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**UNIVERSIDADE ESTADUAL DE CAMPINAS**
Faculdade de Engenharia Mecânica

**PEDRO GERBER MACHADO**

# *Sustainable development potentials and pathways for biobased economy options: an integrated approach on land use, energy systems, economy and greenhouse gases emissions.*

# *Potenciais de desenvolvimento sustentável e caminhos para opções de economia biobased: uma abordagem integrada sobre o uso da terra, sistemas de energia, economia e emissões de gases de efeito estufa.*

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**TESE DE DOUTORADO**

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# RESUMO

Os combustíveis fósseis dominam a oferta atual de energia e produtos químicos e isso leva a um rápido crescimento das emissões globais de gases de efeito estufa (GEE). Uma opção de mitigação é usar matéria-prima renovável para materiais, produtos químicos e principalmente energia. Este estudo desenvolve e demonstra uma estrutura de modelagem interligando os modelos de Equilíbrio Geral Computacional e Insumo-produto, que permitem analisar os impactos sobre aspectos macro e socioeconômicos, emissões de GEE e uso de energia não renovável, de forma integrada para diferentes cenários futuros de implantação da economia baseada em biomassa. A análise foi feita para os produtos químicos e para bioenergia. Três cenários para o ano de 2030 foram comparar os diferentes níveis de produção (quantidade de produtos químicos e produção de energia através de fósseis versus biomassa) para o Brasil, com base na cana-de-açúcar, soja e florestas (eucalipto e pinus). Diferentes níveis tecnológicos também são considerados nesta tese. Dois importantes aspectos metodológicos desta tese são o apoio financeiro fornecido pelo governo para permitir que a bioeconomia se desenvolva, por meio de subsídios, e as limitações de uso da terra estabelecidas pela necessidade de reduzir as emissões. Os resultados mostram que a escolha de uma bioeconomia no Brasil gera uma ligeira redução do PIB devido a mudanças nas componentes de demanda final que a integram (Casa, governo, exportações e importações), de 0,067% no BBE 1 para 0,43% no BBE 2 O consumo do governo cai 1,4% no BBE 2 e, considerando que o consumo do governo está voltado para os serviços públicos, a queda no consumo do governo se traduz diretamente na redução da oferta de serviços públicos para a sociedade brasileira. Após o consumo do governo vem os investimentos, que cai após uma queda na poupança externa. Com a diminuição das importações, focada em matéria-prima fóssil e produtos fósseis, o Brasil reduziria sua dependência de matérias-primas e insumos estrangeiros em um cenário de bioeconomia. As mudanças no emprego vêm com a redução geral da atividade econômica, concentrada especialmente no setor público. Aumentos na taxa de desemprego de 3,87 para 3,92% em BBE 1 e 3,96% em BBE 2 são projetados. O aumento da demanda de terra impõe um aumento no preço da terra de 23% no BBE 1 e de 32% no BBE 2. Esses aumentos têm impactos nos preços de produtos que dependem da terra (agricultura), que afeta negativamente o consumo de alimentos das famílias Focada em atender produtos (bovinos, suínos e aves). No nível regional, são percebidos diferentes resultados. Quando se trata de emissões, o Brasil está empenhado em atingir 1,2 GtCO2-eq em 2030, com vários mecanismos estabelecidos na iNDC. O cenário referência, que tenta incorporar o mais próximo possível as ações propostas na iNDC, mostra que as emissões atingem 1,7 GtCO2-eq e que uma bioeconomia poderia reduzir 1% dessas emissões no cenário atual. As emissões mostram que se deve prestar muito mais atenção à mudança de uso da terra e ao setor florestal. A energia renovável tem um papel importante na redução das emissões, em qualquer cenário. O aumento de 202 para 235 e para 249 x106 tep em energia renovável nos cenários BBE é um passo importante para a independência energética e para preservar as reservas fósseis. Os processos nos biosse- tores, no entanto, não são ainda mais eficientes, uma vez que o uso total de energia passa de 481 x 106 tep no cenário BAU para 509 x106 tep no cenário BBE 2.



Palavras-chave: Bioeconomia, sustentabilidade, modelo de equilíbrio geral computável, modelo de insumo-produto, emissões de GEE.

# ABSTRACT

Fossil fuels dominate the current energy and chemicals' supply and this leads to a rapid growth in global greenhouse gas (GHG) emissions. One mitigation option is using renewable feedstock for materials, chemicals and mostly energy. This study develops and demonstrates a modelling framework interlinking Computable General Equilibrium and Input-Output models, which allow the analysis of the impacts on macro and socioeconomic aspects, GHG emissions and non-renewable energy use, in an integrated way for different future scenarios for deployment of biobased economy. The analysis was done for chemicals and for energy carriers. Three scenarios for 2030 were used to compare different levels of production (amount of chemicals and energy production through fossils versus biomass) for Brazil, based on sugarcane, soy and forest crops (eucalyptus and pine). Different technological levels are also considered in this thesis. Two important methodological aspects of this thesis are the financial support provided by the government to enable the bioeconomy to develop, through subsidies, and the limitations in land use established by the need to reduce emissions. Results show that the choice of a bioeconomy in Brazil generates a slight reduction in GDP due to changes in the components of final demand that integrate it (Household, government, exports and imports), from 0.067% in BBE 1 to 0.43% in BBE 2. Government consumption falls 1.4% in the BBE 2, and, considering that government consumption is focused on public services, the decrease in government consumption translates directly into reduction of public services provision to the Brazilian society. Following government consumption comes the investments, which drops following a drop in foreign savings. With decrease of imports, focused on fossil feedstock and fossil-based products, Brazil would reduce its dependency in foreign feedstocks and inputs in a bioeconomy scenario. Changes in employment come with the overall reduction in economic activity, concentrated especially in the public sector. Increases in the unemployment rate from 3.87 to 3.92% in BBE 1 and 3.96 % in BBE 2 are projected. The increase in land demand imposes an increase in land prices of 23% in BBE 1, and 32% in BBE 2. These increases have impacts on the prices of products that depend on land (agriculture), which affects household food consumption negatively, mostly focused on meet products (cattle, pork and poultry). In the regional level, different results are perceived. When it comes to emissions, Brazil is committed to reach 1.2 GtCO2-eq in 2030, with several mechanisms established in the iNDC (Brasil 2015). Business-as-usual, which attempts to incorporate as closely as possible the proposed actions in the iNDC, shows that emissions reach 1.7 GtCO2-eq, and that a bioeconomy could reduce 1% of these emissions in the current scenario. Emissions show that much more attention should be paid to the land use change and forestry sector. Renewable energy has an important role in emissions reductions, in any scenario. The increase from 202 to 235 and to 249 x106 tep in renewable energy in the BBE scenarios is an important step for energy independency and to preserve fossil reserves. Processes in the biosectors, however, are not yet more efficient as hypothesizes Richardson (2012), since total energy use goes from 481 x106 tep in the BAU scenario to 509 x106 tep in the BBE 2 scenario.

Key words: Bioeconomy, sustainability, computable general equilibrium model, input-output model, GHG emissions.

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## List of Abbreviations and Acronyms

IEA – International Energy Agency

KBBE – Knowledge –based bioeconomy

EU – European Union

EC – European Comissions

CGE – Computable General Equilibrium

GDP – Gross Domestic product

GHG – Greenhouse gases

BBE – Biobased economy

NREU – Non-renewable energy use

EIO-LCA – Environmental input-output life cycle analysis

OECD - Organisation for Economic Co-operation and Development

iLUC – Indirect land use change

LUC – Land use change

GMO – Genetically modified organisms

DOE – Department of Energy

LCA – Life cycle analysis

NPV – Net presente value

CHP – Combined heat and power

GTAP – Global trade analysis project

SAM – Social accounting matrix

CES – Constant elasticity of substitution

MSW – Municipal solid waste

SRC – Short rotation coppice

FAO – Food and agriculture organization

ABRAF – Associação brasileira de produtores de florestas plantadas

CONAB – Companhia nacional de abastecimento

CGEE – Centro de gestão e estudos estratégicos

LHV – Low heating value

ABE – Acetone – Butanol - Ethanol

IBGE – Instituto Brasileiro de Geografia e Estatística

PCJ – Piracicaba – Capivari - Jundiaí

TEM – Ministério do trabalho e emprego

CET – Constant elasticity of transformation

CPI – Consumer price index

USDA – United States Department of Agriculture

MAPA – Ministério da agricultura, pecuária e abastecimento

ROE  - Resto f the economy

SEEG – Sistema de estimative de emissões de gases

FIESP – Federação das indústrias do estado de São Paulo

IPCC – Intergovernmental pannel on climate change

iNDC – intended nationallly determined contribution

UNFCCC – United nations framework convention on climate change

EPE – Empresa de pesquisa energética

IBAMA - Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais

GOS – Gross operating surplus

## Summary

# 1. INTRODUCTION

The recent interest in biomass as industrial feedstock in large-scale and for multiple products is yet another step towards the concept of a sustainable future, when possibly the depletion of nonrenewable resources such as crude oil and natural gas will not be a part of the everyday life of the average human being. It is possible to find examples of the use of biomass to obtain different chemicals and materials as old as humankind, and their production has been conducted on an industrial scale for over 100 years (Dammer et al. 2013).

On the other hand, currently, most of the basic petrochemicals, such as ethylene, propylene and aromatics, are produced via conventional process utilizing naphtha from crude oil and ethane derived from natural gas (Ren et al. 2009). The chemical industry could benefit from the existing infrastructure in which the production of bulk chemicals (ethylene and propylene, for example), polymers and materials based on crude oil occurs, if the research community succeeds in developing effective biobased routes to produce bulk chemicals (Haveren et al. 2008).

Although historically humans have been using biomass as feedstock for many materials and chemicals, presently the use of biomass for energy purposes is in ascendance, with expected increase of at least 1.5 times just in liquid biofuels in volume between 2013 and 2040, and 1.7 times in bioelectricity generation (IEA 2015). From the growth of biomass for biofuels and other energy applications, and the recent development of commercially viable biobased products, as points the Green European Foundation (Eickhout 2012), arises the concept of a bioeconomy, also called the bio-based economy or knowledge-based bio-economy (or KBBE), defined by Langeveld et al. (2010) as “the technological development that leads to a significant replacement of fossil fuels by biomass in the production of pharmaceuticals, chemicals, materials, transportation fuels, electricity and heat”. An economy founded on biomass instead of fossil fuels could represent a significant shift in socioeconomic, agricultural, energy and technical systems, and can meet many of the requirements for sustainability from environmental, social and economic perspectives if it is designed and implemented intelligently (McCormick & Kautto 2013).

It is recognized that there is not a single solution in order to simultaneously reduce the dependence on oil and mitigate climate change in transport and chemical sectors, and that alternative production chains are necessary. Combined actions are needed, including but not restricted to changes in behavior, changes in technologies, expansion of public transport and introduction of innovative fuels and technologies (Cherubini 2010).

Besides emission reductions, the production of biomass is expected to translate into higher income, local independence and greater political stability of developing countries (European Union 2007). Dammer et al. (2013) also mention the potential positive impacts that a biobased economy could have on food security, especially because biorefineries convert most of the feedstock into food, feed, materials and energy, maximizing the total value. On the other hand, other authors consider the current use of biomass for energy purposes a walk against sustainability, in several aspects especially resource efficiency. Eickhout (2012) states that current EU policies do not promote a sustainable bioeconomy. This happens, in the author's point of view, because EU policies promote the use of lower value applications (biofuels, bioenergy) instead of the higher value applications like biomaterials and biochemicals. The European Union's bioeconomy strategy has a review and update planned for 2017 (European Comission 2017).

The expansion of biomass use, and consequently increase the renewable energy share of an entire economy, requires the identification of the best supply chains, considering technological, economic and environmental aspects (Gerssen-Gondelach et al., 2014).

The latent impacts, either positive or negative, and future sustainable versus unsustainable use of biomass are indeed current concerns in Brazil. The possibilities are wide and the applications of biomass use in large scale could lead to higher levels of development and more equal division of benefits, if the potential is properly achieved. In this case, agriculture would have even higher importance in the local economy, and the positive effects of economic development could reach the poorer sections of society. To achieve positive socioeconomic impacts, the environmental constrains need to be taken into account, to avoid the people versus nature problem and preserve high value biodiversity and natural resources so important to future progress. Other conditions of social nature need attention, as food security and to preclude deepening social differences that current biomass production models could generate in the long term (Jordan et al. 2007).

In this thesis, the use of Input-Output models is key to compare alternatives from an economic point of view. From the biofuels perspective, several socioeconomic studies using Input-Output and Computable General Equilibrium (GGE) models have managed to characterize extensively and establish diverse scenarios of future biofuels use and outcomes regarding employment generation, income, Gross Domestic Product (GDP), etc. Although most research results show potential for positive socioeconomic impacts (Passos da Cunha et al. 2015; Hoefnagels et al. 2013), different local realities could induce different outcomes. For example, even though biofuels create jobs, jobs creation could go down due to mechanization of feedstock harvest, or crops intensification (less labor required, for the same amount of biomass) (Herreras Martínez et al., 2013; Wicke et al., 2009)..

As an important agricultural and biofuels producer, it is natural to take Brazil as a case study and to model its economy with focus on new technologies derived from white biotechnology (bioeconomy). This thesis brings novel ways to analyze the introduction of new sectors and technologies based on Input-Output (I/O) models, using virtual blending sectors, which allows determining the shares of each technology to the end product. Also, it tackles the country regionally, which is a novelty for bioeconomy, even though several studies focused on bioenergy alone use interregional models for Brazil ((Ferreira Filho & Horridge 2014; Herreras Martínez et al. 2013). Using regional I/O models, different local characteristics (economic profile, feedstock availability) can be analyzed and relativized, in regards to impacts on GDP, income, job creation and subsidies. In addition, income inequality (functional) are innovatively studied through I/O model.

The analysis was done for bulk chemicals (represented by ethylene and propylene), fine chemicals (represented by butanol and acrylic acid), resins (substituted by polylactic acid), which are feedstock for plastic products production, and energy, represented by liquid biofuels: biodiesel, ethanol and renewable jet fuel, plus bioelectricity. Three scenarios for 2030 were designed to compare different levels of production (amount of chemicals and energy production through fossils versus biomass) for Brazil. This study focuses on the main crops available in Brazil: sugarcane, soy and forest crops (eucalyptus and pine). Different technological levels are also considered in this thesis. The first technological level is the production of chemicals and energy based on sugar crops and oil crops (associated to the so-called first generation biofuels – 1G). Second generation is the production of the same products, but from lignocellulosic feedstock materials by-products (sugarcane bagasse and straw, and forest residues) and dedicated feedstocks (eucalyptus and pine).

The general objective of this study is to develop and demonstrate a modelling framework (with Computable General Equilibrium and input-output modelling components) that allows the analysis of the impacts on macro and socioeconomic aspects, GHG emissions and non-renewable energy use together for different future scenario's for deployment of BBE (where Brazil is the case study). It is a key aspect of the modelling framework the possibility to vary the different technologies, feedstocks and amount of feedstock, as well the different strategies for development of the larger agricultural and livestock sectors, based on technological developments for the 2030 time horizon.

The specific objectives are:

- Identify macroeconomic impacts, with respect to commodity prices, land use and land prices, applying a General Equilibrium Model for the country;
- Identify the socioeconomic impacts regionally, focused on income generation, performing an Input- Output analysis, based on different levels of the bioeconomy;
- Identify the potential Greenhouse Gases emissions and the Non-Renewable Energy Use (NREU), performing an Economic Input-Output Life Cycle Assessment (EIO-LCA).

The methodologies for addressing the three point mentioned above are interlinked, and together they make up the methodological framework of this thesis, which is presented in Chapter 4. Before the methodological framework, in chapter 2, a literature review is presented, followed by the specificities of the bioeconomy in this thesis in Chapter 3.

# 2. LITERATURE REVIEW

A biobased economy, or a knowledge based bioeconomy (KBBE), relies on biotechnology to guarantee the supply of goods, without compromising nonrenewable resources. The KBBE concept was born out of the Knowledge-Based Economy (KBE), which joined technological advance with social progress and, therefore, provided a path to impulse science forward. The KBE started in the 1990s out of the search for a new economic paradigm (Richardson 2012). KBE revolves around the technological and economic factors of competitiveness, a belief in the valorization of the entrepreneurship culture, and commitment to the dynamic contribution of lifelong learning. The policy agenda of the KBE was set around ‘horizontal’ supports that facilitated technology transfer across borders and sectors, increasing the innovation capacity and adaptability of firms (Richardson 2012).

It was in the middle of the 2000s that the bioeconomy entered into policy discussions in the European sphere. Although bioeconomy has an international appeal, Europe seems to have generated a great deal of effort to boost bioeconomy, as well as biotechnology, not only politically but also technologically and innovation wise. The foundations originate from earlier strategic agendas of the European Commission (EC), including the White Paper of 1993 that highlighted the role of biotechnology in innovation and growth. Moreover, in 2002 the EC viewed the life sciences and biotechnology as the most promising of the frontier technologies (Richardson 2012).

As the concept of bioeconomy evolves, also evolves the research on the subject. Alternatively, bioeconomy rose as a metanarrative and found in research the basin to progress and develop. The amount of studies that the subject of bioeconomy comprises is indeed large, and the fields of research are not limited to the ones used in this summary, but it certainly indicates the path that is being outlined for the future biobased economy.

The recent studies on the subject, those that take biobased economy as a central problematic, can be divided in three main areas of study, without misinterpretation of essential characteristics. These areas are: Political, Technological and innovational, and Assessments overviews. The next sections will be divided in these mentioned areas of study.

### 2.1. Political overview

Political studies analyze the historical and political scenarios that led to the main auxiliary structures to support a biobased economy. These studies are based, on its majority, on the potential positive impacts that a biobased economy could bring locally, or even globally.

McCormick & Kautto (2013) list a wide variety of positive impacts, as reduction of emissions, decrease in dependence on fossil resources, wiser management of natural resources, and improved food security. They also name generation of employment in both urban and rural settings as significant positive effects of the bioeconomy. Furthermore, the authors cite the creation of a new non-food market for agriculture as an alternative income source for farmers.

OECD (2001) affirms that the application of biotechnology has led to economic and environmental benefits via processes that are less costly and more environmentally friendly than the conventional processes they replace. Meaning, OECD already affirmed in 2001 that bioeconomy was beneficial to economic progress and to reduce environmental impacts, hypothetically, with a strong contribution to an uncoupling of economic growth from environmental impacts. Other positive features of a biobased economy pointed out by the OECD are cost savings and improved product quality/performance, corroborated by the case studies presented on the report. The organization indicates that the economic and environmental benefits are predicted to grow, as awareness builds and the technology continues to be developed. The diffusion of technology through different industry sectors over the next few decades, again, plays an important part to develop a biobased economy.

The *National Bioeconomy Blueprint* (White House 2012) describes not potential positive impacts, but trends of research instead. In the report The White House intends to show how versatile and productive a biobased economy can be. The text also discuss the perspectives of biotechnology, including white biotechnology (use of enzymes and microorganisms to make biobased products), green biotechnology (applied to agricultural process to improve breeding techniques), blue technology (related with marine and aquatic applications), red biotechnology (applied to human health) and grey biotechnology (used to find solutions for the environment). Related with the trends for energy, the report reinforces the need for clean energy, and exemplifies the new technologies used to increase production and to lessen environmental impacts. In agriculture, the logic is the same as to energy: growth in yields and biotechnology to face environmental conditions, such as drought or heavy rains. Finally, the report mentions how microorganisms are being used to detoxify industrial waste and clean up ecosystems.

Not far from the American vision, lies most of the European policy developers. The Koln Paper (European Union 2007), focuses on the areas to be developed by biotechnology to achieve a biobased economy in the near future: bioenergy, biomedicine and food and nutrition. European Union (2007) concentrates on the technological advances needed to achieve the most urgent and challenging global demands. EuropaBio (2011), representing the biotechnology based industries, focus on the $CO_2$ emissions reductions, and how the shift from a petrobased economy to a biobased would reduce the dependence on fossil (non-renewable) resources. The European Commission, later on, in 2012, published another report with even higher expectations concerning biotechnology and the consequent biobased economy. With *Innovating for Sustainable Growth: A Bioeconomy for Europe,* European Comission (2012) harnessed biotechnology to the problems of the future, as ensuring food security, managing natural resources sustainably, reducing dependence on non-renewable resources, mitigating and adapting to climate change and creating jobs.

This monolithic judgment of the possible future impacts of a biobased economy seems to be unfounded, with the exception of the OECD (2001) report that brings case studies to substantiate the idea that a biobased economy will bring solutions to the main problems of the modern world, especially with population growth.

Richardson (2012) still sees biotechnology as a multiple purpose concept and a mean to overcome barriers to reach sustainable economic growth, but the author intents to identify the antagonistic values and diverging interests surrounding its adoption, instead of glorifying biotechnology as a futuristic panacea. The author draws attention to the fact that the progresses made in biotechnology do not necessarily ensure sustainability and exemplifies saying that the use of biotechnology within expensive and energy-intensive agricultural systems places over-riding constraints on its ultimate ability to deliver ecological surplus.

As Richardson, The Green European Foundation (Eickhout 2012) also sees biotechnology through its concerning points, instead of its potentials. In clear opposition to the European Commission's *Innovating for Sustainable Growth: A Bioeconomy for Europe,* the report *A strategy for a bio-based economy* names concerns of the impacts that a biobased economy could bring, if misleading policies and inappropriate management of resources are in place. The European Green Foundation mentions the latent indirect land use change (iLUC) arising from the inevitable land use change, which will be influenced by market prices of feedstocks. This affects directly the emissions reductions treated as a positive side of the bioeconomy by most authors, in a negative way. Food security, also treated as a hurdle to be tackled *by* biotechnology, is treated as a potential threat *of* bioeconomy, as food prices could rise in competition for feedstock and the rise in foodstuff demand could affect food prices, affecting food security. Land scarcity, as well as resource scarcity, is another concern to be dealt with, since the increase in biomass demand can result in increase in water and nutrients demand. The authors still connect land scarcity to biodiversity and large-scale land acquisition, two negative impacts on sustainability. Finally, Genetically Modified Organisms (GMO) are still a concern, since the consequences on human health remain unclear.

It is clear that there is a dichotomy in knowledge as, on one hand, the future path is clearly defined, and the result is taken as already known. On the other hand, multiple variables are apparently overlooked in the analysis of future shift from a petrobased economy, to a biobased economy. Either way, the solution seems to be unanimously based on policy making.

McCormick & Kautto (2013) review how policies in Europe were developed for bioeconomy, and create a timeline to the present, highlighting the main events that brought the subject to the spotlight. A recent policy is the lead Market Initiative, which selected biobased products as one of its six sectors to encourage the market uptake of products and services (e-health, sustainable construction, technical textiles, biobased products, recycling and renewable energy). Funding is also intended to be boosted, including the Horizon 2020, which is the biggest EU Research and Innovation program and includes direct funding for biobased industries, biotechnology and energy, as well as raw materials and food and healthy diet, which are also part of a biobased economy.

Although McCormick & Kautto (2013) consider Europe a global leader and pioneer in a number of fields of biosciences and related technologies, the USA has shown political progress regarding bioeonomy. One indication of such is the *National Bioeconomy Blueprint*, by the USA, published in 2012 to reinforce its activities around the bioeconomy and bio-based products. With Europe considered to lag behind in market deployment, the European Commission fears that the long-term competitiveness of Europe is at stake.

The *National Bioeconomy Blueprint* was designed to foster growth of new companies and support established companies by increasing commercialization of promising new technologies and products emerging from laboratory's research. Initiatives have been launched to promote the translation of ideas to products. Startup America Initiative, for example, intend to develop entrepreneurial safety by several actions like unlocking access to capital and reducing regulatory barriers to small business. Other initiatives facilitate supply chain connections between original equipment manufacturers and potential suppliers, and others provide tools to obtain patents more quickly. The USA government considers biotechnology applications to health improvements as one of the most important for future development of quality of life, and created the National Center for Translational Sciences for the discovery and development of drugs and diagnostics for human diseases and conditions.

From health to energy, the Department of Energy (DOE) Biomass Program established two consortia with the goal of developing technologies to quicken commercialization of advanced biofuels and bio-products. Furthermore, joint efforts of the secretaries of agriculture, energy and the navy have announced in 2011 the creation of a cooperative effort to develop drop-in fuels (direct replacements to existing liquid fuels without changes to existing engines); this cooperative effort came from the need of a leading position from the government, as the largest energy consumer in the country. The country has also programs to increase investments in high education, bringing new scientists into the biotechnology field of research.

In a broader concept of policy, without concrete initiatives, in 2001 the OECD (2001) saw biotechnology as an important tool to cope with present and future global problems, and it believed that policy should target the development of technologies in the near, medium and long term for selecting and developing value-added crop and tree varieties for conventional and industrial applications. The organization also considers high-yield crops as priority in policy making, as well as tree production for lignocellulosic materials. Other initiatives regarding sustainable practices aim at closing the loop (with by-products, or residues) back to the environment to maintain soil organic content and fertility (as is the case of filter cake and vinasse in the sugarcane processing facilities), utilization of industrial and agricultural residues and prioritization of locally grown feedstock.

The undergoing policies of the United States government and the European Commission, as described in *En Route to the Knowledge-Based Bio-Economy (KBBE),* European Commission (2007), overlap. Public awareness of the opportunities and the risks, and the involvement of scientists in informing the public, improving public acceptance of biotechnology, is considered by the EC also as an important step to break down barriers to the entrance of new products into the market. Schooling and developing the population’s taste for science is another key factor considered by the EC (as well as the US government) to help develop biotechnology locally, as most research in this field comes from China. Technology transfer, with public-private cooperation to enable development of flexible research-oriented and demonstration plants, as well as funding of early-stage companies, in parallel with American Startup, are basic policies to be applied by the EC. Competitive tax incentives attracting capital, as the French and Belgium Young Innovative Companies initiative, prioritizing spin-offs from academic research, and regulatory improvements aiming at simplified procedures, are other examples of synchrony between American and European governments.

Five years after the Koln Paper, the European Commission launched another communication with “Specific actions to maximize the impact of bioeconomy research and innovation” (European Comission 2012). These actions are basically the same as those found in the Koln Paper, reinforcing the needs for investments in knowledge, innovation and skills. In addition, investments in scale-up activities and development of entrepreneurship for the supply chain are mentioned, an idea already  also in the American Communication (White House 2012). Private-Public partnership is considered a key aspect to develop a biobased economy as well. The engagement of citizens and end users, and the informational feature of science to increase public acceptance of biotechnology is mentioned again. The novelty in this Communication lies in the inclusion of new infrastructure, and the necessary investments to endure such a huge transformation from a petro to a biobased economy, as well as the support of standards and standardized sustainability assessment methodologies for biobased products and food production systems. EuropaBio, the biobased industry union, follows the same line of thought, indicating policy needs for infrastructure, research and innovation, programs to stimulate market demand, and improving communication and education for the broad consumer (EuropaBio 2011).

Biomass for chemical and materials application is the motto from the Green European Foundation and, thus, the discouragement of bioenergy use is also part of policy suggestions that is complemented by stricter requirements of avoided $CO_2$ emissions and regulation on efficient use of biomass. The foundation gives concrete and direct policy recommendations, as the inclusion of biobased sustainable products in the European Ecolabel scheme, and in the Green Public Procurement. Incentives, as the ones received by bioenergy (Structural Funds, the European Agricultural Fund for Rural Development and the Cohesion Fund, as listed by the authors), should be amplified to biobased products, and tax exemptions should be given to biodegradable biobased packaging materials, in addition to the banning of fossil based chemicals, plastics and additives. The authors also recommend the creation of a Biomass Framework Directive, which covers all applications of biomass and would have, as a guiding principle, the biomass hierarchy (based on cascade utilization).

BIO (2016), in a 2016 report, reviews the status and existing projections of renewable chemicals production. The institution states that in 2012 biobased chemicals represented 9% of the almost 3 billion dollars sales of chemicals worldwide. It is expected that the highest growth rates until 2020 will be in sales of biopolymers (as Polylactic acid) and biobased chemicals. The growth is supported (at least in the USA, home of the institution) by several policies, as the Farm Bill, with its “biorefineries, renewable chemicals, and biobased manufacturing” assistance program. Other state level initiatives are mentioned, as tax credits for renewable chemicals in Iowa and Minnesota.

The attempts from many NGOs, trade unions as well as academics with diverse points of view to broaden the comprehension of a future biobased economy, have had little or no effect in policy making, as EU and other forefront competitors, seem to self-reinforce a set of institutions and policies that confine technological progress and consequent societal changes to one particular perspective. The expected societal changes explicit previously (jobs creation, $CO_2$ emissions reduction, health improvements and sparing nonrenewable resources) play an important role in directing activities and enabling the uneven interest in a particular technological solution to societal problems. These expectations can overshadow the real intentions of a new basis for economic production, which is, in fact, economic, more than societal in essence (Jordan et al. 2007). The expectations serve also as a sinkhole to direct research towards one particular technological trajectory rather than others (Birch et al. 2014). This is also true when the policy makers call out the scientific community to engage in the propagation of “knowledge” to instruct the public: The expectations are used as hype to enroll diverse social actors as stakeholders in new technological developments.

Although Brazil is one of the biggest bioenergy producers in the world, there is a lack of intellectual publications on the subject of policies regarding the bioeconomy in the country. In fact, the academy and other stakeholders had a delayed start on productions focused on the bioeconomy concept, in its most broad meaning (encompassing energy, chemicals and materials). Nevertheless, two recent publications deserve to be featured: one from Bain & Company, and another one from the National Industry Confederation.

Bain & Company’s report on renewable chemicals (Bain&Company 2014c) proposes public policies to strengthen local production of chemicals from renewable sources. The authors divide the publication by necessary investments in two scenarios: localities with sugarcane industries, and without. Independently of the infrastructure, the development of a bioeconomy in Brazil is driven by investments in basic research, pilot plant scale and pioneer production. The authors analyze the existing policies (“Lei do bem”, which is an incentive for innovation, for example), and propose new policies. These policies are analyzed on their impacts on GDP.

The second publication is from the National Industry Confederation (CNI 2014). The authors study through a sample of stakeholders (from the academy, government and industry), their knowledge on bioeconomy. Based on a questionnaire, the study shows that the stakeholders are aware of the concept of a bioeconomy (81.2%), and they see advantages of Brazil in a bioeconomy scenario, in comparison with other countries (81.5%), with great potential to become a global reference in the production of bioased chemicals and materials (91.9%). The biggest setbacks pointed out by the stakeholders to the accomplishment of the countries’ potentials are the Brazilian regulation mark, the lack of professional training to satisfy the bioeconomy needs, and the lack of research lines specific for the subject.

## 2.2. Technological and innovational overview

The technological and innovational studies either bring only the state-of-the-art in white biotechnology, or include also economic, financial and environmental analysis, with an emphasis on materials and chemicals derived from biological sources. Nevertheless, the prediction of the leading feedstock, conversion technologies and products with the most viable pathways are still the main objectives of the leading publications.

As it is the case of USA, with the objective to promote the biorefineries and their ability to produce many products all at once, the Department of Energy of the USA (Werpy & Petersen 2004) ordered the “Top Value Added Chemicals from Biomass” series, with two volumes. Volume I, presents the top 12 building blocks from sugars, whereas Volume II presents the potential uses of lignin, but inserted into near, medium and long-term opportunities. Volume II has a broader vision of lignin use, including heat and power purposes and direct uses, as in cement industry. This volume also includes, as a final use for lignin, the production of aromatic compounds, as benzene, toluene and xylene. Volume I indicates technical barriers, transformation pathways to other end product chemicals, and the derivatives of direct polymerization.

In this same logic, the International Energy Agency (IEA) focused its study “Bio-based chemicals: Value added products from biorefineries” (Jong et al. 2011) on building blocks from biomass, and also bulk chemicals to some extent, based on the “Top value added Chemicals from Biomass: Volume I” and in the BREW Project, and a compilation of other authors. The report also compiles analysis of multidisciplinary questions, as economic benefits, commercialization and GHG emissions reduction. IEA bases this report on the premise that biofuels are co-products, not the main driver for biomass production expansion.

The BREW project (Patel et al. 2006) provides a list of selected building blocks and derivatives of oils and fats. The project also reports novel economic and environmental analyses of the white technology derived chemicals, and performs a scenario analysis of projections for Europe in 2050, based on different conditions for the development of a biobased economy.

Gerssen-Gondelach et al. (2014) have a broad view of impacts, doing a thorough analysis of production costs, avoided GHG emissions and GHG abatement costs. In order to do so, the authors name the main routes from biomass to bioenergy and biomaterials. Different yields and geographical regions are considered in their work for different feedstock considered to become important in the future, as willow, poplar and eucalypt, but their potential is mainly determined by land availability and yields, with larger applications for degraded and marginal land.

Heat, power, fuels, materials and chemicals at different stages of developed technologies were included in the analysis. The routes to biochemical and materials were limited to direct modification, fermentation, transesterification, polymerization, gasification, pyrolysis and catalytic conversion, which derive a mixture of building blocks and bulk chemicals.

Hermann & Patel (2007) looked for standardized costs of production of organic chemicals, applying a generic approach, which allows the analysis of economic feasibility of products with no lab or pilot level data. The authors compared the results of the generic approach with results from industrial scale white biotechnology products, and petrochemicals equivalents. In order to calculate economic feasibility, the selection of products was an important step of their exercise. A pre-condition was availability of the fermentation process, with basic stoichiometry of fermentation process known, as well as potential to be used in bulk quantities. Shen et al. (2010) focus on products (plastics) and bulk chemicals, but do not indicate the logic of product selection.

Haveren et al. (2008) also focus on bulk chemicals. The authors believe that the petrochemical era is in its end, and the only source of carbon based chemicals and materials is biomass. The authors predict a mid-term development of biobased chemistry, focusing on the materials that can replace today's bulk chemicals produced from fossil, non-renewable resources. The premise of that study is to identify substitutions for the production currently ongoing in the port of Rotterdam, responsible for 5% of the chemicals produced in the world then.

Based on the general rule that fossil feedstock prices will go up while the biomass feedstock prices will drop, it was possible for the authors to describe the current state-of-the-art technologies in white biotechnology of the probable economically feasible compounds of the near future. One group of chemicals that received much attention was the glycols, due to its current production in the port of Rotterdam, and the fact that it can be a product or a precursor of other chemicals. Glycols can be produced from glycerol, sorbitol and lactic acid, depending on the singularities of each glycol. Haveren et al. (2008) show the significance of the aromatic compounds, normally left out of the technological analysis by many authors. The aromatic compounds represent around 40% of the production of chemicals in the port of Rotterdam, but the success of obtaining aromatic chemicals from biomass is not expected in the short-run. Even so, the authors describe the routes to aromatics via lignin, using high-temperature thermal processes.

In Brazil, Bain&Company (2014c) studies products based on oils and fats, and sugars (carbohydrates). The authors include in their analysis the market penetration of the products, although based mostly on speculations. Products foreseen to have great market penetration (between 10 and 50%) in the country in the long term (2030) include Butadiene, Adipic acid, Isoprene, Methionine and acrylic acid. For the mid-term (2025), the report names epichlorohydrin, butanol (iso and n-), 1,4 – butanediol (BDO) and propylene glycol.

### 2.3. Assessments overview

As the political, technical and innovational knowledge, the assessments of biobased economy impacts attain an extensive list of production. These assessments focus on different feedstock, many being able to compare regions and end products, as in Saygin et al. (2014), van Eijck et al. (2014) and Dornburg et al. (2008). The amplitude of the work performed throughout the renascence of the bioeconomy led to several analysis of economic performance, environmental impacts, impacts on agricultural practices, human rights, quality of life and health, land use, energy analysis and overall sustainability aspects. These topics will be overviewed next.

Weiss et al. (2012), after a compilation of trust worthy and complete articles and reports available for the general public, reviewed a total of 44 life cycle assessments (LCA), with 60 biobased materials involving 350 life cycle scenarios. The comparison between the scenarios is not proposed, due to the large variety of assumptions and systems boundaries. The review expresses the environmental impacts of biobased materials in relative terms, in comparison to the environmental impacts of conventional materials. The results show that biobased materials save, on average, $55 \pm 34$GJ/t and $127 \pm 79$ GJ/ha/year of nonrenewable energy, $3 \pm 1$ $tCO_2$-eq/t and $8 \pm 5$ $tCO_2$-eq/(hectare × year) of GHG emissions relative to conventional materials. The other classes of impacts assessed, namely, eutrophication, acidification, stratospheric ozone depletion and photochemical ozone formation, do not show the same performance as GHG emissions or nonrenewable energy use savings. Biomaterials may increase by $5 \pm 7$

$kgPO_4$-eq/t and 6 ± 11 $kgPO_4$-eq/(hectare × year) the eutrophication potential, due to nitrate and phosphate leaching from nitrogen fertilizers and ammonia emissions from manure applications. Stratospheric ozone depletion could also be increased by 1.9 ± 1.8 $kgN_2O$-eq/t and 2.4 ± 1.3 $kgN_2O$-eq/(hectare × year) due to $N_2O$ emissions from fertilizers applications. Acidification and photochemical ozone formation are considered case specific, following the authors conclusions.

The publication by van Eijck et al. (2014) performs an economic analysis covering five fuel types, eight feedstock types, 12 countries and eight agricultural systems for 2010, 2020 and 2030. The authors analyze the economic performance of first and second generation biofuels using Net Present Value (NPV).

With such a large dataset, assumptions had to be made by the authors, as to prices of inputs, which were kept constant between 2010 and 2020. The inclusion of incipient technologies required use of pilot or laboratory level information that could lead to unsound conclusions about economic performance, but more reliable than assumptions and projections. The focus on developing countries also hindered the quality of the dataset, since data on land use, land quality, costs of production and capital costs are poor. The authors conclude that cassava and palm production attained high NPV's, but highly dependent on yields. For jatropha, the findings in the paper indicate that NPV can range from -900 to 2,000 US$/ha. Sugarcane and soy have positive NPV for all scenarios.

Focused on the potentials of using biomass to generate process heat and as feedstock to produce chemicals and polymers, Saygin et al. (2014) conducted technical and economic assessments of the opportunities of industrial use of biomass. For raising steam, the authors estimate the production costs for fossil fuels and biomass (both considering boilers and CHP plants), and then calculate the net present value (NPV) from biomass relative to the fossil fuel based on a bottom-up analysis. The authors consider two biomass prices: low-cost feedstock and expensive sources (residues and dedicated crops, respectively). For materials, the authors determine the ratio of the current and future production costs, or sales prices, of comparable materials. Saygin et al. (2014) also calculated the $CO_2$ emissions reduction achieved with biobased products in comparison to their petrochemical counterparts, excluding non-$CO_2$ GHG and emissions due to land use and indirect land use change. A third indicator determines the ratio of $CO_2$ emissions saved per GJ of biomass required for a given function unit. The study concentrates on the non-

OECD and OECD countries for the period of 2030 and 2050. Results show an average value of US$ 14 ± 3/GJ of fossil fuel mix for steam production in OECD countries, whereas in non-OECD countries the average fuel mix costs US$ 12 ± 4/GJ. If biomass is used as raw material for steam production, costs are estimated to range from USD 5 ± 2 for CHP plants and USD 8 ± 4 per GJ for steam boilers. Costs from expensive sources of biomass are estimated to be three times higher, between USD 15 ± 9 and USD 25 ± 14 per GJ. The authors conclude that steam production from biomass residues in boilers or CHP plants is currently cost competitive (NPV>0). However, only in a few regions steam can be cost effectively when produced from biomass dedicated energy crops. According to the authors, in 2030 fossil fuel based steam production costs are expected to increase by US$ 5/GJ in all regions. For biobased steam, it was estimated an increase by US$ 2-11/GJ.

For biobased materials, two groups were identified: those already being commercialized, and those still in development phase. The group of materials under commercialization (bio-ethylene, bio-polyethylene, polylactic acid, starch polymers) has an estimated price ratio (ratio between biobased and petrobased prices) between 0.9 ± 0.2 and 3.9 ± 1.0, in which polylactic acid shows ratio of 0.9 when compared to polyethylene, and starch polymers have highest ratios (3.9) when compared to the same petrobased counterpart (Polyethylene). For emissions savings, the results show an average abatement of 0.07 ± 0.005 $tCO_2$/GJ when biomass is used for steam generation in boilers or CHP, depending on the regional fuel mix and the industry structure, and 30-45% lower $CO_2$ emissions savings/GJ are estimated for the weighted average of biobased materials, which replace the current mix of all petrochemical plastics.

