AN IMPLEMENTING AGREEMENT UNDER THE AUSPICES OF THE INTERNATIONAL ENERGY AGENCY
INDUSTRY-BASED BIOREFINERIES

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Title: Industry-based Biorefineries: Brief Achievements

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Table of Contents

1. Introduction 0

2. Overview of The Sector 4

   BIOCHEMICAL CONVERSION PROCESSES 7

   THERMAL CONVERSION PROCESSES 9

   1st Generation vs 2nd and 3rd Generation biorefineries 11

   Current Status of biorefineries 14

3. Market Potential 21

   Bioethanol 25

   Bio oil 28

   New fiber materials – nanoceluloses 29

   Biogas / syngas 32

4. Tasks’ description & Achievements 36

   Task I - Bioenergy & Biofuels 36

       Introduction 36

       Objectives & Strategy 37

       Achievements 38

   Task II - Biochemicals & New Fiber Materials 38

       Introduction 38

       Objectives & Strategy 39

       Achievements 40

   Task III - Sustainability Analysis of Process Integrated Biorefineries 40

       Introduction 40

       Objectives & Strategy 43

       Achievements 44
## Task IV - Process Integration of Gasification-based Biorefineries

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>47</td>
</tr>
<tr>
<td>Objectives &amp; Strategy</td>
<td>48</td>
</tr>
<tr>
<td>Achievements</td>
<td>49</td>
</tr>
<tr>
<td>5. Events &amp; Publications</td>
<td>50</td>
</tr>
<tr>
<td>6. Projects Development</td>
<td>62</td>
</tr>
<tr>
<td>6.1 BUGWORKERS - New tailor-made PHB-based nanocomposites for high performance applications produced from environmentally friendly production routes.</td>
<td>62</td>
</tr>
<tr>
<td>6.2 Integrated biofuel production processes based on systematic optimization methodologies</td>
<td>65</td>
</tr>
<tr>
<td>7. Perspectives for the Future &amp; Recommendations</td>
<td>79</td>
</tr>
<tr>
<td>8. References</td>
<td>80</td>
</tr>
</tbody>
</table>
This report presents information, activities and achievements with regard to Industry-based Biorefineries – Annex XI of IEA-IETS, for the period 2008 – 2015.
1. INTRODUCTION

Climate change has become an important issue to consider when defining a development strategy for a sustainable energy future. Greater sustainability in energy systems depends on a right mix of energy technologies and policies, in a situation where about one third of the energy consumption in the world belongs to the industrial sector.

The largest industrial consumers are those producing chemicals, iron and steel, non-metallic materials, pulp and paper and non-ferrous metals. The interest in biorefineries has recently increased significantly as it is aligned with policies of diversification, considering conversion processes for heat and power generation simultaneously with biofuels production and chemicals.

It is essential to turn around the present energy situation and get into a path of transition into decarbonisation. Biomass, especially ligno-cellulosic material, represents an abundant renewable carbon source. This is potentially convertible in energy, fuels and products. The integrated production of bioenergy, biofuels and biochemical products, through advanced technological processes of separation and conversion that minimizes carbon cycle impact, defines the biorefinery concept, presented schematically as follows.

![Biorefinery concept](image)

Figure 1.1 - Biorefinery concept.

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A portfolio on combinations of raw materials, conversion processes as well as technology and final products portfolio, associated to biochemical or thermochemical platforms, will contain virtually unlimited number of cases. Moreover, there is no defined border between these two technology concepts, since there could be plenty of synergetic interactions that can maximize environmental and economical product value. The final decision about biofuels, biochemicals and bionergy production pathway will depend upon raw material availability, technological know-how, regional policies, market regulations and dynamics, in addition to industrial capacity and performance.

Annex XI of the Industrial Energy-related Technologies and Systems (IETS) programme aims at putting together competences in different countries, bringing in projects in different industrial sectors focusing on industry based biorefineries.

Areas for international cooperation which are considered relevant for implementation relate to exchange of information on the optimization of energy efficiency in existing and new integrated industrial plants, to convert internal biomass and wastes to energy and bioproducts as well as the implementation of joint projects leading to promote the concept of Biorrefinery and support information related to a Bio-economy strategy.

During the period 2008-2015, projects were developed in addition to a survey carried out in 2008/2009 to identify existing biorefineries. Figure 1.2 shows the findings at that stage, showing a strong leadership of the United States of America with regard to biorefineries projects and installations. As it can be seen further in the report, the number of installations has been increasing worldwide, with focus on fibers and other bio-products in addition to biofuels. Also, in the case of biofuels, the trend is to produce advanced biofuels as an alternative to 1st generation biofuels.
A bio-based world economy poses many challenges for its sustainability, demanding a comprehensive approach to address the various flows, needs and impacts, namely ecological, environmental, energy, food supply and natural resources. It is believed that, with the right framework, the Bioeconomy will contribute to reduce adverse impacts on the environment as well as the dependence on fossil resources, mitigate climate change and move forward a new era succeeding the “Oil” Society.

The role of research has been crucial to attain new technological solutions and the new developments have put in place biomass as a flexible resource able to provide energy, fuels and materials. The concept of biorefinery emerges in this context in a parallel way to oil refineries. The fact is that a shift to biomass-based raw materials rather than fossil resources and the application of biological processing methods together with chemical or thermochemical ones will lead to substantial savings in terms of CO₂ equivalent of resources leading to new markets for bio-based raw materials and new bio-products.

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1 Annex XI Data Survey (2009), IETS.

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Consolidating a “Bioeconomy” platform of cooperation also poses challenges. Industry-based biorefineries have evolved significantly in recent years. The fact that food chain industry and integration with fuels and energy production have been proven in a few international projects show that competition might not exist in the future, and energy and food could be considered as two end products to integrate when considering process integration and industrial complexes.
2. OVERVIEW OF THE SECTOR

The planet faces nowadays great challenges as a result of a growing world population with an increasing need for food, energy and drinkable water. On the other hand, climate change is a menace needed to be faced, with the urgent need to take measures to reduce greenhouse gases’ emissions.

One way to reduce these emissions is the use of new and more efficient technologies and to ensure environmental sustainability in the long term while maintaining a balance with the necessary economic growth.

The biorefinery concept is one of the promising technological solutions of today’s world to meet the growing energy demand by providing power, fuels and chemicals.

A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, heat and chemicals from biomass. Biofuels can be solid, liquid or gaseous; however, these are usually associated to a biomass liquid fuel, which could be used as an alternative to liquid fossil fuels, such as gasoline, diesel and jet fuel. This means that a biorefinery can be a facility, a process, a plant, or even a cluster of facilities. The sustainability aspect is of major importance when establishing biorefineries; all biorefineries should be assessed for the entire value chain on their environmental, economic and social sustainability covering the whole life cycle.

Various routes can be implemented in a biorefinery, either based on biochemical or thermochemical conversion processes.

Biorefineries can be classified in different manners, usually depending on the type of feedstock used. Figure 2.1 presents the most used systems for biorefinery
classification, *i.e.* Whole Crop, Lignocellulosic Feedstock, Green and Two- or multi-Platform Biorefineries².

![Figure 2.1 - Types of Biorefineries (a) and (b).](image)

(Figure taken from Kamm, B.; Gruber, B.R.; Kamm, M. (2006) "Biorefineries". Industrial Processes and Products, Wiley-VCH).


The term “bio-based products” refers to three different product categories:

- biofuels (e.g. biodiesel and bioethanol);
- bio-energy (heat and power);

Figure 2.1 – Types of Biorefineries (c) and (d).
• bio-based chemicals (e.g. methanol, ammonia, succinic acid, bio-based polyethylene, bio-based polypropylene, p-xylene and polylactic acid) and materials.

Although conversion techniques are generally classified in two main categories, i.e. biochemical and thermochemical processes, there could be applied other type of conversion paths, namely thermal processes with catalysis or hydrothermal processes. This is the case of hydrotreatment, which involves a chemical reaction of vegetable oils, animal-based waste fats or by-products of vegetable oil refining with hydrogen, producing hydrocarbons that can substitute fossil diesel or biodiesel.

The following sections focus on the different types of conversion and technologies.

**BIOCHEMICAL CONVERSION PROCESSES**

**FERMENTATION OF LIGNOCELLULOSIC BIOMASS**

Fermentation is a biological process in which enzymes produced by microorganisms catalyze chemical reactions to convert the sugar-containing polymers, cellulose and hemicellulose, to a rage of products. The lignin part of the biomass cannot be converted via the fermentation route. There is a great variety of bacteria, yeasts (including genetically modified yeast) and fungi able to ferment these sugars. These microorganisms digest sugars to produce energy and chemicals, producing carbon dioxide, organic acids, hydrogen, ethanol, and other products. However, cellulosic or starch biomass need to be broken up into sugar molecules prior to fermentation. The lignocellulosic material is usually and firstly mechanically degraded, i.e. chipped, grinded or milled in order to increase the surface area. Generally, two routes are employed to hydrolyse the lignocellulosic material. One is the use of acid hydrolysis and the other is the use of a pretreatment process prior to enzymatic hydrolysis. In both cases there are several possible methods or operation modes. In all fermentation routes it is very important that all sugar residues are fermented with high product yield in order to use resources efficiently and get good economic performance. That means
that the chosen fermentation microorganism must be able to convert all monosaccharides present in the stream to the desired product with high efficiency level. After the fermentation, the solid fraction containing lignin can be used to produce heat and electricity.

### ANAEROBIC DIGESTION

Anaerobic digestion is a biological process to breakdown biomass by using microorganisms in the absence of oxygen, producing combustible gases.

The anaerobic degradation of organic matter is due to the coordinated activity of microorganisms (Bacteria and Archaea) that operate interdependently in the absence of oxygen, and in successive stages (hydrolysis, acidogenesis, acetogenesis and methanogenesis) that attack structures of complex organic materials by converting them into simple compounds, such as methane (CH$_4$) and carbon dioxide (CO$_2$). Two-stage anaerobic digestion processes are known to be frequently applied to the sequential production of hydrogen and methane from various organic substrates and wastes in a cost effective manner [1]. Figure 2.2 illustrates a schematic two stage anaerobic digestion process$^3$ developed for biogas production from green waste and animal droppings by the University of Western Australia.

![Figure 2.2 – A schematic two stage anaerobic digestion process.](http://www.cfe.uwa.edu.au/research/coal)

$^3$ Process diagram and information of R&D in the UWA’s Energy Centre (consulted April 2017)

THERMAL CONVERSION PROCESSES

BIOMASS GASIFICATION

Gasification is a thermochemical conversion process that involves thermal decomposition of biomass in a reducing atmosphere of steam or air (or both); a medium- or low-calorific value gas is produced which can subsequently be converted to other fuel forms or chemicals. In gasification process biomass is submitted to a complex series of reactions, which involve drying of biomass, pyrolysis, reduction and oxidation. There are various types of gasifiers and plants installed in various countries, given its potential to generate gas that can be converted into liquid fuels and chemicals as well as energy. However, its dissemination has been slow due to economic considerations. Figure 2.3 presents a schematic diagram of a two-step biomass gasification process developed by Biomass Technology Group⁴.

Figure 2.3 - Schematic diagram of BTG two-step gasification process.


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Anaerobic digestion and gasification are processes that complement each other in that, together, can be applied to the conversion of a large part of the effluents produced into utility products. While anaerobic digestion is suitable for degradation of high moist and liquid organic effluents, gasification applies better to lignified materials of low moisture content which are usually difficult and long to decompose by biological processes.

PYROLYSIS OF BIOMASS

Pyrolysis is the thermal decomposition of biomass occurring in the absence of oxygen. It is the fundamental chemical reaction that is the precursor of both the combustion and gasification processes and occurs naturally in the first two seconds. The products of biomass pyrolysis include biochar, bio-oil and gases including methane, hydrogen, carbon monoxide, and carbon dioxide. Depending on the residence time, the thermal environment and the final temperature, pyrolysis will yield mainly biochar at low temperatures, less than 450°C, when the heating rate is quite slow, and mainly gases at high temperatures, greater than 800°C, with rapid heating rates. At an intermediate temperature and under relatively high heating rates, the expected product is bio-oil.

Pyrolysis can be performed at relatively small scale and at remote locations which enhance energy density of the biomass resource and reduce transport and handling costs. Heat transfer is a critical area in pyrolysis as the pyrolysis process is endothermic and sufficient heat transfer surface has to be provided to meet process heat needs. Pyrolysis offers a flexible and attractive way of converting solid biomass into an easily stored and transported liquid, which can be successfully used for the production of heat, power and chemicals. However, there is a need for further research to improve oil yields and reduce technology costs, especially when dealing with high moisture content feeding stocks where hydropyrolysis has a potential. Usually, higher moisture contents than 10%, such as waste streams (sludge and meat processing wastes), are subjected to drying before applying pyrolysis.

