sectors which can be hardly electrified. It is for instance aviation, marine trasportation and transportation by heavy duty trucks (Fasihi et al 2016a, 3; Fasihi et al 2016b, 244). Though biofuels along with synthetic fuels present to be good alternatives to fossil fuels in heavy duty truck transportation, shipping and aviation. There might be a competition of biofuels and synthetic fuels in terms of costs in the future. Therefore it was decided to compare the cost projections for 2030 and 2040 of the most commercially available biofuels of today with synthetic fuels produced by means of electricity from hybrid PV-wind plants in the areas with excellent solar and wind potentials.

There are several research papers from Fasihi, Bogdanov and Breyer related to calculation of production costs of synthetic fuels (synfuels) for 2030 and 2040 in different regions of the world. The data for synfuel production costs used in figures 52-55 was provided by Fasihi from a continuously improving model for synfuel costs in Patagonia and Maghreb region done within the framework of research for Neo Carbon Energy project. The calculations for Patagonia were done with full load hours (Flh) of 2000 for PV single-axis and 5200 for wind with overlap of 0.05. The Maghreb region calculations were done with Flh of 2300 for photovoltaic (PV) single-axis and 4200 for wind with overlap of 0.05. (Fasihi et al 2016a, 2016b; Fasihi 2017a, 2017b) The data for the interrelation between crude oil prices and conventional diesel prices with and without emission costs was taken from papers of Fasihi et al (2016a, 15; 2016b, 255). The 13-year average ratio of 1 barrel (bbl) of diesel to crude oil price is 118.76% (Fasihi et al 2016b, 255).

The concept of synthetic fuels or also known as power-to-X (PtX) is that electricity can be converted by power-to-gas (PtG) and power-to-liquids (PtL) facilities to synthetic fuels such as synthetic natural gas (SNG), liquified natural gas (LNG) or synthetic liquid fuels (SLF). PtG plants which convert electricity to SNG by means of electrolysis and methanation processes as well as gas-to-liquids (GtL) plants which convert natural gas (NG) into liquid fuels are already at the commercialization stage. PtL plants which convert electricity directly into synthetic liquid fuels are ready to be commercialized as well. Solar PV and wind energy based renewable electricity can be used as a primary source of energy at such plants. (Fasihi et al 2016a, 2-3; Breyer et al 2015; Wood et al 2012; König et al 2015; Sunfire 2015 as cited in Fasihi et al 2016b, 243-244)

There will be the comparison analysis below of corn and sugarcane production costs with fossil fuel prices and synthetic fuel production costs. Figure 51 below illustrates the crude oil prices according to Daily FX (2017). In 2017 the price has been roughly 50 USD per bbl.



Notes: WTI Crude Oil, TVC. Unit: USD per bbl

Figure 51 Crude Oil prices 2004-2017 (Daily FX 2017)

Figure 52 below illustrates the comparison of sugarcane and corn ethanol production costs with production costs of synfuels based on renewable electricity (RE) in Patagonia in 2030. The synfuels presented at graph include such as RE-SNG, RE-LNG, methanol (RE-MeOH), RE-DME, RE-FT-liquids and RE-FT-diesel. The conventional diesel prices with and without carbon dioxide emission costs are presented on the graph as well.

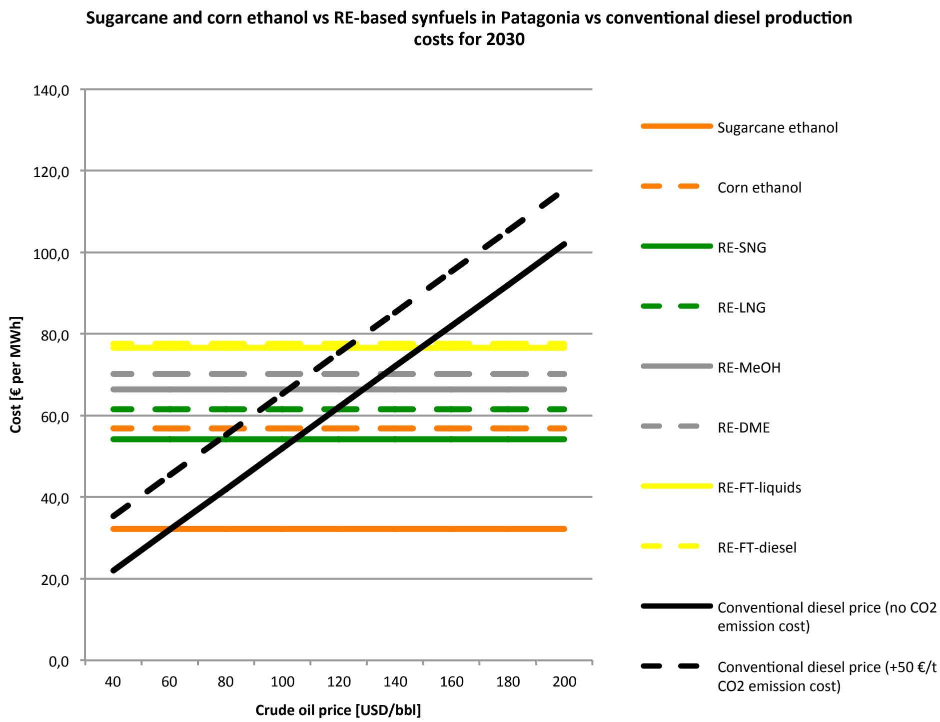


Figure 52 Comparison of production costs in 2030 of biofuels with production costs of synfuels from Patagonia and conventional diesel prices (own artwork based on calculations; Fasihi 2017a; Fasihi et al 2016a, 15)

As it can be seen from figure 52, biofuels are generally cheaper than synfuels produced in Patagonia in 2030 except only a situation when corn ethanol is a bit more expensive than RE-SNG. Sugarcane ethanol production costs are 32.2 € per MWh and it is the cheapest substitution to conventional diesel from the fuels presented at figure 52. RE-SNG production costs, which are 54.2 € per MWh, are pretty close to corn ethanol production costs which are 56.9 € per MWh. The synfuel costs are distributed in such an order: RE-SNG is the cheapest, it is followed by RE-LNG, then goes RE-MeOH, after it – RE-DME, and the most expensive synfuels are RE-FT-liquids and RE-FT-diesel. In case if by 2030 crude oil price was the same as of today namely 50 USD per bbl then only sugarcane ethanol would be relatively competitive option to conventional diesel prices which do not have carbon dioxide emission costs included into the price. Though if carbon dioxide emission costs are included into the diesel price then sugarcane ethanol is fully competitive with conventional diesel when crude oil price is even lower than nowadays and constitutes to 40 USD per bbl and lower. Sugarcane ethanol will be fully competitive with conventional diesel which does not have emission costs included into the price if the crude oil price is 60 USD per bbl and higher in 2030. Corn ethanol is fully competitive with conventional diesel which has emission costs integrated into the price in a situation when crude oil price is around 80 USD per bbl and higher. While with conventional diesel price without carbon dioxide emission costs taken into consideration corn ethanol is competitive when crude oil price is higher than 110 USD per bbl.

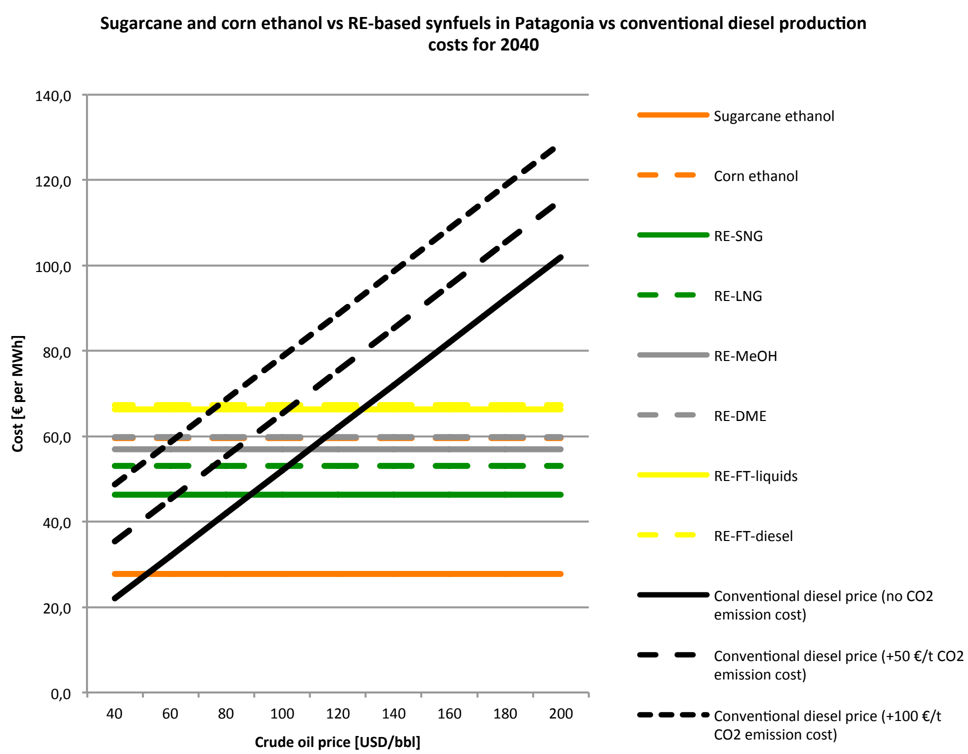


Figure 53 Comparison of production costs in 2040 of biofuels with production costs of synfuels from Patagonia and conventional diesel prices (own artwork based on calculations; Fasihi 2017b; Fasihi et al 2016a, 15)

Figure 53 above illustrates the comparison of the same fuels as in figure 52 presented above but it is for 2040. Also the graph has additional diesel fuel option with emissions taken into account in an amount of 100 € per tCO_2. As it can be observed from figure 53 above sugarcane ethanol stays the cheapest alternative to conventional diesel and it accounts for 27.8 € per MWh. Corn ethanol accounts for 59.6 € per MWh and loses its competitiveness towards several synfuels: in 2040 RE-SNG costs 46.3 € per MWh, RE-LNG – 53 € per MWh and RE-MeOH – 56.9 € per MWh. RE-DME costs are also very close to corn ethanol costs: 59.8 € per MWh. If the crude oil price stays as of today (50 USD per bbl) then only sugarcane ethanol is competitive with conventional diesel. In case if carbon dioxide emission costs are taken into account for conventional diesel price then sugarcane ethanol is cheaper than diesel when crude oil prices are even lower than 40 USD per bbl. Corn ethanol is competitive to conventional diesel without carbon dioxide costs taken into account when crude oil price is around 120 USD per bbl, while it is competitive to conventional diesel with carbon dioxide costs applied in an amount of 50 € per tCO_2 when crude oil price is around 90 USD per bbl and higher, and with conventional diesel with carbon dioxide costs applied in an amount of 100 € per tCO_2 when crude oil price is around 60 USD per bbl.

Figure 54 below illustrates the comparison of sugarcane and corn ethanol production costs with production costs of synfuels based on RE in Maghreb region in 2030. The synfuels presented at graph include such as RE-SNG, RE-LNG, RE-MeOH, RE-DME, NH_3 and RE-FT-liquids. The conventional diesel prices with and without carbon dioxide emission costs are presented on the graph as well.

The data from Maghreb region (figure 54) shows that synfuels produced there have a higher gap with costs of biofuels than synfuels produced in Patagonia (figure 52). According to figure 54 in 2030 the costs for sugarcane ethanol are 32.2 € per MWh, for corn ethanol – 56.9 € per MWh, while for the cheapest synfuel RE-SNG costs are 59.9 € per MWh. The synfuel costs are distributed in such an order in Maghreb region: the cheapest is RE-SNG, it is followed by NH_3, then goes RE-LNG, after it – RE-MeOH, then – RE-DME and RE-FT-liquids close the list. The competitiveness of biofuels with conventional diesel has already been described under figure 52 related to Patagonia: the alignment of forces is the same.

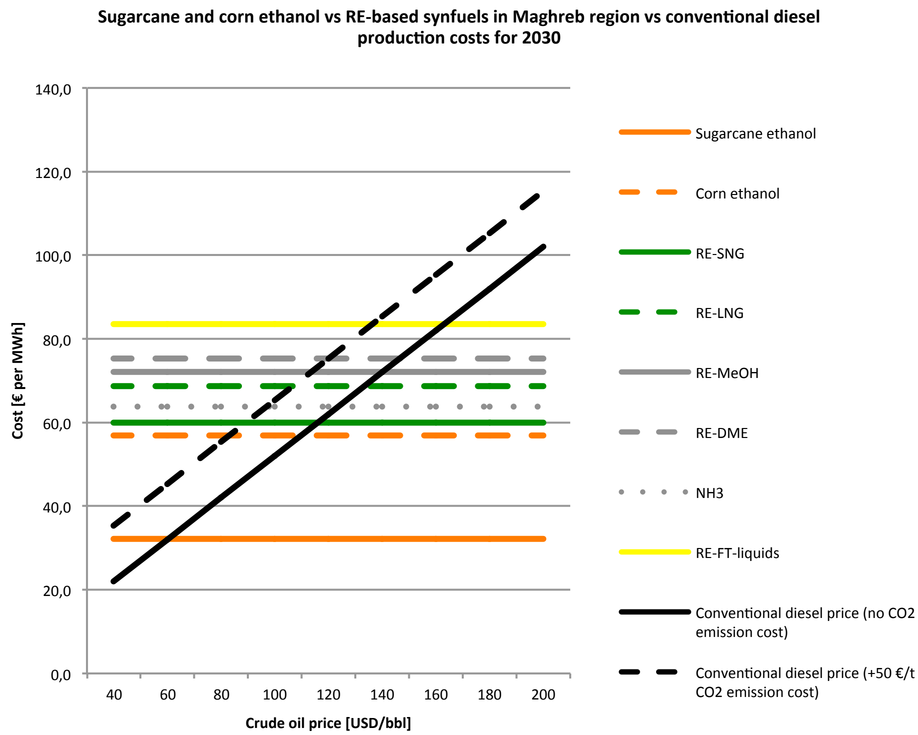


Figure 54 Comparison of production costs in 2030 of biofuels with production costs of synfuels from Maghreb region and conventional diesel prices (own artwork based on calculations; Fasihi 2017a; Fasihi et al 2016a, 15)

Figure 55 below illustrates the comparison of the same fuels as in figure 54 presented above but it is for 2040.

The situation in 2040 changes and synfuels start being competitive with biofuels: namely RE-SNG, RE-LNG and NH_3 are comparable to corn ethanol in terms of costs. Corn ethanol production costs are 59.6 € per MWh, while RE-SNG costs are 51.3 € per MWh, RE-LNG – 58.4 € per MWh, NH_3 – 57.8 € per MWh. Sugarcane ethanol is still far cheaper than the rest of synfuels and it costs 27.8 € per MWh.

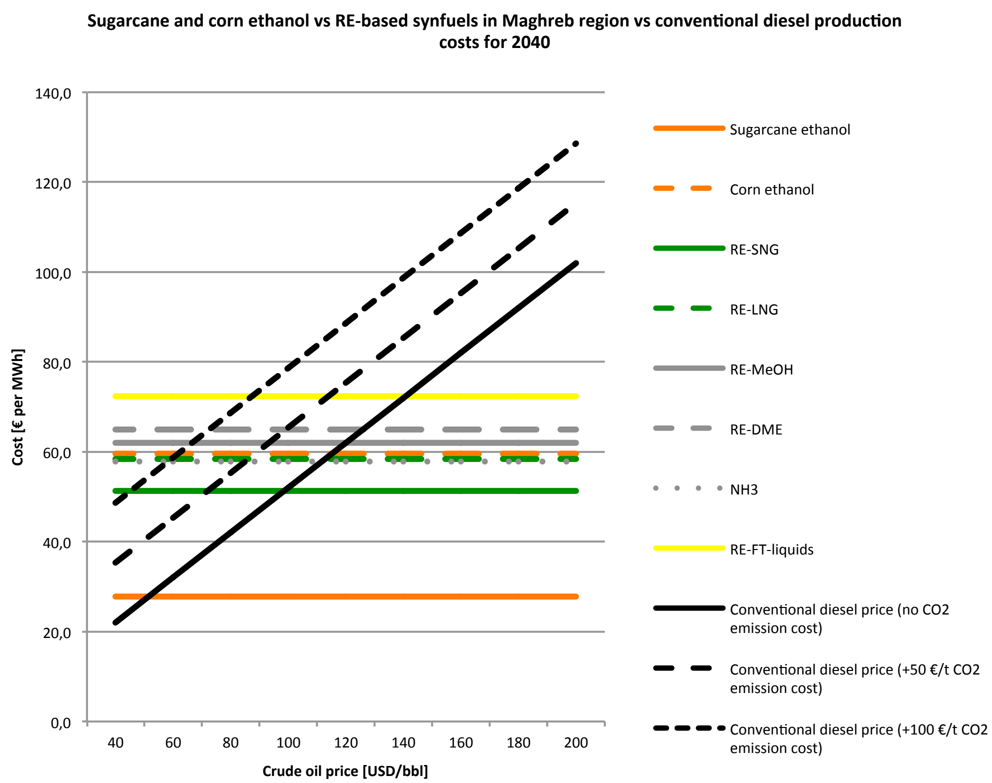


Figure 55 Comparison of production costs in 2040 of biofuels with production costs of synfuels from Maghreb region and conventional diesel prices (own artwork based on calculations; Fasihi 2017b; Fasihi et al 2016a, 15)

4.6 Summary

According to IRENA (2013a) in 2012 biofuel types which in favorable situation could be competitive to the fossil fuels in terms of costs include such as sugarcane ethanol, biochemical advanced ethanol, biodiesel from jatropha and advanced biodiesel produced via pyrolysis. IRENA (2013a) states that production costs for the biofuels are about to grow by 2020 and only advanced ethanol shows the decline of costs by 2020. Though the cost growth for sugarcane ethanol, advanced ethanol, jatropha biodiesel and FT advanced biodiesel happens on the level when the competitiveness of the biofuels with fossil fuels remains. Conventional ethanol produced from grains and conventional biodiesel produced from soy, rapeseed and palm do not show the competitiveness neither in 2012 nor in 2020 according to IRENA (2013a) estimations.

