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Development of advanced BiOREFinery schemes to be iNTEGrated into existing industrial (fuel producing) complexes

Final report

Organisation name of lead contractor for this deliverable: ECN

May 2010

Fons Maes BVBA

Dissemination level

PU	Public	**X**
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the Consortium (including the Commission Services)	

Justification

This is the final report of the BIOREF-INTEG Project. BIOREF-INTEG is a ‘Coordination and Support Action Project’ within the framework of the FP7 Programme (Theme Energy). The project is funded by the European Commission from June 2008 until May 2010, with the main objective to develop advanced biorefinery schemes to be integrated into existing industrial (fuel producing) complexes.

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Executive Summary

Introduction

A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, materials and/or chemicals from biomass. By producing multiple products, a biorefinery can take advantage of the differences in biomass components and intermediates and maximise the value derived from the biomass feedstock, and optimise the cost effectiveness of its products.

A biorefinery might, for example, produce one or several low-volume, but high-value chemical products, and low-value, but high-volume, liquid transportation fuels; while generating power and process heat for its own use, and perhaps enough for external sale.

BIOREF-INTEG is a 'Coordination and Support Action Project' within the framework of the FP7 Programme (Theme Energy). The project is funded by the European Commission from June 2008 until May 2010.

The main objective of the project is to develop advanced biorefinery schemes to be integrated into existing industrial (fuel producing) complexes. Several biomass processing sectors have been considered within the BIOREF-INTEG project including sugar/starch (bioethanol), biodiesel, pulp and paper, conventional oil refineries, power production, the food industry and the agrosector. The identification of innovative biorefinery concepts within this project could be beneficial to the aforementioned sectors by significantly increasing the overall economic profitability, and decreasing the overall environmental impact of their conventional processes.

The project is coordinated by the Energy research Centre of the Netherlands, ECN. Other participants involved are:

- **4 SMEs**: ETC (Sweden / forest-based biorefinery), Ten Kate (the Netherlands / high quality fats & proteins), VFT (Belgium / industrial marketing services with focus on renewable resource materials), and Fons Maes BVBA (Belgium / biodiesel);
- **3 industries**: Abengoa Bioenergy New Technologies (Spain / bioethanol), Cehave (the Netherlands / high quality animal feed), and Repsol (Spain / conventional oil refinery);
- **2 universities**: Aston University (United Kingdom), and University of Ghent (Belgium);
- **3 RTD institutes**: VTT (Finland), WUR Food and Biobased Research/A&F (the Netherlands), and Innventia (Sweden / pulp & paper).

The project is conducted by 7 separate but strongly interrelated work packages, as presented in the figure below:

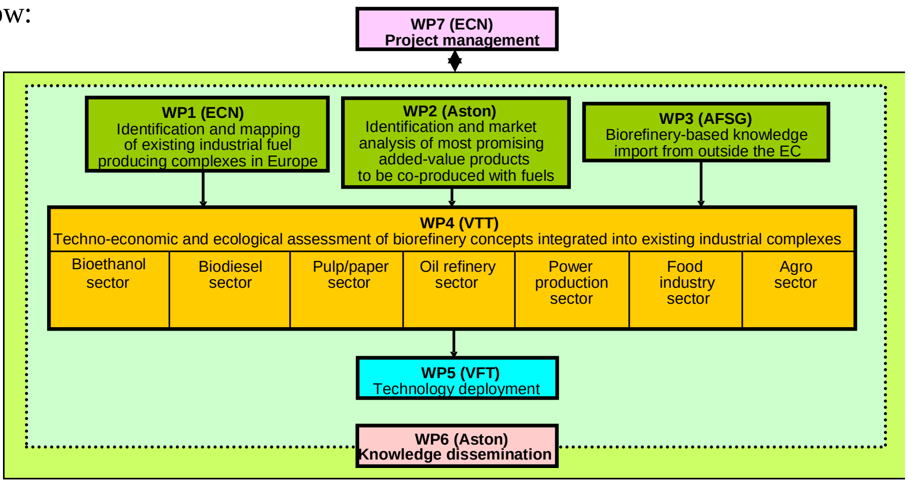

Figure S-1 *Bioref-Integ work packages*

- WP1: Identification of existing industrial (fuel producing) complexes in Europe;
- WP2: Definition of the most promising added value bioproducts;
- WP3: Knowledge import from outside the EC;
- WP4: Integral technical, economic, and ecological system assessments to select the most promising market specific integrated biorefineries;
- WP5: Technology deployment;
- WP6: Knowledge dissemination and training;
- WP7: Project management.

Methodology

A process flow of the Bioref-Integ project is given in Figure S-2.

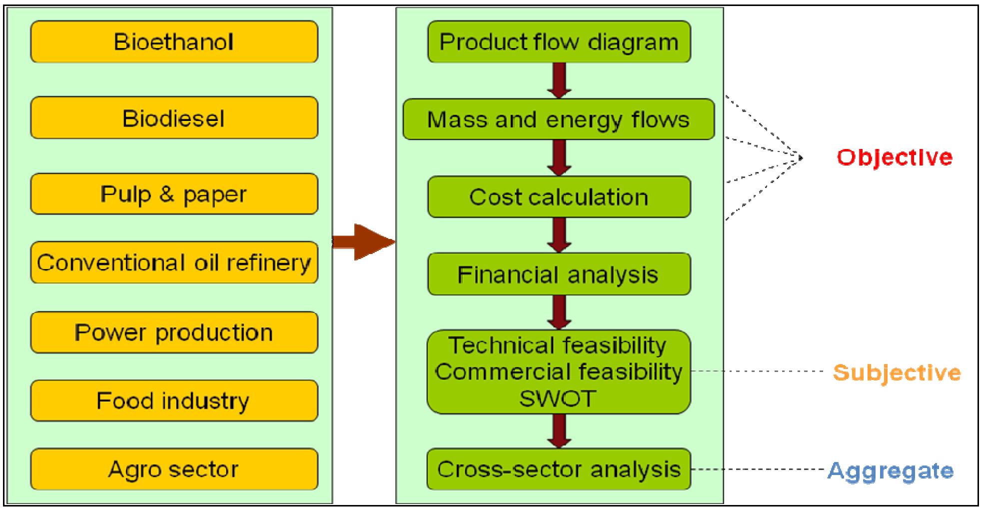

Figure S-2 *Bioref-Integ process flow*

Work package 1

For each considered biomass processing sector, the existing industrial (fuel producing) complexes have been identified for the six partner-related countries (Belgium, Finland, Spain, Sweden, United Kingdom, and the Netherlands). Based on the performed survey, at least one reference case per sector has been defined as a realistic representative of that sector. The reference cases include different feedstocks, such as cereals, oilseed crops, wood, milk, sugar beet, and grass. The cases use different conversion technologies: fermentation, transesterification, anaerobic digestion, combustion, gasification, fluid catalytic cracking and hydrotreating. The reference cases are briefly described, including a block diagram with main overall mass and energy balances (Deliverable 1total, 2009).

Work package 2

A literature analysis has been conducted within the field of biomass-derived products in order to identify current and potential materials and chemicals. The analysis has been based on the composition of the raw materials of the selected reference cases within WP1, i.e. wheat, straw, potatoes, rapeseed, sugar beet, grass, wood, pulp & paper residues, food industry residues and agro residues. More than 300 chemicals have been identified that can be derived from a biorefinery and that are of interest. There is a relatively small number of 'key' chemicals that act as primary sources for families of chemicals and are, therefore, potentially of greater importance. These have a well established presence, well established infrastructure, and well established markets, which have been identified too. A literature and web analysis on current market prices and volumes of the materials and chemicals identified has been carried out. The longer-term potential market developments that directly affect the fu-

ture market volume demand and market price of these products have also been roughly assessed (Deliverable 2total, 2010).

Work package 3

Work on biorefinery views and activities outside the EC have been conducted, comprising the analysis of conference proceedings, seminars, workshops, and websites on biorefinery-related information, including information from the IEA Task 42 on biorefinery. An internal workshop 'Knowledge import from outside EU on advanced biorefineries' was held in January 2009 in Osnabruck, Germany, with invited speakers from Japan, Brazil, and USA, sharing their views on the topic of biorefineries (Deliverable 3total, 2009).

Work package 4

Economic data, regarding the selected reference cases within work package 1, have been gathered by the project partners. These data, together with the data on mass and energy balances of the reference cases, have been used for a techno-economic assessment. In the next step, the results of work packages 1 to 3 have been used to define integrated biorefinery schemes for each selected biomass processing sector.

ECN developed a biorefinery cash flow model for modelling purposes within work package 4. Based on the mass, energy and economic data, the production costs of the main product of each selected sector for both the reference case, as well as for the integrated biorefinery schemes have been calculated (see Figure S-3). Also the IRR (Internal Rate of Return) and the payback time of each case have been determined. The objective is to evaluate to what extent the co-production of the added value products could enhance the economic competitiveness of the main product in the reference cases.

