WORLD ECONOMIC FORUM

COMMITTED TO IMPROVING THE STATE OF THE WORLD

THE FUTURE OF INDUSTRIAL BIOREFINERIES

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The World Economic Forum would also like to acknowledge and thank **McKinsey & Company** for their contribution to this project and the report.

The World Economic Forum would like to thank the members of the Steering Board of the project for their contribution:
Feike Sijbesma, Chief Executive Officer, Royal DSM, Netherlands
Steen Riisgaard, President and Chief Executive Officer, Novozymes, Denmark
Bernardo Gradin, Chief Executive Officer, Braskem, Brazil
Thomas M. Connelly, Executive Vice-President, Agriculture, Nutrition and DuPont Applied BioSciences, DuPont, USA
Council Members of the World Economic Forum's Global Agenda Council on Emerging Technologies

The World Economic Forum would also like to thank for extra contributions:
Rob W. Van Leen, Chief Innovation Officer, Royal DSM, Netherlands
Thomas Schäfer, Senior Director, Novozymes, Denmark
Steve Hamburg, Chief Scientist, Environmental Defense Fund, USA

The World Economic Forum would also like to acknowledge and thank

World Economic Forum Partner Contributors
Royal DSM, DuPont, Novozymes, Braskem, BASF, Bayer, Evonik, Lanxess, Jubilant Bhartia Group, Reliance Industries, Tata Chemical, Mitsubishi Chemical Holdings Corporation, Sibur, Lufthansa, Swiss, Etihad, Airbus, TNT, Renault/Nissan Shell, BP, FMG, SCM, Anglo American

Nongovernmental Organizations
EDF (Environmental Defense Fund), IUCN, Greenpeace

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Contents

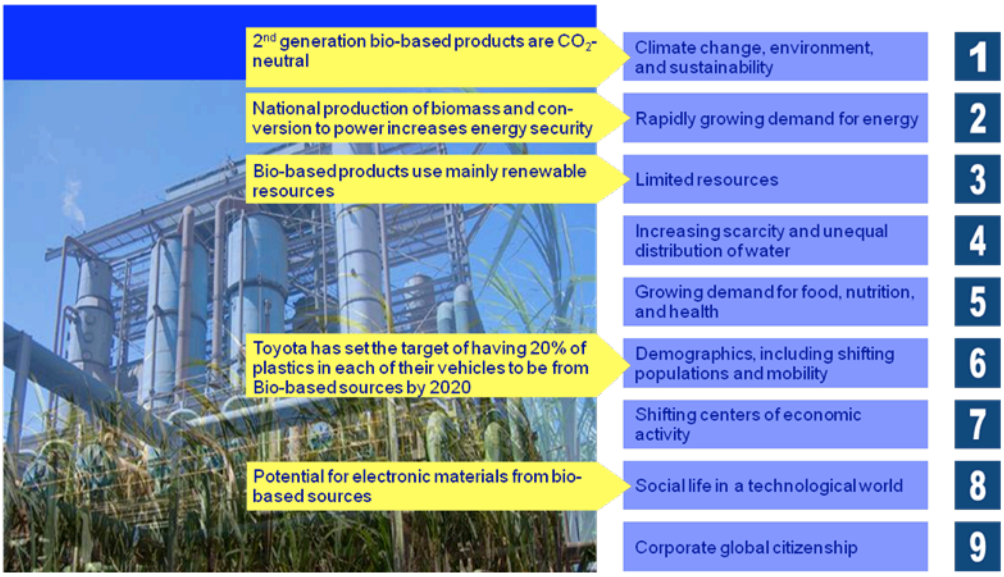
Contents

Foreword

The Collaborative Innovation Initiative was launched in 2009 by the World Economic Forum Chemicals Industry Partners Community to engage a community of chief innovation officers on the challenges and opportunities related to innovation. Together with innovation executives from other industries, policy-makers, experts, academics and NGOs, the initiative aims to explore the key issues facing the world where collaboration-based solutions between business, government and civil society are required. It recognizes that these issues, whether due to the complexity, risks or investments involved, cannot be solved by industry or government alone; action on a broader and more holistic level is required.

Initial efforts in this initiative identified the key global mega-trends and related challenges and innovation needs, providing a roadmap on the key issues that need to be addressed in the context of improving the state of the world. Issues where the Forum's power to convene different stakeholders would be particularly valuable were highlighted. Biorefineries fits well within this context as a first issue to be explored in depth. Climate protection, environment and energy are just some of the areas where biorefineries could provide a solution, and the technical, commercial and strategic challenges highlighted in this report will require collaboration if biorefineries is to realize its potential.

Beginning in 2009, a series of virtual meetings as well as a gathering in Dalian, People's Republic of China, took place over 18 months to explore the key obstacles, challenges, hurdles and enablers involved. The global overview is presented in this report, with work ongoing in 2010-2011 to explore the unique challenges and opportunities specific to different geographies.



Collaborative Innovation and the concept of "division of RD&D" mirroring "division of labour" is becoming increasingly prominent as technologies and issues become too complex and costly for one company – or industry – to tackle alone. Indeed, government as the representative of society is demanding that industry innovate and find solutions. In a way, this makes government a client of industry. By placing its demands on industry and not on individual companies, a new customer-supplier dynamic is established, with industry as the supplier. This has the potential to create an opportunity for industry to act as a whole in a collaborative manner, and to meet these innovation demands in a non-competitive way as truly corporate global citizens.

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Executive Summary

The world is facing many serious challenges. A fast-growing human population and the consequent growing demand for food, energy and water are the most serious. In addition, anthropogenic climatic change is a severe threat to mankind and requires that we significantly reduce our current greenhouse gas (GHG) emissions to avoid detrimental consequences for the globe. Only the use of new technologies will allow us to bridge the gap between economic growth and environmental sustainability in the long run.

Over the course of many multistakeholder discussions driven by the Chemicals Industry Community at the World Economic Forum in 2008 and 2009, industrial biorefineries were identified as one potential solution that may help mitigate the threat of climate change and the seemingly boundless demand for energy, fuels, chemicals and materials.

Biorefineries are facilities that convert biomass – biological materials from living or recently living organisms – into fuels, energy, chemicals and materials (and feed). To date, the industry is still in a nascent state, with most second-generation biorefinery plants (using cellulosic material) only expected to be ready for large-scale commercial production in a few years. The landscape of active players is rather scattered and fragmented with many relatively small technology players, but there is an ever increasing number of large players starting to invest.

Two of the main industry drivers, in addition to energy security and environmental concerns, are mandates and policies. Fuel regulations, such as the Low-carbon Fuel Standard introduced in California in 2007, are examples of potential industry drivers. The Standard requires fuel providers to reduce GHG emissions of the fuel they sell, to achieve a 10% reduction in the carbon intensity of transport fuels by 2020. Additionally, the Renewable Fuel Standard introduced in the US in the same year sets an emissions threshold that includes direct and indirect emissions from land use changes.

Regardless of these legislation-based regional differences in the *status quo* of industrial commercialization, generally the markets for bio-based products are expected to grow very strongly globally over the next few years due to four underlying, irreversible trends. First, the economics of fossil-based products are deteriorating since conventional crude oil resources are getting scarce. Second is the growing need for national energy security and geopolitical security. Third, public pressure for environmental sustainability is increasing due to an increasing environmental awareness. Last, but not least, rapid demographic growth will drive demand supported by rising economic aspirations of developing countries.

These fundamental trends triggered a vast interest in bio-based products and placed them high on the strategic agenda of most players in a variety of industries. In agriculture, for example, new economic opportunities will emerge from the rising demand for biomass. In the chemicals industry, bio-based innovative products outside the conventional petroleum-based product family trees will confer an advantage to players who manage to find the right molecules and insert them into existing or new value chains.

In the automotive and aviation industries, corporations are looking at biofuels as an important means to reduce the GHG emissions of their fleets to comply with regional or national regulations, while utilities are making high investments in the expansion of their renewable power generation assets, with biomass coming third after solar and wind investments.

Despite the great relevance of bio-based products for many industries, experts still see numerous technical, strategic and commercial challenges that need to be overcome before any large-scale commercialization of the industry can succeed.

Most importantly, biorefineries will have to employ the best possible technologies (for fermentation, gasification and chemical conversion, and also for pre-treatment and storage) to ensure that bio-based products break even. This will require the concerted action of many non-traditional partners – such as grain processors, chemical companies, and technology players – to cover all aspects of the complex biomass value chain, from feedstock production to end-user distribution.

Another significant challenge is to establish the necessary infrastructure (supply chain and distribution infrastructure) and raise the high capital costs required. The latter are typically beyond the financial reach of individual private companies, and may therefore require public funding.

In the United States, a recent report from Sandia showed that the US can produce 90 billion gallons of biofuels to replace oil (total use today is around 110 billion gallons). With improvements in mileage, that means that US could run solely on biofuel in 2030-2050. The limitation is not the supply of biomass but, rather, a complete infrastructure built around oil, expected low oil prices at least between now and 2020 and a lack of political decisions.

To overcome these challenges, various stakeholders need to play different roles in the industrialization process of biorefinery systems. Governments interested in supporting biorefineries for reasons of environmental protection and energy security should make significant investments in R&D, supply chain and distribution infrastructure as well as conversion capacity, while carefully regulating the implementation process to ensure food security and avoid land-use change.

Companies highly exposed to fossil feedstock and fuels will need to develop petroleum-replacement strategies to manage their risk, and explore the new business opportunities created by innovative conversion technologies and novel molecular outputs. Retail and business consumers need to be better educated about the benefits of bio-based products both from an environmental sustainability and business opportunity perspective.

Finally, NGOs and public authorities must be involved from an early stage to ensure development of the industry in a manner compatible with the highest environmental and social standards. Without the latter, broad public acceptance and the adoption of bio-based products will be hard to accomplish.

1. Basic Biorefinery Concepts

The term "bio-based products" refers to three different product categories: biofuels (e.g. biodiesel and bioethanol), bio-energy (heat and power) and bio-based chemicals and materials (e.g. succinic acid and polylactic acid). They are produced by a biorefinery that integrates the biomass conversion processes. The biorefinery concept is thus analogous to today's petroleum refineries that produce multiple fuels, power and chemical products from petroleum.

Biorefinery systems generally work by processing a bio-based feedstock input to create fuel, a chemical, feed or power/heat as an output (*see Figure 1*). Biorefineries thus use a wide variety of different inputs/feedstocks and conversion technologies.

1.1 Biomass Feedstock

Bio-based products can be manufactured from various feedstocks. However, at present there is no feedstock or process that would make these a clear alternative to fossil-based products. There are many options available, each with advantages and disadvantages. Two categories of feedstock dominate research: first and second generation. First-generation products are manufactured from edible biomass such as starch-rich or oily plants (*see i-ii*). Second-generation products utilize biomass consisting of the residual non-food parts of current crops or other non-food sources, such as perennial grasses or algae (*see iii-v*). These are widely seen as possessing a significantly higher potential to replace fossil-based products.

1.1.i. *Sugar/Starch Crops.* The most common type of biorefinery today uses sugar- or starch-rich crops. Sugar crops such as sugar cane, sugar beet or sweet sorghum store large amounts of saccharose, which can easily be extracted from the plant material for subsequent fermentation to ethanol or bio-based chemicals. Sugar cane is currently the preferred feedstock from an economic and environmental perspective due to the relative ease of production. However, this feedstock is restricted to certain locations due to weather and soil requirements.

Starch-rich crops such as corn, wheat and cassava can be hydrolyzed enzymatically to deliver a sugar solution, which can subsequently be fermented and processed into fuels and chemicals.[1] The processing of many starch crops also delivers valuable animal feed rich in protein and energy as a side product (e.g. Distiller's Dried Grains with Solubles – DDGS). According to a recent study by the IEA, DDGS could even replace protein-rich feed such as soy, with 20% higher land-use efficiency than conventional feed.[2]

This could become an important issue in relation to the land use of first-generation sugar/starch crops. There are approximately 400 operational first-generation biorefineries around the world yet, despite the efficiency and overwhelming success of this biofuel feedstock, there are still limitations when land-use change and its effect on GHG emissions are taken into account (*see 4.3*).

1.1.ii. *Vegetable Oil.* Vegetable oil is mainly used for the production of biodiesel by transesterification. There are two categories: pure plant oil (PPO) and waste vegetable oil (WVO). Pure plant oil stems from dedicated oil crops such as palm, soybean, rapeseed and sunflower seeds. The production of this is limited only by the agricultural capacity of the country. Use of waste vegetable oil, for example cooking oil or animal fat, is an effective method of recycling our daily wastes; however, it does need refinement as well as hydrogenation to become usable biodiesel.

Sustainable and economic production of biodiesel from vegetable oils has proved a challenge. This is due to the significant land-use change and sustainability issues as a result of pure plant oil production, and the high costs associated with the refinement of waste oil due to its unavoidable impurity. Fuels derived from vegetable oil are widely used; however, its use is likely to be most effective as a supplement to other energy forms, not as a primary source.[3]

1.1.iii. *Lignocellulosic Biomass.* Lignocellulosic biomass refers to inedible plant material mainly composed of cellulose, hemicellulose and lignin. It is deemed likely that this type of second-generation feedstock will be used for the production of biofuels and bio-based chemicals in the future using different conversion technologies. However, it is more difficult to convert lignocellulosic biomass into a usable output than other types of biomass; the main reason for this is that the protective shield of hemicellulose and lignin that surrounds cellulose has to be broken down, which is a highly energy intensive process.

On the pro side, it can be derived from many different sources, including forestry waste (e.g. wood chips), agricultural waste (e.g. straw, corn stover), paper and municipal waste, as well as dedicated energy crops such as switchgrass, miscanthus or short-rotation poplar. These feedstocks exclude direct land-use change and minimize indirect land-use change, *vide infra.* Cellulosic ethanol is ready for deployment due to recent significant breakthroughs in the enzymatic conversion process.[4]

1.1.iv. *Jatropha Oil.* The Jatropha Curcas tree from Central and South America contains 27-40% inedible oil, which can be converted to biodiesel via transesterification. An assessment of *j.curcas* sustainability reveals a positive effect on the environment and GHG emissions, provided cultivation occurs on wasteland or degraded ground.