The calculations of biofuel production costs were done only for corn ethanol produced in the US and sugarcane ethanol produced in Brazil. So it is possible to compare estimations done by IRENA (2013a) with estimations done by LCOF calculations and projections of costs based on the data from World Bank (2017b) only concerning corn and sugarcane. Regarding corn ethanol due to cost calculations and projections it was concluded that production costs are growing and corn ethanol is neither competitive with fossil fuels in 2016 nor in the future: same as IRENA (2013a) estimations. Corn ethanol can be competitive with conventional diesel only when crude oil prices are higher than 110 USD per bbl in 2030 and higher than 120 USD per bbl in 2040. Corn ethanol could be competitive with conventional diesel which has emission costs integrated into the price in a situation when crude oil price is 80 USD per bbl and higher in 2030. In 2040 corn ethanol is competitive with 50 € per tCO_2 diesel when crude oil price is 90 USD per bbl and with 100 € per tCO_2 diesel when crude oil price is 60 USD per bbl . Sugarcane ethanol estimations are a little bit diverse from the ones made by IRENA (2013a). IRENA (2013a) states that sugarcane costs are growing in the future but sugarcane ethanol saves its competitiveness with fossil fuels. Though the estimations done based on LCOF calculations and cost projections based on World Bank (2017b) show that sugarcane ethanol is hardly competitive with fossil fuels in 2016, but in the future by 2030 and 2040 costs decline and then in case if crude oil price is 60 USD per bbl in 2030 or 50 USD per bbl in 2040 sugarcane ethanol is competitive with fossil fuels. Also it is worth mentioning that in case if carbon doixide emission costs are included into fossil fuel prices then sugarcane is fully competitive with fossil fuels in the future even if crude oil prices decline.

Concerning the global prices trend, according to OECD-FAO (2016a) globally bioethanol has been generally cheaper than biodiesel. In the US within the period of 2005-2016 bioethanol E85 along with biodiesel B99-100 have been the most expensive fuel types at the fuel stations. They are hardly competitive within that period with fossil fuels, in contrary to biodiesel B20, which prices are pretty close to the ones of conventional gasoline and diesel. Though in 2017 the alignment of forces changes and bioethanol E85 overtakes all the other fuels and becomes the cheapest one. (AFDC 2017c) The situation in 2005-2016 could be explained. Probably biodiesel B20 price is normally so close to conventional fuel prices because it contains only 20% of biodiesel, while the rest 80% of blend is conventional diesel. So its price is heavily dependent on the prices of fossil fuels. The fact that the price of bioethanol E85 consisting mainly of bioethanol with a small blend of gasoline has declined dramatically from 2016 to 2017 could be explained by the fluctuations in corn feedstock market: there was a decline of corn prices at the US from 2015/16 to 2016/17 and 2017/18. (USDA 2017, 28)

There was a cost breakdown of corn and sugarcane ethanol created based on the calculations of LCOF. For both corn and sugarcane ethanol feedstock component of the cost structure is the most dominating. For corn ethanol it is followed by costs for energy/utility, capital expenditure, operations and maintenance costs, chemicals/enzymes costs and then transportation costs. For sugarcane ethanol after feedstock cost by the amount of contribution to the final cost goes capital expenditure, followed by chemicals/enzymes cost, operations and maintenance costs, energy/utility cost and transportation costs. Also there was a cost model of corn and sugarcane ethanol created where it is seen which cost components of corn ethanol are more expensive than the cost components of sugarcane ethanol and vice versa. Corn ethanol has lower capital costs per liter of ethanol than sugarcane ethanol due to being quite developed process while sugarcane ethanol has higher capital costs due to having more expensive hadling equipment for the feedstock and higher capital recovery factor. Operations and maintenance costs are higher for corn ethanol, while corn ethanol production requires less chemicals and enzymes than sugarcane ethanol. In case of sugarcane ethanol energy/utility costs are very low due to the fact that at the production plants, which co-generate electricity from bagasse of sugarcane, the internal electricity demand is satisfied fully as well as the surplus of electricity is sold to the grid. (APEC 2010, 26, 32; IRENA 2013a, 30, 33) In contrary, corn ethanol plants utilize coal and natural gas for satisfying its internal energy demand and therefore energy and utility costs are much higher for corn ethanol than for sugarcane ethanol (USDA 2016b). Without taking into account co-product credits corn ethanol is slightly cheaper than sugarcane ethanol, but when co-product credits are included into calculations then sugarcane ethanol becomes cheaper.

The sensitivity analysis has shown that for corn ethanol the most influencing cost components are feedstock cost, conversion efficiency and co-product credit followed by energy expenditures at production facility. For sugarcane ethanol the most influencing cost components are feedstock cost, conversion efficiency, co-product credit and capital cost. Nevertheless, fluctuations on feedstock market stay the most influencing factor for corn and sugarcane ethanol production costs: in case of sugarcane ethanol there is even a direct proportional relationship between feedstock costs and ethanol production costs.

According to projections of costs done for 2030 and 2040 in constant 2016 euro production costs of corn ethanol slightly grow from 56 € per MWh in 2016 to 56.9 € per MWh by 2030 and 59.6 € per MWh by 2040, while production costs of sugarcane ethanol fall quite dramatically from 43.5 € per MWh in 2016 to 32.2 € per MWh by 2030 and 27.8 € per MWh by 2040. The future costs of corn and sugarcane ethanol are very much dependent on feedstock prices and they will always follow the dynamics of feedstock market. Synfuels along with biofuels can play major role in the future energy transition from fossil fuels towards renewable energy in aviation, shipping and heavy duty transportation. Synfuels from both regions with good solar and wind conditions namely Patagonia and Maghreb region generally stay more expensive than corn and sugarcane ethanol in 2030. The one exception is that in Patagonia RE-SNG becomes cheaper than corn ethanol by 2.7 € per MWh in 2030. The cheapest synfuel in both regions is RE-SNG, it occupies the closest to corn ethanol costs position. Generally the most expensive synfuel is RE-FT-liquids and RE-FT-diesel. It is fair to state that competition of biofuels with synfuels might start after 2040 and from that time it should integrate also other types of synfuels which will become cheaper due to technological development. Also it is worth saying that synfuels produced at the places with the best solar and wind conditions can supply fuels to the other parts of the world via pipelines or shipping and transportation cost component is relatively low.

The overall results show that Brazilian sugarcane ethanol survives on the global market for sure and possibly in the future corn ethanol is extruded from the market. Though it is still debatable due to the fact that both biofuels are the leaders on the biofuel market nowadays and the growing global transportation demand would put too much pressure to the sugarcane ethanol alone. Possibly corn ethanol will be the one substituted on the global biofuel market by advanced biofuels or synthetic fuels. Locally corn ethanol should stay being widely used at the US due to the mandates applied at the country. Biofuels will compete with synfuels in the future, starting probably from the shipping sector. RE-SNG can be used at ships and it is the lowest in cost among all the synthetic fuels. While for instance RE-FT-liquids are the most expensive synthetic fuels and it is hardly that they will become competitive with biofuels in road transportation any time soon in the future. There might be also a demand for synthetic fuels in aviation in the future. And there they would compete already with advanced biofuels, not with corn or sugarcane ethanol due to the high quality requirements for the aviation fuels (IEA 2015). Advanced biofuels which are suitable for the production of jet fuels are BTL, FAME and SBH advanced biodiesel as well as pyrolysis-based advanced fuels. The closest one to be commercialized is HVO advanced biodiesel.

5 BIOFUEL SUSTAINABILITY

Biofuels offer a good alternative to fossil fuels in transportation sector, although there are several drawbacks related to the sustainability of biofuels. The public and political concerns are related to such potential problems of biofuels as food security, real societal and production costs without subsidies, limited returns on risky investments, decreased share prices of companies listed on the stock market, small benefits of GHG reduction, deforestation and loss of habitat due to land-use change, other resource shortage as e.g. competition for water or fertilizer as well as the complexity of certifying and producting of sustainable biomass. The most critical issues related to biofuels include competition with food production, land use change and utilization of scarce water resources. Competition with food production causes the problem of increased food prices, which is especially essential for the developing countries where disposable income is lower. From one hand high food prices are good for those developing countries, which export food crops, but on the other hand it increases the risk of malnutrition and hunger in other countries. The other critical issue of biofuels' sustainability is related to the competition for land and fresh water. Growing of biomass causes land-use change and deforestation because a lot of forest is converted into agricultural land. The rationality of using the scarce fresh water for irrigation of biomass is also questionable though it is somewhat acceptable when dilute effluent from treated sewage or food processing is used for irrigating energy crops. (IEA 2008, 26-30)

Current chapter contains two analyses: life cycle assesment and efficiency analysis. Life cycle assessment is done in details for sugarcane ethanol, while the problems of corn ethanol are described briefly. Efficiency analysis is more focused on corn ethanol whereas sugarcane ethanol efficiency is described shortly.

5.1 Sustainability indicators

There are some papers proposing sustainable criteria and indicators for any manufacturing facility whereas the other papers propose specific criteria and indicators related solely to biomass growing and biofuel production. Based on the proposed indicators the sustainability of bioethanol can be qualitatively evaluated with the further improvement opportunities suggested. There were 5 sources selected in order to create own framework with significant limitations in criterions. The limitations were done in order to avoid going too much into detail and create more generalized picture of sustainability performance. The focus was done on key criterions representing the main problems associated with biofuels on the stages of a lifecycle.

The chosen sources for indicators include such as OECD (2017a), Worldenergy (2012), NRDC (2014), FAO (2013) and Oeko-Institut (2012). The selected indicators as well as the stages of a lifecycle form a framework for further analysis are presented in figure 56 below.

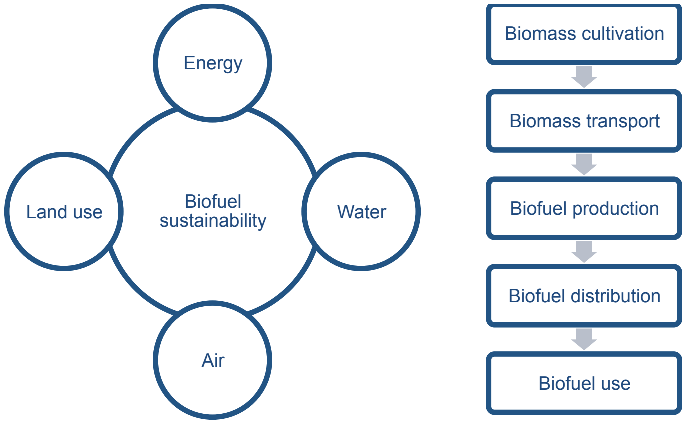


Figure 56 Framework for a lifecycle assessment of Brazilian sugarcane ethanol (own artwork based on OECD 2017a; Worldenergy 2012; NRDC 2014; FAO 2013; Oeko-Institut 2012)

It is worth highlighting each indicator and explaining its importance in the first place. Energy is an important indicator because production facilities utilize high amounts of non-renewable energy resources for instance for heating, cooling, electricity, transportation and so on. It is crucial that organizations take care of increasing their energy efficiency. Water is an important indicator due to the frequent quality issues and local shortages of water in insecure water supply areas. If the water is used for industrial processes but not returned in the same quantity and quality the decreasing of groundwater tables and depletion of lakes and rivers might take place. Not all industrial processes enable to return the water in the same quantity but therefore it is especially important to measure and track the water intake. The water can be released back to the environment either directly or via evaporation. Quality of water releases is important to track because it can affect environment, human health and economy. The residuals in water can be integrated into the food chain due to being consumed by aquatic species. The residuals can be reduced by improving efficiency of the processes, using the less polluting materials and improving the wastewater treatment. Conversion facilities for bioenergy and new bioenergy cropping systems should be located not in the areas with serious water stress. Air quality is a crucial indicator because it is related to environmental and human health issues. Across the whole supply chain biofuels have a negative impact to the air quality on a local and regional level as well as they have an impact on the global level in a form of GHG emissions. The most GHG releasing activities include combustion of fossil fuels, agricultural activities, waste generation and industrial processes. Improving of energy efficiency, conservation and utilization of energy sources which have lower carbon intensity are the most cost-effective ways of decreasing GHGs at industrial facilities. In overall, biofuels should ensure decreasing of GHG emissions in the whole life cycle when compared to conventional fossil fuels. Otherwise the sense of producing biofuels is lost. Land use indicator is important to overview from the perspectives of conservation of biodiversity and ecosystems, soil quality, direct and indirect land use change as well as from the perspective of food security. Preservation of ecodiversity leads to more productive, resilient and healthier biological resources providing greater ecosystem services to the society. It is also vital to ensure soil preservation and fertility as well as to avoid soil erosion for the future land use and for biological sequestering of carbon and keeping of hydrological functions of soil. In case of conversion of land GHG emissions take place. In particular it is carbon dioxide which is released due to organic matter decomposition and burning for clearing land. The indirect land use change happen when grasslands and forests were cut to transform the land into agricultural. Such a transformation causes the risk of increasing the atmospheric carbon dioxide levels because forests and grasslands typically absorb high levels of carbon dioxide. Food security is important to be overviewed because the utilization of food crops in biofuel production as well as the increase in commodity prices influence developing markets. Also using food crops for a fuel production causes contradictory reactions considering the fact that 795 million people out of 7.3 billion people living in the world were suffering from chronic hunger in 2014-2016 years. Food security is based on food availability, access and use according to the World Health Organization. Biofuels are linked to food security either as a function of access and availability or as a function of price or displacement of food crops by biomass production. (OECD 2017a; OECD 2017b; OECD 2017c; OECD 2017d; OECD 2017e; OECD 2017f; OECD 2017g; OECD 2017h; Worldenergy

2012, NRDC 2014, FAO 2013; Oeko-Institut 2012; EC 2017a; World Hunger 2016)

5.2 Life cycle assessment of sugarcane ethanol

The case for life cycle assessment presents to be production of sugarcane ethanol in Brazil. The assessment is done qualitatively based on the literature review. Several researches, which have already done the quantitative life cycle assessment, will be overviewed. The stages of sugarcane life cycle will be described together with identification of the problems on each stage. Afterwards all stages will be evaluated and the most unsustainable stage will be identified. Finally, recommendations and solutions for achieving a better sustainability performance will be presented.

The cultivation of the biomass starts with soil preparation. Sugarcane in an amount of 20% should be replaced every year with other crops like beans, corn and peanuts because sugarcane can be regrown with the same stalk only 5 times. This practice ensures soil recovery. The soil should be prepared and old sugarcane removed via using machines and chemicals. After that manual sugarcane plantation takes place with the help of trucks transporting partial sugarcane, tractors for opening trenches and spreading pesticides as well as buses for workers' transportation. Harvesting takes place annually from April to October in South-Central and from November to March in Northeast region of Brazil. Normally around 64% of harvesting is done manually and 36% with the help of the machines. Harvesting starts with burning the sugarcane in 70% cases: it facilitates cutting as well as repeals snakes and spiders. Cultivation stage has high water consumption due to irrigation and the utilization of diesel and fertilizers which production integrates high amounts of water. Also cultivation stage has consumption of energy resources namely non-renewable diesel fuel mainly during the harvesting activities. Cultivation stage has the highest air emissions compared to the other stages of the lifecycle due to the burning of sugarcane during the harvesting step as well due to the utilization of diesel as a fuel for agricultural machines mainly for harvesting. The air emissions include such as CO_2, particulate matter, nitrogen oxide (NO_x), carbon monoxide (CO), nitrogen dioxide (NO_2), CH_4 and other hydrocarbons. Diesel utilization for harvesting machines also has the highest carbon dioxide emissions compared to the other stages of the lifecycle. The production of diesel, which is utilized at agricultural machines, as well as production of fertilizers used during the cultivation has very high water residual levels in comparison to other activities related to sugarcane production. Also utilization of fertilizers and pesticides causes water pollution due to being carried from the fields by stormwater to the nearest water streams or rivers. The cultivation stage in overall has the highest contribution to the global warming primarily due to burning in harvesting step and due to utilization of diesel for agricultural machines and buses for transportation of workers. Also cultivation stage has the highest ecotoxicity and human toxicity due to the use of pesticides as well as due to burning of sugarcane and utilization of diesel. Burning of sugarcane increases the risk of diseases in the plants, soil erosion as well as it causes enlargement of ozone concentration in troposphere above the sugarcane cultivation areas. Also burning of sugarcane endangers some animals, which come to the agricultural land. The other problem associated with sugarcane cultivation is related to the expansion of the sugarcane cultivation areas because it causes the irreversible change of ecosystems such as deforestation. Deforestation, in its turn, causes extinction of species and habitats. Wide-scale destruction of forests can lead to the change of climate. There is also an issue related to the balance of carbon, which can be destructed due to the actions of transformation of the forests or grasslands into the agricultural lands. Though the promising thing is that though sugarcane areas are expanding (from 7% in 1989 to 19% in 2007), native forest areas in Brazil are expanding as well (from 5% in 1989 to 11% in 2007). The other problem associated with sugarcane cultivation is food security. Potentially in case of rapid expansion of sugarcane areas the arable lands for the food cultivation would face the reduction of availability, which would cause a food supply reduction and price increase. There has already been a change of land-use pattern in Brazilian history from food crops such as maize and rice to sugarcane energy crops, which took place in 1970s - 1980s. Nowadays, genetic improvements help the sugarcane crops to be more adaptive, resistant and productive without significant land expansions. Though it is expected that in the future sugarcane crops will still expand and they will replace not the areas with food crops but the areas of pasture as it has already been happening in Sao Paulo since 1990s. It is not seen as a big issue because cattle productivity is improving and it is prognosed that herd will be increasing despite of the pasture area reduction. Therefore it means that though the problem with deforestation and food security is significant and has high risks associated with it, it is not an acute problem at the moment but more a potential problem of a future (Ometto et al 2009, 238-243; Goldemberg et al 2008, 2088, 2091-2093; Sugarcane 2008, 44, 65, 84, 129-130; Piedmont Triad Regional Water Authority 2014, 2)