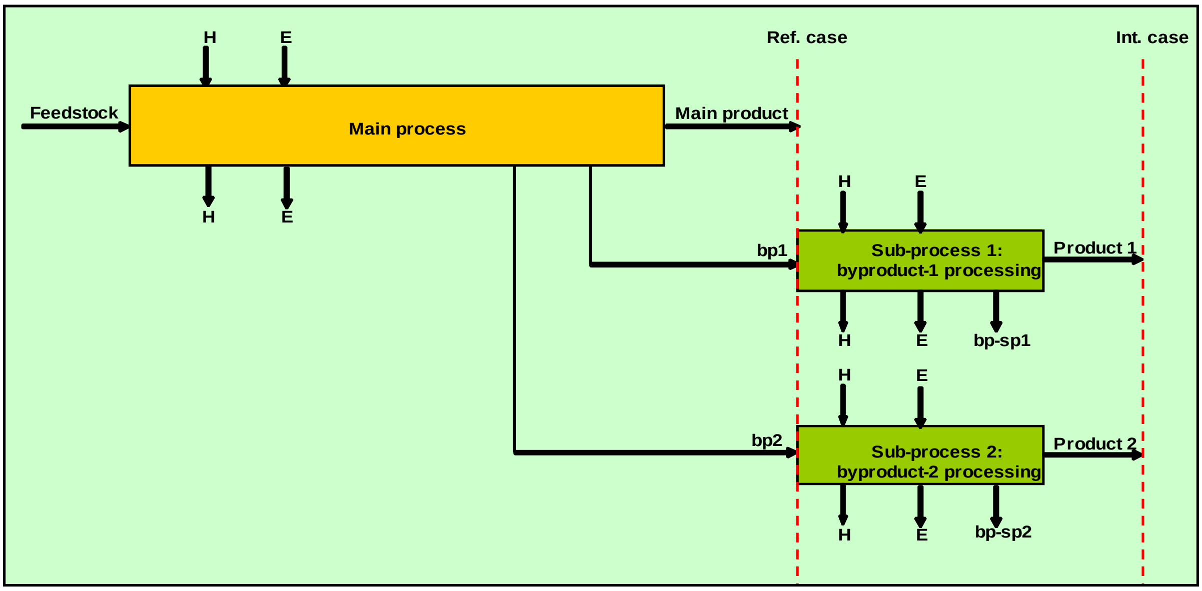

Figure S-3 *Block diagram for the ECN biorefinery cash flow model*

Work package 5

In work package 4, the Consortium has described and evaluated different reference and biorefinery cases for the 7 retained industrial sectors. The results obtained can be considered as 'objective', meaning that they are based on facts and figures gathered amongst sector specialists within and outside the Consortium.

In work package 5, the Consortium has analysed the more 'subjective' aspects of each biorefinery case. There are three steps in doing so:

1. Technical feasibility analysis: how feasible are the proposed processes?
2. Commercial feasibility analysis: are the commercial considerations (market prices, proposed volumes…) realistic?
3. SWOT analysis: what are the strong and weak points of each case? What are the underlying trends influencing potential success?

Next to the evaluation of the subjective aspects, this work package has also covered the cross-sector analysis. By aggregating all the results of different sectors, the Consortium has also tried to draw general conclusions on the addition of biorefinery cases to existing reference processes, including some recommendations (Deliverable 5total, 2010).

To assess the technical and commercial feasibility of the different cases, the Consortium chose to work with a questionnaire.

Statements and weight factors
In a first step, a set of criteria influencing the technical and commercial feasibility was edited as statements. These statements were assessed by the partners of the Consortium according to their importance. Based on the ranking made by the responding partners, each statement received a weight factor (Figure S-4). In both cases, the sum of the weight factors is 50.

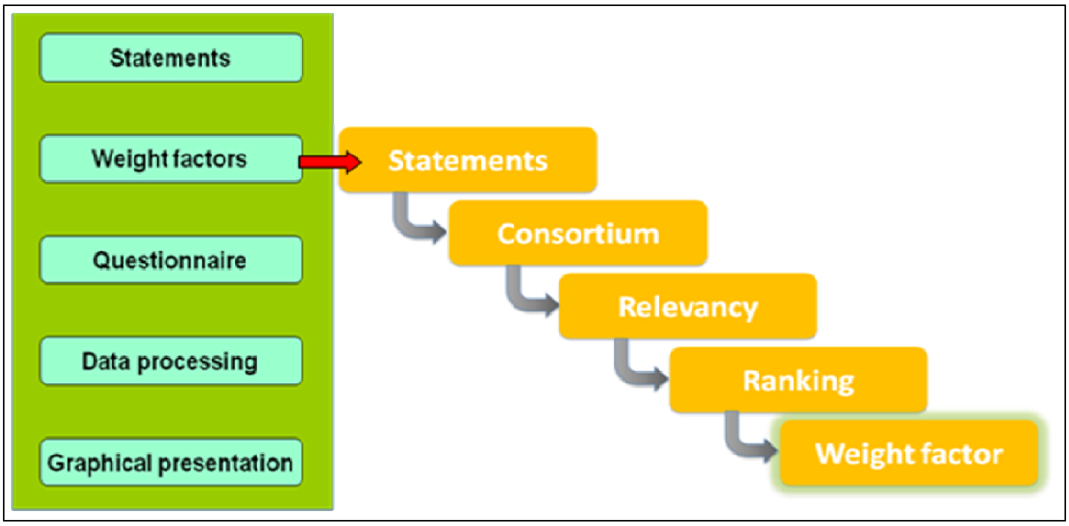

Figure S-4 *Methodology for evaluation of technical and commercial feasibility*

The statements influencing the technical feasibility have been clustered around the process development (required downstream processing, proof-of-concept, up scalability, safety and waste issues) and the applications development of the selected products issued from the biorefinery cases.

Similarly for the commercial feasibility, the statements have been clustered into project characteristics (how many new products/application combinations are proposed), market characteristics, competitive advantages, social & environmental impact, and regulatory impact.
Questionnaire
For each separate case a questionnaire has been filled in. Each statement has been answered as (= the score):

- I agree with the statement ➔ fill in '**2**'
- I'm neutral to the statement (or 'don't know') ➔ fill in '**1**'
- I disagree with the statement ➔ fill in '**0**'

Point of view: all statements were evaluated from the point of view of the state-of-the art of the technology/market, not from the perspective of a particular producer.

Technical and commercial feasibility calculation
The technical and commercial feasibility (TF and CF) has been computed as the sum of the products of the weight factor (WF) and the answer (A) for each statement.

$$\boxed{TF \text{ or } CF = \Sigma(WF_i \text{ x } A_i)}$$

As the sum of the weight factors is 50 and each statement could have a '0, 1 or 2' answer, the technical and commercial feasibility would vary between 0 (all answers are '0' or 'I disagree with the statement') and 100 (all answers are '2' or 'I agree with the statement'). For an easy understanding, the technical and commercial feasibility have been expressed in %.

Aggregate feasibility
For each biorefinery scheme, a questionnaire has been completed by different partners. The final feasibility score could be computed as the average score given by the respondents multiplied by the weight factor.

$$\boxed{TF_{total} \text{ or } CF_{total} = \Sigma_i(\Sigma_j(WF_{ij} \text{ x } A_{ij}) \text{ / \# respondents})}$$

where i = a particular statement and corresponding weight factor
j = a particular respondent

Overall feasibility
By multiplying the technical to the commercial feasibility, the overall feasibility of each biorefinery case could be obtained.

SWOT analysis
Together with the questionnaires on the technical and commercial feasibility, different partners gave also input on the SWOT (strength, weaknesses, opportunities, threats) analysis for each biorefinery scheme.

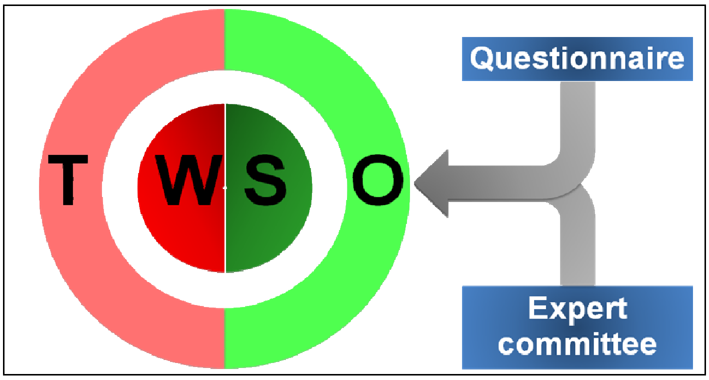

Figure S-5 *SWOT analysis*

All the comments have been brought together, clustered and summarised, to come with a comprehensive list of SWOT items. A lot of attention has been given in putting all comments in the proper SWOT category: S & W referring to the differentiating arguments for a biorefinery concept compared to the reference concept; O & T referring to the external trends affecting the biorefinery schemes. Together with the feasibility analysis, this SWOT completed the 'subjective' evaluation of the biorefinery cases.

Cross-sector analysis
Up to now each biorefinery case has been compared to the reference case and possibly other biorefinery cases within the same sector. In order to find out whether more general conclusions could be drawn out of the Bioref-Integ project, it is necessary to also compare the different sectors to each other.

In a first step, each biorefinery case has been sorted according to the impact on the reference process to a low, medium, or a high impact case.

The major difficulty in comparing the different sectors is that the projects can have a totally different dimension. Also, as no subsidies have been considered in this project (subsidies are indeed highly versatile and different from case to case, from country to country), some projects could have a negative IRR. For all these cases, investment analysis doesn't provide elements to compare projects to each other. In an attempt to 'normalise' the different projects, the Consortium calculated the required sales price and corresponding difference compared to the actual sales price to obtain an IRR of 20%. This has been done for all cases, including the reference cases, and made comparison of projects to each other possible.

Finally, with this additional information on all projects, the Consortium made an attempt to look for correlations and trends between the impact levels / required sales price for IRR @ 20% and the technical and commercial feasibility.

Results

For each of the considered biomass processing sectors 1 to 2 reference case(s), and up to 3 integrated biorefinery cases are defined. This has resulted in 10 reference cases and 14 integrated biorefinery cases, as presented below:

1. Bioethanol: The reference case is a conventional grain-to-ethanol plant, with the following 2 integrated cases:
   1.1. Lactic acid production from C6 sugars;
   1.2. Ethanol production from DDGS via AFEX pretreatment.

2. Biodiesel: A rapeseed-based transesterification process is the reference case, with 2 integrated cases to be:
   2.1. Production of 1,3-propanediol from glycerol;
   2.2. Production of epichlorohydrin from glycerol.

3. Pulp & paper: The reference case is a chemical pulp mill with three integrated cases:
   3.1. Lignin extraction from black liquor;
   3.2. DME production via black liquor gasification (BLG);
   3.3. Ethanol production from softwood pulp.