Hoefnagels et al. (2013) use a computable general equilibrium model to estimate potential macro-economic and environmental impacts in The Netherlands based on a diversity of scenarios, mainly defined by two variables: international cooperation and trade, and technology development rate; the scenarios are then defined as:

- GlobHighTech: Domestic residues and imports of EU and non-EU biomass. Electricity from co-gasification, co-firing, co-digestion and waste incineration. First and second generation biofuels. Bulk C1 chemicals (methane)from lignocellulosic biomass;
- RegHighTech: Domestic Residues and EU biomass. Electricity from co-gasification, co-firing, co-digestion and waste incineration. First and second generation biofuels. Specialty chemicals (Caprolactam) from sugar crops.

- GlobLowtech: Domestic residues and EU and non-EU biomass. Electricity from co-firing, waste incineration and co-digestion. First generation biofuels. Bulk C2 (Ethylene) chemicals from ethanol.
- RegLowTech: Domestic residues and EU biomass. Electricity from co-firing, waste incineration and co-digestion. First generation biofuels (based on domestic feedstock and EU imports of first generation biofuels).

The authors include only three biobased chemicals in their analysis: ethylene from ethanol dehydration, representing the C2 bulk chemicals in the GlobLowTech scenario, Caprolactam, a precursor of Nylon-6, representing the production of high value added specialty chemicals in the RegHighTech scenario, and hydrogen from gasification of lignocellulosic biomass, representing the bulk C1 chemicals in the GlobHighTech scenario.

The analysis is done using LEITAP model, jointly with a spread sheet feeding the model with assumptions regarding electricity consumption, generation mix, biobased materials and bioenergy shares, fossil fuels use and other assumptions pertaining to GHG emissions. LEITAP model is an energy-environment extended version of GTAP (Global Trade Analysis Project) model. LEITAP has a global coverage aggregated in 37 regions, 23 sectors, including land using sectors and energy production/consumption sectors.

Instead of disaggregating the social accounting matrices (SAM) to model the biomass externally, the macro–economic impacts are calculated based on the nested constant elasticity of substitutions (CES). The energy-capital composite is nested and includes all the concurrent sources and feedstocks for energy production. The GHG emissions are calculated on a ‘cradle-to-gate’ base, since transport to the final consumer is not addressed, as well as emissions due to direct and indirect land use change.

The model’s outputs analyzed by the authors are the usual general equilibrium modeling results, as trade balance, land use and value added. Other results were calculated using the auxiliary spreadsheet in combination with the input shares of biomass commodities and growth of final demand per sector, resulted from the LEITAP model.

The results show a huge development of the biobased sectors in The Netherlands. In the RegLowTech scenario, biobased production of electricity, fuels and chemicals would reach 115 PJ, in contrast with the GlobHighTech scenario, reaching 660 PJ, mainly due to the 50% biofuels share in total fuels consumption. In this scenario, the total amount of required biomass could reach 1,410 PJ. Trade balance (a result of LEITAP) shows a decline in all scenarios. The authors explain this decline in trade balance is not due to biomass, but to model calibration. In fact, the biobased scenarios have positive effect on the trade balance of The Netherlands. Overall, the transition to a biobased economy could reduce up to 53Mt $CO_2$-eq in the GlobHighTech, and decrease fossil fuel dependency, avoiding up to 790 PJ of primary fossil fuels in 2030.

Smolker's "*The New Bioeconomy and the Future of Agriculture*" (Smolker 2008) is a thorough appraisal of biobased economy and how a transition from fossil to biobased economy could affect agricultural practices. The deepest concern of the author is land use, and how land use will affect people and society, especially those who could be directly affected by agricultural land expansion. The replacement of forests for industrial monoculture is the center of discussion, which is based on literature review. What is important about Smolker's work is its role as a counterpart to the massive support to biobased products and fuels. The disquiet about agricultural systems shifting to monoculture is already a reality in many countries, as pointed out by the author; 60 million indigenous people could become biofuels refugees (no time period is given). Many countries are named in this article, as examples of current issues that could be enlarged by the increasing demand for biobased products. Tanzania, Mozambique, Ghana and Uganda are examples of land grabbing, conflicts over land and water resources, while Brazil and palm oil producing countries (Asian, mostly) are pointed out as examples of forced labor and human rights violations.

As to regional studies, Brazil is still considered a source of basic resources, as land and biomass, other than an authority in the biobased future forefront, with technological competency and field expertize. This is clear in the assumptions taken in Hoefnagels et al. (2013), Haveren and Sanders (2008), Gondelach et al. (2014) and others, as Brazil is considered an outsourcer of biomass to Europe.

Along with Hoefnagels and its local study on Dutch economy, other authors have focused on regional or national analysis of the shift petro-biobased economy. Although there seems not to exist a comprehensive and single-comparable method to analyze bioeconomy, the effort is growing in single region studies.

Flemish authors Vandermeulen et al. (2011), point out the exponential growth in research of the "biobased" topic in early 1990's to late 2010. In this period, 65% of the published research was on biobased chemistry and polymers or materials science. "Biobased economy", on the other hand started appearing in 2000. After a literature review, the authors use a combined approach to assess the several steps in the production chain of the biobased economy in Flanders (Northern of Belgium). This combined approach is in fact a starting point to estimate the size of a bioeconomy, which could be applied to different regions, and consists of four steps: Conceptualizing biobased economy; Defining the level of disaggregation (disaggregation of the sectors of an economy); Mapping biobased companies; Using the most suitable economic benchmark (in GDP, in market value, in mass, etc.). Distinguished in two sectors, the authors estimated that the Flanders biobased economy is marginal and focused on the energy sector, with 1.6% of heat and electricity and 4% of transport fuels coming from biomass.

Lee (2016) studies the development of bio-pharmaceuticals, bio-hydrogen, biopolymers and genetically modified crops in China, India, Japan, South Korea, Malaysia and Taiwan for 2050. Lee uses a computable general equilibrium model from GTAP. Even though it is an extensive study, with multiple countries and multiple products (unlike Hoefnagels), the results and discussions are limited to projections of GDP growth in a bioeconomy scenario. Differences in a 20% decrease in bioproducts price, and a base line scenario (without decrease in prices) range from 0.0017% decrease in South Korea to an increase of 0.036% in Japan, in GDP. The study also projects total outputs of bio-industries, in the case of costs reduction. The total increase in biobased products goes from 0.27% in Japan to 1.67% in Taiwan in monetary terms, with the most promising industry being the bio-pharmaceutical, followed by bio-plastics.

In Grealis & O'Donoghue (2015), instead of focusing on biotechnology (Knowledge Based Bio-Economy), the authors concentrate on agriculture and food production and on the wider sectors dependent upon the ocean. Four main analytical studies are performed using input-output modeling based on Irish policies. The first set of policies studies is the "Reaching the Food Wise 2025", which is a set of strategies to increase the value of agri-food exports by 85% and the value added in those sectors by 70%. The second is the "Reaching the Harnessing our Ocean Wealth 2020" targets. Harnessing our Ocean Wealth 2020 targets at doubling the value of Irish ocean wealth to 2.4% of their GDP by 2030 and at increasing the turnover from their ocean economy to exceed 6.4 billion Euros by 2020, followed by the study of an expansion in the aquaculture sector, and finally, the authors analyze the impacts from the investments from dairy expansion. All four analyses are well detailed and work with disaggregated sectors, and present typical input-output results (income, job creation, and other value added indicators and industries total production).

As mentioned in Vandermeulen et al. (2011), the studies in biobased products and biobased energy are very broad and the subject has been growing for over two decades. Nevertheless, on the other hand, a biobased economy is in its infancy and scarce studies aim at studying specific countries or regions, and not all of them take into account a bioeconomy based on biotechnology.

It would be knowledgeable then to take Brazil as an important player of the biobased economy scenario, other than a player on the outskirts of large consumers. The complete analysis, as to local socioeconomic study based on input output modeling, national impacts based on computable general equilibrium modeling and life cycle assessment of a biobased economy in Brazil should reveal the pros and cons of this shift from fossil dependency to biomass dependency.

# 3. THE BIOECONOMY

## 3.1. Biomass feedstocks

Biomass composition varies greatly if compared to petroleum feedstocks. One advantage of this variety is that biorefineries can make more classes of products, providing additional stability and new opportunities for products development. A disadvantage is the relatively large range of processing technologies needed (Kim et al. 2009).

Several feedstocks serve as renewable carbon-based raw materials, coming from agriculture, silviculture and microbial systems, as cultivated crops, agricultural waste and algae to produce bioenergy and biomaterials (Kim et al. 2009; Gerssen-Gondelach et al. 2014; Kajaste 2014). Studies specifically related to feedstock issues include a large set of feedstock possibilities, ranging from specific algae species, to well-stablish feedstock such as soy, sugarcane and forest crops. Availability of resources seems not to be a short-term problem: a rough estimate on the annual yield of lignocellulosic matter amounts to $1.3 \times 10^9$ tons and that of natural oil and fats to $132 \times 10^6$ tons (Kajaste 2014). Wood residues and wastes from agriculture, food processing and municipal solid waste (MSW) serve as feedstock for heat and power. Sugar, starch and oil crops are currently the main feedstocks for (liquid) biofuels and for biomaterials. Other feedstocks that are expected to become important for the production of biofuels and biomaterials are dedicated energy crops, including short rotation coppice (SRC, e.g. willow, poplar, eucalyptus) and perennials (switchgrass, miscanthus), and lignocellulosic wastes and agricultural and forestry residues (Gerssen-Gondelach et al. 2014)

Currently, the main biomass resources in Brazil for energy purposes are wood, sugarcane and among the oil seeds used for biodiesel production the most important so far is soybeans (IBGE 2017). Therefore, four primary feedstocks were chosen for analysis in this thesis, due to their national importance and technical potential: soy, sugarcane, and SRC (pine and eucalyptus). Each feedstock could be used in a particular biorefinery configuration, following (Cherubini et al. 2009).

Soy is an annual crop legume with harvesting period in Brazil going from February until May. Soybean has a 14-17% oil content and 33-40% protein content, which makes it the legume with highest protein content and second highest oil content, and puts it as the second most consumed oil source in the world (Souza 2010; USDA 2017). Brazil has a long tradition with soybeans production and is currently the second largest producer (after US), with 86 million tons in 2014 (FAO 2017).

Sugarcane has consolidated its position as the main biomass source energy wise in Brazil in recent years. Its importance is due to the production of ethanol (hydrated and anhydrous), and the use of sugarcane bagasse (biomass derived from the fibers of sugarcane plant) as fuel in cogeneration systems. Sugarcane is also historically important due to the production of sugar (that also uses sugarcane bagasse as fuel). In fact, most of the sugarcane mills in Brazil produce ethanol, sugar and electricity. Sugarcane has been extensively studied through several perspectives and, as La Rovere et al. (2011) mention, several improvements have been made since sugarcane started being used for ethanol production in large scale in the 1970s. The costs of production have also been studied. van Eijck et al. (2014) show production of sugarcane having positive economic returns even with lower yields seen today, while Jonker et al. (2015) shows lowest production costs for sugarcane in today’s conditions, but energycane takes the lead in 2030 (considering an increase in fiber content and reduction of sugar content).

In the context of biorefineries sugarcane can be considered an example, producing biofuels, electricity and food. Brazil presents favorable conditions for the development of sugarcane based biorefineries because part of the surplus biomass can be used to integrate new processes to the present ongoing process (Corrêa do Lago et al. 2012).

Finally, SRC have traditionally been grown for cellulose industrial and for energy purposes. These are considered promising feedstocks because they hold high yields, low costs and are suitable for low quality land. Eucalyptus is among the fastest growing hardwood trees in the world, and is cultivated in over 90 countries. Eucalyptus has adequate chemical properties that make it well suited for cellulosic ethanol conversion processes due to the high content in cellulose and hemicellulose. In Brazil, the total production of planted forests was 267.6 million m³ in 2015 (SNIF 2017). Eucalyptus shows good advantage in comparison to other woody biomass, as presented by Jonker et al. (2015), and the lowest costs, in Brazil, if compared to other lignocellulosic feedstocks in other countries, according to van Eijck et al. (2014). Due to regional differences, eucalyptus and pine were chosen to represent possible woody biomass feedstocks for future biorefineries. Brazil presents good edaphoclimatic and land conditions for the development of the highest productivity in the world for eucalyptus and pine (*Pinus Taeda* and *Elliottii* mostly). (ABRAF 2013).

Table 1 shows the total production, yields and residues production for each feedstock considered in this thesis. 2009 values are given to match the database used in this thesis.

Table 1 – General information on the chosen feedstocks for evaluation

| Feedstock | Residues from the field | Average annual agricultural yield | Total production in Brazil (2009) |
|---|---|---|---|
| **Sugarcane** | 70 kg/TC[a] | 81 t/ha[d] | 633.7[d] |
| **Eucalyptus** | 86 kg/t-biomass[b] | 40.7 m³/ha[e] | 130[e] |
| **Pine** | 97.5 kg/t-biomass[c] | 40.1 m³/ha[e] | 49[e] |
| **Soy** | - | 2.88 t/ha[f] | 68.7[f] |

[a] TC = ton of cane. Based on Dias et al. (2011). Dry basis. Corresponds to the amount of straw brought from the field.
[b] Includes bark and crown branches. Based on Santiago (2013). Dry basis.
[c] Includes tops, branches and leaves. Based on Brand et al. (2014). Dry basis.
[d] Values for the 2009/2010 harvest period. Based on CONAB (2010). Production in million tons.
[e] (ABRAF 2013). Production in million m³.
[f] (CONAB 2010b). Production in million tons.

## 3.2. Bioproducts and bioprocesses

The increasing research and the developments in biobased chemicals and materials result in a wide range of potential building blocks (acrylic acid, for example) and bulk chemicals (ethylene, for example) with similar characteristics to their petrobased counterparts, as well as relatively high levels of interchangeability of final products with original petrobased equivalents (Chen & Patel 2012; Patel et al. 2006; Werpy et al. 2004). The different focus of distinct authors has led to a group of building blocks and bulk chemicals. Building blocks are defined by (Haveren et al. 2008) as chemicals used in the synthesis of other chemicals. The most important aspect of bulk chemicals is their capacity of generating derivatives. On the other hand, bulk chemicals are chemicals being produced at large quantities. Haveren et al. (2008) quantify as bulk chemical, chemicals with a production larger than 50,000 t/year, and end consumers normally use them. Several bulk chemicals, as ethylene and propylene are also building blocks.

In this thesis, the first selection of these chemicals and materials was based on seven papers and/or research projects widely disseminated and referenced. Werpy et al. (2004) did a thorough screening of the possible building blocks, which could be made from sugar via biological or chemical conversion. With a focus on biorefinery products, the International Energy Agency, through its IEA Bioenergy Program, within Task 42, highlighted all biobased products with prompt potential to become a value-added product, regardless if it is bulk chemical or building block.

Haveren et al. (2008) discuss the potential production of several biobased bulk chemicals in the port of Rotterdam, based on short, mid and long term technologies. Shen et al. (2010) focus on the current global market of biobased plastics, their material properties, technical substitution potential and future market (for 2020).

Other authors studied deeply the products from a techno-economic and environmental point of view. Patel et al. (2006) studied those that could be made from white biotechnology and assessed if they could contribute to energy savings, GHG emissions reductions and under which conditions these products could become economically viable. The study from Patel and co-authors focuses on processing biomass-derived feedstock into organic bulk chemicals. In Hermann & Patel (2007), current and future technology routes are evaluated for 15 products assuming different prices of fermentable sugar, while Gerssen-Gondelach et al. (2014) did a review of the status and prospects of biomass value chains for heat, power, fuels and materials, followed by an assessment of their current and long-term levelized production costs and avoided emissions.

In this section, the focus is on high volume materials like bulk chemicals. These will have the largest impact on biomass demand, and the largest potential to reduce fossil fuel use and GHG emissions. In addition, many biomaterials and their production processes are too innovative to have available economic, social and environmental data.

From the energy perspective, the choice of products was based on the most recognized liquid biofuels regarding their drop-in abilities and their presence in the literature, since studies are more commonly directed at studying biofuels. Table 2 shows the products chosen in this thesis, and the references that have mentioned them as possible substitutes of fossil-based technologies in the medium-term (2030).

Table 2 – Biobased products and their supporting references

| Biobased Product | References proposing the product | Technology commercially available? |
|---|---|---|
| **Ethylene** | (Jong et al. 2011; Gerssen-Gondelach et al. 2014; Haveren et al. 2008; Hermann & Patel 2007; Shen et al. 2010; OECD 2014) | Braskem produces 200,000 tons/year in Brazil (OECD 2014). Another 175,000 ton/ year are produced in USA, China and Belgium (Jogdand 2015) |
| **Polylactic Acid** | (Jong et al. 2011; Shen et al. 2010; Gerssen-Gondelach et al. 2014) | Demand of 360,800 tons in 2013 (Grandview Research 2017). No facilities in Brazil. |
| **Acrylic Acid** | (Hermann & Patel 2007; Patel et al. 2006; Bain&Company 2014c) | Novozymes announced in 2014 the total conversion to acrylic acid in pilot scale. Not at commercial scale yet (Novozymes 2017). |
| **Propylene** | (Jong et al. 2011; Gerssen-Gondelach et al. 2014) | Braskem was to launch a propylene plant in 2013, |

| | | |
|---|---|---|
| | | but no official information has been found. Braskem supposedly has a 50,000 tons production capacity in Brazil (Bio-based news 2017). |
| **n-Butanol** | (Jong et al. 2011; Gerssen-Gondelach et al. 2014; Hermann & Patel 2007; Patel et al. 2006; Bain&Company 2014c) | Supposedly total capacity of 7,300 tons at HC sucroquímica in Brazil, but no official information. A total capacity of 165,000 tons in China (Natalense 2013). |
| **Ethanol** | - | Commercially available in several countries. World production of 0.8 mboe/day (IEA 2015). |
| **Electricity** | - | 464 TWh of bioelectricity generated in 2013 (IEA 2015) |
| **Biodiesel** | - | Commercially available in several countries. World production of 0.3 mboe/day (IEA 2015). |
| **Jet Fuel** | (Jogdand 2015; Klein-Marcuschamer et al. 2013) | Nameplate capacity of 32,500 tons of Farnesene/year in Brotas, Brazil (Maxx Chatsko 2014) |

### *3.2.1. Basic configurations: sugarcane and SRC biorefineries*

Three basic configurations were designed as the center of the biorefinery options that will deliver the necessary feedstock (those considered are presented in Table 1) for the production of the products listed in Table 2. For first generation (1G) biorefineries, only sugarcane is used as main feedstock, and the straw brought from the field is directly sent to the CHP unit, without any further treatment.

In a 1G configuration, sugarcane is received and cleaned in a closed water circuit, followed by the conventional procedure of leveling in chippers and shredding and opening cells in shredders of swinging hammers. Sugarcane juice is then extracted via pressure rollers (CGEE 2009). These processes (schemes are presented in Figures 1 and 2) are considered electrified in optimized configurations (Cavalett et al. 2012). The extracted broth is subjected to an initial screening with a rotating sieve with integrated set of extraction. A second screening is done in hydrodynamic fibrous material sieves for removal of smaller size, as the inert part. Finally, the broth is subjected to a sedimentation hydrocyclone for removal of sand and dirt to be further chemically treated.by flocculation and decantation, used to occlude in the flakes as many microorganisms originally present in the broth. The treated broth must pass a final heating, which ensures technical grade sterilization, to be then concentrated to the desired sugar concentration (CGEE 2009). Bagasse is sent to CHP unit along with straw brought from the field for heat and power generation. First generation configurations (as well as combined first and second generations – 2G) operate 167 days a year, processing 500 tons of sugarcane per hour, while 2G (based on SRC) operate for 330 days, processing 160.9 t/h of biomass.

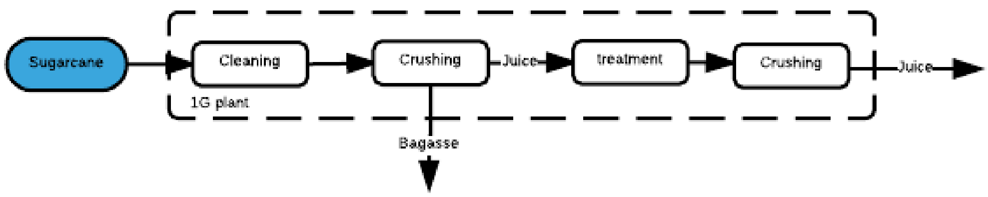



Figure 1 – 1G basic configuration.

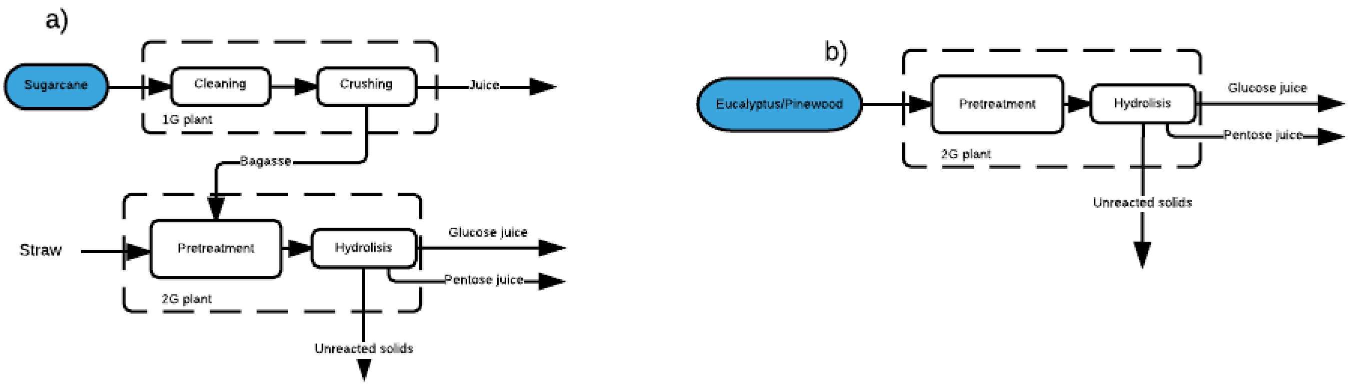



Figure 2 – a) 1G2G and b) 2G basic configurations.

In a 1G2G configuration, the available lignocellulosic residues (from 2 million tons of sugarcane plus straw brought from the field) goes through pretreatment and hydrolysis. The second generation plant receives the residues, and they go through a pretreatment stage consisting of steam explosion, followed by separation of pentose juice from the solid parts (pulp) containing cellulignin. Alkaline delignification comes next, followed by lignin removal and cellulose enzymatic hydrolysis (Dias et al. 2012). . The pentose liquor could be fermented into ethanol, but due to energy demand inside the biorefineries, it was considered that pentose liquors are biodigested into biogas, to satisfy energy needs, with the exception of butanol producing facilities that ferment pentose (Mariano et al. 2013b). The solid fraction of the pretreatment goes through enzymatic hydrolysis, producing a glucose-rich liquor that goes through fermentation in combination with the juices from sugarcane. Unreacted solids are also used in the CHP plant (Dias et al. 2012).

In a 2G stand-alone biorefinery, the process is similar, but with higher pressures for process steam due to the characteristics of the feedstock (eucalyptus and pine) form this technology. Different operation times and processing capacities are also considered for forests, according to (Piccolo & Bezzo 2009).

### *3.2.2. Chemicals*

Table 3 shows the chemicals chosen for further analysis, including the technological routes, biomass used, regions where production will take place and the expected demand for 2030. This section introduces these chemicals.

#### 3.2.2.1. Ethylene

Ethylene is produced commercially by steam cracking of a wide range of hydrocarbon feedstocks. In Europe and Asia, ethylene is obtained mainly from cracking naphtha, gasoil and condensates with the coproduction of propylene, C4 olefins and aromatics (pyrolysis gasoline). The cracking of ethane and propane, primarily carried out in the US, Canada and the Middle East, has the advantage that it only produces ethylene and propylene, making the plants cheaper to construct and less complicated to operate (Cutler 2013).

In this study, biobased ethylene is produced from bioethanol via catalytic dehydration over an aluminum oxide catalyst, which is the same process used by Braskem in Brazil (OECD 2014). The reaction occurs in two main stages (Figure 3): reaction (dehydration) and purification. Bioethanol feed enters the process at 25°C and 1 atm. It is pressurized by a centrifugal pump and subsequently heated by a fired heater. After pressurized and heated, the feed enters a fixed bed reactor and contacts with the aluminum oxide catalyst to form the product ethylene, as well as co-products. A second reactor and fired heater increase the overall conversion of the process. The pressure is than increased and the temperature decreased in the purification phase, before expanding into flash vessels, separating the unreacted bioethanol, water and acetaldehyde contaminant from the ethylene-rich vapor phase. The ethylene is cooled, compressed and flashed again to remove additional impurities. A 10-tray absorption column removes a fraction of the residual diethyl ether as well as the remainder of the unreacted bioethanol. The product exits the process at a purity level of 99.7% ethylene (Poppick et al. 2015).

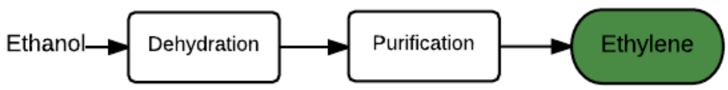



Figure 3 – Conversion of bioethanol to ethylene.
Source: Poppick et al. (2015)

3.2.2.2. Polylactic acid (PLA)

Traditionally, lactic acid has been used in the food and beverage industry as a preservative and pH-adjusting agent, and in the pharmaceutical and chemical industries as a solvent. In recent years, lactic acid consumption in pharmaceutical and chemical industries applications has overtaken the food and beverage industry as the leading market (Bridgwater et al. 2010). The biopolymer formed by lactic acid polymerization is Polylactic Acid (PLA), known since 1845, but commercialized only in the early 1990. (Babu et al. 2013). The process (scheme shown in Figure 4) uses sugarcane juice as input, entering the process to a batch fermentation step, done under uncontrolled pH after 24 hours, in a continuous process. Sucrose-tolerant, homofermentative lactic acid bacterium *Lactobacillus plantarum* is used in the process . The product stream containing lactic acid and unconverted sugars and nutrients are collected in a holding tank for further purification by nanofiltration, whereas the cells are recycled back continuously to the fermentor by microfiltration. The microfiltered broth is mainly composed of lactic acid and unconverted sugars, besides a very small amount of ionic impurities. Lactic acid is dehydrated under mild conditions without solvent to form a cyclic dimer lactide. Lactide is purified by vacuum-distillation at high temperatures. After vacuum-distillation, high molecular weight PLA, with a controlled optical and crystal purity, is formed by ring-opening polymerization. The final polymer is granulated and can be subsequently further processed for the desired application (Groot & Borén 2010; Sikder et al. 2012; Uhde Inventa-Fischer 2012). At least 100,000 tons per year are produced using this process in the world (Babu et al. 2013)

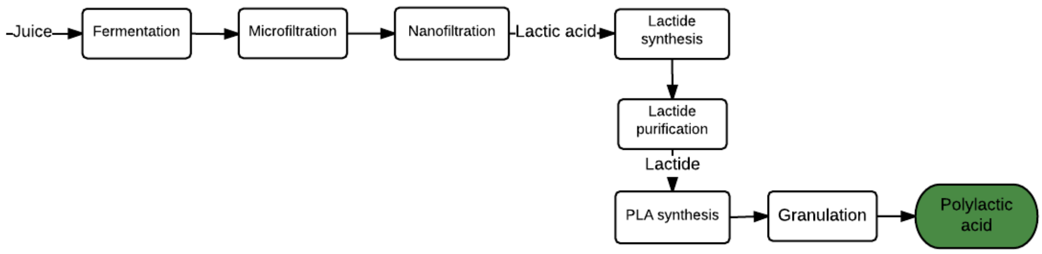



Figure 4 – Conversion of juice to polylactic acid.
Source: (Groot & Borén 2010; Sikder et al. 2012; Uhde Inventa-Fischer 2012)

### 3.2.2.3. Acrylic acid

The current route to produce acrylic acid (AA) is based on the gas phase oxidation of propylene, via its partial oxidation. The usual mechanism for producing acrylic acid utilizes a two-step process in which propylene is first oxidized to acrolein and then further oxidized to AA. Each reaction step usually takes place over a separate catalyst and at different operating conditions, and no by-product is necessarily produced (West Virginia University 2014). The process for biobased acrylic acid was divided into three main stages: fermentation, distillation and dehydration (see a scheme in Figure 5). First, glucose is converted to 3-Hydroxypropionic acid (3-HP) via the aerobic fermentation of *E. coli*. The fermentation broth is sterilized and centrifuged to remove any residual biomass. The remaining 3-HP and water solution is heated and pressurized in multi-effective evaporation flash vessels. A concentrated 3-HP stream flows through a pressure vessel with phosphoric acid, converting 3-HP to acrylic acid. This product flows through a reactive distillation tower. The resulting acrylic acid is further distilled and partially recycled to ensure near complete reaction of 3-HP, recovery of the acid catalyst (phosphoric acid), and purification of the acrylic acid (Cie et al. 2012). The process is not yet commercial, but investments are being made (Novozymes 2017).

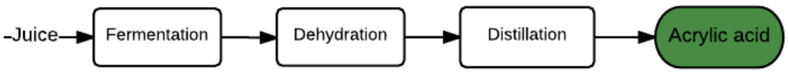



Figure 5 – Conversion of juice to acrylic acid.
Source: Cie et al. (2012)

### 3.2.2.4. Propylene

Propylene is commercially produced in two manners: as a co-product of ethylene manufacturing, and as a by-product of petroleum refining. The steam cracking of several hydrocarbons, as natural gas liquids and petroleum liquids produces ethylene as well as many chemicals as co-products, as methane, hydrogen, ethylene, butadiene, benzene, toluene and finally propylene. In petroleum refining, catalytic cracking is applied to obtain gasoline from heavy gas oils. This process converts a portion of the feed to C1-C4 products, including propylene, accounting for 5 to 9% of the volume of the fresh feed (American Chemistry Council 2007).

Biobased propylene is obtained based on bioethanol, which goes through dehydration to form ethylene. Ethylene then enters the dimerization/isomerization phase, where dimerization and isomerization occur jointly catalyzed by homogeneously dissolved cationic nickel complexes, resulting in 2-butene (Scholz et al. 2014). The metathesis reaction occurs in a fixed bed catalytic reactor. The main reaction that occurs is between ethylene and 2-butenes, to produce propylene. The catalyst used is tungsten oxide supported on silica (Intratec 2013) (see a scheme in Figure 6). There is no clear information about the commerciality of this process, but Braskem had plans to have a plant by 2014 (Bio-based news 2017).

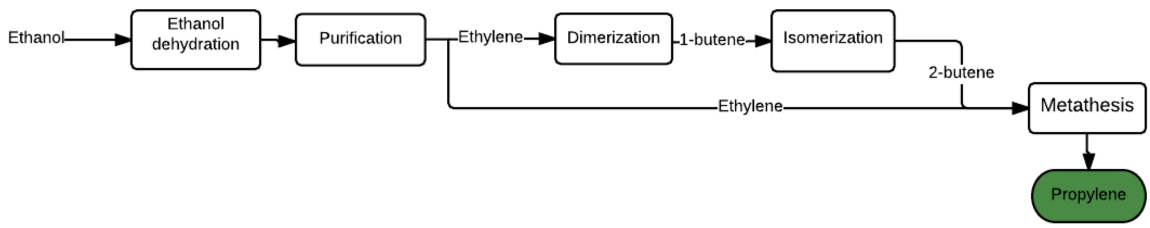



Figure 6 – Conversion of bioethanol to propylene.
Source: (Scholz et al., 2013; Intratec, 2014; Poppick et al, 2015)

### 3.2.2.5. n-Butanol

The chemical n-Butanol is a derivative of butyraldehyde and made from propylene using hydroformylation process (often called “oxo” process). Hydroformylation of propylene, using a mixture of carbon monoxide and hydrogen (in the form of synthesis gas), produces normal butyraldehyde and iso-butyraldehyde, which are then hydrogenated to n-butanol iso-butanol and 2-ethylexanol, as shown in Figure 7 (Tudor & Ashley 2007).

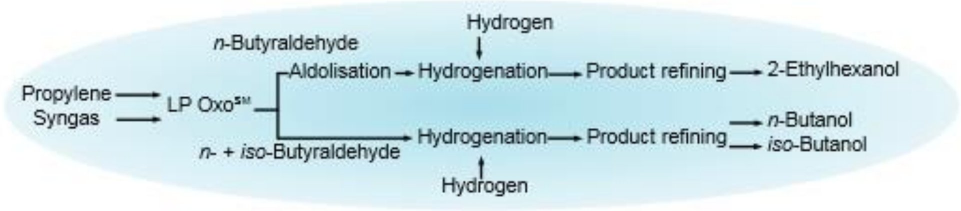



Figure 7 – Hrydroformylation of propylene into n-butanol, iso-butanol and 2-ethylexanol.
Source: Tudor & Ashley (2007)

Biobased n-butanol originates from a well-known process called Acetone-Butanol-Ethanol, but production ceased in the 1980' due to the low prices of crude oil. The scheme of the process shown in Figure 8 is based on sugarcane juice or pentose sugars from SRC, or even sugarcane residues after pretreatment and hydrolysis. The juice is treated with screens and hydroclones to remove sand and fiber and, subsequently, phosphoric acid and lime are added to remove other impurities. After treatment, the diluted juice is continuously sterilized and sent to the fermentation unit, which feeds the *Clostridium* cells. The separation of the fermentation products (acetone, butanol and ethanol) is performed in a series of five continuous distillation columns, with the last two responsible for the separation of butanol from water. The water stream is recycled to the fermentation unit for juice dilution and the hydrous ethanol stream is sent to distillation for further purification (Mariano et al. 2013b; Mariano et al. 2013a)

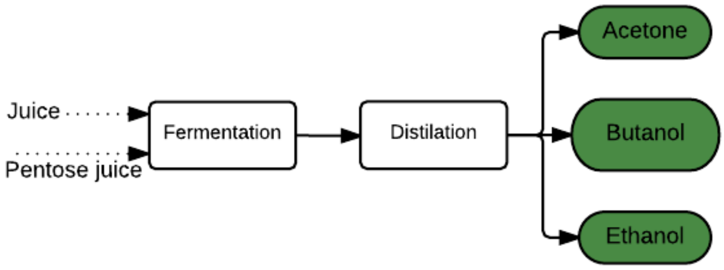



Figure 8 – Conversion of juice and pentose juice to butanol.
Source: (Mariano et al., 2013a; Mariano et al., 2013b)

Table 3 – Chemicals selected after further filtering

| Building block/Bulk chemical | Feedstock | Technological routes | Platforms | Source |
|---|---|---|---|---|
| **Ethylene** | Sugar crops<br>Lignocellulosic | Dehydration of ethanol | Sugarcane Juice<br>C6 sugars | (Poppick et al. 2015) |
| **Polylactic acid** | Sugar crops | Fermentation followed by polymerization. | Sugarcane juice | (Sikder et al. 2012; Groot & Borén 2010; |

| | | | | |
|---|---|---|---|---|
| | | | | Uhde Inventa-Fischer 2012) |
| **Acrylic acid** | Sugar crops | Fermentation to 3-HP, followed by dehydration. | Sugarcane juice | (Cie et al. 2012) |
| **Propylene** | Sugar crops | Dehydration of bioethanol to ethylene, dimerization of ethylene to 1-butene, followed by isomerization to 2-butene and subsequent metathesis of 2-butene/ethylene. | Sugarcane juice C6 sugars | (Scholz et al. 2014; Intratec 2013; Poppick et al. 2015) |
| **n-Butanol** | Sugar crops Lignocellulosic | Fermentation (Acetone-Butanol-Ethanol). | Sugarcane juice C5 sugars | (Mariano et al. 2013b; Mariano et al. 2013a) |

Due to the limited amount of information, only the platforms (Table 3) available in the literature were considered. Therefore, of the chemicals, ethylene, propylene and n-butanol are produced in SRC-based biorefineries.

### *3.2.3. Energy*

The selection for energy carriers converged in three types of liquid fuels, plus electricity. Summary information is presented in Table 4.

#### 3.2.3.1. Bioethanol

Currently in Brazil, the production of sugarcane bioethanol is entirely based on the fermentation of sugar juice from sugarcane and/or molasses in autonomous distilleries (about 35% of the whole production) and in plants associated with sugar mills (65%). This 1G technology has been in commercial use for the past 40 years and can be considered to be mature. As the cost of feedstock accounts for a major part of the production cost, around 60-70%. Compared to other crops used for bioethanol production from sugar and starch, i.e. 1G bioethanol, the production from sugarcane is claimed to have one of the lowest production costs worldwide (Macrelli & Wallberg 2014).

The 2G technologies include biochemical conversion of cellulose into sugars (pentose and hexose), and then fermented into ethanol. Several pretreatment options are available, as calcium hydroxide and alkaline hydrogen peroxide (Rabelo 2010), but steam explosion has shown to be effective for different materials, including sugarcane bagasse (Rocha et al. 2012). Figure 9 shows a scheme of the process of converting sugars to ethanol.

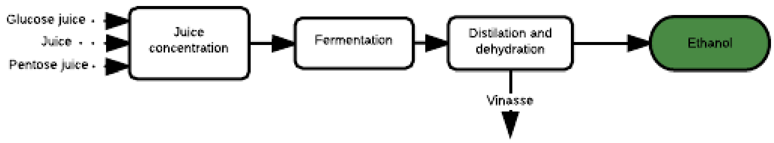



Figure 9 – Scheme of the conversion process from sugarcane juice (C5 and C6 juices) into ethanol.
Source: (Dias et al. 2011)

### 3.2.3.2. CHP/Electricity

Combined heat and power is presented in every biorefinery configuration, in order to guarantee energy sufficiency. Cost reduction, and lower GHG emissions are also aims for using a CHP plant. Figure 10 is a schematic of the possible sources used. Depending on the biorefinery configuration, steam cogeneration systems can burn sugarcane bagasse, lignocellulosic materials from SRC, straw (or residues from SRC), and biogas (e.g., from vinasse and pentose juice biodigestion). No CHP plant is present in the biodiesel production units.

In this thesis, biogas production parameters were taken from Moraes et al. (2014) and it was considered that the unreacted solids from 2G production (lignin) are used for matching the steam demand and maximizing surplus electricity regarding the industry self-consumption. Steam is raised at 100 bar, 530ºC (by hypothesis, steam generators operate with an 85% thermal efficiency, LHV basis), that is the state-of-the art technology in Brazilian mills, and extraction-condensing turbines are used, with extractions at 12 bar and 2.5 bar for feeding the industrial process. In the case of plants based on SRC, extractions occur at 13 and 4 bar. Total surplus electricity depends on the steam and electricity consumption for each modular process. The information on steam requirements, electricity consumed in each process, and the necessary pressure for the processes was taken from literature and applied to a co-generation simulation software (CGEE 2009).

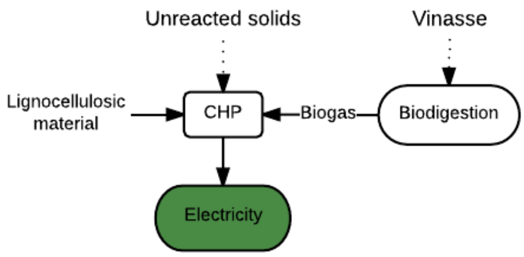


Figure 10 – Possible conversion of residues and co-products to electricity.
Source: (Dias et al. 2011)

### 3.2.3.3. Biodiesel

Biodiesel production starts with crude vegetable oil (soy based, in case of this thesis) preparation, including clarification, depuration and drying. Before clarification, the oil is filtrated and sent to a cyclone to eliminate impurities. The oil's acidity is reduced in a refining stage by eliminating the free fatty acids, resulting in an oil composed of only glycerides. Biodiesel is produced from the reaction of crude oil with methyl alcohol or ethyl alcohol, in the presence of a catalyst. The catalyst used is sodium hydroxide (NaOH) (Cunha 2011). This process is called transesterification and provides as final products biodiesel and glycerin (Figure 11 shows a scheme of the conversion process) (Souza 2010).