After biomass cultivation stage sugarcane transportation by trucks to the production facility takes place. Production of diesel, which is used as a fuel for trucks, has high water residuals. The utilization of diesel has high GHG emissions especially carbon dioxide. Though compared to the cultivation stage diesel utilization and therefore carbon dioxide emissions at biomass transportation stage are not that significant. (Ometto et al 2009, 238-242)

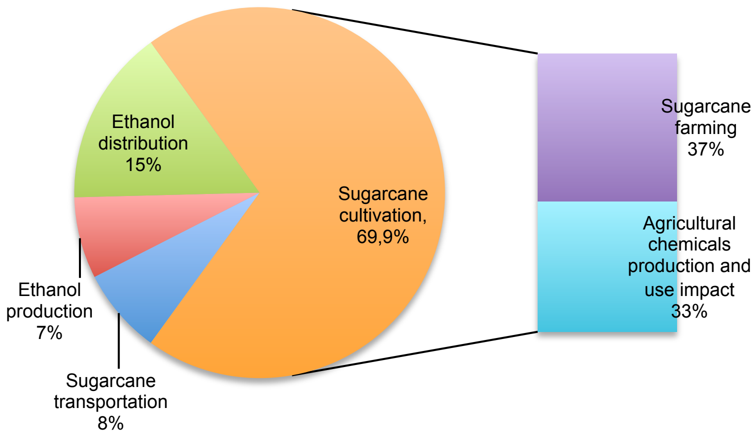
After being transported to the production facility, sugarcane is washed and transported to the millings by conveyor belts. Juice, filter cake and bagasse are the products of sugarcane milling. Production of alcohol happens from juice, filter cake plays the role of a fertilizer for the field while bagasse is burnt in order to generate electricity and steam in cogeneration plants. Production of ethanol has high consumption of energy, though, due to the cogeneration of electrical energy from bagasse, the energy demand for the production is fully satisfied internally. Moreover, there is the excess electricity, which is fed into the grid. Therefore it was considered that the stage does not have considerable effect on energy indicator. The enormous amounts of water are used during the production stage primarily due to washing of sugarcane after it was burnt for harvesting. It is necessary because high amounts of dust from burning are glued to sugarcane, which already starts exuding juice. The other water consuming processes at the production facility include fermentation cooling, alcohol condenser cooling and condenser/multijet in evaporation and vacuum. Also high amounts of water are consumed due to electrical cogeneration from steam. Among that there are also water residuals taking place at the production stage. They cause the risk of human toxicity because of the lubricant used for the machines and its residuals. Though in Sao Paolo the recycling and reuse of water have very high levels (above 95%) as well as water treatment efficiency reaches high levels. It is also important to note that the industrial waste is fully recycled to the field. (Ometto et al 2009, 238-243; Goldemberg et al 2008, 2087, 2089; Sugarcane 2008, 126)

After being produced at the production facility sugarcane ethanol is transported by trucks to the fuel station. Or it can be also transported by rail and pipeline within Brazil, by ocean tanker from ports in Brazil to ports at the US, and furthermore by trucks to terminal within the US. Ethanol distribution has higher GHG emissions than biomass transportation due to the distance differences and due to the fact that more transportation modes are integrated into the distribution processes. (Ometto et al 2009, 238-242; California Environmental Protection Agency 2009, 6, 36)

The example of the use stage of sugarcane ethanol implies the utilization of 100% fuel in 1600 cm^3 engine of car with average consumption of 8 km/l in a city area. The air emissions would include NO_x. (Ometto et al 2009, 238-242)

There is a figure 57 below illustrating GHG emissions distribution within the stages such as sugarcane cultivation including sugarcane farming and agricultural chemicals production and their use impact, sugarcane transportation, ethanol production and ethanol distribution. It shows that the highest emissions take place at the cultivation stage. They account for almost 70% from the whole production life cycle. Ethanol distribution has a bit more emissions (15%) compared to sugarcane transportation (8%). It is so because of the distance differences and there is more variety of transportation modes applied at distribution stage of ethanol rather than at transportation of biomass. Ethanol production has relatively low emissions (7%) compared to the rest of the stages because the bagasse is used for the energy generation at the production plant. In total life cycle of sugarcane ethanol has 95787 gCO_2eq/MWh. For a comparison, petrol lifecycle has 295283 gCO_2eq/MWh and diesel lifecycle has 356500

gCO_2eq/MWh. (IEA 2017; California Environmental Protection Agency 2009, 6; Swedish University of Agricultural Sciences 2013, 1)



Notes: GHG emissions in $gCO_2eq/MWh,th$: Sugarcane farming: 35650; Ag. Chemicals production and use impact: 31329; Sugarcane transportation: 7202; Ethanol production: 6842; Ethanol transportation and distribution: 14764.

Figure 57 GHG emissions for sugarcane ethanol (own artwork based on California Environmental Protection Agency 2009, 6)

In order to address and assess the problems occuring at the life cycle of sugarcane ethanol production table 5 presented below was created. It shows the effect which every stage of the life cycle has on such indicators as energy, water, air and land use. It was considered that biomass cultivation has some effect on energy because it utilizes non-renewable energy sources such as diesel for agricultural machines and buses for workers. The influence to water has been considered significant due to the direct and indirect integration of water into the processes. The direct integration of water happens by means of irrigation and indirect – because of utilizing diesel and fertilizers which have high water consumption and high water residual levels in their production processes. The impact to the air quality is also supposed to be considerable because of the burning during harvesting step as well as due to the utilization of diesel as a fuel for agricultural machines. Potentially from the perspectives of the impact to biodiversity and ecosystems, deforestation, land use change and food security the biomass cultivation has considerable problems. Though in Brazilian context the problem has already been considered nowadays though there might be an acceleration of the problem in the future. The effect of biomass cultivation was considered to be the average. Biomass and biofuel transport stages have some effect on energy and air quality due to the utilization of fossil fuels. Biofuel production stage has some effect on water in terms of high utilization rate and in terms of residuals. It would have been considered to have significant effect if not already applied recycle, reuse and water treatment practices at Brazilian sugarcane ethanol facilities. It was supposed that biofuel production has no impact on energy because of the energy cogeneration practices which ensure fulfillment of energy demand at the facility and moreover have considerable supplies of surplus electricity to the power market. It was also supposed that there is no remarkable air pollution from the production place because it utilizes agricultural residues as a feedstock for energy generation. It was also assumed that there is no remarkable conflict of production facilities with the land use. Concerning biofuel use stage it was supposed that it has some air pollutions in a form of NO_x.

Table 5 The results of lifecycle assessment of Brazilian sugarcane ethanol

	Biomass cultivation	Biomass transport	Biofuel production	Biofuel transport	Biofuel use
Energy					
Water					
Air					
Land use					

- no remarkable effect
- some effect
- considerable or significant effect

As it can be seen from the table 5 the most unsustainable stage of the sugarcane ethanol lifecycle is biomass cultivation especially in terms of water usage and air pollutions. The recommendations relevant to each stage of the life cycle will be furtherly given.

The burning practices during harvesting cause such problems as enormous GHG emissions and high contribution to the global warming, ecotoxicity and human toxicity, increase of the risk of occuring diseases in plants, soil erosion and ozone concentration in troposphere above sugarcane plantations. Also burning of sugarcane endangers some animals which come mistakenly to the plantation areas. Finally, burning of sugarcane enforces subsequent washing of sugarcane with enormous amounts of water at the production facility. In cases when sugarcane is not burnt there is 30% more byproducts left for the electricity production. It would also prevent soil erosion and decrease air emissions from the cultivation stage of a life cycle. Also such great amounts of water would not be needed for washing of sugarcane. There has been already the law in Sao Paulo aiming at phasing out burning practices and using machines instead of that. It is vital that the same results are achieved in the other states growing sugarcane. (Goldemberg et al 2008, 2089, 2090; Sugarcane 2008, 131)

The other practice, which has substantial impact to the environment, is the utilization of fertilizers and pesticides. In their production big amount of water is integrated as well as there are residuals in water left after production. Also utilization of fertilizers and pesticides has a risk of water pollution because they can be carried from the fields by the stormwater to the nearest streams and rivers. It is advisable for the plantations to avoid the use of fertilizers and pesticides as much as possible (Ometto et al 2009, 246).

Utilization of non-renewable fossil fuel diesel is the main reason why cultivation of sugarcane is the stage of life cycle, which has the highest carbon dioxide emissions. Diesel is the fuel, which runs the agricultural machinery and buses for workers. The activity that utilizes the greatest amount of machinery is harvesting. Along with air quality and energy problems utilization of diesel has indirect water issues because production of diesel integrates great amounts of water as well as it has high water residuals. It is recommendable to replace diesel with some renewable fuel like for instance biodiesel or bioethanol (Ometto, Hauschild & Roma 2009, 246).

Cultivation of sugarcane has a potential problem of deforestation and extinction of species, soil erosion, destruction of carbon balance and compromising the food security. It is advisable that land use is monitored and controlled. Also it is important that in case of expansion of sugarcane to new regions environmental risk assessment and proper planning have to be done. In case when it is not possible to avoid expansion of sugarcane crops it is better if they are replacing degraded pastures far away from Amazon. (Martinelli & Filoso 2008, 885; Sugarcane 2008, 12)

The transportation of biomass and ready-made biofuel integrates utilization of fossil fuels. It is advisable to replace them with biofuels.

The only problem at the production stage which needs attention is water usage amounts and water treatment. It is highly recommended to apply recycling, reuse and water treatment practices at the production facilities where they have not been implemented yet. One of the ways to reduce water usage amount could be phasing out washing of sugarcane at the beginning of the production stage. It would be possible if burning of sugarcane during harvesting was not implemented. There is also a new technology which enables transformation of sugarcane ethanol production facilities from water consumers to water exporters. Due to the fact that around 70% of the sugarcane composition is water nearly 300 liters of water per ton of sugarcane can be traded. Concerning water treatment, organic pollutants from wastewater can be reduced via mechanical, aerobic and anaerobic treatment. (Sugarcane 2008, 124-125; Smeets et al., 2006 as cited in Goldemberg et al 2008, 2089-2090; Ometto et al 2009, 246)

On the use stage of the life cycle there are NOx emissions occuring, and therefore the recommendations include such as improvement of the gas emissions control system (Ometto et al 2009, 246)

5.3 Brief sustainability overview of corn ethanol

In comparison to sugarcane ethanol produced in Central-South region of Brazil, ethanol produced from corn grain at the US has lower input of fertilizers and pesticides as well as lower agricultural machinery utilization and diesel input. Also there are no burning practices applied at the harvesting stage of corn ethanol. Water input on cultivation stage is almost twice higher for corn ethanol than for sugarcane ethanol, though at the production stage water consumption for sugarcane ethanol is about 20 times higher than for corn ethanol: mainly due to the fact that sugarcane needs to be washed after burning at harvesting. Sugarcane ethanol production practices cogeneration of electricity which allows to fulfill internal demand as well as to sell surplus of electricity to the power market. Therefore it has negative energy consumption. While corn ethanol production has high energy demand. (Sugarcane 2008, 126; Muñoz et al 2013, 3) And the demand is satisfied by means of coal and natural gas, while corn stover could be used for electricity generation. At least 50% of the energy demand could be satisfied if biomass power was used. (USDA 2016b, 9) According to Muñoz et al (2013, 6) sugarcane ethanol has higher photochemical oxidant formation potential, terrestrial acidification potential, marine eutrophication potential and agricultural land occupation. While sugarcane ethanol and corn ethanol have the same potential for global warming.

5.4 Efficiency

The important aspect of biofuel sustainability is the ratio of energy contained in biofuel relative to the external energy required to grow the feedstock, produce and distribute biofuel (Pimentel as cited in USDA 2016b, 1). There was a transition of ethanol from an energy sink to a moderate gain of energy in the 1990s and furtherly to a considerable gain of energy by 2008. It is important to see which energy components and in which amount they are integrated into the supply chain of biofuels. It is also vital to look into efficiency of the processes such as for example cultivation, transportation and conversion of the biomass into fuel. The energy ratio as well as the efficiency of field-to-feedstock, feedstock-to-fuel, fuel-to-tank, tank-to-wheel and finally field-to-wheel for corn and sugarcane ethanol will be described and analyzed in current subchapter. First the focus will be done on corn ethanol efficiency, which will be followed by sugarcane ethanol efficiency. For corn ethanol the example for the description and calculations was taken from USDA report. It is a production of corn ethanol in dry mill running on conventional sources of energy.

The starting point is cultivation. It integrates the usage of corn seeds, fertilizers such as nitrogen, potash, phosphate and lime, energy inputs of diesel, gasoline, liquid petroleum (LP) gas, natural gas and electricity, custom work and drying, chemicals usage and purchased water usage. The largest energy components for corn cultivation are nitrogen, fuels and electricity. Though since 1990s nitrogen use and use of direct energy components have declined by 20 and 50 percents respectively. According to the measures of USDA in 2010 the amount of energy applied at the cultivation stage was 0.108 MWh per MWh of ethanol. (USDA 2016b, 2-4; IEA Unit Converter 2017; Aqua Calc 2017)

Farm machinery estimates include machinery for planting, spraying, harvesting as well as storing corn. It accounts for required energy for producing, transporting and maintaining the farm machinery and in total it is 0.016 MWh per MWh. (USDA 2016b, 6; IEA Unit Converter 2017; Aqua Calc 2017)

Since the distance from farm to production facility is relatively short transportation of corn is implemented by means of trucks. Nine-State weighted average accounts for 0.008 MWh per MWh. (USDA 2016b, 5; IEA Unit Converter 2017; Aqua Calc 2017)

Conventionally powered production plant applies electricity in an amount of 0.105 MWh per MWh and thermal energy from coal or natural gas in an amount of 0.353 MWh per MWh. When summed up energy required at conversion facility constitutes up to 0.457 MWh per MWh. (USDA 2016b, 7; IEA Unit Converter 2017; Aqua Calc 2017)

Ethanol distribution is implemented by means of truck to intermediate distances and by rail to long distances. The shipment energy was calculated as a weighted average and it accounts for 0.012 MWh per MWh. (USDA 2016b, 5-6; IEA Unit Converter 2017; Aqua Calc 2017)

USDA (2016b, 14) in order to calculate energy ratio or EROI divided the output energy contained in ethanol by input energy of corn cultivation, farm machinery, corn transport, energy used at the production plant and ethanol distribution. Energy ratios or EROI calculated by USDA are 1.5 for a situation without accounting by-product credit and 2.3 with taking it into account. (USDA 2016b, 14; IEA Unit Converter 2017; Aqua Calc 2017)

Though the own framework implied the calculation of field-to-feedstock, feedstock-to-fuel, fuel-to-tank and overall field-to-tank efficiencies. The efficiency of tank-to-wheel will be presented in MWh per 100km. The table 6 contains the initial data used for the calculations and the results.

Table 6 Corn ethanol components for efficiency calculations and calculation results (USDA 2016b, 14; IEA Unit Converter 2017; Aqua Calc 2017)

Components for efficiency calculations	MWh per MWh
Energy content of corn for ethanol	1.544
Transportation losses	0.008
Electricity and heating losses at production plant	0.457
By-product credit	0.199
Energy content of ethanol	1
Distribution losses	0.012
Efficiencies	
Field-to-feedstock	99.46%
Feedstock-to-fuel	59.92%
Fuel-to-tank	98.82%
Field-to-tank	58.89%
Tank-to-wheel	0.063 MWh per 100km

The important role is played by amount of energy of feedstock, which is needed to produce 1

MWh of ethanol. Therefore it is needed to consider corn ethanol yield, which implies the amount of liters of ethanol, which can be produced from 1 ton of feedstock. When the yield is 410 liters per ton and energy content of 1 kg of shelled corn is 16200 kJ (0.0045 MWh) then to produce 1 MWh of ethanol 1.544 MWh of corn energy is needed. (APEC 2010, 23; Ontario Ministry of Agriculture, Food and Rural Affairs 1993; IEA Unit Converter 2017; Convert Units 2017)

The efficiencies in percentages were calculated via dividing the energy output by energy input. In case of field-to-feedstock in order to calculate the efficiency the energy at the feedstock stage (energy contained in corn necessary for 1 MWh of ethanol) was divided by the sum of energy at the field stage (energy contained in corn necessary for 1 MWh of ethanol) and losses of transportation from the field to the production stage. Namely, 1.544 MWh per MWh was divided by the sum of 1.544 and 0.008 MWh per MWh. Field-to-feedstock efficiency shows the efficiency of transportation from the farm to the production facility of ethanol. It is 99.46% so the process is very efficient.

The feedstock-to-fuel efficiency was calculated via dividing the sum of 1 MWh of ethanol and by-product credit for 1 MWh of ethanol by the sum of corn energy necessary for the production of 1 MWh of ethanol and electricity/heating losses necessary for the production of 1 MWh of ethanol. The feedstock-to-fuel efficiency is 59.92%.

Fuel-to-tank efficiency was calculated via dividing 1 MWh of ethanol by the sum of 1 MWh of ethanol and distribution losses. The fuel-to-tank efficiency is 98.82%. It is a little bit less efficient process than for instance corn transportation but the reason is that the distances for the ethanol distribution are much higher than the distances for corn transportation.

The total field-to-tank efficiency is 58.89%, which is a multiplication of all efficiencies. If one takes as an example Volkswagen Golf 2003 running fully on ethanol then tank-to-wheel efficiency would be 9.81 liters per 100 km or 0.063 MWh per 100 km.

Regarding sugarcane ethanol, on the stage of feedstock cultivation it integrates the usage of such chemicals and fertilizers as nitrogen fertilizer, phosphate fertilizer, potash, lime, herbicide and insecticide. The highest consumption falls on nitrogen and lime. There are also such energy inputs on farming step as utilization of diesel, gasoline, natural gas, LPG and electricity. In the production plant bagasse from sugarcane is burnt for the generation of electricity. The sugarcane ethanol production process is energy self-sufficient. The bagasse is used in an amount of 0.992 MWh per MWh. After being produced ethanol can be transported via trucks, rail, pipeline and ocean tanker to the US ports. (California Environmental Protection Agency 2009, 8-9, 32, 34-35). In order to calculate feedstock-to-fuel efficiency of sugarcane ethanol the amount of output energy has to be divided by the amount of input energy. The output energy is a sum of 1 MWh of ethanol and co-product credit namely amount of surplus electricity generated from bagasse (0.272 MWh per MWh). The input energy is the energy contained in sugarcane feedstock necessary for 1 MWh of ethanol namely 3.754 MWh per MWh. The feedstock-to-fuel efficiency of sugarcane ethanol is 33.88%. If assume that the distances for transportation of sugarcane from the field to the production plant as well as for distribution of ethanol from production plant to the fuel stations are relatively similar to the distances and transportation modes related to corn and corn ethanol and if take as a reference same car model (Volkswagen Golf 2003) then field-to-feedstock efficiency is 99.78%, fuel-to-tank efficiency is 98.82%, field-to-tank efficiency is 33.41% and tank-to-wheel efficiency is 0.063 MWh per 100 km.