The factors influencing the environmental impact of using jatropha are much the same, as any other biomass feedstock, cultivation intensity and distance to market are all expected to have an impact. It is thought that jatropha is one of the main drivers for rural development due to its labour-intensive production chain, a reminder that social impacts cannot be ignored. The exact nature of cultivation of jatropha and its effects on the environment are not fully understood, making it difficult to determine its future as a fuel alternative.[5-8]

1.1.v. *Micro-algae.* Micro-algae are a large and diverse group of unicellular photo- and hetero-trophic organisms that have attracted much attention in recent years due to their potential value as a renewable energy source. Focus has been on storage lipids in the form of triacylglycerols, which can be used to synthesize biodiesel via transesterification. The remaining carbohydrate content can also be converted to bioethanol via fermentation.

The advantages of using algae-derived fuels as an alternative are numerous. First, they can provide between 10 and 100 times more oil per acre than other second-generation biofuel feedstock and the resulting oil content of some micro-algae exceeds 80% of the dry weight of algae biomass, almost 20 times that of traditional feedstock. They are safe, biodegradable and need not compete with arable land. In addition, they are highly productive, quick to cultivate and simply require CO_2, sunlight and water to grow.

However, numerous barriers remain to be overcome before the large-scale production of micro-algae-derived biofuels can become a commercial reality. Producing low-cost micro-algal biodiesel primarily requires improvements to algal biology through genetic and metabolic engineering, to achieve “optimum” attributes such as high growth rate, high lipid content and ease of extraction.

Advances in photobioreactor engineering are expected to lower the cost of production. Biofuels produced from the mass cultivation of micro-algae potentially offer a highly attractive and ecologically-friendly fuel resource; however, the challenges still remain to close the cost gap between micro-algae derived fuels and fossil fuels.[9-11]

1.2 Conversion Techniques

Depending on the feedstock and the desired output, biorefineries employ a variety of conversion technologies, transforming the raw biomass into commercial energy sources. These most commonly include fermentation, gasification and transesterification. New and less traditional methods are constantly being investigated, particularly in the development of synthetic biofuels such as biomass-to-liquid (BTL). Novel chemicals and materials produced from biomass are also currently available, but are much less developed at a commercial level compared with fuels *(see 3.2.iv).*

1.2.i. *Fermentation of Sugar/Starch Crops.* The fermentation of sugar solutions originating from either starch crops or lignocellulosic material requires pretreatment of the feedstock to liberate the sugars from the plant material. Starch is usually hydrolyzed enzymatically to deliver sugar solutions, followed by the microbial fermentation stage to produce bioethanol. Sugar crops such as sugar cane can be directly fermented to produce ethanol.[12]

*1.2.*ii. *Fermentation of Lignocellosic Biomass.* When using lignocellulosic biomass, feedstock processing needs to separate the cellulosic and hemicellulosic material from the non-fermentable lignin, which are strongly bonded by covalent cross-links.[13] This is usually done mechanically, followed by acid, alkali and/or steam treatment. While the lignin is currently mostly combusted to deliver energy, the cellulosic and hemicellulosic components are hydrolyzed enzymatically to deliver sugar solutions, followed by fermentation.

As opposed to the fermentation of pure C6 sugars (as in starch or saccharose), fermentation of broken-down hemicellulose also requires special fermentation organisms capable of converting C5 sugars such as Xylose.[14] At present, there is a need for more efficient and robust microorganisms that can withstand higher temperatures and pressures to deliver the fermentation product for both of the above biomass feedstocks *(see 4.1.ii).*

1.2.iii. *Transesterification of Triglycerides.* Transesterification of plant or algal oil is a standardized process by which triglycerides are reacted with methanol in the presence of a catalyst to deliver fatty acid methyl esters (FAME) and glycerol. Waste vegetable oil can also be converted, but requires refinement. Both acid and alkali catalysts can be used, although the alkali catalysed reaction proceeds 4,000 times faster than the same reaction with acid.

The main problems associated with using triglycerides as a diesel replacement tend to be high viscosity, low volatility and polyunsaturated character. Transesterification is a method of reducing the viscosity of the triglycerides and enhancing the physical properties of the fuel. As a result, FAME biodiesel is the most common form of biodiesel used today.[15]

1.2.iv. *Gasification: Formation of Syngas.* Gasification of biomass allows the breakdown of carbonaceous materials into their synthesis gas compounds, namely H_2 and CO, known as *syngas*. Gasification can be achieved by thermal decomposition in the presence of a limited amount of oxygen. The resultant mixture of hydrogen and carbon monoxide is then converted by partial oxidation at elevated temperature or via a Fischer-Tropsch reaction *(see 1.2.vi)* into the molecules of choice.[16]

1.2.v. *Fast Pyrolysis.* Similar to the formation of syngas, pyrolysis is the thermal decomposition of the biomass into a liquid bio-oil containing various hydrocarbons and an oxygen content of 35-40%, which can then be converted via hydrogenation *(see 1.2.vii)* or via gasification into the target hydrocarbon. The use of pyrolysis and the properties of the bio-oil produced are still in development, but it is thought that it can reduce the costs of gasification compared with feeding solid biomass directly into the gasifier.[16]

1.2.vi. *Fischer-Tropsch Synthesis.* The conversion of syngas via the Fischer-Tropsch process into synthetic fuel involves the catalytic conversion of syngas into liquid hydrocarbons ranging from C1 to C50. A selective distribution of products is achievable with control over temperature, pressure and the type of catalyst.[1] Although this process is widely recognized, there is a possibility of catalyst shortages in large-scale productions if catalyst regeneration is not improved. This technology is commonly found in the commercial generation of electricity and synthetic fuels from conventional fossil fuels.

However, the same principles can be applied to biomass and biofuels production; it is therefore commonly referred to as BTL. Gasification of biomass has had little commercial impact owing to competition from other conversion techniques. There has, however, been renewed interest in this process, yet economically viable examples are rare.[16]

1.2.vii. *Hydrogenation.* A more energy-efficient alternative of producing synthetic biofuel, involving hydrotreatment of bio-oils to produce hydrotreated renewable jet fuels (HRJ). Hydrogenation removes oxygen and other impurities from organic oils. These oils can be extracted directly from feedstocks with high oil content, such as *jatropha*, *camelina* or algae, or produced through pyrolysis *(see 1.2.v)*.

Hydrotreating bio-oils with hydrogen at medium to high temperatures converts bio-oils to hydrocarbon fuels, such as HRJ. The resultant fuels are pure hydrocarbon and have indistinguishable physical properties from fossil-based fuels. HRJ fuels tend to have better combustion performance and higher energy content, similar to Fischer-Tropsch fuels and, most importantly, have good low-temperature stability, making them ideal as a renewable source of jet fuel *(see 3.2.iii).* In December 2009, the first aviation test flight powered by biofuel sourced from jatropha oil was undertaken by Air New Zealand.[1, 17, 18]

1.2.viii. *Conversion of Syngas to Methane.* Methane can be produced from syngas as a result of thermal gasification and a variation of the Fischer-Tropsch reaction. It can also be found as a by-product of Fischer-Tropsch biofuel synthesis. Synthetic natural gas (SNG) is a substitute for natural gas that can be fed directly into the national grid, and used as a transport fuel if liquefied.[19-21]

1.2.ix. *Anaerobic Digestion.* SNG production can also involve the conversion of biodegradable waste or energy crops into a gaseous fuel called biogas, made up largely of 50%+ methane and carbon dioxide. Commercial conversion processes typically run via anaerobic digestion or fermentation by anaerobes. This biological process is used as a renewable substitute for commercial natural gas and is estimated to have a conversion efficiency of 70%.[21]

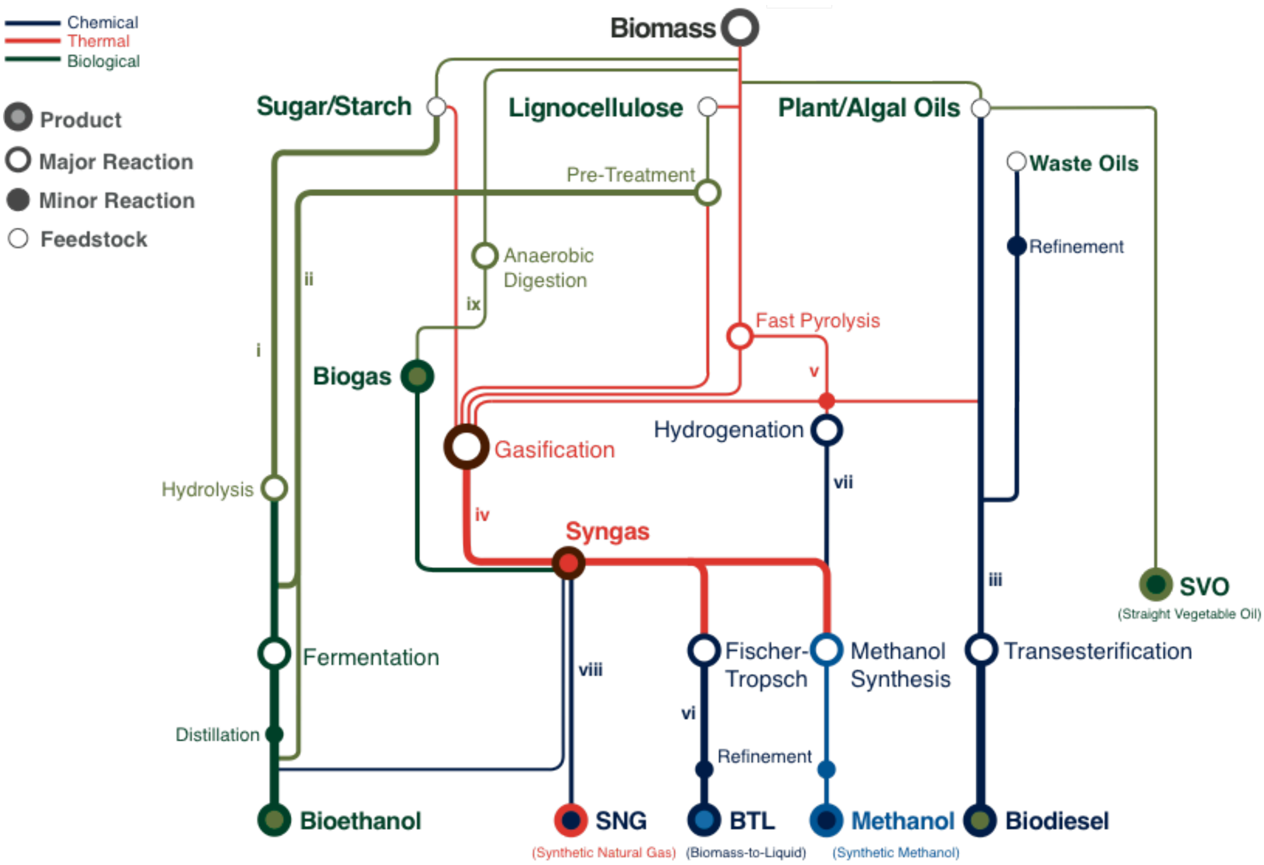

Figure 1: *Biofuel Flow.* The multiple synthetic conversion routes of major biofuels produced from first and second-generation biomass feedstock. Roman numerals correspond to the conversion processes described in *section 1.2.*

1.3. Biorefineries

1.3.i. *Optimization and Efficiency.* A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, chemicals, feed, materials and energy from biomass. The objective of a biorefinery is to optimize the use of resources and minimize wastes, thereby maximizing benefits and profitability.

Biorefineries will encompass a variety of conversion processes and different sized installations due to the range of processes – biological, chemical and thermal – that can be employed. Optimization and high efficiency are the keys to making biorefineries sustainable and economically viable.[22, 23] Optimization can be achieved by future development in key areas and the efficient exploitation of chemical energy from biomass:

- *Technology.* Developments in conversion technologies will lead to more of the plant being used to produce a wider, more flexible range of products – for example, chemicals and materials – in addition to fuels. Much of this development is technology dependent and will lead to improvements in environmental and economic performance of the production processes. The conversion processes and the end products that can be produced are dependent on the feedstocks available and how they are exploited.

- *Exploitation.* The challenge is to find the optimum method of exploiting the chemical energy embedded in the biomass. Developing highly efficient conversion techniques – such as development of new microbial strains for the direct conversion of hemicellulose and advanced catalyst development to improve regeneration after transesterification – is a vital component of improving the conversion process. There are also existing technologies available for improving the crops that produce feedstocks for biorefineries. These include fast-track breeding (non-GM) and the use of GM to increase yield and to facilitate conversion of lignocellulose. Although multiple products can already be gained from a single feedstock, it is important to vastly increase the diversity of these products using a GM strategy for the development of new crops.[1]

- *Logistics.* Optimizing the efficiency of the supply chain will require feedstocks to be developed with characteristics that increase the efficiency of the conversion process and have the necessary characteristics to produce the end products. The logistics of biorefinery outputs must also be considered, including transportation and supply chain infrastructure (e.g. deep-water ports, roads, etc.), organization of storage facilities and identification of new trade routes. Biorefineries that are designed to be flexible and modular will be able to take a wider range of feedstock or adapt to changes in demand for specific chemicals without large capital costs. This flexibility will also mean that a biorefinery will be able to cope with a variety of feedstocks that mature at different times of the year. A modular installation will also be able to change its processing technologies as new feedstocks are developed.

From a research perspective, the emphasis must be on the development of a set of capabilities that are independent of particular fuels, chemicals and materials.