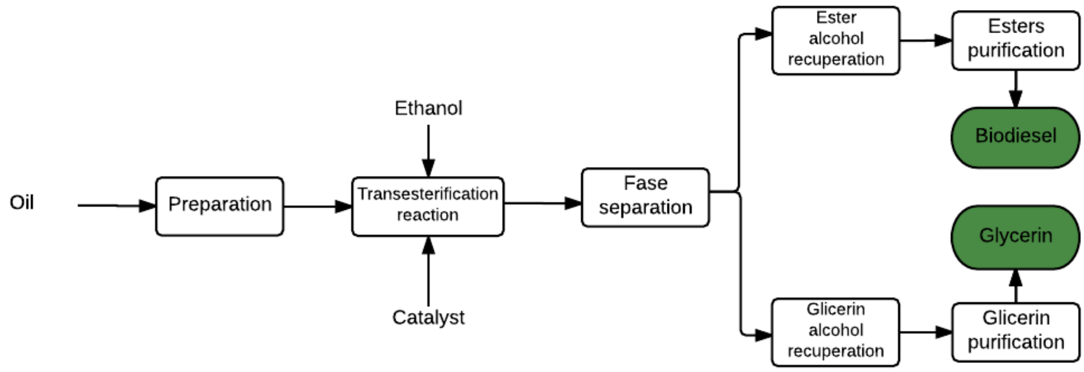


Figure 11 – Schematic conversion of vegetable oil into biodiesel.
Source: (Souza 2010; Cunha 2011)

3.2.3.4. Renewable Jet Fuel

In this thesis, it is considered the production of renewable jet fuel from sugarcane using Amyris' technology platform. The production pathway (Figure 12 shows a scheme) comprises the fermentation of sugars into farnesene ($C_{15}H_{24}$) using specialized yeasts. The farnesene forms a separate phase on top of the fermentation broth, facilitating subsequent recovery and purification. The farnesene produced is then hydrogenated into farnesane (the renewable jet fuel) to finally be blend with regular jet fuel (Moreira et al. 2014).

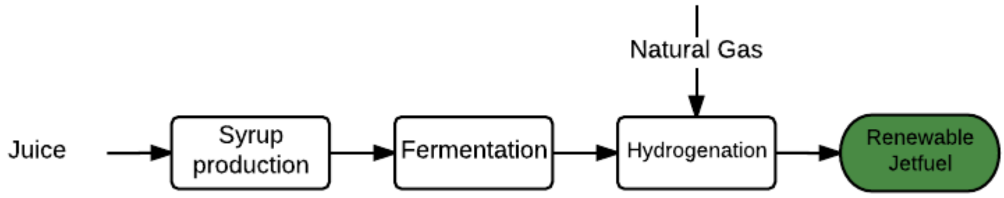



Figure 12 – Scheme of the conversion of sugarcane juice to renewable jet fuel.
Source: (Moreira et al. 2014)

Table 4 – Summary of energy carriers selected

| Energy carrier | Feedstock | Technological routes | Platforms | Source |
|---|---|---|---|---|
| **Bioethanol** | Sugarcane | Fermentation | Sugarcane juice | (Dias et al. 2011; Cavalett et al. 2012) |
| | Lignocellulosic | Steam explosion pretreatment and enzymatic hydrolysis | C6 sugars C5 sugars | (Dias et al. 2012) |
| **Electricity** | Residues | Steam cogeneration systems | Lignin/Biogas Bagasse/straw | Simulation |
| **Biodiesel** | Soy | Transesterification | Oil | (Souza 2010; |

| | | | | |
|---|---|---|---|---|
| | | | | Cunha 2011) |
| **Renewable jet fuel** | Sugarcane | Fermentation | Sugarcane juice | (Moreira et al. 2014; Klein-Marcuschamer et al. 2013) |

Out of the energy products, only ethanol and electricity are produced in SRC-based biorefineries, due to the lack of information of renewable jet fuel using other sources rather than sugarcane juice. Biodiesel is also not produced in the SRC biorefineries, being produced only from soy.

### 3.3. Technical improvements

Industrial biotechnology offers the possibility to replace not only fossil-fuel derived products with renewable ones, but also to replace energy-intensive chemical processes with more efficient biological ones (Richardson 2012), if maturity level is reached. In the field of chemical transformation of biomass to final products, many existing technologies may be implemented. For the production of bulk chemicals and more affordable renewable energy, increase in yields on sugars and chemical processes are required. Several improvements are anticipated in the coming decade as use of specific organisms in fermentation of novel chemicals, development of catalystic systems as well as breakthroughs in product separation and purification (Eickhout 2012; Langeveld et al. 2010). An important technological development crucial for the sustainability of the biobased economy is the deconstruction of lignocellulosic biomass. Considerable amount of resources have been allocated to research the use of non-food crops and residues as feedstock in the industrial biotechnology. The accessibility of cellulose (and hemicellulose) must be increased (based on current stage of extraction) while being economically attractive (O'Donohue 2014; Langeveld et al. 2010).

Research and innovation are crucial for the development of the biobased economy and have a major role in the viability of an industrial biotechnology (European Comission 2011). The technological development in this thesis was the result of the assessment of the techno-economic performance of a range of BBE options for today and medium (2030) term based on a literature review. Improvements in crop yields, conversion efficiency and costs are taken into account and translated in key performance parameters. Yields influence the costs of several stages within a system, especially in the cost of raw materials per unit of product and in the reaction and separation equipment, which are proportional to the volume produced and number of stages involved (Kamm et al. 2008).

Tables 5 to 14 provide the current and future parameters used in modeling the process presented in the bioproducts and bioprocesses section. The future values presented are based on literature review and are mostly unrealistic for current technological maturity of the processes, but can be potentially reached in the mid-term (10-20 years).

The new parameters are applied to each stage of each process. This interferes in the mass and energy balances, and provides the new total outputs of each product.

Table 5 - Sugarcane composition parameters considered in the simulation process

| Item | | Unit | Current value | 2030 value |
|---|---|---|---|---|
| **Sucrose content in sugarcane** | | % | 14.5[a] | 16.0[a] |
| **Fiber content in sugarcane** | | % | 14[b] | 12.6[b] |
| **Sugarcane juice extraction efficiencies** | | % | 96[b] | 97.5[c] |
| **Losses of sugar in the cleaning process** | | % | 0.5[b] | 0.2[c] |
| **Sugar content in molasses** | | % | 52[d] | 52[d] |
| **Molasses from sugar production** | | kg/TC | 35[e] | 35[e] |
| **Chemical composition of sugarcane residues (dry basis)[f]** | Glucan | % | 40.6 | 40.6 |
| | Xylan | % | 20.9 | 20.9 |
| | Galactan | % | 0.9 | 0.9 |
| | Arabinan+mannan | % | 4.0 | 4.0 |

[a] Based on Macedo et al. (2008) and the assumptions in (Jonker et al. 2015)
[b] Based on Jonker et al. (2015)
[c] Based on (Walter et al. 2008)
[d] Based on Ponce et al. (2016)
[e] Embrapa (2017)
[f] Batalha et al. (2015)

Table 6 - SRC composition parameters considered in the simulation process

| Item | Unit | Current values | 2030 values |
|---|---|---|---|
| **Eucalyptus[a]** | Glucan | 44 | 44 |
| | Xylan | 12 | 12 |
| | Galactan | 1.2 | 1.2 |
| | Arabinan+mannan | 1.2 | 1.2 |
| | Lignin | 27.2 | 27.2 |
| **Pine[b]** | Glucan | 41.9 | 41.9 |
| | Xylan | 19 | 19 |
| | Galactan | 0 | 0 |
| | Arabinan+mannan | 1.1 | 1.1 |

| | | | |
|---|---|---|---|
| | Lignin | 28.1 | 28.1 |

[a] Based on (Gomes et al. 2015). No changes in SRC composition is expected. Ashes and extractives totalize the biomass composition.
[b] Based on (Amarasekara 2013). No changes in SRC composition is expected. Ashes and extractives totalize the biomass composition.

Table 7 - Ethanol production parameters considered in the simulation process

| | Item | Unit | Current value | 2030 value |
|---|---|---|---|---|
| **1G** | Fermentation efficiency | % | 90[a] | 94.5[a] |
| | Distillation efficiency | % | 96[b] | 99.5[b] |
| **2G** | Glucan-glucose | % | 75[a] | 91[a] |
| | Galactan-galactose | % | 60[a] | 80[a] |
| | Mannan-mannose | % | 60[a] | 80[a] |
| | Xylan-xylose | % | 60[a] | 80[a] |
| | Arabinan-arabinose | % | 60[a] | 80[a] |
| | Glucose-ethanol | % | 80[a] | 90[a] |
| | Galactose-ethanol | % | 0[a] | 84[c] |
| | Mannose-ethanol | % | 0[a] | 75[a] |
| | Xylose-ethanol | % | 75[a] | 80[a] |
| | Arabinose-ethanol | % | 0[a] | 75[a] |

[a] Based on Jonker et al. (2015)
[b] Based on Walter et al. (2014)
[c] Moniruzzaman et al. (1997)

Table 8 - Ethylene production parameters considered in the simulation process

| Item | Unit | Current value | 2030 value |
|---|---|---|---|
| **Ethanol dehydration efficiency** | % | 87.2[a] | 95.8[b] |
| **Ethylene purification** | % | 98[a] | 99.5[c] |

[a] Based on the process in Poppick et al. (2015)
[b] Based on the review in Chanchuey et al. (2016)
[c] Based on similar separation processes in Jonker et al. (2015)

Table 9 - Propylene production parameters considered in the simulation process

| Item | Unit | Current value | 2030 value |
|---|---|---|---|
| **Ethylene dimerization selectivity towards butenes** | % | 91[a] | 94[a] |
| **Butene isomerization selectivity towards 2-butene** | % | 95[a] | 96[a] |
| **2-butene selectivity towards propylene (Metathesis)** | % | 90[b] | 100[c] |

[a] Scholz et al. (2014)
[b] (Intratec 2013)
[c] Gartside & Greene (2006)

Table 10 - Lactic acid production parameters considered in the simulation process

| Item | Unit | Current value | 2030 value |
|---|---|---|---|
| **Fermentation efficiency** | % | 96[a] | 96[b] |
| **Lactic acid/PLA conversion** | % | 77[c] | 92[c] |

[a] Sikder et al. (2012)
[b] Ghaffar et al. (2014) indicates that lactic acid fermentation yields have limitations, depending on the pH, temperature and substrate concentration.
[c] Inventa-fischer (2012)

Table 11 - Butanol production parameters considered in the simulation process

| Item | | Unit | Current value[a] | 2030 value[a] |
|---|---|---|---|---|
| **Mass yield from C6 and C5 sugars** | Butanol | w/w | 0.20 | 0.30 |
| | Acetone | w/w | 0.10 | 0.08 |
| | Ethanol | w/w | 0.02 | 0.01 |

[a] Based on Mariano et al. (2013b)

Table 12 - Acrylic acid parameters considered in the simulation process

| Item | Unit | Current value[a] | 2030 value[a] |
|---|---|---|---|
| **Fermentation efficiency** | % | 92.5 | 92.5 |
| **Dehydration efficiency** | % | 29.8 | 29.8 |
| **Distillation efficiency** | % | 99.7 | 99.7 |

[a] Based on Cie et al. (2012). No improvements were considered due to the long-term development period expected for this technology, as mentioned in Haveren et al. (2008)

Table 13 - Renewable jet fuel parameters considered in the simulation process

| Item | Unit | Current value[a] | 2030 value[a] |
|---|---|---|---|
| **Fermentation efficiency** | % | 82.8 | 91.4 |
| **Hydrogenation efficiency** | % | 100 | 100 |

[a] Moreira et al. (2014)

Table 14 - CHP parameters considered in the simulation process

| Item | Unit | Current value | 2030 value |
|---|---|---|---|
| **Steam pressure** | bar | 42-65[a] | 100[b] |
| **Steam temperature** | °C | 480[a] | 530[b] |
| **Boiler efficiency** | % | 75[c] | 85[b] |

[a] CGEE (2009)
[b] Alves et al. (2015)
[c] Dias et al. (2011)

In Appendix A, Table A.3 shows the final outputs in physical units for each biorefinery option. No technological improvements are expected in biodiesel production from transesterification.

### 3.4. Bio-sectors

In this thesis the development of the bio-sectors was based on a biorefinery concept, which converts the biomass into useful and more valuable products, analogous to oil refineries (Chong

2011). Cherubini (2010) takes the definition of a biorefinery from the International Energy Agency (IEA) Task 42: biorefining is the sustainable processing of biomass into a spectrum of marketable products and energy. Although it is extremely debatable that every biorefinery is by definition sustainable, the core idea is that a biorefinery can, with renewable feedstocks, provide the same (or even novel) chemicals and energy carriers as an oil refinery.

In oil refineries, several combinations of end-products can be found, as well as different feedstocks (crude oil, ethane, naphtha, etc.), and the concept of biorefinery itself indicates that the same features apply for them. In that sense, it was necessary to organize the processes, products, feedstocks and their combinations.

Figure 13 shows a generic configuration of the bio-sectors that are based on sugars. Figure 13 is not applicable to biodiesel, since Biodiesel is considered an oil-based biorefinery. Figure 11 shows the configuration for biodiesel producing biorefineries. Each bio-sector receives only one type of feedstock, being sugarcane, eucalyptus or pine. In the beginning of the biorefinery, the feedstock enters one of four options for basic configurations: Either a first generation or a first generation combined with a second generation in the case of sugarcane (section 3.2.1). It can also enter a second-generation basic configuration, in the case of eucalyptus and pine. In the case of soybeans, it is processed to extract the oil.

Each process followed by the basic configuration is responsible for one or more products. For example, ABE fermentation is considered as one process, but will generate three final products (acetone, butanol and ethanol). Not necessarily, there will be three processes in every biorefinery, and there is the option of more than one sugar stream to go to the same process. For example, in a 1G2G basic configuration, C6 sugars stream and sugarcane juice stream can go to fermentation to ethanol, providing only one final product.

Each process can be followed by another process. Therefore, “process 1” can mean a combination of processes. For example, propylene starts with the production of ethanol, and then the ethanol is dehydrated to ethylene, for it to be finally transformed into propylene. In this example, 3 processes would represent process 1.

Not every process has by-products, even though figure 13 shows as so. By-products are vinasse, and C5 sugars stream. Section 3.2.3.2 shows the functionality of the CHP plant.

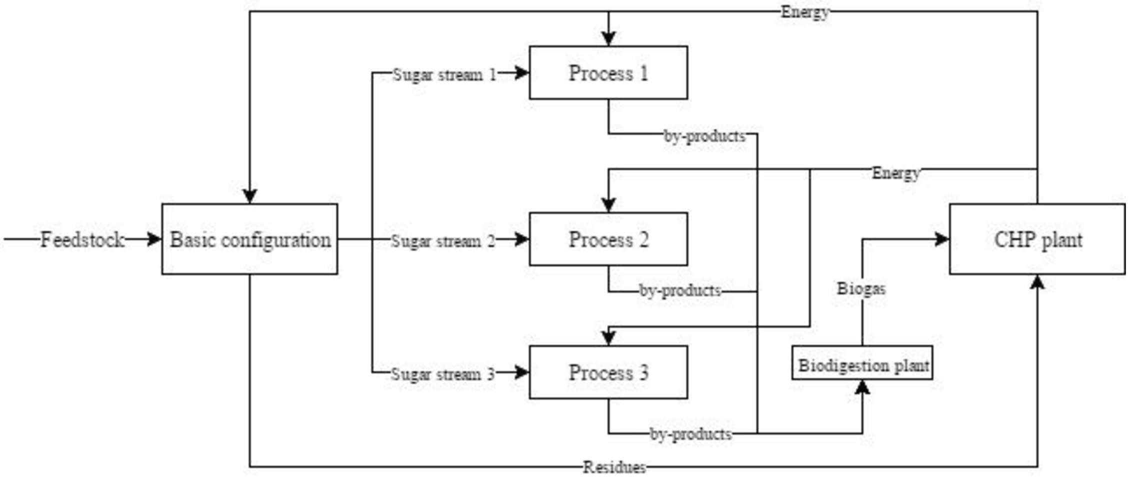



Figure 13 – Generic configuration of the Bio-sectors, based on the biorefinery concept.

After the integration, the input-output coefficients were calculated. Technical coefficient's equation is shown in equation 7, in the next chapter. The technical coefficient is defined as the ratio between the total value of an input consumed by producers of a certain product, and the total value of that product. Therefore, in order to describe the bio-sectors into technical coefficients, the total input requirements were necessary, and were taken from the literature. With their other information provided by the references in section 3.2, the processes after being integrated provided a total amount of products. This total amount of products was then translated in output coefficients, in monetary terms. Figure 14 shows a schematic of the process going from products definition, to the insertion of the technical coefficients in the Brazilian economy.

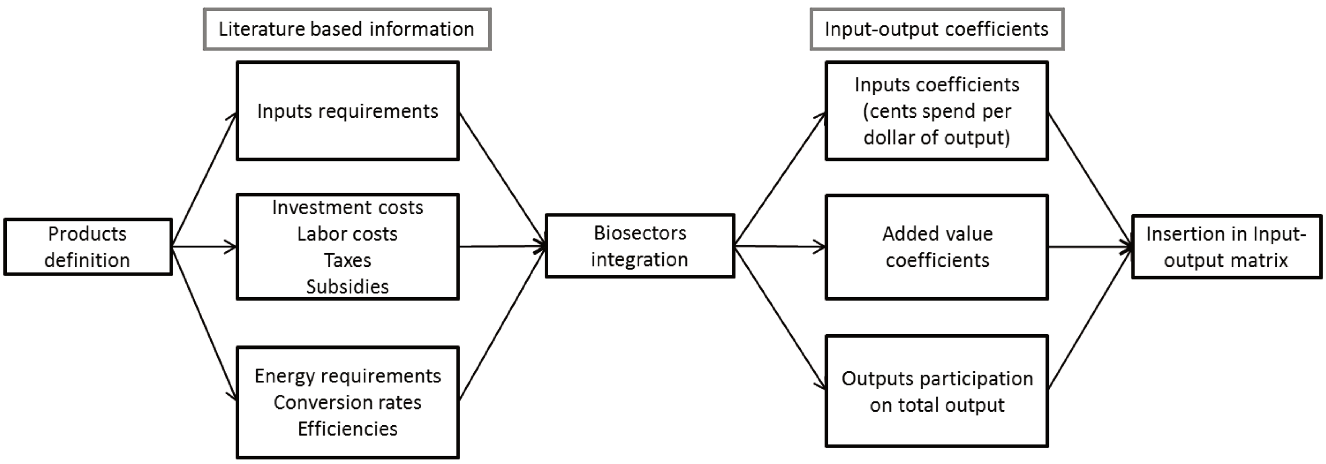



Figure 14 – From products definition to insertion in the input-output matrix of Brazilian economy.

To translate the physical processes and their integration into economic values, presuppositions were made in order to maintain a coherent base of comparison between the final integrated biorefineries. Table 15 shows the basic assumptions for the integrated biorefineries (bio-sectors).

Table 15 – Basic assumptions for the integrated bio-sectors

| **Item** | | **Value** |
|---|---|---|
| **Base year** | | 2009 |
| **Biomass processed** | Sugarcane ($x10^6$t) | 2 |
| | Sugarcane moisture content (%) | 70 |
| | SRC ($x10^6$t dry basis) | 1.27 |
| | Soybeans ($x10^3$t) | 1.2 |
| **Weighted average capital cost (%)** | | 12 |
| **Project's lifetime (years)** | | 30 |
| **Days in operation** | Sugarcane based | 167 |
| | SRC based | 330 |
| | Biodiesel bioref. | 250 |
| **Income taxes (%)** | | 34 |
| **Plant supervisors' salary (R$/h)** | | 22.3[a] |
| **Plant operators' salary (R$/h)** | | 9.2[a] |
| **Water costs (R$/m³)** | | 0.01[b] |

[a] Based on the average monthly salary of employees in chemical plants and their average hours of work in 2009, provided by the Annual Statement of Social Information (MTE 2016). Used in the bio-products processes, but not in the biomass handling plants (from cleaning to sugars availability).

[b] Based on the costs applied for the use of national water resources (PCJ 2012).

Inputs were translated from physical to monetary units using local prices in 2009, based on the Annual Industry Survey, done by IBGE (IBGE 2017d). Total value of output was also calculated in monetary terms multiplying the total amount for the local prices in 2009, based on IBGE.

The overall cash flow has to equalize inputs and value added to the total value of production, in monetary terms. Notwithstanding, a group of biorefineries was unable to reach economic viability, which required a subterfuge to guarantee remunerating all the production factors and the intermediary consumption. For that reason, subsidies are applied in order to guarantee the feasibility.

Subsidies are a key aspect of this study. The application of subsidies will determine the government's ability to maintain its level of expenditures and provision of public services, in exchange for the consolidation of a biobased economy.

The processes considered in this thesis are based on literature review, and are have been improved for 2030 realities, based on the information provided in the previous section 3.3. The improvements considered, however, have not included learning effects, nor scale effects. As seen in previous studies, besides learning and scale, another important factor to the feasibility of enterprises is the weighted average capital cost. If lower returns were expected from the investors, higher feasibility would have been possible (Machado et al. 2016).

Different than other studies like van den Wall Bake et al. (2009), however, this thesis does not analyze feasibility based on oil prices. It sets the prices of bioproducts as the same as their counterparts, which means that, if those products have higher prices (due to increase in oil prices), biobased feasibility would be improved. This variation is, however, not applicable to the model framework of this thesis, which is based on static models.

In Appendix A, Tables A.1 and A.2 show the final coefficients of each biorefinery option, including the amount of subsidies necessary.

More information on the procedure can be found in previous publication, which exemplifies with propylene production and include other analysis of economic viability (Machado et al. 2016). Appendix B shows the paper with detailed information on the process modeling.

# 4. METHODOLOGY

The methodologies presented in this section compose the methodological framework of this thesis. The Computable General Equilibrium (CGE) and Input-Output (I/O)models are connected each order in order to maintain coherent results between assessed macroeconomic and regional impacts. Figure 15 shows the structure of the methodological framework.

The first step of the model framework is to specify each biorefinery into technical coefficients. The biorefineries are simulated using literature information, and integrated following the procedure explained in 3.4. With the information from inputs and outputs, the bio-sectors (biorefineries) are then inserted in the model, in combination with the baseline economy of Brazil, for the year of 2009.Combined with the macroeconomic projections, based on literature review, the chocks on the size of the bioeconomy will generate the impacts to be evaluated, based on the CGE model. These results are on the national level.

Then, the results on quantities are regionalized and serve as input to the I/O model, which has results at the regional level, regarding income, jobs and inequality. Also at the regional level are the emissions and non-renewable energy use.

Each methodology (CGE, I/O and EIO-LCA) will be detailed next.

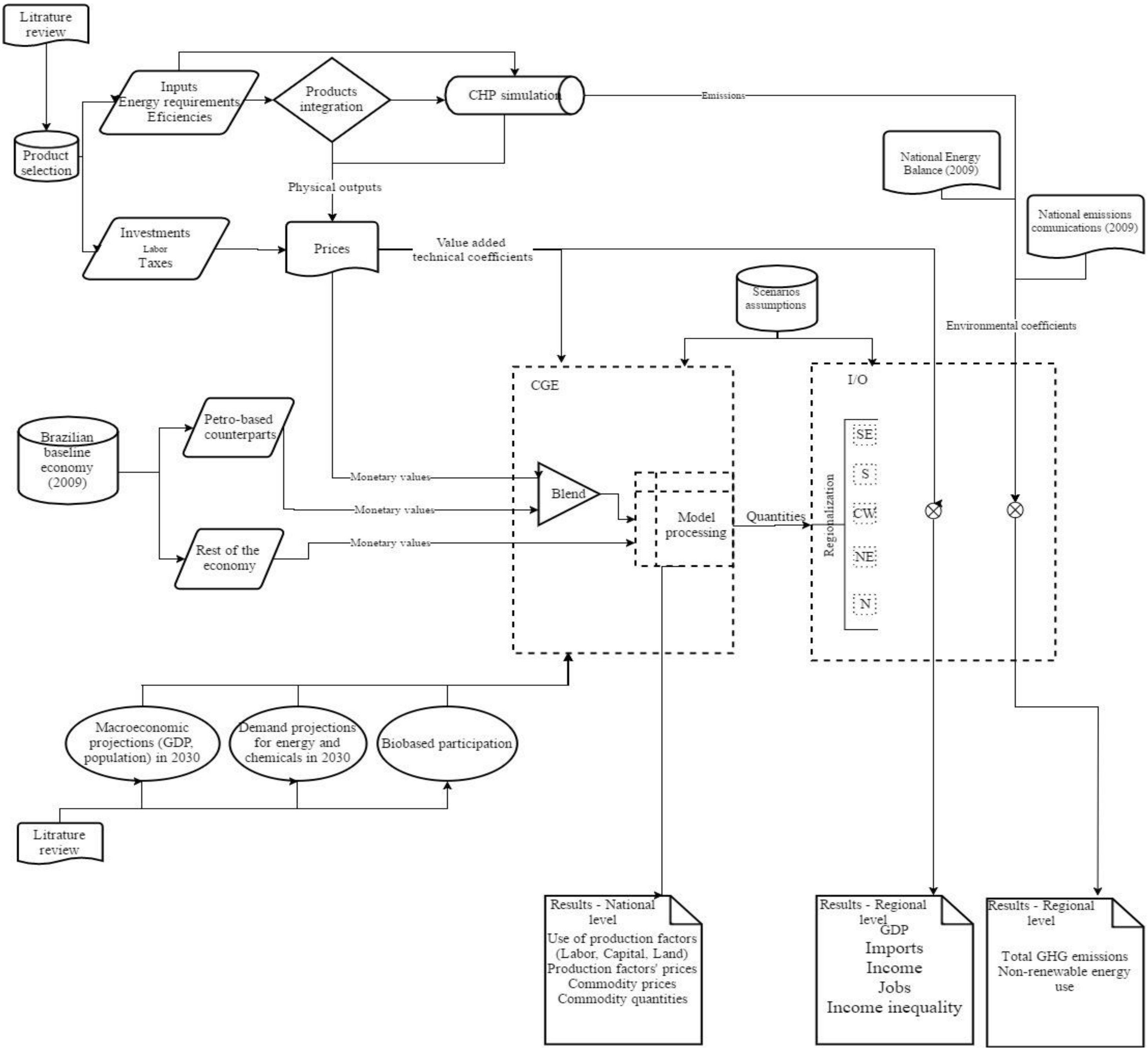



Figure 15 – Modeling framework of this thesis.

## 4.1. Computable General Equilibrium modeling

Markets are harbors to organized production and distribution of products with several players. The behavior of agents in these markets is what conditions outcomes, prices of goods and services and quantities traded. In a country, two main agents influence market conditions: firms and households. Firms organize production of commodities and services, which are supplied and sold in markets. To do so, they demand primary (labor, capital and land) and non-primary goods and services that will be transformed to the final product. Firms have an objective: chose a production plan that yields the larger return (return being the difference between the income associated to selling the production plan and the expenditure in inputs needed to make that particular plan possible). On the other hand, households demand commodities and services to satisfy their consumption needs and, at the same time, are responsible for providing primary factor assets to the firms. Households want to maximize utility (utility is a consumption schedule that best fits their value system, under whatever their available income makes possible) (Cardenete et al. 2012).

In the market place, households and firms act as demanders and suppliers wanting to maximize return (or utility). The two blocks of agents can reach a trade agreement based on a mutually compatible price, i.e., a price at which the specific amount being demanded equals the amount being produced. This is called market equilibrium (Cardenete et al. 2012).

Computable or applied general equilibrium models (CGE) are simulations that combine the abstract concept of market equilibrium with realistic economic data, to solve numerically for the levels of supply, demand and prices that support equilibrium across a set of markets. The empirical basis of CGE models is the Social Accounting Matrix (SAM), which records the revenues and expenses of all agents in the economy, as businesses, factors of production, households, government and the rest of the world (or the country). These matrices, in turn, are constructed from information contained in Input/output matrices and in the National or Regional Accounts.

Equilibrium in the economy results in three basic conditions. The *conservation of products* is a reflection of the physical principle of material balance. Therefore, if a commodity is produced by firms, it must be completely absorbed by the firms, households and the rest of the economy (exports, government, etc.). *Value conservation* reflects the accounting principle of budgetary balance (income values must balance values of expenditures). The conservation of products is also known as market clearance, whereas value conservation is known as zero profit condition. Lastly, household factor endowments (labor, capital, land) are fully employed, as well as their income is fully expended even if for the purpose of savings. The exhaustion of income and production factors is known as *income balance* condition (Batabyal 2011).

Ultimately, CGE models are algebraic frameworks based on the impositions of the axioms of producers and consumers maximization, following the observed conditions above mentioned. Figure 16 shows the relationship between the demand and supply of the various agents in the economy (in the figure, portrayed as an economy with two sectors producing two distinctive products/services). Since this study aims at understanding the different macroeconomic impacts due to the introduction of a bioeconomy in Brazil, in 2030, the model is required to incorporate this change. Therefore, as in the regional input-output model, the concept of a virtual blending sector was introduced. The three blending sectors represent virtual agents that add all the similar products to become one single aggregation of the products to the end consumer. The aggregated products are represented by the three total products ($TP_i$). For example, the bio-sectors 1 and 2 produce the bioproduct 1, which is equivalent to the common product 1. The blending sector 1 is responsible for consuming these three products and making a final product 1. This allows the analysis of an economic shift at the national level, instead of analyzing single sectors decisions to change from fossil-based to biobased products.

No imports of bioproducts is considered, and no exports as well. The exports are treated only at the total products level.

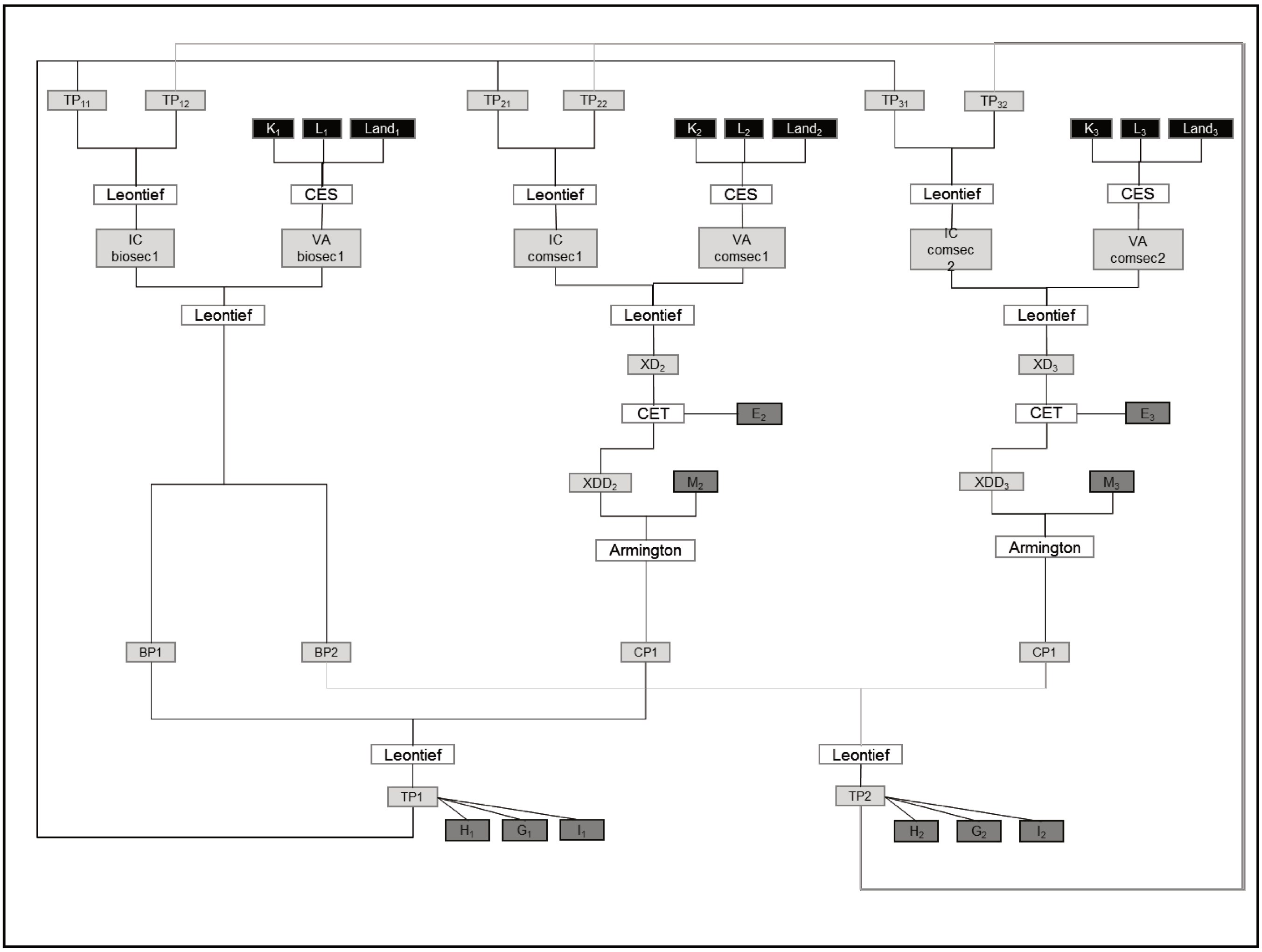



Figure 16 – Scheme of the structure of the General Equilibrium Model for a biobased economy.

The equations that describe the interactions between the agents in the markets are described below.

The bioeconomy penetration is controlled by equation 21 (generalized for *i* sectors), by changing the parameter $\theta_{i,j}$, which represents the total relative participation of a biobased product in the total output of product $TP_j$.

$$TP_j = \sum_i \theta_{i,j} \cdot BP_{i,j} + \omega_{i,j} \cdot CP_{i,j} \tag{21}$$

Where $TP_j$ is the total amount of product *j* offered in the market, $\theta_{i,j}$ is the share of bioproduct *j* coming from bio-sector *i*, and $\omega_{i,j}$ is the share of common products coming from a traditional sector (produced from fossil-based feedstock).

The production of each product in the bio-sectors is based on Leontief fixed output, in a product-based technology, as given by equation 22:

$$TP_j = \sum_i a_{i,j} \cdot BP_i \tag{22}$$

The demand of factors of production in each economic sector (capital, labor and land) is modeled by a CES (Constant Elasticity of Substitution) function, represented by equations 23 and 24a and 24b.

$$K_j = \gamma_{K_j}^{\sigma_j} \cdot (1+\omega_k) \cdot p_K^{-\sigma_j} \cdot \left(\gamma_{K_j}^{\sigma_j} \cdot (1+\omega_k) \cdot p_K^{1-\sigma_j} + \gamma_{L_j}^{\sigma_j} \cdot (1+\omega_L) \cdot p_L^{1-\sigma_j} + \gamma_{Land_j}^{\sigma_j} \cdot p_{Land}^{1-\sigma_j}\right)^{\sigma_j / 1-\sigma_j} \cdot \frac{x_j}{Q_j}$$

$$L_j = \gamma_{L_j}^{\sigma_j} \cdot (1+\omega_L) \cdot p_L^{-\sigma_j} \cdot \left(\gamma_{K_j}^{\sigma_j} \cdot (1+\omega_k) \cdot p_K^{1-\sigma_j} + \gamma_{L_j}^{\sigma_j} \cdot (1+\omega_L) \cdot p_L^{1-\sigma_j} + \gamma_{Land_j}^{\sigma_j} \cdot p_{Land}^{1-\sigma_j}\right)^{\sigma_j / 1-\sigma_j} \cdot \frac{x_j}{Q_j}$$

$$Land_j = \gamma_{Land_j}^{\sigma_j} \cdot p_L^{-\sigma_j} \cdot \left(\gamma_{K_j}^{\sigma_j} \cdot (1+\omega_k) \cdot p_K^{1-\sigma_j} + \gamma_{L_j}^{\sigma_j} \cdot (1+\omega_L) \cdot p_L^{1-\sigma_j} + \gamma_{Land_j}^{\sigma_j} \cdot p_{Land}^{1-\sigma_j}\right)^{\sigma_j / 1-\sigma_j} \cdot \frac{x_j}{Q_j}$$

Where γ is the distribution parameter for each production factor, σ is the elasticity of substitution between the production factors capital and labor; p is the price of each factor and $Q_j$ is a measure of efficiency.

With intermediate consumption and demand for production factors, there is the final output of each sector ($XD_j$). The offer of this product can be either internal ($XDD_j$), or external ($E_j$), and the choice of each producer for the fate of its product is modeled using a CET (Constant Elasticity of Transformation) function, represented by equations 25 and 26.

$$XDD_j = \gamma_{XDD_j}^{\sigma_{tj}} \cdot pDD_j^{-\sigma_{tj}} \cdot \left(\gamma_{E_j}^{\sigma_{tj}} \cdot pE_j^{1-\sigma_{tj}} + \gamma_{XDD_j}^{\sigma_{tj}} \cdot pDD_j^{1-\sigma_{tj}}\right)^{\sigma_{tj} / 1-\sigma_{tj}} \cdot \frac{XD_j}{\alpha T_j} \tag{25}$$

$$E_j = \gamma_{E_j}^{\sigma_{tj}} \cdot pE_j^{-\sigma_{tj}} \cdot \left(\gamma_{E_j}^{\sigma_{tj}} \cdot pE_j^{1-\sigma_{tj}} + \gamma_{XDD_j}^{\sigma_{tj}} \cdot pDD_j^{1-\sigma_{tj}}\right)^{\sigma_{tj} / 1-\sigma_{tj}} \cdot \frac{XD_j}{\alpha T_j} \tag{26}$$

Where $\gamma$ is the parameter of production supply distribution, pDD is the price of the product offered internally, pE is the export price, $\sigma$ is the elasticity of substitution between production destinations, and $\alpha T$ is a measure of efficiency.

To offer various products and services to end consumers, $TP_j$ (consumption by Government, Investment and Families), an option is to count on imports ($M_j$). The competition between domestically produced and imported goods is modeled by an Armington function, presented by equations 27 and 28.

$$XDD_j = \gamma_{XDD_j}^{\sigma_{aj}} \cdot pDD_j^{-\sigma_{aj}} \cdot \left(\gamma_{M_j}^{\sigma_{aj}} \cdot pM_j^{1-\sigma_{aj}} + \gamma_{XDD_j}^{\sigma_{aj}} \cdot pDD_j^{1-\sigma_{aj}}\right)^{\sigma_{aj}/1-\sigma_{aj}} \cdot \frac{X_j}{\alpha A_j} \tag{27}$$

$$M_j = \gamma_{M_j}^{\sigma_{aj}} \cdot pM_j^{-\sigma_{aj}} \cdot \left(\gamma_{M_j}^{\sigma_{aj}} \cdot pM_j^{1-\sigma_{aj}} + \gamma_{XDD_j}^{\sigma_{aj}} \cdot pDD_j^{1-\sigma_{aj}}\right)^{\sigma_{aj}/1-\sigma_{aj}} \cdot \frac{X_j}{\alpha A_j} \tag{28}$$

The parameters of the Armington functions have the same meanings as those of the CET function, but obviously with different values. pM in this case is the price of imported products.

The demand by households for goods $H_j$ is modeled by a LES (Linear Expenditure System) function, and is represented by equation 29.

$$H_j = \mu_{H_j} + \frac{\alpha_{H_j}}{(1+t(j))\cdot p_j} \cdot \left(InH - \sum_{j=1}^{n}(1 + t(j)) \cdot p_j \cdot \mu_{H_j}\right) \tag{29}$$

Where $\mu_{H_j}$ is considered the households subsistence consumption of commodity *j*, $\alpha_{H_j}$ is the distribution parameter for households, $p_j$ is the price of commodity *j*. t(*j*) is the tax rate applied to product *j* and $InH$ is the total amount of income allocated for expenses by the households.

The demand for goods by the government, $G_j$, is also modeled by a LES (Linear Expenditure System) function:

$$G_j = \mu_{G_j} + \frac{\alpha_{G_j}}{p_j} \cdot \left(InG - \sum_{j=1}^{n}(1 + t(j)) \cdot p_j \cdot \mu_{G_j}\right) \tag{30}$$

Where $\mu_{G_j}$ is understood as the government's subsistence consumption of commodity *j*, $\alpha_{G_j}$ is the distribution parameter for the government, and $InG$ is the government income.

The investments are a relationship between savings and prices of commodities.

$$I_j = \alpha_{I_j} \cdot \frac{S}{p_j} \tag{31}$$

Where $\alpha_{I_j}$ is the distribution parameter for investments, S is the savings in the economy and $p_j$ is the price for commodity *j*.

Four other set of equations are necessary in order to include the equilibrium conditions. *Zero profit*:

$$p_j \cdot X_j = p_{M_j} \cdot M_j + P_{XDD_j} \cdot XDD_j \tag{32}$$

*Income balance:*

$$S_f + \sum_j pE_j \cdot E_j = \sum_j pM_j \cdot M_j \tag{33}$$

*Market clearance of goods*:

$$TP_j = I_j + H_j + G_j + \sum_j TP_{i,j} \tag{34}$$

*Market clearance of factors*:

$$TF_n = \sum_j Factor_{n,j} \tag{35}$$

Where $TF_n$ is the total endowment of Factor *n* (capital, land or labor), and $Factor_{n,j}$ is the amount of factor *n* used by sector *j*.