5.5 Summary

It is debatable whether biofuels produced from energy crops are sustainable. It can be seen from the example of sugarcane ethanol that even though biofuels are referred to renewable energy fuels the whole production life cycle integrates high amount of fossil fuels. Fossil fuels are used for running agricultural machinery and buses for workers at the field as well as on transportation and distribution stages. Also there are other problems associated with biofuels as the usage of fertilizers and pesticides, aggressive practices during harvesting like burning of sugarcane, utilization of fossil energy at corn ethanol production plants, risk of deforestation and extinction of species, soil erosion, food security issues and utilization of high amounts of water and water residuals.

The most unsustainable part of sugarcane ethanol life cycle is cultivation. It has impact on all four chosen sustainability indicators: energy, water, air and land use. There is a practice of burning sugarcane on the harvesting stage with the aim of facilitating the cutting of feedstock. If the practice was eradicated then GHG emission performance of sugarcane would improve, there would be no danger for animals at the field as well as considerable amounts of water would be saved which were needed for washing the sugarcane from ashes. It is highly recommendable to exterminate burning practice. Along with it the other recommendations for the other issues occuring at the life cycle include reducing the amount of fertilizers and pesticides used, substitution of fossil fuels for running the agricultural machinery and transportation purposes with biofuels. In case of corn ethanol it is advisable to start using biomass residuals for electricity generation at the production plant. Also in order to prevent deforestation or food security problems in case of energy crop expansion the risk assessment and proper planning have to be done. It is also advisable to implement expansion on degraded pasture lands far away from Amazon in case of sugarcane ethanol for example. Concerning water usage problems, the recycling, reuse and water treatment systems have to be installed at production plants.

Regarding the efficiency analysis, growing of energy crops requires application of fertilizers, water, agricultural machinery and transportation for workers by buses all running on fossil fuels. Also feedstock needs to be transported to the production facility by trucks utilizing diesel. Production process is energy demanding as well and for corn it requires application of coal and natural gas. Distribution of fuel needs to be furtherly implemented by means of trucks or rail and it also applies fossil energy for that. Energy ratio for corn ethanol is 1.5-2.3. Field-to-feedstock efficiency for corn ethanol is 99.46%. Feedstock-to-fuel efficiency is 59.92%. Fuel-to-tank efficiency is 98.82%. Field-to-tank efficiency is 58.89%. Tank-to-wheel efficiency is 0.063 MWh per 100 km. For sugarcane ethanol field-to-feedstock efficiency is

99.78%. Feedstock-to-fuel efficiency is 33.88%. Fuel-to-tank efficiency is 98.82%. Field-to-tank efficiency is 33.41% and tank-to-wheel efficiency is 0.063 MWh per 100 km.

6 GLOBAL ENERGY TRANSITION

It is interesting to see how biofuels are treated in various energy scenarios for the future: whether they are neglected or taken into scenarios despite of the sustainability constraints associated with biofuels.

According to IEA (2015, 364) biofuels consumption in road transport increases very significantly globally with the predominance in favor of bioethanol rather than biodiesel. The main investments into biofuel sector will be done at the US, EU, Brazil, India and China. But regions like EU or the US do not fully support biofuels. The European Parliament for example approved a law, which limits the utilization of biofuels based on food energy crops to a maximum of 7% out of the 10% target. The US faces challenges related to the usage of high blends of biofuels due to the limited availability of blends higher than 10% of ethanol, though, nevertheless, the biofuel consumption doubles in general there. Brazil increases its requirements towards the usage of biofuels by 2040 and it has a fully available infrastructure for that. Also China and India have a growing market for biofuels driven by blending mandates and enhancing transport energy demand. India could produce 488.5 GWh,th/d of bioethanol from sugarcane and molasses, which would represent about 30% of the projected road transport gasoline demand. Though possibly India can not reach its mandates of 20% blend of ethanol due to supply issues, competition with food production, water security issues and protection of forest areas. In order to play a major role in transportation sector globally biofuels have to avoid food security issues and other sustainability concerns. Nowadays the main driver for demand of biofuels in transport is ensured by blending mandates. Subsidies to biofuels grow by 2020 mainly due to low oil prices, which increase the gap between prices of fossil fuels and biofuels. The more political support globally could be gained by developing advanced biofuels instead of biofuels based on energy crops. Moreover, according to IEA advanced biofuels are the only option, which can replace fossil fuels in aviation and comply with very specific quality requirements of the aviation industry. Though there is a lack of progress in commercializing advanced biofuels globally and therefore it is hard to predict when there would be an increase in their deployment and decrease in costs. (IEA 2015, 77, 92, 128, 183, 363-365, 285, 487, 541-542; Unit Juggler 2017)

There are different scenarios for biofuel contribution towards global energy transition from such organizations as IEA, Greenpeace, WWF, ExxonMobil, MIT and Shell. They were overviewed and compared to see which estimations exist for the biofuels future and how they differ. Figure 58 below presents the comparison of scenarios for 2030 and 2040.

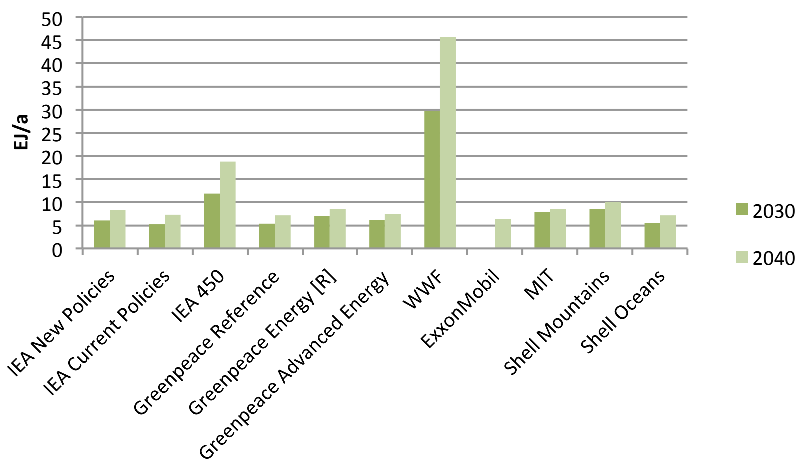


Figure 58 Comparison of different scenarios for biofuel contribution to global energy transition in 2030 and 2040 (own artwork based on IEA 2015; Greenpeace 2015; WWF & ECOFYS & OMA 2011; ExxonMobil 2017; MIT 2014; Shell 2013)

As it can be seen from the graph the majority of scenarios are in line and show approximately the same contribution of biofuels namely around 5.2-8.6 EJ per year for 2030 and 6.3-8.6 EJ per year for 2040. There are two scenarios (IEA 450 scenario and WWF scenario) which show higher numbers: 11.9 and 29.7 EJ per year for 2030, 18.7 and 45.7 EJ per year for 2040. In general scenarios assume that biofuels will contribute by around 4-8% in 2030 and 4-11% in 2040. Though in cases of IEA and WWF the contribution of biofuels is projected to be much higher: 10% in 2030 and 16% in 2040 in IEA 450 scenario and 32% in 2030 and 73% in 2040 in WWF scenario. Synthetic fuels distinguished as a separate fuel category appears only in Greenpeace scenarios, and only Advanced Energy [R]evolution scenario which projects 0.5% contribution in 2030 and 4% contribution in 2040 for the transportation sector.

It is interesting to see whether sugarcane ethanol could contribute significantly to the projected demand in biofuels in 2030 and 2040. As a start it is good to look at Brazilian biofuel demand separately. It is projected by IEA (2015) that in 2030 Brazil will have demand of biofuels in an amount of 1-1.7 EJ per year in 2030 and in 2040 – 1.3-2.3 EJ per year. Whereas according to Souza (2017) sugarcane ethanol potentials in Brazil in 2030 are as follows: theoretical potential – 80 EJ per year, technical – 17-21 EJ per year, economic – 10.6-16.2 EJ per year, environmental – 1.57-1.62 EJ per year and sustainable – 0.44-1.61 EJ per year. It shows that if produced purely sustainably sugarcane ethanol would hardly satisfy even Brazilian internal biofuel demand. Though technically, economically and environmentally it is more than feasible in 2030. Concerning satisfying global biofuel minimum demand taken from the IEA Current Policies scenario for 2030 (5.2 EJ per year) technically and economically Brazilian sugarcane ethanol could fully satisfy it. If taken into consideration environmental potential of Brazilian sugarcane then it could satisfy roughly 30% of global biofuel demand. Though if produced purely sustainably than sugarcane ethanol could satisfy 8-30% of minimum global biofuel demand. The main market for Brazilian sugarcane ethanol possibly will be Brazil itself, but also China and India because they have growing transportation demand and mandates applied while producing enough biofuel from sugarcane locally would bring too high risks of competition with food production (IEA 2015). These two countries are one of the leaders of sugarcane production, but they produce it mainly for food market and the areas of China and India are much lower than Brazil, so they have less possibilities for sugarcane expansion (OECD-FAO 2016a).

There should be other biofuels playing on the global market along with sugarcane ethanol in order not to put so much pressure to Brazil and not neglect sustainability concerns related to sugarcane ethanol. Possibly corn ethanol would keep its strong positions at least by 2030 till advanced biofuels do not start occupying the biofuel market.

7 DISCUSSION AND CONCLUSION

Biofuels have been overviewed from the perspectives of technologies, resources, economics, sustainability and alternative options. From the huge number of biofuels, which are technically feasible only a small amount has reached the commercialization stage. Among them are bioethanol produced from sugar and starch crops, biodiesel produced via transesterification and biogas produced via anaerobic digestion. All of these biofuels are conventional ones, which are generally associated with sustainability constraints, though they still offer sufficient GHG emission reduction if compared to fossil fuels. GHG emission reduction and EROI are critical indicators because they show the contribution of the biofuel to the society. In case if GHG emission reduction is too low it is hard to justify the use of biofuels instead of fossil fuels because then there is no benefit for the society. Biofuels have many concerns in terms of sustainability and they should at least have emission reduction in order to "pay off" the problems they might cause during their life cycle. EROI indicator is also critical because it shows how much energy effort it caused to produce biofuel. When a lot of fossil fuels are integrated into the supply chain of biofuels especially in the production stage while the energy return of biofuel is relatively low then there is also no benefit for the society to produce such a biofuel. From the point of GHG emission reduction the best results are shown by sugarcane ethanol, biogas, biochemical advanced ethanol and advanced biodiesel BTL. From the point of EROI the best results come from sugarcane ethanol, wheat ethanol, diesel from animal fats, biogas, biochemical advanced ethanol and advanced biogas. There are biofuels which are good in terms of GHG emissions reduction, but the EROI is low for example like in case of advanced biodiesel BTL, or vice versa when EROI is good but emission reduction is low like in case of wheat ethanol. Some biofuels have been commercialized, though they do not show excellent performance in terms of emission reduction and EROI. Mostly among this category are conventional ethanol types, while conventional biodiesel types generally show good performance in both emission reduction and energy return. There are also biofuel types, which are good or excellent in emission reduction and energy return, but they have not been commercialized yet. Among these biofuels are biochemical advanced ethanol and advanced biogas. All these observations show that it is really hard to find a biofuel, which would satisfy all the requirements. The best ones are sugarcane ethanol, biogas and biochemical advanced ethanol. From the perspective of technology these biofuels might have a good contribution to the society.

From the resource analysis it was concluded that energy crops and agricultural products including agricultural residues, animal fats and manure might play the most substantial roles in fulfilling global biomass demand in the future. By 2030 the biomass demand is going to switch from traditional buildings to transportation, power and DH generation. The biomass supply potential for 2030 could almost satisfy the transportation energy demand alone. Though if biomass is produced sustainably then the supply is not enough and the other types of fuels have to be integrated into the system. Corn ethanol and sugarcane ethanol with the predominance of corn ethanol represent the highest shares in global biofuel production nowadays. Therefore these two biofuel types are considered to be the ones playing the major roles in biofuel market of today. Brazil and the US are the leaders on bioethanol market and Brazil is usually associated as the main global sugarcane ethanol producer, while the US is the major corn ethanol producer. For sugarcane ethanol it is clear that it has very strong positions nowadays and prospects for the future because it is one of the most widely used biofuel and it has excellent performance in terms of GHG emission reduction and EROI. Corn ethanol is the main biofuel of today but its position is uncertain in the future because it has only an average GHG emission reduction and an average EROI. There are some improvement opportunities for corn ethanol performance for instance the utilization of agricultural residues as an energy source for running a production facility. It would somewhat improve the emission reduction and EROI because less fossil fuel would be needed in the life cycle of corn ethanol which means less emissions and less energy investments. It was decided to continue the further economic and sustainability analysis based on corn and sugarcane ethanol mainly due to the fact that they represent together around 60% on the liquid biofuel market but also because sugarcane ethanol has excellent technological performance while corn ethanol has opportunities for improvement of the processes.

In economics part the focus was done on LCOF calculation for corn and sugarcane ethanol, cost projections for 2030 and comparison of biofuel costs in the future to fossil fuel prices and costs of synthetic fuels. The LCOF calculation has shown that corn ethanol production costs are higher than sugarcane ethanol production costs in 2016. According to sensitivity analysis LCOF of corn ethanol is very sensitive to the fluctuations in feedstock cost, conversion efficiency, co-product credit and cost for energy/utility. Sugarcane ethanol LCOF is very sensitive to feedstock cost, conversion efficiency, co-product credit and capex total. It means that corn and sugarcane ethanol mostly follow the dynamics of the feedstock market. Though the production cost can be also influenced by the changes in co-product credit. Especially it is relevant to sugarcane ethanol because its co-product credit depends on the wholesale electricity price, which is quite shifting. For corn ethanol it is hardly that the profit from selling co-product in a form of DDGS would change significantly. For corn ethanol fluctuations in energy costs are more relevant. Due to the fact that corn ethanol plants utilize coal and natural gas fluctuations on these markets influence the cost of corn ethanol quite much. The projections for 2030 and 2040 show that corn ethanol production costs slightly grow whereas sugarcane ethanol production costs decline dramatically. If compared corn ethanol and sugarcane ethanol production costs to fossil fuels nowadays they are not competitive. In the future the competition is possible when crude oil prices grow or when carbon dioxide emission costs are taken into the price of fossil fuels. When corn ethanol and sugarcane ethanol production costs are compared to synfuel production costs the results show that sugarcane ethanol stays the cheapest substitution to fossil fuels in both 2030 and 2040 and no synfuel cost is even close to the production costs of sugarcane ethanol. Whereas corn ethanol starts losing its competitiveness by 2030 and let RE-SNG overtake its positions, but only in Patagonia. In Maghreb region corn ethanol is still cheaper than RE-SNG in 2030.

Nevertheless, it shows that corn ethanol might be extruded from the global market in the future while sugarcane ethanol will stay for sure. Also it shows that competition of biofuels with synthetic fuels will start in the shipping sector because ships can also run on RE-SNG. It is hardly that synthetic fuels will be competitive with biofuels in road transportation any time soon because there is still sugarcane ethanol on the market and RE-FT-liquids are still too expesive in 2030 and 2040. But synthetic fuels will possibly compete with advanced biofuels in aviation after 2040 when advanced biofuels might enter the market and also synthetic fuel costs decline due to technological development. It is still hardly that corn ethanol is out of market when there is still a demand for it and no substitution, which is lower in cost than corn ethanol. So even if its prices grow probably it stays on the market until advanced biofuels do not start occupying it as well. For them it will be hard to compete with sugarcane ethanol in terms of costs but much easier to compete with corn ethanol. There might be three scenarios for corn ethanol extrusion. In the first one advanced ethanol becomes commercialized and its costs decline due to technological development and it extrudes corn ethanol from the road transportation market. In the meantime advanced biodiesel enters the transportation market but it is mainly focused on aviation and shipping sectors where it starts competing with synthetic fuel costs. In the second scenario advanced ethanol is commercialized but the costs decline slowly while advanced biodiesel also becomes commercialized and its costs decline faster and it extrudes corn ethanol as well as starts competing with synthetic fuels in aviation and shipping. In the third scenario the development of advanced biofuels is going very slow and synthetic fuels extrude corn ethanol from the road transportation market. If talked about advanced biodiesel it is good in that sense that it can replace gasoline, diesel, jet fuel and oil used for chemical processes. While the application of advanced ethanol is limited to gasoline. Therefore it is considered that advanced biodiesel will be the one really competing with synthetic fuels in the future in the aviation and shipping sectors. Though the further research in the area of advanced biofuels needs to be done with the focus on calculation of the production costs of advanced biofuels and projections of costs for the future.