The *economics* and *sustainability* of biorefineries are dependent on their efficiency and can consequently be improved by optimization of the entity:

- *Economics.* The cost of production of bio-based products and, in particular, the investment needed for infrastructure and supply will have a direct bearing on their success as an alternative to fossil-based products. An efficient biorefinery will ensure cost minimization and a cost competitive end product. At present, efficiency is difficult to define since an efficient biorefinery is still a concept. However, if one describes biorefinery efficiency in terms of utilizing local resources and the existing infrastructure, maximizing biomass-to-product conversion rates, ensuring flexibility in the products produced by the refinery and streamlining supply chains, then it is clear it will have a large impact on the economic viability of biorefineries.

- *Sustainability.* How the various processes in the conversion stage are combined will have significant impacts on the sustainability of bio-based products. Throughout the biorefinery, there is the opportunity for improved recycling of heat/energy or the regeneration of catalysts in an integrated approach, which will have an impact on the carbon footprint of the overall process and resulting products. New biorefineries are often generating excess energy from waste products, which is then fed into the grid, often lowering the net CO_2 emissions from the overall process. Just as efficiency had an effect on the economics, the efficiency will also have an effect on the sustainability. The optimal biorefinery should be capable of utilizing biomass as a renewable energy source that can sustain our energy needs in the long term.

1.3.ii. *The Biorefinery Concept.* Adapted from the National Renewable Energy Laboratory (NREL),[24] a simple biorefinery concept has been devised that is built on three different "platforms" to promote different product routes *(see Figure 2).*

The *Biochemical Platform* is currently based on biochemical conversion processes and focuses on the fermentation of sugars extracted from biomass feedstocks. The production of bioethanol requires three main steps: fermentation of the sugars, distillation to remove the bulk of the water and dehydration to further remove water from the remaining azeotropic water/ethanol mixture.

Starch-based feedstock requires saccharification to produce fermentable sugars. Lignocellulosic biomass requires steps to separate the lignin from the cellulose before the sugars can be extracted. The latter (second generation) process may be viewed as a "bolt on" to the former (first generation) process using the same fermentation processes but requiring an additional enzymatic step to extract the sugars.

The *Thermochemical Platform* is currently based on thermochemical conversion processes and focuses on the gasification of biomass feedstocks and resulting by-products. Where gasification of carbonaceous materials is widely used (e.g. syngas production from coal), gasification of lignocellulosic biomass is still a developing technology. Thought must given to how this process would fit in to the biorefinery concept, and how heat and power can be combined from both platforms as by-products.

Algae biofuels occupy a third *Microorganism Platform*, where cultivation and extraction occur on the same site. The two main methods of cultivation are within:

a) Raceway-type ponds – cheap, high capacity open air ponds exposed to the elements
b) Photobioreactors – closed systems providing a light source and all required nutrients

Photobioreactors provide a greater oil yield per hectare due to their higher volumetric biomass productivity. In addition to oils, micro-algal biomass contains significant quantities of proteins, carbohydrates and other nutrients. A micro-algal biorefinery can simultaneously produce biodiesel, animal feed, biogas and electrical power. The cost of producing micro-algal biodiesel can be reduced substantially by using a biorefinery based production strategy, improving capabilities of micro-algae through genetic engineering, designing new synthetic microorganisms and advances in engineering of photobioreactors.[11, 25]

Two important concepts are guiding NREL's efforts to create novel, successful biorefineries:

- To take maximum advantage of intermediate and by-products to manufacture additional chemicals and materials
- To balance high-value/low-volume bio-based chemicals and materials with high-volume/low-value biofuels

A biorefinery might produce one or several low-volume, but high-value, chemical products and a low-value, but high-volume liquid transportation fuel, while simultaneously generating electricity and process heat for its own use and perhaps enough for the sale of electricity. The high-value products enhance profitability, the high-volume fuel helps meet national energy needs, and the power production reduces costs and avoids GHG emissions.[24]

Around a dozen additional chemicals apart from syngas and fuels may currently be produced per refinery but, ultimately, the local market value for the final products will determine which products will be produced. The production of chemicals will be an important part of the economics of a biorefinery (flexibility to adapt to timely market needs), as the composition of plant material allows easy derivation of primary chemicals, quite different to those derived from oil. Consequently, a bio-based chemical industry will be built on a different selection of "platform" chemicals than those in the petrochemical industry.[12]

At present there is no definitive answer to determine the "optimal" biorefinery. A highly efficient, sustainable and economically viable one, however, can be achieved by making conversion processes more efficient, designing with flexibility in mind, maximizing the exploitation of chemical energy from feedstock and developing a set of conversion capabilities that are independent of particular fuels, chemicals and materials.

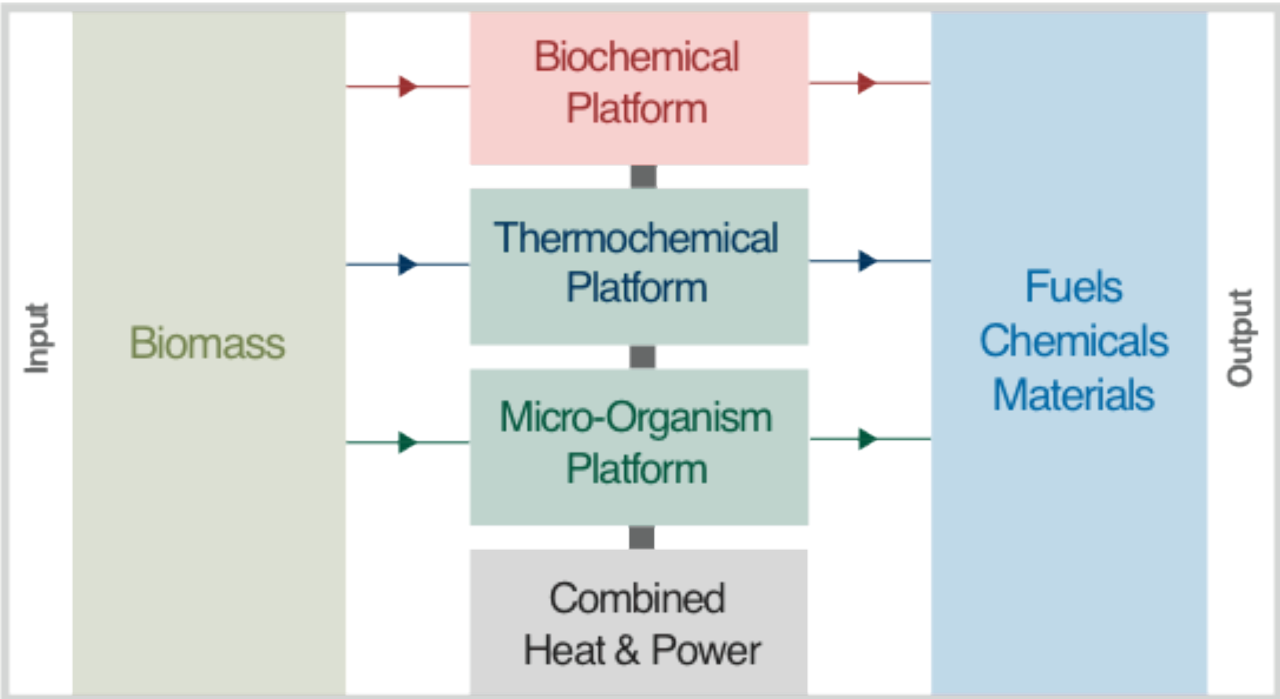

Figure 2: *The Biorefinery Concept*. A simple three "platform" concept adapted from a model devised by the National Renewable Energy Laboratory to include a microorganism platform. This concept demonstrates how any number of conversion processes can take place within one biorefinery, analogous to today's oil refinery.

2. Current Status of Industrialization

2.1. History of Bio-based Products

In contrast to current public perception, converting biomass into energy or fuels has a very long history. As early as 1860, the German Nikolaus August Otto invented the Otto engine using ethanol as automotive fuel. Similarly, during the early decades of the 20th century, Rudolf Diesel invented the diesel engine, built to run on peanut oil, while Henry Ford designed his Model T car to run on hemp-derived ethanol.

However, biofuel use declined dramatically as large-scale exploration of crude oil began in the 1930s, marking the start of an industrial era dominated by oil that has remained unchallenged to this day. For the rest of the last century, biofuels surfaced only twice during relatively short periods, where external circumstances forced a partial replacement of petroleum. One such period was World War II, where the shortage of fuels led to various inventions, such as the use of gasoline along with alcohol derived from potatoes (Germany) or from grain (Great Britain).

The second period was the oil crisis in the late 1970s, where the high oil price attracted governments and scientists to the reuse of biofuels as a means of increasing energy security. In 1977, for example, the Brazilian scientist Parente invented and submitted a patent for the first industrial process converting biomass into biodiesel. Yet, it still took another decade until the Austrian company Gaskoks erected the first biodiesel pilot plant in 1987.

Biorefineries were built in many European countries during the last decade of the 20th century. About the same time, concerns about global warming and climate change were emerging on public agendas worldwide. These concerns began to translate into national and regional legislation during the beginning of the 21st century, further pushing the industrialization of biorefineries. For example, the EU adopted its biofuels directive in 2003, which set a reference value of 5.75% for the market share of biofuels in 2010.

In 2007, the EU council adopted a 10% binding minimum target for the share of biofuels in petrol and diesel consumption in transportation by 2020 *(see 2.2.ii)*. In the near future, additional national legislations, subsidies or mandates are expected to promote the establishment of second-generation pilot biorefineries by 2011 or later, while experts estimate that cellulosic biofuels will be fully commercial on a large scale in five to 10 years.

2.2. Industrialization

The biorefinery industry is gathering pace, with most second-generation plants expected to be ready for large-scale commercial production in a few years. Furthermore, the landscape of active players consists mainly of relatively small technology players, but also an increasing number of large multinational companies willing to invest in sustainable energy. Nonetheless, a number of technology clusters, networks and partnerships are developing, often composed of partners with complementary expertise along the biomass value chain, particularly with regard to second-generation technologies.

National mandates and policies are among the main industry drivers, which is why the status of industrialization differs substantially between countries or regions. Before some of the inter-regional or international differences are explored below, some remarks about regulatory regimes in general are warranted. Generally speaking, all biofuel-producing countries have a mix of mandates and subsidies in place to support their national biofuel industries as a means to increase fuel supply security, CO_2 reduction or local farm revenues. Biomass-based power production is supported by similar measures.

Subsidies can be generous, but vary from country to country, even within the same region. Italy, for example, guarantees feed-in tariffs of 280 euros/MWh, which is substantially higher than the average power price in Europe.[26] Bio-based chemicals generally do not enjoy a lot of regulatory support beyond research grants and statements of political will. While EU targets also support an increasing share of bio-based materials in chemicals production, no related subsidies or mandates exist in the chemical industry.

As mentioned above, national legislations and regulatory regimes are the main drivers of regional or national differences in the industrial commercialization of bio-based products *(see Figure 3).*

2.2.i. *United States.* In the US, the biofuels industry has undergone significant expansion in recent years. The focus has been on achieving increasing efficiencies of first-generation biofuels production, which invariably means reductions in the use of energy and other resources. The majority of facilities in the US run at an efficiency rate of some 60%, with improvements derived, as in all processes, through knowledge and experience over time.

Furthermore, the US has in many instances been at the forefront of developing sustainability standards for biofuels. The active role played by the US Department of Energy has made the country a leading player in the emerging biofuel industry. This has been achieved by a large number of public technology grants, not just to domestic companies, but also to investors worldwide.

The US government has also committed to high targets for the replacement of fossil transportation fuels – 36 billion gallons of biofuels by 2022 in the following proportions: 15 billion corn-based, 16 billion from cellulosic ethanol and 5 billion from advanced processes (In 2008, US biofuel and ethanol production amounted to 9 billion gallons). There are, however, no subsidies for other bio-based products so far.[27]

2.2.ii. *Brazil.* In Brazil, the promotion of the sugar cane industry has led to the highest penetration worldwide of flex-fuel vehicles (FFVs) that can run on any mixture of bioethanol with gasoline. However, while domestically a tremendous success, the export of ethanol or sugar is still very limited due to tariffs imposed on these products by other regions, e.g. the US and the EU.

The highly developed sugar cane and ethanol industry is now attracting additional investments in bio-based plastics, for example via the conversion of bioethanol into ethylene and subsequent processing to materials such as HDPE and PVC. Second-generation technologies making optimal use of the biomass generated in sugar cane farming (conversion of the bagasse into ethanol instead of burning it) are also seeing strong growth, despite the wide availability of sugar cane. With Braskem about to start a new biorefinery, and more in the pipeline, the industry is expected to gather pace in Brazil and globally.[28]

United States	Brazil	European Union	China	India
Mandate of 36 billion gallons of biofuels by 2022. Volumetric tax credit: USD 0.51/gal ethanol + USD 1.00/gal biodiesel. Cellulosic biofuel producer tax credit: USD 1.01/gal. Small producer tax credit: USD 0.1/gal. USD 1 billion in support for 2nd generation technology.	30+ year commitment to 'alcohol program'. Annual blending target for ethanol (25%). Biodiesel target of 5% by 2013. Lower taxes for ethanol (E100) than gasoline. FFV sales tax of 14% compared to 16% for gasoline-only vehicles.	5.75% blending target by 2010 and 10% by 2020. Discussion on target waiver triggered by food crisis, but no change of policy so far. Country-level subsidies average USD 1.90/gal for ethanol and USD 1.50/gal for biodiesel. Penalty fee in 5 countries for noncompliance with biofuel target.	Plan to substitute 20% of crude imports by 2020. Target of 1.7 billion gallons of ethanol by 2010. Investments in feedstock-rich countries. Commitment to develop non-food based biofuels - COFCO (Nat. Food Corp.) with PetroChina and Sinopec - 2nd generation multiple projects.	Blending targets in current drafts are 5% by 2012, 10% by 2017, 20% for long term. Target of 20% biofuels by 2020. Duty-free imports of jatropha to support biodie-sel. Individual states may set additional measures to promote biofuels or restrict transport of molasses over state boundries.
***Corn/ Lignocellulose**	***Sugarcane**	***Rapeseed/ Lignocellulose**	***Lignocellulose/ Various**	***Various**

Figure 3: *Worldwide Mandates and Subsidies*. Current policy status in five major world regions. (*) denotes key feedstock.[29]

Brazil has also instigated a policy of agricultural zoning for sugar cane, which will block the expansion of sugar cane production on native vegetation. There are also moves to mechanize the harvesting of all sugar cane by the middle of this decade. The Brazilian bioenergy industry is working within the framework of a voluntary agreement with the Government of the State of São Paulo – home to the vast majority of sugar cane production in Brazil – to achieve this goal. To date, some 55% of sugar cane is now harvested mechanically and a separate programme to retrain workers into other positions is also underway.