CONVERSION OF SYNGAS TO METHANE

Methane can be produced from syngas, this composed usually by methane, hydrogen, carbon monoxide and dioxide. CO and CO₂ streams can be converted to methane by
means of a catalyst. Methane 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.⁵

SNG production can also involve the conversion of biodegradable waste or energy crops into a gaseous fuel called biogas, made up largely by 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%.⁶

1⁰ GENERATION VS 2⁰ AND 3⁰ GENERATION BIOREFINERIES

Biofuels are referred to solid, liquid or gaseous fuels derived from organic matter. They are usually divided into primary and secondary biofuels. Primary biofuels are used in an unprocessed from primarily for heating, cooking or electricity production. Secondary biofuels such as bioethanol and biodiesel are produced by processing biomass and are able to be used in vehicles and various industrial processes. The secondary biofuels can be categorized in three generations: first, second and third generation biofuels on the basis of different parameters, such as the type of processing technology and type of feedstock. Figure 2.4 shows a classification of biofuels according to Dragone G. et al⁷.

First generation fuels refer to those that are most widely commercially available today. Generally, these are obtained from food crops and commodity agricultural products as raw materials. The most common concern related to the first generation biofuels is that as production capacity increases, so does the competition with agriculture for arable land used for food production. The increased pressure on arable land currently used for food production can lead to food shortages and/or increase in food prices. In addition the intensive use of land with high fertilizer and pesticide applications and water use may also cause significant environmental problems.

Second generation biofuels are intended to be derived from lignocellulosic biomass, the woody part of plants that do not compete with food production. Main sources include forest harvesting residues or wood processing waste as leaves, straw or wood chips as well as non-edible components of corn or sugarcane, but special energy crops or municipal waste can also be used. Making the transition to this second generation is widely regarded as being the only sustainable way in which biofuels can continue to grow their share of the fuels market. However, whilst there are up to forty organizations focusing on second generation bioethanol in the US alone, there remain technological hurdles to be overcome. Converting the woody biomass into fermentable...
sugars requires costly technologies involving pre-treatment with special enzymes, which is a challenge for an economic production on a large scale.

Concerning third generation biofuels, they are obtained from microalgae, and are considered to be a viable alternative energy resource. Microalgae are able to produce 15-300 times more oil for biodiesel production than the traditional crops on an area basis. As microalgae have a very short harvesting cycle (1 to 10 days depending on the process) comparing to the conventional crop plants which are usually harvested once or twice a year, a significant increased yield can be obtained. There are several ways to convert microalgal biomass to energy sources, which may be classified into biochemical conversion, chemical reaction, direct combustion, thermochemical and hydrothermal conversion. Figure 2.5 illustrates pathways from feedstock into final products.

![Figure 2.5 – Conversion processes for biofuel production from microalgal biomass.](Diagram taken from Dragone, G., Fernandes B., Vicente A. A., Teixeira J. (2010). "Third generation biofuels from microalgae". In: Technology and Education Topics in Applied Microbiology and Microbial Biotechnology, Ed. A. Méndez-Vilas.)

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Next generation fuels will be those obtained from CO₂ fixation producing primarily methane with the use of catalysts. The challenge is on cost reduction and closing the cycle in an efficient manner in energy terms.

In a global way, Fig. 2.6 presents a diagram of conversion processes to biofuels as a function of the feeding stock.

**Conversion Processes to biofuels**

![Conversion Processes to biofuels](Diagram taken from www.eubia.org, consulted in October 2016)

**CURRENT STATUS OF BIOREFINERIES**

One way of evaluating the current state of worldwide development of biorefineries is through the number of existing biorefineries as well as by their increasing production capacity facing previous years. In terms of biofuels, biodiesel has increased its share significantly, having the largest share in the biofuels market in Europe. Figure 2.7
confirms this increase from 1998 into 2013, with exception of a decrease in 2011 that is attributed to the oil processes’ variation. As it can be seen, Germany is the leading production country in Europe.

Data shows that biofuel production has maintained its increase up to 2015. Figure 2.8 shows the production pattern for the period 2009 – 2015.

Figure 2.7 - Biodiesel EU production (1998-2013).
(Diagram obtained from www.ebb-eu.org, consulted in October 2016).

Figure 2.8 – Total biofuel production capacity in the period 2009-2015.
(Data taken from Advanced Biofuels Project Database published in Biofuelsdigest)\(^8\)

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\(^8\) Data taken from www.biofuelsdigest.com (consulted in October 2016).
With respect to advanced fuels production, data show that there is a positive trend to increase its production as production capacity has been increasing, but still further progress is needed. The following figures compare levels of production in different regions. The low levels of production of most of the fuels show that it is still needed further development to take place to improve its push into the market.

The following data and figures were taken from [www.biofuelsdigest.com](http://www.biofuelsdigest.com) and refer to the following regions: Europe, North America, South America, Asia and Oceania.

**Europe:**

![Advanced Biofuels Production in Europe](image1)

![Europe Total Production capacity](image2)

*Figure 2.9 – Advanced biofuel and total production in Europe in the period 2009-2015.*

IETS-ANNEX XI Industry-based biorefineries
**North America**

Figure 2.10 – Advanced biofuels production in North America in the period 2009-2015.

**South America**

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As it can be seen in Fig. 2.11, South America had a sharp rise in installed capacity from 2011 to 2013, maintaining a constant value in the last three years. However, the installed capacity in South America is about 12 times lower than that of Europe.

**Asia**
The production capacity of advanced biofuels in Asia was kept almost constant over the period 2010-2012, increased slightly in the following two years (2013-2014) and almost doubled the previously installed capacity in 2015. The reason for this behaviour is linked to the growth of fast pyrolysis capacity raise.

**Oceania**

**Figure 2.12 – Biofuels and total production capacity in Asia in the period 2009-2015.**

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Although there has been an effort to implement advanced technologies for algal feedstock in the last three years, the contribution of Oceania to the overall world biofuels production capacity is very small.

North America, especially in the recent years, has shown the greatest increase in its biofuel production growth, outstanding when compared to other regions. Figure 2.15 confirms this leading role.

**Figure 2.13** – Biofuels and total production capacity in Oceania for 2009-2015.

**Figure 2.15** – Biofuels total production capacity in the period 2009-2015.
3. MARKET POTENTIAL

Mankind lives now a brief period on its history, at which dependence from fossil resources stands for the structural basis for primary energy supply and products production. These fossil resources allowed the relevant technological leap that our societies have seen within the last century, however, no matter how optimistic the studies are, all are unanimous in concluding that this brief period of humankind history (massive use of fossil fuels, particularly for mobility), may not be kept within a few decades, making it necessary to find alternatives. We may still have / use oil for more 100 years but its economic feasibility will decline, as it become harder to extract, purify and refine, and consequently more expensive. Coal and natural gas may last longer due to massive reserves, and replace part of the oil, but if natural gas seems to be less pollutant, the same cannot be said regarding coal, unless carbon capture and sequestration technologies are installed. Will the price of these energy sources be kept acceptable within the next decades? Will a fast growing world population and consumers willing for more ecological and sustainable products allow fossil age to last many more decades?

In the last decade’s biorefinery has been an exciting subject for researchers, discussed at scientific forums, conferences, within universities and research institutes, but in the last years this subject has also grabbed the industry attention and nowadays many industrial projects are already at the field. It cannot be forgotten that some of the bio refinery concepts were developed long ago, for example during the Second World War, but recently technological developments and process optimization have driven to more efficient and cost competitive processes / products / fuels.

The oil price instability along with consumers willing for ecological and sustainable products has progressively been made viable the production and trade of biomass base chemicals, fuels and polymers, replacing the ones with petrochemical origin. Consequently, a bio base industry is emerging, showing steeply growing rates.
International legislation is being drawn to prevent raw material supplies with its origin on agricultural lands, thus forest biomass and agricultural residues may become the source for these new bio industry raw materials. Industrial bio refineries have been identified as the most promising route for the creation of a new bio based industry / economy. Various sources (Chemical industry, consultancy companies, European Union, other entities) estimate a rapid growth in the production of products such as bioethanol, bioplastics, biogas or biochemical, in a 10 year time span. Following, some of these studies will be mentioned.

- Pöyry Management Consulting estimates the renewable chemicals market will worth 40 bn€ in 2020, providing 43.600 new jobs within the biochemical industry only.\(^1\); \(^2\)

- Royal DSM evaluated biochemical building blocks market in 4,5 bn$ in 2015 and estimates 9 bn$ in 2020 \(^3\). This company production affords to target the bio-based succinic acid and bio-based adipic acid.

![Growth of renewable building blocks](image)

**Figure 3.1 – Biochemical Building Blocks.**

- Brew Project, predicts that by 2050, 17 to 38 % of the organic chemicals will be produced based on renewable sources (e.g. biomass). This represents 26 to
113 kton/year. The same study predicts that 42 kton of polymers, presently produced in Western Europe (from petrochemical sources) could be replaced by biopolymers. [4]

- In 2010, the Silicon Valley Bank released a report that evaluated the renewable chemicals and biofuels market in 148 bn$. It predicts that by 2025, 17% of chemicals and fuels are bio-based, accounting for 1.4 trillion$ (Figure 50). [5]

![Figure 3.2 – Renewable Chemicals and Biofuels Market.](image)

- Market value for bio-based products might triple until 2020 to an estimated €250 billion globally, which could result in a similar increase in jobs (380,000). As of 2005, bio-based products already accounted for 7% of global sales and around 77 billion euro in value within the chemical sector. The EU industry accounted for approximately 30% of this value. [6]

- European Bioplastics predicts that global bioplastic production will grow 300% from 2012 to 2018 to reach approximately 6.700 kton per year. Bioplastics are
a broad family of materials with widely varying properties. Ultimately, bioplastics have the same properties of conventional plastics and can be used in all market segments where the latter are used. Several kinds of bioplastics are being produced (Figure 51), not only conventional plastics (e.g. PE, PET) but also other plastics, with lower applications so far (e.g. PLA, PHA, PHB).[7]

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**Figure 3.3 – Global Bioplastics Production Capacity.** [7]

- A market overview for key fermentation products in 2013 and annual growth projection until 2020 was published by Deloitte on a 2014 study. According to this study this market value reached 127 bn$ in 2013, and will continue rising within the next years, between 4.6%/year for alcohols and 6.5%/year for other products, as can be seen in Table 3.1 [8].
Table 3.1 - Market overview for key fermentation products in 2013 and annual growth projection until 2020. [8]

<table>
<thead>
<tr>
<th>Category</th>
<th>Market size in product output (quantity produced)</th>
<th>Average theoretical yield</th>
<th>Market size in carbohydrate input required</th>
<th>Market size in value</th>
<th>Average added value generated from carbohydrate</th>
<th>Market growth until 2020</th>
<th>Arable land use*</th>
<th>Min ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alcohols</td>
<td>99.8 Min ton</td>
<td>0.51 Ton product/ton glucose</td>
<td>195.1 Min ton CHEQ</td>
<td>110.0 Bn USD</td>
<td>164 USD/IOQ</td>
<td>4.4% CAGR</td>
<td>25.08</td>
<td></td>
</tr>
<tr>
<td>Amino Acids</td>
<td>7.1</td>
<td>0.92</td>
<td>7.8</td>
<td>11.0</td>
<td>1,010 USD/IOQ</td>
<td>5.6% CAGR</td>
<td>1.00</td>
<td></td>
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<td>Organic Acids</td>
<td>2.9</td>
<td>1.05</td>
<td>2.8</td>
<td>3.5</td>
<td>850 USD/IOQ</td>
<td>8.8% CAGR</td>
<td>0.36</td>
<td></td>
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<tr>
<td>Biogas</td>
<td>0.1</td>
<td>0.27</td>
<td>0.5</td>
<td>0.2</td>
<td>0 USD/IOQ</td>
<td>5.0% CAGR</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Polymers</td>
<td>0.2</td>
<td>0.93</td>
<td>0.2</td>
<td>0.6</td>
<td>2,600 USD/IOQ</td>
<td>13.5% CAGR</td>
<td>0.03</td>
<td></td>
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<tr>
<td>Vitamins</td>
<td>0.2</td>
<td>0.96</td>
<td>0.2</td>
<td>0.7</td>
<td>3,100 USD/IOQ</td>
<td>2.6% CAGR</td>
<td>0.03</td>
<td></td>
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<tr>
<td>Antibiotics</td>
<td>0.2</td>
<td>1.00</td>
<td>0.2</td>
<td>0.8</td>
<td>3,600 USD/IOQ</td>
<td>4.0% CAGR</td>
<td>0.03</td>
<td></td>
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<tr>
<td>Industrial Enzymes</td>
<td>0.1</td>
<td>1.00</td>
<td>0.1</td>
<td>0.3</td>
<td>2,600 USD/IOQ</td>
<td>8.0% CAGR</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>110.5</strong></td>
<td><strong>206.8</strong></td>
<td><strong>127.0</strong></td>
<td><strong>4.6%</strong> CAGR</td>
<td><strong>26.6</strong> USD/IOQ</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Source: BCC Research, FO Licht Renewable Chemicals Database, NOVA Institute, FAO/OECD - Deloitte Analysis. [8]

**BIOETHANOL**

Bioethanol is a biofuel already spread worldwide, but major consumption is verified at USA, Brazil and Europe. According to Deloitte [8], in 2013 alcohols market value reached 110 billion $. At Europe, bioethanol consumption and productions has not grown so steeply as at Brazil and USA, nevertheless, according to LMC International, consumption at Europe reached the 8 billion liters at 2013 and 14 billion litters are predicted to 2020 [11]. Europe is also a net importer of bioethanol, having imported nearly 1 billion litters at 2013. By 2020 it is expected that importations may reach 4 billion litters.
Bioethanol consumption has grown steadily during the last years, nearly 18% / year between 2000 and 2010 [9]. According to OECD/FAO, current production reaches 115 billion liters. Forecast point to a steadily market growth within the next years, being predicted nearly 170 billion liters by 2022 [10].