4. Conventional oil refinery: The reference cases consist of 2 sub processes of a conventional oil refinery: the Fluid Catalytic Cracking process (FCC) and the Hydrodesulfurisation process (HDS). The integrated cases are:
   4.1. Vegetable oil as partial feed of FCC unit;
   4.2. Vegetable oil as partial feed of HDS unit.

5. Power production: The medium-scale reference case is a conventional CHP power plant fuelled with peat or biomass. For large-scale power plant an IGCC fuelled with biomass is considered. The following integrated cases are defined:
   5.1. Pyrolysis integrated in CHP;
   5.2. Chemical recovery in gasification process.

6. Food industry: The reference case for food industry is taken from the dairy sector, more specifically from cheese manufacturing, and the considered integrated case is:
   6.1. Lactic acid production from whey.

7. Agro sector: Finally, two reference cases are considered for the agro sector. The first reference case is a sugar beet refinery. The second reference case is a CHP system based on anaerobic co-digestion of grass and manure. The integrated cases for this sector are:
   7.1. Decentralised sugar beet biorefinery;
   7.2. Grass biorefinery.

The calculated cost of main product in each sector for 10 reference cases and the related 14 integrated biorefinery cases are presented in Table S-1. For comparison, the market price of main product in each sector is presented too. The colour codes used in Table S-1 are:

- **Black** for reference cases;
- **Green** for improvement compared to reference;
- **Red** for worse compared to reference.

Table S-1 *Main product costs and related current market prices*

	Case	Current market price	Main product cost
1	Bioethanol:reference	€800/T	€628//T
1.1	Bioethanol: lactic	€800/T	€368/T
1.2	Bioethanol: AFEX	€800/T	€577/T
2	Biodiesel: reference	€700/T	€726/T
2.1	Biodiesel: PDO	€700/T	€732/T
2.2	Biodiesel: ECH	€700/T	€668/T
3	Pulp & paper: reference	€500/T	€398/T
3.1	Pulp & paper: lignin	€500/T	€347/T
3.2	Pulp & paper: DME	€500/T	€367/T
3.3	Pulp & paper: ethanol	€500/T	€586/T
4a	Refinery: reference FCC	n.a.	n.a.
4.1	Refinery: vegetable oil FCC	n.a.	n.a.
4b	Refinery: reference HDS	n.a.	n.a.
4.2	Refinery: vegetable oil HDS	n.a.	n.a.
5a	Power: reference CHP	€50/MWh	€60/MWh
5.1	Power: CHP/pyrolysis	€50/MWh	€88/MWh
5b	Power: reference gasification	€50/MWh	€74/MWh
5.2	Power: gasification/chemicals	€50/MWh	€48/MWh
6	Food: reference	€2250/T	€1916/T
6.1	Food: lactic	€2250/T	€1441/T
7a	Agro: reference beet	€400/T	€329/T
7.1	Agro: decentralised beet	€400/T	€252/T
7b	Agro: reference grass	€50/MWh	€177/MWh
7.2	Agro: grass biorefinery	€50/MWh	€171/MWh

Figure S-6 shows the technical vs. commercial feasibility for all biorefinery schemes studied in Bioref-Integ. The chart is divided in 4 quadrants with axis crossing set at the average feasibility for the whole set of cases evaluated within this project, being 71%, both for technical as commercial feasibility.
The green area covers the zone with overall feasibility above par, the red below par.

Out of this graph, the following conclusions can be made per sector:

- **Bioethanol:** both retained cases are overall below average feasibility;
- **Biodiesel:** the two cases are in the top right quadrant of high feasibility;
- **Pulp & Paper:** three cases from neutral to above average;
- **Conventional oil refinery:** both cases technically well feasible, but commercially borderline;

- **Power generation:** both cases are underperforming regarding both technical and commercial feasibility;
- **Food:** the retained biorefinery case is below average on both feasibilities;
- **Agro:** this is the only sector with a positive (decentralised beet plant) and negative (grass bio-refinery) case.

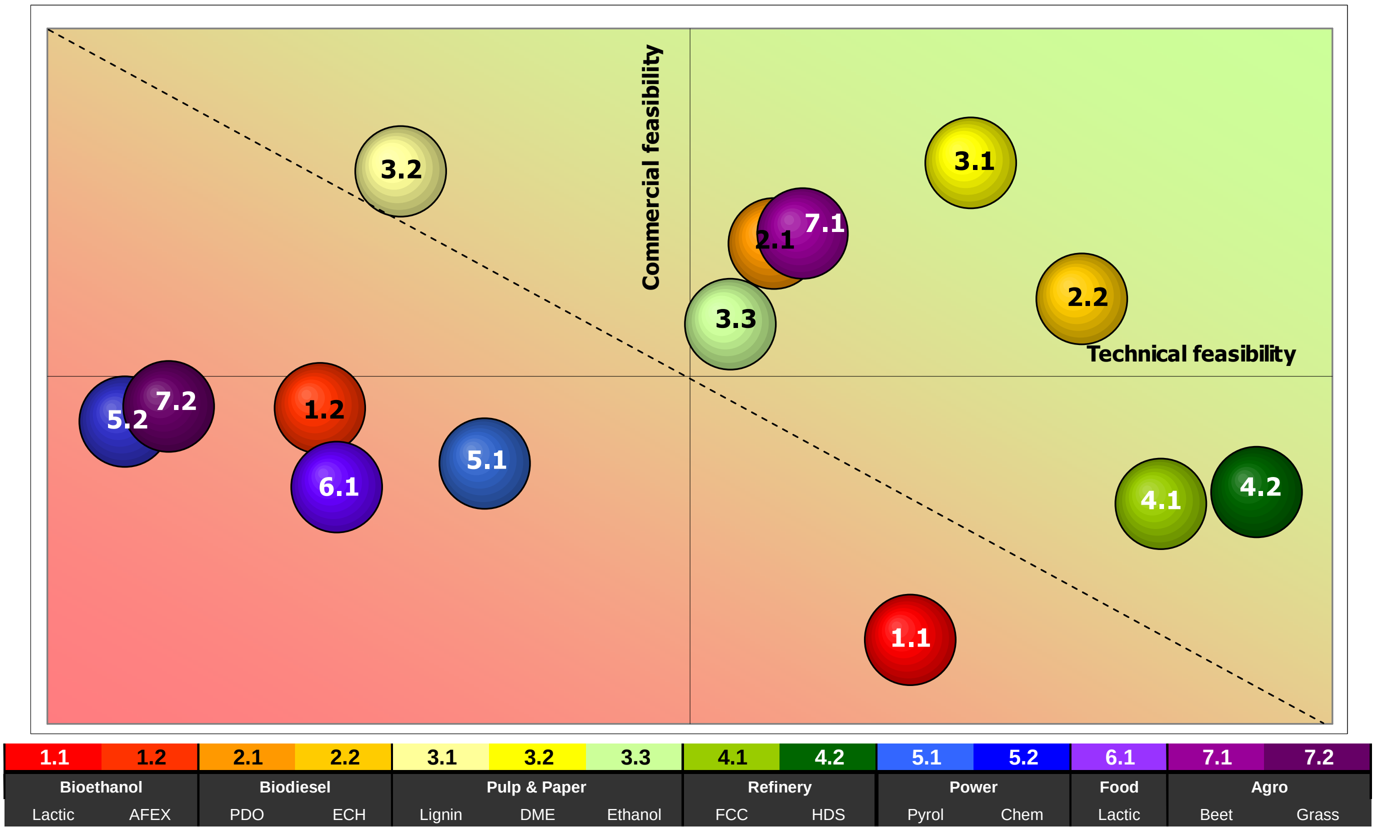

Figure S-6 *Graphical representation of the technical, commercial and overall feasibility*

Table S-2 gives a complete overview of the discriminating criteria for each reference and corresponding biorefinery case(s).

Colour code: Subjective criteria; **Green**: above average
Orange: average
Red: below average
Objective criteria: **Black**: reference cases
Green: improvement compared to reference
Red: worse compared to reference.

The new target sales price for an IRR of 20%, as well as the related percentage change versus market price are presented as objective criteria. For the refinery cases the IRR analysis could not be done, as no extra investment was needed and the operating cost in all cases was higher than the reference case. The required sales price for an IRR of 20% can be considered as a target for sales teams or as a combination of the market price and possible subsidies (subsidies have been discarded in this project due to their regional specificity).

Looking at the projects from this perspective gives a slightly different view than the product cost analysis as done in work package 4, with results presented in Table S-1.

Table S-2 *Subjective and objective criteria*

	Subjective criteria			Objective criteria	
	Impact level	Technical feasibility	Commercial feasibility	New target sales price (for IRR 20%)	% change vs market price (for IRR 20%)
Bioethanol: reference				€775/T ethanol	-3%
Bioethanol: lactic	Low	78%	56%	€545/T ethanol	-32%
Bioethanol AFEX 80	Medium	60%	69%	€710/T ethanol	-11%
Biodiesel: reference				€765/T biodiesel	9%
Biodiesel: PDO	Low	74%	79%	€815/T biodiesel	16%
Biodiesel: ECH	Low	83%	75%	€735/T biodiesel	5%
Pulp & Paper: reference				€630/T pulp	26%
Pulp & Paper: lignin	Low	80%	83%	€550/T pulp	10%
Pulp & Paper: DME	Medium	62%	83%	€710/T pulp	42%
Pulp & Paper: ethanol	Medium	72%	74%	€990/T pulp	98%
Refinery: reference FCC				n.a.	n.a.
Refinery: veg. oil in FCC	High	86%	64%	n.a.	n.a.
Refinery: reference HDS				n.a.	n.a.
Refinery: veg. oil in HDS	High	89%	64%	n.a.	n.a.
Power: reference CHP				€150/MWh	200%
Power: CHP/pyrolyse	High	65%	66%	€185/MWh	270%
Power: reference gasification				€110/MWh	120%
Power: gasification/chemicals	High	53%	68%	€200/MWh	300%
Food: reference				€2.250/T cheese	0%
Food: lactic	Low	60%	65%	€2.050/T cheese	-9%
Agro: reference beet				€430/T sugar	8%
Agro: decentralised beet	High	75%	79%	€385/T sugar	-4%
Agro: reference grass				€280/MWh	460%
Agro: grass biorefinery	High	55%	69%	€330/MWh	560%

Bioethanol:
Both bioethanol cases are an improvement compared to the reference case. This can give an edge to bioethanol producers, to preserve a sustainable profitability in case of fluctuations in feedstock price and crude oil benchmark.