The model, static, was calibrated using the System of National Accounts provided by IBGE (IBGE, 2009), and the system with the described equations (levels equations) was solved using the Newton method, within GEMPACK software. A total of 126 sectors (being 24 new bio-sectors) produce 168 products (67 products from bio-sectors).

Armington, CET and CES elasticities were taken from Tourinho et al. (2010), and income elasticities (as well as the Frisch parameter) from (Almeida 2011). Frisch parameter measures the propensity of consumers to replace consumer goods considered essential by those not considered essential. It is widely used in CGE modeling because it avoids the income elasticities to be positive, which would mean that the increase in prices would result in increase in consumption.

Unemployment is modeled based on the Phillips curve, which shows the tradeoff between unemployment and inflation in an economy.

$$\frac{p_L}{IPC} \cdot \frac{IPC'}{p_{L'}} - 1 = \varphi \cdot (\frac{Unemployment}{L} \cdot \frac{L'}{Unemployment'} - 1) \quad (36)$$

Where $p_L$ is the labor price, CPI is the consumer price index, $\varphi$ is a phillips curve coefficient, L is the total labor endowment, and Unemployment is the unemployment rate. $p_L{}'$, IPC$'$, L$'$ and unemployment$'$ are the initial values (in 2009) for the correspondent variable.

In this sense, if labor remuneration price falls in relation to the inflation, unemployment increases. This reflects the workers choice to get a job or not, based on the value of their work. If their salary decreases (fall of remuneration prices) in relation to their expenses, employees are not encouraged to work anymore, increasing unemployment. Figure 17 shows the relationship between unemployment and real income increase from 2001. The correlation fits the characteristics of a Philips curve.

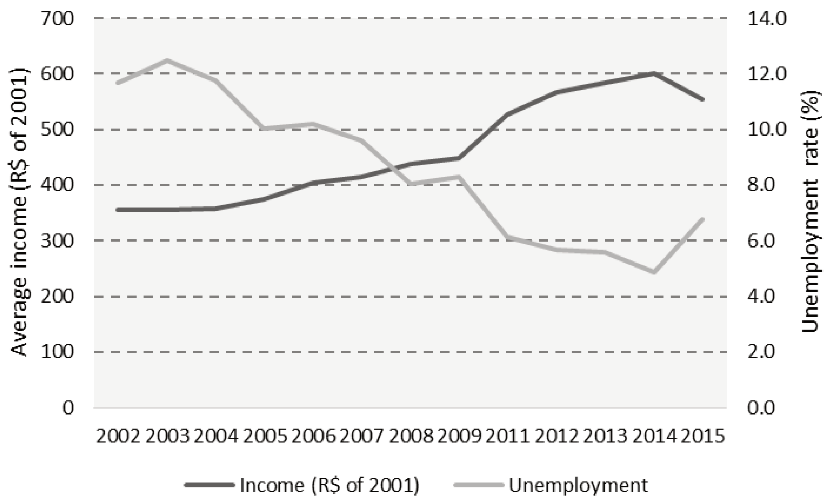



Figure 17 – Relationship between unemployment and income in Brazil from 2001 and 2015. Source: (IBGE 2017b)

The use of the Phillips curve as a policy guide has been refuted by several authors, as mentioned in Chletsos et al. (2016), however, its use in economic modeling has been proven in Rocheteau et al. (2007) as a plausible idea: “inflation is a tax on economic activity that uses cash, and so if either labor-intensive goods are substitutes for this activity or leisure is complementary with this activity, inflation reduces unemployment".

The exogenous variables of the model are chosen based on the aims of the research. For this study, the exogenous variables are:

- Taxes rates: Household consumption, Income and Imports taxes;
- Exchange rate;
- Technical coefficients $\theta_{i,j}$: control of the biobased economy participation;
- Technology parameters (production efficiencies);
- International price of imports (pM);
- International price of exports (pE);
- Government savings (S);
- Government transfers (social security, pensions, welfare programs);
- Government subsistence consumption ($\mu_{G_j}$);
- Cobb-Douglas exponents for Investments done by households, the government and sectors;
- Household marginal propensity to save;
- Household subsistence consumption ($\mu_{H_j}$) ;
- Total endowment of three primary factors (capital, labor and land);
- Consumer Price Index (numeraire): the choice of this variable as numeraire is based on the ease of interpretation of changes in income.

The remaining variables (prices and quantities of commodities) are taken as endogenous:

- Total household consumption;
- Total government consumption;
- Total investments;
- Total exports;
- Total imports;
- Unemployment;
- Commodities price;
- Total sectorial production;
- Government income;
- Prices of production factors;

- Sectorial use of production factors (except land in livestock, which is endogenous).

The mix between biobased versus fossil-based products will depend on the scenarios being analyzed, and the simulation action is changing the θ parameter of the blending sectors. The higher the parameter, higher the share of a certain biobased product. Projections of the final demand, which is due to expenditures by the government, by households, investment and exports were done based on GDP projections and historic components participation. With the GDP projections for Brazil (USDA 2015), final demand components were calculated for 2030, changing the exogenous variables until the targets were met. Other variables projected for 2030 are shown in Table 16.

Table 16 – Targets and parameters of Brazilian economy in 2030

| Variable | 2010-2030 increase | 2030 target |
|---|---|---|
| **GDP (Billion US$ of 2010)[a]** | 53.94% | 3,161.2 |
| **Economically active population (Million people)[b]** | 17.96% | 116.9 |
| **Households (Billion US$)[d]** | 52% | 1,581 |
| **Government (Billion US$)[d]** | 37% | 489,998 |
| **Investments (Billion US$)[d]** | 76% | 500,708 |
| **Livestock land use (Mha) [e]** | -14% | 157 |

[a] (USDA 2015)
[b] (Alves et al. 2010)
[c] (INPE 2017; Brasil 2015)
[d] (IBGE 2017e)
[e] (Moreira et al. 2016)

Targets for the components of the final demand (household consumption, government consumption and investments) were calculated using historic data of the use and resources tables that presented the same aggregation level and used the same methodology of the National Account System. An average of the years 2000-2013 was used (IBGE 2017e). In this period, household's consumption represented 59.7% (± 2.4) of the final demand, while government consumption represented 19% (± 1.9) and investments 18.7% (± 7.7%). Exports and imports were calculated based on the investments targets, since one component of the investments is the external savings (Imports minus exports).

The several exogenous variables were changed in order to achieve these targets in the Business-as-Usual scenario. No differences in population nor in land availability (for agriculture and livestock) exist between scenarios; therefore, the comparisons are based only on the increase of the share of biobased chemicals and energy in the countries' economy. The differences among scenarios are discussed in detail in section 4.5.

The model accounts for subsidies, which are treated as direct negative tax on total output of sectors ($X_j$), following the same method as the National Accounts System (IBGE 2017e). Subsidies are used in this thesis as a mechanism to compensate for the negative cash flows of the biorefineries, guarantying their economic feasibility. This allows analyzing the public expenditures necessary to boost the bioeconomy, in addition to the required private investments.

Whether or not subsidies are required depends first on the costs of BBE options versus the fossil reference and consequently on the oil price (and to some extent natural gas and coal). Costs of BBE options have been compared to their fossil counterparts in a number of publications as in Hermann & Patel (2007), van den Wall Bake et al. (2009) and Saygin et al. (2014). The authors show that ethanol from sugarcane can compete already against oil prices of about 38 U$/barrel, without subsidies, and will be more competitive in the future with its learning potential. The same is true of the advanced BBE options, which also depends on the efforts on technological learning, research and development. The static models in this thesis, however, do not allow the analysis of the subsidies requirements in the case of higher oil prices.

### *4.1.1. Land use modeling*

The increase in demand for biomass, for several different purposes, can lead to an increase in demand for arable land, depending strongly on the ability of stakeholders to increase yields in faster paces.

To capture the changes in land use, it is necessary to model the land factor in an explicit way. One approach to land-use modeling is to treat land as a homogenous factor of production in the agricultural sector, considering that it is fixed in supply (Kretschmer & Peterson 2010). This can be addressed in different ways, based on the primary factors and their elasticities of substitution. The basic proposition is that all primary factors appear in the same nest, followed by assuming that land is nested together with capital-labor composite, or that land is nested with capital, or even that land is nested with labor. Figure 18 shows the possible combinations.

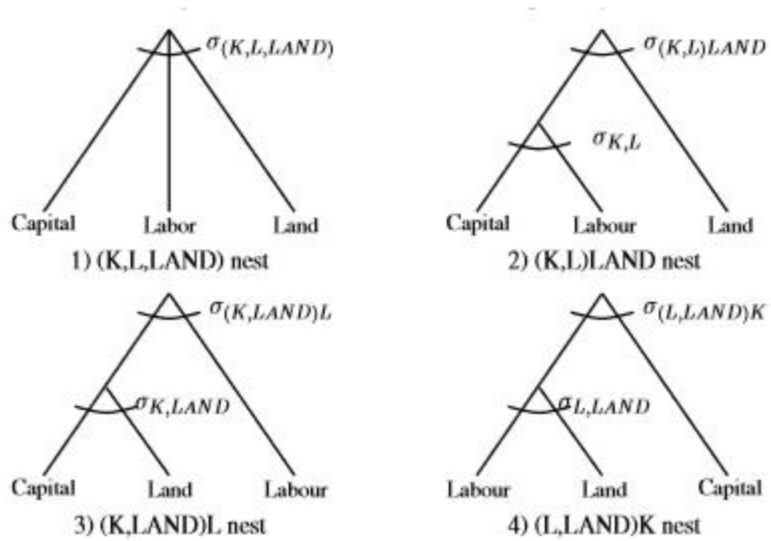



Figure 18 – Nest structure for the three production factors. 1) Same nest; 2) Land nested with capital-labor composite; 3) Land nested with capital and 4) Land nested with labor.
Source: Simola (2013)

In this study, land use is modeled following the same assumptions as in Ferreira Filho (2015), who consider land in the same nest as capital and labor (Figure 18 – 1). Land compensation data is extracted from GTAP database.

Total land endowment (amount of land available for agricultural and livestock use) follows the decrease in land use for livestock, provided by (Moreira et al. 2016), and the increase in agricultural yields provided by (MAPA 2016), and (Cardoso 2014) shown in table 17.

Productivity increases in agricultural and livestock production have been the aim of several studies and have a wide variety of results, especially in global comparisons. Gerssen-Gondelach et al. (2017) show that higher yields in beef production are still possible over 1.3 heads/ha, and, in some world regions, productivity can be 5 times higher. FIESP (2016) also projects a productivity of 1.3 heads/ha, but with faster increments, reaching this level already in 2026.

Corn and soy also show realistic increases in productivity. Bhattarai et al. (2017) show similar yields for soy (around 3.3 ton/ha) in the USA, but Brazil has a difficult challenge of reaching soy productivity beyond 3 ton/ha, as mentioned in MAPA (2016). Corn, on the other hand show room for increase in the second harvest, as a rotation crop interleaved mostly with soy. This is tendency in Brazil, and land use for first harvest corn has been dropping, going from 8.8 to 5.5 Million hectares in 2015, while second harvest has gone from 4.5 to 9.9 million hectares (IBGE 2017c).

Sugarcane productivity follows is the most optimistic of projections, since sugarcane productivity in Brazil has gone from 81 tons/ha in 2009, to 72.6 ton/ha in 2016. Regardless of the actual evolution of productivity, Cardoso (2014) projects a 91.3 ton/ha productivity, which is compatible with other studies, as Lapola et al. (2009) reaching 103 ton/ha, and Carvalho et al. (2015) with potential to reach 100 ton/ha.

Table 17 – Productivity increase for 2030 for main agricultural crops and livestock

| Crop/product | Total area in 2009 (x$10^6$ ha) | Current values (t/ha) | 2030 values (t/ha) |
|---|---|---|---|
| **Rice** [a] | 2.9 | 5.5 | 11 |
| **Cotton** [a] | 0.8 | 1.53 | 2.08 |
| **Grains** [a] | 3.6 | 3.38 | 3.89 |
| **Corn** [a] | 8.8 | 4.84 | 5.76 |
| **Soy** [a] | 21.7 | 2.88 | 3 |
| **Sugarcane** [b] | 8.8 | 81 | 91.3 |
| **Livestock** [c] | 183 | 1.1 | 1.3 |

[a] MAPA (2016). Corn reports only the first crop area. Grains do not include soy and corn.
[b] Current values based on (CONAB 2010a), and 2030 values based on Cardoso (2014).
[c] Based on the land use and total production in (Moreira et al. 2016). Productivity values in heads/ha.

The model allows exogenous changes in productivity regarding land, but also endogenous changes regarding all three factors of production Capital, Labor and Land, which changes the overall cost structure of the agricultural and livestock sectors.

### *4.1.2. From national to regional – The regionalization of impacts*

This thesis uses two models in two different geographic levels: CGE at the national level, and the I/O model at the regional level.

Two main components of the results from the CGE model have to be regionalized in different ways. First, the production of the bio-sectors ($X_i$), and the final demand for each product of the economy.

In order to spread the results, a solid reference had to be used. Since the bio-sectors use agriculture as feedstock, it is reasonable to limit their activities to the regions where it is possible to grow those crops (Sugarcane, Soy, Eucalyptus and Pine) based on the suitability of production regarding regional conditions, yet, the economic model does not consider that. Meaning, the economic model does not look for the best options of land use for each crop, since it is not an allocation model. Therefore, the previous work of Verstegen et al. (2016) using a land use change model with physical aspects was chosen to serve as basis of the allocation of the bio-sectors. Verstegen et al. (2016) projects the direct and indirect land use change in Brazil due to an increase in biofuels demand. Their work is based on the integration of two models, a global computable general equilibrium and a land use change model. The land use model PLUC is calibrated using 2007-2012 data based on trends per land-use type. The CGE model projects the supply and demand of all commodities in all world regions up to 2030 and the areas they occupy. This information is then input for the spatially explicit land-use change projections up to 2030.

It is no surprise that different total areas for each crop and consequently for the whole country were found between this thesis and the authors work. Even so, the share of each macroregion was used to allocate the nationally aggregated information on land use. Therefore, the biorefineries were regionalized using Verstegen et al. (2016) regional shares. Moreover, interregional agricultural coefficients in the input-output model were corrected to assure that the resulting regional production was compatible with the regional shares in the abovementioned reference.

Table 18 shows the shares of each region for each type of basic configuration. The description of types of basic configuration can be found in section 3.2.1.

Table 18 –Regional share of output of each biorefinery basic configuration

| % | SE | S | CW | NE | N | Total |
|---|---|---|---|---|---|---|
| **1G and 1G2G sugarcane based** | 50.42 | 5.62 | 30.85 | 10.59 | 2.52 | 1.00 |
| **Biodiesel** | 8.45 | 27.95 | 32.88 | 21.50 | 9.21 | 1.00 |
| **2G SRC[a] based** | 21.41 | 20.67 | 6.55 | 42.81 | 8.56 | 1.00 |

[a] Eucalyptus and pine

From the description of the I/O model in the next section, one finds that the final demand for every product (common products, other products of the economy, bioproducts and total products) are exogenous to the model. On that account, the regionalization of the final demand had to be addressed differently than the $X_i$ of the bio-sectors.

Each region in Brazil has a different path of development, and consequently they have different projections to how much they can grow. For example, the room for development in the Northeast and the Center-West is much larger than other regions that already achieved reasonable quality of life. However, due to lack of better references, the same regional structure in 2009 was used in 2030.

## 4.2. Input-Output Analysis

Formulated by Wassily Leontief in the 1930s, the input-output model describes the flow of money between the productive sectors in an economy. Its first application was to show the inter-sectoral relations in the US economy in two periods: first, in 1919, and later in 1929 (Miller & Blair 2009). Since then, the model has been used in several studies in applied economics, regional economics, in energy and the environment.

Miller and Blair (2009) describe the basics of the input-output analysis. An economy can be determined by the interaction of its sectors, covering a network of transactions among the productive sectors, which can be widely diversified, depending on its development stage. The application of the comparative static analysis allows the evaluation of the generated impacts due to economic changes or insertion of one or more technologies, comparing the previous scenarios with the ones obtained. Here, the described methodology is based on Cunha (2011) and Cardoso (2014). A simplified version of an economy is shown in Figure 19, which shows the intersectional transactions of an economy with three sectors.

| | S1 | S2 | S3 | Household consumption | Government consumption | Exports | Investments | Total |
|---|---|---|---|---|---|---|---|---|
| **S1** | $z_{1,1}$ | $z_{1,2}$ | $z_{1,3}$ | $H_1$ | $G_1$ | $E_1$ | $I_1$ | $X_1$ |
| **S2** | $z_{2,1}$ | $z_{2,2}$ | $z_{2,3}$ | $H_2$ | $G_2$ | $E_2$ | $I_2$ | $X_2$ |
| **S3** | $z_{3,1}$ | $z_{3,2}$ | $z_{3,3}$ | $H_3$ | $G_3$ | $E_3$ | $I_3$ | $X_3$ |
| **Imports** | $Imp_1$ | $Imp_2$ | $Imp_3$ | $Imp_H$ | $Imp_G$ | | $Imp_I$ | IMP |
| **Taxes** | $T_1$ | $T_2$ | $T_3$ | | | | | T |
| **Value added** | $W_1$ | $W_2$ | $W_3$ | | | | | W |
| **Employment** | $L_1$ | $L_2$ | $L_3$ | | | | | |
| **Total** | $X_1$ | $X_2$ | $X_3$ | F | G | E | I | |

Figure 19– Scheme of the input-output matrix for three sectors (S1 to S3).
Source: Cardoso (2014)

Where:

$S_i$: Sector of the economy *i*

$z_{i,j}$: Production from sector *i* used as intermediate input used by sector *j*

$H_i$: Household consumption of sector *i*

$G_i$: Government expenses with sector *i*

$E_i$: Total exports by sector *i*

$I_i$: Demand of investment goods produced by sector *i*

$X_i$: Total domestic production of sector *i*

$Imp_j$: Imports done by sector *j*, and total imports (IMP)

$T_j$: Total indirect taxes payed by sector *j,* and total indirect taxes (T)

$W_j$: Value added generated by sector *j*, and total value added (W)

These variables are bound by equation 37.

$$\sum_{i=1}^{n} z_{i,j} + F_i + G_i + I_i + E_i = X_i \quad (37)$$

Equation 37 shows that the production value of each sector *i* ($X_i$) is the sum of inputs provided to other sectors ($z_{i,j}$), the household consumption of products from sector *i* ($H_i$), the expenses of the government with sector *i* ($G_i$), the demand for investment goods produced by sector *i* ($I_i$) and the total amount exported by sector *i* ($E_i$). In an input-output matrix, the variables $F_i$, $G_i$, $I_i$ and $E_i$ can be aggregated as a final demand vector $Y_i$; and the value added W corresponds to the remunerations of production factors labor, capital and land (Cunha, 2011).

With the variables defined, it is also possible to establish direct technical coefficients of production (in monetary terms). The technical coefficient indicates the amount of inputs that a sector *j* uses from sector *i* for the production of one monetary unit of products from sector *j*, as shown in equation 38.

$$a_{i,j} = {}^{z_{i,j}}/_{X_j} \qquad (38)$$

Equations 37 and 38 can be rewritten as:

$$\sum_{i=1}^{n} a_{i,j} \cdot X_j + Y_i = X_i \qquad (39)$$

Transforming to the matrix form, it becomes:

$$A.X + Y = X \qquad (40)$$

Solving equation 40 for $X$ as a function of $Y$, the total value of production to satisfy the final demand and the intermediate consumption ($z_{i,j}$) would be:

$$X = (I - A)^{-1} \cdot Y \qquad (41)$$

Where $I$ is an identity matrix of order $n$ and $(I - A)^{-1}$ is the Leontief matrix.

In Input-Output analysis, two basic hypothesis are taken in relation to the type of production and the participation of the sector in the total market:

1) Product-based technology: The share of each product in total production is constant in relation to the total sectoral value of production;
2) Industry-based industry: Each sector has a constant market share of the products produced.

   A mixed technology hypothesis can be assumed, i.e., a combination of product-based and industry-based technologies. In this thesis, this approach was adopted to allow the inclusion of new biorefinery-based sectors, in which multiple products are produced in fixed proportions (product-based), into the economy, with fixed market shares of each sector (industry-based).

To better understand the mixed-technology hypothesis, an exemplifying reduced model, divided into Use (U) and Production (V) matrices, representing the implemented model, is shown in Figures 19 and 20. It also allows identifying the possible exogenous and endogenous variables in the model that portray the economy with mathematical and economic logic, with the insertion of the desired biorefineries in the economy. Exogenous variables are those chosen by the modeler to receive a certain chock, while endogenous variables are the outcome of a model, as a response to the solution of the equation system. In this thesis, an important exogenous variable is the amount produced by each biorefinery (bio-sector). The choice of exogenous and endogenous variables is called the model closure, and it will be detailed in the end of this section.

| U | | Biosector1 | Biosector2 | Comsector1 | Comsector2 | Blend1 | Blend2 | Blend3 | ROE | E |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Bioprod$_1$** | | | | | Z1 | | | | $E_1$ |
| **Biosector1** | **Bioprod$_2$** | | | | | | Z4 | | | $E_2$ |
| | **Bioprod$_3$** | | | | | | | Z7 | | $E_3$ |
| | **Bioprod$_1$** | | | | | Z2 | | | | $E_4$ |
| **Biosector2** | **Bioprod$_2$** | | | | | | Z5 | | | $E_5$ |
| | **Bioprod$_3$** | | | | | | | Z8 | | $E_6$ |
| | **Comprod$_1$** | | | | | Z3 | | | | $E_7$ |
| | **Comprod$_2$** | | | | | | Z6 | | | $E_8$ |
| | **Comprod$_3$** | | | | | | | Z9 | | $E_9$ |
| | **Totprod$_1$** | $u_{10,1}$ | $u_{10,2}$ | $u_{10,3}$ | $u_{10,4}$ | $u_{7,5}$ | $u_{7,6}$ | $u_{7,7}$ | $u_{10,8}$ | $E_{10}$ |
| | **Totprod$_2$** | $u_{11,1}$ | $u_{11,2}$ | $u_{11,3}$ | $u_{11,4}$ | $u_{8,5}$ | $u_{8,6}$ | $u_{8,7}$ | $u_{11,8}$ | $E_{11}$ |
| | **Totprod$_3$** | $u_{12,1}$ | $u_{12,2}$ | $u_{12,3}$ | $u_{12,4}$ | $u_{9,5}$ | $u_{9,6}$ | $u_{9,7}$ | $u_{12,8}$ | $E_{12}$ |
| | **OP** | $u_{13,1}$ | $u_{13,2}$ | $u_{13,3}$ | $u_{13,4}$ | $u_{10,5}$ | $u_{10,6}$ | $u_{10,7}$ | $u_{10,8}$ | $E_{13}$ |
| | **Imports** | $Imp_1$ | $Imp_2$ | $Imp_3$ | $Imp_4$ | $Imp_5$ | $Imp_6$ | $Imp_7$ | $Imp_8$ | $Imp_E$ |
| | **Taxes** | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | $T_6$ | $T_7$ | $T_8$ | |
| | **Value added** | $W_1$ | $W_2$ | $W_3$ | $W_4$ | $W_5$ | $W_6$ | $W_7$ | $W_8$ | |
| | **Employment** | $L_1$ | $L_2$ | $L_3$ | $L_4$ | $L_5$ | $L_6$ | $L_7$ | $L_8$ | |
| | **$X^t$** | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_7$ | $X_8$ | |

Figure 20 – Exemplifying reduced model –Use matrix (U).

Considering a model able to simulate eight sectors and 13 products, the U matrix shown in Figure 20 includes two bio-sectors, representing the biorefineries included in the economy; three bioproducts, representing the products produced in the biorefinery; two common sectors, which represent current technologies and current feedstock to produce the concurrent products, and three common products (here called common, because it is produced via current petro-based technologies) that will concur with the bioproducts (for example, ethylene from fossil resources is a common product produced in a common sector, as an oil refinery, but could compete with ethylene produced from biomass in a biorefinery). The model also incorporates hypothetical blending sectors. The three blending sectors represent virtual agents which combine all the similar products (but from different feedstock, biobased and petro-based) to become one single aggregation of the products to the end consumer. The aggregated products are represented by the three total products. For example, the bio-sectors 1 and 2 produce the bioproduct 1, which is equivalent to the common product 1. The blending sector 1 is responsible for consuming (receiving) these three products and making a final total product 1. This structure allows the analysis of an economic shift at the national/regional level, instead of analyzing single sector decisions to change from fossil-based to biobased products. The model also includes one "rest of the economy" sector (ROE) and one "other products" (OP) to represent other economic sectors and their activities.

Summarizing, in the U matrix the parameters represent:

$u_{i,j}$: Amount of product *i* used by sector *j* as input;

$X_j$: Production value of sector *j*;

$E_i$: Final demand for product *i*;

$Q_i$: total production of product *i*;

$Z_n$: Amount of product *i* sent to the blend sector *j*.

Three sets of equations are drawn from U matrix, in figure 20.

First set deals with the "Total Products" ($Totprod_i$) and the "Other Products" of the economy (OP), following line *i* ($10 \leq i \leq 13$); the sum of the elements $u_{i,j}$ and $E_i$ result in the total amount of product *i* consumed, as in equation 6.

$$\sum_j u_{i,j} + E_i = Q_i \text{ (with } 10 \leq i \leq 13) \quad (42)$$

Where *i* equals 10 is the first total product, and 13 is the aggregation of the other products of the economy.

From the *U* matrix, it is possible to calculate the technical coefficients of the intermediate consumption for each sector:

$$b_{i,j} = \frac{u_{i,j}}{X_j} \quad (43)$$

Being $b_{i,j}$ the amount used by sector *j* of product *i* to produce one monetary unit. The direct technical coefficient matrix of the sectors in relation to the products is defined by:

$B = [b_{i,j}]$

Equation 42 and Equation 43 can be rewritten as:

$$\sum_j b_{i,j} \cdot X_j + E_i = Q_i \text{ (with } 10 \leq i \leq 13) \quad (44)$$

Which, in the matrix form, correspond to

$$B.X + E = Q \tag{45}$$

The second set deals with the consumption of the competing sectors in analysis: the bio-sectors and the conventional sectors, responsible for the production of the bioproducts and the traditional products, respectively.

$$Z_i + E_i = Q_i \text{ (with } 1 \leq i \leq 9) \tag{46}$$

Where $i$ equals 1 is the first bioproduct ($Bioprod_1$) and 9 represents the last common product ($Comprod_3$).

The third set states that the value of production in the blending sectors equals the intermediate consumption of competing products:

$$Blend_j = \sum_{i=j.n-2}^{j.n} Z_i \text{ with } (1 \leq j \leq 2) \text{ and n=3} \tag{47}$$

From the production side, the production matrix ($V$) in Figure 21 derives three sets of equations, regarding the outputs of the bio-sectors, traditional sectors, as well as the virtual blending sectors.

| **V** | **Biosector1** | | | **Biosector2** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **$Bioprod_1$** | **$Bioprod_2$** | **$Bioprod_3$** | **$Bioprod_1$** | **$Bioprod_2$** | **$Bioprod_3$** | **$Comprod_1$** | **$Comprod_2$** | **$Comprod_3$** | **$Totprod_1$** | **$Totprod_2$** | **$Totprod_3$** | **OP** |
| **Biosector1** | $c_{1,1}.X_1$ | $c_{1,2}.X_1$ | $c_{1,3}.X_1$ | | | | | | | | | | |
| **Biosector2** | | | | $c_{2,4}.X_2$ | $c_{2,5}.X_2$ | $c_{2,6}.X_2$ | | | | | | | |
| **Comsector1** | | | | | | | $d_{3,7}.Q_7$ | $d_{3,8}.Q_8$ | $d_{3,9}.Q_9$ | | | | |
| **Comsector2** | | | | | | | $d_{4,7}.Q_7$ | $d_{4,8}.Q_8$ | $d_{4,9}.Q_9$ | | | | |
| **Blend1** | | | | | | | | | | 1 | | | |
| **Blend2** | | | | | | | | | | | 1 | | |
| **Blend3** | | | | | | | | | | | | 1 | |
| **ROE** | | | | | | | | | | | | | $d_{8,13}.Q_{13}$ |

Figure 21 – Exemplifying reduced model – Production matrix ($V$)

The bio-sectors follow the product-based technology, which means that the sum of the value of production of each product equals the total value of production of the sector, with:

$$\sum_{j=1}^{3} c_{i,j} = 1 \text{ with } (1 \leq i \leq 2) \tag{48}$$

Where $i$ represent the two new bio-sectors available in the economy.

Resulting in the equation for each quantity of output for products:

$$Q_j = c_{i,j} \cdot X_j \tag{49}$$

Which, in the matrix form, becomes:

$$Q = C^{\mathrm{T}}.\, X \tag{50}$$

The rest of the economy, on the other hand, follows the industry-based technology, with:

$$\sum_{j=7}^{9} d_{i,j} = 1 \text{ (with } 3 \leq i \leq 4) \tag{51}$$

Where *j* is the number of the products (7 and 9 represent the common products), and *i* represents the sectors (3 and 4 are the common sectors).

The hypothesis that the "rest of the economy" (ROE) produces the remaining "other products" (OP) in the economy is a simplified aggregation of sector and products, following the same definition in equation 51. Equation 52 shows the production value of each sector as a function of the amount of products produced:

$$X_i = \sum_{j=7}^{9} d_{i,j} \cdot Q_j \text{ (with } 3 \leq i \leq 4) \tag{52}$$

Which, in the matrix form, correspond to

$$X = D.Q \tag{53}$$

Finally, the production matrix (*V*) indicates that the total products are only delivered by the blending sectors:

$$Blend_i = Totprod_j \tag{54}$$

Having defined the equations for the exemplifying model (total of 28), the total number of variables is 43: eight sectoral values of production ($X_j$), 13 total production of products ($Q_i$), 13 final demand for products ($E_i$) and nine intermediate consumption by the blending sectors ($Z_i$). This requires 15 exogenous variables. These assumptions, presented in an exemplifying model for a single region, can be expanded to an inter-regional model. The inter-regional model presents the exchanges within and between regions, expressed in fluxes of goods and services for the intermediate consumption, as well as for final demand (Cardoso, 2014). In the model of this thesis, there are five regions included, according to the macro-regions in Brazil, as schematic shown in Figure 22: Southeast, South, Center-west, Northeast and North.

| | | Sectors | | L | M | |
|---|---|---|---|---|---|---|
| | | Region L | Region M | | | |
| Sectors | Region L | Intermediate consumption LL | Intermediate consumption LM | Final demand LL | Final demand LM | Total production L |
| Sectors | Region M | Intermediate consumption ML | Intermediate consumption MM | Final demand ML | Final demand MM | Total production M |
| | | Imports L | Imports M | | | |
| | | Taxes L | Taxes M | | | |
| | | Added value | Added Value | | | |
| | | Total production L | Total production M | | | |

Figure 22 – Scheme of inter-regional input-output relationships.
Source: Cardoso (2014).

Thus, the number of variables and equations depend on the number of regions, bio-sectors and bio-products considered, common sectors (already present in the economy) and common products (already produced in the economy from conventional feedstock). It is important to highlight that the number of blending sectors and total products depend on the number of bio-products and the number of regions considered.

The final step is to define the closure of the model, and which variables will be shocked. The choice of exogenous variables must be appropriate to what is being assessed with the model; the choice of exogenous and endogenous variables is called model closure, which should allow the mathematical resolution and be coherent with the economic reality (Cunha, 2011).

Table 19 shows a summary of the equations in the model developed for this thesis.

Table 19 – Summary of equations in the developed model

| **Equation group** | **Matrix** | **Number of equations** |
|---|---|---|
| | **Conventional sectors** | |
| $\boldsymbol{B.X + E = Q}$ | $U$ | 605 |

| | | |
|---|---|---|
| $\boldsymbol{X = D.Q}$ | $V$ | 510 |
| **Bio-sectors** | | |
| $\boldsymbol{Z_i + E_i = Q_i}$ | $U$ | 2145 |
| $\boldsymbol{Q = C^t.X}$ | $V$ | 2090 |
| **Blending sectors** | | |
| $\mathbf{Blend}_j = \sum \mathbf{Z}_i$ | $U$ | 55 |
| $\mathbf{Blend}_j = \mathbf{TP}_i$ | $V$ | 55 |

In this thesis, the exogenous variables are: final demand for products (2750 $E_i$), and the value of production of the bio-sectors included in the economy (190 $X_j$ ). Table 20 shows the variables involved in the model.

Table 20 – Summary of variables in the model

| Variables | Name of variables | Number of Variables |
|---|---|---|
| **Sectorial value of production** | $Blend_j$ | 55 |
| | $X_j$ | 510 |
| **Total production of each product** | $TP_i$ | 55 |
| | $Q_i$ | 2695 |
| **Products final demand** | $E_i$ | 2750 |
| **Intermediate consumption by blending sectors** | $Z_i$ | 2145 |

### *4.2.1. Brazilian regions: Regional differences in the country*

Brazil is a continental country with an extension of 8.5 x$10^6$ km² and is divided in 5 regions (shown in figure 23) since 1970 (IBGE 2017a).


Figure 23 – Brazil and its regions.

These five regions vary greatly in population, economic activities and development. The Southeast (SE) region is the most developed region in terms of GDP, with 55% of the GDP. South (S) is the second richest region (based on GDP) but still 70% lower than SE, representing 17% of the countries' GDP, followed by the Northeast (NE) (13%), Center-West (CW) (9%) and North (N) (5%) (Ipeadata 2017a). SE also has the highest GDP per capita, being 173% higher than the NE, the lowest GDP per capita in the country. SE is followed by the Center-west (CW) in GDP per capita, 2% lower than SE, and then the South, 14% lower than the SE (Ipeadata 2017c).

Population wise, SE is the most populous region, with 80 million inhabitants, in contrast with 14 million in the Center-west, the least populated region (Ipeadata 2017d). N region is slightly more populated than the CW, with 16 million inhabitants, but it is 3 times bigger in area

(Francisco 2017). NE is the second most populous region (53 million), followed by the South (27 million) (Ipeadata 2017d).

In agricultural production, SE has the highest share, with 27% of the agricultural outcome (Ipeadata 2017b). Followed by the South (25%), Center-west (19%), Northeast (18%) and the North with 9%.

Regarding the oil-refining sector, there is a concentration of refineries in the SE, S and NE. SE houses 6 refineries, followed by NE and S with 4. North region has only 1 refinery, focused on energy production and asphalt (Petrobras 2017). The basic petrochemicals (like ethylene, propylene and aromatics) are produced only in the SE, S and NE region (Braskem 2017), while acrylic acid and n-butanol are only produced in the NE region (BASF 2012; Natalense 2013)

## 4.3. Economic Input-Output Life cycle assessment (EIO - LCA)

LCA is defined in ISO 14040 as “compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle”. This translates as the environmental weight of products or services at the different phases of production or formulation (Guinée et al. 2001). Moreover, LCA is a tool to analyze and assess the environmental impacts over the entire life cycle of a product or service (Joshi 2000). This is called process-based Life Cycle Assessment, which describes activities in a bottom-up manner, in a more detailed and deeper understanding at the product level. The advantages of the process-based LCA is that it can answer questions concerning materials and energy balances of each facility studied, while the disadvantage lies on the difficulty to properly draw the process boundaries, normally excluding many relevant inputs to activities within the overall system (Joshi 2000; Matthews et al. 2013; Majeau-Bettez et al. 2011).

On the other hand, in an EIO-LCA, or Environmental Extended Input-Output (EEIO), the specific system boundary is not required, since the boundary is the entire economy itself. In comparison with process-based LCA, EIO-LCA is considered quick and inexpensive, since it is not necessary to gather data for every process. On the other hand, it is less detailed and specific, since it considers the aggregated information, based on the productive sectors of an economy (Matthews et al., 2014).

The basic EIO-LCA follows the flow chart in Figure 24.

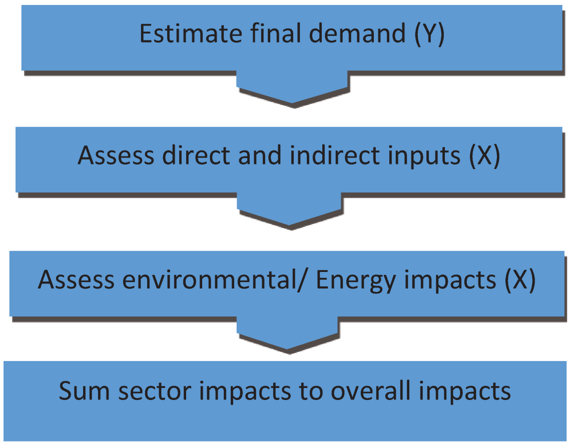



Figure 24 – Flow chart for EIO – LCA model.
Source: Matthews et al. (2013)

In this thesis, instead of calculating the total environmental impacts by sector (X), the impacts are divided in two parts: The first part when the environmental burdens are related to the sectorial levels of activities, and when they are related to the use of certain products.

The vector of sectorial outputs to meet an exogenous demand $X_j$ (n x 1) is obtained by equation 5, presented in the previous section. From the sectorial, the total amount produced of each product ($Q_i$) will depend on the output coefficients in the case of bio-sectors, or in the market share of each sector, in the case of the common products. With the $X_j$ vector of sectorial production and the $Q_i$ vector of products, the input-output technique can be extended to environmental analysis. Let $\boldsymbol{r_X}$ be a k x n matrix, where k is the number of environmental burden of interest in this case 2, GHG emissions in tons of $CO_2e$ and Non-Renewable Energy Use (NREU), in mega Joules (MJ). Here, n is the total amount of sectors, in this thesis 151 sectors per region. Now let $r_Q$ be a k x m matrix, where k is 2 (as $r_X$), representing two environmental burdens analyzed (emissions and non-renewable energy use). In addition, m is the total number of products, which is 550 per region in this thesis. Then, equation 55 represents the total of each environmental burden (GHG and NREU) (Joshi 2000).

$$\begin{bmatrix} GHG_{tot} \\ NREU_{tot} \end{bmatrix} = r_{X\ (2xn)} \cdot X_{j\ (nx1)} + r_{Q\ (2xm)} . Q_{i(mx1)} \qquad (55)$$

Equation 19 does not allow for double counting. Meaning, sectors that are accounted for in the sectorial emissions will not have emissions calculated for the products they produce. The opposite is also true, that is, products that have their emissions calculated in their use will not be accounted for in the sectorial emissions. NREU calculations follow the same rules.

In this thesis, emissions are calculated on the basis of sectorial activity for the following sectors: Ethylene production, steel production, resins production, other organic chemicals production, inorganic chemicals production, non-ferrous metals production, cement production, electric equipment production, coal, oil, natural gas, oil refining, swine production and paper and celluloses production.

The emissions are calculated based on product use for the following products: agricultural production, fertilizers use, fuels and caustic soda.

For the calculation of environmental coefficients $r_X$ and $r_Q$, two approaches were used. One for GHG emissions, and another one for NREU calculations.

For the calculation of emission factors, in turn, two approaches were used. One for the bio-sectors of interest, and another for the rest of the economy.

For the bio-sectors, the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* were used for two operations: the combustion of biomass for heat and power generation, and the leakage emissions from biogas production. Equation 56 (as defined in Tier 1) shows the emissions from combustion of biomass (Gomez & Watterson 2006). Only $CH_4$ and $N_2O$ are accounted for, since $CO_2$ is considered biogenic:

$$Emissions_{GHG,fuel} = Fuel\ consumption_{fuel} \cdot Emission\ Factor_{GHG,fuel} \quad (56)$$

Where $Emissions_{GHG,fuel}$ is the emissions of a given GHG by type of fuel (kg GHG), $Fuel\ consumption_{fuel}$ is the amount of fuel combusted (TJ) and $Emission\ Factor_{GHG,fuel}$ is default emission factor of a given GHG by type of fuel (kg gas/TJ). In this thesis, the basic fuels for the biorefineries (bio-sectors) are bagasse, sugarcane straw and biogas, in sugarcane based biorefineries. For eucalyptus-based biorefineries, bark and crown branches are used, while in pine based biorefineries the availability of tops, branches and leaves are used for heat and power generation. Biogas is produced whenever biodigestible material is available (vinasse and unfermented juices).

In biogas production, emissions of $CH_4$ from unintentional leakages during process disturbances or other unexpected events are generally between 0 and 10% of the amount of $CH_4$

generated. A default value of 5% was used (based on Tier 1 of IPCC), in the absence of more specific data (Pipatti 2006).

When the own process emits GHGs other than in energy conversion, the correspondent emission factor was taken from literature. Equation 57 shows the final GHG emission per biorefinery configuration.

$$Emissions_{GHG} = Emissions_{GHG,fuel} + Emissions_{leakage} + Emission\ factor_{GHG,process_i} \cdot Q_i \quad (57)$$

Where Emission factors for the process *i* are shown in table 21. $Q_i$ is the total amount of product in energy or in mass, depending on the process.