Biofuels were also overviewed from the sustainability perspective in order to identify the main problems, which occur during the life cycle and what are the possible solutions for them. Sustainability of biofuels is a very critical aspect because it is one of the inhibiting factors for the deployment growth of biofuels in the future. Even when the costs are relatively low the sustainability concerns do not allow increasing the production of biofuels. Therefore the analysis shows the boundaries which production growth cannot cross and the problems, which should be solved in order to increase the chances for production growth. The efficiency analysis, which was done after sustainability analysis shows whether the processes in the supply chain are efficient or not. For the case of inefficiency there are also improvement opportunities, which have the capability to increase EROI of biofuels. The problems in the life cycle of sugarcane ethanol and corn ethanol are the utilization of fossil fuels for agricultural machinery, buses for workers and transportation of biomass and bioethanol, usage of fertilizers and pesticides, aggressive practices of burning during harvesting in case of sugarcane, utilization of fossil fuel energy at corn ethanol production plant, risk of deforestation and extinction of species, soil erosion, food security issues and utilization of high amounts of water and water residuals. Some of these problems could be solved but some not. For example, fossil fuels in machinery and transportation could be replaced by biofuels, utilization of fertilizers could be diminished, burning of sugarcane during harvesting could be expelled, corn ethanol production plants could contribute to the fulfilling of internal energy demand at least by 30% by means of using corn stover for energy generation and water problems could be solved by installing water treatment and recycling systems. Whereas the problem with the land use is very hard to solve: when it is not allowed to expand on food crop lands, forests and sometimes even pasture lands then there are not many opportunities for sugarcane ethanol to increase its production. This is the main boundary, which cannot be fully overcome in the future. It should be just accepted that sugarcane ethanol potential is limited. Even though sugarcane ethanol is a very low cost technology the production cannot be just increased while neglecting such a big problem of land use. The efficiency analysis has shown that the biggest amount of energy is applied at production stage of biofuels with cultivation stage following. The yield of corn ethanol is higher than the yield of sugarcane ethanol, but on the contrary corn ethanol needs a lot of external fossil energy in production. Whereas sugarcane ethanol yield is lower but it satisfies the internal energy demand at the production plant alone via using bagasse. There are some improvement opportunities for corn ethanol to increase the EROI: it could be done by utilizing a corn stover for partial production of energy at the plant. It would also improve the sustainability performance for corn ethanol. Though for sugarcane ethanol there are no improvement opportunities for the processes. Therewith the results show that it is hard to significantly improve the EROI when all the production processes are well established already.

Biofuels were also shortly overviewed from the perspective of global energy transition scenarios for transportation sector. The majority of the scenarios are in line and they show the contribution of biofuels towards energy transition in an amount of 4-8% in 2030 and 4-11% in 2040. Whereas two scenarios (IEA 450 and WWF) show the contribution of biofuels much higher: 10-32% in 2030 and 16-73% in 2040. It was also tested whether sugarcane ethanol is capable to satisfy global biofuel demand in transportation alone in the future. Sugarcane ethanol is an extremely low in cost technology and in case it is possible for it to satisfy the global biofuel demand in transportation alone, it would be hard for other biofuels to compete with it, particularly in road transportation. But the analysis has shown that if produced purely sustainably sugarcane ethanol can satisfy from 8% to 30% of global biofuel demand in transportation in 2030. Though technically and economically sugarcane ethanol can satisfy global biofuel demand in transportation fully. So it shows that in the future there might be increased debates related to the sustainability of sugarcane ethanol. For the producers it would be desirable to increase the production of sugarcane ethanol especially when there is such a growing global demand for it. Though the society and non-commercial sustainability organizations probably will be against the expansion. In such a case the best situation would be coopetition (competition and cooperation simultaneously) of several types of biofuels, which would satisfy different demands. For example, sugarcane and corn ethanol would play on the road transportation biofuel market together. And sugarcane ethanol could stimulate corn ethanol to improve its processes in the production plant and start utilizing the residues for energy generation which would actually also improve the economics of corn ethanol. Whereas several advanced biofuels would play on the aviation and shipping biofuel market and also stimulate each other to become lower in cost. The further global development or deployment of conventional biofuels other than sugarcane or corn ethanol is not really making sense because the conventional biofuels will all have the same boundaries for expansion. Whereas advanced biofuels have less sustainability concerns and they are less area-dependent in a sense that they can be produced anywhere in the world: there is no need for special weather conditions necessary for growing any feedstock. So also the global dependance from the main producers would be overcome. Also when the technology develops and advanced biofuels become lower in cost they could be a good solution for the agrarian countries with poor economies and energy-dependence on the other countries: agricultural residues could be used there to produce fuels. It would decrease energy dependence, improve the economy of the country as well as create new jobs for the people and mitigate GHG emissions.

Coming back to the research questions, which were asked at the beginning of the paper. The main research question of the study was about what is the contribution of biofuels to the global energy transition. It was supported by several sub-questions. The first sub-question was about what is the main biofuel technology of today and of the future. The main biofuels of today are corn and sugarcane ethanol. But in the future there will be the other players entering the market such as advanced biofuels, which will first have a demand in shipping and aviation. After becoming lower in cost they will extrude corn ethanol from the road transportation market while sugarcane ethanol will stay for sure.

The second sub-question was whether biofuel resources are sufficient enough to satisfy the transport energy demand and which countries can contribute the most. The answer is that biomass potential for the future could almost satisfy the transportation energy demand but if produced sustainably biofuels cannot satisfy the transportation energy demand alone. The main players on the biofuel market are the United States, Brazil and European Union. The

United States are known on the market for corn ethanol they produce, Brazil – for sugarcane ethanol, whereas the EU area has the main biodiesel producers.

The third sub-question was about what are the sustainability constraints of biofuels and how they could be overcome. The sustainability constraints of biofuels include utilization of fossil fuels for agricultural machinery, buses for workers and transportation of biomass and biofuel, fossil fuel energy utilization at the production stage, usage of fertilizers and pesticides, aggressive practices during harvesting in case of sugarcane, risk of deforestation and extinction of species, soil erosion, food security issues and utilization of high amounts of water and water residuals. The solutions include substitution of fossil fuels used for transportation purposes and running agricultural machinery with biofuels, starting practicing utilization of residuals for energy generation at production plants, mitigation and control of the usage of fertilizers and pesticides, eradication of burning practices during harvesting, implementation of risk assessment and proper planning before energy crop expansion, implementation of expansion of energy crops on degraded pasture lands far away from forests and installment of recycling, reuse and water treatment systems at production plants.

The fourth sub-question was about how the cost of biofuels will change in the future. Corn and sugarcane ethanol costs are very sensitive to the fluctuations in the feedstock market and they will always follow the dynamics of feedstock costs. It was projected that corn ethanol becomes slightly more expensive in the next two decades, while sugarcane ethanol costs fall quite dramatically. Corn ethanol costs change from 56 € per MWh in 2016 to 56.9 € per MWh by 2030 and 59.6 € per MWh by 2040, while production costs of sugarcane ethanol change from 43.5 € per MWh in 2016 to 32.2 € per MWh by 2030 and 27.8 € per MWh by 2040. As it can be seen, if in 2016 corn and sugarcane costs are still more or less comparable, by 2040 sugarcane ethanol becomes more than twice cheaper than corn ethanol.

The fifth sub-question was about when biofuels might lose their cost competitiveness. Sugarcane ethanol keeps its strong positions on the market due to the falling costs in the future, whereas corn ethanol might lose its cost competitiveness towards synthetic fuels by 2040 and let RE-SNG overtake its positions.

The main research question of the study was about what is the contribution of biofuels to the global energy transition. Contribution of the biofuels to the global energy transition happens on transportation market. The biomass resources are not enough to satisfy the global transportation demand alone so biofuels contribution is limited. Conventional biofuels such as corn and sugarcane ethanol will contribute the most to the global energy transition of road transportation, whereas advanced biofuels will contribute mainly on aviation and shipping markets with the further expansion towards road transportation. The key conclusion is that electrification, synthetic fuels and biofuels should contribute to the global energy transition of transportation sector together and stimulate each other to become lower in cost, improve the sustainability of the life cycle and efficiency. And they should be applied to the sectors, which have the higher demand for their type of fuel. Also when some areas in the world have good solar and wind conditions they should produce synthetic fuels and export it to the other areas of the world. The areas like Brazil and the US can exchange sugarcane and corn ethanol with the rest of the world. The areas with the good technological development for advanced biofuels can produce them and also exchange with the areas, which have a demand for it. So the point is that there should be a coopetition of different fuels and only when they are applied for satisfying the transportation demand together there can be a balance.

8 SUMMARY

The starting point of the research was the understanding that in order to comply with COP21 agreement and prevent climate change energy transition from fossil fuels towards renewable energy should be implemented. In transportation there are such alternatives as electrification, biofuels and synthetic fuels. It is hard to electrify heavy duty truck transportation, shipping and aviation sectors and therefore biofuels along with synthetic fuels might play the major roles there in the future. It was decided to overview the biofuels from the perspectives of

technologies, resources, economics, sustainability and alternative options in order to assess their contribution towards global energy transition in transportation. The research was done based on secondary sources. It also includes the calculations of production costs for corn and sugarcane ethanol as well as the projections of the costs up to 2040. All the research questions have been answered. The summary of the main findings is presented below.

Biofuels can be divided into five groups such as ethanol-type, diesel-type, biomethane, hydrogen and other fuels. Also the biofuels can be divided into two groups: conventional and advanced biofuels. Conventional biofuels are produced from energy crops and have sustainability concerns associated with them while advanced biofuels are produced from agricultural and forest residues and waste and therefore their sustainability performance is better. Conventional biofuels are commercialized, while advanced biofuels – not yet. The main biofuel producers of today are the US, Brazil and EU. The US is known for its corn ethanol, Brazil – for sugarcane ethanol, while EU – for biodiesel. Global biomass resource potential is not enough to satisfy the global biofuel demand in transportation alone. Though one of the main roles are played by sugarcane and corn ethanol. Nowadays sugarcane and corn ethanol are not competitive with fossil fuel prices though in the future in case if crude oil prices grow or carbon dioxide emissions are included into the price of fossil fuels biofuels will be competitive. In the future the costs for corn ethanol will grow, though for sugarcane ethanol they will decline. Both corn and sugarcane ethanol costs highly depend on the fluctuations on feedstock market and they will always follow its dynamics. In the future biofuels might lose their cost competitiveness towards synthetic fuels though it is not expected to happen before 2040 globally. Biofuels have sustainability concerns associated with them. The constraint which cannot be overcome is the competition with food production and deforestation. Therefore the potential of biofuels produced from energy crops is limited. And even when they are combined with advanced biofuels in the system they cannot satisfy the global energy demand in trasportation alone. The system should include electrification, conventional biofuels, advanced biofuels and synthetic fuels. The road transportation could be satisfied by conventional biofuels, advanced biofuels and electrification, while the main players of the shipping and aviation markets could be advanced biodiesel and synthetic fuels. The conventional biofuels will be extruded from the system when advanced biofuels and synthetic fuels become cheaper and have enough capacity to satisfy the road transportation, shipping and aviation demand without the contribution of conventional biofuels.

The further research opportunities include the assessment of advanced biofuels from the perspectives of technologies, resources, economics, sustainability and alternative options. In order to have a more clear picture of the future competitions it is important to know when advanced biofuels will enter the market and how their costs will develop in the future.

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APPENDICES

Appendix 1 Biofuel types and their characteristics

Biofuel type	Conversion technology	Feedstock	Co-products	Blending characteristics	Fossil fuel replacement	EROI	GHG emissions savings vs fossil fuels, %	Commercialization status
Conventional Biofuel Technologies (1st Generation)								
Bioethanol	Biochemical process: Fermentation + distillation [1, p. 7; 2, p. 13]	Sugarcane [1, p. 7]	Bagasse [1, p. 23; 2, p. 27]	E10-E15 (E25 in Brazil) in conventional gasoline vehicles; E85-E100 in flexible-fuel or ethanol vehicle [2, p. 47]	Gasoline [2, p. 16]	2.5-3.0 [1, p. 23]; 0.8-10 [5, p. 109]; 3.1-9.3 [41, p. 7]	70-105% [1, p. 14]; 70-110% [2, p. 16]	Commercial [1, p. 12; 2, p.12]
		Sugar beet [1, p. 7]	Beet pulp [1, p. 14; 2, p. 27]			4.14 [8, p. 268]; 1.2 [41, p. 7]	25-65% [1, p. 14]; 25-65% [2, p. 16]	
		Sorghum [1, p. 7; 18, p. 5]	DDGS, WDGS [18, p. 117]			0.7-1 [41, p. 7]	23-72% [57, p. 1]	

	Biochemical process: Hydrolysis + fermentation [1, p. 7; 2, p. 13]	Corn (maize) [1, p. 7]	DDGS [1, p. 14; 2, p. 27], WDG, CGM, CGF, CDO, corn kernel fiber [15, p. 11, 12], corn gluten meal [11, p. 10]			1.3 [8, p. 268]; 0.8-1.7 [41, p. 7]; 1.3-1.6 [1, p. 23]; 0.8-1.6 [4, p. 351; 5, p. 109]; 0.8-1.3 [9, p. 1806]; 1.2-1.7 [11, p. 1]; 0.84-1.65 [44, p. 2]	-20-60% [1, p. 14]; -20-60% [2, p. 16]	
		Wheat [1, p. 7; 18, p. 5]	DDGS [15, p. 10; 16, p. 22]			1.6-5.8 [41, p. 7]; 3.5 [44, p. 2]	-10-90% [2, p. 16]	
		Potatoes [1, p. 7; 18, p. 5]	Roots, culls, aerial vines, alcohol distillery waste water [17, p. 113]			1.6 [44, p. 2]	-	
		Cassava (tapioca) [1, p. 7; 18, p. 5]	Root fibre [18, p. 5]			1.3-1.9 [41, p. 7]	73% [58, p. 542]	
Biodiesel	Transesterification [1, p. 7]	Rapeseed [1, p. 14]	Glycerine, presscake [1, p. 14; 2, p. 27], rapeseed meal [15, p. 12], fatty acids [18, p. 7]	Up to B20 in conventional diesel engines [2, p. 47]	Diesel [2, pp. 12, 16]	1.3-1.6 [1, p. 23]; 1.05-3.71 [3, p. 163]; 1.38-3.49 [35, p. 38]; 2.3 [41, p. 7]	15-85% [1, p. 14]; 15-90 [2, p. 16]	Commercial [1, p. 12; 2, p. 12]
		Soy seed [1, p. 14]	Glycerine, bean meal [1, p. 14; 2, p. 27], fatty acids [18, p. 7], bean meal [15, p. 12]			0.78-4.56 [3, p.163]; 3.2 [36, p. 53]; 1-3.2 [41, p. 7]	n/a [1, p. 14]; 57-74% [37, p. 1]	
		Palm seed [1, p.	Glycerine,			1.3-1.6 [1, p. 23];	25-80% [1, p. 14];	

		14]	bunches [1, p. 14; 2, p. 27], fatty acids [18, p. 7], palm kernel cake pulp [15, p. 10, 11]			2.4-2.6 [41, p. 7]	38-79.5% [37, p. 1]; 20-80% [2, p. 16]	
		Sunflowers [1, p. 7]	Glycerine, fatty acids [18, p. 7] Protein meal [19]			0.76-4.5 [3, p.163]; 3 [62, p. 13]	> 55% [38, p. 2]	
		Animal fats, waste oil [1, p. 7]	Glycerine, fatty acids [18, p. 7]			4.85-5.88 [3, p. 163]; 5-6 [41, p. 7]	83% [40, p. 63]	
		Castor beans [15, p. 9]	Glycerine, fatty acids [18, p. 7], castor cake [20, p. 241, 244]			2.60 [42, p. 1]	90% [39]; 68.9% [42, p. 8]	
		Jatropha [15, p. 9]	Glycerine, fatty acids [18, p. 7], jatropha cake [20, p. 241]			1.4-4.7 [41, p. 7]; 2 [62, p. 13]	49-72% [37, p. 1]	
Biogas	Anaerobic digestion [2, p. 13, 28]	Maize, grass, crop wheat, organic waste, animal manure, sewage sludge [2, p.13, 28]	Organic fertilizer [2, p. 28]; biogas digestate [11, p. 5]	After upgrading: fully compatible with natural gas vehicles and fueling infrastructure [2, p. 47]	Natural gas [2, p.16]	2.2-10.2 [11, p. 1]; 1.4-4.8 [47, p. 203]	75-200% [43, p. 1]; 20-80% [2, p. 16]	Commercial [1, p. 12; 2, p. 12]
Advanced Biofuel Technologies (2nd, 3rd Generation)								
Cellulosic ethanol	Biochemical process. Hydrolysis + fermentation + distillation [1, p. 8; 2, p.13]	Lignocellulosic feedstock [2, p. 13]; agricultural residues [7, p. 6];	Lignin [1, p. 14; 2, p. 27] Syngas, hydrogen, carbon dioxide,	E10-E15 (E25 in Brazil) in conventional gasoline vehicles; E85-E100 in flexible-fuel or	Gasoline [2, p. 16]	4.4-6.6 [1, p. 23]; 0.38-0.48 [7, p. 112]; 5.4 [41, p. 7]; 4.40-6.61 [44, p. 2]	50-110% [1, p. 14]; 86.9-89.6% [7, p. 112]; 50-120% [2, p. 16]	Demo [1, p. 12; 2, p. 12]; Demo - Pre-Commercial [7, p.5]