Biodiesel:
For biodiesel, the cases are only dealing with a better –integrated- valorisation of glycerol. Depending on the case, this can improve the overall profitability of a biodiesel plant.

Pulp & Paper:
Here we have a first discrepancy between a simple cost calculation and a targeted investment analysis: the DME case reduces the pulp cost, but the profitability –with the current assumptions- is worse than the reference case.

Power generation:
None of the proposed biorefinery cases are improving the profitability of the reference cases. The targeted investment analysis revealed that even in the gasification/chemicals case, a lower product cost compared to reference case is not sufficient for a profitable process.

The message for thermal treatment of biomass seems to be double:

- Next to electricity, it is recommended to have a valuable outlet for heat;
- Keep it simple! Making the downstream complex does not improve the profitability.

Food:
Simple case, in correlation with the cost analysis.

Agro:
Especially for the grass biorefinery, the recommendations of the Power sector are valid: simplicity is the message. Alternatively, increasing the amount of products extracted from grass at the expense of electricity can also improve the picture.

Based on Table S-2, in many cases there is some concordance between the impact level and the targeted investment analysis: a low impact project tends to be more profitable. There is also a reasonable correlation between the technical feasibility and the economical value. However, there is surprisingly no correlation between the commercial feasibility and the economical value: data may look attractive, but the challenges may be big. This tends to prove the added value to incorporate such a feasibility analysis to more conventional objective return on investment analysis.

Finally, some projects have been clustered and compared to each other, as shown in Table S-3. The project clusters are:

- Co-product valorisation projects: biodiesel: PDO, biodiesel: ECH, pulp & paper: lignin, food: lactic;
- Co-production projects: bioethanol: lactic, pulp & paper: ethanol, agro: decentralised beet;
- Fermentation projects: bioethanol: lactic, bioethanol: AFEX 80, biodiesel: PDO, pulp & paper: ethanol, food: lactic, agro: decentralised beet;
- Power generation projects: CHP/pyrolysis, gasification/chemicals, grass biorefinery;
- Thermal treatment projects: pulp & paper: DME, power: reference CHP, power: CHP/pyrolysis, power: reference gasification, power: gasification/chemicals;
- Legislation-driven projects: refinery: vegetable oil in FCC, refinery: vegetable oil in HDS.

The first three clusters of projects are mostly low impact projects, have average or higher technical and commercial feasibility, as well as a good economical value. On the other hand, the last three clusters of projects are mostly high impact projects, have lower to average technical and commercial feasibility, as well as a poor economical value. In case of legislation-driven projects, both selected projects have a high technical feasibility. Commercial feasibility however is below par, fully explained by the higher cost and the lack of technical benefits (as perceived by some respondents). This score has to be put into the right perspective: our model gives a lower weight to legislative support compared to price and technical benefits. Seen the directive character of the legislative support for these projects, this should be opposite.

Table S-3 *Cross-sector overview against average*

Project type	Impact level	Technical feasibility	Commercial feasibility	Return on investment
Co-product valorisation	Low	Higher	Higher	Higher
Co-production	Low/Med/High	Higher	Average	Higher
Fermentation	Low/Med	Average	Average	Higher
Power generation	High	Lower	Average	Lower
Thermal treatment	Med/High	Lower	Lower	Lower
Legislation-driven	High	Higher	Lower	Lower

Conclusions

- 366 existing industrial (fuel producing) complexes in partner-related countries have been identified, and 10 market-specific reference cases have been defined.
- Based on the results of WP1, WP2, and WP3, 14 integrated biorefinery cases for 7 considered biomass processing sectors have been defined within WP4.
- Integral technical and economic system assessments of defined biorefinery schemes have been performed within WP4.
- In WP5 the Consortium tried to analyse the different biorefinery cases according to both objective (profitability measurement) and subjective (technical and commercial feasibility; SWOT analysis) criteria.
- The technical and commercial feasibility, as well as the SWOT analysis were measured by a questionnaire filled in by experts within the Consortium.
- Regarding Technical Feasibility, major deviation from the average are related to process development (proof-of-concept, scalability…). Application development (referencing new products in the market) are mostly considered as less critical.
- Concerning the Commercial Feasibility, not surprising, the tangible competitive advantages (cost, price, technical benefits) are key success factors. The other key determinant, the perception of the products, processes… by the consumers is generally speaking scoring rather high for all projects. A good point for 'bio-based economy' projects as studied in Bioref-Integ! But this makes the perception criteria less discriminative for the different projects.
- The objective criteria used are related to investment analysis. In WP5 we proposed a 'targeted investment analysis'. In a similar IRR calculation model as used in WP4, we computed the required sales price for the main product to reach an IRR = 20%. This gives a better perspective to compare the different projects to each other.
- Another new parameter is the 'impact level': how deep will a biorefinery concept affect the reference process. We clustered the biorefinery projects in 3 groups: low, medium and high impact.
- Out of our study, there is a positive correlation between the technical feasibility and the economical value (measured as targeted sales price for IRR=20%). Low impact projects are also leading to a higher economical value.
- The commercial feasibility has no correlation with the economical value. It should be considered together with financial analysis to make an educated decision on biorefinery schemes.
- Projects involving thermal treatment of biomass (CHP, pyrolysis, gasification) are clearly still immature and not yet industrially feasible. This appears clearly in a low technical feasibility and a negative economic value.
- Power generation (electricity from biomass) projects also have a negative evaluation (subsidies were not taken into account!). This is of course in line with the comments on thermal treatment, as frequently the same technology is used. The message to electricity-from-biomass projects is: find a value application for heat and … keep it simple or … change focus and produce products from biomass.
- Biorefinery projects that have the potential to improve the economics of reference cases are low impact projects (no significant impact on the reference process), fermentation projects and co-product valorisation projects. These projects frequently also have an above average technical and commercial feasibility score.
- Finally, legislation is an important factor, driving the use of bio-based feedstock (see biofuel directive) or supporting directly biorefineries by several subsidy incentives.

Bioref-Integ newsletters, public reports and presentations

Deliverable 1total (http://www.bioref-integ.eu/publications/): *Identification and mapping of existing fuel producing industrial complexes in Europe*. Deliverable lead contractor: ECN, January 2009

Deliverable 2total (http://www.bioref-integ.eu/publications/): *Identification and market analysis of most promising added-value products to be co-produced with the fuels.* Deliverable lead contractor: Aston University, May 2010

Deliverable 3total (http://www.bioref-integ.eu/publications/): *Biorefinery-based Knowledge Import from outside the EC*. Deliverable lead contractor: WUR Food and Biobased Research (A&F), December 2009

Deliverable 5total (http://www.bioref-integ.eu/publications/): *Technology deployment plan.* Deliverable lead contractor: VFT, April 2010

Final report (http://www.bioref-integ.eu/publications/): *Development of advanced biorefinery schemes to be integrated into existing industrial (fuel producing) complexes.* Deliverable lead contractor: ECN, May 2010

Internal Workshop (presentations: http://www.bioref-integ.eu/publications/): *Knowledge Import from outside EU on Advanced Biorefineries, 29th January 2009, Osnabruck, Germany*

Public Workshop (Presentations: http://www.bioref-integ.eu/publications/): *Preliminary results assessments and innovative biorefinery concept*. 2nd December 2009, Solihull, UK

Bioref-Integ Seminar on final project results (Presentations: http://www.bioref-integ.eu/publications/). 9th June 2010, Düsseldorf, Germany

Biorefinery Researcher, Issue 01, December 2008

Biorefinery Researcher, Issue 02, June 2009

Biorefinery Researcher, Issue 03, November 2009

Biorefinery Researcher, Issue 04, May 2010

1. Introduction

A biorefinery is a facility that integrates biomass conversion processes and equipment to produce fuels, power, materials and/or chemicals from biomass. By producing multiple products, a biorefinery can take advantage of the differences in biomass components and intermediates and maximise the value derived from the biomass feedstock, and optimise the cost effectiveness of its products.

A biorefinery might, for example, produce one or several low-volume, but high-value chemical products, and low-value, but high-volume, liquid transportation fuels; while generating power and process heat for its own use, and perhaps enough for external sale.

1.1 Bioref-Integ: Objective, Consortium, and Work Packages

BIOREF-INTEG is a 'Coordination and Support Action Project' within the framework of the FP7 Programme (Theme Energy). The project is funded by the European Commission from June 2008 until May 2010.

The main objective of the project is to develop advanced biorefinery schemes to be integrated into existing industrial (fuel producing) complexes. Several biomass processing sectors have been considered within the BIOREF-INTEG project including sugar/starch (bioethanol), biodiesel, pulp and paper, conventional oil refineries, power production, the food industry and the agrosector. The identification of innovative biorefinery concepts within this project could be beneficial to the aforementioned sectors by significantly increasing the overall economic profitability, and decreasing the overall environmental impact of their conventional processes.

The project is coordinated by the Energy research Centre of the Netherlands, ECN. Other participants involved are:

- **4 SMEs**: ETC (Sweden / forest-based biorefinery), Ten Kate (the Netherlands / high quality fats & proteins), VFT (Belgium / industrial marketing services with focus on renewable resource materials), and Fons Maes BVBA (Belgium / biodiesel);
- **3 industries**: Abengoa Bioenergy New Technologies (Spain / bioethanol), Cehave (the Netherlands / high quality animal feed), and Repsol (Spain / conventional oil refinery);
- **2 universities**: Aston University (United Kingdom), and University of Ghent (Belgium);
- **3 RTD institutes**: VTT (Finland), WUR Food and Biobased Research/A&F (the Netherlands), and Innventia (Sweden / pulp & paper).