2.2.iii. *European Union.* In contrast to the leading positions of the US and Brazil, the EU's ambitious goals for the establishment of renewable energies and transportation fuels have so far been met only to a moderate extent, and have not effectively positioned the EU in a leading role globally, despite public policy incentives, direct investments and research grants. This is because, on an industrial level, fewer biorefineries are being established in the EU than in the US. This is partly due to the fragmented nature of the EU's R&D efforts and insufficient funding and resources for large demonstration plants.

As a result, a large portion of the knowledge on biorefinery technologies generated by European universities, research institutes and industry players is currently being shifted overseas because of the lack of development projects in Europe.[30] By 2020, the EU expects 20% of its power to come from renewables, part of which will have to be delivered by power derived from biomass. Additionally, 10% of all transportation fuels should come from renewable sources, which will require a substantial increase in penetration of biofuels.[31]

2.2.iv. *Asia.* The situation is similar in Asia. Despite declarations of ambitious biofuel plans and repeated support for biofuels by many Asian governments (e.g. India), actual achievements have been modest so far. Inconsistent implementation of biofuel policies also makes it impossible to forecast whether the biofuel targets announced will be achieved.

China, however, is an exception. It appears intent on injecting large sums into biorefinery projects due to the importance assigned to biomass-derived energy production in its latest Five-Year Plan. With regard to bioethanol, for example, China has licensed five fuel ethanol plants (mostly state refineries) for operation, all of them based on starch crops. China's fuel ethanol production was consequently forecast to rise to 1.70 million metric tons (MMT) in 2009, an increase of 8% compared to 2008.

That said, food security concerns have recently led the Government of China to restrict ethanol production from grain processing and to turn to supporting non-grain-based fuel ethanol production instead.[29] While limited feedstock supplies and competition with land use for grain production may still be an issue, several lignocellulosic biofuel plants are being developed, e.g. by COFCO. Indeed COFCO, Sinopec and Novozymes recently announced plans to construct the largest cellulosic biofuel demonstration facility in China by 2011.

Chinese biodiesel production plants, on the other hand, are small scale and often use waste cooking oil instead of dedicated oil crops, operating only a few months of the year due to the lack of sufficient feedstock supply. Therefore, while overall 2008 biodiesel production capacity in China (four plants, mostly private ownership) was estimated at three MMT, actual biodiesel production in 2008 was only 250,000 MT due to a feedstock deficiency.[32]

Compared to China, India's national biofuels policy is still under debate. However, drafts of future blending targets have already been drawn up that aim for 5% penetration of biofuels in India by 2012, 10% by 2017 and 20% long term (2017+).[33]

2.2.v. *Africa.* Africa has recently come into focus as a potential production hub for biorefineries, particularly biofuel production. This is mainly due to the strong raw materials position that many African countries could have, provided four main challenges are addressed. One is their low agricultural productivity caused by suboptimal agricultural practices, such as lack of fertilizers, deficient crop protection, shortcomings in the education and know-how of farm workers, insufficient irrigation and the dominance of smallholder subsistence farming. Another is the scarcity of food in some regions, with concomitant social/ethical concerns about food security (i.e. the food vs fuel debate).

Infrastructural limits to the production and transportation of bio-based goods (roads and harbours, for instance) also play a major role. Additionally, there is political instability in some African countries, which makes investments less attractive. However, some African countries have recently strongly encouraged investments in biotechnology, particularly biofuels. This has led to a large number of projects in Mozambique, Tanzania, South Africa, Ghana and other African nations. The predominant type of bio-based company produces biofuels – especially bioethanol – from sugar cane, and biodiesel from jatropha.[6] While some investments have been made by foreign companies with the long-term goal of exporting biofuels to Europe, most projects target domestic markets.

Irrespective of these regional and national differences, it is expected that the markets for bio-based products will grow very heavily over the next few years. Biofuels markets are estimated to more than triple by 2020. The combined sales of biodiesel and ethanol will surge to around US$ 95 billion in 2020 due to mandates alone. The resulting combined US and EU27 demand for biomass in the fields of heat and power is also expected to more than double by 2020.

Finally, bio-based chemicals are expected to grow significantly and increase their share in overall chemicals production to some 9% of all chemicals. However, this growth will be less than in biofuels and biopower because (as mentioned previously) there are no mandates and no incentive schemes in place in the chemicals arena.[34]

2.3. Revenue Potential

In addition to the revenue potential offered by the above-mentioned output categories (fuels, energy, chemicals and materials), the biomass value chain also offers attractive revenue potentials at its other stages, of which a significant portion may be captured by the chemicals industry *(see Figure 4).*

2.3.i. *Agricultural Inputs.* On the input side, new types of energy crops, including the development of new traits such as drought and disease resistance, crop protection and fertilizers are needed to improve volume and the quality of biomass output such as energy density and molecular composition. All three offer interesting complementary business opportunities for the chemicals industry. According to estimates these opportunities amount to a business potential of US$ 15 billion by 2020.

2.3.ii. *Biomass Production.* Actual biomass production offers farmers and grain processing companies new business opportunities in addition to traditional land uses. This includes the cultivation of energy crops for biofuels (e.g. miscanthus) or for biogas (e.g. white sweet clover), cultivation of short rotation forestry or cultivation of sugar cane, in particular for biorefining chemicals.

Overall, it is estimated that the additional business potential amounts to approximately US$ 90 billion by 2020, which is the largest single business potential along the entire biomass value chain. Improved farming practices will help produce and extract the optimal amount of biomass from the field. First innovative collaborations are emerging, as the partnership between Archer Daniels Midland, John Deere and Monsanto on corn stover research demonstrates.[35]

2.3.iii. *Biomass Trading.* Between biomass production and biomass conversion, numerous logistical challenges offer new opportunities for traditional or emerging niche players. To reduce the bulk load of biomass, for example, new densification techniques (e.g. briquetting or pelletization) are needed to handle logistics economically, particularly, when biomass is imported from abroad.

Second, highly-coupled supply chains have to be set up to manage seasonal nature of harvesting. Third, new preservation techniques are needed to control molecular composition of biomass throughout the supply chain (i.e. harvesting, transportation and storage). Finally, the trade of biomass itself offers a substantial revenue potential to the respective trading parties. It is estimated that the accumulated revenue potential of these opportunities amount to US$ 30 billion by 2020.

2.3.iv. *Biorefining Inputs.* Prior to the actual biorefining conversion process, new business opportunities are, for example, offered by improved methods of biomass pre-treatment (e.g. dilute acid pre-hydrolysis and hydrothermal methods), which can help improve the biomass accessibility to downstream enzymatic and fermentative processes. In addition, the development of more efficient enzymes and fermentation organisms will bring down biomass conversion costs. Several players have already emerged in this area successfully (e.g. Danisco/DuPont, Novozymes, DSM).

In February 2010, Novozymes launched a commercial enzyme mix for large-scale production of advanced biofuels. It will enable second-generation production at a production cost of US$ 2 when the first commercial scale comes online within the next couple of years.[36] Overall, the market for pre-treatment chemicals, enzymes and new organisms is estimated to yield US$ 10 billion in revenues and chemicals companies are well-positioned to establish new businesses in all three areas by 2020.

2.3.v. *Biorefining Outputs (fuels, chemicals, power and heat).* Finally, the actual ownership of biomass conversion and the respective sale of end products is estimated to yield revenue potentials of US$ 80 billion for biofuels, US$ 10-15 billion for bio-based bulk chemicals and bioplastics alone, and US$ 65 billion for power and heat by 2020. Here, chemicals companies are well-positioned to run their own conversion plants.

However, some highly integrated traditional chemical companies will be somewhat less flexible with respect to bio-based feedstock than others. Companies ideally positioned may be those backward-integrated into feedstocks. Braskem, for example, has large petrochemical operations but owns access to sugar cane and ethanol manufacturing through its controlling company Odebrecht, which established ETH Bioenergia in 2007 – a sugar cane ethanol operation. This led to the generation of the first "green" polyethylene in 2007.[37]

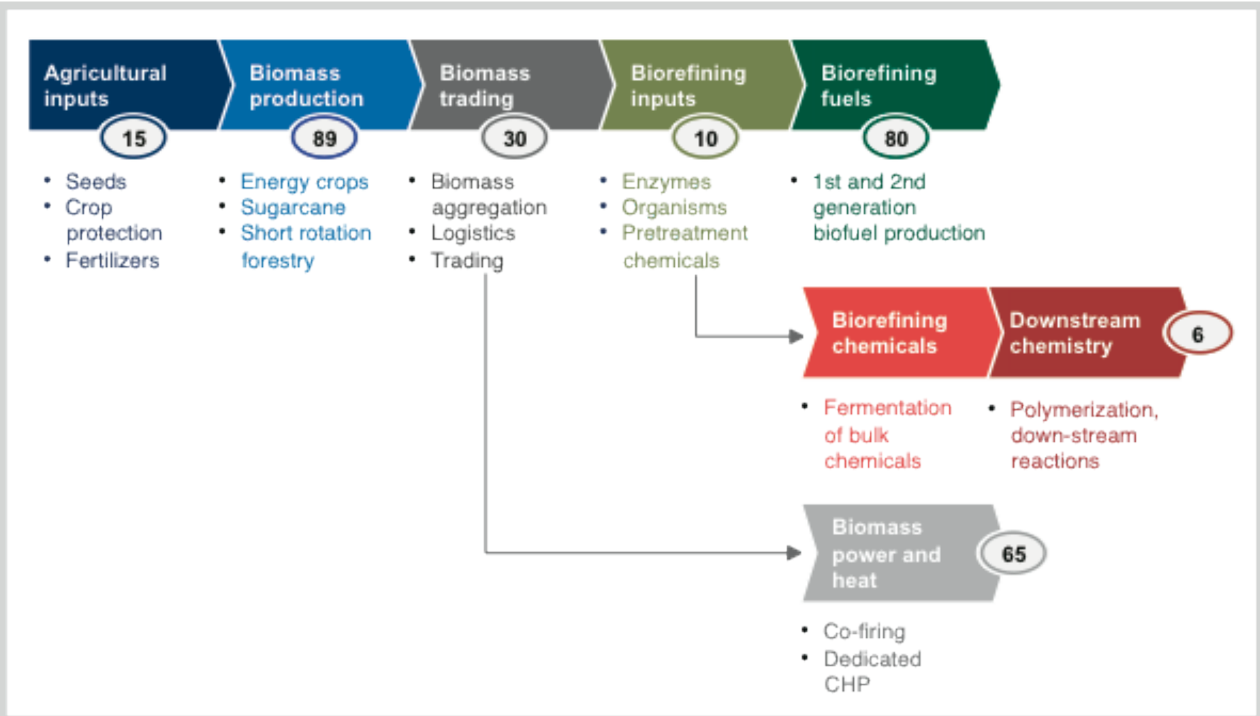

Figure 4: *Revenue Potential*. There are significant revenue potentials along the entire biomass value chain. The values given are approximate business potential in US$ billions by 2020.

3. Strategic Relevance for Industry

As the above mentioned revenue potentials along the biomass value chain have indicated, there are many new business opportunities, and some industrial sectors may be better positioned to seize these opportunities than others. That said, offering new business opportunities is not the only way in which the production of bio-based products will affect different industries. The newly established value chain will have room for non-traditional partnerships: grain processors integrating forward, chemical companies integrating backwards, and technology companies with access to key technologies, such as enzymes and microbial cell factories joining them.

In addition, a number of underlying trends have put bio-based products high on the strategic agenda of players in many industries. This chapter examines those fundamental trends and then describes the strategic consequences for six key industries.

3.1. Long-term Trends Driving Adoption of Biofuels

Bio-based products are likely to become ever more important for various key industries in the future due to four underlying, irreversible global trends:

3.1.i. *Demographic Growth and Rising Economic Aspirations of Developing Countries.* The constantly escalating consumption of fossil fuels and feedstock in combination with tremendous demographic and economic growth in emerging regions is resulting in exponentially increasing demand for these raw materials. Given the limited availability of fossil reserves, alternative, sustainable sources to satisfy the needs of humankind may be the only viable alternative.

3.1.ii. *Need for Increased Geopolitical Energy Security.* Many countries strive to reduce the economic and geopolitical exposure associated with their need for oil by replacing at least part of their fuel and feedstock demand by the domestic production of bio-based alternatives.

3.1.iii. *Deteriorating Economics of Fossil-based Products.* Increasing prices for crude oil have made the production of selected bio-based products economically attractive. Some biofuels, for example, break even below US$ 50/bbl without subsidies and, in the long run, bioethanol is expected to break even at US$ 0.35/litre, effectively making it cheaper than current gasoline.

3.1.iv. *Increasing Public Pressure for Environmental Sustainability.* Mitigation of the risk of catastrophic climate change requires the reduction of global GHG emissions. Since bio-based production routes to fuel, chemicals and power could deliver at least part of the GHG savings necessary to mitigate the dangers of catastrophic climate change, the use of bio-based sources of energy and feedstock is strongly encouraged by regulation and is eliciting increasing pull from consumers.

3.2. Strategic Relevance for Selected Industries

The fundamental trends sketched out above have put biorefineries and bio-based products high on the strategic agenda of most industry players. In addition, the innovation potential of bio-based technologies will allow the production of new molecules for fuel, chemical and material applications, which are not currently available from fossil resources and harbour true innovation potential. The following points summarize the strategic consequences for six industries.