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**Figure 3.4 - Global ethanol production by country and region, 2007-2013.** [9]
Nowadays, sugarcane and cereals are the bioethanol main raw-materials, however, due to discussions related with ‘Indirect Land-Use Change’ (ILUC), and use of agricultural soils for biofuels production, second generation bioethanol has become a target, using agricultural wastes and forest biomass. The OECD / FAO outlook predicts that cereals weight at bioethanol production may drop within the incoming years (nearly 10%), being replaced by second generation bioethanol (≈ 17 bilion L /year, by 2022).
BIO OIL

Pyrolysis bio oil is known for decades but recently interest on bio refinery led to further development and technologic leaps. This product may be directly burned at kilns / boilers, replacing heavy fuel oil (HFO) or light fuel oil (LFO), with proper equipment modifications. Can be also submitted to an upgrading, for oxygen removal, allowing its blend with fossil crude, and by thus, technically, conventional gasoline and diesel could be produced with it. This possibility has raised industry attention (including the petrochemical industry). Besides biofuels other products may be obtained with bio oil. According to Ensyn (a company producing and trading bio oil products since 1989), more than 30 different food ingredients are currently produced from Ensyn’s RTP bio oils, as well value-added chemicals [12].

Following may be found the results of some surveys, regarding pyrolysis plants, settled or under construction.

<table>
<thead>
<tr>
<th>Company</th>
<th>Country</th>
<th>Biomass consumption (kg/h)</th>
<th>Applications</th>
<th>Operation status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABRITech</td>
<td>Canada</td>
<td>70 - 700</td>
<td>Fuel</td>
<td>Operational</td>
</tr>
<tr>
<td>Agri-Therm</td>
<td>Canada</td>
<td>420</td>
<td>Fuel</td>
<td>Upgrade</td>
</tr>
<tr>
<td>Biomass Engineering</td>
<td>UK</td>
<td>250</td>
<td>Fuel /Products</td>
<td>Construction</td>
</tr>
<tr>
<td>BTG</td>
<td>Netherlands</td>
<td>250</td>
<td>Fuel</td>
<td>Operational</td>
</tr>
<tr>
<td>BTG BioLiquids EMPYRO</td>
<td>Netherlands</td>
<td>6500</td>
<td>Fuel</td>
<td>Design</td>
</tr>
<tr>
<td>Ensyn</td>
<td>Canada</td>
<td>3 - 3100</td>
<td>Fuel</td>
<td>Operational</td>
</tr>
<tr>
<td>Fraunhofer UMSICHT</td>
<td>Germany</td>
<td>250</td>
<td>Fuel</td>
<td>Construction</td>
</tr>
<tr>
<td>Fortum</td>
<td>Finland</td>
<td>10000</td>
<td>Fuel</td>
<td>Operational</td>
</tr>
</tbody>
</table>
### NEW FIBER MATERIALS – NANOCELULOSES

Cellulosic materials have potential to be used on a wide range of applications, on papers, board, packaging, inks, and varnishes, coating applications, adhesives, food additives, cements, cosmetic and pharmaceutical applications, vehicles and aerospatial industry, filters and membranes, textiles and electric components.

From the conventional cellulosic fibre it is possible to produce 3 different materials; NFC - nano fibrillated cellulose; MFC – micro fibrillated cellulose and NCC – nano crystalline cellulose (Fig. 3.7). There are already industrial facilities producing these materials.

<table>
<thead>
<tr>
<th>Company</th>
<th>Country</th>
<th>Year</th>
<th>Product</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genting</td>
<td>Malaysia</td>
<td>2000</td>
<td>Fuel</td>
<td>Inactive</td>
</tr>
<tr>
<td>GTI</td>
<td>USA</td>
<td>50</td>
<td>Fuel</td>
<td></td>
</tr>
<tr>
<td>KiOR</td>
<td>USA</td>
<td>21000</td>
<td>Fuel</td>
<td>Inactive</td>
</tr>
<tr>
<td>KIT</td>
<td>Germany</td>
<td>1000</td>
<td>Fuel</td>
<td>Operational</td>
</tr>
<tr>
<td>METSO</td>
<td>Finland</td>
<td>300</td>
<td>Fuel</td>
<td>Operational</td>
</tr>
<tr>
<td>Pytec</td>
<td>Germany</td>
<td>200</td>
<td>Fuel</td>
<td>Construction</td>
</tr>
<tr>
<td>Red Arrow/Ensyn</td>
<td>USA</td>
<td>125 - 1250</td>
<td>Products</td>
<td>Operational</td>
</tr>
<tr>
<td>Renewable Oil</td>
<td>USA</td>
<td>105</td>
<td>Fuel</td>
<td>Operational</td>
</tr>
<tr>
<td>International LLC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTI International</td>
<td>USA</td>
<td>40</td>
<td>Fuel</td>
<td>Construction</td>
</tr>
<tr>
<td>UOP</td>
<td>USA</td>
<td>40</td>
<td>Fuel</td>
<td>Construction</td>
</tr>
<tr>
<td>Cool Planet</td>
<td>USA</td>
<td></td>
<td></td>
<td>Construction</td>
</tr>
<tr>
<td>ABRITech</td>
<td>Canada</td>
<td>70 - 700</td>
<td>Fuel</td>
<td>Operational</td>
</tr>
<tr>
<td>Agri-Therm</td>
<td>Canada</td>
<td>420</td>
<td>Fuel</td>
<td>Upgrade</td>
</tr>
</tbody>
</table>
According to the literature survey, it is possible to divide the applications according to market potential and volume.

<table>
<thead>
<tr>
<th>Table 3.3 – Applications according to market potential and volume.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High volume application</strong></td>
</tr>
<tr>
<td>Cements</td>
</tr>
<tr>
<td>Vehicles structure and interiors</td>
</tr>
<tr>
<td>Packaging / papers and board</td>
</tr>
<tr>
<td>Replacement of plastic packaging and barriers</td>
</tr>
<tr>
<td>Absorbent materials / Textiles</td>
</tr>
</tbody>
</table>
Market potential has been assessed on some studies. According to the *Forest Products Laboratory - US Department of Agriculture* (May 2014), market potential was quantified on 35 Mton by 2020. As a comparison, cellulosic pulp consumption at Europe and North America reached respectively 46 Mton and 55 Mton (2013).

Nanocellulose production capacity was assessed on 1300 ton at 2013 and Future Market Inc., (*Nanocelluloses, May 2014*) forecasts 5500 ton / year by 2020. There are still high uncertainty regarding this market evolution, reflecting the difference between the market potential and foresee production.

According to the literature review, there are already some companies producing or able to produce some of these new materials (NFC, MFC or NCC):

- Asai Kasei Chemicals Corporation, Japan
- BASF AG, Germany
- Borregard Chemcell, Norway
- Cellucomp, UK
- Cellulab, Canada
- Cellutech AB, Sweden
- Daicel Corporation, Japan
- FMC Biopolymer, USA
- Green Core Composites Inc, Canada
- J. Rettenmaier & Sohne GmbH, Germany
- Jenpolymers Ltd, Jena, Germany
- Nanocrete Technologies, USA
- Nippon Paper, Japan
- Norske Skog, Norway
- Oji Paper, Japan
- Seiko PMC Corporation, Japan
- Stora Enso Ltd, Finland
- UPM Kymmene Ltd, Finland
- Verso Paper Corp., USA
- Zelfo Technology (BASF), Germany
The advantage of these materials lies on its renewable origin, security (natural material) and properties. They can be used on the replacement of materials / products with petrochemical origin, and this may open a wide range of application and market potential. Drying these materials for transportation and watering again for re-dispersion / application might be an issue (high hydrophilic materials). There are also still process challenges and several approaches being developed for their production. Different approaches and the uncertainty hinder the scale-up which keeps the production prices still high. A well-established petrochemical industry and its products represent also a tough competition for these new products.

**BIOGAS / SYNGAS**

Biogas plants have been increasing in recent years in Europe. In the the year 2014, it was verified an increase of 18.3% on the existent plants in 2013 in Europe. Figure 3.8 shows the number of biogas plants installed in Europe as well as related capacities.⁹

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In terms of biogas production, this represented an installed capacity of 8,287 MW$_{el}$ in 2014 with 63.6 TWh of electricity produced\(^\text{10}\).

The potential of biomethane that can be derived from biogas, in addition to methane derived from syngas, is great as it can be used to substitute natural gas. Figure 3.10 presents the number of biomethane plants installed in European countries since 2011.

\(^{10}\) 14\textsuperscript{th} EurObserv'\textsuperscript{e}r Report on the State of Renewable Energies in Europe, 2013.

\textbf{IETS-ANNEX XI Industry-based biorefineries}
In these countries biomethane is obtained through an upgrading biogas processing technique, using different feedstocks for biogas production. Water scrubbers are the most common techniques, in the case of Sweden, Finland and Germany.

Figure 3.11 illustrates the various upgrading technologies installed in various countries in Europe and separately, fig. 3.12 presents the situation in the case of Germany.
Figure 3.12 – Biomethane upgrading installations and technologies located in Germany. (Figure taken from EBA report on Biomethane and Biogas 2015)

Production of biomethane by upgrading biogas and/or syngas could provide a wider gas market with diversified applications. Biomethane can also be used through injection in natural gas pipelines, giving rise to cross-border trade. This is at the moment very limited in Europe but expected to grow in the future.
4. TASKS’ DESCRIPTION & ACHIEVEMENTS

The cooperation platform has a multi-disciplinary approach to the concept of biorefineries integrated in industrial complexes, aiming at the optimization of energy efficiency in global terms. The objective of sharing knowledge and experiences, as well as conducting research assessment based studies and R&D projects to promote the industry-based biorefineries’ concept. The work was performed divided into the following tasks:

- Bioenergy & Biofuels,
- Biochemicals & New Fibre Materials
- Sustainability Analysis of Process Integrated Biorefineries
- Process Integration of Gasification-based Biorefineries

TASK I - BIOENERGY & BIOFUELS

INTRODUCTION

World’s primary energy consumption is expected to increase significantly and in accordance to IEA data, it is foreseen that 2/3 of this increase is justified by developing countries growth, where oil is the prime fuel. The use of fossil energy needs to be reviewed due to political constrains (Kyoto protocol, geo-political issues) and economical reasons (oil price, oil reserves availability). This leads to the opportunity to orientate policy on the basis of a bio-economy.

Biomass is the most common form of renewable energy used in the world, having various applications which include fuel production, power generation and heating and cooling.

Nowadays, it is possible to produce electrical energy from biomass by integrating a biomass boiler with a conventional steam turbine. Global electrical energy production efficiency is limited to 20-25%. For a full co-generation system, including thermal energy production, global efficiencies are within a 60-70% range.
However, there are other technological pathways, namely the application of the gasification process, enabling production of heat and/or power, fuels and/or chemicals. The choice of whether to generate power or transportation fuels would be driven by economics of circumstances and/or location.

Biofuels production is presently being promoted worldwide. Several policy measures are in action in order to achieve this. EU and USA are in the forefront of this movement. The search for energy security supply and fulfilment of Kyoto protocol are the main driving forces justifying technological development in this area. At present days, biofuels production is sustained by first generation technologies. However, due to competition for food supply, second generation biofuels are a more consensual solution for biofuels in the future. This generation of biofuels are based upon lignocellulosic material and large-scale plants are more adequate to wood logistics supply. It also eliminates seasonal cropping nature of raw material. Other paths are also considered important and worth exploring in a longer term perspective, justifying investing in research related to third generation biofuels.

Within Annex XI, Task I goal was to promote sharing knowledge and experience as well as cooperation in the field. In this last case, ALGAECASCADE « The biorefinery of Algae- a CASCADE approach» was implemented with the view to promote research focusing on 3rd generation biofuels.

**OBJECTIVES & STRATEGY**

There are various conversion technologies that can be applied to produce fuels and/or energy from biomass. Feedstocks can also be diverse. The objective of the task was to identify the state-of-the-art and share experiences and information on conversion techniques and energy and fuels production processes.

Activities have been implemented to reinforce international cooperation to structure partnerships that lead to optimization of energy efficiency in existing and new integrated industrial plants. The strategy was also to include R&D on sustainability assessments, biofuels/bio-materials production technologies and yields from thermo-chemical and biological conversion of biomass and waste materials.
The cooperation set up with the implementation of ALGAECASCAD was to develop a generic technology for converting non-food related marine micro- and/or macro-algae to a multipurpose, flexible, storable energy carrier, liquid bio-methane (LBM). Using anaerobic digestion to convert the marine algae avoids the need for complete dewatering, drying and fractionation of the biomass, thus increasing energy efficiency.