The project is conducted by 7 separate but strongly interrelated work packages, as presented in Figure 1-1:

- WP1: Identification of existing industrial (fuel producing) complexes in Europe;
- WP2: Definition of the most promising added value bioproducts;
- WP3: Knowledge import from outside the EC;
- WP4: Integral technical, economic, and ecological system assessments to select the most promising market specific integrated biorefineries;
- WP5: Technology deployment;
- WP6: Knowledge dissemination and training;
- WP7: Project management.

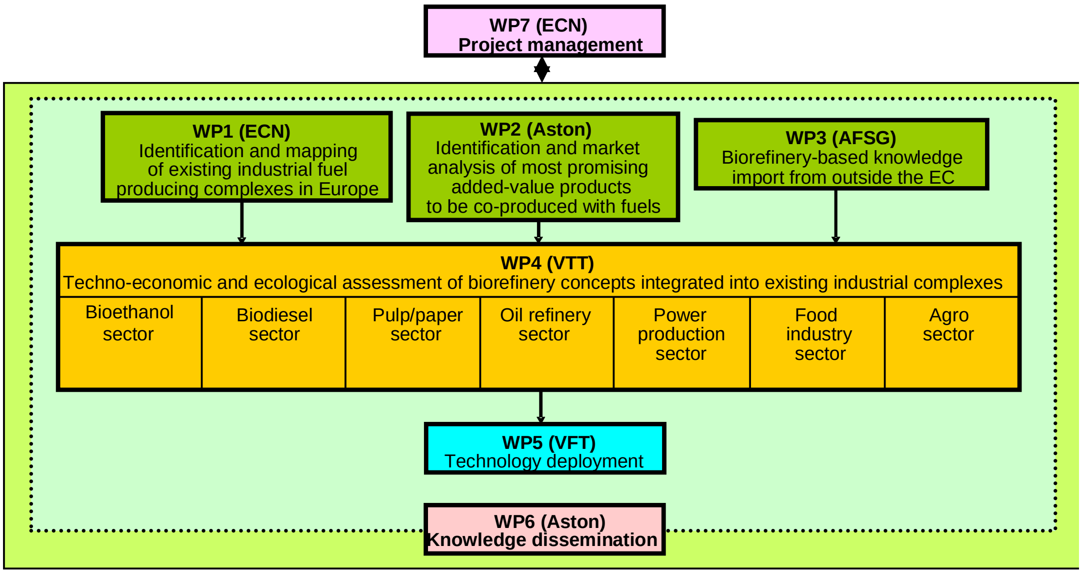

Figure 1-1 *Bioref-Integ work packages*

1.2 Methodology

1.2.1 Work package 1

For each considered biomass processing sector, the existing industrial (fuel producing) complexes have been identified for the six partner-related countries (Belgium, Finland, Spain, Sweden, United Kingdom, and the Netherlands). Based on the performed survey, at least one reference case per sector has been defined as a realistic representative of that sector. The reference cases include different feedstocks, such as cereals, oilseed crops, wood, milk, sugar beet, and grass. The cases use different conversion technologies: fermentation, transesterification, anaerobic digestion, combustion, gasification, fluid catalytic cracking and hydrotreating. The reference cases are briefly described, including a block diagram with main overall mass and energy balances.

1.2.2 Work package 2

A literature analysis has been conducted within the field of biomass-derived products in order to identify current and potential materials and chemicals. The analysis has been based on the composition of the raw materials of the selected reference cases within WP1, i.e. wheat, straw, potatoes, rapeseed, sugar beet, grass, wood, pulp & paper residues, food industry residues and agro residues. More than 300 chemicals have been identified that can be derived from a biorefinery and that are of interest. There is a relatively small number of 'key' chemicals that act as primary sources for families of chemicals and are, therefore, potentially of greater importance. These have a well established presence, well established infrastructure, and well established markets, which have been identified too. A literature and web analysis on current market prices and volumes of the materials and chemicals identified has been carried out. The longer-term potential market developments that directly affect the future market volume demand and market price of these products have also been roughly assessed.

1.2.3 Work package 3

Work on biorefinery views and activities outside the EC have been conducted, comprising the analysis of conference proceedings, seminars, workshops, and websites on biorefinery-related information, including information from the IEA Task 42 on biorefinery. An internal workshop 'Knowledge import from outside EU on advanced biorefineries' was held in January 2009 in Osnabruck, Germany, with invited speakers from Japan, Brazil, and USA, sharing their views on the topic of biorefineries.

1.2.4 Work package 4

Economic data, regarding the selected reference cases within work package 1, have been gathered by the project partners. These data, together with the data on mass and energy balances of the reference cases, have been used for a techno-economic assessment. In the next step, the results of work packages 1 to 3 have been used to define integrated biorefinery schemes for each selected biomass processing sector.

ECN developed a biorefinery cash flow model for modelling purposes within work package 4. Based on the mass, energy and economic data, the production costs of the main product of each selected sector for both the reference case, as well as for the integrated biorefinery schemes have been calculated (see figure below). Also the IRR (Internal Rate of Return) and the payback time of each case have been determined. The objective is to evaluate to what extent the co-production of the added value products could enhance the economic competitiveness of the main product in the reference cases.

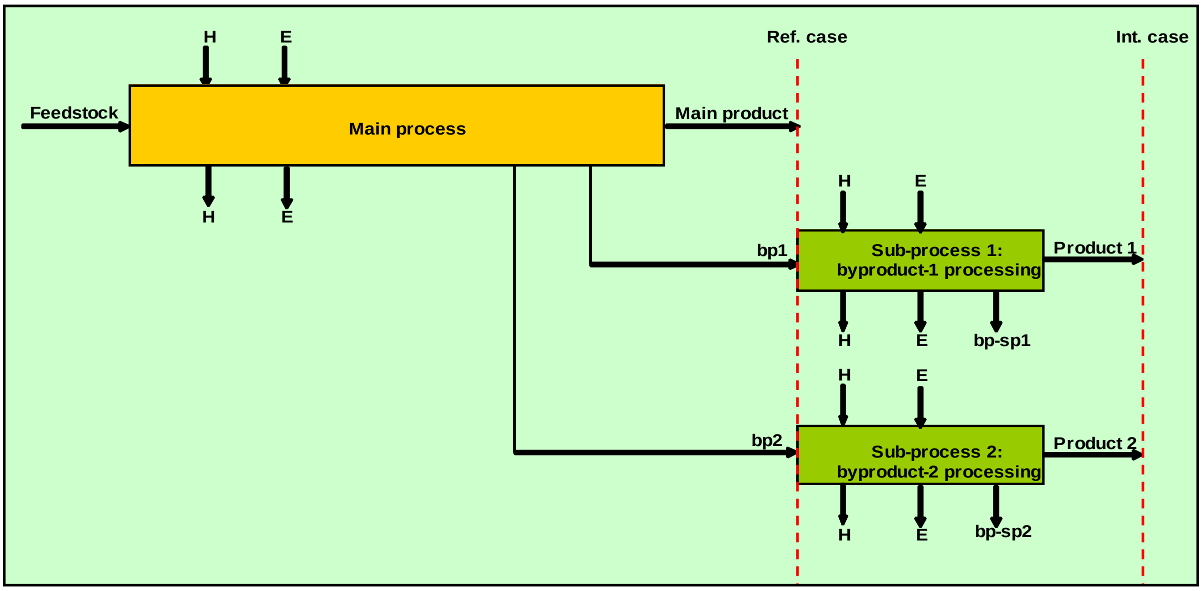

Figure 1-2 *Block diagram for the ECN biorefinery model*

1.2.5 Work package 5

In work package 4, the Consortium has described and evaluated different reference and biorefinery cases for the 7 retained industrial sectors. The results obtained can be considered as 'objective', meaning that they are based on facts and figures gathered amongst sector specialists within and outside the Consortium.

In work package 5, the Consortium has analysed the more 'subjective' aspects of each biorefinery case. There are three steps in doing so:

1. Technical feasibility analysis: how feasible are the proposed processes?
2. Commercial feasibility analysis: are the commercial considerations (market prices, proposed volumes…) realistic?
3. SWOT analysis: what are the strong and weak points of each case? What are the underlying trends influencing potential success?

Next to the evaluation of the subjective aspects, this work package has also covered the cross-sector analysis. By aggregating all the results of different sectors, the Consortium has also tried to draw general conclusions on the addition of biorefinery cases to existing reference processes, including some recommendations.

1.2.5.1 Technical and commercial feasibility

To assess the technical and commercial feasibility of the different cases, the Consortium chose to work with a questionnaire.

Statements and weight factors

In a first step, a set of criteria influencing the technical and commercial feasibility was edited as statements. These statements were assessed by the partners of the Consortium according to their importance. Based on the ranking made by the responding partners, each statement received a weight factor. In both cases, the sum of the weight factors is 50.

The statements influencing the technical feasibility have been clustered around the process development (required downstream processing, proof-of-concept, up scalability, safety and waste issues) and the applications development of the selected products issued from the biorefinery cases. The process development statements account for 2/3 of the total weight.

Similarly for the commercial feasibility, the statements have been clustered into project characteristics (how many new products/application combinations are proposed), market characteristics, competitive advantages, social & environmental impact and regulatory impact. The competitive advantage and the social & environmental impact are the main issues. This seems logic as a commercial success depends highly on objective benefits (competitive advantage) and the perception of the product by customers/consumers (social & environmental impact).

The lists of criteria with respective weight factor are shown in Table 1.1 and 1.2.