	Thermochemical process: Gasification + mixed alcohol synthesis [7, p. 114]	Cotton stalks, husks and straw, canola straw, wheat straw, rice husks and straw, wild sugarcane bagasse, sugarcane bagasse, corn cobs, algarroba, spruce, waved old paper, thin paper, cellulose floccules, sweet sorghum bagasse, mustard residue, maize ear and cob, banana cellulosic residue [21, p. 625-626]	synthetic gasoline and diesel, lignin, succinic, lactic, acetic, fumaric acids, n-butenol, xylitol, furfural, benzene, toluene, xylene, cellulose nanofibers, polyhydroxyalkanoate, lignosulfanate, carbon fiber, high purity lignin, pentose C5 sugars, protein, biochar [22, p. 6]	ethanol vehicle [2, p. 47]		0.44-0.54 [7, p. 114]; 0.46 [33, p. 166]	91.2-92.8% [7, p. 114]	R&D - Demo [7, p.5]
	Hybrid process: Gasification + syngas fermentation [7, p. 113]					0.51-0.58 [7, p. 113]	96.1-96.5% [7, p. 113]	Demo [7, p. 5]
Advanced biodiesel	Biomass-to-liquid (BTL). Thermo-chemical process: Pre-treatment + gasification+ clean-up of syngas + FT [1, p. 8; 2, p. 13]	Forest residues [7, p. 116]; almost any type of biomass [23]; forest residues, wastes [24]	Low-temperature heat, pure CO2 [1, p. 14; 2, p. 28]	Fully compatible with existing vehicle and distribution infrastructure [2, p. 47]	Diesel, jet [49, p. 3; 2, p.16, 47; 24]	n/a [1, p. 23]; 0.43-0.52 [7, p. 116]	55-120% [1, p. 14]; 95.2-96% [7, p. 116]; 50-120% [2, p. 16]	Demo [1, p. 12; 2. p. 12]; R&D - Demo [7, p.5]
	HVO: Catalytic hydrogenation + cracking [1, p. 9; 2, p. 13]	Rape, palm, Jatropha oil [12, p. 129]; waste, residue fat fractions from food, fish and slaughterhouse industries, as well as from	Glycerine [1, p. 14; 2, p. 28]; naphtha, propane [25, p. 7]			n/a [1, p. 23]	15-84% [1, p. 14]; 10-80% [2, p. 16]	Pre-commercial [1, p. 12; 2, p. 12]

		non-food grade vegetable oil fractions [13, p. 3]						
	FAME: Oil extraction + transesterification [7, p. 6]	Micro-algae [7, p. 6]	Several [1, p. 14]; oil, protein, carbohydrates [26, p. 2]	After hydro treating: fully compatible with existing vehicle and distribution infrastructure [2, p. 47]		n/a [1, p. 23]; 0.92-0.93 [7, p. 119]; 0.01-7.01 [41, p. 7]	-50-65% [1, p. 14]; 60.6-61.1% [7, p. 119]; -50-65% [2, p. 16]	R&D [1, p. 12; 2, p. 12]
	Sugar-based hydrocarbons: Hydrolysis+ aqueous phase reforming of sugars [7, p. 6]	Agricultural residues [7, p. 118]	Lignin, acetate [27, p. 2]	Fully compatible with existing vehicle and distribution infrastructure [2, p. 47]		0.42-0.49 [7, p. 118]	70-73.8% [7, p. 118]	R&D [2, p. 12]
Bio-synthetic gas (bio-SG) (biomethane)	Thermal processes [2, p. 14]: Gasification+ purification of gas+ upgrading to methane [55, 56]	Any biomass fuel that can be gasified and cannot be broken down in traditional anaerobic digester plants, solid recovered fuels (SRF) [14, p. 1] virgin (woody) biomass, waste biomass (MSW and sludge) [54, p. 3825; 14, p. 1]	Pure CO2 [2, p. 28]; heat [28, p. 44]	After upgrading: fully compatible with natural gas vehicles and fueling infrastructure [2, p. 47]; can be used in natural gas vehicles (NGV) [2, p. 14]	Natural gas [2, p.16]	3.6-5.5 [6, p. 22]; 7-10 [10, p. 75]	90% [45]; 30-90% [2, p. 16]	Demo [1, p. 12; 2, p. 12]
Biomethanol	Pretreatment + gasification to syngas + removing of impurities and contaminants +	Biomass, waste and by-products from various sectors, such as biogas from	Electricity, heat, hydrogen, bio-ethanol, urea [29, p. 11]	10%-20% blends in gasoline; blends up to 85% in flexible-fuel vehicles [2, p. 47]	Petro-chemical methanol, ethylene, propylene, gasoline, diesel	0.50-0.60 [29, p. 11]; 0.55-0.61 [7, p. 115];	24-40% [29, p. 12]; 93.4-94.1% [7, p. 115]	Pre-commercial [1, p. 12; 2, p. 12]

	optimization of composition + catalytical conversion to methanol + distillation [29, p. 6]	landfill, sewage, solid waste treatment, glycerin (glycerol) from biodiesel production, and black liquor from the pulp and paper industry [29, p. 5]			[29, p. 16]			
Biobutanol	Biological and chemical conversion of sugars into alkanes [1, p. 10]	Lignocellulosic biomass [1, p. 10]; agricultural residues, crop biomass, non-food crop biomass, wood-based biomass, industrial by-products, biodegradable municipal waste [46, p. 61]	Solvents, coatings, fibers [30]; acetone, DDGS, ethanol, fatty acids, hydrogen [31, p. 22]	Use in gasoline vehicles in blends up to 85% [2, p. 47]; can be blended with gasoline or diesel fuel without the need for retrofitting of vehicle [46, p. 59]	Gasoline [2, p. 16], diesel [46, p. 59]	<1 [47, p. 203]	32-48% [46, p. 64]; -30-110% [2, p.16]	Demo [1, p. 12; 2, p. 12]
Bio Dimethyl ether (DME)	Conversion of biogas into methanol + distillation + dehydration using zeolite catalysts [1, p. 10]	Forest residues [7, p. 115]	Electricity [33, p. 44]	In diesel engines [1, p. 10]; compatible with liquefied petroleum gas (LPG) infrastructure [1, p. 10; 2, p. 47]	Diesel [32]	0.45 [33, p. 166]	95% [34, p. 2]	Demo [1, p. 12; 2, p. 12]; Demo - Pre-commercial [7, p. 5]
Pyrolysis-based	Fast pyrolysis. Low-temperature gasification in the absence of oxygen + quick cooling [1, p.	Forest residues [7, p. 117]	Exscess solids (biochar), fuel gas (CO4/CO mixture), steam [48, p. 6, 25]	More data on the composition of these fuels will be required in order to assess any	Diesel [1, p. 9]; gasoline [48, p. 1]; jet [49, p. 6]	0.57-0.65 [7, p. 117]; 5 [10, p. 75]	74.6-77.9% [7, p. 117]	Demo [1, p. 12; 2, p. 12]; R&D - Demo [7, p. 5]

	9]			possible limit on blend level. For widespread application, biodiesel blending is limited to 20% volume due to lack of engine manufacturer approval and limited data on compatibility with infrastructure for higher blends. [49, p. 30]					
Hydrogen	Thermochemical processes: - gasification and steam gasification - supercritical water gasification - pyrolysis - steam reforming of bio-oils - partial oxidation - cracking. [61, p. 13064; 51, p. 7418; 60, p. 12; 50, p. 3]	Bio-nut shell, olive husk, tea waste, crop straw, black liquor, municipal solid waste, crop grain residue, pulp and paper waste, petroleum basis plastic waste, manure slurry [51, p. 7418]; rice husk, rubber seed shell, sawdust, coconut shell, coffee husk [52, p. 988]; microalgae, purple, fermentative, photosynthetic, methanogenic bacteria, cyanobacteria	Carbon monoxide, carbon dioxide, methane, acetylene, ethylene, benzene, toluene, xylene, light tars, heavy tars, ammonia, water, solvents, acide, electricity, heat, FT diesel, SNG [51, p. 7421]	-	-	0.52 [51, p. 7418]	35-60% [53, p. 6]; 52-57% [59, p. 2684]	R&D - Demo for gasification with reforming [1, p. 12; 2, p. 12]
	Biological processes: - direct and indirect biophotolysis of water - high-yield dark-fermentation - photo-fermentation - water gas shift reaction - two-phase H2 + CH4 fermentations			-	-	0.56 [50, p. 2]		Demo for steam reforming from methanol and ethanol [1, p. 12; 2, p. 12]

	- steam reforming of bioethanol or methanol. [61, p. 13064; 51, p. 7418; 60, p. 12; 50, p. 3]	[60, p. 12]							

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Appendix 2 Wholesale electricity prices in Brazil (based on CCEE 2017)

	Pesado SE	Médio SE	Leve SE	Pesado S	Médio S	Leve S	Pesado NE	Médio NE	Leve NE	Pesado N	Médio N	Leve N	Average for month	Average for month in euro	Exchange rate euro per BRL
JANUARY 2010	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	5,0432	0,394
	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8			
	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8			
	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8			
FEBRUARY 2010	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	13,188125	5,235685625	0,397
	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8	12,8			
	12,8	12,8	12,8	12,8	12,8	12,8	14,84	14,84	14,84	12,8	12,8	12,8			
	12,8	12,8	12,8	12,8	12,8	12,8	16,97	16,97	16,97	12,8	12,8	12,8			
MARCH 2010	33,29	31,34	23,28	33,29	31,34	23,28	34,81	34,56	34,56	33,29	31,34	23,28	26,609167	10,96297667	0,412
	17,7	17,57	12,8	17,7	17,57	12,8	20,89	20,89	20,89	17,7	17,57	12,8			
	25,99	25,7	12,8	25,99	25,7	12,8	25,99	25,7	25,55	25,99	25,7	12,8			
	36,72	36,17	35,05	36,72	36,17	35,05	36,67	36,17	35,38	36,67	36,17	35,05			
APRIL 2010	38,83	38,19	37,15	38,83	38,19	37,15	38,83	38,19	38,19	38,83	38,19	37,15	24,678	10,438794	0,423
	26,76	26,09	12,8	26,76	26,09	12,8	26,76	26,58	26,58	26,76	26,09	12,8			
	12,8	12,8	12,8	12,8	12,8	12,8	20,63	20,63	20,63	12,8	12,8	12,8			
	24,81	24,47	23,26	24,81	24,47	23,26	24,62	24,47	23,48	24,62	24,47	23,26			
	24	23,67	22,09	24	23,67	22,09	23,67	23,67	22,71	23,67	23,67	22,09			
MAY 2010	25,16	24,87	22,35	25,16	24,87	13,46	25,16	25,01	25,01	25,16	24,87	22,35	29,895	13,123905	0,439
	30,27	29,69	22,87	30,27	29,69	12,8	30,6	30,6	30,6	30,27	29,69	22,87			
	33,77	33,05	32,43	33,77	33,05	32,43	34,48	34,48	34,48	33,77	33,05	32,43			
	36,25	35,22	34,49	36,25	35,22	27,9	36,25	36,25	36,25	36,25	35,22	34,57			
JUNE 2010	58,07	56,44	56,07	58,07	56,44	56,07	58,07	56,44	56,07	58,07	56,44	56,07	60,8275	27,5548575	0,453
	61,38	60,86	59,9	61,38	60,86	59,9	61,38	60,86	59,9	61,38	60,86	59,9			
	60,48	59,88	59,49	60,48	59,88	59,49	60,48	59,88	59,49	60,48	59,88	59,49			
	66,05	65,88	65,43	66,05	65,88	65,43	66,05	65,88	65,43	66,05	65,88	65,43			
JULY 2010	103,36	100,61	99,67	103,36	100,61	99,67	110,68	110,68	110,68	110,68	110,68	110,68	95,498167	42,30568783	0,443
	104,59	102,75	102,29	104,59	102,75	102,29	104,59	102,75	102,75	104,59	102,75	102,75			
	100,03	96,26	95	100,03	96,26	95	100,03	98,5	98,5	100,03	98,5	98,5			
	86,6	81,64	78,15	86,6	81,64	78,15	94,51	94,51	94,51	94,51	94,51	94,51			
	79,16	73,16	71,36	79,16	73,15	71,36	89,21	89,21	89,21	89,21	89,21	89,21			
AUGUST 2010	107,23	105,3	104,64	107,23	105,3	104,64	107,23	105,49	105,49	107,23	105,49	105,49	118,67	52,33347	0,441
	128,74	125,39	124,16	128,74	125,39	124,16	128,74	125,39	125,39	128,74	125,39	125,39			
	120,23	118,18	114,95	120,23	118,18	114,95	120,23	118,18	118,18	120,23	118,18	118,18			
	125,73	123,77	122,27	125,73	123,77	122,27	125,73	123,77	123,77	125,73	123,77	123,57			
SEPTEMBER 2010	111,4	105,87	104,53	111,4	105,87	104,52	154,88	154,88	154,88	154,88	154,88	154,88	147,01104	65,41991354	0,445
	137,6	125,78	124,43	128,26	125,78	124,43	174,53	174,53	174,53	174,53	174,53	174,53			
	122,46	117,3	115,68	122,46	117,3	115,68	172,78	171,65	171,65	172,78	171,65	171,65			
	139,53	132,52	130,72	134,59	132,52	130,72	187,76	187,76	187,76	187,76	187,76	187,76			

OCTOBER 2010	170,74	168,95	167,47	170,74	168,95	167,47	246,32	246,32	246,32	246,32	246,32	246,32	191,692	81,852484	0,427
	149,09	142,04	135,97	149,09	142,04	135,97	221,61	221,61	221,61	221,61	221,61	221,61			
	124,99	117,78	112,7	124,99	117,78	112,7	181,54	180,34	180,34	181,54	180,34	180,34			
	146,88	144,62	140,34	146,88	144,62	140,34	257,54	257,54	257,54	257,54	257,54	257,54			
	145,43	145,38	140,62	145,43	145,38	140,62	294,33	292,4	292,4	294,33	292,4	292,4			
NOVEMBER 2010	149,48	149,03	147,15	149,48	149,03	147,15	149,48	149,03	147,15	149,48	149,03	147,15	124,19646	53,15608417	0,428
	121,71	121,71	117,68	121,71	121,71	117,68	121,71	117,68	117,68	121,71	121,71	117,68			
	128,58	127,22	125,45	128,58	127,22	125,45	128,58	125,45	125,45	128,58	127,22	125,45			
	103,41	103,41	98,34	103,41	103,41	98,34	103,41	98,15	98,15	103,41	103,41	98,34			
DECEMBER 2010	81,79	81,79	77,56	81,79	81,79	77,56	81,79	77,56	77,56	81,79	81,79	77,56	72,339333	32,26334267	0,446
	92,88	92,88	84,74	92,88	92,88	84,74	83	82,34	82,34	92,88	92,88	84,74			
	78,04	77,21	72	78,04	77,21	72	78,04	72	72	78,04	77,21	72			
	66,99	64,68	61,98	66,99	64,68	61,98	66,99	61,98	61,98	66,99	64,68	61,98			
	55,09	53,87	52,44	55,09	53,87	52,44	55,09	53,43	52,44	55,09	53,87	52,44			
JANUARY 2011	71,81	70,08	67,24	71,81	70,08	67,24	71,81	70,08	67,24	71,81	70,08	67,24	29,778333	13,310915	0,447
	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08			
	15,81	15,81	14,97	15,81	15,81	14,97	15,6	15,6	14,97	15,6	15,6	14,97			
	22,16	22,14	21,29	22,16	22,14	21,29	22,16	22,14	21,29	22,16	22,14	21,29			
FEBRUARY 2011	17,44	17,44	12,08	17,44	17,44	12,08	23,27	23,27	23,27	17,44	17,44	12,08	42,165208	18,51052646	0,439
	38,35	38,35	36,79	38,35	38,35	36,79	38,35	38,35	36,79	38,35	38,35	36,79			
	54,91	54,91	52,67	54,65	54,91	51,43	54,91	54,91	52,67	54,91	54,91	52,67			
	66,88	64,23	60,88	66,88	64,23	12,08	63,47	63,47	60,88	63,47	63,47	60,88			
MARCH 2011	81,16	81,06	77,47	81,16	81,06	12,08	80,75	79,78	77,47	80,75	79,78	77,47	30,989792	13,32561042	0,43
	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08			
	25,67	24,46	18,77	25,67	24,46	18,77	29,13	29,13	29,13	25,67	24,46	18,77			
	13,72	13,47	12,08	13,72	13,47	12,08	13,72	13,47	13,47	13,72	13,47	12,08			
APRIL 2011	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	5,27896	0,437
	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08			
	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08			
	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08			
	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08	12,08			
MAY 2011	15,94	15,62	15,31	15,94	15,62	15,31	15,94	15,62	15,38	15,94	15,62	15,31	15,536458	6,727286458	0,433
	14,32	13,91	13,54	14,32	13,91	13,54	13,79	13,79	13,54	13,78	13,78	13,54			
	15,91	15,64	15,11	15,91	15,64	15,11	15,91	15,64	15,11	15,91	15,64	15,11			
	17,46	17,09	16,9	17,46	17,09	16,9	17,46	17,09	16,9	17,46	17,09	16,9			
JUNE 2011	30,46	29,96	29,96	30,46	29,96	29,96	30,46	29,81	28,6	30,46	29,81	28,6	31,663667	13,83702233	0,437
	33,25	32,74	32,73	33,25	32,74	32,73	33,25	32,74	32,73	33,25	32,74	32,73			
	35,72	35,01	34,63	35,72	35,01	34,63	35,72	35,01	34,63	35,72	35,01	34,63			
	30,59	29,78	29,23	30,59	29,78	29,23	30,59	29,78	29,23	30,59	29,78	29,23			
	31,22	30,73	29,7	31,22	30,73	29,7	31,22	30,73	29,7	31,22	30,73	29,7			
JULY 2011	28,23	27,88	27,48	28,23	27,88	27,48	28,23	27,88	27,48	28,23	27,88	27,48	22,978125	10,27122188	0,447
	23,75	23,14	22,96	23,75	23,14	22,96	23,75	23,14	22,97	23,75	23,14	22,97			
	21,8	20,92	20,79	21,8	20,92	20,79	21,8	20,92	20,79	21,8	20,92	20,79			
	20,26	19,43	18,8	20,26	19,43	18,8	20,26	19,43	19,4	20,26	19,43	19,37			