Table 21 –emission factors for different emissions sources

| Item | Unit | Value |
|---|---|---|
| **Biomass combustion – Residues**[a] | kg $CH_4$/TJ | 30 |
| **Biomass combustion – Residues**[a] | kg $N_2O$/TJ | 4 |
| **Biomass combustion – Biogas**[a] | kg $CH_4$/TJ | 1 |
| **Biomass combustion – Biogas**[a] | kg $N_2O$/TJ | 0.1 |
| **Biogas leakage**[b] | % | 5 |
| **Propylene production**[c] | t$CO_2$-eq/t-product | 0.009 |
| **Renewable Jetfuel production**[d] | g$CO_2$-eq/MJ | 9 |

[a] Gomez & Watterson (2006)
[b] Pipatti (2006)
[c] Intratec (2013)
[d] Moreira et al. (2014)

With the total emissions per bio-sector (per biorefinery in the model), the resulting emissions factor ($GgCO_{2\text{-}eq}$/MR$) is calculated dividing the total emissions for the total value of production of each biorefinery in Million Reais (MR$).

For the rest of the economy, the annual estimates of GHG emissions in Brazil (for the base year, 2009). Data from SEEG (Greenhouse Gas Emissions Estimate System, in Portuguese) was used. SEEG is an initiative from the *Observatório do Clima*, a Brazilian network of entities to debate climate change issues in the country's context (Observatório do clima 2017). Combined with the Social Accounting Matrix, in which the total sectorial value of production and total quantities of products are available, the emissions per monetary unit are calculated ($tCO_{2-eq}$/$).

The annual estimates of GHG were then divided in five sectors: Energy, Industrial processes, Agriculture, Land use change and forest and Residues treatment.

Each of these five sectors is divided in subsectors, and emissions were discriminated for each one. In the energy sector, emissions are divided from burning fuels and fugitive emissions from oil, gas and coal. Industrial processes include mineral products, metallurgy and chemicals, as well as production and consumption of HFCs and $SF_6$ (both not included in this study). Agriculture comprises emissions due to enteric fermentation of livestock, management of animal waste, agricultural soils, rice cultivation and burning of agricultural waste. The emissions from solid waste disposal and treatment of sewage, both domestic/commercial and industrial, in addition to emissions from waste incineration are reported under the residues treatment sector. Emissions due land use change and in the forest sector are not considered since land use change is assessed through modeling in combination with the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* for Agriculture, Forestry and Other Land Use. Table 22 shows the emissions for Brazil in 2005 and 2009, for the major sectors.

Table 22 – Brazilian emissions in 2005-2009

| | **2005 ($TgCO_{2-eq}$)** | **2009 ($TgCO_{2-eq}$)** | **Δ %** |
|---|---|---|---|
| **Energy** | 314.0 | 339.0 | 7.96 |
| **Industrial processes** | 81.0 | 75.5 | -6.79 |
| **Agriculture and livestock** | 392.0 | 395.5 | 0.89 |
| **Land use, land use change and forestry** | 2319.0 | 1,037.0 | -55.28 |
| **Residues treatment** | 52.0 | 58.0 | 11.54 |
| **Total** | 3,158.0 | 1,905.0 | -39.68 |

Source: (Observatório do clima 2017)

For the year of 2030, it is considered that the livestock sector has major increases in productivities (heads/ha), which changes the emissions portfolio of this sector. Because of these structural changes, the emissions factors for livestock are not calculated using the same procedure than the common sectors of Brazilian economy. In its turn, emission factors are based on Gouvello (2010), a study by the World Bank on land use change in Brazil. The emissions are discriminated by production system, and are shown in table 23.

Table 23 – Livestock emission factors and share of production of each productive system in 2030

| **Management system** | **Emissions per animal (kg/year)[a]** | | **Share of production in 2030 BAU (%)[b]** |
|---|---|---|---|
| | **$CH_4$** | **$N_2O$** | |
| **Extensive pastures** | 51.71 | 0.22 | 81 |
| **Crop-livestock integration** | 51.73 | 0.21 | 7.5 |
| **Confinement** | 51.53 | 0.21 | 11.5 |

[a] Based on Gouvello (2010)
[b] Based on Moreira et al. (2016)

Since this study intends to determine the contributions of a larger bioeconomy to GHG emissions, the reference scenario is based on the Brazilian intended Nationally Determined Contribution (iNDC) (Brasil (2015). The iNDC is a document proposed by every signatory country to the United Nations Framework Convention on Climate Change (UNFCCC), in which state their proposed measures and actions to mitigate GHG emissions. Brazil intends to reduce 37% of its emissions related to 2005 levels, by 2025, and 43% of them by 2030.

NREU is analyzed using data of the National Energy Balance (BEN) for 2009, published by EPE (EPE 2010). First, the total renewable and nonrenewable primary energy input coefficients were calculated dividing the energy inputs for each sector, by their total production value in that year (MJ/MR$, in 2009). The coefficient for the bio-sectors was calculated based on their biomass input, and on their lower heating value (LHV) (EPE 2010). Table 24 shows the primary energy consumption in 2009 for Brazil.

Table 24 – Primary energy use in 2009 for Brazil

| Primary energy | Category | Consumption (PJ) |
|---|---|---|
| **Oil** | Non-Renewable | 5,035.2 |
| **Natural Gas** | Non-Renewable | 1,186.7 |
| **Steam coal** | Non-Renewable | 163.7 |

| | | |
|---|---|---|
| **Coking coal** | Non-Renewable | 284.4 |
| **Uranium** | Non-Renewable | 173.6 |
| **Hydro power** | Renewable | 1,407.8 |
| **Wood** | Renewable | 1,030.3 |
| **Sugarcane products** | Renewable | 1,874.6 |
| **Other primary sources** | Renewable and non-renewable | 442.4 |

Source: EPE (2010)

Only sectorial use of energy is calculated, instead of the primary energy incorporated in each product. Therefore, the elements of $r_Q$ for NREU are zero for all products.

### *4.3.1. Emissions from land use change*

An important source of emissions in Brazil is the land use change and deforestation, responsible for 54% of total emissions in 2009 (Observatório do clima 2017).

To estimate emissions from the land use change sector, this thesis follows the methodology of the Intergovernmental Panel on Climate Change (IPCC) entitled Generic Methodologies Applicable to Multiple Land Use Categories (Aalde et al. 2006). From three approaches made available in the methodology, approach 1 fits data availability of this thesis.

Approach 1 requires only the net changes in land use area through time, which means that the exact changes in land use among categories are not necessary in this approach. IPCC defines six land use categories, and emissions should be calculated for each one of them in two periods in time (or in two different scenarios).

This approach is used to estimate changes in biomass carbon stocks and change in carbon stock in soils. Default IPCC values for aboveground carbon content were used for native vegetation, planted forests and perennial crops.

Initial native vegetation (in 2009) was taken from the "Brazilian biomes deforestation satellite monitoring system" (IBAMA 2017). Table 25 shows the information for each biome.

Table 25 – Aboveground carbon content and remaining areas of Brazilian Biomes in 2009

| Biome | Remaining area in 2009 (Mha) | Aboveground carbon content (tC/ha) |
|---|---|---|
| **Caatinga** | 44.1 | 80 |
| **Cerrado**[a] | 104.3 | 104 |
| **Atlantic forrest** | 24.5 | 220 |
| **Pampas** | 6.3 | 80 |
| **Pantanal** | 12.6 | 80 |
| **Amazon** | 336.8 | 300 |
| **Perennial crops** | | 21 |
| **Planted forests** | | 100 |

[a] Specific information for Cerrado's aboveground carbon was found in Fernandes et al. (2010)

Stock change factors of carbon in the soil in Gouvello (2010) were used. The author calculates the aggregated factor (combination of the land use, management and additions factors) for each macro-region in Brazil, for each crop. Table 26 shows the factors used in this study.

Table 26 – Soil carbon stock change factor for each region and each land use type

| Land use/region | SE | S | CW | NE | N |
|---|---|---|---|---|---|
| **Corn** | 0.45 | 0.55 | 0.45 | 0.50 | 0.45 |
| **Soy** | 0.45 | 0.55 | 0.45 | 0.55 | 0.45 |
| **Sugarcane** | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| **Other crops** | 0.85 | 0.85 | 0.85 | 0.85 | 0.85 |
| **Livestock** | 1 | 1 | 1 | 1 | 1 |
| **Abandoned land** | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |

Source: (Gouvello 2010)

Dynamics between regions are key to calculate emissions from changes in land use, considering that in 2030 the share of each region on total land for each crop will be different. The spatialization model in Verstegen et al. (2016) allows the areas of each crop in the national level to be designated to each region, based on local physical attributes, as previously explained.

## 4.4. Functional inequality indicator

With the results from the I/O model, one can analyze the impacts of the bioeconomy on inequality using income data. Inequality measures differs from poverty measures. Poverty measures look at the situation of individuals that are at the bottom of the income distribution. Inequality, in its turn, is defined for the entire population, not just the individuals below a certain income line (World Bank 2005). Inequality measures can be calculated for distributions of a diverse set of continuous or discrete variables, and in this thesis, with focus on local development, it is of interest to measure functional income inequality.

Functional income distribution regards the partition of income generated by the production factors capital and labor of used in production processes. The term functional, according to Hallak Neto & Saboia (2014), is due to the fact that division of income is done taking into account the function performed the economic agents in the productive process. In this thesis, functional income distribution is measured through the labor's share of income. Labor's share of income is defined in the work of Duenhaupt (2013) as the compensation of employees (salaries and benefits) (W) measured as a share of total income (Y), with total income being the sum of salaries, benefits, gross mixed income (GMI), and gross operating surplus (GOS), as expressed in equation 58, with w% being the share of labor in total income.

$$w\% = \frac{W}{W+GMI+GOS} \tag{58}$$

Measures of income distribution are calculated, in most publications (Bastos 2012), using household income per capita, which includes salaries from the main work activity (labor remuneration), retirement and other pensions, rent earnings, interest from financial applications and government transfers. This thesis, in its turn, calculates distribution only of the labor remuneration. Even though the level of inequality changes when considering only labor remuneration, it represents an underestimation of inequality of 3% (Bastos 2012). Besides, the portion of donations, rents and interest in the total income does not reach 4%. The most representative portion that is not included in the calculations are pensions (18% of all income) (Hoffmann 2009).

## 4.5. Scenarios

This thesis analyses the bioeconomy using three scenarios, consistent with the objectives outlined in the introduction, with one scenario in accordance with current policies used as a reference scenario, and two scenarios with focus on the bioeconomy, regarding technology levels, and amount produced in the biobased context.

The scenarios have key variables that are common to all three: 1) GDP Projections; 2) Economically active population projections; 3) Total land endowment; 4) Final demand projections.

GDP projections are based on USDA (2015), and are presented in figure 25, and also in table 16.

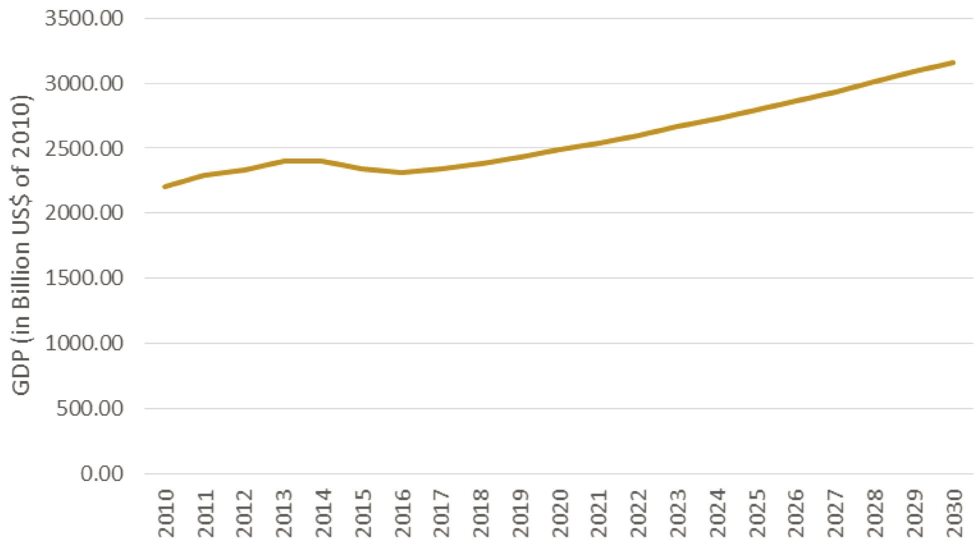



Figure 25 – Brazilian GDP evolution from 2010 until 2030.
**Source:** (USDA 2015)

Economically active population is the amount of people from the population in active age (15-64) that is inserted in the labor market or that, in a certain way, is trying to insert itself in it to carry out some kind of remunerated activity (Alves et al. 2010). The projections until 2030 are presented in figure 26.

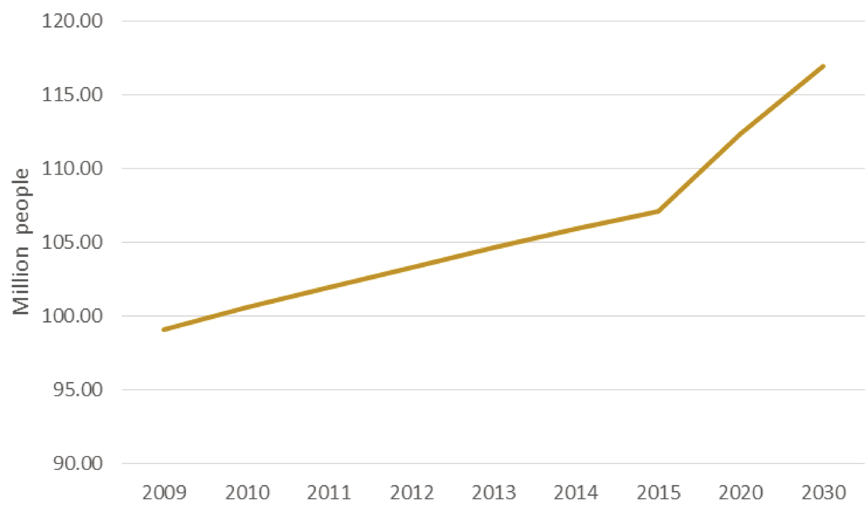



Figure 26 – Evolution of the economically active population.
Source: (Alves et al. 2010)

Land endowment (total land available for use) is endogenous to the model, and is kept constant in the bioeconomy scenarios, in comparison to the reference scenario (hereafter called Business-as-usual, BAU).

Final demand projections are an important factor of modeling seeing that each component of the final demand (household, government, investments, and exports) has a different behavior considering the consumption of products. The final demand is divided using projections based on an average of the years 2000-2013 of the shares in the National Account System ((IBGE 2017e). The final demand is divided as previously mentioned: households consumption represents 59.7% (± 2.4) of the final demand, government consumption represents 19% (± 1.9), exports 12.9% (± 14.6) and investments 18.7% (± 7.7%).

Established the similarities, the scenarios can be described regarding their differences. Fives aspects differ the scenarios: 1) The amount of biobased chemicals and materials produced; 2) The amount of bioenergy produced; 3) The production of 2G technologies; 4) The use of SRC-based biorefineries and 5) the Regional consumption of biobased products, in contrast to regional transactions of petrobased products.

### *4.5.1. Chemicals and materials*

Since this work aims at studying drop-in chemicals (chemically identical to their petrochemicals counterparts, which requires no changes in the downstream processing, according to Dammer et al. (2013), first the total amount of these chemicals (fossil and biobased) needs to be projected. Based on literature, the total Brazilian demand expected in 2030 for the chemicals studied is shown in Table 21.

Despite the efforts made by several authors to identify the possible future market size of bioproducts, as Dornburg et al. (2008) and Shen et al. (2010), the evolution of these markets depend on several factors and a variety of projections could be found. Therefore, the scenarios also differ in relation to the share (%) of bioproducts, in relation to the total amount, presented in Table 27.

The only biobased product produced in the BAU scenario is Ethylene, as mentioned in Table 2. Ethylene is already produced from ethanol dehydration at a Braskem plant in the South of Brazil (OECD 2014).

Table 27 – Brazilian market and biobased share of products in 2030

| Product | Total market in 2030 (fossil and biobased) (x$10^6$t) | Biobased economy 1 (BBE 1) (%) | Biobased economy 2 (BBE 2) (%) |
|---|---|---|---|
| **Ethylene** | 7.9[a] | 10[f] | 47[f] |
| **Total resins** | 8.3[b] | 6.5[g] | 10.0 [g] |
| **Acrylic acid** | 0.221[c] | 5.8[h] | 50[h] |
| **Propylene** | 4.9[d] | 10[i] | 30[i] |
| **n-Butanol** | 0.108[e] | 5.8[j] | 100[j] |

[a] Based on the projections presented by Bain & Company (2014b); conservative scenario. In the BAU scenario, part of the ethylene produced (5%) comes from sugarcane ethanol produced by BRASKEM

[b] Based on the demand projections in ABIPLAST (2015).

[c] Based on the assumptions for acrylic acid market in Bello (2008), and the production of new acrylic acid facility in Brazil in BASF (2012).

[d] Based on the projections presented by Bain & Company (2014b)..

[e] Based on the studies done by Natalense (2013).

[f] Studies vary considerably on the potential substitution of fossil ethylene with biobased. Dornburg et al. (2008) indicate a 47% substitution, while OECD (2014) indicates a minimum of 40% potential substitution. Haveren et al. (2008) consider a 10-15% substitution in the short term for bulk chemicals, and Hoefnagels et al. (2013) use a 20% substitution in their analysis.

[g] Substitution potential of PLA for composite of resins. Lower values based on Shen et al. (2010) for technical substitution, and upper values based on Dornburg et al. (2008) in the high scenario, taking into account the share of participation of each resin in the total resin production (PE, PP, PVC, PS and PET).

[h] USDA (2008) projects a substitution of 5.8-10% for commodity chemicals (case of acrylic acid). Higher value based on market penetration in the long term of biobased acrylic acid, as presented in Bain & Company (2014).

[i] Upper values based on Deloitte (2014) assumption of the potential substitution of petro chemicals for agricultural feedstock. Lower values based on Haveren et al. (2008) assumption of the substitution potential of bulk chemicals.

[j] (USDA 2008) projects a substitution of 5.8-10% for commodity chemicals (case of n-butanol). Dornburg et al. (2008) consider a 100% substitution potential in the high scenario. Bain & Company (2014) considers a penetration of over 50% for n-butanol.

The authors use different approaches to calculate the shares of products that could be offered based on biomass. For example, Shen et al.(2010) calculates substitution based on the technical specifications demanded by the use of each type of resin, and estimates if PLA can achieve those specifications, while Deloitte (2014) extrapolates the already existing biobased economy.

### *4.5.2. Bioenergy production*

Energy supply and demand are issues seldom presented in the several outlooks and statistical database of national and international, public or private, agencies.

For this thesis, the BAU scenario, regarding bioenergy production, was based on the projections in (EPE 2016), which defines total amount of bioenergy required to meet the GHG emission reduction announced in the intended Nationally Determined Contributions made by Brazil to the United Framework Convention on Climate Change (UNFCCC) (Brasil 2015).

In the bioeconomy scenarios (BBE 1 and BBE 2), the hypothesis of the International Energy Agency for emissions reductions (450 scenario) was used based on the Brazilian share of production for the world. The IEA 450 scenario assumes more strict policy actions to guarantee stabilization of the GHG concentration in the atmosphere at 450 ppm (IEA 2015). Table 28 shows the shares of bioenergy produced in Brazil in the different scenarios in 2030.

Bioelectricity generation has a particular setting because it is considered endogenous to the model. As explained in section 3.2.3.2 and 3.4, each biorefinery has its own CHP plant, and generates heat and electricity for the processes and still outputs surplus electricity to the grid. This surplus electricity is a function of the total amount produced by each biorefinery, and does not follow any projections, and therefore is taken as a response from the model.

Table 28 – Brazilian biofuels share in the Business-as-Usual and Bioeconomy scenarios and total amount in 2030

| | **Share (%)** | | **Total amount (x10$^6$m$^3$)** | |
|---|---|---|---|---|
| | BAU scenario[a] | BBE scenarios[b] | BAU scenario[a] | BBE scenarios[b] |
| | 2030 | 2030 | 2030 | 2030 |
| **Biodiesel [a]** | 10 | 20 | 7.4 | 15 |
| **Bioethanol [b]** | 45 | 60 | 43.6 | 74.1 |
| **Renewable jet fuel [c]** | 0.45 | 8.0 | 0.02 | 0.4 |

[a] Shares regarding total diesel consumption (blend mineral diesel plus biodiesel). BAU scenario based on EPE (2016), corrected for this thesis' GDP projections. BBE scenarios based on (IEA 2015).
[b] Share of ethanol regarding total gasoline equivalent. BAU scenarios based on EPE (2016) corrected for this thesis' GDP projections. BBE scenarios based on IEA (2015).
[c] BAU and BBE scenarios based on IEA (2015).

### *4.5.3. 2G technologies and SRC-based biorefineries*

Second generation (2G) technologies are technologies based on lignocellulosic materials, and have as feedstock either residues or dedicated crops, like eucalyptus and pine.

Two options are available for this type of technologies. It could be coupled with first generation technologies (1G) in 1G2G facilities based on sugarcane as feedstock, and it could be a stand-alone 2G facility based on SRC dedicated crops.

These two option occupy the scenarios is different ways. In the BAU scenario and in the BBE 1 scenario, only 1G2G facilities are available (no stand alone 2G), and the amount produced follow projection of the Brazilian government, which states that 2.5 billion liters of ethanol will be produced in 2030 in sugarcane-based biorefineries (EPE 2016). In BBE 2, the total amount of products are now produced in 1G2G biorefineries, and the SRC based biorefineries start production, with a 5% share of total products, as it is the case of 2G ethanol considered in EPE (2016b). It is important to keep in mind that SRC based biorefineries produce only ethanol, ethylene, propylene and butanol, due to the lack of information of the other products on their production based on lignocellulosic materials.

#### *4.5.4. Regional consumption*

In the reference year (2009), most of the products had limitations to where they could be produced, due to the technical features of the oil refining sectors. For example, paint and polish industries in the Southeast would consume acrylic acid from the Northeast, because it was the only region that produced that chemical (BASF 2012). In the BAU scenario, these inter-regional transactions from 2009 are kept for 2030.

In the BBE 1 and BBE 2 scenarios, with the local (regional) production of biobased products, the industries that use those chemicals and materials (and fuels) as input, will now consume from their own region, limited to the amount produced. That is, if the amount produced (biobased) regionally is not enough for their levels of activity; these industries will seek petrobased products in other regions to meet their total demand. Table 29 shows a summary of the premises of each scenario in this thesis.

Table 29 – Basic assumptions in each scenario

| | **BAU** | **BBE1** | **BBE2** |
|---|---|---|---|

| | | | |
|---|---|---|---|
| **Biobased products** | The same installed capacity as in 2009 (Ethylene produced by BRASKEM) | Biobased products are produced in a minimum proportion, using the lowest values of the gap in Table 27 | Biobased products are produced in a maximum proportion, using the highest values of the gap in Table 27. |
| **Bioenergy** | As projected by EPE (2016). Total values in table 28. Bioelectricity modeled. | Liquid biofuels as projected by IEA (2015); values in table 28. Bioelectricity modeled. | Liquid biofuels as projected by IEA (2015); values in table 28. Bioelectricity modeled.. |
| **2G technologies** | Only as projected by EPE (2016): 2.5 billion liters of ethanol in sugarcane-based biorefineries. | Only as projected by EPE (2016): 2.5 billion liters of ethanol in sugarcane-based biorefineries. | Sugarcane-based 1G facilities are substituted by 1G2G facilities. Stand alone 2G included (SRC). |
| **SRC-based biorefineries** | No SRC biorefineries are included. | No SRC biorefineries are included. | SRC-based biorefineries produce all additional ethylene, propylene and butanol in comparison with BBE1. |
| **Regional consumption** | Regional interactions are as in 2009 | Part of chemicals' demand is produced regionally. | Part of chemicals' demand is produced regionally. |

# 5. RESULTS: MACROECONOMIC IMPACTS OF A BIOBASED ECONOMY IN BRAZIL IN 2030

The results that will be shown in this session are based on the assumptions and premises in the methodology session. The Business-as-usual scenario is fully realized when key variables reach the targets found in the literature. Reaching the targets for the major variables in table 16, and the targets of the Brazilian intended Nationally Determined Contribution for emissions reduction requires several economic changes, and will have consequences that will reflect also in the comparison of scenarios when analyzing the biobased scenarios.

The amount of each chemical in 2030 is defined using the specialized literature, and their total amount is shown in table 27. For energy carriers, figure 27 shows the total amount of each product and figure 28 shows the share of each energy source in electricity generation in 2009 (a) and in 2030 (b).

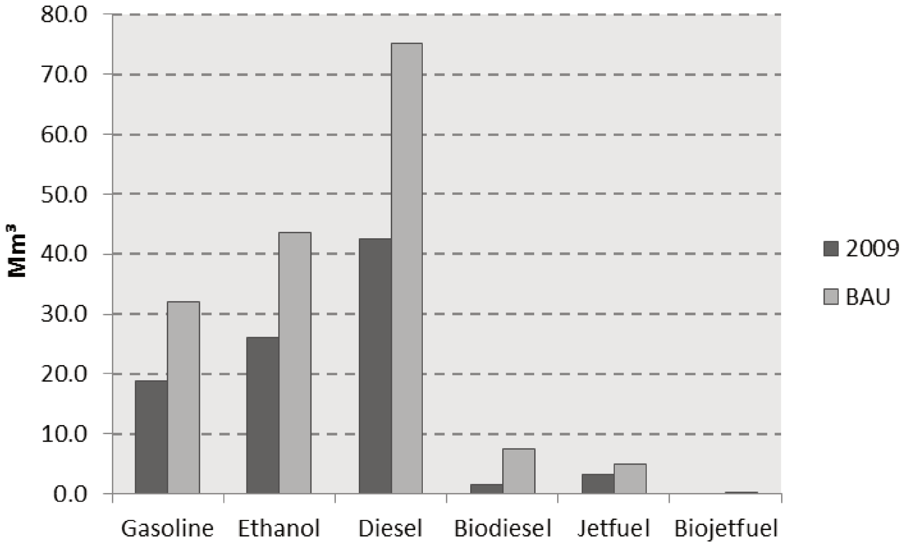
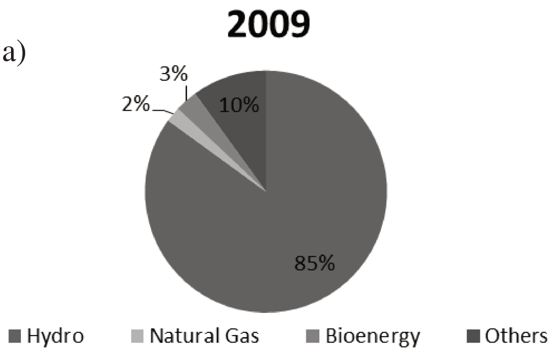



Figure 27 – Total amount of liquid fuels in 2009 and in 2030 in the reference scenario.

Ethanol, biodiesel and biojetfuel shares are defined exogenously based on values in table 26. This will translate in the total volume shown in figure 27, based on the resulting amount of diesel and gasoline. These amounts are in place with the total energy requirements linked to the Brazilian iNDC (EPE 2016).

a)




b)

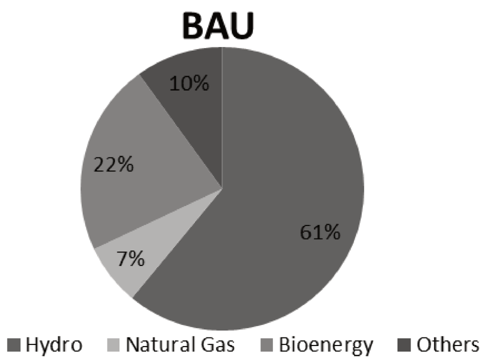



Figure 28 – Share of each source in electricity production in 2009 (a) and reference scenario in 2030 (b).

Electricity shares in 2030 for hydro power and natural are based on (EPE 2016), while bioenergy is an output of the model, based on the electricity surplus of the biorefineries described in session 3.2.3.2.

The first major implication in reaching the Brazilian energy matrix and an increase in GDP of 54%, with an increase of economically active population of 17.9%, is the necessary increase in efficiency in the economy, taken as 0.5% a year from 2009 until 2030. Even with such efficiency increase, the unemployment rate in 2030 reaches very low levels, even beyond the natural unemployment rate for Brazilian reality (Doege 2010). Figure 29 shows the unemployment rate in 2009 and in the business-as-usual scenario in 2030.

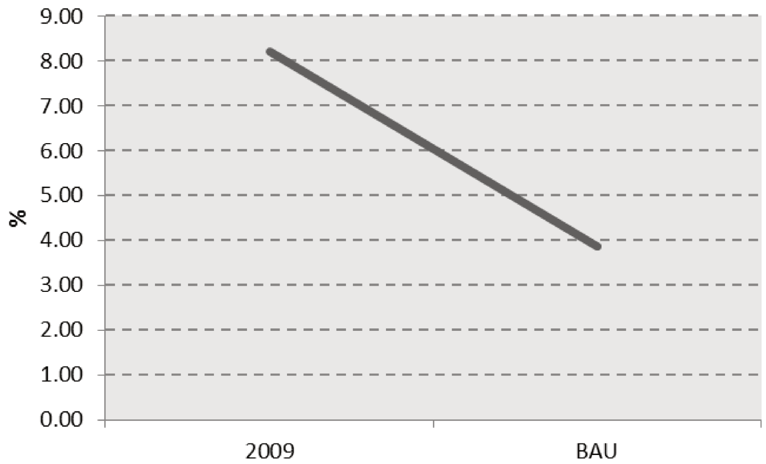



Figure 29 – Unemployment rate in 2009 and in the BAU scenario in 2030.

The unemployment rate decreases from 8.2% in 2009 to 3.87% in 2030. With the decrease in unemployment, and with the increase in production factors remuneration, the total household income increases, leading to a higher consumption in the final demand, and consequent increase in foodstuff consumption by households, as depicted in figure 30.

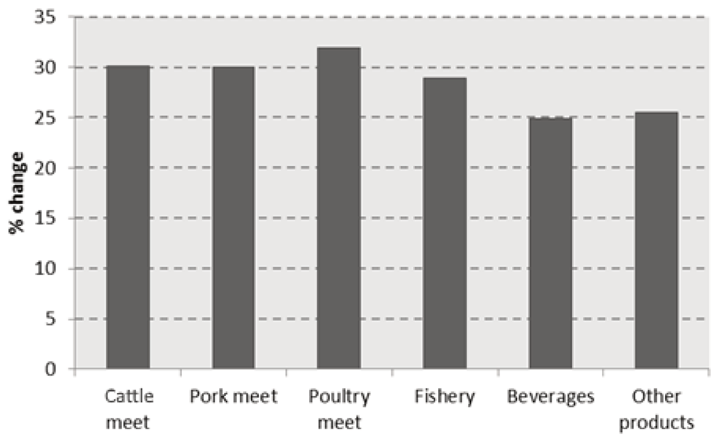



Figure 30 – Increase in households' foodstuff consumption from 2009 to the business-as-usual scenario in 230.

The changes in foodstuff consumption will be an important feature, representing a proxy to food security, or food access, when the bioeconomy scenarios are compared to the reference business-as-usual scenario.

Another issue to reach GDP growth by 2030 is the share of investments in the total gross domestic product. Since investments are modeled as a sum of households' savings, government savings and foreign savings, it was practically impossible to reach the targets of investments, imports and exports concomitantly. Therefore, the exports and imports were defined based on the project growth in investments. Figure 31 shows the evolution of both components.

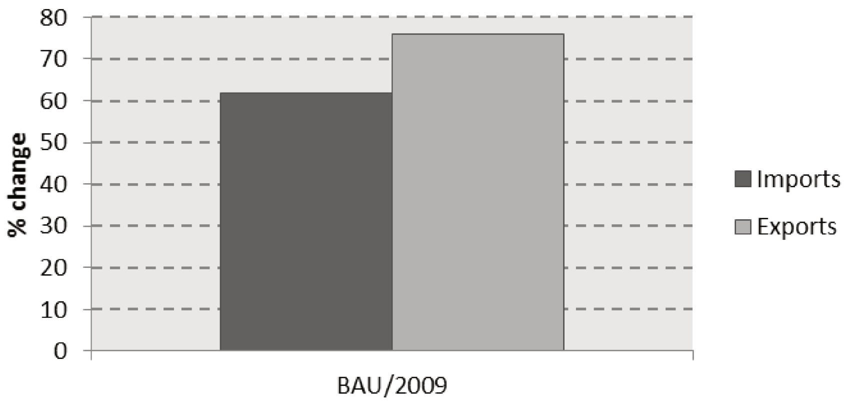



Figure 31 – Percent change between 2009 and BAU scenario in 2030 of exports and imports.

Finally, an important aspect of this study is land use and land use change. To properly relativize the results when comparing bioeconomy scenarios with BAU, the total increase (or decrease) in land use for the major land use types have to be taken into consideration. The land use in 2030 in the reference scenario is in accordance with the increases in agricultural yields in table 17, and the final land use in livestock production in table 16. These changes would result in a total increase of 0.95% from 2009 and 2030. Figure 32 shows the evolution of land use change for each land use type.

The improvements in agricultural yields are exogenous in the BAU scenarios and, coupled with the total production of each commodity, results in the land use of each crop in 2030. The introduction of a more intense bioeconomy will require the increase in productivities, since land endowment is kept constant in a first analysis. This increase is endogenous to the model and is a response from the model based on the limited factors of production.

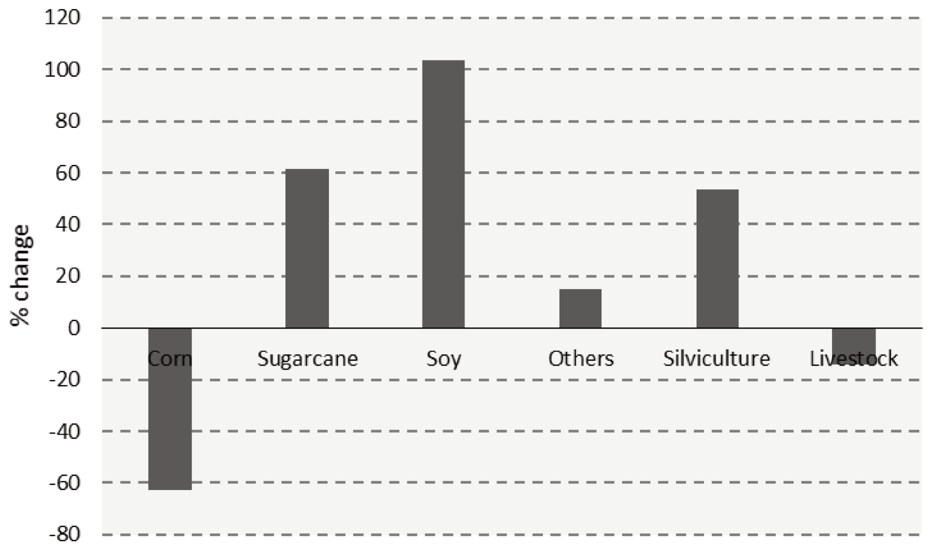



Figure 32 – Land use change for each land use type between 2009 and 2030 in the BAU scenario.

Sugarcane and soy increases in land use are induced by the higher uses of biofuels in the energy matrix that are exogenously imposed to the model, jointly with the endogenous trending growth in other products that use them as feedstock (sugar from sugarcane, oil and feed from soy, for example).

Corn production will require less exclusive land, since its growth in production will occur in second harvest corn, intercropped with several other crops, which is already the tendency in Brazil (IBGE 2017c).

Livestock reduction in land is in alignment with Moreira et al. (2016), to enable the Brazilian commitments regarding greenhouse gases emissions reductions established in the iNDC (Brasil 2015), as closely as possible.

## 5.1. Bioeconomy scenarios

For the two scenarios of a biobased economy, figure 33 depicts the changes in total supply of each product studied. The total amount of production for each product in the BAU scenario is determined based on table 26 and 27, and in each biobased scenario the total amount will be different, based on the interactions of the new economies in each scenario. The most impact products are ethylene and propylene, due to indirect impacts of plastic resins substitution. Since ethylene and propylene consumption is concentrated in resins manufacture, the direct substitution of resins for polylactic acid will directly impact those product's demand. With the increase in polylactic outputs in the BBE 2, ethylene and propylene supply declines even further in this second bieconomy scenario. Other products slightly decrease comparing to BAU scenario mostly due to reduction in overall economic activity, as will be seen posteriorly.

The products in figure 33 are a combination of local supply of petro-based products and biobased products.

Ethanol increase was achieved by chocking the share of ethanol in gasoline, associated with the increase of households' preference of ethanol over gasoline (flex-fuel vehicles allow this consumer's choice). For both bioeconomy scenarios, these shocks were held the same.

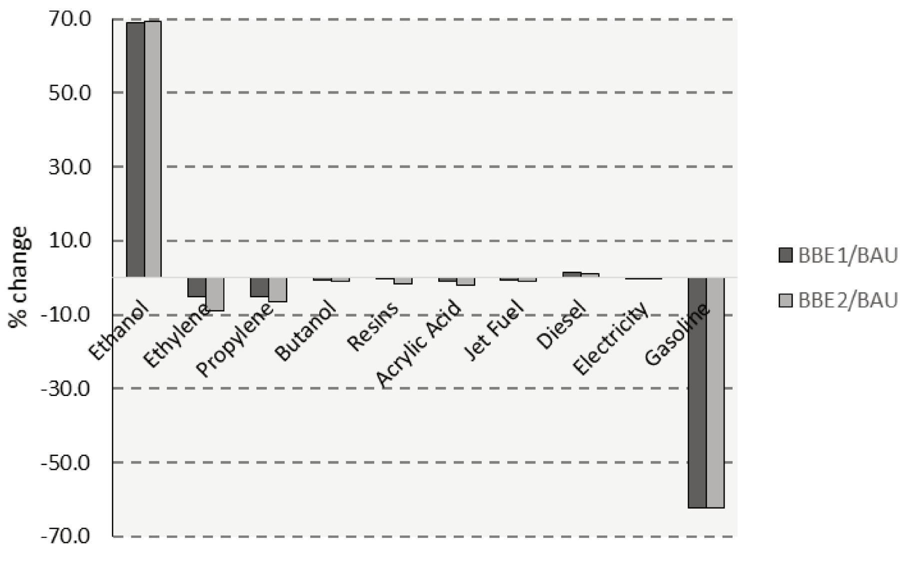



Figure 33 – Changes in local supply of each product of interest between bioeconomy and reference scenarios in 2030.

The increase in energy carriers' production from biomass plus the increase in the shares of biobased chemicals will generate an increase in biomass demand, and a decrease in fossil feedstocks demand. Figure 34 shows the dynamics of the major feedstock in the economy, regarding the products of interest. The differences between scenarios rely on the different assumptions regarding technology and amount of chemicals. From BBE1 to BBE2, there is a shift from sugarcane to eucalyptus and pine due to the production of chemicals in 2G-based biorefineries. Although small amounts are produced of chemicals, a considerable amount of ethanol is produced as co-product in the butanol SRC-based facilities. Since butanol is only produced from C5 sugars in 2G facilities, the remaining sugars are forwarded to ethanol production, therefore the total amount of bioased butanol will require considerable amounts of SRC products, and will consequently produce large amounts of ethanol (14% of total volume). Reductions in sugarcane production in BBE2 is also a reflection of changes in technology (inclusion of 2G from sugarcane residues), associated with the shift substitution of ethanol produced in SRC-based biorefineries.

Soy shows virtually no difference between scenarios since the share of biodiesel remains the same. Reductions in absolute volumes follow a trend of overall economic activity reductions.

Crude oil reduction in the second bioeconomy scenario is slightly higher than the first scenario, and since their differences rest on the amount of chemicals produced, it is possible to conclude that the production of chemicals is marginal when it comes to crude oil use in Brazil. In fact, only 8% of total crude oil in 2009 (EPE 2010) was used for Naphtha production, the main feedstock for basic petrochemicals (80% of ethylene and 70% of propylene, based on Bain&Company (2014b)).