3.2.i. *Agriculture.* The increasing demand and regulatory push for biomass will increase the overall market size for agricultural and forestry products substantially, and may shift the relative economics of food/feed production vs other land uses, such as cellulosic energy crops, opening up new economic opportunities for farmers, particularly in developing countries. Agricultural commodity prices may also be influenced by the increased production of bio-based materials in biorefineries.

However, the impact on food prices strongly depends on the kind of feedstock used in the production process. Second-generation feedstock (such as lignocellulose or jatropha) tends to have very little influence on food prices. By contrast, first-generation feedstock (particularly, corn, wheat, palm oil and rapeseed) could contribute to increasing food prices if used excessively without providing additional capacity for the production of this input.[38]

Technology-wise, the growing global demand for biomass will lead to an increasing focus on agricultural productivity across the globe. New plants and novel traits (e.g. drought and salt resistance) will make it possible to use less fertile land. This may open new opportunities for developing countries, especially in Africa, to participate in a new agricultural revolution.

This greater focus on agricultural productivity will also lead to a substantial increase in fertilizer use, especially in places where best practices are not yet in place in farming, for example, in Africa. Nitrogen fertilizers can easily be manufactured and mineral fertilizers can be found as naturally occurring rock phosphate. However, it is worth noting that the carbon footprint of fertilizers is high and can have detrimental effects on water supply – another scarce resource in many African countries.[39]

As a result, a new international division of labour in agriculture is likely to emerge between countries with large tracts of arable land – and thus a likely exporter of biomass or densified derivatives – versus countries with smaller amounts of arable land (i.e. biomass importers, e.g. Holland). The biggest biomass export hubs are expected to be Brazil, Africa and North America.

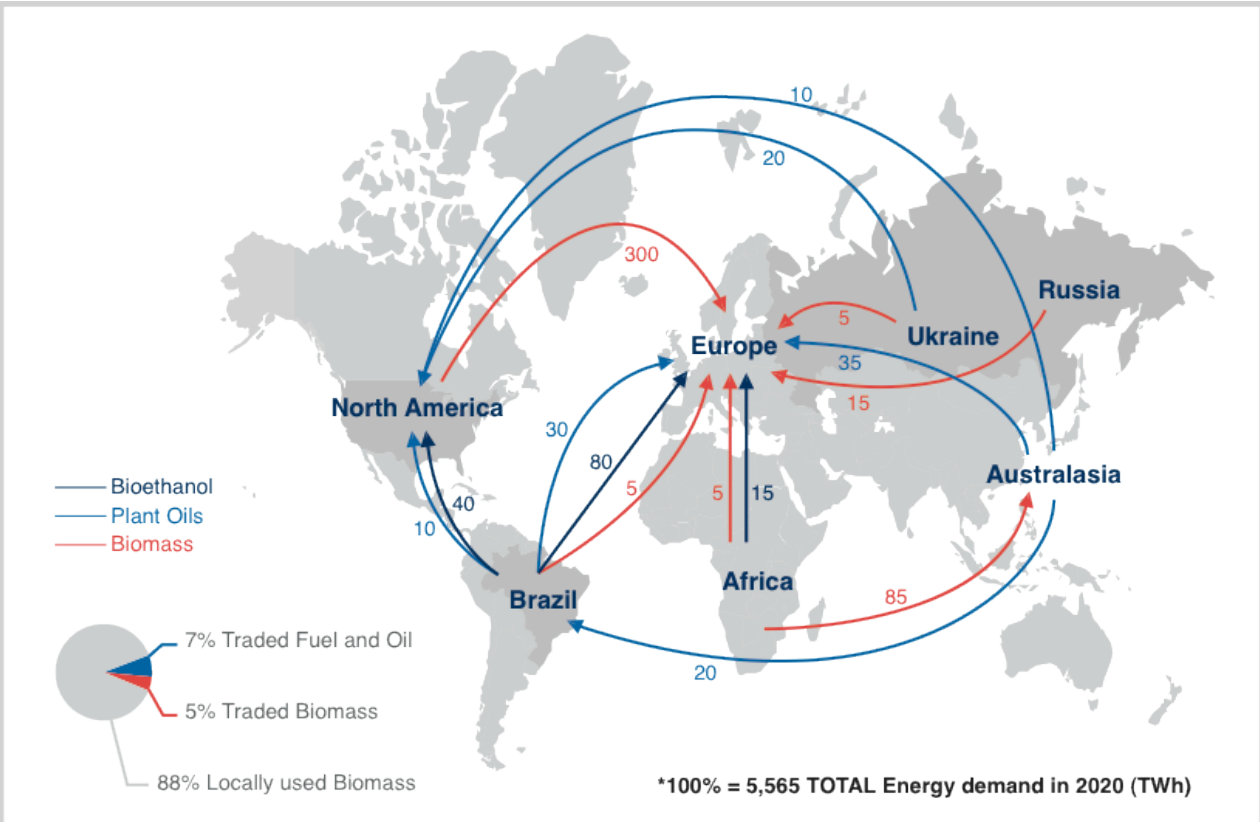

Figure 5: *Expected Biomass Trade Routes.* Values represent final energy demand in 2020.

3.2.ii. *Automotive Industry.* The replacement of conventional gasoline and diesel by biofuels is technologically straightforward. So-called flex-fuel vehicles being sold in Brazil and the US can cope with pure fossil fuel and pure biofuel and any mixture of the two.[40] Moreover, OEMs anticipate that the car fleet can be renewed at cost. Renault, for example, claims that flexible engines increase the total cost of a car by only US$ 300. Additionally, engines of cars already in use can be upgraded to make them into FFVs at cost.

The automotive industry is facing strict upcoming regulations to reduce the tailpipe GHG emissions of their passenger vehicle fleet. OEMs are therefore looking at biofuels as one potential means to meet these targets.

In Europe, regulations to limit tailpipe emissions of the passenger vehicle fleet will take effect as early as 2013. The EU proposal would require 65% of the European fleet to emit a maximum of 120 grams of CO_2 per kilometre in 2012, and 100% of the fleet to meet this standard in 2015.[41] Current versions of the legislation imply that every gram of CO_2/km emitted on top of this value will be met with penalties of up to 95 euros for the OEM. It is currently being discussed whether bio-based/renewable fuels may count towards achieving this target.

In the United States, the Obama administration is signalling that it intends to tackle climate change vigorously. The US Congress has just passed the Waxman-Markey Act, setting an "open fuel standard" that essentially requires US auto producers to manufacture an increasing share of flexible fuel vehicles.[42]

This is considered a major regulatory breakthrough in a country with very low energy efficiency in individual transportation. Equally, the Low-carbon Fuel Standard introduced in California in 2007 requires fuel providers to reduce GHG emissions of the fuel they sell. The programme intends to achieve a 10% reduction in the carbon intensity of transport fuels by 2020.[43]

In other countries such as Brazil, FFVs already have a market share of 90%; in France, the penetration of FFVs has risen to almost 10% from 0% in the past two years; in Sweden, tax exemption for distributors for installing biofuel dispensers has increased the market share of FFVs. By contrast, in Germany, the instability of tax exemption for biodiesel and bioethanol has restricted the blended bioethanol share to 4%, and biodiesel to 6%.[40]

The US already has significant regulations in place, most notably the Corporate Average Fuel Economy (CAFE) standard. Designed to improve the average fuel economy of cars and trucks, it is the average fuel economy (in mpg) of a vehicle under 4,500 kg, If the calculated value for a manufacturer's annual fleet of vehicle production falls below the standard value set by Congress, then a penalty must be paid by the manufacturer.[44]

CAFE standards in the US have been "technology forcing", which has pushed technological advances forward. But, although they may reduce fuel consumption and CO_2 emissions, they also reduce the cost of driving, resulting in a stronger incentive to drive, thus offsetting any savings made in emissions. Regulations such as this also promote alternative means of reducing tailpipe CO_2 emissions that are also very much at the centre of attention of automotive OEMs, such as downsizing motors, using lightweight materials (including bio-based plastics) in vehicles, and intelligent motor electronics.

All in all, the automotive industry is currently most concerned with the threat posed by non-fuel propulsion systems. New propulsion systems/energy carriers (e.g. hydrogen or electric vehicles) – the choice of which may depend on different regulatory regimes in different countries – could jeopardize the industry leadership of traditional OEMs whose core competence is fuel-powered engines, giving focus to the development of new fuel technology that may allow these to continue to dominate the automotive industry. The aspiration to partially replace existing plastics with bio-based plastics in vehicles should also be noted.

3.2.iii. *Aviation Industry.* Replacing kerosene that is used in commercial aviation is more challenging than replacing fuels that are used in road vehicles. Alternative fuels for aviation have to have a high energy density, a low freezing point and most importantly, at least as reliable as Jet A1 kerosene. Just as alternative fuels for the road transportation sector, alternative aviation fuels should be drop-in fuels, miscible with petroleum-derived kerosene at any percentage.

Of these alternatives, a drop-in low-carbon fuel that include fuels derived from biological feedstocks manufactured using the Fischer-Tropsch process or via hydrogenation of oils is preferred. A number of flight tests have recently occurred, the first test undertaken in February 2008 by Virgin Atlantic in a Boeing 747 powered by GE engines. Here an 80:20 mix of Jet A1 and a palm oil/babassu nut fuel was used.[45] The flight gave some important data on burning biofuels in modern commercial engines allowing for the later tests to occur. The next flight test used a fuel derived from Jatropha.[46]

The following month an algae-based biofuel was tested in one engine of a Continental 737-800 with a CFM-56 engine. It flew with a blend of algae and jatropha oil in a 50:50 mix with Jet A1.

The bio-fuelled engine burned less fuel than the conventionally fuelled engine, showing that mixing biofuels has no detrimental effects on performance.[47]

The final flight test used a fuel derived mainly from camelina (camelina 84%, jatropha 16% and algae less than 1%) in a Japan Airlines 747-300.[48] Camelina is of interest as it can be grown in rotation with wheat in temperate climates.

Current, commercial bio-based fuels are not technically and economically suitable as “drop-in” fuels for aviation. Ethanol is not miscible with kerosene, which has fuel properties closer to diesel than gasoline. Biodiesel has issues too, in that it does not usually come at a quality reliable enough to use at a large scale – mainly due to the varying properties of different feedstocks. While some tests have been performed to assess the suitability of these fuels in jet engines, the technical challenges around ethanol and biodiesel make it likely that they will not be used on a large scale for aircraft propulsion.

Nevertheless, the aviation industry is intensively looking for alternative fuels suitable for jet propulsion (e.g. Fischer-Tropsch liquids such as BTL, as well as hydro-treated vegetable oil) as a means of reducing the industry’s carbon footprint, given the challenging goal of reducing its CO_2 emissions by 50% by 2050.

By 2050, second-generation biofuels, in the form of BTL are expected to contribute 30% of the aviation fuel mix.[2] First-generation biofuels that are made from crops rich in sugars or starch are not typically suitable for use in aircraft as they do not have the necessary performance and safety attributes for use in modern jet engines.

Despite the ongoing efforts to promote biofuels, the greatest and economically most attractive lever towards carbon abatement for the aviation industry remains the reduction of fuel consumption (by reducing the weight of aircraft, for example). This is because fuel costs make up approximately 50% of the operational costs of airlines. The industry’s goal will be to achieve efficiency improvements of 1.5% per year through to 2020. Other alternative (non-bio-based) fuels such as coal-to-liquid (CTL) or gas-to-liquid (GTL) have better economics than BTL.

However, while these fuels may help to increase security of supply, they are very CO_2 intensive technologies. For instance CTL fuels have a carbon footprint higher than that of conventional fossil fuels even when their synthesis is combined with carbon capture and storage (CCS). An example of this is CTL produced by SASOL of South Africa. It is already used in aviation, although its current benefit to reducing emissions is minimal as the process is heavily carbon intensive.[49]

Logistically, aviation may be better positioned than other industry sectors (e.g. automotive) to replace jet fuel by BTL as the aviation industry has fewer fuelling locations (1,679 airports handle 95% of the world’s passengers vs 161,768 retail petrol stations in the US alone) and vehicles (23,000 aircraft vs around 580 million road vehicles globally).

3.2.iv. *Chemical Industry.* The dominating current approach of the chemical industry to biorefining limits the use of bio-based chemicals to the substitution of traditional petroleum-based chemicals with a “green” alternative of the same functionality and performance. Rather than building entire biorefineries, chemical companies operating in this field have therefore mostly chosen to replace selected chemical intermediates in their current product portfolios. This is mostly driven by economics (not regulation) and sustainability concerns. Based on this approach, the following types of player may emerge in the future:

- *Traditional chemical companies* that replace fossil chemicals with green alternatives along existing chemical product trees, often within their existing product lines
- *New players* focused on the production of completely novel products out of biomass; however, the main challenges will be to integrate these new molecules into existing value chains, and the related long commercialization process
- *Technology players* that deliver technologies like cell factories designed by metabolic pathway engineering, with the potential to deliver both existing and novel chemical compounds into the value chain without producing the chemicals themselves; for many of these companies, a royalty-based business model would be preferred

It is important to note that materials, namely “green” plastics and other biodegradable materials, can also be made from non-fossil-based sources. Lee Sang-Yup, Distinguished Professor, Director and Dean, Korea Advanced Institute of Science and Technology-KAIST, Republic of Korea, has developed polylactic acid (PLA), a bio-based polymer that holds the key to producing plastics from natural and renewable sources.

