Development of integrated lignocellulose biorefinery for co-production of chemicals, transportation fuels, electricity and heat

Overview and first results of the EU FP6 integrated project biosynergy

J.H. Reith

R. van Ree

R. Capote Campos

P. Gutiérrez Gómez

R. R. Bakker

P.J. de Wild

F. Monot

B. Estrine

A.V. Bridgwater

B. Kavalov

Paper prepared for 16th European Biomass Conference & Exhibition, Valencia, Spain, 2-6 June 2008

ECN-M--08-063 June 2008

DEVELOPMENT OF INTEGRATED LIGNOCELLULOSE BIOREFINERY FOR CO-PRODUCTION OF CHEMICALS, TRANSPORTATION FUELS, ELECTRICITY AND HEAT

OVERVIEW AND FIRST RESULTS OF THE EU FP6 INTEGRATED PROJECT BIOSYNERGY

J.H. Reith* 1), R. van Ree 2), R. Capote Campos 3), P. Gutiérrez Gómez 3), R. R. Bakker 2), P.J. de Wild 1), F. Monot 4), B. Estrine 5), A.V. Bridgwater 6), B. Kavalov 7)

1) ECN Biomass, Coal and Environmental Research, Petten, The Netherlands 2) WUR - Agrotechnology and Food Sciences Group, Wageningen, The Netherlands 3) Abengoa Bioenergía Nuevas Tecnologías, Sevilla, Spain 4) IFP, Rueil-Malmaison, France 5) Agro Industrie Recherches et Developpements, Pomacle, France 6) Aston University, Birmingham, United Kingdom 7) Joint Research Centre - Institute for Energy, Petten, The Netherlands.
* corresponding author Hans Reith, ECN Biomass, Coal and Environmental Research, P.O. Box 1, 1755 ZG Petten, The Netherlands, Phone: +31 224 564371, e-mail: reith@ecn.nl

ABSTRACT: The objective of the Integrated Project BIOSYNERGY (2007-2010) is to contribute to the cost-effective use of biomass –especially lignocellulose and residues– by sound techno-economic process development of integrated production of value-added chemicals, transportation fuels and energy from lab-scale to demonstration at pilot-scale. The aim is to develop innovative, fully integrated, synergetic biorefinery concepts, using advanced fractionation and conversion processes, and combining biochemical and thermochemical pathways. One of the objectives is to make the production of biofuels more cost effective by utilisation of all biomass components at maximum added value. Furthermore the project addresses the identification of the most promising biorefinery chains for the EU based on energy efficiency, environmental performance, socio-economic aspects and cost. The project is performed by a consortium comprising 17 partners from industry, research institutes and universities from 10 EU countries and is supported by the European Commission through its Sixth Framework Programme. This paper highlights the objectives and approach of the project and provides an overview of the R&D results to date.

Keywords: biorefining, bio-ethanol, chemicals from biomass

1. INTRODUCTION

Biomass is a versatile resource that can fulfil a substantial share of the growing demand for renewable energy and products. Today biomass is mostly used for generation of electricity and heat, while application as feedstock for renewable transportation fuels is growing rapidly, due to ambitious targets in the EU and elsewhere. The current, 1st generation biofuels are produced from vegetable oils (PPO, biodiesel) and from sugar and starch crops (ethanol). Concern has risen over the net Green House Gas (GHG) mitigation effect of these fuels and other issues such as potential competition with food production [1]. In this context the European Commission is designing environmental and socio-economic criteria for biofuels production.

The use of abundant and low-cost lignocellulosic biomass (grass, wood etc) and waste streams as feedstock for 2nd generation biofuels such as bio-ethanol will enable application at large scale due to the absence of competition with food production and a high net reduction of GHG emissions. The technology development for cellulose ethanol is progressing rapidly [2,3,4]. Increasingly lignocellulosic biomass is also considered as feedstock for chemicals and other products to substitute for petrochemicals [5,6]

An approach to improve both the economics and the ecological benefits of biomass processing is the biorefinery concept i.e. the sustainable processing of biomass into multiple products that are separately marketable. In a biorefinery, a range of biomass types is converted (through an array of processes) into multiple products including transportation fuel e.g. bioethanol, other bio-based products such as solvents, plastics, resins, surfactants, and electricity and heat for internal use and for export.

The Integrated Project BIOSYNERGY aims to use BIOmass for SYNthesis processes (transportation fuels, platform chemicals) and enERGY production (power, CHP) by application of innovative, fully integrated, synergetic biorefinery concepts, using advanced fractionation and conversion processes, and combining biochemical and thermochemical pathways. One of the main project objectives is to enhance the cost effectiveness of biofuels production by utilisation of all biomass components at maximum added value. This paper highlights the objectives and approach of the project and provides an overview of the major R&D results thus far.