Table 1-1 *Technical feasibility statements and respective weight factors*

Technical feasibility statements	Weight factor
Process development	
The integrated concept does not require significant downstream processing	7
All steps of the integrated concept are well identified	7
Required technologies are already developed for the targeted products	6
Required technologies are proven on industrial scale for the targeted products	6
Process does not require toxic or hazardous auxiliaries	4
The integrated concept does not generate additional waste that has to be treated	4
Application development	
Most of the selected applications are already existing	6
Products can be used in most of the selected applications	3
Products are referenced in most of the selected applications	4
Secondary products are referenced in the applications	3

Definitions:

- *'Integrated concept':* one of the concepts described in work package 4 (other than the reference case);
- *'Product(s)':* all products made additionally to those in the reference case; includes energy and waste as well;
- *'Secondary products':* products generated inevitably by producing main product(s);
- *'Auxiliaries':* processing aids needed to come to the product(s) (like solvents, enzymes, reagents…);
- *'Downstream processing':* all process steps needed to come to the final product(s);
- *'Application':* field of usage of the product(s);
- *'LCA positive':* the concept reduced greenhouse gas emissions, energy consumption, use of hazardous auxiliaries…compared to the reference process.

Table 1-2 *Commercial feasibility statements and respective weight factors*

Commercial feasibility statements	Weight factor
Project characteristics	
The integrated concept is leading to 1 new product	1
The product(s) can be used in several applications/markets	1
Market characteristics	
The integrated project addresses existing product/market combinations	4
The addressed markets are innovative (= open for new products/concepts)	2
The targeted markets are large enough to absorb the foreseen volumes	4
Competitive advantage	
Introduction of the new product(s) will lead to an economical benefit for the user	5
The new product(s) have functional benefits	5
There are specific benefits related to the integrated concept compared to the conventional processes	4
Social & environmental impact	
The new product(s) is an alternative to fossil-based products	3
The integrated concept is not in competition with food supply	2
The integrated concept does not require large quantities of fresh water	2
The integrated concept is leading to additional renewable energy production	3
The integrated concept is 'LCA positive'	4
The integrated concept improves the European competitive position in a global market	3
Regulatory impact	
There are no regulatory barriers affecting the market introduction of the product(s)	3
There is a supporting EU directive promoting the integrated concept	4

Questionnaire

For each separate case a questionnaire has been filled in.

Each statement has been answered as (= the score):

- I agree with the statement ➔ fill in '**2**'
- I'm neutral to the statement (or 'don't know') ➔ fill in '**1**'
- I disagree with the statement ➔ fill in '**0**'

Point of view: all statements were evaluated from the point of view of the state-of-the art of the technology/market, not from the perspective of a particular producer.

The limited choice between 0, 1 and 2 as possible answer has the advantage that the respondent has to make an 'educated choice'.

Technical and Commercial feasibility calculation

The technical and commercial feasibility (TF and CF) has been computed as the sum of the products of the weight factor (WF) and the answer (A) for each statement.

$$\text{TF or CF} = \Sigma(WF_i \times A_i)$$

As mentioned, the sum of the weight factors is 50 and each statement could have a '0, 1 or 2' answer. Hence, the technical and commercial feasibility varied between 0 (all answers are '0' or 'I disagree with the statement') and 100 (all answers are '2' or 'I agree with the statement'). For an easy understanding, the technical and commercial feasibility have been expressed in %.

Aggregate feasibility
For each biorefinery scheme, a questionnaire has been completed by different partners. The final feasibility score could be computed as the average score given by the respondents multiplied by the weight factor.

$$TF_{total} \text{ or } CF_{total} = \Sigma_i(\Sigma_j(WF_{ij} \text{ x } A_{ij}) / \text{\# respondents})$$

where i = a particular statement and corresponding weight factor
j = a particular respondent

Depending on the sector, 3 to 6 partners completed a questionnaire.

Overall feasibility
By multiplying the technical to the commercial feasibility, the overall feasibility of each biorefinery case could be obtained.
Graphical representation
For a visual impression on the feasibility, a graphical representation has been proposed (Figure 1-3). On one chart, the technical feasibility is represented against the commercial feasibility. The chart is divided in 4 quadrants with axis crossing set at the average feasibility for the whole set of projects, evaluated within this project. The green area covers the zone with overall feasibility above par, the red below par.

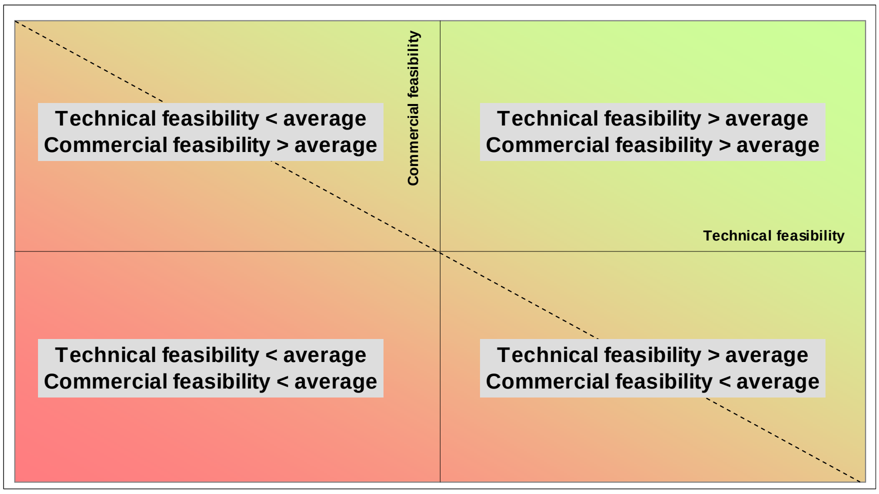

Figure 1-3 *Graphical framework for project feasibility*

1.2.5.2 SWOT analysis

Together with the questionnaires on the technical and commercial feasibility, different partners gave input on the SWOT (strength, weaknesses, opportunities, threats) analysis for each biorefinery scheme.

All the comments have been brought together, clustered and summarised, to come with a comprehensive list of SWOT items. A lot of attention has been given in putting all comments in the proper SWOT category: S & W referring to the differentiating arguments for a biorefinery concept compared to the reference concept; O & T referring to the external trends affecting the biorefinery schemes. Together with the feasibility analysis, this SWOT completed the 'subjective' evaluation of the biorefinery cases.

1.2.5.3 Cross-sector analysis

Up to now each biorefinery case has been compared to the reference case and possibly other biorefinery cases within the same sector. In order to find out whether more general conclusions could be

drawn out of the Bioref-Integ project, it is necessary to also compare the different sectors to each other.

Impact level
In a first step, each biorefinery case has been sorted according to the impact on the reference process to a low, medium, or a high impact case.

Δ sales price for Internal Rate of Return at 20%
The major difficulty in comparing the different sectors is that the projects can have a totally different dimension. Also, as no subsidies have been considered in this project (subsidies are indeed highly versatile and different from case to case, from country to country), some projects could have a negative IRR. For all these cases, investment analysis doesn't provide elements to compare projects to each other.

In an attempt to 'normalise' the different projects, the Consortium calculated the required sales price and corresponding difference compared to the actual sales price to obtain an IRR of 20%. This has been done for all cases, including the reference cases, and made comparison of projects to each other possible.

Correlation analysis
With this additional information on all projects, the Consortium made an attempt to look for correlations and trends between the impact levels / required sales price for IRR @ 20% and the technical and commercial feasibility.

1.3 Report outline

For each considered biomass processing sector, the reference case(s), as well as the related biorefinery scheme(s) are described and evaluated in separate chapters (chapter 2 to chapter 9). The results of portfolio scan of integrated biorefineries are presented in chapter 10. Finally, the conclusions are presented in chapter 11.

2. Integration of different biorefinery concepts into existing bioethanol plants

2.1 Introduction

The objective of Bioref-Integ is the study and analysis of the integration of advanced Biorefinery concepts into existing industrial facilities in order to evaluate the economic and environmental feasibility of the process schemes defined.

Different market sectors are being considered within Bioref-Integ:

- Bioethanol sector
- Biodiesel sector
- Pulp/paper
- Conventional oil refinery
- Power production
- Food industry
- Agro sector

In this section, the work related to the Bioethanol Sector is presented.

2.2 Reference case

A conventional grain-to-ethanol plant has been chosen as reference case to represent the Bioethanol sector. The size of the industrial plants already existing, as well as the raw materials that they employ and the main product they produce make any of them suitable for representing the Bioethanol sector.

A block diagram for the production of ethanol from grain through the fermentation of sugars is offered in Figure 2-1.

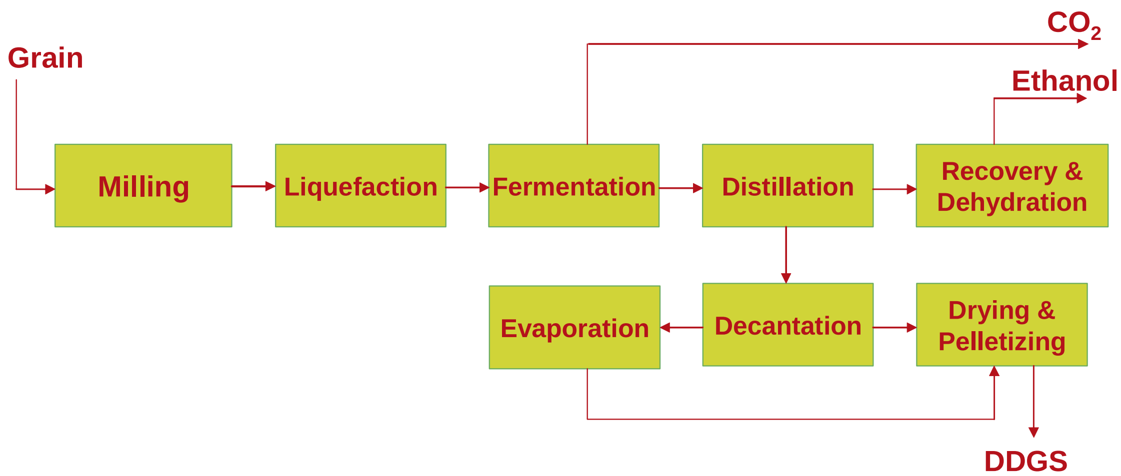

Figure 2-1 *Block diagram for a conventional grain-to-ethanol process via fermentation of sugars*

First of all, grain is milled until flour with determined particle distribution is obtained and afterwards mixed with process water to obtain slurry.