**ACHIEVEMENTS**

Cooperation was set up involving academia, research centres and industry from the following countries: the Netherlands, Belgium, Portugal, Luxembourg and India, with the objective to implement a project leading to the production of liquid biomethane; however, due to the lack of funding it was not possible to go ahead with the development of the concept.

**TASK II - BIOCHEMICALS & NEW FIBER MATERIALS**

**INTRODUCTION**

Biomass, especially lignocellulosic material, represents an abundant renewable carbon source. This is potentially convertible in energy, fuels and products. The integrated production of bioenergy, biofuels and biochemicals, through advanced technological processes of separation and conversion, which minimizes carbon cycle impact, defines the bio refinery concept.

To answer these new challenges several new processes are being developed. These processes are associated to two different technology basis or platforms: Biochemical and Thermochemical Platforms. Biochemical platform can be defined as an application of several extractions, separation and biological conversion processes of biomass elemental components in order to produce biofuels and biochemicals. The sugar-to-ethanol processes, lignin valorization, plant extracts are examples of different routes within this platform.
Thermochemical platform can be defined as biomass thermal treatment processes that envisage the production of syngas or bio-oil, as possible building blocks, for further conversion in bioenergy, biofuels and biochemicals. Biomass gasification, black liquor gasification, biomass pyrolysis or liquefaction and carbonization, are examples of different technological routes within this platform.

The combinations of raw materials, conversion process / technology and final products portfolio, associated to any of these platforms, are virtually unlimited. Moreover, there is no defined border between these two technology concepts, since there could be plenty of synergetic interactions that can maximize environmental and economical product value. The final decision about biofuels, biochemicals and bioenergy production pathway will depend upon raw material availability, technological know-how, regional policies, market regulations and dynamics.

Within Annex XI, Task II goal was the dissemination of works related to Biochemicals & New Fiber Materials development. The BUGWORKERS project was one of those disseminated through the Annex.

**OBJECTIVES & STRATEGY**

The largest industrial consumers are those producing chemicals, iron and steel, non-metallic materials, pulp and paper and non-ferrous metals. The interest in biorefineries has recently increased significantly as it is aligned with policies of diversification, considering conversion processes for heat and power generation simultaneously with biofuels production and chemicals.

This Annex, and task, tried to gather competences in different countries, share information, projects conclusions, join persons and promote new ideas /
projects constitution, across different industrial sectors, focused on industry based biorefineries.

Periodic meetings took place between the Annex Manager and the task leader for management optimization. The task manager promoted and had the opportunity to gather / meet with R&D projects leaders, start-ups, SMEs, Industry and technology providers. The strategy for the task / Annex dissimination and information exchange can be shortly described.

**ACHIEVEMENTS**

With regard to the European project BUGWORKERS, a process for the production of wheat straw hydrolysates by AFEX (ammonia fiber expansion) was successfully scaled up by a factor of 10. In addition, a solvent-free purification process was developed and optimized, with which a fairly clear polymer with a molecular weight comparable to that of the commercial PHB can be obtained. Different cellulose raw materials were tested for the production of cellulose nanowhiskers, including microcrystalline cellulose, and cellulose from paper sludge (from sulphite pulp and from kraft pulp), the latter provided by Portucel-Soporcel, as a result of the interaction with Annex XI team.

**TASK III - SUSTAINABILITY ANALYSIS OF PROCESS INTEGRATED BIOREFINERIES**

**INTRODUCTION**

Resources are becoming scarce and the planet will not last long with the current levels of consumption, of fossil fuels, minerals, among other resources. The industrial productive system is responsible for the production of products and services, required to meet the demanding standards of a consumerist population. The major problem in this civilization is the use amount of resources
extract from the nature, and out of that only 20 % in terms of weight is effectively used (OECD, 2012). The remaining resources are wasted in different ways, gaseous emissions, liquid effluents and solid disposals. Due to the aforementioned situation, a strong activity has been carried out in the industrial production sites in order to improve the sustainability of the industrial processes. Among the scientific/technical developments it can be highlighted the new and more efficient catalysts and more efficient separations through the integration of new agents. Moreover, the industrial process intensification and integration attitudes also move the processes towards the right direction, leading to systems, which seem to have all the plant inside of an environment-friendly container, sometimes called the “Banana Container”. The widespread awakening on the issue of sustainability in the development of society was made during the decade of the 60s of the twentieth century. However, sustainability has only been considered a landmark, achieving the public recognition, with the publication of the book Limits to Grow in 1972 by (Meadows et al., 1972). This book was the result of a group of industrialists who gathered in Rome to discuss the "new" international problems. This work describes the results of a computer model of human evolution ("World 3"), which identifies the consequences for the planet, of the current exponential industrial development and population growth. The book's conclusions are something catastrophic, and are based on scenarios away from the reality of a finite world. These conclusions had a strong impact on public opinion and especially in political power.

The concept of Sustainability was formally introduced by the World Commission on Environment and Development (WCED) of the UN headed by the Prime Minister of Norway, Gro Harlem Brundtland in the report "Our Common Future" or Brundtland Report (Brundtland 1987). In this report sustainability has been defined as: "meet the needs of the present generation without affecting the
ability of future generations get their supply." The report indicates a number of measures that should be taken by countries to promote sustainable development. One of the proposed measures, in the Brundtland report, concerns the need for the United Nations (UN) to implement a sustainable development program. This recommendation of the commission led to the development of Agenda 21 that began in 1989 with the approval of a special meeting with the United Nations, in a conference on environment and development. In 25-27 of September, 2015 the United Nations Development Summit defined the new Agenda 2030, which is a plan of action for people, planet and prosperity. It also seeks to strengthen universal peace in larger freedom.

The concept of sustainable development must be assimilated by the leaders of the companies as a new way to produce without degrading the environment, extending this culture at all levels of the organization. A systematic analysis of the company's production process in terms of impact on the environment, economic and social aspects should be conducted. This analysis should result in the implementation of a project, which combines production, social and environmental preservation, with technology adapted to that principle (Ramôa Ribeiro, 2009). Sustainability Analysis of Industrial Processes emerges as an indispensable practice to design and evaluate new processes and/or existing ones (retrofit design). It is essential to assess the existing process and propose new design alternatives in terms of the three pillars of sustainability. The three main components of sustainability analysis in industrial processes are accordingly to its basic definition the following:

• Stability and cost-effectiveness: should be sought technological solutions that lead to optimum operating point at the level of minimum total cost or maximum profitability;

IETS-ANNEX XI Industry-based biorefineries
• Ecological balance: by including the rational use of raw materials, the preservation of natural ecosystems and mitigating the effects of climate change;

• Social development and equity: adapting the existing rule to the concrete situation, observing the criteria of safety, justice and equality.

OBJECTIVES & STRATEGY

The main objective of this task is to use the concept of Sustainability that is comparable to a tripod where each leg corresponds to a specific pillar: Economic, Environmental and Social to assess alternatives of production of goods using Biorefineries and if applicable compare those results with conventional ways of production. For that purpose, it is required to have methodologies and tools, which deal with the three pillars of sustainability within harmonized order to achieve an appropriate outcome. It is also required to incorporate sustainability indicators, covering the different areas, so that industrial processes can be assessed.

As a main Strategy it was developed a methodology for analysing sustainability in industrial processes, namely Industry-based Biorefineries (Carvalho, Matos, and Gani 2013). The methodology identifies the critical points of the process to change (operating equipment, change materials, etc.) The methodology could guarantee in the end a more sustainable process alternative according to economic, environmental, social and safety issues. The method uses mass and energy indicators, which screen the process, allowing the identification of process bottlenecks; this means the process point that presents mass losses, high costs or undesirable accumulation of species. The indicators that have more severe problems (i.e. high potential for improvement) are selected. A sensitivity analysis to identify target windows, as well as target variables to the desired improvement is performed. The method further involves the use of
process synthesis algorithms to suggest new process alternative(s). The new alternatives are assessed in terms of indicators and metrics.

ACHIEVEMENTS

Several achievements were obtain in this task, namely the methodology mentioned to carried out the Sustainability Analysis has been incorporated in a software tool, called *SustainPro* (Carvalho, Matos, and Gani 2013). Figure 3.13 shows the overview of the *SustainPro* methodology and the usage of different simulations or characterization tools.

![SustainPro methodology overview with the tools interaction](image)

Figure 3.13 – *SustainPro* methodology overview with the tools interaction

Several Master Thesis were also carried out in the field during this period, as follows.

1) **Title:** Analysis of a Sustainable "Model" Biorefinery - Sustainability and Life Cycle Assessment of the Bioethanol Production Process from Lignocellulosic Feedstock.

IETS-ANNEX XI Industry-based biorefineries
Abstract: This project intends to serve as a base for a posterior complete analysis of the best possible sustainable "model" biorefinery. The emphasis of this work will be on the bioethanol production from lignocellulosic feedstock. A very complete flowsheet of the bioethanol production process with 33 components and 31 reactions, over 31 units, and over 56 streams, was implemented in the simulation software PRO/II 8.1. Several tools were tested using information generated by the PRO/II simulation, starting with the sustainability tool SustainPro, from which were obtained targets for improvement, and generated a new design alternative. SustainPro provided evidence of being a reliable and useful tool, although too demanding in terms of specific component properties at specific process conditions. Regarding environmental sustainability, the analysis is made through the Waste Reduction (WAR) algorithm. The software Integrated Computer Aided System (ICAS), also from CAPEC, was used to generate the WAR algorithm results. A Water Pinch Analysis (WPA) was performed to part of the process in order to validate improvements pointed out by SustainPro. A complete economic evaluation of the base case and new design was elaborated. The Life Cycle Assessment (LCA) was carried out for three design alternatives using GaBi 4, which database proved to be insufficient, and should be improved in the future. LCA results were too dependent on the process energy consumption, and a stricter definition of the boundaries is necessary in order to increase confidence in the results.

2) Title: Strategic and Technological Analysis of Electricity Generation from Biomass in Poland and Portugal: Present Situation and Future Prospective.

Abstract: Nowadays, Europe is facing the consequences of the world last economic crisis. Strong and balanced energy policy can provide conditions for achieving stable, continuous economic and social development. This requires stable and predictable regulations. Energy production in Poland is still based on traditional energy sources such as coal and lignite. However, the depletion of fossil fuels and the problem of excessive carbon dioxide emissions cause a growing interest in renewable energy sources. In recent years, Poland has increased awareness of the environmental damage caused by conventional energy, and membership in the European Union created an additional stimulus to the restructuring of the Polish energy sector. Consequently, the concept of renewable energy sources (solar, wind, hydro, geothermal and biomass) is gaining recognition in the Polish energy policy and environmental strategy. However, Polish power sector will need in the near future, a very large investment, as a consequence of the aging of the existing power plants. Moreover, the development of new technologies like dedicated biomass blocks and biomass gasification are needed. Although biomass is a very attractive and popular energy source, in Poland still exists barriers to its use. It is necessary to establish a simple system of support for the widespread use of individual plant biomass (small heating plants and power plants). Portugal, like all other European countries, is giving an increasing focus to renewable energy. Bioenergy, which comes from the transformation of biomass, is pointed out as having a big potential to reach the environmental targets. Even though promising resources, there are still existing barriers for the use of the biomass as an energy source. The difficulties flow basically because of the lack of labour on the rural areas and appropriate equipment specialized in the recovery of the forest biomass. The non-existence of a heating market, especially in what refers to the biomass, is essentially due to the lack of search from the possible consumers. The whole forest policy has as major objectives the promotion of sustainable forest management, based on logic of multifunctionality of forests.
This strategy will increase the economic value of forests through the exploitation of many resources produced on them. Biomass is reliably supply that can be properly stored and the electricity thus created can be introduced in the grid when there is a real demand for it. However, the biggest challenge for Portugal is to decrease the level of energy dependence on energy imports, particularly of natural gas and oil, forms the backdrop for policy concerns relating to the security of energy supplies. This study was also analysed an existing biomass power plant in Portugal and suggested some improvements in the construction of a future biomass power unit.

3) **Title:** Bio-Ethanol Production Process: Techno-Economic, Sustainability & Environmental Impact Approach.

**Abstract:** The on-going price increase of fossil resources, their uncertain availability and the growing concern about climate change have encouraged the replacement of fossil-fuel products. The aim of this bio-industry is to be competitive in the market and lead to the progressive replacement of oil refinery products. However, the biofuel production process sustainability in terms of raw material, water and energy consumption has been raising severe concern about the future of biorefineries. The present work aims to propose a framework, so-called ‘Techno-Economic Sustainability Environmental Impact Diagnosis’ (TESED) that allows the user to perform a complete techno-economic, sustainability and environmental impact analysis on chemical/biochemical biorefinery processes and simultaneously generate more sustainable, economic and environmentally feasible options. The proposed framework incorporates different methodologies, which were previously developed at Computer-Aided Process Engineering Center (CAPEC), which were incorporated into computer-aided tools such as: SustainPro, LCSoft, and ECON. Bioethanol, produced from biomass, was the case-study selected to verify and validate the proposed framework (TESED), therefore a complete techno-economic, sustainable and environmental analysis was performed on the bioethanol production processes from 6 different feedstocks: Hard-wood chips, Cassava, Corn, Corn Stover, Switch grass and Sugarcane. The proposed framework was proven to work successfully, allowing the final user (i) to compare and evaluate several processes producing the same product through a multi-criteria evaluation (tech-no-economic, sustainability, environmental impact) (ii) and then to achieve a bettered process design option. Therefore, the proposed framework entail a robust decision-making framework for product and process design of current and future sustainable chemical/biochemical processes.
INTRODUCTION

Industrial biorefineries play a central role in the path to a bio-based economy demanding energy efficient solutions. Integration of gasification can lead to flexibility in terms of products (energy and/or fuels) that could result in higher efficiency and cleaner solutions. The choice of whether to manufacture power or transportation fuels would be driven by economics of circumstances and/or location.