Previously, producing plastics of this kind involved a two-step fermentation and a chemical hydrolysis. This has now been replaced by a single step enzymatic process using a metabolically engineered strain of *E.coli*. Although this is not yet a commercial process, strategies like this will be useful in developing and manufacturing new materials from renewable sources.[50]

Reliance on oil does not just affect transport needs, but also material needs, most notably plastics. If efficient polymer producing strategies such as the one designed by Professor Lee can be developed, then there is a strong case for integrated biorefineries that are capable of producing chemicals and materials from biomass alongside biofuels *(see 1.3).*

3.2.v. *Energy Industry.* Renewable power generation has been gaining strong momentum over the last few years. Between 2000 and 2007, renewable power generating capacities (excluding large hydropower plants) increased by almost 16% worldwide. Even though biomass-based technologies have not grown as fast as wind and solar photovoltaics, their contribution will be essential to meet political targets for renewables.[2, 51, 52]

Given the increasing share of renewables in the power generation industry overall, almost all major players active in conventional power generation have started to capture a share of the market or at least take stakes for the future. Many European energy utilities have already put the expansion of their renewable power generation assets high on their strategic agenda and have allocated considerable amounts in their investment plans.[53]

The fundamentals of power generation from biomass are economically quite attractive when compared to other renewable power options, and will require lower subsidies in contrast to wind and solar power. Hurdles to overcome include the above-mentioned concerns about supply chain management: should utilities manage the biomass supply chain themselves despite this not being their core competence?

The related supply security issue also makes it risky to allocate large-scale investments to this novel technology. One approach to mitigate this risk has been taken by RWE, which has invested in growing short-rotation poplar itself for combustion in its power plants to secure production and supply chain management.

3.2.vi. *Transportation.* Transportation constitutes almost 60% of global oil demand, of which freight transportation such as shipping drives a significant and growing share. What is more, three-quarters of the expected increase in global demand for oil by 2030 (45% increase = average 1.6% per year) is expected to come from the transportation sector.[2]

It is fair to say that today’s transportation industry is addicted to oil. Thus, as with the aviation and automotive industries, the transportation industry is looking at biofuels as a means to reduce the carbon footprint caused by its huge oil consumption. However, this is a small lever when compared to other measures that improve the energy efficiency of transportation, for example, increasing the value density of shipped products by reducing their weight, size or packaging.

4. Key Challenges of Commercialization

Despite the strategic relevance of bio-based products for many industries, numerous technological and strategic challenges still hamper commercial industrialization. Overall, many of the individual steps of biorefining are still considered to be suboptimal, and very few attempts have been undertaken to make biorefineries work at scale. Additionally, the industry will have to adhere to the highest social and environmental standards to gain broad public acceptance.

4.1. Technical Challenges

Technical challenges are multiple; covering feedstock yield, enzyme improvements, microbial cell factories, and processing and logistics:

4.1.i. *Feedstock Yield and Composition of Biomass.* It is crucial to improve feedstock yield and composition of biomass for optimal conversion efficiency. This involves plant genomics, breeding programmes and the chemical engineering of desirable traits (e.g. drought resistance, photo-cycle insensitivity, cold-tolerance, sugar composition C5/C6). By making feedstock more robust, further improvements can be made to the economics and security of feedstock availability around the year.

4.1.ii. *Efficient Enzymes.* A related technical challenge is the need to develop more efficient and robust enzymes, particularly for the conversion of lignocellulosic material from a variety of feedstock like corn cobs, stover, wheat straw, bagasse, rice, woody biomass, etc. *(see 2.3.iv Novozymes' successful enzyme mix).* Additionally, utilization of a larger part of the biomass will require new processes that allow conversion of materials to extract their maximum value. For example, lignin is thermochemically converted into power/heat rather than into value-adding chemicals. There are some indications that lignin could be used as a value-adding component of slow-release fertilizers and as a starting compound for vanillin fermentation.

4.1.iii. *Microbial Cell Factories.* A further yield-related challenge is the need to develop microbial cell factories, i.e. production hosts that produce a desired product – be it a biofuel or biochemical – in high yields and with high productivity. A combination of metabolic pathway engineering with bioinformatics and engineering for fermenter design is the key. Once a compound can be produced via fermentation, it has to be recovered from the fermentation broth. New recovery methods are needed for most novel compounds to achieve this. Further novel heterogeneous catalysis technologies are also needed to transform the chemical intermediates into commercial products.

4.1.iv. *Processing and Logistics.* The second group of technical challenges relates to optimizing feedstock processing and logistics. This includes a number of different areas: developing densification techniques (e.g. briquetting and pelletizing) is one, allowing the transport of originally low-density feedstocks at low cost. Establishing preservation techniques to control physical and chemical modification of biomass during pre-conversion processing (i.e. harvesting, storage, transportation) is another.

Developing highly coupled feedstock logistics systems that can deal with the seasonal nature of feedstock production economically is also vital. Investments in this kind of infrastructure may prove difficult to make for individual companies due to the capital required, as well as the difficulty of capturing the value of IP.

Finally, setting up a bio-based product distribution network is another necessity, ideally making use of existing infrastructure, e.g. using oil pipelines, or upgrading petrol stations to allow distribution of a higher share of biofuels. The US is currently funding the retrofitting of former corn-based biofuels plants and giving R&D money to accommodate new technologies and processes.

4.2. Commercial and Strategic Challenges

The commercial challenges facing the industrialization of bio-products fall into three main categories: issues with integration into existing value chains, funding difficulties and other challenges related to the uncertainty associated with a novel, unconventional field.

4.2.i. *Integration into Existing Value Chains.* One of the main commercial challenges is to integrate biorefinery output into existing value chains. One can distinguish two different classes of products.

On one hand, there are bio-based products that directly replace molecules in existing value chains, e.g. bio-based succinic acid that replaces petroleum-based succinic acid in polyester manufacturing, or biobased acrylic acid. A recent example is green polyethylene (PE), the first real commodity chemical made from a renewable resource, namely, ethanol from sugar cane by Braskem. In these cases, no or limited change of processing technologies will be required by the customer, provided quality requirements are met. Another example is co-firing wood chips in coal-fired power plants, which can be done without or with only limited modification of the boilers in most cases. The two key parameters for success are price and performance – both have to at least equal the existing petrochemical compound.

On the other hand, there are bio-based products that are novel or that cannot easily be integrated into existing value chains. Bioethanol, for example, can only be mixed into conventional fuel up to a volume share of around 15%[54] without modification of a standard engine. Flex-fuel vehicles can accommodate higher blends. They are widely distributed in Brazil and are emerging in some other countries, e.g. in Sweden, where one in three new cars are FFVs.

Also, novel chemical intermediates such as levulinic acid are very promising chemical compounds. However, no established large-scale chemical processes exist for this molecule, which makes it hard to integrate into current production networks. Additionally, novel products based on new intermediates, e.g. bio-based polymers, usually have different properties to existing polymers, potentially requiring a tedious and lengthy commercialization process. Some of the better known examples of this phenomenon are the polymers polylactic acid (PLA) and polyhydroxyalkanoates (PHAs), which have been known for a long time.

Several companies are working on the commercialization and large-scale production of PLA and PHA, with some success. However, the speed of volume build-up has usually lagged behind expectations for reasons of performance and pricing issues, resulting in problems with value-chain penetration. This is why Brazil is so well placed as a biofuel producer, as markets already largely exist so there is little trouble with value chain penetration.

4.2.ii. *Funding Difficulties.* A second challenge is that funding is becoming increasingly tight. Because of the current financial crisis, both venture capital and private equity funding have become tougher to access, making it difficult to finance pilot commercial plants and to obtain follow-up bank loans.

This also holds true for the funds required for investing into building full-scale commercial plants and infrastructure. Given the overcapacity the chemical industry has been facing in some product segments in 2009, the willingness to invest in new assets has further shrunk.

In addition, venture interest in the biorefinery/biotech business has been decreasing independently of the current financial crisis, as funds are beginning to realize that large amounts of capital are needed to commercialize the technology. This tendency is exacerbated further by high uncertainty with respect to the profitability of a biorefinery, since governments only provide financial support and incentives on a relatively short-term basis (years), while the horizon for success is long term (decades).

4.2.iii. *Uncertainty Facing a New, Unconventional Field.* Other commercial hurdles include the risk aversion of first movers, the inability to get a price premium for bio-based products when compared to conventional petroleum-based products, and insufficient, uncertain public incentives. And then there is the uncertainty about which technology to back, if any at all: biofuels for combustion engines, electric vehicles, or the hydrogen economy?

4.3. The Sustainability Challenge

While one of the original intentions of switching to production of bio-based products is the conservation of resources, caution is advised to ensure that the implementation of biorefineries does not jeopardize the environment. The following issues are of most concern:

4.3.i. *Land-Use Change and Its Effect on GHG Emissions.* It has previously been established that the impact of bio-based products on GHG emissions strongly depends on feedstock, land-use impact and synthesis efficiency. Assessing the GHG emissions of these products using a full life cycle analysis critically depends on the inclusion of emissions caused by land-use change.

Land-use change affects the GHG balance by conversion of native ecosystems – often by slash and burn – and release of soil carbon. This key factor in determining the realistic life cycle emissions was recently established and is characterized into two main types.[55]

Direct land-use change (DLUC) occurs if feedstock for biorefinery purposes (e.g. soybean for biodiesel) displaces a prior land-use (e.g. forest), thereby generating possible changes in the carbon stock of that land. This effect is well studied, but default values can often differ substantially from actual values and, furthermore, depend on an arbitrary choice of accounting period. It is, however, widely accepted that deforestation due to increased demand for biomass feedstock is a direct land-use change that should not occur if we are to make biomass a sustainable energy source for the future.

The second type of land-use change has been long overlooked, mainly due to the inaccuracies in identifying and quantifying it. These too must be addressed to maintain a healthy GHG balance.

Indirect land-use change (ILUC) occurs if pressure on agriculture – due to the displacement of a previous activity from the production of biomass feedstock – induces land-use changes in other locations. The displacement of current land-use to produce biofuels and other bio-based products can trigger direct land-use changes elsewhere. There are four types of ILUC: Spatial, Temporal, Use and Displaced Activity, all of which describe the different mechanisms by which biomass production puts pressure on land activity.

Studies into the effects of land-use change, in particular on US corn ethanol production, come to a variety of conclusions. Previous estimates by Searchinger put US corn ethanol GHG releases at 100 g CO_2e/MJ. Later estimates by Hertel indicate a release of only 27 g CO_2e/MJ, roughly one-quarter of the previous estimate. However, it was concluded

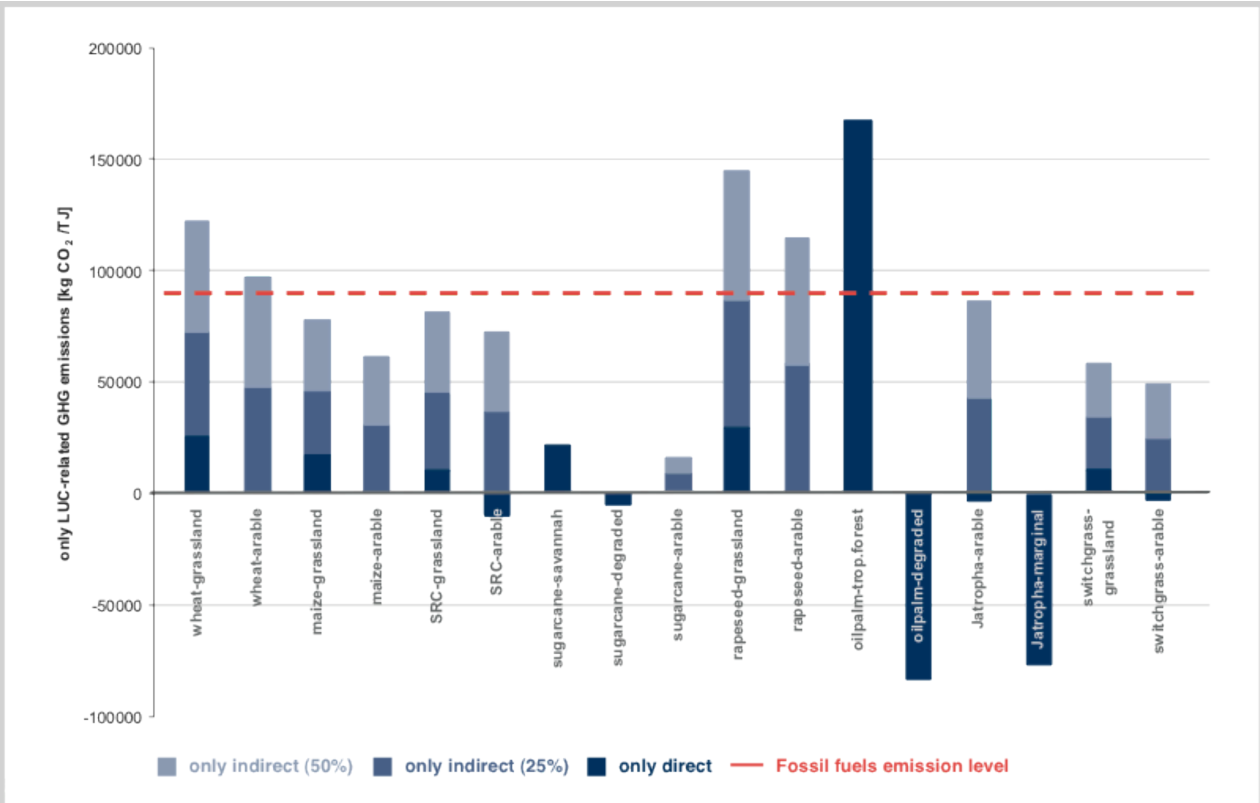

Figure 6: *Land-Use Change Induced GHG Emissions*. The data from the Oeko-Institute, Darmstadt, is for indirect and direct changes in GHG emissions excluding life cycles.[56] (only indirect [25%] = if ILUC displacement risk of feedstock is 25%)

that this was still enough to cancel out any carbon benefits corn ethanol had over regular gasoline.[57]

More recent estimates have put US corn ethanol GHG emissions at 38-48 g CO_2e/MJ. However, this estimate does not include indirect land-use change and focuses on life cycle efficiency and energy consumption rather than land-use change effects.[58] More sophisticated efforts to model ILUC has been performed by Tyner et al., who found that the marginal climate impact in terms of ILUC from US corn ethanol is 15 g CO_2e/MJ, assuming land-use change contributed to only 25-34% of GHG emissions.[59]

At present, there is still much uncertainty about ILUC and the current methodology relies on arbitrary choices of production periods of biofuels with significant implications for the final results.[60]

Dependent on the methodology employed, land-use change can have either a positive or negative effect on the GHG balance of biorefinery outputs. The conversion of forests, wetlands and grasslands to cropland usually results a net emission of carbon from biomass and soils to the atmosphere (a negative effect). However, where sparsely vegetated or disturbed lands are converted to cropland, this can result in a net gain in both overall biomass production and soil carbon owing to carbon sequestration.