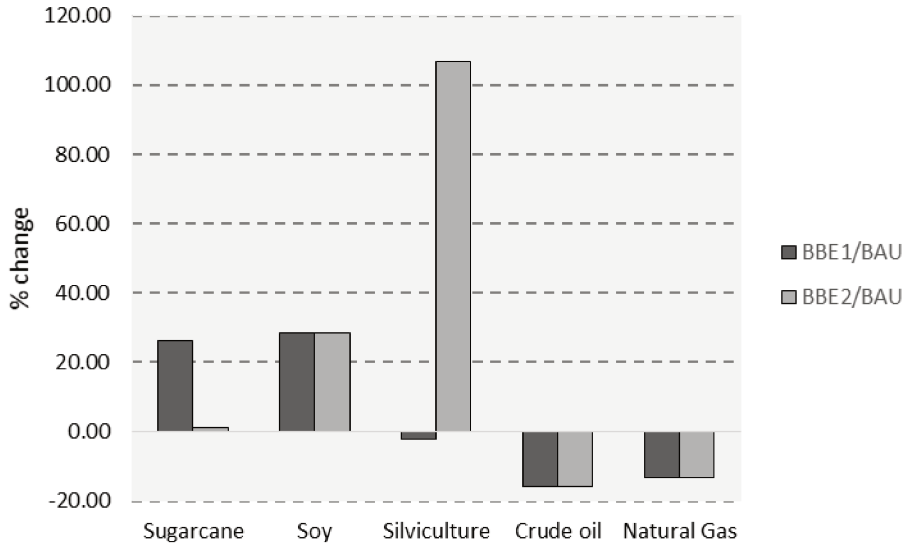



Figure 34 – Changes in amounts of local supply of the major feedstocks affected by the bioeconomy in 2030 in comparison with the reference scenario.

Since no expansion in total land endowment is allowed between scenarios, the model manages to fit all production into the same amount of land, which will require further increases in agricultural and livestock yields, if compared to the BAU scenario. In this case, figure 35 shows the changes in land use for each land use type, in the case of an increase of biomass use for chemicals and energy, in two types of technology levels. Since silviculture has lower productivities regarding land comparing to sugarcane, the pressure on land due to eucalyptus and pine expansion is higher than the first scenario. In that case, all other land use types are required to decrease their land use, which is given endogenously by the model.

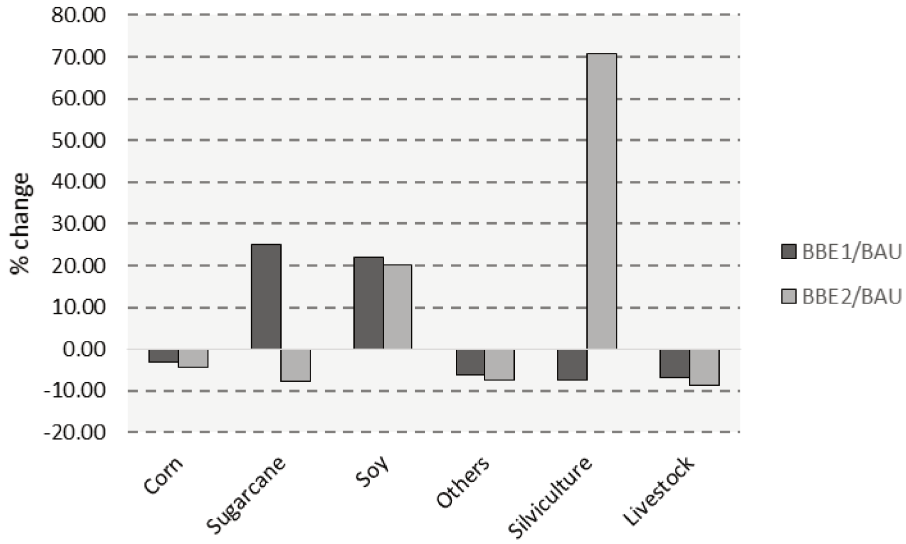



Figure 35 – Change in land use of major land use types between bioeconomy and the reference scenario in 2030.

Pressure on land demand causes land prices to increase, which is the main influence for agricultural sectors to increase their productivity in regards to land use. In addition, increase in land prices affect food prices, as it is the main factor of production of food products. Yet, the CGE model has the CPI as numeraire and the increase in food prices not necessarily will cause decreases in food consumption. For that reason, the analysis in section 5.1.2 was done in terms of quantities demanded.

### *5.1.1. Changes in GDP*

The structural changes in the economy, in order to provide more biobased products to the economy coupled with the choice of funding part of the bioeconomy through subsidies, which guarantee the economic feasibility of the technologies in 2030, have direct and indirect impacts in the creation of wealth and total economic activity.

The GDP calculated through the expenditure approach is a sum of the components of final demand households' consumption, government consumption, gross fixed capital formation (or the consumption of good for investments) and exports, minus the imports.

When the biobased economy path, at both levels, is chosen for the country, the GDP suffers a slight reduction due to changes in the components of final demand that integrate it. Figure 36 shows the changes in total GDP between the biobased economy and the business-as-usual scenarios.

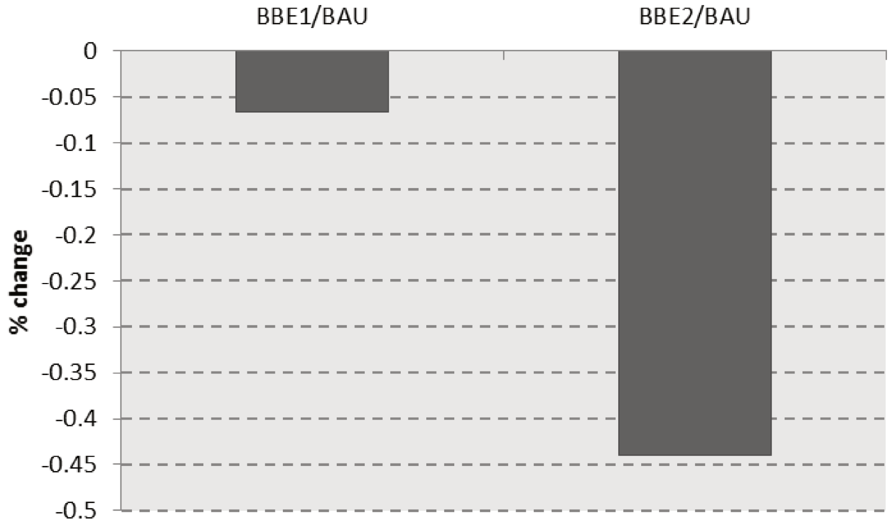



Figure 36 – Change in GDP between the reference scenario and the bioeconomy scenarios in 2030.

The most affected component in absolute terms is the government consumption. With the increase of subsidized activities in the bioeconomy, with most subisidies going to biodiesel, propylene, jet fuel, and the 2G SRC-based biorefineries in the second biobased economy scenario. Figure 37 shows the changes in subsidies between scenarios. The values of subsidies where relativized regarding the GDP, to depict a cohesive increment. In that sense, the graph shows the increase in subsidies share of the GDP. The increase from BAU to BBE1, for example was of 83%, concentrated mainly in the changes of biodiesel shares and second-generation facilities.

Considering that government consumption is focused on public services (the government is the sole consumer of public services, which will be provided to society), the decrease in government consumption translates directly into reduction of public services provision to the Brazilian society.

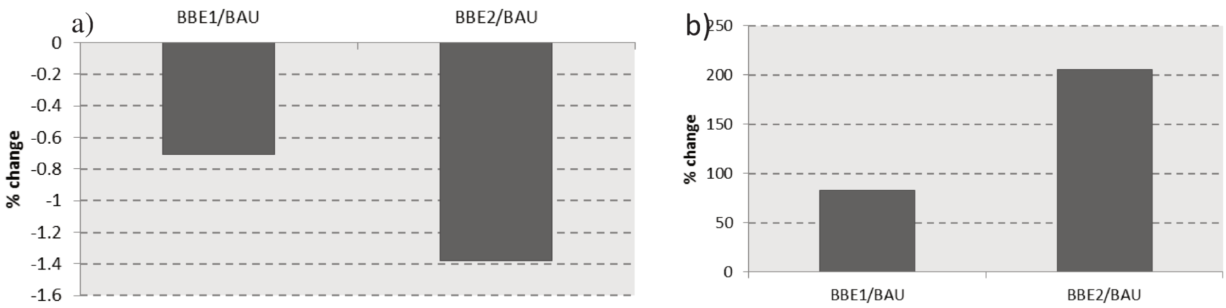



Figure 37– Changes in Government Consumption (a) and Changes in subsidies (b) between biobased economy and the reference scenario in 2030.

Subsidies for the bioeconomy, in total amount, reach, in the BBE 1 scenario, similar amounts to today's subsidies for the rest of the economy (IBGE 2017e), and is still marginal in relationship to the whole GDP. Figure 38 shows the total subsidies and figure 39 shows the subsidies in relation to the GDP.

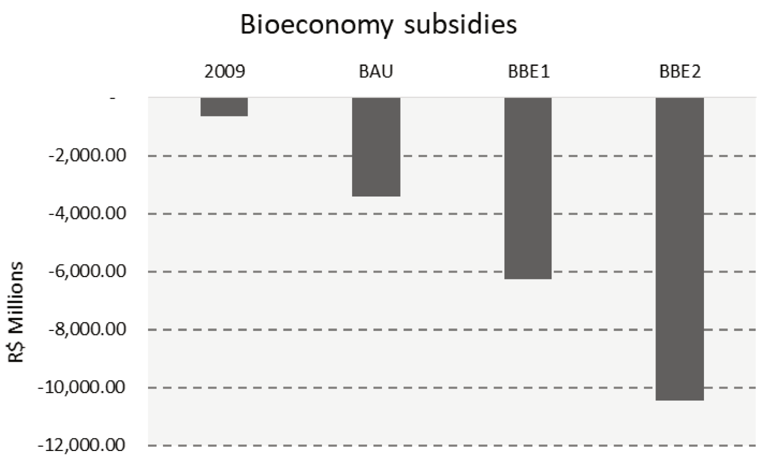



Figure 38 – Total subsidies in the economy (2009 and 2030 for all scenarios).

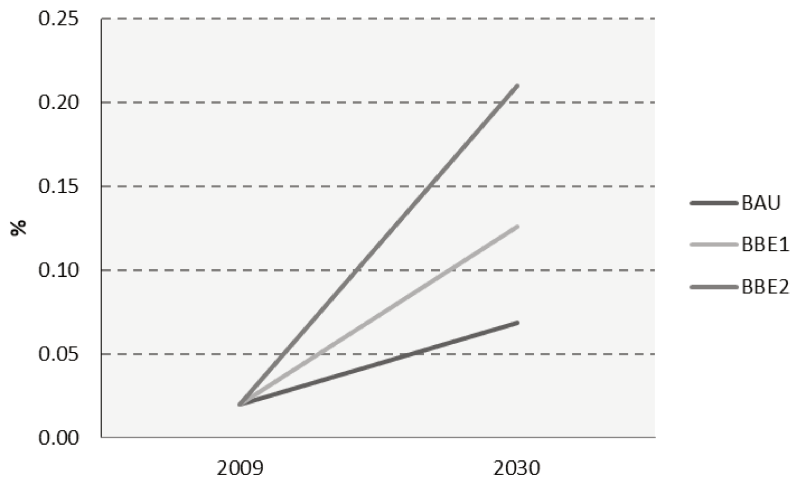



Figure 39 – Subsidies as a share of total GDP.

Although government consumption is retracting regarding the different scenarios, the impact, when relativized, can be considered minor. From 2009 until 2030, regardless of the scenario, there is an increase in government consumption per person, as shows figure 40, from R$ 3,550 in 2009, and R$ 4,210 in the BAU scenario. In the BBE scenarios, government *per capita* consumption goes to R$ 4,186 and 4,158, respectively.

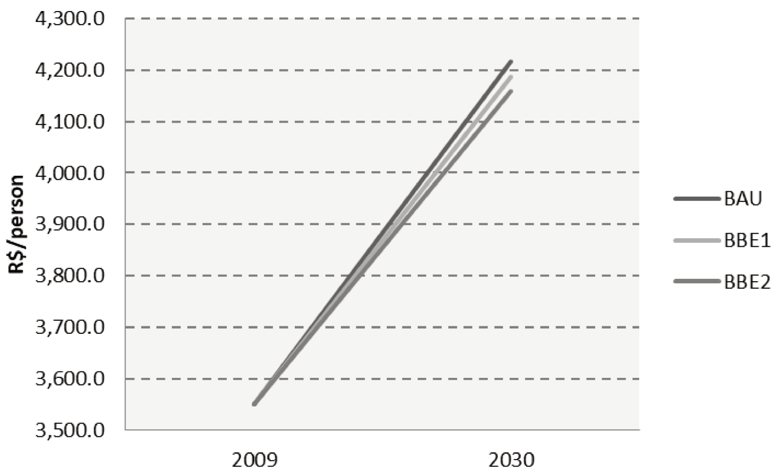



Figure 40 - Government consumption per person in 2030 scenarios.

Following government consumption come the investments. Calculated as the sum of households', government and foreign savings, investments in 2030 drop following a drop in foreign savings. Foreign savings is the opposite of trade balance, or imports minus exports, as shown in figure 41.

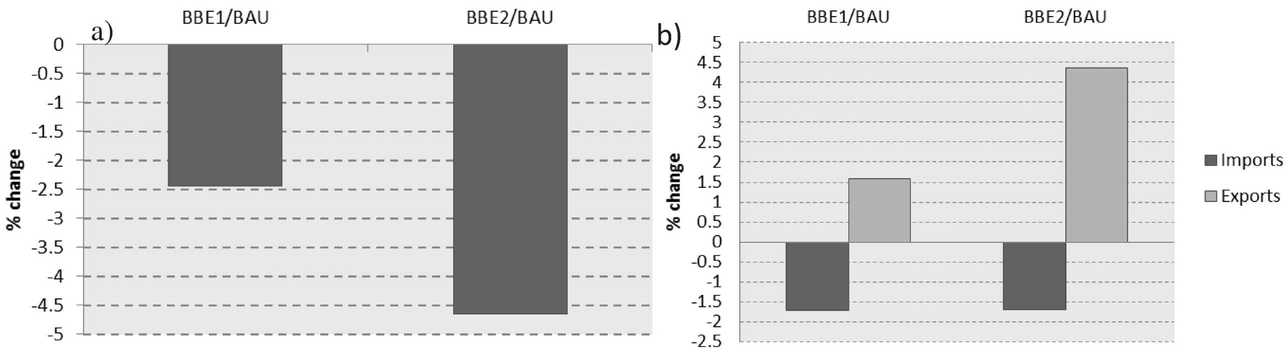



Figure 41 – Changes in investments (a) and imports and exports (b) between the biobased economy and the reference scenarios in 2030.

With the increase in local biomass use, Brazil would reduce its dependency in foreign feedstocks and inputs. In BBE1, the decrease in imports occur mainly in fossil feedstock and products, while the largest increases in imports happen in inputs for the agricultural sectors. Increases in other agricultural products (From perennial crops, and temporary crops that are not corn, soy, sugarcane, tobacco and cotton) are also observed due to their lost in local production, due to the increase in biomass for bioproducts. Figure 42 shows the changes in imports for main sectors.

In BBE2, the increase in organic chemicals comes from the increase in demand for enzymes in second generation production, categorized as organic chemical. Resins from petrobased feedstock are also impacted, since crude oil availability for the production of inputs for local resins production is decreasing.

Decreases in machinery and vehicle parts follow the highest decrease in investments in the economy in the second biobased economy scenario.

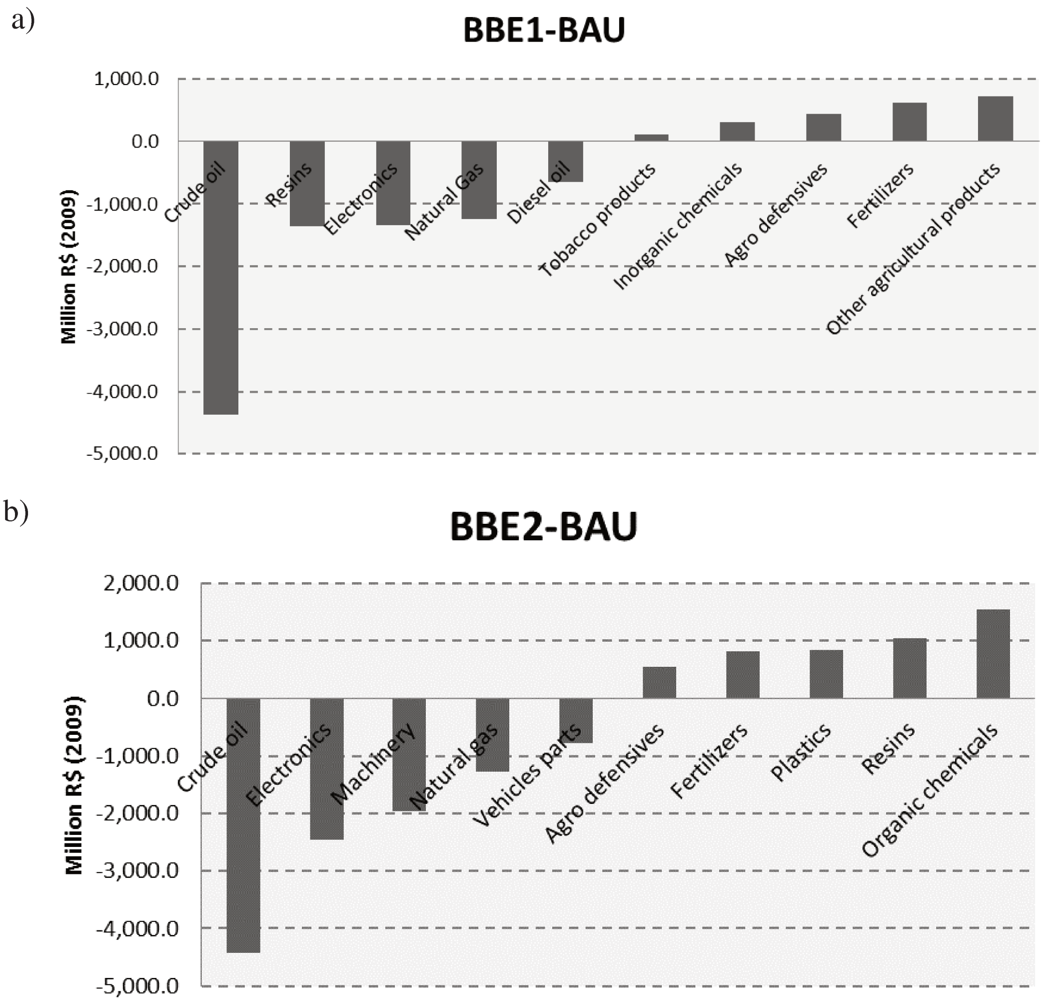



Figure 42 – Top highest and lowest absolute different in imports in (a) biobased ecnonomy scenario 1 and (b) biobased economy scenario 2.

Increases in exports (figure 43) accompany the stimulus of the soy industry, and the pulp and paper industry induced by the increase in silviculture production in the second biobased scenario. Contrasting with the highest decreases that concentrate mainly in the oil industry.

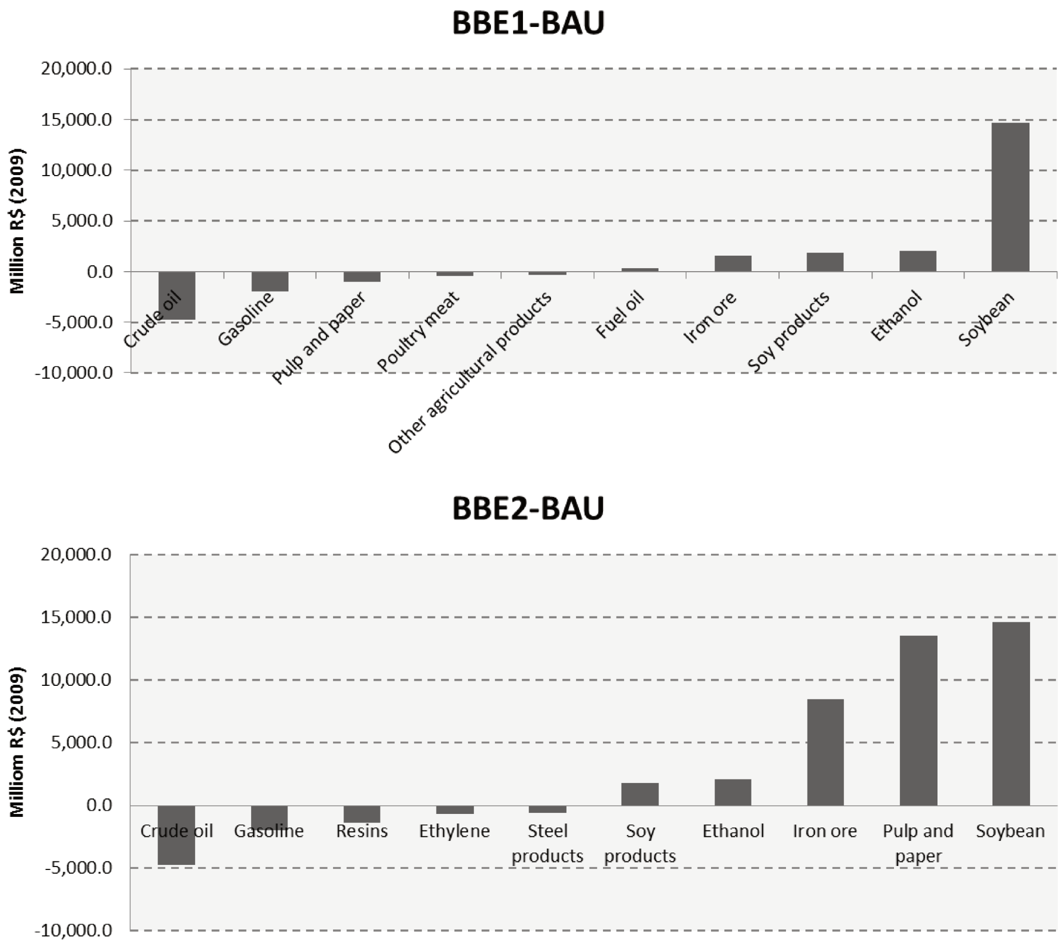



Figure 43 - Top highest and lowest absolute different in exports in (a) biobased ecnonomy scenario 1 and (b) biobased economy scenario 2 in 2030.

### 5.1.2. *Changes in Employment and households' consumption*

Changes in employment were analyzed based on the unemployment rate of each scenario in 2030. The rationale behind the unemployment rate is the Phillips curve. With a decrease of the price of the labor factor in relation to the consumer price index (which is the numeraire) causes the unemployment to go up, following employees decision to not be employed, since salaries will not cover expenses.

The decrease in the price of the labor factor, which shows the changes in labor remuneration, happen due to the relative scarcity of production factors capital, land and labor. In one hand, with the increase in subsidies required, government will not be able to provide the same level of services as in the BAU scenario, which reflects the lower amount of jobs in the public services sector. With less workers being demanded, labor factor becomes less scarce in the economy, so its price goes down. On the other hand, with more land being demanded, its prices will go up, as it becomes scarcer in comparison to the other factors labor and capital. This considerable increase in land prices has impacts in the prices of products that depend on land (agriculture), which causes the CPI to go up. The comparison of both will determine the trend in unemployment. In the case of BBE1, labor prices go down 1.11% in relation to the CPI, resulting in an increase in unemployment. The same happens to BBE2, with a decrease of 1.43% in labor prices, generating an even higher unemployment rate (figure 44).

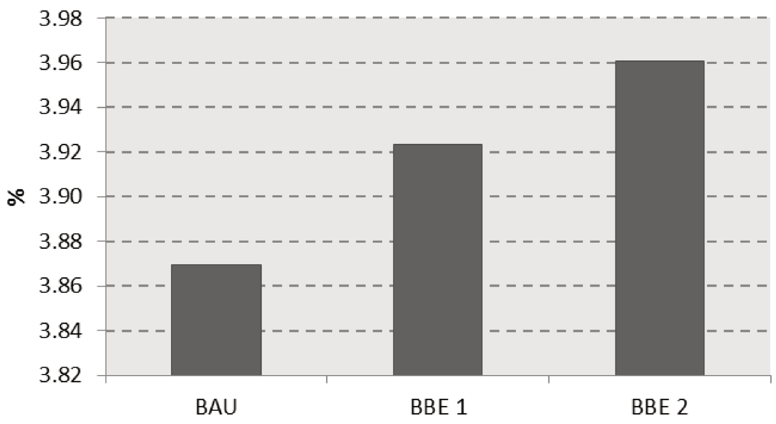



Figure 44 – Unemployment rate in each scenario in 2030.

Although it has been pointed out by other authors that a bioeconmy generates employment (McCormick & Kautto 2013; Thornley et al. 2014), this statement should not be generalized to every situation. Increase in demand for a company's product increases the firm "creates" jobs by hiring more workers. Meanwhile, if overall demand in the economy does not also increase, or if there is a decrease in activity of other sectors, these new jobs will simply be shifted from other sectors of the economy, with no net gain in total employment.

It is true, as stated in Thornley et al. (2014), that the shift from fossil-based products to biobased ones can generate jobs, as is seen in figure 45a. The graph in figure 45a shows the dynamics in jobs creation among the sectors involved in the substitution of fossil-based products with biobased ones. While the number of jobs created in the biosectors increase, the number of jobs in the fossil-based counterparts reduce, but the total sum of biosectors and counterparts rises in both biobased scenarios. The same is valid for the comparison of agricultural and fossil feedstock jobs.

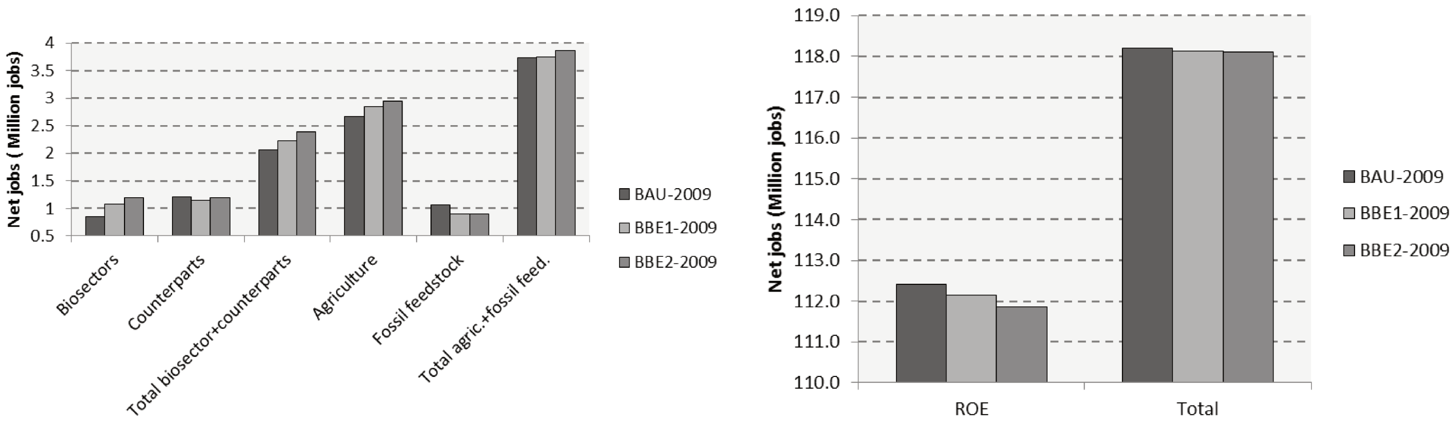



Figure 45 – Net employment generation in (a) the sectors related to the bioeconomy and (a) the rest of the economy (ROE) and the total number of jobs in the economy, between 2009 and 2030.

However, the several indirect impacts of a biobased economy, as reduction in investments and reduction in government consumption, cause an overall reduction in employment positions in the rest of the economy (ROE) and consequently in the total economy. Figure 45b shows the reduction of jobs in the ROE and in total jobs. The highest decreases in jobs in in the public services sector, follows by the reduction in the government ability to provide the same level of services as in the BAU scenario. Crude oil and gasoline are also among the highest decreases, along with machinery and civil construction, after a decrease in the investments.

The changes in the prices of factor of production also affect the total consumption of foodstuff by households (figure 46). This was taken as determining factor of food accessibility, instead of food prices. With the PCI as numeraire, analyzing the change in food prices would not provide a view of the impacts in food consumption, since there is the possibility of an increase in consumption in the case of higher prices of labor even with an increase in food prices.

With the increase in land demand, land prices rise affects directly the prices of food products. With higher food prices, households' consumption decrease. The different changes in the scenarios are a direct cause of the larger land demand in the second biobased economy scenario, in which SRC-based biorefineries produce a large amount of ethanol and other chemicals. The lower yields of eucalyptus and pine compared to sugarcane when it comes to land use causes the higher demands.

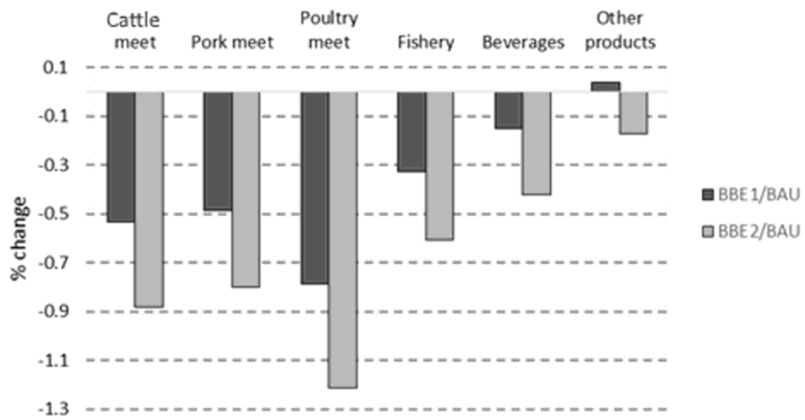



Figure 46– Percent changes of foodstuff consumption by households comparing biobased economy scenarios with the reference scenario.

The consumption of food products is affected in either scenarios, with higher impacts on meet consumption.

## 5.2. Discussions

### *5.2.1. Land is a key factor for the bioeconomy*

The pressure on the agricultural land increases in a biobased economy. Several authors have calculated the necessary land for different levels of production of chemicals, materials, fuels and other types of energy, as Bos et al. (2012) and Dornburg et al. (2003). Until now, the total land endowment (total land used in the economy) was kept constant between BAU, BBE 1 and BBE 2 scenarios. In this case, the land prices would go considerably up, with an increase of 23% in BBE 1 and 32% in BBE 2.

Keeping land constant is a choice based on the idea that, to understand the impacts of substituting fossil-based products for biobased ones, all other variables should be kept constant, in a *ceteris paribus* analysis. However, Brazilian government has recently (2012) review its forest act (the major legal framework for conservation of natural vegetation on private land) and, according to Sparovek et al. (2015), the forest act has become weaker when it comes to protection of natural vegetation, and less demanding regarding requirements on restoration planting and promotion of natural regeneration on agricultural land. This creates an inconsistency when affirming that, in the case of an increase in land prices, no deforestation would occur, since it would be legal to deforest, which is the cheapest choice for the producer. The amount of land available for legal deforestation is yet unknown, but several studies indicate that the protection of natural vegetation has decreased importantly and that the remaining restoration requirements are minor. Sparovek et al. (2015) found that a substantial increase in crop production is possible, using an area 1.5-2.7 times the current cropland area.

On the other hand, several studies show that the livestock production in Brazil has increased considerably its productivity. Dias Filho (2014) shows that form 1975 until 2006, the stocking rate went up 92%, with highest intensification in the center-west. Even with such increase, further intensification is possible and other authors as Gouvello (2010) and Moreira et al. (2016) consider higher stocking rate in the mid-term. Therefore two options to increase land availability for the bioeconomy are chosen: Increasing land endowment through deforestation, or increasing land available for other crops, with intensification of the stocking rate in livestock production.

Figure 47 (a) and (b) show the variation in land price when land endowment and stocking rate are increased, respectively. To reach a land price variation equal to zero, land endowment would have to be 9.4 and 11.4% higher in the BBE1 and BBE2 scenarios, respectively, in relationship to the BAU scenario. In the case of stocking rate, an increase from 1.3 to 1.57 in BBE1 and from 1.3 to 1.62 in BBE2 are required to reach a zero increase in land prices, also when comparing to the BAU scenario.

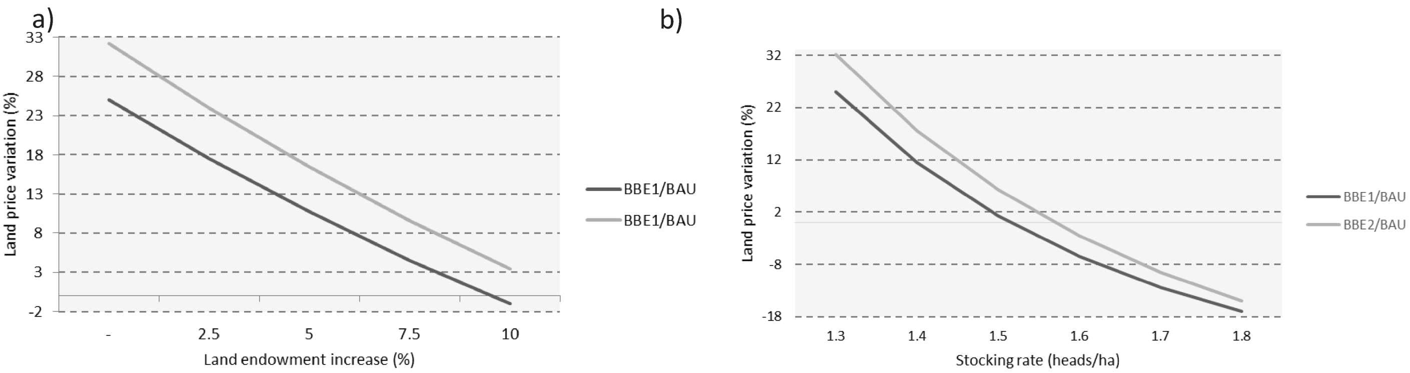



Figure 47 – Land price variation when increasing land endowment (a) and livestock stocking rates (b) between biobased economy and reference scenarios.

When no changes in land prices occur, different impacts are noticeable. Increase in land availability means more economic activity, and therefore higher GDP. Figure 48a shows the changes in GDP when comparing the BAU scenario with the BBE scenarios. When more land is given to the economy in the biobased scenarios all agricultural activity goes up, pushing their prices down. In both variables (GDP and unemployment), increasing stocking rates have better impacts than increasing land endowment, in any scenario. This happens because more land is spared when stocking rates are raised, with approximately 30 million hectares, compared to 25 million when increasing around 10% of land availability.

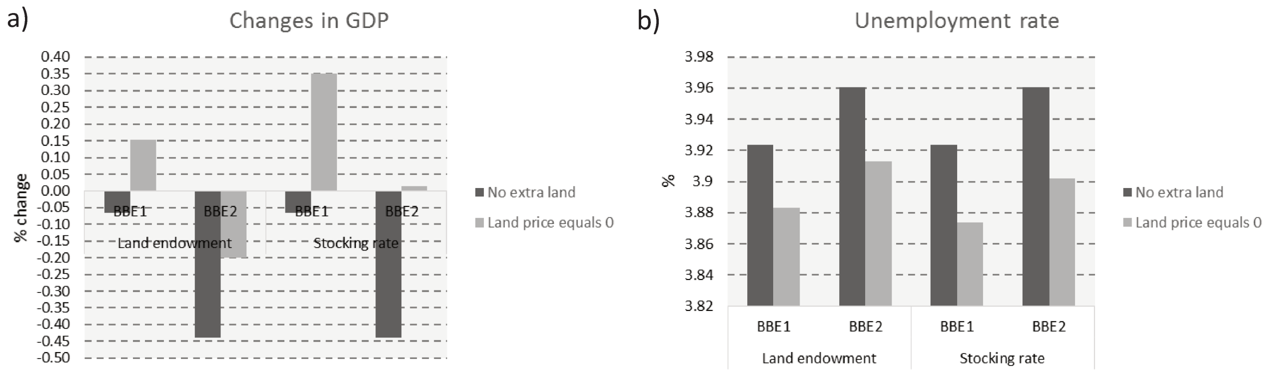



Figure 48 – Changes in GDP (a) and in employment (b) when land price changes are zero between BAU and BBE scenarios.

The decreased pressure on land stimulates all agricultural activity to go up, pushing their prices down. This causes the consumption of food products by households to go up (figure 49).

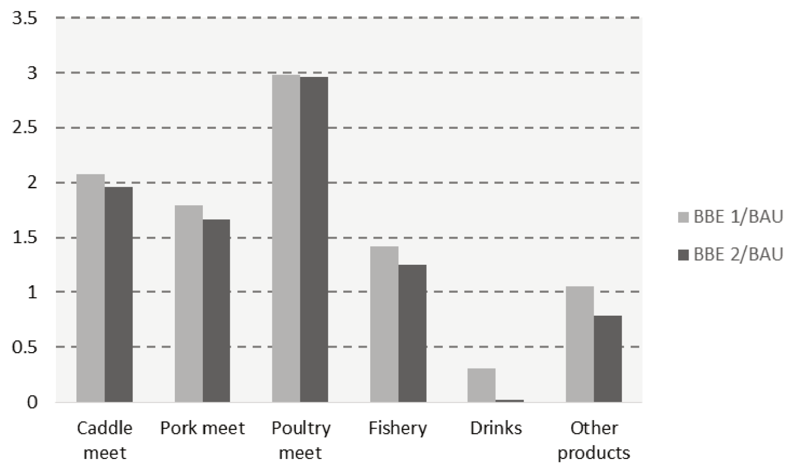



Figure 49 - Percent changes of foodstuff consumption by households comparing biobased economy scenarios with the reference scenario, with no changes in land price.

Economically speaking, it seems less probable that the actors in the livestock sectors would choose to further increase the stocking rates in the case of permissible deforestation. In this case, it is up to the government to incentive intensification of livestock activities to maximize the positive impacts of a bioeconomy.

In the case of the second biobased scenario, the choice of SRC over sugarcane can create slightly worst impacts as land demand increases. The decision of using dedicated crops compared to using residues in 2G plants is also a key factor to consider, since land use is a major issue for the bioeconomy. Leal et al. (2013) show that ethanol from lignocellulosic crops require more land than first generation sugarcane ethanol. This corroborate the idea of Odegard et al. (2012) that residues use should be prioritized over dedicated lignocellulosic crops for energy purposes.

### *5.2.2. Technological improvements in agriculture and industry and the second generation of technologies*

As mentioned in the previous section, land use is the key factor in a bioeconomy. In order to provide the requested amount of bioenergy and bio-chemicals, the economy will require further increases in agricultural yields regarding land. The highest pressure on land demand, with the consequent increase in land price, causes the actors in the agricultural sector to search for less expensive factors of production (labor or capital), increasing their productivity in amount/ha, shown in table 30.

Table 30 – Increases in agricultural yields regarding land between BAU and BBE scenarios

| Land use type | Increase in yield | |
|---|---|---|
| | BBE1/BAU (%) | BBE2/BAU (%) |
| **Corn** | 3.0 | 4.0 |
| **Soy** | 8.4 | 9.7 |
| **Sugarcane** | 0.7 | 9.7 |
| **Other crops** | 5.2 | 6.6 |
| **Silviculture** | 4.9 | 24.3 |
| **Livestock** | 2.6 | 2.6 |

It is important to keep in mind that these increases in yields are related to the BAU scenario, which already takes into account yields improvements (shown in table 17). These improvements are based in specialized literature and is not a theoretical maximum, therefore leaving room for further improvements.

The yield increases are feasible with different improvement in agricultural management practices. According to Strassburg et al. (2014), livestock productivity in cultivated pasturelands are only 32-34% of its potential. For silviculture, 48% increases in yields are foreseen to be achievable, based on (Stape et al. 2010). Sugarcane also has room for improvements to reach higher yields than 91.3 tons/ha, as commented in Cardozo et al. (2016), and . The most challenging improvements are in soy production. As mentioned in MAPA (2016), the average productivity has been stagnated in the 3 ton/ha. On the other hand, FIESP (2016) foresees that the 3 ton/ha barrier will be breached in 2020, with 12% increase until 2026 (reaching 3.36 ton/ha), more than what is required in this study.

The pressure on land caused by the bioeconomy is indeed the main issue, but it should be relativized as to which product has the most effect. Overall volumes of energy carriers are responsible for 97% of the land use when chemicals are produced in a lower level in the first biobased economy scenario, and 87% in the second stage of production represented in the second scenario. The discussion in Odegard et al. (2012) and Eickhout (2012) brings to light the need to debate whether chemicals production should be prioritized over fuels. Regarding land use, satisfying Brazilian chemicals' demand could lead to less impact on land price, in comparison to the BAU scenario. Table 31 shows the land use of each product in each scenario. The total land use was calculated based on the share of total output of the products of each biorefinery in monetary terms.