In the case of pulp and paper mills, once gasification technology is implemented, there will be choices on how to best utilize and convert their synthetic gas, either for the production of:

- Clean, renewable and sustainable electric power: BLG in an integrated combined cycle (BLGCC) has the potential of producing twice the electrical output per ton and in many cases, excess power could be produced and exported. (Combined cycle denotes the use of a gaseous fuel in gas turbine followed by the production of steam, which is subsequently used in steam turbine such that both turbines produce electricity).
- Clean, renewable and sustainable liquid fuels: when gasified, black liquor converts to a high quality synthetic gas low in methane and similar to syngas produced from fossil residual oil. Conventional processes can then be used to convert the gas to DME, methanol or hydrogen.

Process integration (PI) refers to analysis and optimization of large and complex industrial processes. Pinch analysis is a widely-used PI tool in many industrial sectors that enables to investigate energy flows within a process, and identify
the most economical way to maximize heat recovery and minimize the demand for external utilities (e.g. steam and cooling water).

Figure 3.13 illustrates the concept of Pinch technology that can be applied to integrate processes in an optimized and efficient manner.

![Figure 3.13 – Basic concepts of PINCH Analysis.](Image)


Within Annex XI, Task IV goal was to share knowledge and develop process integration tools for industrial applications.

**OBJECTIVES & STRATEGY**

International cooperation on the demonstration of a self-sustainable decentralized multi-resource and multi-process based installation, for heat and power, towards zero emissions, taking advantage of competences held in different entities and countries will in principle advance technological options in a faster way.

IETS-ANNEX XI Industry-based biorefineries
The objective of this task was to promote cooperation by involving teams in different countries with expertise on the development of process integration tools to develop and integrate gasification-based solutions for industry-base biorefineries. In this context, it was also aimed at strengthening the collaboration with other IEA Technology Cooperation Platforms, namely the Bioenergy TCP.

**ACHIEVEMENTS**

Establishment of collaboration with IEA Bioenergy Task 42 Biorefinery aiming at sharing information on biorefineries, by implementation of joint activities such as joint workshops and studies.
5. EVENTS & PUBLICATIONS

In this period several events occurred in Portugal and Belgium under the auspices of this annex.

Event 1- In 2009, an International Conference on Industry-based Bioenergy and Biorefinery – The role of Biomass in Portugal was organized in Lisbon, Portugal at Auditorium Campus Lumiar, November 19 and 20th.

Programme:

**Thursday, November 19**

9:15 - Opening Session
Secretary of State for Energy and Innovation, President of IAPMEI, President of LNEG, Bastonário da Ordem dos Engenheiros, President of the National Authority of Forests

A - Overview on the strategic role of Bioenergy and Biorefinery
Chairperson: Thore Berntsson

09:45 - The EC policy on promoting biofuels - Oyvind Vessia, DGTREN, EU
10:15 - Biomass as a renewable energy source in Portugal - Claudia Mendes, Biomass Centre for Energy, Portugal

10:45 - Coffee-break and poster session
11:15 - Availability of biomass in the Portuguese forests - Cristina Santos e Graça Louro, National Authority of Forests, Portugal
11:45 - IETS Annex XI: Industry-based Biorefineries - Isabel Cabrita, LNEG, Portugal
12:15 - Biomass and Carbon Trade - Ana Pipio, IDMEC-IST, Portugal
12:45 - Lunch

B – Optimization of Biomass Based Industrial Processes using the Best Available Technologies
Chairperson: Pedro Sampaio Nunes

14:00 - The Conversion of Forest Biomass into Electricity: The Experience of EDP – Produção Bioeléctrica - Gil Patrão, EDP Bioeléctrica, Portugal
14:30 - Biomass Based Combustion and Gasification - Awf Al-Kassir, U. Extremadura, Spain
15:00 - Process Integration in a Biomass based Industrial Plant - Henrique Matos, Cristina Fernandes, Ana Rita Seita, IST, Portugal
15:30 - Process Integration for Biorefinery Implementation - Thore Berntsson, Chalmers, Sweden
16:00 - Coffee-break and poster session

C – Biorefinery and BioProducts
Chairperson: Isabel Cabrita
16:30 - Pulp Mill Biorefinery Concepts - Peter Axegard, INNVENTIA, Sweden
17:00 - CIMV biorefining process - Michel Delmas., CIMV, France
17:30 - Pulp and Paper Industry: "Turning" into a 2nd Generation Biorefinery - Gabriel Sousa, RAIZ - Research Institute for Forestry and Paper, Portugal

Friday, November 20

D – Bioenergy and Biofuels
Chairperson: Gabriel Sousa
09:30 - Bioenergy Implementing Agreement – Task 42 - Ed de Jong, Avantium Technologies BV, The Netherlands
10:00 - The challenges facing the new Biomass-based power stations - Carlos Alegria, Central de Biomassa de Oliveira de Azeméis, Portugal
10:30 - Biofuels production from microalgae - Luisa Gouveia, LNEG, Portugal
11:00 - Coffee-break and poster session
11:20 - First generation biodiesel: an industrial case study - Cristina Borges Correia, PRIO-Martifer, Portugal
11:45 - 2nd generation Biodiesel, pros and cons - Hugo Pereira, GALP Energia, Portugal
12:10 Round Table Discussion and Global Conclusions -Moderator: Clemente Pedro Nunes (IST/DEQB)
José Perdigoto (Director General for Energy and Geology), Vitor Santos (President of ERSE), Gil Mata (Portucel), Mira Amaral (IST-DEG)
13:00 - Lunch
14:00- 18:00 Visit to Portucel Plant at Setúbal
IETS- Brainstorming Session for new tasks in Annex XI

Conclusions:
This International Conference was very relevant for the dissemination, namely in Portugal, of the economic, technological and environmental importance of Bioenergy and Biorefineries.

As it is a crucial theme, it is of the utmost importance to make concrete proposals for future actions which will allow reinforcing the industrial use of biomass, including for energy production, with various perspectives.

Thus, the following priority actions were proposed:

- Promote an R&D project that applies Process Integration methodologies in biomass-based power stations, to increase its global energy efficiency. Due to the economic relevance of this project, the Portuguese Group for Process Integration decided to...
support it financially, in cooperation with the scientific and technological capabilities of the Group members.

- **Stimulate the cleaning of the forests and endorse a positive differentiation to be contemplated in the electric tariff of their biomass-based power stations.** This principle has already been established in certain European countries and, in Portugal, it may be able to attain a value about 140 €/MWh, in the case of those municipalities needing further developments.
- This positive differentiation should be increased when these power stations use process integration to promote the waste heat recovery, namely in nearby industrial units that in these regions are dedicated to the production of wood “pellets” production.
- Promote the use of European financial aid programs (in the case of Portugal QREN), to invest on an integrated system of logistic means for collecting forest-based biomass, to ensure the outflow to the industrial units of the forest products and byproducts of small and medium forest producers, thus allowing the optimization of forest management in more than 80% of the sylvan land.
- Reduce to 5% the VAT tax rate applied to biomass, in the case of Portugal, in order to avoid the situation of applying a tax of 20% to purchase firewood, which is a renewable energy source produced in Portugal, whilst natural gas, which is an imported fossil fuel, pays a reduced VAT tax rate of only 5%.
- This VAT reduction will also allow the use, in Portugal, of wood “pellets” presently exported due to lack of incentives to its use in the country. It must be noted that the reinforcement of these incentives will also be able to re-launch, in Portugal, boiler manufacturers that use wood pellets as a fuel, both for domestic and SME use.
- Disseminate the selected biomass species of more rapid growth, namely among the small and medium size forest producers, allowing the increase of the forest production in terms of tons/hectar per year. At the same time, this will guarantee that the raw material needs of both the cellulose industry and the biomass based energy industrial units are fully protected.
- Promote the R&D projects focusing on the optimization of microalgae lineages that can be industrially used in the biofuels production and the CO₂ removal from the atmosphere.
- Define a policy for fiscal incentives, to be applied at least till 2018 for the biofuels production; in the case of Portugal, it will allow the development and the technological optimization of its production chain.
- Deepen the analysis of the effects on the CO₂ emissions reduction caused by the joint effects of the biomass-based power stations, the optimized forest management and the reduction of forest fires incidence. This analysis results must be integrated in the priority actions already under way, having in consideration the engagements already undertaken, or to be undertaken, towards the reduction of CO₂ emissions.
- Promote R&D projects that will improve industrial processes in the pulp and paper production, as a way to increase its energy efficiency, as well as the production of biomaterials, in order to develop new concepts of integrated Bio-refineries that can be economically competitive and sustainable.
- Promote the coordination of the activities of Annex XI – Biorefineries of IETS Implementing Agreement and of Task 42 of Bioenergy Implementing Agreement within the framework of the International Energy Agency, in order to develop joint R&D projects in this area and to increase the impact of the dissemination of the technological knowledge created in this way.
**Event 2** – In 2010, a one day International Workshop on Energy Optimization in Industry and reduction of CO₂ emissions was organized in Lisbon, Portugal at Auditorium Campus Lumiar, November 3rd.

**Programme:**

8h30   Registration

**Welcome Session**

9h00   Secretary of State for Energy and Innovation, President of LNEG, President ADENE, President of IAPMEI, President of IST

**Session I – Energy Outlook**

9h30   Jayen Veerapen (IEA Secretariat), "The IEA strategic view on the World Energy Outlook"
Clemente Pedro Nunes (IST), "Portuguese Energy Outlook"

Discussion

10h30  POSTER SESSION & COFFEE BREAK

**Session II – IEA based International Cooperation**

10h45  Jan Sandvig Nielsen (IETS - Industrial Energy-Related Technologies and Systems)
Gabriel Sousa (Industry-based Biorefineries)
James Quinn (Excess Heat Recovery)

Discussion

**Session III (A) – Industrial perspective on the reduction of CO₂ emissions**

12h00  Preto dos Santos (APEB), "The Biomass Based Power Stations and the Reduction of CO2 Emissions in Portugal"

12h30  LUNCH BREAK

**Session III (B) – Industrial perspective on the reduction of CO₂ emissions**

14h00  Cândida Felício (GALP), "Hands-on management of the crude oil preheating train"
Fernando Mendes (CUF), "Integração Energética na Etapa de Purificação da Anilina"
Luís Machado (Instituto RAIZ), "The Problematic of Excess Heat and Water usage on Pulp and Paper Industry"
Isabel Cabrita (LNEG), "CO₂ and NO₅ emission reduction in Combustion Systems"

Discussion

15h30  POSTER SESSION & COFFEE BREAK

**Session IV – R&D projects on Energy Efficiency**

16h00  Rui Barbosa (FCT-UNL), "Study of the valorization of ashes produced in a thermoelectric power plant, working under co-combustion of coal and biomass, and in a pulp and paper industry"
Jaime Puna (ISEL/IST), "Biodiesel production with heterogeneous catalysts: a new challenge to bioenergy"
Rui Ribeiro (FEUP), "Electric Swing Adsorption for CO₂ capture"
Henrique Matos (IST), "Process Integration as a tool to increase the Industrial Energy Efficiency"

Discussion
Conclusions:
The increase in population and the expansion of economic activities in emergent countries has resulted in a significant increase in energy consumption. The sustainability of the supply of energy to society is an increasing concern of governments, having to consider the economic implications as well as the environmental impacts with regard to the intensive use of fossil fuels and the consequences that are expected in relation to climate change. The IEA, in its 2010 publication of Energy technology Perspectives, refers to the need to have a mix of energy resources and addresses technologies that could have an important role to half in 2050, the level of 2005 CO₂ emissions. Having a technological roadmap is important and the scenarios developed by the IEA show the importance of energy efficiency, which could contribute to reduce the final end-use energy consumption by 38% resulting in a reduction of CO₂ levels. In addition, better use of energy in the energy sector could have an impact of 5% in CO₂ reduction levels and fossil fuels’ substitution could contribute to an additional 15% reduction of emissions level. Other options to reduce CO₂ emissions considered in the scenario was Carbon Capture and Storage (CCS), which could contribute with 19%, renewable energies with 17% and nuclear energy with 6%.

Given the importance of the role of industry in this context, it was organized this workshop by the Executive Committee of IEA/IETS Implementing Agreement in Portugal, with the involvement of the following Portuguese entities: National Group for Process Integration (GNIP), IST, ISEL, IAPMEI, LNEG and RAIZ Institute. This workshop took place in Lisbon and had 152 participants.