The slurry is heated and sent to the cooking step, where the mixture is held for a determined time. During the cooking process, the starch in the flour starts to become physically and chemically prepared for fermentation, since the hydration of the starch granules facilitates the penetration of enzymes for hydrolysis of starch in subsequent steps. After cooking, the mixture is cooled and liquefaction then takes place. The resulting mixture is cooled down before saccharification, where enzymes break down the starch into short chain. Finally, the mixture is pumped into the fermentation tanks.

Once inside the fermentation tanks, transformation of glucose into ethanol is carried out through alcoholic fermentation by the yeast *Saccharomyces cerevisiae*:

$$\underset{\text{Glucose}}{C_6H_{12}O_6} + \text{S. cerevisiae} \longrightarrow \underset{\text{Ethanol}}{2C_2H_5OH} + 2CO_2$$

As a result of the fermentation process, a mixture containing ethanol, not fermented solids from grain and yeast is obtained. Purification of ethanol takes place by means of distillation and dehydration. As a result, 99% pure ethanol is obtained. Outsourced wine alcohol is purified on-site by this process. During ethanol recovery a solid by-product is obtained, which is dried and pelletised to form DDGS.

A summary of the global mass and energy balance for the reference case is offered in Table A-1. Only main streams are included. Ethanol from wine alcohol is not included.

2.3 Integrated biorefinery cases

Based on the results of WP1, WP2 and WP3, two different biorefinery concepts to be integrated into the existing grain-to-ethanol facility have been defined within WP4 of Bioref-Integ. A description of each integrated case is offered in this section.

2.3.1 Sugars to lactic acid instead of ethanol

The first integrated biorefinery scheme based on an existing ethanol facility consists of production of lactic acid from sugars obtained from the main process. After liquefaction, part of the stream which contains mainly C6-sugars is sent to the lactic acid process and the rest of the stream is directed to the sugars fermentation unit to produce ethanol, which is the main product in this biorefinery case. Figure 2-2 below shows the block diagram for the whole integrated biorefinery concept.

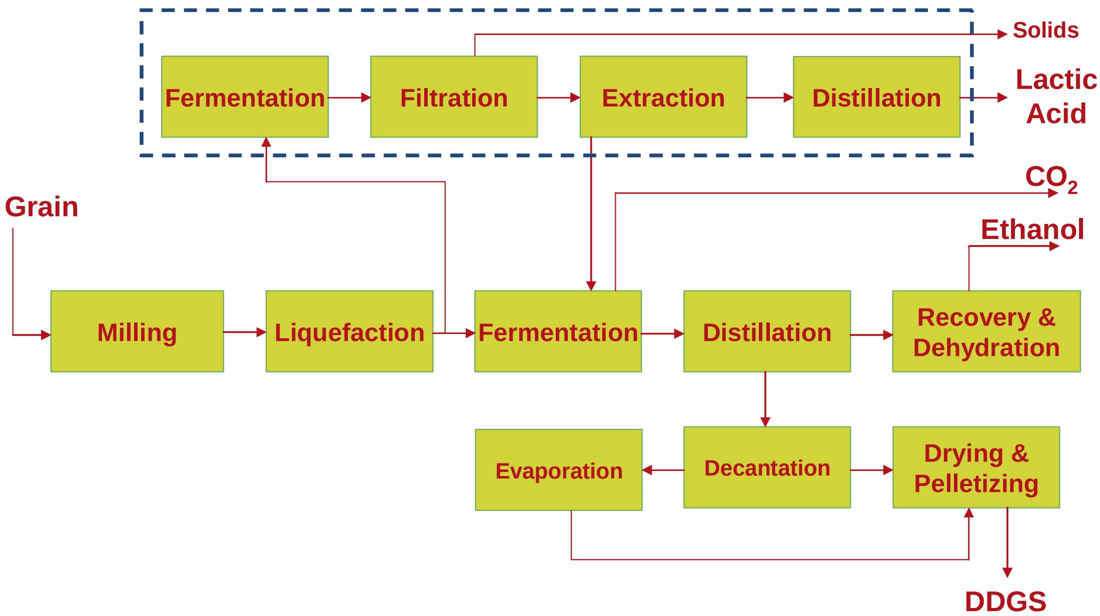

Figure 2-2 *Integrated case I: Lactic acid production from starch sugars*

Lactic acid can be manufactured by chemical synthesis or by carbohydrate fermentation. The latter is usually preferred because there are some problems connected to chemical synthesis. For instance, material cost increases and environmental contamination problems (Park *et al.*, 2005), which can be avoided by means of biological conversion processes. In addition, chemical synthesis produces a racemic mixture consisting of equal amounts of D-lactic acid and L-lactic acid, whereas the use of micro organisms in a biological process enables selective production of D-lactic acid or L-lactic acid (depending on the strain applied), each of which offers different applications.

L-lactic acid is preferably used in cosmetic or food industries, because the D-enantiomer is not metabolised in the body. Likewise, pure lactic acid can be used for preparation of plastic components such as polylactic acid (Young *et al.*, 2005).

Based on the advantages of the biological process in comparison with chemical synthesis, the first one was chosen for design in this project. A brief description of the process taking place in this concept is offered below.

As seen in Figure 2-2, sugars leaving the cooker are split so that 80% of the sugar stream is sent to ethanol production and 20% is converted to lactic acid via fermentation[1].

The fermentation process is carried out by using the *Lactobacillus lactis* bacteria. The choice of organism primarily depends on the carbohydrate to be fermented, and *Lactobacillus lactic* can ferment glucose, which is the main carbohydrate in the feed stream. Transformation takes place in a range of temperatures between 32-38°C, most preferably at around 35°C. As feed stream coming from liquefaction arrives in this range of temperature, it is not necessary to manipulate it. Nevertheless, pH should be at approximately 4.5, so sulphuric acid is added before the lactic acid fermentation stage in order to reach this pH value. The reactions that occur in the fermentor are described below (Eyal *et al.*, 2001):

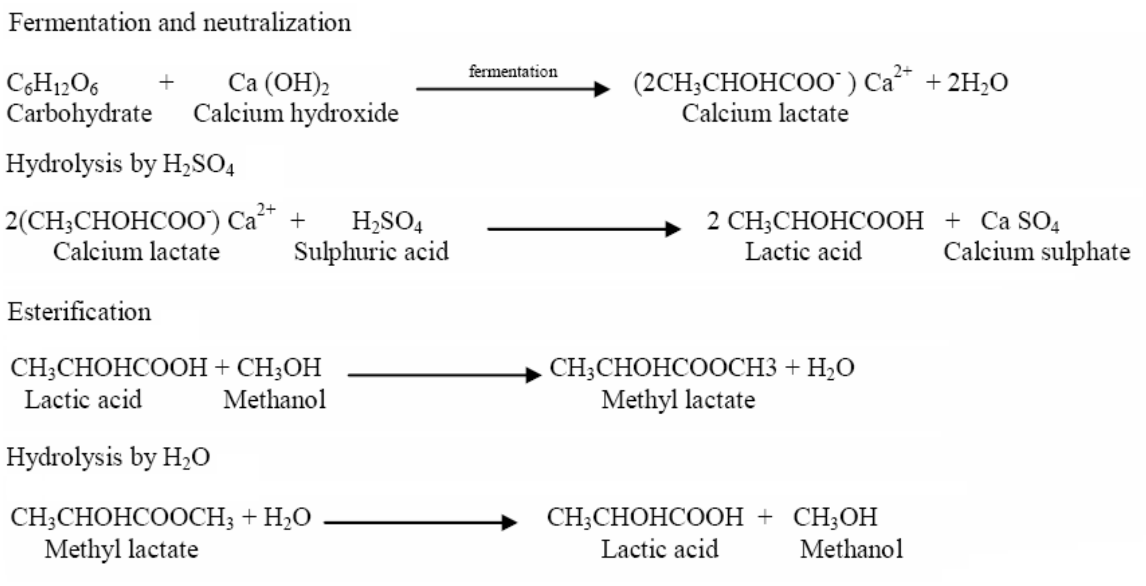

Figure 2-3 *Fermentation of C6-sugars to lactic acid, (Narayanan et al., 2004)*

[1] This percentage is representative to analyse the influence of integrating lactic acid production into a conventional grain to ethanol process. No higher amount of sugars was in principle chosen for lactic acid production because otherwise the main product (ethanol) would not be produced at a high enough rate to be classified as industrial production.

After fermentation the reactor content is sent to a filtration unit, where solids such as cell material and insoluble calcium sulphate are removed. This solid stream is managed as a residue. Cells are usually directed back into the fermentor if desired (Eyal *et al.*, 2001).

The clarified liquid being obtained after filtration, containing an aqueous solution of lactic acid and lactate salt, is transferred to an extraction unit where lactic acid is recovered using butanol as solvent in a multi-stage plate column. Lactic acid is dissolved in n-butanol and separated from the remaining aqueous phase that contains residual components such as not fermented sugars.

After filtration, the raffinate containing lactic acid is directed to a distillation column, where n-butanol is recovered and separated from the final product lactic acid at 99% purity.

The overall mass balance for this integrated concept is summarised in Table A-2. Only main streams are shown.