2 OBJECTIVES

The use of biomass as feedstock for the production of transportation fuels – and to a lesser extent energy – is still more costly than the use of fossil resources. The aim of the BIOSYNERGY project is to contribute to the cost-effective use of biomass –especially lignocellulose and residues– by sound techno-economic process development of integrated production of value-added chemicals, transportation fuels and energy by process development from lab-scale to demonstration at pilot-scale.

The main scientific and technological objectives of the BIOSYNERGY project are:

- To develop the best thermochemical/(bio-)chemical conversion and fractionation technologies for major side-streams of an ethanol fermentation plant, but also applicable for other wet and dry feedstocks.
- To define the potential of identified platform chemicals for both the (fine) chemical and petrochemical industries.
- To come from lab-scale to pilot-scale processes using techno-economic assessments and clear exploitation guidelines.
- Making the production of biofuels more cost competitive.

3 CONSORTIUM

The project is performed by a consortium comprising 17 partners from industry, research institutes and universities from 10 EU countries, listed below. The project is coordinated by ECN.

1. Energy research Centre of the Netherlands (ECN) – The Netherlands
2. Abengoa Bioenergía Nuevas Tecnologías S.A. (ABNT), Spain
3. Compania Espanola de Petroles S.A. (Cepsa) – Spain
4. DOW Benelux B.V. (Dow) – The Netherlands
5. VTT Technical Research Centre of Finland (VTT) – Finland
6. Aston University (Aston) – United Kingdom
7. WUR Agrotechnology and Food Innovations B.V. (A&F) – The Netherlands
8. Agro Industrie Recherches et Développements (ARD) – France
9. IFP – France
10. Centre for Renewable Energy Sources (CRES) – Greece
11. Biomass Technology Group (BTG) – The Netherlands
12. Joanneum Research Forschungsgesellschaft m.b.H. (JR) – Austria
13. Biorefinery.de (Biorefinery) – Germany
14. Glowny Instytut Gornictwa (GIG) – Poland
15. Joint Research Centre – Institute for Energy (JRC-IE) – The Netherlands
16. Chimar Hellas S.A. (Chimar) – Greece
17. Delft University of Technology (TUD) – The Netherlands

The project budget is EU€ 13.4 million and is supported with a grant up to EU€ 7.0 million by the European Commission through its Sixth Framework Programme under contract number 038994 – (SES6). The project addresses Thematic Priority "Sustainable development, global change and ecosystems". The project started on the 1st of January 2007 and has a duration of 48 months.

4 APPROACH

The biorefinery concept as addressed in this project is one of the main approaches to improve the cost efficiency of biofuels. In the IP BIOSYNERGY particular emphasis is placed on the valorisation of residues from bio-ethanol production. The biomass feedstocks assessed in the project include Distillers Dried Grains with Solubles (DDGS), barley and wheat straw (both raw and pre-treated with steam) and soft wood and hard wood as representatives of major European biomass streams.

The approach of the project includes the following elements:

- Development of advanced technologies for physical/chemical fractionation of biomass feedstock into their composing components for further downstream processing.
- Development of innovative thermo-chemical conversion technologies and advanced biochemical conversion techniques for the processing of feedstock into biomass-derived intermediate products (e.g. butanol, phenolic oils, furfural).
- Designing and developing downstream conversion processes for synthesizing value-added chemicals and fuels from intermediates obtained from the thermochemical and biochemical processing steps.
- Identification of the most promising biorefinery chains for the EU and for specific market sectors based on energy efficiency, environmental performance, socio-economic effects and cost. The project also addresses the integration of biorefinery with conventional petrochemical refineries.
- Implementing and demonstrating technologies that result from the project at pilot scale.
- Integrating the developed technologies in a basic design for an innovative cellulose ethanol based biorefinery process in close collaboration with the 'lignocellulose-to-bioethanol' pilot-plant of Abengoa Bioenergía Nuevas Tecnologías in Salamanca, Spain.
- Training and knowledge dissemination

The work in the project is divided into nine, interrelated Work packages (Table 1).

Table 1. Work packages in the IP Biosynergy.

WP 0 – Management activities
WP 1 – Advanced physical/chemical fractionation
WP 2 – Innovative thermo-chemical conversion
WP 3 – Advanced biochemical conversion
WP 4 – Innovative chemical conversion and synthesis
WP 5 – Conceptual design Biorefinery pilot-plant
WP 6 – Integral biomass-to- products chain design, analysis and optimisation
WP 7 – Demonstration at pilot-scale
WP 8 – Training and knowledge dissemination

5. R&D PROGRESS PER WORK PACKAGE

The project started in January 2007. The objectives and status of the R&D are presented in this section per Work package (WP).