The most recent technological advancements were presented by international experts and discussed. Biorefineries could have an important role in the future as they could be a way to substitute fossil fuels to reduce CO₂ levels and also could be implemented with CO₂ capture and fixation systems to improve its reduction with a beneficial impact regarding climate change.

**Event 3** - In 2012, an International Workshop was organized in Bruges, Belgium, May 10th on Industry-based Biorefinery Systems & Process Efficiency, which was held as a satellite event within the scope of i-SUP 2012 Conference.
Programme:

<table>
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<tr>
<th>Time</th>
<th>Event</th>
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<tr>
<td>8h30</td>
<td>Registration (late participants)</td>
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<tr>
<td></td>
<td><strong>Welcome Session</strong></td>
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<td>9h00</td>
<td>Opening REMARKS – Ludo Diels (Vito NV), Isabel Cabrita (Annex-XI Manager)</td>
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<td>9h15</td>
<td>Biorefinery of the Future an Industrial Opportunity – Yvon Le Henaff (ARD)</td>
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<td><strong>Session I – IEA Technology Framework</strong></td>
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<td>9:45</td>
<td>• Industry Energy-related Technology Systems (IETS) – Clemente Pedro Nunes (ExCo-IETS Member)</td>
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<td>• Industry-based Biorefineries (IETS/Annex XI) – Isabel Cabrita (Annex-XI Manager)</td>
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<td>• Biorefineries: Co-production of Fuels, Chemicals, Power and Materials from Biomass (Bioenergy/Task 42) – Ed de Jong (Bioenergy-Task 42 Manager)</td>
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<tr>
<td>10h45</td>
<td><strong>COFFEE BREAK</strong></td>
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<td><strong>Session II – EU Technology Platforms</strong></td>
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<td>11h15</td>
<td>• The EU’s challenges and opportunities for a world-leading bioeconomy: a policy perspective – Joanna Dupont (Industrial Biotechnology Director at EuropaBio)</td>
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<td>• Star Colibri project – Johan Elvnert (Manager of Forest-based Sector ETP)</td>
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<td>• BioDME project – Patrik Löwnertz (ChemRec)</td>
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<td>• ARBOR project - Willem Dhooghe (FlandersBio)</td>
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<td>12h30</td>
<td><strong>LUNCH BREAK</strong></td>
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<td><strong>Session III – Annex XI Projects : Progress Report</strong></td>
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<td>14h00</td>
<td>• BUGWORKERS – Bruno Sommer Ferreira (Biotrend-Inovação e Engenharia em Biotecnologia, SA)</td>
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<td>• ALGAECASCADE/MARFORCE – Ludo Diels (Vito, NV)</td>
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<td>• Integrated Biofuel Production Processes Based on Systematic Optimization Methodologies – José Granjo (DEQ/FCTUC), Nuno Oliveira(DEQ/FCTUC)</td>
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<td>• Process Integration of Gasification-based Biorefineries – Thore Berntsson (Chalmers University), Anders Åsblad (Industrial Energy, Chalmers Industrial Technology)</td>
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<td>15h15</td>
<td><strong>COFFEE BREAK</strong></td>
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<td><strong>Session IV – Round Table &amp; Final Debate on New Projects</strong></td>
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<td>15h45</td>
<td>Moderators: Isabel Cabrita (Annex- XI manager); Clemente Pedro Nunes (ExCo-IETS Member)</td>
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<td>• Presentation of potential research and/or industry-oriented biorefinery projects - Ludo Diels</td>
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Conclusions:

There is an extensive work being carried out worldwide towards energy reduction and process efficiency, focusing in various conversion processes. It is believed that the real challenge is closely connected to the integration of different processes leading to energy production, fuels and high-added value bio-products by using cheap resources, while guaranteeing feedstock availability for energy efficient decentralized applications. Fuels diversity, along with energy efficiency and reduction of CO₂ emissions, is one of the areas selected for implementing cooperation at R&D level within the scope of the work of IEA-IETS Technology Collaboration Platform on Industry-based Biorefineries (Annex XI).

The one-day workshop was organised with the objective of sharing experiences and debate on opportunities to enlarge cooperation, leading to new projects, bringing together experts from academia, research centres and industry. This took place within the scope and program of the i-SUP 2012 Conference in Bruges, Belgium, event that was hosted by VITO. Opening of the workshop was officially done by Ludo Diels, who welcomed all participants. IETS Implementing Agreement’s activities were presented by Clemente Pedro Nunes and the work of its Annex XI, on Industry-based Biorefineries was presented by its Annex Manager, Isabel Cabrita. After this introduction, projects with International and European cooperation were discussed.

Challenges were identified in various areas related to consolidating a “Bio economy” platform of cooperation, as was put by Joanna Dupont (EuropaBio). Industry-based biorefineries have evolved significantly in recent years. The fact that food chain industry and integration with fuels and energy production as presented by Yvon Le Hanaff (ARD), have been proved in a few international projects show that competition might not exist in the future, and energy and food could be considered as two end products to integrate when considering process integration and industrial complexes. Biorefineries are important to consider in terms of industrial plants that actually could help providing employment in rural areas and give an added value to farming activities.

An example of EU collaboration is the Star Colibri project that was presented by Johan Elvnert. The success of its mapping activities could be a basis for collaboration, expanding information exchange outside Europe. PPP’s on the biorefinery concept can become an European flagship. Still focusing on European examples of transnational collaboration, after Patrik Löwnertz (ChemRec) presentation of the demonstration project “BIODME”, Willem Dhooghe (FlandersBio) presented the ARBOR project, focusing on waste streams to be valorized and synergies needed to feed the bio–based economy system.

Through IEA cooperation under the scope of IEA- IETS Annex XI, ongoing projects were presented: “Bugworkers”, an ongoing EU funded project that aims at developing a new cost competitive process for composite materials to be produced, presented by Bruno Sommer Ferreira (Biotrend); “Algaecascade” proposal that focus on algae utilization for fuels and bio
materials production presented by Bert Lemmens (VITO); sustainability studies that uses a simulation tool to orientate research to be implemented, ongoing research within the scope of a Ph.D. research work developed by José Granjo (DEQ/FCTUC); and process integration of gasification-based biorefineries, just starting project presented by Anders Åsblad (Chalmers Industrial Technology Centre). All these projects aim at producing fuels, materials and energy with an overall optimized energy efficiency.

Finally, the round table gave a practical perspective and presented examples of industrial experience including integration with oil refineries, where J.M. Roque (GALP Energia) focused on advantages related to some of the technologies, safety procedures and standards for biofuel production integration in an oil refinery. Henrique Matos (IST/UTL) addressed the importance of the use of wastes and the value of impact analysis in a social, economic and environmental balance related to a current strategy on the Sustainable Development. Patrick Löwnertz referred to the importance of catalysis. Ludo Diels pointed out the importance of the interaction with different platforms, giving emphasis in the case of Europe, EuropaBio through Joana Dupont and Star Colibri through Johan Elvnert, taking into account the Vision 2030 and related recommendations. The cooperation with respect to countries like India was also addressed on bio-based projects.

In conclusion, the following recommendations were addressed with respect to Annex XI programme of work:

- Implement actions leading to more visibility of the work, namely through publication of reports as well as the publication of the proceedings of the workshop;
- Update the survey conducted in the past promoting collaboration with Star Colibri project team as well as through the participation of countries in IETS Tecnology Collaboration Platform;
- Develop more activity in new ideas to bring relevancy to biorefinery applications for better visibility of the added value and promote dissemination worldwide;
- Promote cooperation with non-member IEA countries like India in the development of new initiatives that can initiate added value projects to all participants.

**Event 4** - In 2013, it was held an International WORKSHOP "System and Integration Aspects of Biomass-based Gasification", at Gothenburg, Sweden, 19-20 November.

A joint Workshop between IEA Bioenergy Task 33 (thermal gasification of biomass), and IEA Industrial Energy-related Technologies and Systems Annex XI (industry-based biorefineries) took place in Gothenburg on 19 and 20 November 2013. The topic of the workshop was "System and Integration Aspects of Biomass-based Gasification". The aim of this workshop was to initiate a dialogue across the technology/system interface, as well as on methods and results for technical, economic and environmental evaluations of integrated biomass-based gasification systems. The other aim was to identify topics for further international cooperation in these areas.

Over 50 experts participated on the workshop, which was divided into 4 sessions to cover all the areas of biomass gasification, system and integration aspects:
- Session 1: **Biomass Gasification to Fuel Gas; Integration into Power and CHP**
- Session 2: **Biomass Gasification into Syngas Part I; Upstream and Internal Integration**
- Session 3: **Biomass Gasification into Syngas Part II; Downstream and Product**
- Session 4: **Methodologies for Assessing Techno-economic Performance and Climate Impact**

All the presentations given on the workshop can be found at the Task 33 website, [www.ieata33.org](http://www.ieata33.org).

http://www.ieata33.org/content/home/minutes_and_presentations/2013_November_WS/

**Programme:**

**19 November 2013, Gothenburg, Sweden**

Gaspar, RAIZ Institute, Portucel Soporcel, Portugal:  
**IEA Industrial Energy-related Technologies and Systems. Annex XI** (pdf 1.5 MB)

K. Whitty, University of Utah, USA:  
**IEA Bioenergy Agreement, Task 33: Thermal gasification of Biomass** (pdf 1.7 MB)

H. Wagner, TU of Hamburg-Harburg, Germany:  
**Gasification of Urban Biomass Residues - Possibilities in Hamburg / Germany** (pdf 0.8 MB)

M. Möller, DONG Energy, Denmark:  
**Status of DONG Energy’s Pyroneer Gasification Technology for High Alkaline Fuels** (pdf 2.3 MB)

C. Breitholz, Metso Power, Sweden:  
**Gasification of Biomass and Waste for Production of Power in Lahti and Vaasa** (pdf 3.2 MB)

H. Thunman, Chalmers University of Technology, Sweden:  
**Beyond 80% Efficiency for Standalone Production of Bio-methane from Wet Biomass** (pdf 1.1 MB)

T. Kolb, KIT, Germany:  
**Biomass gasification for BtL - The Bioliq Process** (pdf 4.6 MB)

I. Landälv, Lulea University of Technology, Sweden:  
**Methanol as Energy Carrier and Bunker Fuel** (pdf 6.7 MB)

R. Rauch, Vienna University of Technology, Austria:  
**Dual Fluidized Bed Gasification for CHP and Production of Advanced Biofuels** (pdf 0.6 MB)

B. van der Drift, ECN, the Netherlands:  
**Chemicals from Gasification** (pdf 0.9 MB)

I. Hannula, VTT, Finland:  
**Production of Synthetic Methanol and Light Olefins from Lignocellulosic Biomass** (pdf 2.7 MB)

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**IETS-ANNEX XI Industry-based biorefineries**
20. November 2013, Gothenburg, Sweden

S. Harvey, Chalmers University of Technology, Sweden:
Assessing the Performance of Future Integrated Biorefinery Concepts based on Biomass Gasification (pdf 3.2 MB)

E.D. Larson, Princeton University, USA:
Techno-Economic Systems Analysis of Jet Fuel and Electricity Co-Production from Biomass and Coal with CO2 capture: An Ohio River Valley (USA) Case Study (pdf 1.4 MB)

M. Talmadge, NREL, USA:
Techno-economic and Market Analysis of Tathways from Syngas to Fuels and Chemicals (pdf 0.5 MB)

A. Faaij, University of Utrecht, the Netherlands:
Bio-CCS: Negative Emissions to Meet the Global Carbon Budget (pdf 2.3 MB)

General discussion
B.F. Möller, Eon, Sweden:
Bio2G - A comercial-scale gasification to SNG plant Eon (pdf 0.4 MB)
Event 5 - In 2014, it was held an International WORKSHOP “On the way from Biorefineries to a Bioeconomy” as a satellite event within the scope of ChemPor’ 2014 Conference at Oporto, Portugal, in September 12th.