Converting rain forests, peatlands, savannahs or grasslands to produce food crop-based biofuels in Brazil, South-East Asia, and the United States creates a "biofuel carbon debt" by releasing 17 to 420 times more CO_2 than the annual GHG reductions that these biofuels would provide by displacing fossil fuels. As land generates more

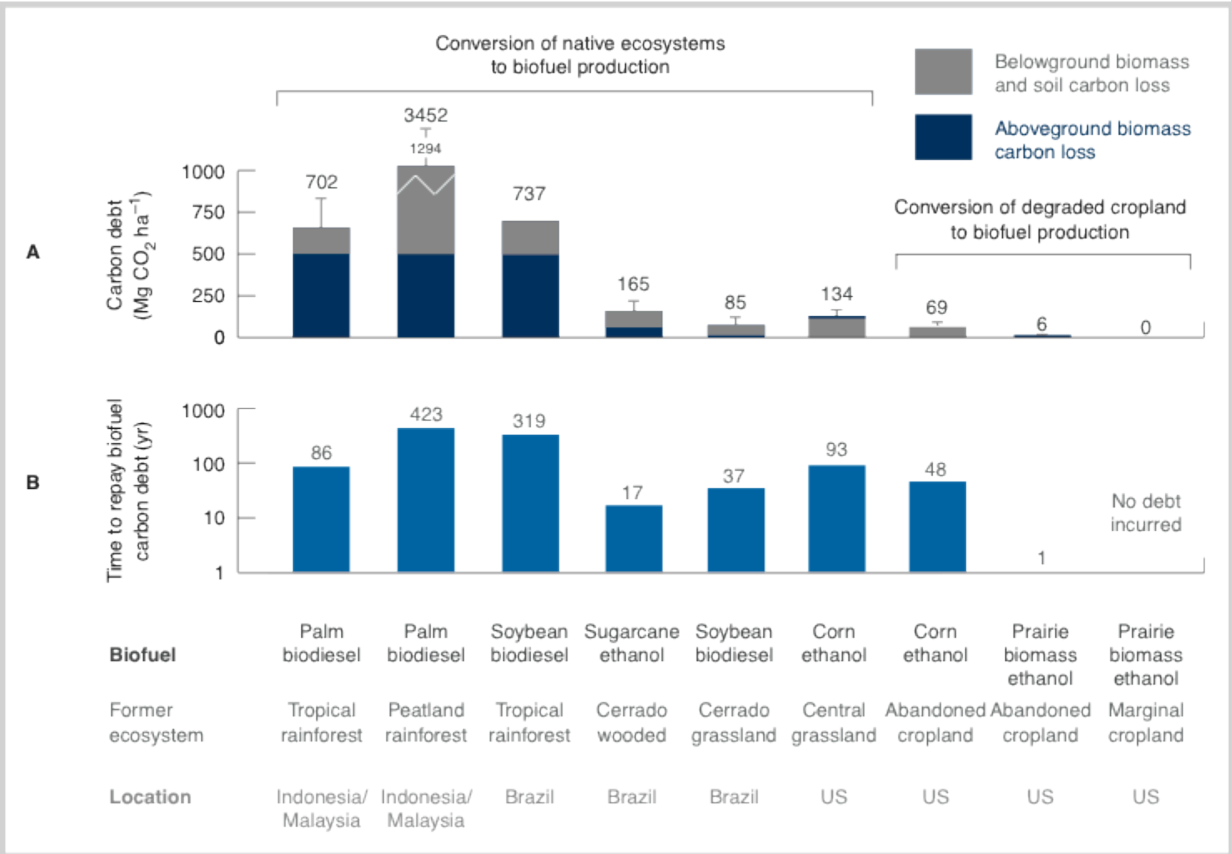

Figure 7: *Carbon Debt and Time to Repay Biofuel Carbon Debt* for nine scenarios of biofuel production. (A) Carbon debt, including CO_2 emissions from soils and above ground and below ground biomass resulting from habitat conversion. (B) Number of years after conversion to biofuel production required for cumulative biofuel GHG reductions, relative to the fossil fuels they replace, to repay the biofuel carbon debt.[61]

biomass over the years, the reduced emissions from its use will eventually offset the carbon debt from land-use change.

When calculating the GHG emissions, the net impact on the carbon debt must be accounted for, and not solely the direct benefit of using the land for biomass production. Put simply, to generate greenhouse benefits, the carbon generated on the land must exceed the carbon storage and sequestration given up directly or indirectly by land-use changes.[62]

Until recently, the majority of studies that investigate that GHG balance of biofuels failed to realize the extent to which land-use change affects the suitability of biofuels as a sustainable energy source (geographically specific).

In one case, it was found that GHG savings from corn ethanol would equalize and therefore pay back carbon emissions in 167 years, meaning that GHGs will increase until that time[55, 61] *(see Figure 7).*
A newer study by US Environmental Protection Agency in 2010 arrives at a carbon payback time for corn ethanol (ILUC) of only 14 years. Again, it is clear that this is a hotly debated topic and different calculations of carbon payback due to land-use change can produce very different results.

There are isolated cases in the US and Brazil where sustainable production of first-generation biofuels has been achieved, demonstrating the realities of continual improvements in production, legislative frameworks and industry initiatives that surround the bioenergy and biofuels industries.

This shows that, regardless of the life cycle emissions methodology employed, it is possible to produce biofuels without having such an impact, and regulatory requirements must be put in place to ensure that only biofuels that minimize the conversion of habitat and enhance environmental quality are commercially successful. This also applies for chemicals and other materials produced in biorefineries.[63-65]

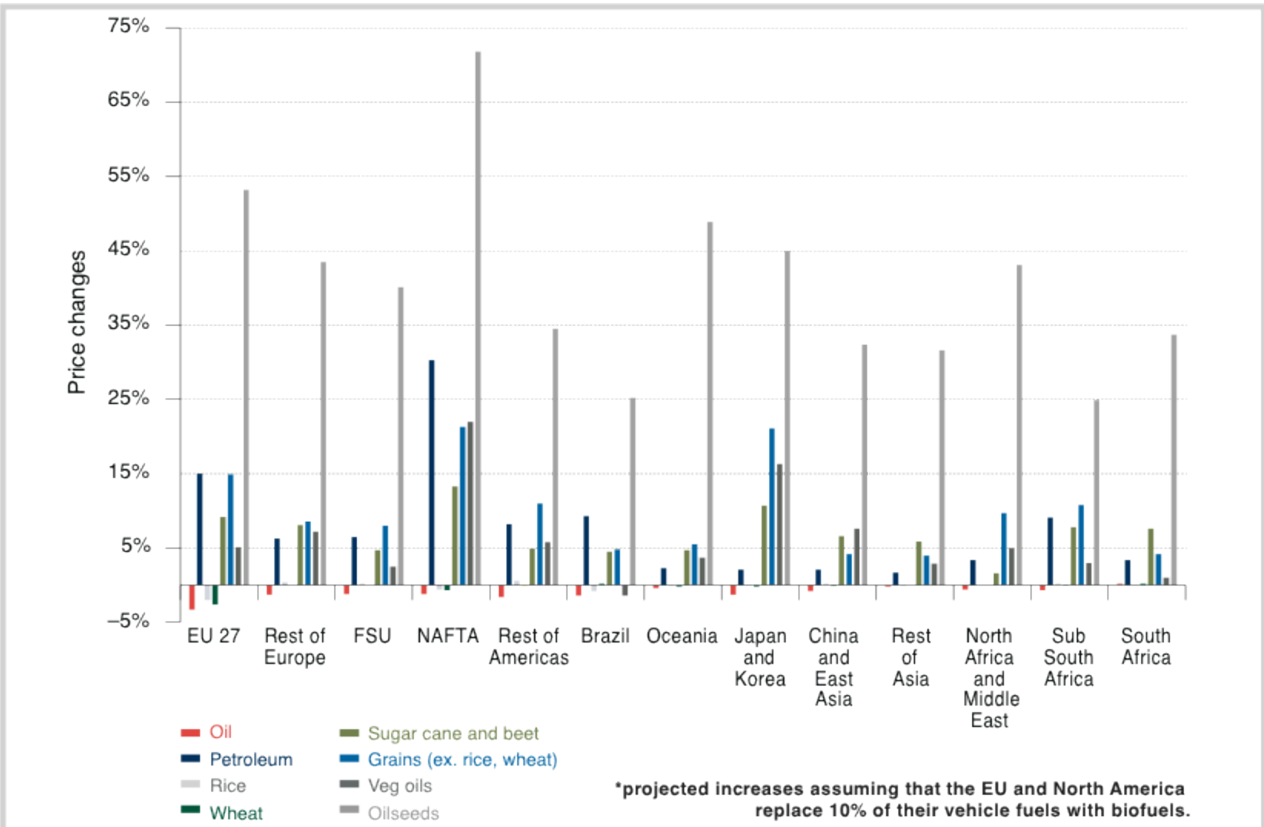

Figure 8: *Changing Commodity Prices from Biofuel Expansion*. Shows the general equilibrium view of projected increases assuming that the EU and North America replace 10% of their vehicle fuels by biofuels.[66]

4.3.ii. *Link between Commodity Prices and Biorefineries.* Internationally traded food commodities prices have increased sharply since 2002, especially since late-2006. The prices of major staples, such as grains and oilseeds, have doubled in the past two years. Rising prices have caused food riots in several countries and led to policy actions such as the banning of grain and other food exports by a number of countries, and tariff reductions on imported foods in others.

The policy actions reflect the concern of governments about the impact of food price increases on the poor in developing countries, who on average spend half of their household incomes on food. It is being reported that the increase in bio-production is one of many factors in food price increases[38] *(see Figure 8).*

As previously discussed, first-generation biofuels require biomass from food-based feedstock such as sugar cane, corn, etc. A study into US corn ethanol production predicts that, as fuel demand puts pressure on corn markets, and soybean and wheat lands switch to corn, the prices may increase by 40%, 20% and 17%, respectively.[55]

Equally, as more US croplands support ethanol production, US agricultural exports also decline sharply, most notably corn by 62%.[55] This is just one of many examples of how changes in land use as described before and demand for first-generation feedstocks have some impact on food supply and cost. There is a need for a comprehensive agronomic model of food and fuel production that would provide a better understanding of the true impact of the bio-industry on food sources.

As global demand for food is expected to double within the coming 50 years and global demand for transportation fuels is expected to increase even more rapidly, there is a great need for renewable energy supplies that do not cause significant environmental harm and do not compete with food supply.[62, 67] As before, attention now turns to the development of second-generation biofuels based on non-food energy crops that may put less pressure on the link between food prices and fuel.

4.3.iii. *Reputational Risks.* On top of this, the practices according to which biorefineries are run are currently not broadly accepted in their entirety by the general public and the position of most NGOs remains vague. Concerns are multiple: that biorefineries may pose a threat to biodiversity, damage rural communities through large multinational corporations, adversely affect labour conditions, make excessive use of water resources or damage the food supply. All of these factors represent a reputational and commercial risk for corporations investing in biorefineries.

4.3.iv. *Legislation-driven Deforestation.* There are significant uncertainties in emissions arising from deforestation, but the IPCC estimate that deforestation contributes about 8 GT of CO_2 equivalents. This equates to about 18% of total global carbon emissions in 2004. Drivers of deforestation include the demand for agricultural land and biomass used for heating and household cooking. This could be reduced by the use of biofuels, provided they are sourced sustainably.

On a global basis, increased demand for land for food and feed (200-500 million hectares by 2020) will continue to cause a greater proportion of land-use change than the additional land demand for biomass. This demand is estimated to be between 56 and 166 million hectares. Although biomass uses only about 1% of current arable land, the marginal effects may be more important, particularly in specific high-risk locations where there are huge releases of soil carbon from peat soils or loss of high value conservation areas.[66]

The two examples below describe how current biofuels legislation in developed nations – to meet new energy targets – may be doing more harm than good.

European Union. A report by the Kiel Institute for the World Economy states that biofuels have a negative impact on the concentration of GHG in the atmosphere under the current EU regulations. Using cultivated land to produce the biomass for biofuels results in indirect land-use change elsewhere.

In extreme cases, the new land cleared is in tropical forests. Since this can generate considerable amounts of GHG, the use of biofuels under the current regulations hardly helps the climate.[68] Current EU sustainability requirements for the production of biofuels provide incentives to minimize direct land-use change and thus the ecological and climatic consequences that such changes can result in, but these requirements can motivate indirect land-use change *(see 4.3.i)*.

Thus, according to various reports, the EU target of ensuring 10% of petrol and diesel comes from renewable sources by 2020 may not an effective way to curb GHG emissions. A team of UK-based scientists suggested that reforestation and habitat protection was a more effective option. These forests could absorb up to nine times more CO_2 than the production of biofuels could achieve on the same area of land.[69]

United States. US President Obama's Memorandum on Fuel Efficiency Standards encourages the production of domestic biofuels to provide more jobs and to gain support from farm states. A presidential committee recommended increasing investment to make biofuels such as ethanol, otherwise the US may not meet its renewable energy targets.[27]

However, the biofuels industry is concerned that the Obama administration will move too quickly away from ethanol, which is mostly made from corn, to more difficult techniques using wood chips and other biomass. Critics are concerned revived focus on biofuels will lead to more deforestation to make room for crops either at home in the US or abroad.