Table 31 – Land use of each product in each biobased scenario in 2030

| x10³ ha | Ethylene | Polylactic acid | Acrylic acid | Propylene | n-Butanol | Biodiesel | Bioethanol | Renewable jet fuel |
|---|---|---|---|---|---|---|---|---|
| **BBE1** | 141 | 165 | 2 | 99 | 7 | 11,043 | 7,841 | 87 |
| **BBE2** | 1,849 | 198 | 10 | 549 | 209 | 11,279 | 8,431 | 47 |

Increasing yields in agriculture will follow the increase in land price increase and the sectors' need to reduce dependency on land. Nevertheless, further improvements in the industrial processes would also reduce land use. However, the effects of the industrial processes in subsidies requirements are more important than their ability to reduce use of land. This study takes into consideration several technological improvements described in section 3.3, which guarantee the economic viability of most of the processes, but not all of them. The choice of producing economically unfeasible products is what demands such amount of subsidies in the biobased economy. This can be avoided if other measures are taken, besides yield improvements. As seen in Machado et al. (2016), scaling is an important factor on industrial costs and, indeed, ethanol production costs are influenced by the mill's size. Even though this study considers an average size of 2 million tons of sugarcane crushed, reaching 6 million tons is reasonable for Brazil. Another point to consider is the expected return in investments. If lower rates of return were applied, higher feasibility is foreseen, and consequently less subsidies required. Still, funding mechanisms from the government would be necessary to reduce investors' risk.

## 5.3. Conclusions

This thesis analyses the effects of large-scale substitution of fossil resources by biomass for energy and chemicals on GDP, unemployment, food security, and land use changes on a national level for Brazil. For this purpose, a macroeconomic CGE model was used to address the changes in the economy relevant for biobased industries. The model allows the modeler to choose the share of biobased products in the economy, without discrimination of industrial choices.

The analysis intends to capture the effects in different stages of industrial technological development, based on two scenarios with different rate of technological change and total amount of chemicals. These aspects result in different shares of biomass supply in the economy. The first scenario is only based on first generation technologies, and lower amount of chemicals is produced, and the second one uses second generation technologies with higher amounts of chemicals.

The results show that in a first technological level the needs for biomass increase 25% in sugarcane and 28% in soy. This represents a reduction of 15% in crude oil and natural gas, in value of production. In the second level, Eucalyptus and pine increase 105%, and sugarcane only 1%.

The demand for biomass in a biobased economy increases land demand and land prices go up. This forces the producers to search for other factors of production (capital and labor), increasing their yields regarding land. However, higher increases in land yields are necessary to avoid the decreases in food accessibility. Choosing dedicated woody crops only for high value (low volume) products would probably cause less pressure on land if compared to the production of ethanol. Livestock intensification is required in all three scenarios, including BAU, to avoid further deforestation. Since voluntary reductions in deforestation are not encouraged by the government with the new forest act, which is weaker in native forestation protection (Sparovek et al. 2015), other legal instruments or of financial nature should be prioritized.

Choosing a bioeconomy requires a considerable amount of investments, to support the structural changes required in the form of biorefineries. With high fixed costs, surges the necessity for a mechanism to guarantee the economic feasibility of the new economic activities. In this thesis subsidies payed to the producer were inserted in the model, representing the social costs of choosing the bioeconomy.

The increase in subsidies causes direct and indirect effects in the economy, with reduction in GDP. If the government were responsible for part of the stimulus for a biobased economy, it would affect its expenditures, affecting negatively the GDP. If higher subsidies are necessary, as in second-generation technologies, higher reductions are expected.

The bioeconomy has positive impacts in the trade balance. Producing chemicals and energy from local sources decreases dependency on imported feedstock and products. With lower imports and higher exports, trade balance goes up; however, foreign savings go down. Less foreign savings mean less investments, which also causes the GDP to go down.

The bioeconomy creates more jobs than the fossil-based economy, but the total economy suffers an increase in unemployment rate. Subsidizing the bioeconomy structure come at a cost of reducing government provision of public services, which will require less workers which causes the majority of the unemployment in the biobased economy scenarios.

Reducing the need for subsidies is therefore seen as a key factor to promote the bioeconomy. Further increases in industrial yields, and investing in large scale plants to reduce fixed costs are important to guarantee economic feasibility, and avoid the negative indirect effects of the biobased shift. Increasing investors' confidence in the sector, with special financial lines with lower rates is a way to indirectly fund the bioeconomy reducing total weighted average cost of capital.

# 6. RESULTS: REGIONAL SOCIOECONOMIC IMPACTS OF A BIOBASED ECONOMY IN BRAZIL IN 2030

The results are related to three economic aspects: local GDP, income, and functional income inequality. They are presented in Table 32 for the regional economies (as a whole). The five macro-regions in Brazil are Southeast (SE), South (S), Center West (CW), Northeast (NE) and North (N). Not all regions have all sectors present, as it is the case of n-butanol production (only present in the Northeast), acrylic acid (also only present in the Northeast), ethylene and propylene, not present in Center-west nor North, and diesel and jetfuel, which are not present in the Center-West. This assumption is based on the current existence of industries that produce these products in each region.

Southeast of Brazil has been historically the most important region, economically speaking, and in 2009 it was responsible for 54.4% of the country's GDP. This concentration changes with the scenarios, ranging from 54.2% in the BAU and 53.9% in the BBE2. However, the relative results for the shift from petrobased to biobased economy are different considering the five regions.

The aggregated results for the whole economy are due to the direct changes in levels of production in eight major sectors: Petrochemicals, Energy, Oil, Natural Gas, Sugarcane, Silviculture, Soy and the Biosectors, which compose a bioeconomy. These changes have indirect impacts in the rest of the economy, as seen in the previous chapter, which also affect local GDP and income. Detailed results are presented below.

Considering the chock that corresponds to the bioeconomy growth, the results can be decomposed into the direct (and indirect) effects in the eight sectors previously highlighted, as well as in the rest of the economy (ROE). The aggregated results regarding GDP and income in an economy, for the five regions considered, are presented in Table 32.

Table 32 – Results for 2030, regarding GDP income and functional distribution

| **Region** | **GDP** | | | **Income** | | | **Income in the GDP** | | |
|---|---|---|---|---|---|---|---|---|---|
| | BAU ($x10^9$R$) | BBE1/BAU (Δ%) | BBE2/BAU (Δ%) | BAU ($x10^9$R$) | BBE1/BAU (Δ%) | BBE2/BAU (Δ%) | BAU (%) | BBE1/BAU (Δ%) | BBE2/BAU (Δ%) |
| **SE** | 2,700 | -0.35 | -0.80 | 1,063.25 | -1.01 | -1.65 | 39.4 | -0.659 | -0.860 |
| **S** | 813 | -0.12 | -0.51 | 310 | -0.77 | -1.22 | 38.1 | -0.656 | -0.704 |
| **CW** | 525 | 1.44 | 0.80 | 243 | -0.17 | -1.00 | 46.2 | -1.584 | -1.788 |
| **NE** | 673 | -0.07 | -0.06 | 274 | -0.96 | -0.89 | 40.7 | -0.889 | -0.824 |
| **N** | 272 | 0.03 | 0.06 | 100 | -0.83 | -1.09 | 36.8 | -0.861 | -1.156 |
| **Total** | 4,982 | -0.067 | -0.44 | 1,990 | -0.85 | -1.37 | 39.9 | -0.788 | -0.938 |

2009 exchange rate: US$ 1 = R$ 1.99

The analysis of results is presented the following sections. From now on, SSS identifies the combined results of sugarcane, soy and silviculture sectors, while the energy sector encompasses diesel, gasoline and jetfuel production, as well as electricity from other sources, besides bioelectricity.

## 6.1. Gross domestic product (GDP)

Here, GDP was calculated using the income approach, in which it is the sum of Gross Operating Surplus (GOS), income and taxes, minus subsidies. The net impact of the bioeconomy in the national GDP is a slight decrease, as seen in the previous section, but estimates at local level change.

Regionally, Southeast, Northeast and South regions (notorious petrobased regions) have similar decreases in GDP, while Centre West shows the highest increases, in BEE 1 scenario, as seen in figure 50. Besides the introduction of biobased processes, the regionalization of consumption also induces regional changes between regions and scenarios.

In the second generation scenario (BBE 2), lower decreases in NE and lower increases in CW are foreseen, while the North shows higher increases In GDP.

The adoption of SRC-based biorefineries changes the location of production due to the suitable areas available in each region. Therefore, more activities move to regions where eucalyptus and pine tend to expand, based on (Verstegen et al. 2016). Besides the changes in biosectors' level of activity, the regional's share of production in the whole economy affects final results in GDP percent-change between scenarios. As is the case of SE, the national retraction of GDP will have highest impact in the most important region.

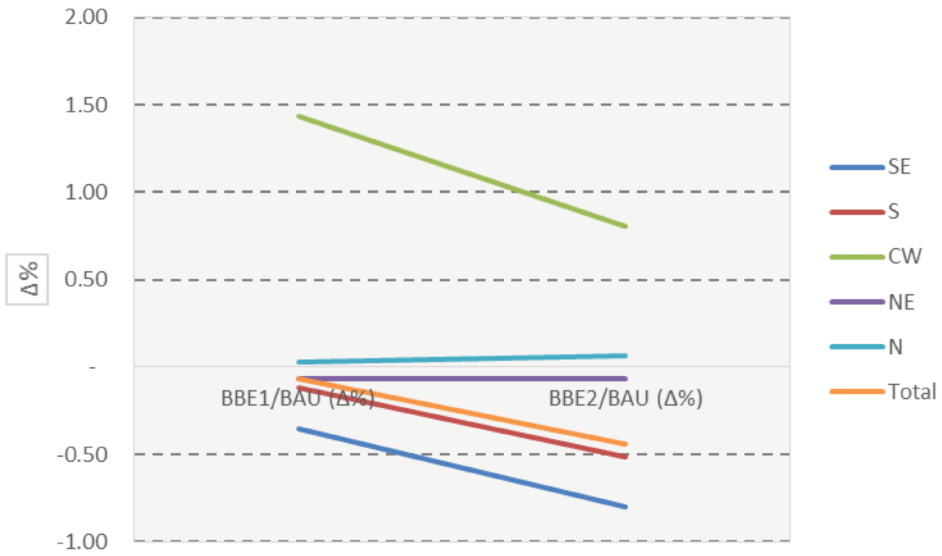



Figure 50 – Relative changes is regional GDP (%) – BBE1 and BBE2 vis-à-vis BAU.

## 6.2. Income

Income in the Brazilian economy income has a slight decrease from BAU to BBE. Here, income regards to labor remuneration, excluding any other type of revenues. Although this leaves out critical information, as interests, retirements and rents, labor remuneration answers for over 76% of all income and fits the type of data resulted from the input-output model.

While all sectors of the economy suffer a small reduction in total income (reduction in BBE1), due to overall economic reduction, the direct substitution of oil for biomass, therefore the introduction of biobased sectors in the economy increases income. Figure 51 shows the dynamics in income when analyzing with (a), and without the rest of the economy (b), where most of the reduction occurs.

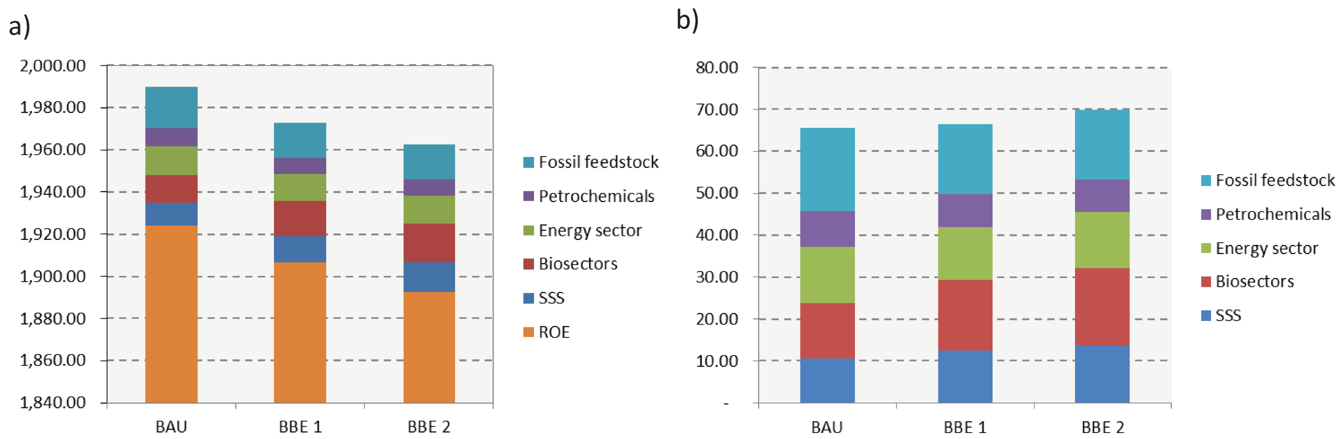



Figure 51 – Income profile for each scenario in 2030

The economic sectors related with fossil fuels and petrochemical industries have the highest salaries in the country. and, even showing a small number of employees, the total income from fossil feedstock and petrochemicals production alone represents between 4% (Center-west) and 54% (Southeast) in the BAU scenario (in relation to the sectors of interest), and the reduction from BAU to BBE 1 of these sectors reach 12.2% in the North, 12.4 in the Northeast and around 7% in the South and Center-west. Energy sector also suffers reductions between 1.2 (N) and 10% (SE).

Sugarcane, soy and silviculture are most representative in the CW region (31.3% of the income in the BAU scenario, among the sectors of interest). Figure 52 shows the income among the involved sectors (excluding the rest of the economy) and biosectors for each region.

South region present interesting increases in income when comparing BBE 1 and BBE 2 (3.6% increase in BBE 1 and 15.2% increase in BBE 2, in the sectors of interest), reflecting the higher salaries of a RSC-based biorefinery and of the silviculture sectors. RSC-based biorefineries have salaries similar to the pulp and paper sectors, which are slightly higher than the traditional ethanol/sugar sectors (IBGE 2017e).

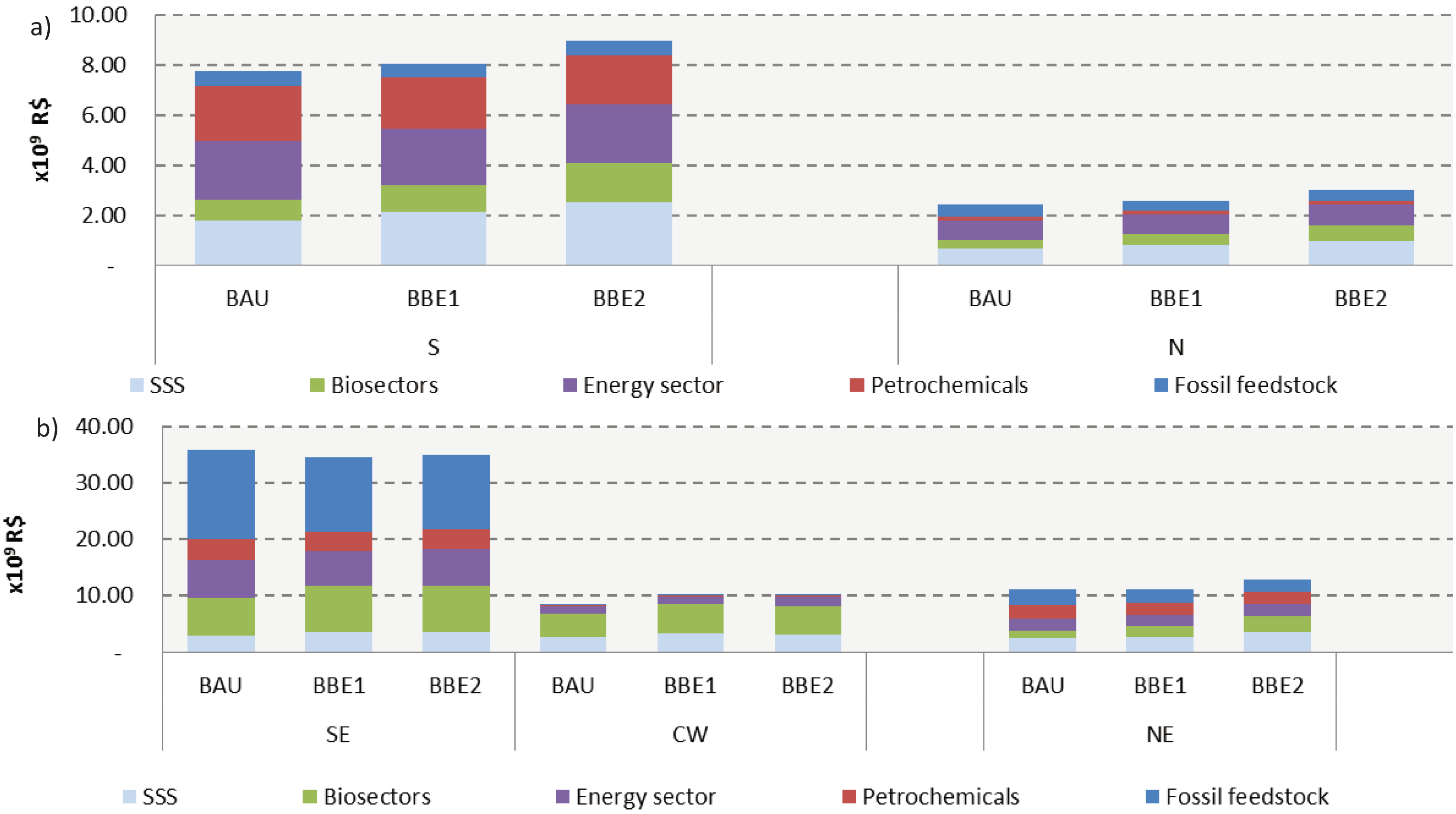



Figure 52 – Income in the S and N regions (a) and SE, CW and NE regions (b) for the three scenarios for the selected sectors.

North region also sees increases in income in BBE 1 and BBE 2, while Southeast and Northeast drop in the first biobased economy scenario, followed by a recovery in the second one. Center-west, on the other hand, sees an increase in the first scenario and a decrease in the second one. This changes result from the relative importance of the petrochemical and fossil feedstock sectors in each region, and the type of biomass that will be used in the future. For example, Center-west, with a small petrobased sector, will see an increase in income if new biobased business enter the region, with a positive net income, since there is nothing to be substituted; only additional income is entering the region. However, when sugarcane is partially substituted for SRC-based refineries, Center-west loses production, since the region is not the most suitable for eucalyptus and pine. Sugarcane productivity increase, with the adoption of 1G2G biorefineries, also affects income negatively in the regions where sugarcane is most important, as is the case of Center-west.

### 6.3. Functional income distribution

Functional income distribution is able to comprehensively characterize how the returns from growth and the losses of stagnation are shared among the economy (Dünhaupt, 2013). Although functional distribution and personal income distribution seem to be unrelated (Francese and Mulas-Granados, 2015), if functional income distribution worsens, economic growth would not necessarily reduce poverty. Figure 53 shows the share of labor in total GDP for each scenario in 2030.

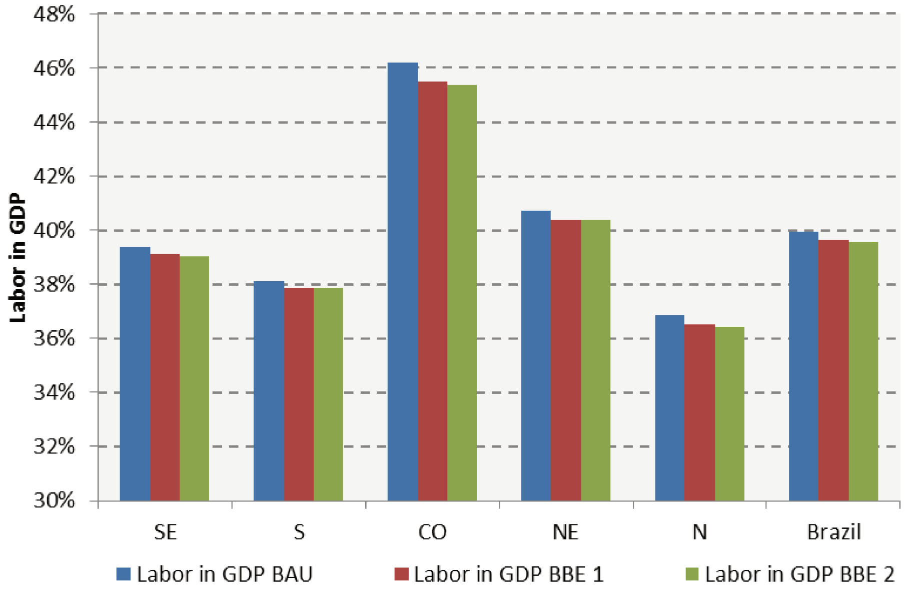



Figure 53 – Share of labor in the Regional GDP in 2030 for each scenario.

In 2009 (baseline year), the share of labor in GDP was 43.6% in Brazil. With the increase in capital needs to guarantee the 54% GDP increase, associated with a lower increase in economically active population induces a total reduction in share of labor in total GDP to 39.9% in the business-as-usual scenario.

The increase in bioeconomy participation has an overall negative impact on the participation of wages in the GDP (-0.8 and -0.9% from BAU to BBE1 and BBE2, respectively). The impacts vary from region to region, and reductions are seen in all regions. NE is the only region with lower reductions in BBE2, while all other regions continue to drop from the business as usual scenario, or remain practically steady (figure 53).

## 6.4. Discussions

### *6.4.1. Input-Output analysis*

Although useful outcomes are provided by an I/O analysis, several shortcomings are worth mentioning. A 2009 I/O table is used to calculate impacts in 2030, and one aspect of uncertainty in this study is the assumption that the biobased economy will improve technologically, while other sectors of the economy remain unchanged. Despite the improbability of such development, technological maturity of current economic sectors indicate less room for improvements. Even so, projecting changes in the economy and in the sectorial interlinkages would be highly uncertain (Wicke et al. 2009). The static-comparative nature of this study aims at minimizing the effects of not considering improvements in other sectors.

Furthermore, particular changes in Brazilian economy could be caused by the bioeconomy associated with demand regionalization that are not measurable in an I/O model. Upstream and downstream sectors can also develop (or be created) in order to satisfy local consumption. For example, machinery and other input industries could be reallocated to feed the new biosectors, and downstream industries could be installed in these regions to drain the production of certain building blocks addressed in this thesis (as acrylic acid and n-butanol). Other uncertainties are found in the disaggregation of different expenditures and the allocation over different sectors of the economy, mostly petrochemical sectors (Herreras Martínez et al. 2013).

### *6.4.2. Choices of products, size, technologies and regions for a biobased economy*

The definition of a biobased economy is wide, and many are the possible outcomes. An economy based on biomass can have different meanings, as for example the one in Grealis & O'Donoghue (2015), in which the authors concentrate on agriculture and food production and on the wider sectors dependent upon the ocean. In this thesis, however, choosing to analyze the substitution of oil-based products for biobased ones has a direct implication on the research outcomes.

In addition, the size of a biobased economy, as defined in this thesis, has also major influence in the results. From the definition of products, to the amount of each product to be developed, the uncertainty lies in every step of the research definition. As shown in different publications, as Gerssen-Gondelach et al. (2014) and Hoefnagels et al. (2013), a variety of process technologies are available for a single product. These technologies can vary in every parameter, from efficiency to total capital costs. The choices made in this study were driven by data availability and technological maturity.

Besides the choice of process technologies, the technological improvement is an important aspect of this study, and, again, a very uncertain one. It is difficult to predict the evolution of efficiencies and yields and how the processes will behave, if they occur. For example, there could be changes in the necessary investment or different inputs could be required to guarantee the increase in efficiency pointed out by this study.

Furthermore, besides technological improvements, learning effects and scale effects should be taken into consideration, but they are not included in this study, due to the static characteristic of I/O models.

Finally, different regions have different responses to such paradigm change. If a region such the Center-west is injected with a considerable amount of investments in the biobased sectors, there is no substitution to be analyzed, since it is not a petrobased region. On the other hand, regions like the Northeast with high petrochemicals' outputs have fewer advantages in this change, since it requires a substitution of production.

### *6.4.3. Income and income distribution in the biobased economy*

Differences between biosectors and petrobased sectors are the most influential aspects of the impacts on income and income distribution between the scenarios. A shift of employees from petrobased to biobased sectors of same skill levels could be foreseen, mostly in the fuel production sectors. In that case, the tendency is an increase in wages in the new sectors, in comparison with the traditional ethanol/sugar sectors, which should reduce the inequalities between scenarios, induce a larger increase in income generation, but also a larger increase in income inequality in low-skilled labor regions. The question is whether the new sectors will be able to remunerate the employee at the same level as the sectors that depend on oil.

Technological changes, such as second-generation technologies, raise demand for capital and lower demand for employment, prioritizing labor that is even more skilled over low skilled and unskilled, which also happens in the mechanization of sugarcane cultivation, for example. These technological progresses also affect the share of labor in the GDP. The participation of income in GDP is historically decreasing, which increases inequality between capital and labor. In 1995 until 2004, there was a reduction of participation (Bastos 2012). This trend, however, does not need to be accepted and can be stopped or even reversed in the future (Duenhaupt 2013).

## 6.5. Conclusions

This study quantified socioeconomic impacts of the increase of biomass use in Brazil in 2030, for the production of different products.

GDP changes can be considered marginal, driven mostly by the high levels of investments required by the new bioeconomy, and the size of this substitution.

Income is steady in the national level, but regionally the pre-existing petrobased sectors will determine if the entrance of a biosector will increase or decrease the levels of income, if comparing BAU to BBE1. From BBE1 to BBE2, the differences in technology levels between the biosectors, energy and petrochemicals, as well as the agricultural and fossil feedstock sectors are responsible for the bulk of the differences between those scenarios, followed by the substitution of high-income oil and natural gas sectors (but high income levels), by low income level sectors. The different levels of SCR and sugarcane-based biorefineries have also a considerable impact in the results for income.

Regionally, the five aggregated sectors of interest show considerable changes in income, but the small relative size of these sectors in regards to the whole economy dissolves the impacts, resulting in minor changes in the total economy. This shows that the chock of introducing bioeconomy, as considered in this paper, does not represent a dramatic change in economic paradigm.

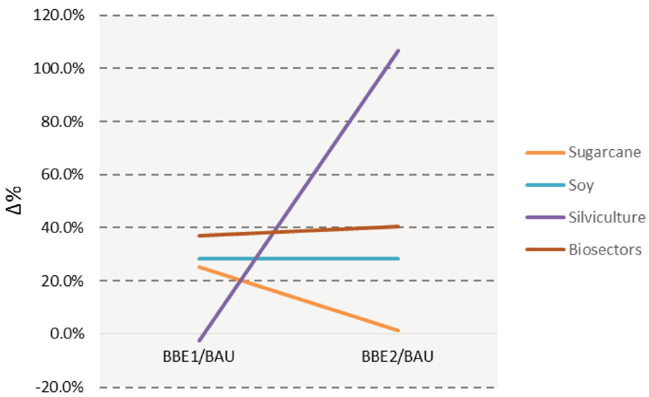
Overall, the share of labor in GDP reduces especially in the second biobased scenario. This indicates that, different from the perspective in Langeveld et al. (2010) and EuropaBio (2011), the bioeconomy might not increase rural development, since capital is being remunerated, but there is no guarantee that it is being locally reinvested, as labor remuneration would.

# 7. RESULTS: INPUT–OUTPUT LIFE CYCLE ASSESSMENT OF GREENHOUSE GASES EMISSIONS AND PRIMARY ENERGY USE FOR A BIOBASED ECONOMY IN BRAZIL.

The results are divided in 2 sections: GHG emissions and Primary energy use and are presented in table 33. The five macro regions in Brazil are shown in the graphs: Southeast (SE), South (S), Center west (CW), Northeast (NE) and North (N). The results are presented in terms of the main sectors of the economy, as it is in displayed in the annual estimates of GHG emissions in Brazil: Energy, Industrial processes, Agriculture and Livestock, Land use, land use change and forestry, and residues treatment (Ministério da Ciência 2013), and in the databased used for these calculations. Not all regions have all sectors present, as it is the case of n-butanol (only present in the northeast), acrylic acid (also only present in the northeast), ethylene and propylene, which are not present in Center-west nor North, and diesel and jetfuel, which are not present in the Center-west.

Southeast of Brazil has been historically the most important region in the country economically speaking, representing 55% of the GDP in the three scenarios. This is reflected in the absolute levels of emissions, especially in the energy and industrial processes share, regardless of the scenario. However, the 5 country regions show different patterns when analyzing the results in relative values. Depending on their status quo, the shift from petrobased to biobased economy has different impacts on each region.

The aggregated results for the whole economy are due to the changes in levels of production in 8 major sectors: Petrochemicals, Energy, Oil, Natural Gas, Sugarcane, Silviculture, soy and the biosectors, which compose a bioeconomy. Figure 54 shows the relative changes in production in BBE 1 and BBE 2 in comparison with BAU scenario.



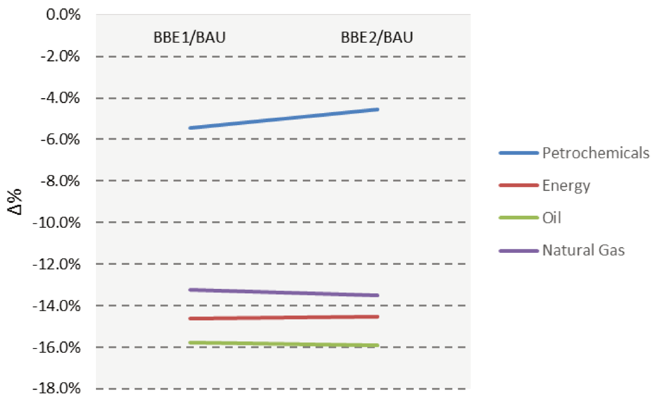




Figure 54 – Percentage change (Δ %) between BAU and BBE 1 and BBE 2 of the value of production of the most important sectors in a bioeconomy.

Changes in production due to the shocks provided exogenously to stablish a bioeconomy involve directly the sectors exposed in figure 54. The final results, are composed by the direct (and indirect) effects of the changes in these sectors added to the remaining direct and indirect impacts of the rest of the economy (ROE).

Table 33 – Results for BAU, BBE 1 and BBE 2 for 2030 regarding GHG emissions, non-renewable and renewable energy use

| | | **SE** | **S** | **CW** | **NE** | **N** | **Total** |
|---|---|---|---|---|---|---|---|
| **GHG emissions ($Gg\ CO_{2\text{-}eq}$)** | BAU | 549,342.99 | 448,733.85 | 209,682.27 | 182,871.60 | 328,539.40 | 1,719,170.10 |
| | BAU/BBE 1 (Δ%) | -6.2 | 7.5 | 4.2 | -0.1 | -7.4 | -1.1 |
| | BAU/BBE 2 (Δ%) | -3.0 | 13.9 | -6.0 | -10.5 | -11.6 | -1.2 |
| **Non-renewable energy use ($x10^3$ toe)** | BAU | 158,717.4 | 54,410.3 | 9,266.1 | 42,339.2 | 14,583.1 | 279,316.1 |
| | BAU/BBE 1 (Δ%) | -12.7 | -13.1 | 13.3 | -11.3 | -10.2 | -11.6 |
| | BAU/BBE 2 (Δ%) | -9.7 | -10.4 | 43.9 | -5.6 | -4.0 | -7.1 |
| **Renewable energy use ($x10^3$ toe)** | BAU | 84,723.9 | 37,894.3 | 43,649.1 | 25,132.1 | 10,873.0 | 202,272.3 |
| | BAU/BBE 1 (Δ%) | 16.4 | 8.3 | 24.0 | 16.3 | 11.6 | 16.2 |
| | BAU/BBE 2 (Δ%) | 15.1 | 24.4 | 11.6 | 66.9 | 33.2 | 23.5 |

### 7.1 GHG emissions

GHG emissions in total decrease 1.1% from BAU to BBE 1, and 1.2% between BAU and BBE 2, as seen in figure 55.

Reductions in industrial processes and residues treatment can be considered marginal, even with the substitution of petro-based chemicals for biobased ones. This is due to the low emissions in the chemicals chosen to be substituted. Most of emissions in Brazil in the industrial processes is not in the petrochemical industries, but in industries in which activities cause limestone calcination, as in cement and lime industries, and also in steel and metallurgy industries. The production of chemicals contribute with less than 1% of emissions. Residues treatment has an indirect contribution to emissions reductions, since it only reduces due to the reduction in activity of other sectors that demand it.

Energy is the most important sector in energy reduction. The substitution for bioelectricity, ethanol, biodiesel and renewable jetfuel in BBE 1 reduces by 7.3% emissions in the energy sector in the country, and BBE 2 reduces by 3.7%.

Agriculture and livestock as a whole show reduction in emissions due to reduction of total activity in the national economy and consequently in the livestock sector, although sugarcane and soy emissions go up 29%, which is expected in a bioeconomy.

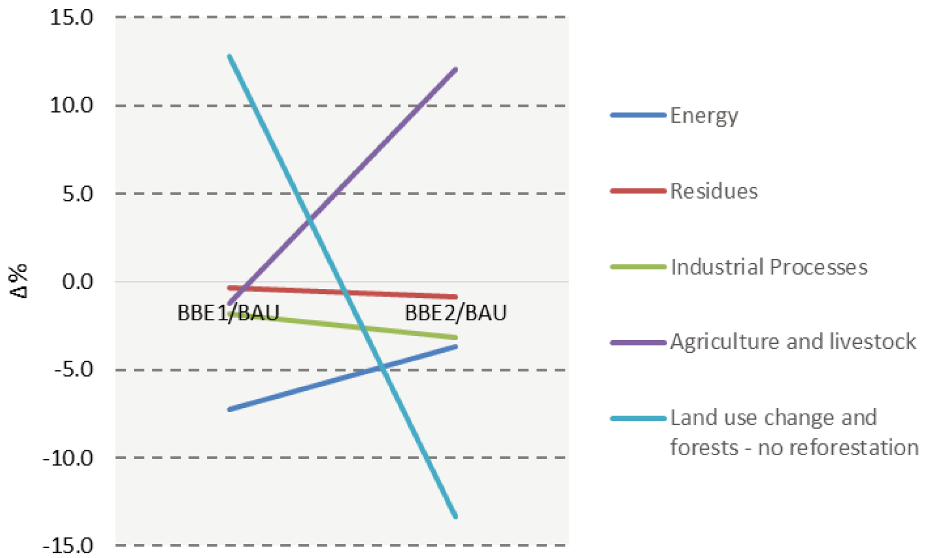



Figure 55 – Change in emissions from BAU to BBE 1 and BBE 2 scenarios in 2030.

Regionally, the emissions in a bioeconomy of industrial processes and residues treatment represent from 4% in the CW region to 31% in the Southeast. Energy, on the other hand, range from 8% in the N and 52% in the S. Agriculture is the most emitting sector in the CW, and emissions share of the agriculture sector range from 19% in SE and 48% in the CW. Figure 56 shows the profile of emissions of each region.

Livestock emissions represent 50% of emissions of the agricultural sector, and reductions occur mainly in the CW , where the share of emissions from livestock production reaches 73% of the total agricultural emissions.

Regarding changes in emissions, the highest increase in the agriculture and livestock sector happens in the BBE 2 scenario in the South region, due to the increase in silviculture production, with an increase of 25%, while in the North, in this sector, the increase is only 2.4% for the same scenario.

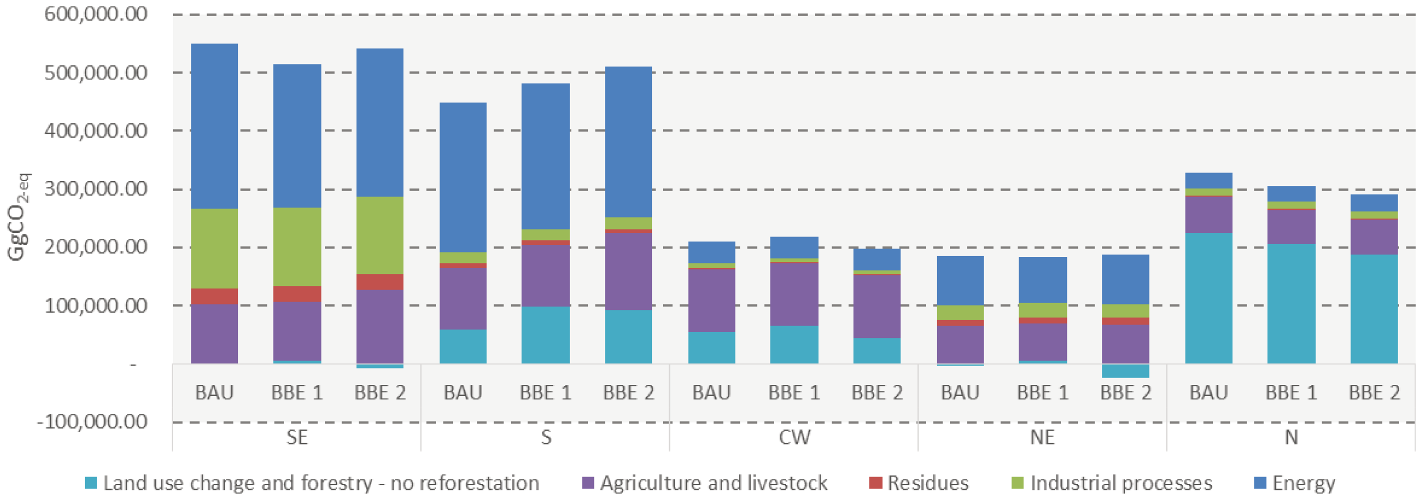
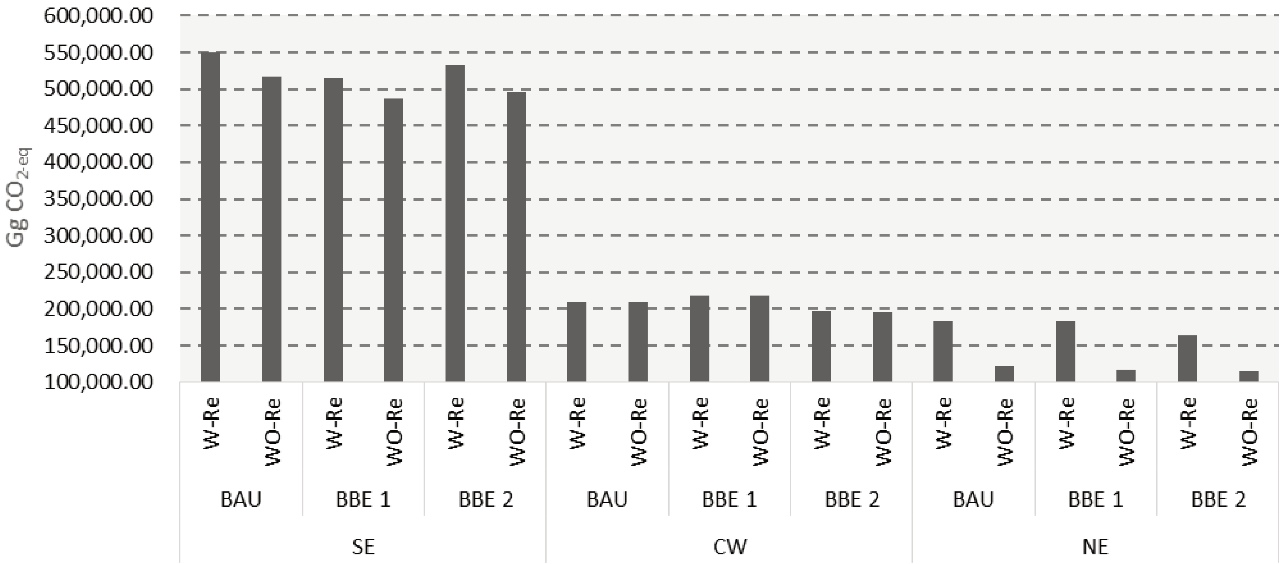



Figure 56 – Regional emissions profile in 2030 for all regions.

Emissions from land use change and forestry represent historically the largest share of total emissions, but have gone down from 52% to 43% from 2009 to 2015. In 2030, for the bioeconomy scenario, emissions from land use change would reach 20% of total emissions, varying from region to region. Regionalization based on Verstegen et al. (2016) conducts how expansion of land use will occur. In the case of regions losing their share of land use for a certain crops, reductions in total land use might take place. Figure 57 shows the emissions in the case that these reductions result in simple land abandonment. For example, Southeast region increases emissions in the first bioeconomy scenario, but sees reductions in the second one. This happens because sugarcane land use drops from the BBE 1 to BBE 2, while eucalyptus and pine go up, and SE represents 50% of all sugarcane, while only 20% of SRC crops.