Programme:

<table>
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<tr>
<th>9-14h</th>
<th>Registration</th>
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<tbody>
<tr>
<td>14h30</td>
<td>Welcome Session</td>
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<td>Opening Remarks &amp; Introduction</td>
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<td>Clemente Pedro Nunes (Professor at Técnico in Lisbon University in Portugal and IEA IETS Vice-Chair)</td>
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<td>Isabel Cabrita (Research Coordinator at LNEG in Portugal and IEA IETS Annex XI Manager)</td>
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<td>15h00</td>
<td>Session I – Vision on Biorefineries/ Bioenergy &amp; Cooperation</td>
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<td>Chairperson: Henrique Matos</td>
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<td>Professor at Técnico in University of Lisbon (PT) and IEA IETS Annex XI Task Manager</td>
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<td>Keynote Speech</td>
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<td></td>
<td>Thore Berntsson (Chalmers University Professor in Sweden and IEA IETS Chair)</td>
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<td>‘The Biobased Economy - A Sustainable Way Forward’</td>
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<td>Invited Speakers</td>
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<td>Juan Carrasco (Head of the Biomass Unit in CIEMAT (Spain) and EERA Bioenergy Joint Program Coordinator)</td>
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<td>‘Some considerations about the sustainable implementation of biorefineries concepts’</td>
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<td>Francisco Giro &amp; Luis Duarte (1; Head of LNEG’s Bioenergy Unit (Portugal), member of EERA-Bioenergy Management Board, Portuguese delegate of European Bioenergy Industrial Initiative and Chair of SIADEB, 2; Researcher in LNEG’s Bioenergy Unit and Secretary General of SIADEB)</td>
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<td>‘Biomass Biorefineries—an industrial concept that requires a joint R&amp;D effort between industry and RTO’s’</td>
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<td>Rocío Díaz-Chavez (Imperial College Professor in United Kingdom)</td>
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<td>‘Socio-economic considerations of lignocellulosic biorefinery projects. Towards a sustainable bioeconomy’</td>
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<td>Mario João Fernandes &amp; Ana Raposo (National Contact Point for Horizon 2020 - GPPQ/FCT)</td>
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<td>‘Opportunities and challenges for Biorefineries &amp; Bioenergy in the context of Horizon 2020’</td>
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<td>17h00</td>
<td>Coffee break</td>
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<tr>
<td>17h15</td>
<td>Session II – Round Table - The Way Forward</td>
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<td>Moderator: Isabel Cabrita</td>
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<td>Invited Speakers</td>
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<td>Clemente Pedro Nunes (Professor in Técnico, Lisbon University, and member of the Strategic Council of the Biomass Centre for Energy (Portugal))</td>
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<td>Dmitri Yu. Murzin (Professor in Åbo Akademi University (Finland))</td>
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<td>José Ataide (Innovation and Industrial Research Director in Portucel Group (Portugal))</td>
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<td>Thore Berntsson (Chalmers University Professor in Sweden and IEA IETS Chair)</td>
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<td>18h15</td>
<td>Conclusions &amp; Recommendations</td>
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Conclusions:

In 2012, Europe adopted a strategy - “Innovating for Sustainable Growth: A Bioeconomy for Europe”. It is believed that, with the right framework, the Bioeconomy will contribute to reduce adverse impacts on the environment, as well as, the dependence on fossil resources, mitigate climate change and move forward to a new era, succeeding the “Oil” Society. But, the Bio-based world economy poses many challenges for its sustainability, demanding a comprehensive approach to address the various flows, needs and impacts, namely at ecological, environmental, energy, food supply and natural resources levels. The role of research has been crucial to attain new technological solutions and the new developments have put in place biomass as a flexible
resource able to provide energy, fuels and materials. The biorefinery concept emerges in this context in a parallel way to oil refineries. The fact is that a shift to biomass-based raw materials rather than fossil resources and the application of biological processing methods together with chemical or thermochemical ones will lead to substantial savings in terms of CO$_2$ equivalent of resources leading to new markets for bio-based raw materials and new bio-products. Consolidating a Bioeconomy cooperation platform poses challenges. Industry-based biorefineries have evolved significantly in recent years. The fact that food chain industry and integration with fuels and energy production have been proven in a few international projects show that competition might not exist in the future, and energy and food could be considered as two end products to integrate when considering process integration and industrial complexes. Biorefineries are important to consider in terms of industrial plants that actually could help providing employment in rural areas and give an added value to farming activities.

The workshop focused on the challenges and outcomes related to the biorefinery concept, sharing experiences and debating on the suitability of the concept and opportunities in a market driven framework towards a bio-based economy society, in the near future. There were 121 participants from different countries and stakeholders that came together to discuss what could be done to turn Bioeconomy a reality.

The role of industry and its active involvement was considered on key issue to be addressed. Industry is driven by profit and academia and researchers provide solutions mainly driven by curiosity. Mechanisms are needed to be identified to motivate all stakeholders to work together on a common basis. A new framework needs to be identified to ensure involvement of all relevant parties in a market context with a sound basis with regard to regulations and policy instruments. Planning should focus both on short and long term. How can Research and Business work together efficiently to guarantee both resource and technology sustainability taking into consideration the risk involved?

Annex XI’s motivation is to serve as a cooperation platform which could promote a network to discuss needs and gaps, addressing the fundamental issue regarding a Bioeconomy set-up: is it a dream or a reality? In the final discussion at the round table the following areas were identified as studies to be performed or activities to be pursued in the future:

- Technology Sustainability Standards;
- Short Term Regulation;
- Short Term Opportunities and Long Term Perspective;
- Strategic Approaches for Business Development.

Joining efforts between IETS – Annex XI network and other international cooperation structures such as SIADEB and the European Project BioConSept, given the already existing partnership with regard to bio-products and biorefineries studies and dissemination activities, could serve as an initial platform for a broader network set-up to implement joint work to assess the key issues above listed.
6. PROJECTS DEVELOPMENT

Two of the activities followed up by IETS- annex XI were of experimental nature. These were classified as projects and are presented below in more detail. In the case of Bugworkers project, IETS – annex XI was solely involved in the dissemination of results.

6.1 BUGWORKERS - NEW TAILOR-MADE PHB-BASED NANOCOMPOSITES FOR HIGH PERFORMANCE APPLICATIONS PRODUCED FROM ENVIRONMENTALLY FRIENDLY PRODUCTION ROUTES.

BUGWORKERS was a European collaborative project aiming to develop new tailor-made materials from environmentally friendly production routes. The materials are based on a polyhydroxyakanoate (PHA) biopolymer matrix and lignocellulosic nanofibers and aimed to provide alternatives to existing engineering materials. The outcomes of this project were targeted at two main sectors: household appliances and communication devices.

The projected included 14 partners and had a 48 months duration, from July 2010 to June 2014 and it was funded with 3.4 M€ (over a total budget of 4,5 M€).

The main technological targets in BUGWORKERS comprise:

- Increase PHB yield by high density fermentation cultures and hydrolyzing sugars from agricultural waste.
- Develop 2 grades of PHB
  - Homopolymer: highly crystalline, high thermal & chemical resistance
  - Copolymer: improved flexibility & impact resistance
- Develop functionalized lignin-based nanofibers and cellulose-whiskers obtained through enzymatic treatments from renewable resources.
- Compounding and processing technologies with the aim of reducing material needs and improving the end product properties
The expected impact of the project was the development of a nanocomposite material with improved properties, at a sustainable cost. The material developed should be biodegradable, and should present the benefit of being produced using lignocellulosic residues, as one of the raw materials. It was expected to have a potential impact on the current market of biodegradable plastic materials, which is continuously searching for materials with superior properties and low cost in order to compete against traditional non-biodegradable materials.

During the project main tasks comprised:

- Production of wheat straw hydrolysates
- Selection of adequate microbial strains
- Fermentation process development and optimization
- Purification process development and optimization
- Process scale-up

The deconstruction process included the Ammonia Fiber Expansion (AFEX), followed by enzymatic hydrolysis. Further work was undertaken for sugar syrups concentration and absence of inhibitors, which may affect microbial growth. It was also assessed the ability to use both C6 and C5 sugars.

The bacteria *Burkholderia sacchari* was first grown in 2L reactors. P limitations vs N limitations were the triggers for PHB accumulation. The process was optimized varying:

- Phosphate concentration
- Magnesium concentration
- Ammonium concentration
- Type of antifoam used
- Feeding regime
The scale was increased, from lab development scale to pilot, demo and industrial scale. First development and optimization were carried at 2L fermenters, followed by scale ups to 10, 50 and 250 L fermenters (Fig. 3.15).

The fermentation was successful validated at the 250 L fermenter, showing similar profiles as those obtained at the lower scales (2L, 10L, 50L).

**Figure 3.14 - Biological system (Bugworkers Webinar)** \cite{13}.

**Figure 3.15 - Scale-up (Bugworkers Webinar)** \cite{13}.

IETS-ANNEX XI Industry-based biorefineries
Regarding purification, a new organic solvent-free process was developed and optimized, which showed to be suitable for scale-up to pilot and industrial scales. The PHB extracted from *B. sacchari* showed to be similar to the commercial one.

As main conclusions can be pointed that:

- A fermentation process was implemented with a C6 + C5 sugar metabolizing strain
- Excellent productivities achieved
- Process validations across 100 fold scale increase
- An organic solvent free purification process implemented
- Polymer with specifications of the commercial material (without additives) can be obtained
- kg-scale production implemented

6.2 INTEGRATED BIOFUEL PRODUCTION PROCESSES BASED ON SYSTEMATIC OPTIMIZATION METHODOLOGIES

The present project involves the conception of both industrial plant structures and efficient supervision schemes for the integrated production of biofuels and food products from oleaginous biomass, of various origins. In order to achieve this goal, a significant vertical integration between adjacent products/processes is sought, including the extraction of oil from seeds, the production of biodiesel, the production of alkali catalyst for biodiesel manufacture, the purification of glycerol, the extraction and valorisation of proteins from the oleaginous seeds, the extraction of sugars and their fermentation to produce ethanol, and the extraction of additional special compounds from the fermentation products. The soybean crop is here used as case study to highlight the benefit resulting from the application of systematic strategies in the analysis, optimization and integration of these processes.

Some specific goals of the present project include:
• Build mechanistic and statistically based models to describe kinetics of reaction as a function of the main operating variables of reactive systems.

• Collect data to describe the thermophysical properties of the systems. Build phenomena-based models for detailed characterization of the process units, and its computational implementation.

• Design and compare alternative manufacturing processes of an alkaline catalyst in biodiesel production (sodium methoxide).

• Application of systematic methodologies in the design of networks of multiphase reaction processes for the production of biodiesel and bioethanol. This study includes the impact of distinct operation modes (continuous/discontinuous) and scales (medium/large).

• Design of separating systems based on equilibrium stages concept and mass transfer with special focus on complex distillation systems. Simultaneously, possible energy/mass integrations with reactive systems will be studied. In this phase flexibility studies are made on the physical robustness of the solutions obtained, to ensure the implementability of the optimal solutions obtained.

• Association of the simultaneous production of bioethanol and biodiesel in the food sector industries to set a vertical integration of production, and a complete utilization of raw materials.

• Identification and characterization of the key costs in the final product prices and the main limiting factors for each technology solution studied.

To accomplish the above mentioned goals, a phenomena-oriented approach is first used to build detailed models for the various process units (e.g., reactors, fermenters, distillation and extraction columns, pervaporators) based on mass balances, conditions of equilibria, and heat and mass transfer. Moreover, kinetic models are constructed and/or use whenever possible on a mechanistic basis of acid hydrolysis, enzyme and fermentation in the case of bioethanol, and the different types catalysis for biodiesel reaction step. The following phase is to proceed to a more system-oriented approach by applying and extending methods for the synthesis of optimal reaction and

IETS-ANNEX XI Industry-based biorefineries
separation networks based on the concepts of superstructures and sequential modules in the design of reactors/fermentators and separation systems for the processes production of biodiesel and bioethanol. Here the aim is also to study the application of techniques to reformulate discrete problems (MINLP) to continuous problems like NLP and introduce the concept of flexibility of the reaction network, using techniques of multi-criteria optimization. In the latter case, the solutions can be simultaneously optimized to maximize/minimize the production of a given chemical species (due to difficulties of separation, or economic value) and to improve the adaptability of production (producing more or less certain products depending on market).

Some of the work performed and the results obtained can be summarized:

- Kinetic models were obtained from experimental data in the open literature, for both the alkaline (sodium hydroxide) and acid (sulfuric acid) homogeneous catalysis of the transesterification reaction, used to produce biodiesel from vegetable oils. For both catalysis types, the kinetic models obtained show average absolute errors of approximately 4%, well within the precision of the experimental procedures.

- Development of a systematic strategy for the parameter estimation of equilibria data which incorporates thermodynamic consistency metrics and phase stability analysis, overcoming common pitfalls found in state-of-art approaches in literature. This methodology was successfully applied in various liquid-liquid and vapour-liquid equilibrium systems containing ionic liquids (ILs), modeled with different thermodynamic models; and can be easily extended to other type of equilibria (e.g., VLLE, SLE).

- Performance optimization of an industrial De Smet horizontal extractor used in solvent extraction of soy flakes by incorporating governing equations describing rigorously the soy oil concentration (bulk and flakes) in the mathematical formulations to minimize the equipment unit overall cost constrained by its geometry, flow patterns and extraction efficiency. Results indicate a 30% overall costs reduction and an increase by 20% of oil concentration exiting in miscella are achievable.
• Identification and design of an alternative process based on reactive distillation to manufacture sodium methoxide (NaOCH$_3$). The break even price (in dry mass basis) of NaOCH$_3$ estimated for this method is $3128/t, which is close to $3033/t estimated for the traditional process considering a continuous base production of 18 kt-year$^{-1}$ of NaOCH$_3$. Other identified advantages include greater safety, greater production flexibility, lower raw-materials costs and greater integration opportunities with the biodiesel manufacturing process.

• A conceptual analysis of an alternative to the classical distillation for the ethanol recovery steps. The design suggested includes a liquid-liquid extraction stage coupled to an extractive fermentation with the further ethanol concentration being carried out by pervaporation aiming at reducing the energy costs involved. The potential use of seven phosphonium-based ionic liquids (ILs) as extraction solvent was assessed. Experimental data was obtained COSMO-RS and NRTL models were used to describe the ternary system (IL)-liquid–ethanol–water.