Deforestation due to demand for biofuels is closely linked to the land-use change previously described. However, the above examples show that policy-makers may be making a mistake in setting high targets for bio-based product manufacture. Although these targets favour biorefineries and bio-based economy, they do not account for sustainability issues. In many circumstances, incentives exist to cut down forests in the name of emissions reduction.

5. Conclusions and Recommendations

To overcome the challenges outlined in the previous chapters, multiple stakeholders need to play an active role in promoting the industrialization of biorefinery systems. Biorefineries may have a major role to play in tackling climate change by supplementing demand for sustainable energy, chemicals and materials, potentially aiding energy security and independence, and creating new opportunities and markets in a move towards bio-based manufacturing. The growth of a partially bio-based economy might create significant economic growth and job creation opportunities, particularly in rural areas where incomes and economic prospects are currently moderate.

The Role of Government

The development of the bio-based economy is at an early and high risk stage, and no single industry or company is capable of managing this phase of its development independently. Governments therefore have a key role to play in providing seed support – particularly at the pre-competitive stage – to the emerging bio-based sector and creating markets to ensure that it becomes established and successful.

A short analogy will help explain the current state of biorefineries. In 1975, the catalytic converter was introduced in the US. The US Government set tough emissions regulations, and the car manufacturers responded by developing the catalytic converter to comply. The same principle of "command and control" applies to biorefineries. By setting stringent regulations in a sustainable manner, the bio-industry will respond in a similar way, driving technological advances and overcoming commercial challenges. However, it is crucial that these policies come into effect sooner rather than later; otherwise, the industry will have no incentive to expand. The threat of climate change simply is not enough to drive a new global industry.

Fundamental Reshape of the Industrial Landscape. Future biorefineries will be analogous to modern day oil refineries, using biomass as feedstock, thereby causing a transition from fossil carbon to more sustainable bio-based production across all industries. This could fundamentally reshape the industrial landscape having particular impact on:

Energy Security. The emergence of biorefineries and the bio-based economy will have a major impact on energy security by reducing dependency on imported fossil fuels. Additionally, with their untapped agricultural assets such as waste land becoming feedstocks themselves, Africa and Brazil could become very important players in the more diversified international energy marketplace. Encouraging local energy security will also benefit the environment and boost rural communities. However, overuse will have detrimental effects on natural resources and the global ecosystem, which could potentially undermine the use of biomass as a renewable energy source.

Creating Markets. Markets for bio-based products would stimulate a new wave of innovation, creating high-value and truly green fuels, chemicals and materials, and enhancing energy security by diversifying energy sources. Both mandates and subsidies introduced by governments will ultimately create the markets to support biorefineries and encourage global competition. By announcing new projects and asking competing consortia to bid for each project, industry will gain the motivation to expand in a sustainable and economically competitive yet collaborative way.

Climate Change. There is increasing public pressure for environmental sustainability requiring the reduction of global GHG emissions. Since bio-based production routes to fuel, chemicals and power could deliver at least part of the GHG savings necessary to mitigate the dangers of catastrophic climate change, the use of bio-based sources of energy and feedstock should be encouraged by governmental regulation.

According to the WWF, biofuels in 2030 could lower CO_2 emissions by 207 to 1,024 Mt CO_2e and biochemicals could lower emissions by 282 to 668 Mt CO_2e. To significantly increase its investment in biorefineries and bio-based production, business would benefit from a comprehensive global climate change agreement; one that provides clear and ambitious targets for GHG emission reductions and eventually ensures a level playing field between different countries and regions.

Collaboration. There are real technical, strategic and commercial challenges to be overcome if we are to realize the potential of biorefineries and the bio-based economy. To do so, we must develop and apply the best possible existing and emerging technologies and ensure all stakeholders – from government and NGOs to business and academia – are actively engaged, and are prepared to accept new forms of partnership and ways of working.

Bio-based science and new emerging technologies have a substantial role to play in maximizing the full potential of the bio-based economy and accelerating its development. To capture, develop and commercialize the best science, we need to break down the barriers that currently exist between organizations, countries and regions that inhibit the development of the bio-based economy.

Multiple Products. Biorefineries and the bio-based economy are not just about biofuels. Biorefineries have the potential to reduce our dependence on fossil fuels by allowing us to develop bio-based chemicals, materials and power – the foundations upon which a more sustainable bio-based economy will be built *(see 3.2.iv).* Additional benefits include the diversification of energy supplies and a whole host of biodegradable materials and chemicals, substantially more environmentally friendly and sustainable than fossil-based products.

Challenges

As previously described in Chapter 4, there are numerous challenges that still hamper commercial industrialization. These are divided into three categories:

- *Technical* challenges are multiple, covering conversion process efficiency, feedstock yield, enzymes and catalysts, processing and logistics

- *Commercial* challenges fall into three main categories: issues with integration into existing value chains; funding difficulties; and other challenges related to the uncertainty associated with a novel, unconventional field

- *Sustainable* challenges: while one of the original intentions of switching to production of bio-based products is the conservation of resources, caution is advised to ensure that the implementation of biorefineries does not jeopardize the environment

To address these challenges, the following need to be achieved:

- Technological developments
- Development of biomass supply chain
- Regulatory steering
- Environmental sustainability

Governments interested in supporting biorefineries for reasons of environmental protection, energy security and innovation leadership need to support significant investments in R&D technology by creating markets and carefully regulating the industrialization process in order to trigger private sector investments and simultaneously minimize adverse effects on the environment.

Business and Investment

Investment is essential to:

- Support the development of global biomass supply chain
- Develop and support a reliable upstream supply chain able to mobilize a sufficient level of feedstock available for conversion, but not at the expense of food/land use
- Grow larger quantities of energy crops than is currently under cultivation
- Organize feedstock storage facilities to ensure a continuous supply of feedstock throughout the conversion process
- Ensure growth of a global industry through transportation and trading infrastructure

Investments in biorefinery infrastructure must be supported at an early stage to ensure biofuels production can keep up with the growing demand for sustainable fuels.

The private sector should strengthen current investments in petroleum replacement strategies to enhance energy security, emissions and dependence on unconventional fossil fuel resources. Recent events, such as the Gulf of Mexico oil disaster, show that reliance on unconventional resources is fraught with risks. Deep-sea oil drilling is an expensive and risky operation and the secondary costs, such as environmental degradation, can be enormous. The extraction of oil from unconventional sources – such as tar sands – on the other hand, requires vast amounts of water and is extremely energy intensive.

Businesses need to appreciate newly crafted markets as a potential source of revenue and an opportunity to boost their portfolios. Aviation and automotive industries need to adapt to alternative fuels and it is clear they are already moving in the right direction *(see 3.2iii)*. The chemical and energy industries will benefit greatly from investment in biorefineries, providing new chemical products and a renewable energy source in the process.

Multinational oil companies can reduce their reliance on environmentally unfriendly unconventional oil resources, which simultaneously releases constraints on scarce water supplies, reduces GHG emissions and the risk of environmental disasters, such as the Gulf of Mexico oil spill.

Research and Development

First and foremost, investment in technological research is critical; three areas have been identified as vital for development:

Research into *conversion techniques and feedstock processing* should be encouraged to achieve the diversification of feedstock supply and greater conversion efficiency. This will ultimately increase the scale and value for money of the fuels and chemicals produced in biorefineries that can be achieved. Development of new enzyme and catalyst technology, densification techniques and metabolic pathways will allow feedstock processing to become more efficient and economical.

Research into *agriculture and crops* should be supported to gain a better understanding of crop rotation, land management, land-use change issues, the food vs fuel trade-off, cultivation and harvesting techniques, and natural resources (water, sun, fertilizer). The genetic engineering of energy crops and microorganisms will vastly increase the diversity of available feedstock and the potential for multiple products from a single feedstock. Understanding these critical issues is vital in securing a sustainable feedstock supply.

Research into the *optimization of biorefineries* should be supported to create a biorefinery analogous with today's oil refinery. Such measures could increase the efficiency of the whole process – from raw starting material to end product beyond the chemical reaction – which improves the economics of bio-based products, especially the cost competition with oil, on an energy parity basis. An optimized biorefinery will be capable of larger-scale and more commercially viable bio-based production, with additional benefits, such as a reduced carbon footprint. Flexibility in the type of products produced and regulations, such as a low-carbon fuel standard, can add to this, *vide infra*.

Policy and Regulation

The challenges outlined above can be tackled if governments set the right impulses by implementing a policy framework of incentive-based and command-and-control policies. Regulators need to balance energy security, local revenues and environmental drivers to define their policies.

Mandates set by governments will support the production of bio-based products, analogous to the so-called "technology-forcing" phenomena that resulted from the CAFE standards in the US automotive industry. The drawback of such policies is that they can encourage excessive investment in unsustainable or inefficient processes that would not otherwise have succeeded. Over the past decade, the effectiveness of mandates designed to promote bio-production has been limited by a lack of regulation of natural resources (e.g. EU and US). It is clear that there is a strong need for tighter regulations to stop excessive land-use change, food shortages and the promotion of first-generation feedstock production from unsustainable sources.

Subsidies and incentives should be given to entrepreneurs or businesses considering low-carbon petroleum replacement strategies to encourage investment in new technology and infrastructure and reduce the reliance on public funding. Biodegradable chemical products could be exempt from industry fining schemes, such as the deposit on drink cans in Germany. Plastics and other materials produced from biomass could be subject to tax reductions, driving bio-production into the consumer goods industry. Production tax credits could be introduced for the production of bio-based products, especially in the US.

Whether tax exemption schemes or direct subsidies should be granted to all bio-based products is controversial. While such aid can help get the industry off the ground, long-term subsidies should avoid supporting an industry that is not competitive long term. Support should also be given to the G20 agreement on phasing out subsidies for oil; according to the IEA, the world uses more than US$ 557 billion per year in oil subsidies.

Trade barriers to biomass feedstock or products are a substantial obstacle to the establishment of a working marketplace for biomass. Prominent examples of this are the duties and tariffs on sugar and ethanol that Brazilian exports are facing. Although partial exemptions for exports to the EU have been achieved by Sweden and the Netherlands, governments should consider minimizing these trade barriers to allow greater trade freedom and encourage the establishment of new biomass trade routes. Such measures could enhance the biomass market.

Environmental Sustainability Criteria

The development of commonly accepted criteria for sustainable biomass supply is required to avoid undesired changes in land use, ensure food supply is not affected, mitigate reputation risk for investors and enable trading of biomass. Two important criteria have been identified as the most important aspects of any bio-based industry regulation.

- *Certification and Assessment of Sustainability Criteria to Help Combat Land-use Change* – both direct and indirect *(see 4.3.i)*. The EU is prime example of where implementation of biofuels regulation has triggered adverse effects on the environment *(4.3.iv)*. Introduction of this measure should stop unnecessary deforestation and food shortages *(4.3.ii)* as a result of biofuel production.

- *Total GHG Emissions Criteria* that will account for the entire life cycle of biomass to avoid misinterpretation of GHG data, starting from the living biomass right the way through to its use as a product. This will allow accurate determination of how efficient certain bio-product life cycles are, whether they are suitable as fossil-based product alternatives, and not whether they reduce emissions, for example, solely in combustion. Regulations such as a low-carbon fuel standard *(see 3.2.ii)* can further support optimization of biorefineries: the more efficient a biorefinery is, the lower the carbon footprint of the product that is produced, which increases its value when LCFSs apply.

Conclusion

Policy-makers need to accept that no true low-carbon technology will penetrate the mass market in the short-term and industry will continue to rely on fossil-based production for the time being. The most effective measures to induce a significant impact of bio-based production on all industries are listed below.

- Create new markets for businesses to support bio-based products and encourage competition

- Set up public-private partnerships to initiate private sector investments and reduce the delay between product development and commercialization

- Identify potential growth and impact areas for key industries and provide them with incentives to achieve specified targets, such as CO_2 equivalents reduction

- Inform the public that bio-based products are a realistic supplement to fossil-based products but that they cannot mitigate the rising demand for fossil fuels

The future of industrial biorefineries is a positive one. As has been discussed in this report, biorefineries may have a major role to play in supplementing our growing demand for sustainability, whether it is to tackle climate change or to create novel energy sources and fossil replacements. A sensible, proactive, collaborative approach to decision-making will achieve the successful creation of a new global industry that has enormous potential.

Glossary

BTL	– Biomass-to-Liquid
CAFE	– Corporate Average Fuel Economy
CCS	– Carbon Capture and Storage
CO_2e	– Carbon Dioxide Equivalents
COFCO	– China National Cereals, Oils and Foodstuffs Corporation
CTL	– Coal-to-Liquid
DDGS	– Distiller's Dried Grains with Solubles
DLUC	– Direct Land-Use Change
FAME	– Fatty Acid Methyl Esters
FFV	– Flex-fuel Vehicle
GHG	– Greenhouse Gas
GM	– Genetically Modified
GT	– Giga Tonnes
GTL	– Gas-to-Liquid
HDPE	– High Density Polyethylene
HRJ	– Hydrotreated Renewable Jet (Fuel)
IEA	– International Energy Agency
ILUC	– Indirect Land-Use Change
IPCC	– Intergovernmental Panel on Climate Change
LCFS	– Low-carbon Fuel Standard
MJ	– Mega Joules
MMT	– Million Metric Tonnes
MSW	– Municipal Solid Waste
MT	– Metric Tonnes
OEM	– Original Equipment Manufacturer
PE	– Polyethylene
PHA	– Polyhydroxyalkanoates
PLA	– Polylactic Acid
PPO	– Pure Plant Oil
PVC	– Polyvinyl Chloride
SNG	– Synthetic Natural Gas
US$	– United States Dollars
WVO	– Waste Vegetable Oil

Additional Notes

Any uncited information or data presented in this report is the result of independent analysis and/or interviews with the following partners/research fellows: their name, position and company/institution is given.

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