WP 1: Advanced physical / chemical fractionation. Coordinator: WUR Agrotechnology and Food Innovations (A&F), NL.

The subject of this WP is the lab-scale experimental development and optimisation of technologies for physical and chemical pre-treatment and fractionation of biomass into separate C5/C6 sugar and lignin fractions. The C6-sugars will be used for the production of bioethanol, whereas the C5-sugars and lignin fractions will be converted to value-added products making the integrated process more economically profitable and environmentally friendly. This WP also includes work on enzymatic hydrolysis. The R&D progress to date includes:

- Laboratory set-up and establishment of experimental facilities;
- Distribution and full (bio)chemical characterisation of feedstock materials straw, wood and DDGS;
- Literature review of available fractionation technologies and related knowledge;
- Lab scale fractionation experiments on 5 different routes in progress;
- Benchmarks for comparison of the various fractionation pathways defined;
- Start of the work on enzymatic hydrolysis.

WP 2: Innovative thermochemical conversion. Coordinator: Energy research Centre of the Netherlands ECN, NL.

This Work Package aims at the development on lab and bench scale of technologies for (catalytic) staged degasification and pyrolysis for fractionation and conversion of lignin and biomass into chemical intermediates and/or secondary energy carriers. An integral part of the work is the development of high-efficiency, low-cost technologies for separation of intermediates from thermochemically derived, complex product mixtures. The main progress to date includes:

- Delivery of Proof-of-Principle for the staged degasification concept;
- Conversion of various feedstocks to bio-oil using rotating-cone fast pyrolysis technology;
- Elaboration of procedures to improve the quality of pyrolysis bio-oil;
- Assessment of separation technologies for thermo-chemically derived product mixtures.

WP 3: Advanced biochemical conversion. Coordinator: IFP, FR.

This WP focuses on the development of advanced biochemical processes for conversion of sugars and lignin into value-added products or intermediates including higher alcohols, platform chemicals and functional lignin derivates. To date significant advancement has been achieved in the lab-scale experimental work on:

- Acetone-butanol-ethanol (ABE) fermentation;
- Production of fermentation based platform chemicals;
- Production and analysis of lignin derivates;
- Separation of product mixture by Multiphase Rotating disk Contactors.

WP 4: Innovative chemical conversion and synthesis. Coordinator: Agro Industrie Recherches et Développements (ARD), FR

Various promising chemical conversion technologies for the valorisation of C5-sugars, lignin and thermo-chemically derived intermediates are under development at lab-scale in this WP. Furthermore the work addresses design and development of processes for the synthesis of final products from value-added intermediates (furfural, phenols,…). Thusfar the research and experimental work has mainly focussed on the following items:

- Production and characterisation of platform chemicals;
- Lab scale synthesis of products from selected platform chemicals;
- Pentose valorisation as raw materials for surfactants;
- Application of innovative membrane reactor concepts for product recovery.

WP 5: Conceptual design biorefinery validation pilot-plant ABNT in Salamanca, Spain. Coordinator: Abengoa Bioenergía Nuevas Tecnologías S.A. (ABNT), ES.

The goal of this WP is the conceptual design of an innovative biorefinery facility at the existing BCyL cellulose ethanol pilot-plant of Abengoa in Salamanca (Spain). The pilot-plant has a production capacity of 5 Million litres of cellulose ethanol per year. The design for the biorefinery facility will include integrated physical/ chemical fractionation processes coupled to advanced biochemical or (thermo-)chemical conversion processes. The targeted output of the facility includes upgraded bio-products (chemicals and/or materials), refined transportation biofuels as well as power and/or heat. To date the following has been achieved:

- Set-up of an extended component database with physical & chemical properties for process design;
- Preparation of integrated model for the lignocellulose to bio-ethanol process, including scale-up to commercial scale;
- Draft economic model to evaluate different design concepts and scenarios.

WP 6: Integral biomass-to-product chain design, analysis and optimisation. Coordinator: Aston University, UK..

The objective of this WP is to perform a comprehensive (technical, economic, environmental and socio-economic) assessment and optimisation of biorefinery chains from feedstock to end-products. The ultimate goal of this work is to identify the most promising biorefinery chains (in coordination with WP5) within a future European biobased economy, and the possibilities for their integration with conventional oil refineries. The progress achieved so far includes:

- Creation and validation of process synthesis methodology and modelling tool to identify the optimum process chain design and literature review;
- Definition of the main structure of the LCA model;
- Initiation of a biorefinery database.

WP 7: Demonstration at pilot-scale. Coordinator: WUR Agrotechnology and Food Innovations (A&F), NL.