• Biodiesel and the sodium methoxide manufacturing processes coupled with soybean crushing&processing facilities processing were analysed in Aspen Plus® employing detailed thermodynamic and kinetic models from previous works to study potential synergies. Several integration opportunities in the global process are identified with the biodiesel production costs be significantly reduced from $795/t to $584/t with the inclusion in the chemical supply chain of soy meal, lecithins and soy deodorization distillate (SODD) products with high commercial value. The integration of these processes helps to further reduce the biodiesel production costs by 2.6% and the amount of effluent generated by almost 10%.

The project plan to achieve the goals encompasses several tasks which can be divided by the following phases:

IETS-ANNEX XI Industry-based biorefineries
1) A preliminary analysis of the problem including:

- The building and/or use of, whenever possible, phenomena-based kinetic models for the various reactions and their incorporation in the reactors unit models
- Selection of thermodynamic methods, collecting experimental data and empirical correlations that best describe the thermophysical properties of mixtures.
- Computational implementation of detailed models for the several processing units (e.g., distillation and extraction columns, pervaporation, reactors, fermentators) using mass balances, equilibrium conditions, mass and heat transfer.

2) Application and extension of methodologies for the optimal synthesis of reaction networks based on superstructure and sequential modules concepts in the project of reactors/fermentators network systems in the production of biodiesel and bioethanol. Other studies in this phase will include the impact of the processing scale as well as sensibility studies in the optimal reaction networks configurations found.

3) Detailed study of the manufacture of the alkaline catalyst commonly used in the biodiesel production process (sodium methoxide). Preliminary assessment is going to be performed and the grass-root solution found is then optimized using mathematical methods for the optimal process configuration.

4) Synthesis of optimal separation network systems for all processes in study. Here is pretended to perform the optimal design and retrofit by applying concepts of equilibrium stages (e.g., distillation columns) and mass transfer (e.g., pervaporation). In this step, possible more complex separation unit configurations and interconnections that lead to a more economical separation sequences are studied.
5) In this step is intended to identify opportunities to integrate processes, characterizing the added value generated by the reduction of energy and utilities consumptions and the valorization of additional sub-products.

The tasks performed so far cover phases 1, 3-5. We started with regression studies to obtain kinetic semi-empirical and statistical models for the homogeneous alkaline and acid catalysis in biodiesel production. The development of parameter estimation strategies for thermodynamic model building was followed by a techno-economic assessment of alternative processes in sodium methoxide manufacturing. Then, the optimal design of industrial solid-liquid extraction units and the conceptual analysis of an alternative separation system for bioethanol purification were carried out. Finally, the integration of soybean crushing & processing facilities with biodiesel and catalyst manufacturing processes was also studied.

The overview of the system studied in this project is represented in Fig. 3.16. The work and results performed can be divided in four parts:

1) Regression studies to obtain kinetic models for the homogeneous alkaline and acid catalysis in biodiesel production.

2) Economical assessment of different alternative processes configuration in the production of sodium methoxide.

3) Separation of ethanol–water mixtures by liquid–liquid extraction using phosphonium-based ionic liquids.

4) Integration of biodiesel and sodium methoxide manufacturing processes with soybean crushing & processing facilities.
PART 1

The objective of this part was to provide results relative to kinetic models based on experimental data available in the open literature, for the transesterification reaction of vegetable oils, through homogeneous alkaline (sodium hydroxide) and acid systems (sulfuric acid). Experimental data of several authors was used to obtain kinetic models that could describe the reaction rate as a function of the main variables (temperature, catalyst concentration and methanol excess) in a wider region of operation that existing kinetic models were able to. Two approaches, designated as statistical, where models are obtained by performing a multivariate linear regression; and empirical
where the rate of reaction is viewed as a product of functions of each operating variable with a given structure that contains physical significance. In the statistical approach two different procedures to select the best set of predictors were used – forward stepwise regression and an optimization based on the direct minimization of the Bayesian Information Criteria.

Results show that data from literature fits better to a pseudo 2\textsuperscript{nd} order kinetic model for the alkaline catalysis, and a pseudo 1\textsuperscript{st} order kinetic model with acid catalysis, since the mean error for both strategies are lower in these cases and the correlation factors higher. These results are in agreement with the literature. For both catalysis types, the kinetic models obtained show average absolute errors of approximately 4\%, well within the precision of the experimental procedures.

**PART 2**

By reviewing the open literature it was possible to identify four different paths for the production of sodium methoxide:

I. Reacting methanol with sodium amalgam in a packed distillation column.

II. Controlled adding of melted sodium metal with methanol in a reactor unit. To the best of our knowledge this is the process more commonly used to produce alkali alkoxides.

III. Sodium methoxide production by reacting methanol with an aqueous solution of sodium hydroxide in a homogeneous reactive distillation column.

IV. The reaction of sodium acetate with methanol in an electrodialysis unit.

Processes I and IV were readily discarded because of the use of highly hazardous raw-materials in the former case, and the latter due to the low efficiency and capacity of production. Processes II and III were design and compared techno-economically. The results obtained show that the break even price (in dry mass basis) of NaOCH\textsubscript{3} in process II is $3033/t, while for process III this value is $3128/t considering a continuous base production of 18 kt\-year\textsuperscript{-1} of NaOCH\textsubscript{3}. Therefore, and although Process II and III are identical in terms of economic performance, they can be preferred in
different contexts. Because the process to manufacture NaOCH$_3$ from Na requires a relatively low initial capital investment and the cost of Na is high, it may be more suitable to be included within the chemical supply chain of organometallic producers where Na is usually already part of the portfolio. Additionally, the required experience of handling and processing highly hazardous materials might be advantageous in this case. Alternatively, Process III may be preferred when the production of NaOCH$_3$ can be integrated with other processes involving methanol and NaOCH$_3$, such as in biodiesel production, in order to reduce the capital and utilities costs of this process, and originate a larger supply chain with further opportunities for process integration. The simulated operating conditions were confirmed to be within typical values found in the literature.

PART 3

The use of phosphonium-based ionic liquids (ILs) for the extraction of ethanol from fermentation broths was investigated. Ternary phase diagrams, necessary for the design and to implement an alternative liquid–liquid extraction process for the alcohol recovery, were determined for seven ionic liquids. The modelling of the equilibrium data was performed using the COSMO-RS and NRTL models; the first aiming at screening other ionic liquids not experimentally studied, and the latter aiming at designing a separation process. The gathered data indicate that phosphonium-based ionic liquids are the best yet reported to perform water–ethanol separations. Based on the most promising phase diagrams, an analysis of the alcohol and ionic liquid recovery steps was carried out and a liquid–liquid extraction stage coupled to an extractive fermentation, where the ionic liquid is continuously recycled to the fermentator and the ethanol concentration is carried out by pervaporation, was proposed as an alternative to distillation (Fig. 3.17).
PART 4

This part makes use of all the information gathered in previous tasks and is where all the processing areas depicted in fig. 3.15 are simulated and analyzed together in Aspen Plus®. For model validation purposes, each processing area was simulated separately at typical conditions, and then they were all connected, forming the case base scenario. When the biodiesel manufacturing process is considered individually, the estimated production costs are $795/t of biodiesel, including glycerol credits and equipment depreciation costs. When the production of NaOCH₃ is coupled and the excess quantity marketed, the biodiesel production costs drops 2% to $779/t. The nominal costs decrease significantly to $584/t when the biodiesel production is incorporated in soybeans crushing facilities. This reduction is primarily explained by the improvement of the chemical supply value due to the incorporation of soy meal, lecithins and soy deodorization distillate (SODD) products that are of great commercial value. After the whole process be simulated at base case conditions, process integration possibilities were readily identified with the overall consumption of utilities being reduced by 8.4%, the wastewater generated is reduced by 9.7% to 46 kg/t of products, and the biodiesel production costs decrease 2.6% to 569 $/t. The model framework here developed of the whole process can be a valuable supporting tool for multiple studies: data reconciliation, process reconfiguration, optimal design of heat transfer, and economic analysis.
exchanger (Fig. 3.18) and mass exchanger networks, life-cycle analysis, products portfolio management and production planning at an enterprise-wide level.

The work developed met most of the initial goals established for this project. Considerable effort was put on building rigorous and detailed models to describe phase and chemical equilibria, reaction kinetics and the performance of equipment units. Simultaneously, were designed innovative mathematical strategies for parameter estimation of thermodynamic models, performance optimization of solid-liquid extraction units typically used in soybean processing plants; and mathematical programming strategies for model selection and outlier detection using the Bayesian Information Criteria. Afterwards, a consistent and rigorous model for a whole soybean biorefinery plant (fig. 3.15) was developed allowing the readily identification of integration possibilities and opening the possibility for a variety of studies with industrial interest. To complete the proposed goals for this project, bioethanol production process is to be included in the biorefinery plant model so that systematic methodologies can be applied for the optimal synthesis of bioethanol process using the liquid-liquid extraction/pervaporation alternative for ethanol purification; and for the

Figure 3.18 – NaOCH$_3$ production process.
optimal design of heat exchanger and mass exchanger networks of the overall biorefinery system.

![Graph showing temperature vs. Enthalpy](image)

**Figure 3.19** - Soybean biorefinery hot (red) and cold (blue) streams composite curves (optimal $\Delta T_{\text{min}}$ is $7 \, ^\circ\text{C}$).

Due to the computational nature of this project, its impact and acceptance of the solutions proposed are still being foreseen. Results show that the solution for the production of sodium methoxide can bring economical advantages for the biodiesel manufacturing industry. Rather buying directly the sodium methoxide, calculations suggest that the production on-site of the methanolic solution of sodium methoxide coupled with the existing facilities to produce biodiesel using an aqueous solution of sodium hydroxide can significantly reduce the total operating costs associated with biodiesel production. More importantly, the studies show that the economical performance and sustainability of the biodiesel production can be greatly improved by including the process within a wider supply chain with a broad product portfolio since various integration opportunities are generated leading to significant reductions on energy and water consumptions.

At this point, an alternative process for the production of NaOCH$_3$, an alkaline catalyst normally used in biodiesel production was proposed. The suggested configuration consisting on a homogeneous reactive distillation column coupled with a methanol
recovery distillation column (process III) was shown to be economical competitive relatively to the traditional process (II), while safer, simpler to operate, more flexible and with lower raw-materials costs. Furthermore, process III can be easily integrated with biodiesel plants employing this catalyst, resulting in considerable energy and water consumption savings.

Kinetic models were obtained using experimental data from several authors to describe the influence of the operating variables in the rate of the transesterification reaction using homogeneous alkaline and acid catalysis. These models can be used for preliminary process design using systematic methodologies, and to suggest more interesting regions where additional (and more precise) kinetic studies should focus.

In the bioethanol separation system, a design was proposed coupling a liquid-liquid extraction stage with an extractive fermentation, with further ethanol concentration being carried out by pervaporation. This approach can be designed to use less energy comparatively to the traditional separation setups, which involves a more distillation. Further experimental work is needed to characterize the ionic-liquids, perform the optimal design of this separation system and complete the biorefinery plant model.

A mathematical framework to describe the whole soybean biorefinery plant was developed and implemented in AspenPlus®. Simulations indicate that the integration of the biodiesel plant with the catalyst manufacture and the soybean crushing & processing facilities generates significant nominal costs reduction, from $795 to $569 per ton of biodiesel. In addition, the need for fresh water in the biodiesel process is eliminated and the amount of wastewater produced reduced by almost 10%. This model framework is a valuable tool to support further studies including the optimal design of biorefinery plant heat exchanger and mass exchanger networks.

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IETS-ANNEX XI Industry-based biorefineries

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7. PERSPECTIVES FOR THE FUTURE & RECOMMENDATIONS

Given the multi-disciplinary approach to the concept of biorefineries integrated in industrial complexes involving different industrial sectors, which include the integration of bio – with oil refineries, together with CCS options yielding hydrocarbons and/or hydrogen, it is important that biorefinery studies are pursued looking into technology and systems aspects for a better use of energy. The approach should be based on industry needs and applications, combining the knowledge of industrial technologies with energy efficiency and biomass conversion processes.

Industry-based Biorefineries should be a long-standing Annex that could aim at providing a sound basis for the integration of the biorefinery concept in different industrial sectors where biomass is used as resource or biomass based waste is available, which could be used for fuel and/or energy production, also considering opportunities of bio-products generation with added value.

Synergies need to be considered with other Technological Collaboration Programmes, namely the IEA Bioenergy. This collaboration should combine the knowledge of industrial technologies with energy efficiency, along with the biomass conversion processes, looking into the following objectives:

- To provide a global forum for participants to exchange information, disseminate knowledge and lessons learned promoting interaction and collaboration;
- To encourage participants to engage in truly collaborative, value-adding R&D activities and to promote demonstrations;
- To focus research efforts by regularly updating a prioritized list of research needs and knowledge gaps;
- A must to involve industry, communicating progress not only to the industrial sector but also to government representatives and other stakeholders.

IETS-ANNEX XI Industry-based biorefineries
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