AUGUST 2011	24,21	23,81	22,98	22,71	22,71	12,08	24,21	23,81	22,98	24,21	23,81	22,98	19,737083	8,625105417	0,437
	16,97	16,35	15,68	16,97	12,08	12,08	16,97	16,35	15,68	16,97	16,35	15,68			
	18,68	18,09	17,34	18,68	18,09	12,08	18,68	18,09	17,34	18,68	18,09	17,34			
	25,08	24,4	23,41	23,41	23,41	12,08	25,08	24,4	23,41	25,08	24,4	23,41			
SEPTEMBER 2011	17,6	16,77	15,9	12,08	12,08	12,08	17,6	16,77	16,09	17,6	16,77	16,09	19,690667	8,250389333	0,419
	18,07	17,47	16,73	12,08	12,08	12,08	18,07	17,47	16,73	18,07	17,47	16,73			
	21,44	21,01	20,25	20,25	20,25	12,08	21,44	21,01	20,25	21,44	21,01	20,25			
	24,84	23,8	22,83	24,84	23,8	12,08	24,84	23,8	22,83	24,84	23,8	22,83			
	25,76	24,8	23,61	25,76	24,8	12,08	25,76	24,8	23,61	25,76	24,8	23,61			
OCTOBER 2011	44,03	43,42	41,99	44,03	43,42	41,55	44,03	43,42	41,99	44,03	43,42	41,99	37,138958	15,30125083	0,412
	44,1	43,29	42,75	43,14	42,94	42,75	44,1	43,29	42,75	44,1	43,29	42,75			
	39,14	38,92	37,48	39,14	38,92	37,48	39,14	38,92	37,54	39,14	38,92	37,48			
	24,1	23,92	22,95	24,1	23,92	22,95	24,1	23,92	22,95	24,1	23,92	22,95			
NOVEMBER 2011	39,32	38,44	37,73	39,32	38,44	37,73	39,32	38,44	37,73	39,32	38,44	37,73	41,705625	17,22442313	0,413
	44,03	44,03	42,94	44,03	44,03	42,94	44,03	44,03	42,94	44,03	44,03	42,94			
	40,41	39,72	39,01	40,41	39,72	39	40,41	39,72	39,01	40,41	39,72	39,01			
	45,45	45,45	43,94	45,45	45,45	43,94	45,45	45,45	43,94	45,45	45,45	43,94			
DECEMBER 2011	64,74	64,47	61,97	64,74	64,47	61,97	64,74	64,47	61,97	64,74	64,47	61,97	44,709	18,464817	0,413
	52,45	52,45	49,68	52,45	52,45	49,68	52,45	52,45	49,68	52,45	52,45	49,68			
	35,72	35,72	34,08	35,72	35,72	34,08	32,27	28,96	27,54	32,27	28,96	27,54			
	45,73	45,7	44,38	45,73	45,7	44,38	38,66	34,68	34,51	38,66	34,68	34,51			
	40,76	40,48	39,71	40,76	40,48	39,71	32,21	29,32	29,32	32,21	29,32	29,32			
JANUARY 2012	47,73	47,47	45,31	47,73	47,47	45,31	47,73	12,2	12,2	47,73	12,2	12,2	20,149583	8,70462	0,432
	29,69	29,69	28,57	29,69	29,69	28,57	12,2	12,2	12,2	12,2	12,2	12,2			
	12,2	12,2	12,2	12,2	12,2	12,2	12,2	12,2	12,2	12,2	12,2	12,2			
	12,2	12,2	12,2	12,2	12,2	12,2	12,2	12,2	12,2	12,2	12,2	12,2			
FEBRUARY 2012	17,57	17,57	12,2	17,57	17,57	12,2	12,2	12,2	12,2	12,2	12,2	12,2	30,176667	13,27773333	0,44
	37,7	37,7	35,45	37,7	37,7	35,45	12,2	12,2	12,2	12,2	12,2	12,2			
	55,85	55,85	53,86	55,85	55,85	53,86	12,2	12,2	12,2	12,2	12,2	12,2			
	63,2	63,2	62,2	63,2	63,2	62,2	12,2	12,2	12,2	12,2	12,2	12,2			
	69,25	68,26	65,99	69,25	68,26	65,99	14,35	14,35	14,35	14,35	14,35	14,35			
MARCH 2012	98,47	98,46	94,84	98,47	98,46	94,84	86,52	86,52	86,52	86,52	86,52	86,52	120,51792	50,97907875	0,423
	139,24	139,24	133,72	139,24	139,24	133,72	117,08	117,08	116,31	117,08	117,08	116,31			
	142,26	141,05	139,53	142,26	141,05	139,53	119,74	119,42	118,63	119,74	119,42	118,63			
	134,91	133,48	130,51	134,91	133,48	130,51	134,91	133,48	130,51	134,91	133,48	130,51			
APRIL 2012	187,82	185,44	185,44	187,82	185,44	185,44	174,02	168,63	166,95	174,02	168,63	166,95	189,3175	77,620175	0,41
	201,95	194,07	186,15	201,95	201,95	186,15	189,58	187,38	186,15	189,58	187,38	186,15			
	210,35	204,01	196,83	219	219	196,83	184,26	181,42	179,13	184,26	181,42	179,13			
	197,19	192,76	189,19	197,19	192,76	189,19	197,19	192,76	189,19	197,19	192,76	189,19			
MAY 2012	190,83	188,96	188,82	190,83	188,96	188,82	187,83	187,83	180,2	187,83	187,83	180,2	182,28292	71,81946917	0,394
	181,05	180,2	179,28	181,05	180,2	179,28	181,05	180,2	179,28	181,05	180,2	179,28			
	171,67	171,66	168,5	171,67	171,66	168,5	171,67	171,66	168,5	171,67	171,66	168,5			
	191,92	191,89	188,99	191,92	191,89	188,99	191,92	191,89	188,99	191,92	191,89	188,99			

JUNE 2012	179,19	177,49	176,42	179,19	177,49	176,42	179,19	177,49	176,42	179,19	177,49	176,42	130,91867	50,92736133	0,389
	148,61	146,92	146,19	148,61	146,92	146,19	148,61	146,92	146,19	148,61	146,92	146,19			
	151,79	148,19	146,14	151,79	148,19	146,14	151,79	148,19	146,14	151,79	148,19	146,14			
	105,79	103,46	101,16	105,79	103,46	101,16	105,79	103,46	101,16	105,79	103,46	101,16			
	79,39	78,25	74,33	79,39	78,25	74,33	79,39	78,25	76,17	79,39	78,25	74,33			
JULY 2012	58,5	56,86	54,83	58,5	56,85	54,83	58,5	56,86	54,83	58,5	56,86	54,83	90,898125	36,45014813	0,401
	97,67	95,32	94,11	97,67	95,32	94,11	97,67	95,32	94,11	97,67	95,32	94,11			
	108,4	106,31	106,01	108,4	106,31	106,01	108,4	106,31	106,01	108,4	106,31	106,01			
	105,55	103,85	103,37	105,55	103,85	103,37	105,55	103,85	103,37	105,55	103,85	103,37			
AUGUST 2012	90,43	88,78	87,12	90,43	88,78	87,12	90,43	88,78	87,12	90,43	88,78	87,12	116,099	46,207402	0,398
	109,88	106,77	105,35	109,88	106,77	105,35	109,88	106,77	105,35	109,88	106,77	105,35			
	118,43	116,3	115,67	118,43	116,3	115,67	118,43	116,3	115,67	118,43	116,3	115,67			
	131,1	128,8	128,01	130	128,8	128,01	131,1	128,8	128,01	131,1	128,8	128,01			
	140,37	137,74	137,01	140,37	137,74	137,01	140,37	137,74	137,01	140,37	137,74	137,01			
SEPTEMBER 2012	177,64	173,66	173,5	177,64	173,66	173,5	177,64	173,66	173,5	177,64	173,66	173,5	183,88417	70,61152	0,384
	185,38	181,24	180,47	185,38	181,24	180,47	185,38	181,24	180,47	185,38	181,24	180,47			
	191,61	191	188,6	191,61	191	188,6	191,61	191	188,6	191,61	191	188,6			
	189,56	188,15	185,8	189,56	188,15	185,8	189,56	188,15	185,8	189,56	188,15	185,8			
OCTOBER 2012	185,24	184,02	173,98	185,24	184,02	173,98	185,24	184,02	184,02	185,24	184,02	184,02	267,1975	101,53505	0,38
	249,78	244,58	240,08	249,78	244,58	240,08	256,3	256,3	256,3	256,3	256,3	256,3			
	325,06	323,85	319,75	325,06	323,85	319,75	329,04	329,04	329,04	329,04	329,04	329,04			
	291,4	289,92	284,61	291,4	289,92	284,61	330,39	330,39	330,39	330,39	330,39	330,39			
NOVEMBER 2012	364,61	362,76	360,38	364,61	362,76	360,38	364,61	362,76	360,38	364,61	362,76	360,38	373,868	141,322104	0,378
	429,85	429,85	427,54	429,85	429,85	427,54	429,85	429,85	427,54	429,85	429,85	427,54			
	453,51	453,51	449,61	453,51	453,51	449,61	453,51	453,51	449,61	453,51	453,51	449,61			
	315,56	315,56	314,35	315,56	315,56	314,35	315,56	315,56	314,35	315,56	315,56	314,35			
	311,76	311,76	307,41	311,76	311,76	307,41	311,76	311,76	307,41	311,76	311,76	307,41			
DECEMBER 2012	205,96	205,96	198,54	205,96	205,96	198,54	205,96	205,96	198,54	205,96	205,96	198,54	248,91417	91,102585	0,366
	275,47	275,47	264,94	275,47	275,47	264,94	275,47	275,47	264,94	275,47	275,47	264,94			
	188,67	187,63	179,69	188,67	187,63	179,69	188,67	187,31	179,69	188,67	187,31	179,69			
	349,93	343,85	341,57	349,93	343,85	341,57	349,93	312,16	312,16	349,93	312,16	312,16			
JANUARY 2013	348,22	343,19	338,63	348,22	343,19	338,63	348,22	343,19	338,63	348,22	343,19	338,63	428,9975	158,729075	0,37
	554,82	554,82	554,82	554,82	554,82	554,82	554,82	554,82	546,18	554,82	554,82	546,18			
	341,7	341,7	336,55	341,7	341,7	336,55	341,7	341,7	336,55	341,7	341,7	336,55			
	480,62	480,62	478,43	480,62	480,62	478,43	480,62	480,62	474,77	480,62	480,62	474,77			
FEBRUARY 2013	312,87	312,87	298,14	312,87	312,87	298,14	292,78	291,47	289,55	292,78	291,47	289,55	210,98083	79,96173583	0,379
	176,85	176,85	171,72	176,85	176,85	171,72	176,85	176,85	171,72	176,85	176,85	171,72			
	158,72	158,72	153,88	158,72	158,72	153,88	153,39	153,39	151,6	153,39	153,39	151,6			
	217,6	217,6	209,35	217,6	217,6	209,35	216,53	216,53	207,71	216,53	216,53	207,71			
MARCH 2013	317,48	315,92	306,3	317,48	315,92	306,3	317,48	315,92	306,3	317,48	315,92	306,3	337,666	131,014408	0,388
	376,87	376,87	368,69	376,87	376,87	368,69	376,87	376,4	365,69	376,87	376,4	365,69			
	344,5	344,5	337,57	344,5	344,5	337,57	344,5	344,5	336,93	344,5	344,5	336,93			
	340,15	340,15	336,68	340,15	340,15	336,68	340,15	340,15	336,68	340,15	340,15	336,68			
	321,76	321,49	316,99	321,76	321,49	316,99	321,76	321,49	321,49	321,76	321,49	316,99			

APRIL 2013	302,27	299,71	298,76	302,27	299,71	298,76	302,27	299,71	298,76	302,27	299,71	298,76	192,54625	73,93776	0,384
	191,98	190,62	186,05	191,98	190,62	186,05	191,98	190,62	187,92	191,98	190,62	186,05			
	152,86	151,45	147,86	152,86	151,45	147,86	152,86	151,47	150,46	152,86	151,45	147,86			
	129,78	129,38	126,38	129,78	129,38	126,38	133,31	133,31	128,25	129,78	129,38	126,38			
MAY 2013	282,03	279,27	275,05	282,03	279,27	275,05	282,03	280,45	276,09	282,03	279,27	275,05	338,17767	128,1693357	0,379
	343,51	342	339,57	343,51	342	339,57	343,51	342	339,57	343,51	342	339,57			
	360,6	357,33	354,26	360,6	357,33	354,26	360,6	357,33	354,26	360,6	357,33	354,26			
	360,17	356,8	348,98	360,17	356,8	348,98	360,17	356,8	348,98	360,17	356,8	348,98			
	361,81	357,29	353,44	361,81	357,29	353,44	361,81	357,29	353,44	361,81	357,29	353,44			
JUNE 2013	327,93	324,69	320,57	327,93	324,69	320,57	327,93	324,69	320,57	327,93	324,69	320,57	216,22146	75,46128896	0,349
	182,33	180,95	179,63	182,33	180,95	179,63	182,33	180,95	180,95	182,33	180,95	179,63			
	196,12	193,93	188,14	196,12	193,93	188,14	196,12	193,93	188,14	196,12	193,93	188,14			
	170,29	167,9	162,16	169,04	167,9	162,16	170,29	167,9	162,16	170,29	167,9	162,16			
JULY 2013	99,86	98,56	94,3	80,79	78,82	14,13	99,86	99,38	99,38	99,86	98,56	95,49	108,64917	36,94071667	0,34
	109,05	108,21	102,84	109,05	107,49	14,13	109,05	108,21	102,84	109,05	108,21	102,84			
	126,77	125,33	120,51	102,64	101,31	97,7	126,77	125,33	120,51	126,77	125,33	120,51			
	131,53	129,2	125,7	131,53	129,2	125,7	131,53	129,2	125,7	131,53	129,2	125,7			
AUGUST 2013	155,55	153,54	151,57	155,55	153,54	151,57	155,55	153,54	151,57	155,55	153,54	151,57	156,37783	50,1972845	0,321
	168,39	165,84	164,62	168,39	165,84	164,62	168,39	165,84	164,62	168,39	165,84	164,62			
	151,6	148,8	143,77	143,77	143,77	14,13	151,6	148,8	148,8	151,6	148,8	143,77			
	176,91	174,06	169,16	169,16	169,16	151,27	176,91	174,06	174,06	176,91	174,06	169,16			
	161,43	159,26	153,23	153,23	153,23	116,29	161,43	159,26	159,26	161,43	159,26	153,23			
SEPTEMBER 2013	263,68	259,04	255,16	255,16	255,16	244,48	263,68	259,04	255,16	263,68	259,04	255,16	266,51813	87,68446313	0,329
	276,13	273,97	264,93	265,51	264,93	255,64	276,13	273,97	264,93	276,13	273,97	264,93			
	278,22	276,54	271,58	278,22	276,54	271,58	278,22	276,54	271,58	278,22	276,54	271,58			
	271,87	266,13	250,1	252,58	250,1	242,06	272,51	272,51	272,51	272,51	272,51	272,51			
OCTOBER 2013	269,73	268,06	260,29	260,29	260,29	27,33	269,73	268,06	265,47	269,73	268,06	265,47	239,67458	80,29098542	0,335
	254,35	249,15	227,93	138,13	138,13	14,13	254,35	254,35	255,44	254,35	249,15	227,93			
	259,29	254,33	237,72	237,72	237,72	232,99	259,29	254,33	250,86	259,29	254,33	250,86			
	255,87	252,59	242,2	244,81	244,81	242,2	270,87	270,87	270,87	255,87	252,59	242,2			
NOVEMBER 2013	311,47	311,47	305,29	311,47	311,47	305,29	311,47	311,47	305,29	311,47	311,47	305,29	328,59867	106,1373693	0,323
	326,09	322,11	308,11	326,09	322,11	308,11	326,09	322,11	308,11	326,09	322,11	308,11			
	319,24	319,24	316,09	319,24	319,24	316,09	319,24	319,24	316,09	319,24	319,24	316,09			
	340,44	340,44	329,82	340,44	340,44	329,82	340,44	340,44	329,82	340,44	340,44	329,82			
	362,69	362,69	353,79	362,69	362,69	353,79	362,69	362,69	353,79	362,69	362,69	353,79			
DECEMBER 2013	313,81	313,81	302,28	313,81	313,81	302,28	313,81	313,81	302,28	313,81	313,81	302,28	297,79583	92,61450417	0,311
	280,78	280,78	270,33	280,78	280,78	270,33	280,78	280,78	280,78	280,78	280,78	270,33			
	310,55	310,55	303,81	310,55	310,55	303,81	310,55	310,55	307,2	310,55	310,55	303,81			
	294,91	294,54	293,94	294,91	294,54	293,94	294,91	294,54	293,94	294,91	294,54	293,94			
JANUARY 2014	249,92	249,92	249,92	249,92	249,92	249,92	249,92	249,92	249,92	249,92	249,92	249,92	361,18667	111,60668	0,309
	286,58	286,58	280,22	286,58	286,58	280,22	286,58	286,58	280,22	286,58	286,58	116,49			
	391,8	391,8	384,02	391,8	391,8	384,02	391,8	391,8	391,8	391,8	391,8	384,02			
	410,67	410,67	409,38	410,67	410,67	409,38	410,67	410,67	409,38	410,67	410,67	409,38			
	486,59	486,59	480,64	486,59	486,59	480,64	486,59	486,59	486,59	486,59	486,59	480,64			