The pilot-scale demonstration in this WP includes the operation of ABNT's bioethanol pilot-plant and other facilities. The aim is to produce representative and market sound samples of bio-based intermediates for the technology development on lab and bench scale in WP's 1-4, and to examine the potential for scaling-up these technologies. The main progress thusfar includes:

- Production, distribution of pre-treated wheat straw;
- Start of the modification of Abengoa's pilot facility;
- Production of 280 kg pyrolysis bio-oil – for downstream technology development – in a fast pyrolysis installation.

WP 8: Training and knowledge dissemination. Coordinator: Joint Research Centre-Institute for Energy (JRC-IE), NL.

The objective of WP8 is to ensure the two-way communication of the project with the outside world. This includes general promotion of project results, exchange of views and information with external stakeholders, training of persons in relevant industries and institutions, dissemination of policy options and recommendations to national and European stakeholders and policy-makers. The results to date include

- establishment of a dedicated project website http://www.biosynergy.eu/
- production of a project brochure and two 6-monthly newsletters; available for download at project website
- preparation of scientific publications [7,8,9]
- organisation of a workshop

On April 17th and 18th 2008 a successful Biosynergy Enlargement and Integration Workshop on biorefineries was organized by JRC-IE in Petten, The Netherlands. The main goal of this workshop was to exchange views and information on the potential of biorefineries in the EU Newest Member States (accession 01.01.2007), EU Candidate Countries and Potential EU Candidate Countries. These countries have been identified as potentially promising for the implementation of the biorefinery concept, considering that on average they have larger land area per capita, a lower level of bioenergy penetration and a higher import dependence on fossil fuels (oil and gas) than the elder EU-15/25 member states. The workshop report will be made available via the BIOSYNERGY website [10].

6 PERSPECTIVES

The work in the project is well underway and shows good progress.

One of the main challenges in the biorefinery field is the need for fully integrated technology development ranging from feedstock supply through conversion into intermediates and down stream processing to final products, while at the same time complying with economic criteria and ecological and socio-economic sustainability criteria. The development clearly requires multidisciplinary input.

Overall, the further development and implementation of the biorefinery approach is expected to increase in order to optimize the use and the added value of available biomass resources.

7 REFERENCES

[1] Daniel De la Torre Uagrte and Lixia He, 2007. Is the expansion of biofuels at odds with the food security of developing countries? Biofuels, Bioprod. Bioref. 1:92-102 (2007).

[2] Henning Jorgensen, Jan Bach Kristensen and Claus Felby, 2007. Review. Enzymatic conversion of lignocellulose into fermentable sugars: challenges and opportunities. Biofuels, Bioprod. Bioref. 1:119-134 (2007)

[3] New Improvements for Ligno-cellulosic Ethanol (NILE). Integrated Project in the 6th Framework Program of the European Union (2006-2009) http://www.nile-bioethanol.org/

[4] February 28, 2007. DOE Selects Six Cellulosic Ethanol Plants for Up to $385 Million in Federal Funding. http://www.doe.gov/news/4827.htm

[5] Birgit Kamm, Patrick Gruber, Michael Kamm (Eds.), 2005. Biorefineries - Industrial Processes and Products. Wiley-VCH, Weinheim. 964 pages. ISBN: 978-3-527-31027-2

[6] Haveren, J. van; Scott, E.L.; Sanders, J.P.M. 2007. Bulk chemicals from biomass. Biofuels Bioproducts and Biorefining 2 (1). - p. 41 - 57.

[7] Mattinen, M.-L., Suortti, T., Gosselink, R., Argyropoulos, D. S., Evtuguin, D., Suurnäkki, A., de Jong, E., and Tamminen, T. (2008). Polymerization of different lignins by laccase, BioRes. 3(2), 549-565.http://www.ncsu.edu/bioresources/BioRes_03/BioRes_03_2_0549_Mattinen_SGAESJT_PolymLignin_Laccase.pdf

[8] P.J. de Wild, H. den Uil, J.H. Reith, J.H.A. Kiel, H.J. Heeres (2008). Biomass Valorisation by Staged Degasification. A new pyrolysis-based thermochemical conversion option to produce value-added chemicals from lignocellulosic biomass. Submitted to the Journal of Analytical and Applied Pyrolysis.

[9] Marcotullio G., Heidweiller H.J., De Jong W. Reaction kinetic assessment for selective production of furfural from C-5 sugars contained in biomass. In preparation.

[10]Website IP Biosynergy http://www.biosynergy.eu/

8 ACKNOWLEDGEMENT

The BIOSYNERGY project is supported by the European Communities through the Sixth Framework Programme for Research and Technological Development (2002 – 2006) with a grant up to 7.0 million € under contract number 038994 – (SES6). The project addresses Thematic Priority "Sustainable development, global change and ecosystems". The project started on the 1st of January 2007 and has a duration of 48 months.