Regional land use change will cause land use reduction in certain regions, which could be simply abandoned, as shows in figure 57, or the land left behind could be reforested. In this case, changes in emissions would occur. The Brazilian iNDC foresees 12 million hectares of

reforestation "for multiple purposes", while this thesis, for basis of calculation, considers only native vegetation reforestation, of 10.5 million hectares, which is the total amount of land that is reduced adding all regions.
Figure 57 shows the difference in emissions due to land use change in the case of reforestation of abandoned areas, in the regions when retraction happens (SE, CW in BBE 2 and NE).




W-Re = With reforestation; WO-Re = Without reforestation.
Figure 57 – Total emissions with, and without reforestation of abandoned land.

The variation in emissions due to land use change have an aboveground and a soil carbon parcels. These emissions occur from 2009 until 2030, considering the initial vegetation remaining in each region and are based on the exogenous decision of onto which biome expansion would take place. For the SE, and the CW, *Cerrado* was chosen. In the NE, *Caatinga* would be displaced, while in the North *Amazônia* biome is reduced due to agricultural land expansion. In the S, *Mata atlântica* was chosen.

**7.2 Primary energy use**

Brazil increases its total primary energy use by 0.09% in BBE 1 and 5.7% in BBE 2. Figure 58 shows the differences in energy use for each scenario, aggregated for the national level. The participation of renewable energy increases from 42% in the BAU scenario, to 48.8% in BBE 1, and 49.1% in BBE 2.

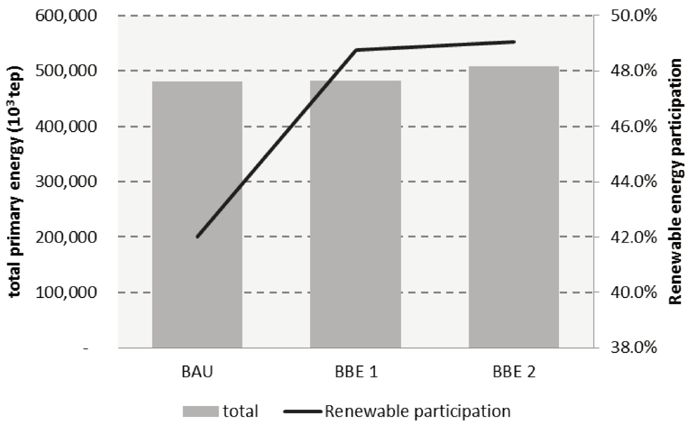



Figure 58 – Total primary energy use and renewable energy share in the economy in 2030.

Regionally, renewable energy use grows in BBE 1between 8.3% in the South to 24% in the Center-west. Non-renewable energy, on the other hand has a considerable reduction in 4 regions, from 10% in the North to 13% in the South in BBE 1, except for CW, with an increase of 13% due to the increase in sugarcane and soy diesel consumption. BBE 2 shows other dynamics with the introduction of 2G and SRC biorefineries. In CW, the non-renewable primary energy use increases 43%, accompanied by an increase in renewable energy of 11%. In the South, the growth of renewable energy reaches 24% in BBE 2, in contrast with a reduction of 10% in Non-renewables. Figure 59 shows the evolution of energy shares.

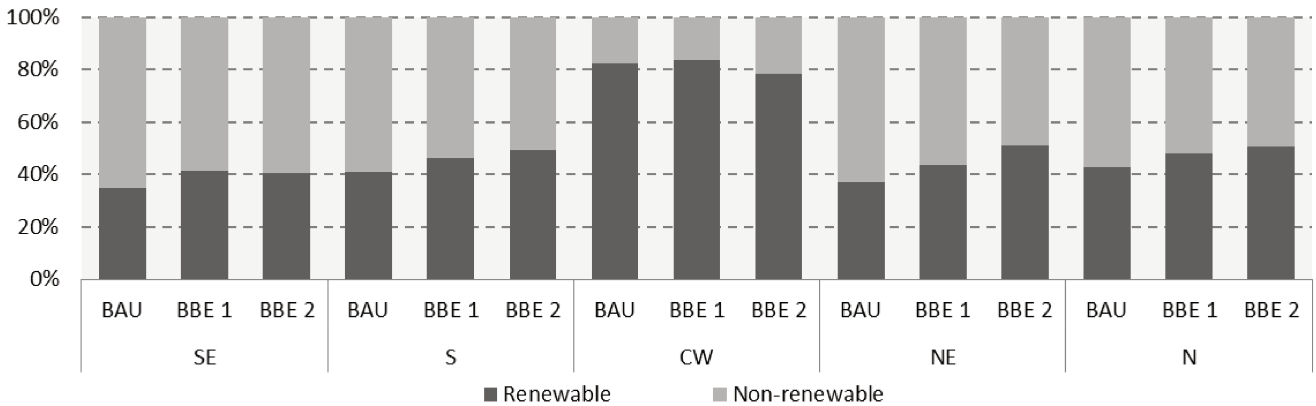



Figure 59 – Regional renewable and non-renewable share of total primary energy consumption in 2030.

The introduction of a bioeconomy changes the energy matrix of the country, for electricity generation and in other energy uses. Figure 60 shows the different shares of renewable energy.

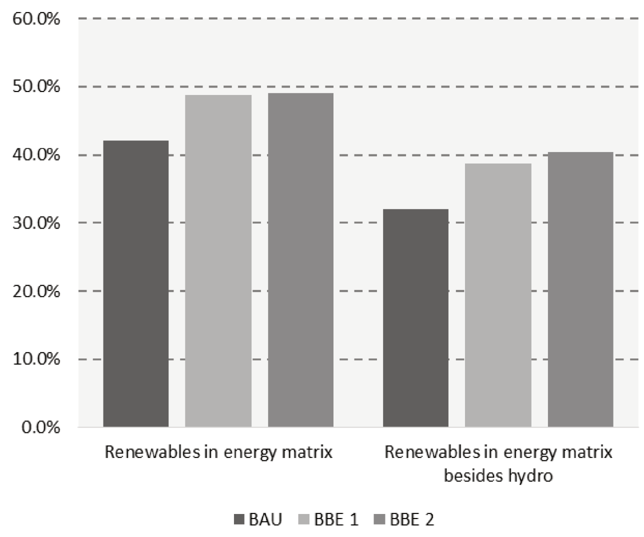



Figure 60 – Renewables share in different divisions of energy sector in 2030.

Primary energy use in Biobased economy helps reaching the targets of renewable shares in the energy matrix determined in the iNDC. The increases in renewable energy differ specially in electricity generation, due to the dispute between electricity and other products in the second-generation scenario. With the decrease in electricity generation in biorefineries, the whole mix of electricity generation will be demanded, raising the use of non-renewable primary energy.

## 7.3 Discussions

### *7.3.1 Input-output analysis and technology choices*

Several factors influence the results of outcomes of an input-output analysis, and one of them is the choices of technologies and the choices of the base year of the national account systems to be used. In this study, the analysis uses the 2009 Brazilian transactions tables to project 2030 scenarios. This time gap leaves room for uncertainties regarding the future efficiencies of the productive sectors in an economy. Although consolidated technologies have less room for improvements, not considering them could change results. Since this study has its basis on a comparative statics, the consequences of not considering improvements in the traditional sectors are minimized.

Besides the traditional technologies, the introduction of new biobased processes also carries uncertainties. Including a certain type of process without a range of values could induce the wrong conclusions, hence the existence of two scenarios with different technological levels.

The calculations of emission and non-renewable energy factors use data from 2009 of emissions and primary energy and the information of values of production in 2009 of the different sector in the economy. No reductions in emissions are included in the model due to increase in efficiencies of traditional sectors (those substituted by new biobased ones) and of sectors in the rest of the economy.

The Brazilian intended Nationally Determined Contributions served as basis for the construction of the reference scenario (BAU), but this study does not intent to calculate the emissions of that plan. The methods of calculations are different, and use different base years. Furthermore, the shares of renewable energy in the iNDC are explicit in terms of secondary energy use, while this study deals with primary energy.

Efforts in reducing emissions from 2009 until 2030 in the livestock sector is an important action to be taken, encouraging the intensification of livestock and the recuperation of low-productivity pasturelands. The assumptions on these thesis are towards the adoption of more efficient livestock management systems regarding the use of land. However, the displaced land due to livestock intensification, if not reforested, will be made available for other crops, which will increase emissions, instead of decreasing. Figure 61 shows the increase in emissions due to economic activity increase in the second biobased scenario, followed by the liberation of land for other agricultural sectors.

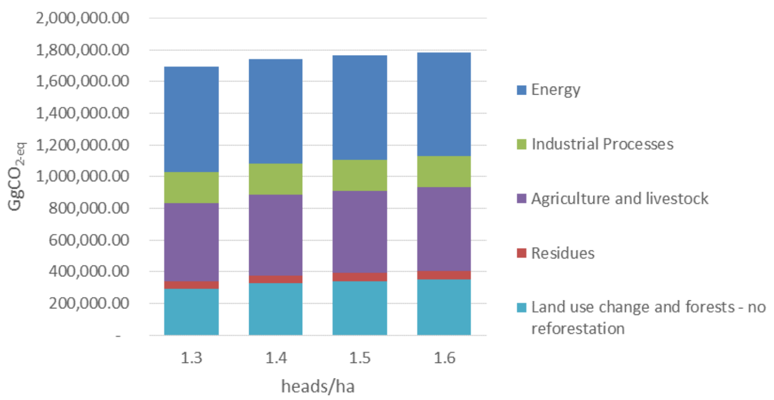



Figure 61 – Emissions after livestock intensification in 2030, for the BBE 2 scenario.

*7.3.2 Land use change and emissions*

Based on the stipulated emissions for 2030, the iNDC is not strict enough regarding emissions reductions in the land use sector. While the bioeconomy decreases 1.1% of emissions, the simple reforestation in the BAU scenario reduces 5.7% of total emissions. Even with the efforts to reach the 1.2 $GtCO_{2\text{-}eq}$ targeted for 2030 by the Brazilian government, the emissions from land use change will have to be contained in order to reach it, which means no deforestation shall happen in this period, or stronger reforestation will be required. This goes against the current legal framework for land use in the country, since new forest legislation allows further deforestation, reaching from 1.5 to 2.7 the current agricultural land being used (Sparovek et al. 2015).

Since legal deforestation might occur, it would be unrealistic to imagine that, in the case of a higher land use demand, deforestation would not happen. However, in order to keep emissions reductions of the biobased scenarios in relationship to the BAU scenario, land use expansion is limited. Figure 62 shows the increase in net emissions in relationship to the BAU scenario, in the case of land use expansion (in relation to 2009).

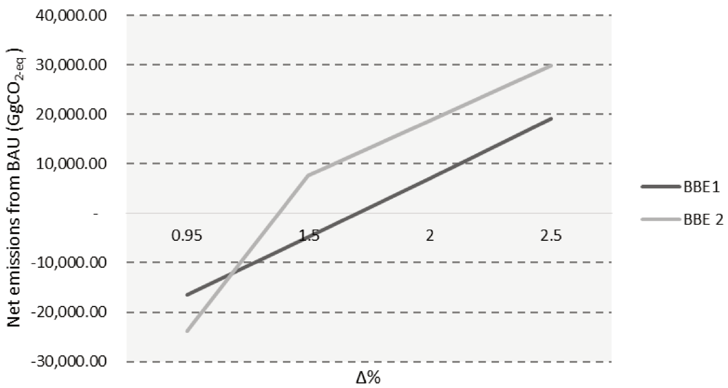



Figure 62 – Increase in net emissions due to land expansion in the BBBE 1 and BBE 2 scenarios, from 2009.

*7.3.3 Energy versus chemicals*

The discussion on energy versus chemicals revolves around the fact that biomass has limit supply, and that high value added products (as chemicals) should be prioritized over energy uses. Authors like Keegan et al. (2013) and Odegard et al. (2012) call it cascading use of biomass, while Eickhout (2012) mentions a "discrepancy between low and high value applications of biomass". The hypothesis that the use of biomass for energy is not sustainable is in fact not applicable for Brazilian realities, as seen in this study. The real emissions reductions lie on the energy sector, and chemical industrial processes have only marginal contributions, even when considering leakage emissions from oil extracting.

## 7.4. Conclusions

This study quantifies the emissions and non-renewable energy use in a biobased economy in Brazil in the year 2030, for different technological levels.

Even though the accumulated reductions in a higher technology level scenario reach only 1.2%, the absolute reductions of 53.2 $TgCO_{2\text{-eq}}$ is the equivalent of countries like Panama and Nicaragua (World Bank 2017). Energy use, also changed only slightly in the aggregated economy, but important contribution for the national targets can be made by a bioeconomy, when it comes to renewable energy use.

Regional differences shows that the bioeconomy benefits the emissions profile of different types of economies. When there is higher presence of agriculture, as it is the case of Center-West, or when it is an energy-intensive region, as the Southeast. The level of emission reductions vary, but it exists. In the case of energy use, the choices of destination for the residues could determine if more non-renewables would be used. If a region has a high share of bioelectricity to begin with, diverting residues to other ends could increase the use of other sources of electricity, including non-renewables.

Emissions due to land use change and livestock are at the center of this study. Most of reductions could be achieve with reforestation and livestock intensification, most desirably both together. The bioeconomy alone is not sufficient to satisfy the determined emissions reductions, especially if deforestation is not controlled beyond the legal framework current available in Brazil.

# 8. OVERALL CONCLUSIONS AND RECOMMENDATIONS

## 8.1. Overall conclusions

The global demand for energy and fossil feedstock is increasing. Fossil fuels dominate the current energy and chemicals' supply and this leads to a rapid growth in global greenhouse gas (GHG) emissions. Several GHG emissions mitigation options are available; and one of them is using renewable feedstock for materials, chemicals and mostly energy. Currently, most of the basic petrochemicals are produced using naphtha from crude oil and ethane derived from natural gas; however, the recent development of commercially viable biobased products originated the concept of a bioeconomy, defined as the innovation that enables the replacement of fossil fuels by biomass in the production of several products, including energy and chemicals.

Besides emission reductions, biomass feedstock deployment many positive socioeconomic impacts on different scales have been reported such as raising and diversifying farm income, increasing rural employment, general improvement of the local quality of life, improvement in agricultural techniques and local food security and increased access to energy (Wicke et al. 2009; Diaz-Chavez et al. 2013; Machado 2014; Eijck 2014). Others report that the production and use of bioenergy does not necessarily contribute to sustainable development. Negative impacts include deforestation and loss of biodiversity, as well as competition for arable land and other resources and consequent social impacts on food security, land ownership, displacement of communities and economic activities, and unequal distribution of benefits (Smolker 2008; Eickhout 2012; Odegard et al. 2012; McCormick & Kautto 2013).

Brazil has been an important biofuels' producer and it could be in the forefront of the development of a bioeconomy not only as a feedstock provider, but as a reference in biomass transformation. Considering the country a as a case study and to model its economy with focus on new technologies from biomass is then coherent with recent events.

In the Brazilian bioeconomy context, mainly focused on biomass for bioenergy, there has been several studies on socioeconomic and environmental impacts (with special attention to GHG emissions) pinpointing biofuels as rural development vectors capable of reducing GHG emissions. This thesis intends to bring new evidence to the bioeconomy debate, with particular interest in the macro-socioeconomic impacts of the large-scale deployment of biomass, substituting fossil fuels-based products, and the GHG emissions reductions followed by the adoption of a bioeconomy in Brazil.

This study aimed at developing and demonstrating a modelling framework interlinking Computable General Equilibrium and Input-Output models, which allow the analysis of the impacts on macro and socioeconomic aspects, GHG emissions and non-renewable energy use, in an integrated way for different future scenario's for deployment of BBE (where Brazil is the case study). The possibility of working with different technological levels and different feedstock is a key aspect of the modelling framework, based on technological developments for the 2030 time horizon.

The analysis was done for the chemicals ethylene, propylene, butanol, acrylic acid and polylactic acid, and for energy carriers, represented by biodiesel, ethanol and renewable jet fuel, plus bioelectricity. Three scenarios for 2030 were to compare different levels of production (amount of chemicals and energy production through fossils versus biomass) for Brazil, based on sugarcane, soy and forest crops (eucalyptus and pine). Different technological levels are also considered in this thesis. The first technological level is based on sugar crops and oil crops (associated to the so-called first generation biofuels – 1G). The second generation of technologies is the production of the same products, but from lignocellulosic feedstock materials by-products (sugarcane bagasse and straw, and forest residues) and dedicated feedstocks (eucalyptus and pine).

Two important methodological aspects of this thesis are the financial support provided by the government to enable the bioeconomy to develop, through subsidies, and the limitations in land use established by the need to reduce emissions. Subsidies will impact the government’s capacity to provide public services, and a series of impacts follow that effect. Land use limitations will also cause higher land prices, which will ultimately cause higher prices in the economy.

Results show that the choice of a bioeconomy in Brazil generates a slight reduction in GDP due to changes in the components of final demand that integrate it (Household, government, exports and imports), from 0.067% in BBE 1 to 0.43% in BBE 2. The most affected component in absolute terms is the government consumption. With the increase of subsidized activities in the bioeconomy, with most subisidies going to biodiesel, propylene, jet fuel, and the 2G SRC-based biorefineries in the second biobased economy scenario. Government consumption falls 1.4% in the BBE 2, and, considering that government consumption is focused on public services, the decrease in government consumption translates directly into reduction of public services provision to the Brazilian society. Following government consumption comes the investments. Calculated as the sum of households', government and foreign savings, investments in 2030 drop following a drop in foreign savings. Although foreign savings decrease with decrease of imports, focused on fossil feedstock and fossil-based products, Brazil would reduce its dependency in foreign feedstocks and inputs in a bioeconomy scenario.

Changes in employment come with the overall reduction in economic activity, concentrated especially in the public sector. Increases in the unemployment rate from 3.87 to 3.92% in BBE 1 and 3.96 % in BBE 2 are projected. Although net employment is positive in the BAU-BBE comparison, limitations arise when it comes to generalizing the statement about bioeconomy and employment generation. One of the reasons economic models are used is to consider all the direct and indirect impacts, when decisions have to be made.

The increase in land demand imposes an increase in land prices of 23% in BBE 1, and 32% in BBE 2. These increases have impacts on the prices of products that depend on land (agriculture), which affects household food consumption negatively, mostly focused on meet products (cattle, pork and poultry). Other food products (which encompasses most of the food products) has decline in household consumption only in the second bioeconomy scenario.

For the main analysis, land was kept constant to capture the impacts solely of the substitution of fossil products for biobased ones. However, Brazilian efforts to reduce deforestation have become weaker since the revision of its forest act, and less demanding regarding requirements on restoration of natural vegetation. With this in mind, allowing land to be expanded (deforestation) would change the overall macroeconomic impacts to positive ones. Land prices decreases with land endowment increase, as well as food consumption. GDP would increase, and unemployment rates would decrease. Increasing land endowment can also be done by increasing efficiency in the livestock sector. The same change in impacts would take place, with even higher impacts than deforestation.

The pressure on land caused by the bioeconomy is indeed the main issue, but volumes of energy carriers are responsible for 97% of the land use in BBE 1 and 87% in BBE 2. Regarding land use, satisfying Brazilian chemicals' demand could lead to less impact on land price, than meeting energy demand. However, bioenergy is an important contributor to avoided emissions in all scenarios (including BAU). These impacts on land could be reduced increasing yields in agriculture and further improvements in the industrial processes.

The effects of the industrial processes in subsidies requirements are more important than their ability to reduce use of land. Subsidies can be avoided if other measures are taken, besides yield improvements. As seen in Machado et al. (2016), scaling is an important factor on industrial costs and reaching 6 million tons is reasonable for Brazil. Another point to consider is the expected return in investments. If lower rates of return were applied, higher feasibility is foreseen, and consequently less subsidies required. Still, funding mechanisms from the government would be necessary to reduce investors' risk.

In the regional level, different results are perceived. This shows that generalizations of hypothesis based on assumptions should be carefully done, since regional differences will result in different outcomes. This is valid not only for within-country comparisons, but also for between-country comparisons. Southeast, Northeast and South regions (notorious petrobased regions) have similar decreases in GDP, while Centre West shows the highest increases, in BEE 1 scenario. Besides the introduction of biobased processes, the regionalization of consumption also induces regional changes between regions and scenarios. In BBE 2, the adoption of SRC-based biorefineries changes the location of production due to the suitable areas available in each region. Therefore, more activities move to regions where eucalyptus and pine tend to expand.

Differences between biosectors and petrobased sectors are the most influential aspects of the impacts on income and income distribution between the scenarios. Additionally, technological changes, such as second-generation technologies, raise demand for capital and lower demand for employment, which decreases labor share in GDP. Its consensus, at least among international institutions as the International Monetary Fund (IMF) and the International Labor Organization (ILO) that policies should prevent economic disparities, by supporting inclusive growth, with the increase in participation in the labor market and enhance the human capital of groups with lower income (Duenhaupt 2013; Francese & Mulas-Granados 2015). IMF also shows a negative relationship between functional and personal income distribution, i.e, income inequality goes up when labor share goes down.

When it comes to emissions, Brazil is committed to reach 1.2 $GtCO_{2\text{-eq}}$ in 2030, with several mechanisms established in the iNDC (Brasil 2015). Business-as-usual, which attempts to incorporate as closely as possible the proposed actions in the iNDC, shows that emissions reach 1.7 $GtCO_{2\text{-eq}}$, and that a bioeconomy could reduce 1% of these emissions in the current scenario. Emissions show that much more attention should be paid to the land use change and forestry sector. While a 1% reduction is seen in biobased eoconomy, reforestation in the BAU scenario reduces 5%.

The main difference from the results in this thesis and the iNDC lie on the carbon stocks in natural forests considered as anthropic removal when located in protected areas or indigenous lands by the Government. According to Observatório do clima (2017), the IPCC allows countries to decide whether these data are considered as anthropic removals. However, strictly speaking, these removals are natural (they occur as the trees grow in these forests), which distorts the result. If maintained constant until 2030, removals could reach 0.52 $GtCO_{2\text{-eq}}$, guaranteeing Brazilian goals.

On the other hand, public policies give productive sectors a different signal, when relaxed laws are proposed when it comes to deforestation and land productivity increases. If deforestation, a cheap solution to land shortage, is allowed, then emissions targets will not be reached.

Renewable energy has an important role in emissions reductions, in any scenario. The increase from 202 to 235 and to 249 $x10^6$ tep in renewable energy in the BBE scenarios is an important step for energy independency and to preserve fossil reserves. Processes in the biosectors, however, are not yet more efficient as hypothesizes Richardson (2012), since total energy use goes from 481 $x10^6$ tep in the BAU scenario to 509 $x10^6$ tep in the BBE 2 scenario.

## 8.2. Recommendations

Bioeconomy is an opportunity to increase renewable energy deployment and emissions reductions in Brazil with implications that follow the intensive need for capital (investment) and governmental support to reach a robust infrastructure of biorefineries all over the country. The support for a bioeconomy should start in the agricultural sector, with incentives mechanisms to increase productivity and better remunerate rural workers. If agriculture is to increase its share in total economic activity, wages have to improve in order to attract labor force as well as have actual positive impacts in local communities.

Strong environmental legislation coupled with incentive mechanisms for productivity increases would prevent emissions increase while decreasing fossil dependency. This is not the governmental signal passed on to productive sectors when it comes to deforestation with the new forest act.

Livestock intensification is an important factor of emissions reductions, but historical tendencies have only shown increase. The livestock sector has to be seen as key to the success of a bioeconomy, and to the achievement of emissions targets.

Regional expansion should also be a concern, and the positive effects of land use change should guide planning.

For Brazil, prioritizing energy production is the way to reduce emissions, since industrial emissions reductions are only marginal in a bioeconomy. Additional reductions in the industrial sector could be achieved if other sectors were substituted by biomass feedstock, like the construction sector (iron and cement production represent 77% of the total emissions in the industrial process sector).

Second generation technologies should be incentivized for residues, although scale effects could be a constraint. Logistically, the scaling production based on residues can be a challenge solved only by financial support.

Research wise, a number of recommendations can be done for future studies. First, regional CGE models should be build in order to internalize changes in regional transactions. A dynamic model is another step to improving the modeling framework. A stochastic model would light up the deviations in each methodological choice. Finally, the break down of land types and employment types would refine the research even further.

Future research should also look at the livestock sector more closely, analyzing the endogenous changes in the economy when different management systems are in place. This should also be done when it comes to reforestation, analyzing the economic options that can make reforestation economically viable.

Other forms of financial support, rather than subsidies, can be analyzed, as premium prices for biobased products, $CO_2$ taxes or other types of crossed subsidy. The comparison would show the best option to finance the massive infrastructure needed for a bioeconomy. The inclusion of a range of oil prices would also allow the actual need for subsidies, since higher oil prices would incentivize the use of biobased products.

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## APPENDIX A – Technical coefficients

This appendix present the technical coefficients of the biorefineries (biosectors) included in the model.

Table A.1 – Direct output technical coefficient matrix for the new biobased sectors (Based on monetary values)

| | Ethanol | Sugar | Bio-ethylene | Bio-propylene | Bio-butanol | Acetone | Bio-PLA | Bio-acrylic Acid | Bio-JetFuel | Biodiesel | Electricity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | 0.941 | 0.03 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.029 |
| **2** | 0.09 | 0.89 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.02 |
| **3** | 0.387 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.376 | 0 | 0.237 |
| **4** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| **5** | 0.495 | 0.346 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.159 |
| **6** | 0.857 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.143 |
| **7** | 0.081 | 0 | 0.768 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.151 |
| **8** | 0.071 | 0.396 | 0 | 0.368 | 0 | 0 | 0 | 0 | 0 | 0 | 0.165 |
| **9** | 0 | 0.128 | 0 | 0 | 0 | 0 | 0.862 | 0 | 0 | 0 | 0.01 |
| **10** | 0 | 0.146 | 0 | 0 | 0 | 0 | 0 | 0.772 | 0 | 0 | 0.082 |
| **11** | 0.518 | 0.288 | 0 | 0 | 0.116 | 0.02 | 0 | 0 | 0 | 0 | 0.058 |
| **12** | 0.712 | 0.269 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.019 |
| **13** | 0 | 0 | 0.979 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.021 |
| **14** | 0 | 0 | 0 | 0.971 | 0 | 0 | 0 | 0 | 0 | 0 | 0.029 |
| **15** | 0.296 | 0 | 0 | 0 | 0 | 0 | 0.697 | 0 | 0 | 0 | 0.006 |
| **16** | 0.167 | 0 | 0 | 0 | 0 | 0 | 0 | 0.776 | 0 | 0 | 0.057 |
| **17** | 0.722 | 0 | 0 | 0 | 0.19 | 0.032 | 0 | 0 | 0 | 0 | 0.056 |
| **18** | 0.621 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.351 | 0 | 0.028 |
| **19_E*** | 0.956 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.044 |
| **19_P*** | 0.898 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.102 |
| **20_E*** | 0 | 0 | 0.984 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.016 |
| **20_P*** | 0 | 0 | 0.912 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.088 |
| **21_E*** | 0 | 0 | 0 | 0.892 | 0 | 0 | 0 | 0 | 0 | 0 | 0.108 |
| **21_P*** | 0 | 0 | 0 | 0.898 | 0 | 0 | 0 | 0 | 0 | 0 | 0.102 |
| **22_E*** | 0.881 | 0 | 0 | 0 | 0.063 | 0.012 | 0 | 0 | 0 | 0 | 0.044 |
| **22_P*** | 0.762 | 0 | 0 | 0 | 0.123 | 0.023 | 0 | 0 | 0 | 0 | 0.092 |

*E stands for Eucalyptus, and P for Pine.

Table A.2 – Direct input technical coefficient matrix for the new biobased sectors

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Soybean** | 0.000 | 0.000 | 0.000 | 0.893 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **sugarcane** | 0.278 | 0.470 | 0.484 | 0.000 | 0.395 | 0.382 | 0.407 | 0.451 | 0.147 | 0.167 | 0.380 | 0.307 | 0.336 | 0.412 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Silviculture products** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Natural gas** | 0.000 | 0.000 | 0.015 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Crude soybean oil, cake and soybean meal** | 0.000 | 0.009 | 0.009 | 0.000 | 0.009 | 0.009 | 0.010 | 0.010 | 0.002 | 0.004 | 0.008 | 0.009 | 0.006 | 0.009 |
| **Products of mills and sugar refining** | 0.189 | 0.018 | 0.018 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.005 | 0.181 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Textiles** | 0.000 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.003 | 0.001 | 0.000 | 0.000 | 0.001 | 0.000 |
| **Paper, cardboard and packaging** | 0.002 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.003 | 0.001 | 0.000 | 0.000 | 0.001 | 0.000 |
| **gasoline/ethanol mix** | 0.001 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 |
| **Fuel oil** | 0.005 | 0.004 | 0.000 | 0.037 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Diesel** | 0.005 | 0.005 | 0.000 | 0.004 | 0.001 | 0.001 | 0.000 | 0.000 | 0.009 | 0.002 | 0.000 | 0.001 | 0.004 | 0.000 |
| **Ethanol** | 0.000 | 0.000 | 0.000 | 0.044 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Other inorganic chemicals** | 0.001 | 0.000 | 0.000 | 0.025 | 0.000 | 0.000 | 0.000 | 0.000 | 0.002 | 0.001 | 0.000 | 0.000 | 0.001 | 0.000 |
| **Other organic chemicals** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.018 | 0.000 | 0.032 | 0.011 |
| **Fertilizers** | 0.002 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Pesticides** | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Other chemical preparations** | 0.002 | 0.001 | 0.000 | 0.007 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 |
| **Rubber articles** | 0.001 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Plastic articles** | 0.003 | 0.008 | 0.008 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.002 | 0.003 | 0.008 | 0.009 | 0.006 | 0.009 |
| **Ciment** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Other non-metallic mineral products** | 0.000 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.004 | 0.001 | 0.000 | 0.001 | 0.002 | 0.000 |
| **Steel Castings** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Metal products - except machinery and equipment** | 0.000 | 0.000 | 0.011 | 0.007 | 0.012 | 0.012 | 0.012 | 0.013 | 0.003 | 0.004 | 0.000 | 0.012 | 0.008 | 0.012 |
| **Other Machinery and Equipment** | 0.005 | 0.010 | 0.011 | 0.003 | 0.011 | 0.011 | 0.012 | 0.000 | 0.003 | 0.004 | 0.010 | 0.011 | 0.007 | 0.011 |
| **Electrical machinery, appliances and equipment** | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Parts and accessories for motor vehicles** | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Products of various industries and recycled scrap** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Production of Electricity (cane)** | 0.003 | 0.005 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Rest of electricity generation** | 0.000 | 0.000 | 0.000 | 0.019 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Electricity Distribution** | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Water and sewage** | 0.001 | 0.002 | 0.010 | 0.000 | 0.011 | 0.012 | 0.020 | 0.013 | 0.003 | 0.005 | 0.009 | 0.012 | 0.010 | 0.014 |
| **Urban cleaning services** | 0.000 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Construction** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Trade** | 0.045 | 0.012 | 0.008 | 0.068 | 0.005 | 0.006 | 0.005 | 0.003 | 0.007 | 0.035 | 0.005 | 0.006 | 0.009 | 0.006 |
| **Road Transport Cargo** | 0.016 | 0.014 | 0.019 | 0.017 | 0.017 | 0.017 | 0.018 | 0.019 | 0.021 | 0.010 | 0.016 | 0.016 | 0.015 | 0.018 |
| **Road transport of passengers** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 |
| **Mail** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Information Services** | 0.003 | 0.002 | 0.000 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.003 | 0.001 | 0.000 | 0.000 | 0.001 | 0.000 |
| **Financial intermediation, insurance and pension and related services** | 0.031 | 0.018 | 0.018 | 0.019 | 0.019 | 0.019 | 0.020 | 0.021 | 0.005 | 0.007 | 0.017 | 0.019 | 0.013 | 0.019 |
| **Real estate activities and rentals** | 0.004 | 0.003 | 0.000 | 0.002 | 0.000 | 0.001 | 0.000 | 0.000 | 0.006 | 0.001 | 0.000 | 0.001 | 0.003 | 0.000 |
| **Maintenance and repair services** | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Accommodation and food services** | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.002 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 |
| **Business services** | 0.007 | 0.010 | 0.010 | 0.004 | 0.010 | 0.010 | 0.011 | 0.012 | 0.003 | 0.004 | 0.009 | 0.010 | 0.007 | 0.010 |
| **Household services** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **associative services** | 0.000 | 0.001 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.001 | 0.000 |
| Imports | 0.009 | 0.009 | 0.010 | 0.010 | 0.007 | 0.007 | 0.007 | 0.003 | 0.005 | 0.003 | 0.013 | 0.007 | 0.021 | 0.011 |
| Income | 0.227 | 0.106 | 0.073 | 0.040 | 0.114 | 0.114 | 0.115 | 0.129 | 0.033 | 0.043 | 0.114 | 0.114 | 0.079 | 0.117 |
| Gross operating surplus (GOS) | 0.070 | 0.224 | 0.556 | 0.110 | 0.350 | 0.360 | 0.384 | 0.562 | 0.703 | 0.486 | 0.366 | 0.437 | 0.404 | 0.738 |
| Subsidies | 0.000 | 0.000 | -0.292 | -0.358 | 0.000 | 0.000 | -0.062 | -0.272 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | -0.424 |
| Labor factor (Jobs) | 8.726 | 3.844 | 3.076 | 1.255 | 4.920 | 4.920 | 5.328 | 5.645 | 1.446 | 1.859 | 4.920 | 4.920 | 3.428 | 6.576 |

Table A.2 – direct technical coefficient matrix for the new biobased sectors (Cont.)

| | **15** | **16** | **17** | **18** | **19_E** | **19_P** | **20_E** | **20_P** | **21_E** | **21_P** | **22_E** | **22_P** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Soybean** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **sugarcane** | 0.119 | 0.169 | 0.311 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Silviculture products** | 0.000 | 0.000 | 0.000 | 0.000 | 0.459 | 0.599 | 0.524 | 0.525 | 0.602 | 0.648 | 0.497 | 0.632 |
| **Natural gas** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Crude soybean oil, cake and soybean meal** | 0.008 | 0.004 | 0.009 | 0.000 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 |
| **Products of mills and sugar refining** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Textiles** | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Paper, cardboard and packaging** | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **gasoline/ethanol mix** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Fuel oil** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Diesel** | 0.001 | 0.000 | 0.002 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Ethanol** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Other inorganic chemicals** | 0.000 | 0.001 | 0.015 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Other organic chemicals** | 0.000 | 0.000 | 0.000 | 0.000 | 0.118 | 0.111 | 0.115 | 0.125 | 0.150 | 0.120 | 0.109 | 0.094 |
| **Fertilizers** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Pesticides** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Other chemical preparations** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Rubber articles** | 0.000 | 0.000 | 0.009 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Plastic articles** | 0.007 | 0.004 | 0.000 | 0.000 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 |
| **Ciment** | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Other non-metallic mineral products** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Steel Castings** | 0.000 | 0.000 | 0.012 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Metal products - except machinery and equipment** | 0.010 | 0.006 | 0.011 | 0.000 | 0.012 | 0.012 | 0.012 | 0.012 | 0.012 | 0.012 | 0.012 | 0.012 |
| **Other Machinery and Equipment** | 0.009 | 0.005 | 0.000 | 0.000 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 | 0.011 |
| **Electrical machinery, appliances and equipment** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Parts and accessories for motor vehicles** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Products of various industries and recycled scrap** | 0.000 | 0.000 | 0.013 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Production of Electricity (cane)** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Rest of electricity generation** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Electricity Distribution** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Water and sewage** | 0.009 | 0.006 | 0.000 | 0.000 | 0.014 | 0.010 | 0.013 | 0.013 | 0.014 | 0.013 | 0.013 | 0.013 |
| **Urban cleaning services** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Construction** | 0.000 | 0.000 | 0.007 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Trade** | 0.004 | 0.002 | 0.009 | 0.000 | 0.018 | 0.018 | 0.018 | 0.019 | 0.022 | 0.019 | 0.017 | 0.017 |
| **Road Transport Cargo** | 0.004 | 0.008 | 0.000 | 0.000 | 0.026 | 0.029 | 0.027 | 0.016 | 0.030 | 0.030 | 0.026 | 0.029 |
| **Road transport of passengers** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Mail** | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Information Services** | 0.000 | 0.000 | 0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Financial intermediation, insurance and pension and related services** | 0.016 | 0.009 | 0.001 | 0.000 | 0.019 | 0.019 | 0.000 | 0.019 | 0.019 | 0.019 | 0.002 | 0.019 |
| **Real estate activities and rentals** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Maintenance and repair services** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Accommodation and food services** | 0.000 | 0.000 | 0.004 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Business services** | 0.009 | 0.005 | 0.000 | 0.000 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
| **Household services** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Associative services** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Imports** | 0.006 | 0.003 | 0.013 | 0.013 | 0.082 | 0.085 | 0.083 | 0.088 | 0.103 | 0.091 | 0.079 | 0.078 |
| **Income** | 0.095 | 0.055 | 0.114 | 0.148 | 0.143 | 0.143 | 0.170 | 0.170 | 0.202 | 0.217 | 0.162 | 0.178 |
| **Gross operating surplus (GOS)** | 0.686 | 0.781 | 0.440 | 0.792 | 0.227 | 0.226 | 0.270 | 0.239 | 0.402 | 0.427 | 0.215 | 0.225 |
| **Subsidies** | 0.000 | -0.076 | 0.000 | -0.602 | -0.207 | -0.346 | -0.323 | -0.319 | -0.654 | -0.697 | -0.222 | -0.394 |
| **Labor factor (Jobs)** | 4.093 | 2.376 | 4.920 | 6.305 | 1.268 | 1.262 | 1.497 | 1.499 | 1.774 | 1.911 | 1.683 | 2.057 |

E = Eucalyptus, P = Pine.

Table A.3 – Physical outputs for each facility

| | Ethanol (M*l*) | Sugar (kton) | Bio-ethylene (kton) | Bio-propylene (kton) | Bio-butanol (kton) | Acetone (kton) | Bio-PLA (kton) | Bio-acrylic Acid (kton) | Bio-JetFuel (M*l*) | Biodiesel | Electricity (kWh/ton) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1*** | - | - | - | - | - | - | - | - | - | - | - |
| **2*** | - | - | - | - | - | - | - | - | - | - | - |
| **3** | 95.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 59 | 0 | 184 |
| **4*** | - | - | - | - | - | - | - | - | - | - | - |
| **5** | 106 | 102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 184 |
| **6** | 189.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 172 |
| **7** | 17 | 0 | 78 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 170 |
| **8** | 13.2 | 102 | 0 | 33 | 0 | 0 | 0 | 0 | 0 | 0 | 168.2 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **9** | 0 | 102 | 0 | 0 | 0 | 0 | 154 | 0 | 0 | 0 | 31 |
| **10** | 0 | 102 | 0 | 0 | 0 | 0 | 0 | 133.3 | 0 | 0 | 225 |
| **11** | 94.7 | 51 | 0 | 0 | 21.1 | 4.6 | 0 | 0 | 0 | 0 | 159.6 |
| **12** | 176.1 | 102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 27.6 |
| **13** | 0 | 102 | 77.8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 28.4 |
| **14** | 0 | 102 | 0 | 61.7 | 0 | 0 | 0 | 0 | 0 | 0 | 31 |
| **15** | 176 | 0 | 0 | 0 | 0 | 0 | 136.7 | 0 | 0 | 0 | 20 |
| **16** | 176 | 0 | 0 | 0 | 0 | 0 | 0 | 133.3 | 0 | 0 | 23 |
| **17** | 227.9 | 0 | 0 | 0 | 11.9 | 2.8 | 0 | 0 | 0 | 0 | 47.8 |
| **18** | 163.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 58.5 | 0 | 29.1 |
| **19_E** | 416.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 164.1 |
| **19_P** | 393.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 240.8 |
| **20_E** | 0 | 0 | 184.4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 148 |
| **20_P** | 0 | 0 | 174.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 213.3 |
| **21_E** | 0 | 0 | 0 | 126.2 | 0 | 0 | 0 | 0 | 0 | 0 | 271.2 |
| **21_P** | 0 | 0 | 0 | 103.6 | 0 | 0 | 0 | 0 | 0 | 0 | 207.5 |
| **22_E** | 353.3 | 0 | 0 | 0 | 37.6 | 10 | 0 | 0 | 0 | 0 | 148.8 |
| **22_P** | 289.8 | 0 | 0 | 0 | 69.1 | 18.4 | 0 | 0 | 0 | 0 | 296.8 |

*

# APPENDIX B – Biopropylene paper