FEBRUARY 2014	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	726,5125	223,0393375	0,307
	822,83	822,83	822,83	822,83	822,83	822,83	744,88	744,88	732,99	612,71	160,61	152,08			
	822,83	822,83	822,83	822,83	822,83	822,83	732,99	732,99	725,22	612,71	612,71	506,33			
	822,83	822,83	822,83	822,83	822,83	822,83	732,99	732,99	725,22	612,71	160,61	152,08			
MARCH 2014	822,83	822,83	822,83	822,83	822,83	822,83	634,86	625,25	625,25	634,86	612,71	119,8	773,19938	240,4650056	0,311
	822,83	822,83	822,83	822,83	822,83	822,83	725,25	725,25	725,25	725,25	725,25	612,71			
	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83			
	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83			
APRIL 2014	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	791,29813	256,3805925	0,324
	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	821,65	822,83	822,83	637,03			
	822,83	822,83	822,83	822,83	822,83	822,83	771,31	750,1	750,1	771,31	750,1	619,64			
	822,83	822,83	822,83	822,83	822,83	822,83	714,81	697,82	689,95	714,81	697,82	619,64			
MAY 2014	822,83	822,83	822,83	822,83	822,83	822,83	646,14	632,61	619,91	619,64	194,35	160,61	686,07067	225,0311787	0,328
	810,89	800,1	777,23	810,89	800,1	777,23	697,82	697,82	697,82	619,64	192,55	160,61			
	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	815,52	160,61	160,61	130,05			
	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	160,61	160,61	124,94			
	822,83	822,83	806,9	822,83	822,83	806,9	822,83	822,83	806,9	822,83	822,83	806,9			
JUNE 2014	597,66	591,81	551,09	597,66	591,81	551,09	595,23	591,81	551,09	595,23	591,81	551,09	383,51521	126,1765035	0,329
	336,95	333,8	237,76	272,25	252,99	154,57	336,95	333,8	237,76	336,95	333,8	237,76			
	427,41	420,29	335,59	15,62	15,62	15,62	427,41	420,29	335,59	427,41	420,29	335,59			
	511,89	503,7	314,63	176,67	176,67	105,28	511,89	503,7	314,63	511,89	503,7	314,63			
JULY 2014	400,74	398,95	314,63	15,62	15,62	15,62	400,74	398,95	314,63	400,74	398,95	314,63	539,47688	179,1063225	0,332
	560,82	548,68	535,31	548,68	548,68	15,62	560,82	548,68	535,31	560,82	548,68	535,31			
	680,06	670,92	613,57	670,92	670,92	613,57	680,06	670,92	613,57	680,06	670,92	613,57			
	734,87	731,08	686,2	734,87	731,08	686,2	734,87	731,08	686,2	734,87	731,08	686,2			
AUGUST 2014	593,73	583,01	576,78	593,73	583,01	576,78	593,73	583,01	576,78	593,73	583,01	576,78	687,916	227,700196	0,331
	817,53	815,92	797,56	817,53	815,92	797,56	817,53	815,92	797,56	817,53	815,92	797,56			
	658,5	652,35	643,96	658,5	652,35	643,96	658,5	652,35	643,96	658,5	652,35	643,96			
	702,27	702,27	688,35	702,27	702,27	688,35	702,27	702,27	688,35	702,27	702,27	688,35			
	700,76	700,76	684,99	700,76	700,76	684,99	700,76	700,76	684,99	700,76	700,76	684,99			
SEPTEMBER 2014	735,03	735,03	717,91	735,03	735,03	717,91	735,03	735,03	717,91	735,03	735,03	717,91	737,78667	245,68296	0,333
	711,89	711,89	688,25	711,89	711,89	688,25	711,89	711,89	688,25	711,89	711,89	688,25			
	778,34	778,34	757,1	778,34	778,34	757,1	778,34	778,34	757,1	778,34	778,34	757,1			
	752,54	751,91	735,21	752,54	751,91	735,21	752,54	751,91	735,21	752,54	751,91	735,21			
OCTOBER 2014	690,65	682,21	650,71	690,65	682,21	650,71	690,65	682,21	650,71	690,65	682,21	650,71	756,78367	243,6843407	0,322
	714,65	705,71	680,48	680,48	680,48	175,02	714,65	705,71	680,48	714,65	705,71	680,48			
	822,83	818,36	790,39	822,83	818,36	790,39	822,83	818,36	790,39	822,83	818,36	790,39			
	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83			
	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83			
NOVEMBER 2014	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	259,19145	0,315
	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83			
	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83			
	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83	822,83			

DECEMBER 2014	549,18	549,18	547,99	549,18	549,18	547,99	549,18	549,18	547,99	549,18	549,18	547,99	635,63917	195,1412242	0,307
	677,68	677,68	673,67	677,68	677,68	673,67	677,68	677,68	673,67	677,68	677,68	673,67			
	665,96	665,96	644,18	665,96	665,96	644,18	665,96	665,96	644,18	665,96	665,96	644,18			
	658,73	658,73	658,73	658,73	658,73	658,73	658,73	658,73	658,73	658,73	658,73	658,73			
JANUARY 2015	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	126,64448	0,326
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48			
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48			
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48			
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48			
FEBRUARY 2015	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	121,59424	0,313
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48			
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48			
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48			
MARCH 2015	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	386,47083	113,622425	0,294
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	366,24	366,24	336,52			
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48			
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48			
APRIL 2015	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	98,22	98,22	30,26	324,37467	98,60989867	0,304
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	98,22	98,22	81,17			
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	207,16	171,19			
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	118,6	117,13	98,01			
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	141,74	117,13	117,13			
MAY 2015	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	117,13	98,01	98,01	332,53933	97,766564	0,294
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	92,96	92,96	92,96			
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	170,37	140,79	112,13			
	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	388,48	171,19	171,19	136,34			
	379,7	374,07	364,49	379,7	374,07	364,49	379,7	374,07	364,49	379,7	374,07	364,49			
JUNE 2015	384,74	379,04	369,33	384,74	379,04	369,33	384,74	379,04	369,33	384,74	379,04	369,33	373,56	106,83816	0,286
	388,48	388,48	375,73	388,48	388,48	375,73	388,48	388,48	375,73	388,48	388,48	375,73			
	367,58	364,85	352,18	367,58	364,85	352,18	367,58	364,85	352,18	367,58	364,85	352,18			
	380,09	374,62	357,6	380,09	374,62	357,6	380,09	374,62	357,6	380,09	374,62	357,6			
JULY 2015	383,25	383,25	368,82	383,25	383,25	368,82	383,25	383,25	368,82	383,25	383,25	368,82	252,39717	71,42839817	0,283
	324,22	322,17	309,5	324,22	322,17	309,5	324,22	322,17	309,5	324,22	322,17	309,5			
	239,06	236,51	222,38	239,06	236,51	222,38	248,07	248,07	222,38	239,06	236,51	222,38			
	216,19	214,86	98,33	186,33	140,2	30,26	216,19	214,86	117,95	216,19	214,86	112,52			
	217,19	216,15	112,52	195,49	119,12	30,26	217,19	216,15	117,95	217,19	216,15	112,52			
AUGUST 2015	121,29	120,67	115,36	121,29	120,67	115,36	121,29	120,67	115,36	121,29	120,67	115,36	131,49083	33,79314417	0,257
	131,03	130,9	127,05	131,03	130,9	127,05	131,03	130,9	127,05	131,03	130,9	127,05			
	139,09	139,09	133,16	139,09	139,09	133,16	139,09	139,09	133,16	139,09	139,09	133,16			
	142,07	142,07	136,11	142,07	142,07	136,11	142,07	142,07	136,11	142,07	142,07	136,11			
SEPTEMBER 2015	279,03	279,01	267,9	279,03	279,01	267,9	279,03	279,01	267,9	279,03	279,01	267,9	236,47	54,15163	0,229
	251,46	250,06	240,36	251,46	250,06	240,36	251,46	250,06	240,36	251,46	250,06	240,36			
	203,46	203,46	193,63	203,46	203,46	193,63	203,46	203,46	193,63	203,46	203,46	193,63			
	227,07	224,05	218,15	227,07	224,05	218,15	227,07	224,05	218,15	227,07	224,05	218,15			

OCTOBER 2015	214,11	210,56	198,83	214,11	210,56	198,83	214,11	210,56	198,83	214,11	210,56	198,83	213,31567	49,06260333	0,23
	227,13	222,92	205,88	227,13	222,92	205,88	227,13	222,92	205,88	227,13	222,92	205,88			
	216,77	210,98	197,57	216,77	210,98	197,57	216,77	210,98	197,57	216,77	210,98	197,57			
	215,6	214,4	194,1	215,6	214,4	152,81	215,6	214,4	194,1	215,6	214,4	194,1			
	220,59	220,59	204,74	220,59	220,59	155,85	270,61	265,59	204,74	270,61	265,59	204,74			
NOVEMBER 2015	266,02	265,34	219,09	266,02	265,34	86,95	266,02	265,34	219,09	266,02	265,34	219,09	234,96375	57,8010825	0,246
	215,58	215,58	195,18	215,58	215,58	160,54	215,58	215,58	206,79	215,58	215,58	206,79			
	194,23	194,23	179,31	194,23	194,23	179,31	279,04	279,04	267,66	279,04	279,04	267,66			
	214,12	214,12	174,05	214,12	214,12	155,85	328	328	314,63	328	328	314,63			
DECEMBER 2015	153,84	153,84	141,86	153,84	153,84	141,86	376,66	376,66	361,3	196,62	196,62	196,62	187,16188	44,35736438	0,237
	140,31	140,31	123,83	140,31	140,31	123,83	328	328	314,63	161,17	159,42	159,42			
	114,93	114,93	101,63	114,93	114,93	69,37	314,63	314,63	301,8	175,7	175,7	175,7			
	149,43	145,44	132,45	149,43	145,44	102,99	205,36	205,36	196,99	205,36	205,36	188,18			
JANUARY 2016	53,19	52,33	48,15	53,19	52,33	48,15	353,05	343,56	343,56	109,12	109,12	109,12	119,38933	27,220768	0,228
	48,02	48,02	42,5	48,02	48,02	41,84	358,16	358,16	343,56	112,21	112,21	109,27			
	37,64	37,64	32,46	37,64	37,64	32,46	323,02	323,02	309,85	85,28	85,28	85,28			
	30,25	30,25	30,25	30,25	30,25	30,25	314,63	314,63	301,8	30,25	30,25	30,25			
	30,25	30,25	30,25	30,25	30,25	30,25	314,63	314,63	286,47	30,25	30,25	30,25			
FEBRUARY 2016	30,25	30,25	30,25	30,25	30,25	30,25	139,88	139,88	139,88	30,25	30,25	30,25	62,319792	14,14659271	0,227
	30,25	30,25	30,25	30,25	30,25	30,25	115,96	111,23	111,23	30,25	30,25	30,25			
	30,25	30,25	30,25	30,25	30,25	30,25	139,88	139,88	134,18	30,25	30,25	30,25			
	30,25	30,25	30,25	30,25	30,25	30,25	243,95	243,95	242,45	30,25	30,25	30,25			
MARCH 2016	33,25	33,25	30,25	33,25	33,25	30,25	223,17	223,17	223,17	33,25	33,25	30,25	88,068542	21,40065563	0,243
	54,3	54,3	47,76	54,3	54,3	47,76	243,95	243,95	234	54,3	54,3	47,76			
	31,31	30,65	30,25	31,31	30,65	30,25	263,16	263,16	252,43	31,31	30,65	30,25			
	30,25	30,25	30,25	30,25	30,25	30,25	253,08	253,08	242,76	30,25	30,25	30,25			
APRIL 2016	43,09	42,63	40,26	43,09	42,63	40,26	269,52	269,52	258,53	43,09	42,63	40,26	103,5395	25,677796	0,248
	44,77	43,77	41,71	44,77	43,77	41,71	280,98	280,98	269,52	44,77	43,77	41,71			
	49,97	48,24	46,5	49,97	48,24	46,5	279,64	279,64	268,24	49,97	48,24	46,5			
	53,68	51,98	50,42	53,68	51,98	50,42	267,46	267,46	256,55	53,68	51,98	50,42			
	54,72	51,41	49,38	54,72	51,41	49,38	279,64	279,64	267,46	54,72	51,41	49,38			
MAY 2016	89,7	86,99	84,7	89,7	86,99	84,7	103,2	103,2	103,2	89,7	87,82	87,49	85,249583	21,31239583	0,25
	84,25	81,43	77,73	84,25	81,43	77,73	99,79	99,79	99,79	84,25	81,86	81,86			
	79,53	76,46	70,19	79,53	76,46	64,77	99,79	99,79	99,79	79,53	76,46	76,21			
	77,64	74,96	70,62	77,64	74,96	70,62	99,79	99,79	99,79	80,72	78,11	77,28			
JUNE 2016	62,78	61,03	56,79	62,78	61,03	46,12	145,83	145,83	139,88	145,83	145,83	139,88	86,792917	22,47936542	0,259
	64,05	61,34	55,57	64,05	61,34	30,25	115,43	115,43	110,72	96,69	91,29	88,19			
	64,04	60,23	53,75	64,04	60,23	31,54	139,88	139,88	114,83	93,7	86,41	86,41			
	61,8	57,64	54,1	61,8	57,64	43,96	114,83	114,83	109,14	109,14	109,14	109,14			
JULY 2016	76,62	73,97	70,35	76,62	73,97	70,35	104,17	104,12	104,12	104,17	104,12	104,12	93,512667	25,809496	0,276
	85,93	83,1	79,62	85,93	83,1	79,62	104,12	104,12	79,62	86,41	86,41	79,62			
	90,06	87,05	83,87	90,06	87,05	83,87	108,93	108,93	108,88	108,93	108,93	108,88			
	85,06	80,51	77,64	85,06	80,51	77,64	113,56	113,56	108,93	113,56	113,56	108,93			
	81,71	78,47	74,45	81,71	78,47	74,45	119,01	119,01	113,6	119,01	119,01	113,6			

AUGUST 2016	120,99	119,01	114,5	120,99	119,01	114,5	120,99	119,01	114,5	120,99	119,01	114,5	118,92567	33,06133533	0,278
	122,29	118,29	114,78	122,29	118,29	114,78	122,29	118,29	114,78	122,29	118,29	114,78			
	119,09	117,09	112,47	119,09	117,09	112,47	119,09	117,09	112,47	119,09	117,09	112,47			
	102,75	95,68	90,36	102,75	95,68	90,36	115,15	115,15	105,75	115,15	115,15	105,75			
	150,96	148,65	126,11	150,96	148,65	75,05	150,96	148,65	126,11	150,96	148,65	126,11			
SEPTEMBER 2016	154,91	152,96	129,51	154,91	152,96	75,05	154,91	152,96	129,51	154,91	152,96	129,51	147,497	40,414178	0,274
	163,02	157,73	133,94	163,02	157,73	87,84	163,02	157,73	133,94	163,02	157,73	133,94			
	155,83	154,51	136,9	155,83	154,51	102,28	155,83	154,51	136,9	155,83	154,51	136,9			
	150,47	148,62	139,47	150,47	148,62	139,47	150,47	148,62	139,47	150,47	148,62	139,47			
	161,22	158,49	148,67	161,22	158,49	148,67	161,22	158,49	148,67	161,22	158,49	148,67			
OCTOBER 2016	217,84	216,18	207,74	217,84	216,18	207,74	217,84	216,18	207,74	217,84	216,18	207,74	204,45	57,85935	0,283
	217,27	217,27	210,48	217,27	217,27	210,48	217,27	217,27	210,48	217,27	217,27	210,48			
	195,75	195,75	189,23	195,75	195,75	189,23	195,75	195,75	189,23	195,75	195,75	189,23			
	168,7	168,7	160,74	168,7	168,7	160,74	168,7	168,7	160,74	168,7	168,7	160,74			
	235,97	235,97	229,16	235,97	235,97	229,16	235,97	235,97	229,16	235,97	235,97	229,16			
NOVEMBER 2016	181,53	181,32	174,71	181,53	181,32	174,71	181,53	181,32	174,71	181,53	181,32	174,71	171,88	47,61076	0,277
	186,33	186,33	180,54	186,33	186,33	180,54	186,33	186,33	180,54	186,33	186,33	180,54			
	171,59	171,59	167,7	171,59	171,59	167,7	171,59	171,59	167,7	171,59	171,59	167,7			
	155,42	155,42	150,08	155,42	155,42	150,08	155,42	155,42	150,08	155,42	155,42	150,08			
DECEMBER 2016	144,07	144,07	140,71	144,07	144,07	140,71	144,07	144,07	140,71	144,07	144,07	140,71	124,662	35,154684	0,282
	102,9	102,9	100,4	102,9	102,9	100,4	102,9	102,9	100,4	102,9	102,9	100,4			
	122,58	122,58	119,78	122,58	122,58	119,78	122,58	122,58	119,78	122,58	122,58	119,78			
	143,87	143,87	141,27	143,87	143,87	141,27	143,87	143,87	141,27	143,87	143,87	141,27			
	113,95	113,95	113,03	113,95	113,95	113,03	113,95	113,95	113,03	113,95	113,95	113,03			

year	Average for year in euro	Average for year in 2016 euro	CPI
2010	33,30753342	36,06206643	100
2011	12,42729402	13,05046677	103,1
2012	63,37977056	64,84104468	105,83
2013	91,76157722	92,48767423	107,42
2014	211,1004826	211,6086404	108,01
2015	81,30583252	81,5090971	108
2016	31,01228141	31,01228141	108,27
Total average for 2010-2016 in euro 2016			**75,79589586**

Appendix 3 Projections of future costs for corn feedstock and corn ethanol

World Bank corn prices for the world (Constant 2010=100)												Average growth by % for 5 years 2020-2025	Average growth by % for 5 years 2025-2030	Average growth by % for 5 years
year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2030	3,0488	2,3669	2,7078
USD 2010 per ton	170,0000	164,0000	163,0000	164,0000	164,0000	165,0000	166,0000	167,0000	168,0000	169,0000	173,0000			
% growth per year		-3,5294	-0,6098	0,6135	0,0000	0,6098	0,6061	0,6024	0,5988	0,5952	2,3669			

Own projection based on World Bank data													
	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2030	2035	2040
Feedstock cost, € per ton at harvest	128,9761	124,4240	123,6653	124,4240	124,4240	125,1827	125,9413	126,7000	127,4587	128,2174	131,2521	134,8062	138,4565
% growth per year		-3,5294	-0,6098	0,6135	0,0000	0,6098	0,6061	0,6024	0,5988	0,5952	2,3669	2,7078	2,7078

LCOF 2030/2040 projections			
	2016	2030	2040
Feedstock cost, € per ton at harvest	128,9761	131,2521	138,4565
LCOF, € per liter	0,3612	0,3667	0,3843
LCOF, € per MWh	55,9962	56,8569	59,5812

Appendix 4 Projections of future costs for sugarcane feedstock and sugarcane ethanol

World Bank sugar prices for the world (Constant 2010=100)												Average growth by % for 5 years 2020-2025	Average growth by % for 5 years 2025-2030	Average growth by % for 5 years
year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2030			
USD per kg	0,4200	0,3800	0,3700	0,3700	0,3600	0,3500	0,3500	0,3500	0,3400	0,3400	0,3100	-5,5556	-8,8235	-7,1895
% growth per year		-9,5238	-2,6316	0,0000	-2,7027	-2,7778	0,0000	0,0000	-2,8571	0,0000	-8,8235			

Own projection based on World Bank data													
	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2030	2035	2040
Feedstock cost, € per ton at harvest	21,4403	19,3983	18,8878	18,8878	18,3774	17,8669	17,8669	17,8669	17,3564	17,3564	15,8250	14,6872	13,6313
% growth per year		-9,5238	-2,6316	0,0000	-2,7027	-2,7778	0,0000	0,0000	-2,8571	0,0000	-8,8235	-7,1895	-7,1895

LCOF 2030/2040 projections			
	2016	2030	2040
Feedstock cost, € per ton at harvest	21,4403	15,8250	13,6313
LCOF, € per liter	0,2805	0,2075	0,1790
LCOF, € per MWh	43,4822	32,1758	27,7589