2.3.2 Ethanol production from DDGS via AFEX treatment

The Second Integrated Biorefinery Scheme is based on the ethanol production by Ammonia Fibre Explosion (AFEX) pre-treatment of DDGS. After drying, part of the DDGS stream, containing mainly proteins and non fermented sugars, is sent to the AFEX treatment and enzymatic hydrolysis, whereas the rest of the stream is sold as animal feed. The reason why not the whole DDGS stream is used for AFEX process is the fact that this process is still an immature technology and therefore not yet implemented at industrial scale, which makes the employment of the whole DGGS stream for this purpose risky.

In any case, the process itself seems to offer great potential for ethanol production and that is the reason why this concept has been chosen.

The block diagram for the second integrated biorefinery concept is offered below (Figure 2-4).

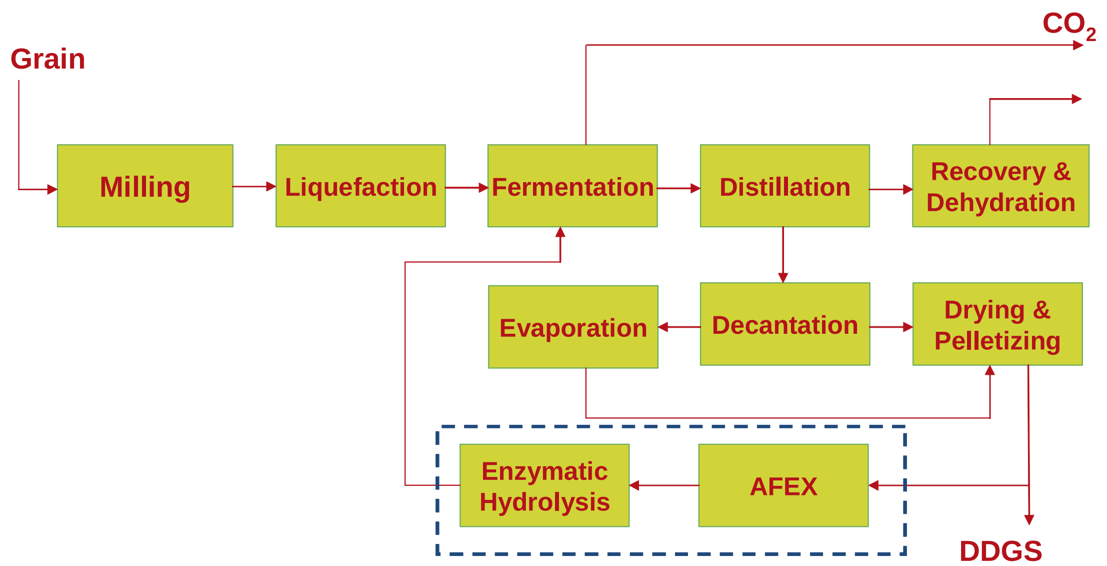

Figure 2-4 *Integrated Biorefinery Concept for Ethanol Production from DDGS*

A brief description of the DDGS treatment process taking place in this integrated concept is offered below.

Ammonia Fibre EXplosion (AFEX) consists of treating DDGS at high-temperature (and pressure liquid ammonia for a few minutes. Typical conditions for AFEX are 70°C and 0.8 :1 kg DDGS/kg ammonia loading (Bryan *et al.*, 2009) for 5 minutes. Then the pressure is swiftly reduced, breaking down

the structure of DDGS, releasing some simple (fermentable) C6 sugars. The slurry obtained is afterwards sent to an NH_3 recovery column that operates at 3 bar and 140ºC, where ammonia is for 99.9% recovered. The head stream is condensed to obtain liquid ammonia and fed to the AFEX reactor. The bottom stream which includes the pre-treated slurry is directed to the enzymatic hydrolysis, where C6 sugars polymers are broken into simple C6 sugars.

To analyse the effects of integrating the DDGS treatment into a conventional grain-to-ethanol process, two alternatives were proposed and analysed: using 20%, respectively 80% of the DDGS stream.

The overall mass balances for the 20% and 80% DDGS integrated concepts are summarised in Tables A-3 and A-4 respectively. Only main streams are shown, which means other input/output streams are not presented.

2.4 Techno-economic assessment

Based on the results from the modelling task, which included the calculation of mass and energy balances for the integrated concepts, operating and capital expenses, as well as feedstock and product values, a techno-economic evaluation of each proposed concept has been carried out to determine the production cost related to the different process schemes.

As a result of the techno-economic evaluation, the production cost of bioethanol in the lactic acid production case is 41% lower than in reference case, whereas in the case of DDGS-to-ethanol, the production cost is 5-8% lower. In all cases, as expected, the production cost of bioethanol is lower than the ethanol market price.

2.5 Technical and commercial feasibility

2.5.1 Technical feasibility

Results of technical feasibility analysis for the concepts proposed under bioethanol sector are presented in Table C-1 (orange = below average; green = above average).

The lactic acid production case is considered more feasible than average, mainly due to the proven technologies used in this scheme, whereas the DDGS-to-ethanol case is more challenging and therefore less technical feasible than average.

2.5.2 Commercial feasibility

Results of commercial feasibility for the concepts included in bioethanol sector are shown in Table C-2 (orange = below average; green = above average).

In case of lactic acid production, the biorefinery concept proposed is below average in terms of commercial feasibility, mainly due to the lactic market not being elastic enough to absorb the targeted volumes without price erosion, the lack of economical benefit (not perceived as a cheaper process) and the poor social & environmental score. Comparatively, the DDGS to ethanol concepts are medium- average, since the perceived competitive advantages are outbalanced by the concerns on social (food crop) & environmental impact (NH_3 issue).

2.5.3 SWOT analysis

A SWOT analysis of each biorefinery concept has been carried out as well. This is presented in Appendix D.1, and summarised in Tables 2-1 and 2-2 below.

Table 2-1 *SWOT analysis for Lactic Acid production*

Lactic Acid production	
Strengths • More value out of feedstock • Lower production cost of ethanol by coproducing lactic acid • Less dependence on EU Directive • Flexibility of products depending on market conditions	***Weaknesses*** • Technological challenge • Cost structure, potentially higher because of 2 fermentation sections
Opportunities • Increasing market for lactic acid, mainly driven by bioplastics • Lactic acid market is not dependent on EU directives (it is a 'natural' market) • On the other hand, a "Bioplastic directive" could boost lactic acid demand • Possibility to extend technology to lignocellulose feedstock • Less sensitive to world oil market prices • Attractive concept for investors	***Threats*** • New process • Market growth for lactic acid mainly driven by bioplastic: still speculative • Higher ethanol prices will increase profitability of competitors more than profitability of integrated refinery owners • Underestimation of capital costs • Traces of hazardous chemicals involved in lactic acid downstream processing might cause DDGS to be a waste instead of a product

Table 2-2 *SWOT analysis for DDGS to ethanol*

DDGS to Ethanol	
Strengths • More value out of the feedstock material: more ethanol and higher DDGS price • Contribution to meeting EU targets on biofuel consumption with less feedstock (less competition with food) • Platform for other 2nd generation fermentations	***Weaknesses*** • AFEX treatment not at industrial scale yet • Ethanol fermentation on other sugars than glucose, sucrose not yet developed on industrial scale • Safety issues with high pressure ammonia handling • Expensive process
Opportunities • Less competition with food supply • Bio-ethanol from DDGS is 2nd generation ethanol which is much supported by EU • Lower value for normal DDGS due to market saturation will increase competitiveness of the biorefinery concept • New markets for higher quality DDGS in animal feed, possibly human food	***Threats*** • Dependence on biofuel legislation • AFEX DDGS not yet accepted in feed industry • Underestimation of capital costs

2.6 Summary and conclusions

An integral assessment of different biorefinery concepts that may be integrated into existing grain-to-ethanol plants has been carried out as part of the activities included in the 2-years project Bioref-Integ.

Based on the results of identification of industrial fuel-producing complexes and most promising products to be co-produced with biofuels, two different biorefinery concepts have been proposed within Bioethanol sector, i.e.:

- Lactic acid production from starch sugars
- Ethanol production from AFEX-treated DDGS.

The techno-economic assessment showed that integration of lactic acid production into an existing grain-to-ethanol leads to much lower production costs of main product bioethanol in comparison with the base case, which makes this concept very interesting from the economic point of view.

Comparatively, the techno-economic evaluation of the DDGS-to-Ethanol concept also led to lower production costs in comparison with the base case, although % of improvement is lower than the value obtained for the lactic acid case.

When analysing technical and commercial feasibility of the proposed concepts in bioethanol sector, results show that both biorefinery concepts are globally below average feasibility which means further research and development is required to make these concepts suitable for implementation at industrial scale.

3. Evaluation of integrated biorefinery schemes based on valorisation of glycerol

3.1 Introduction

Biodiesel is a renewable, environmental friendly fuel which is used to power diesel engines without having to modify any of the engine's parts. It is defined as a fuel comprised of monoalkyl esters of long chain fatty acids derived from vegetable oils or animal fats. Compared with bioethanol, biodiesel is currently produced and used on a far smaller scale worldwide. However, production capacity has been increasing steadily in recent years and biodiesel is clearly expected to occupy an increasingly larger portion of the renewable fuels in the years to come.

In Europe, strong growth in biodiesel production is being driven in part by the 2003 European Biofuels Directive (2003/30/EC). This directive mandates the use of biofuels in a percentage ranging from 2% in 2005 to 5.75% in 2010 (calculated on the basis of energy content) for all transportation fuels marketed within the member states. The Renewable Energy Directive (RED), adopted by the European Council on April 6th 2009, added a mandatory 10% target for renewables in transport for all member states in 2020. It is expected that a significant portion of this amount will be biodiesel due to the growing "dieselisation" of the fuel markets in some European countries.

The major by-product from the biodiesel production is glycerol. Per tonne of biodiesel, 100 kg of raw glycerol is obtained. Due to the rapidly developing green fuel industry both in Europe and the United States, the amount of glycerol as by-product from transesterification constantly increases. However, this is not beneficial for biodiesel companies because the massive production also forces a collapse in market price of glycerol. With less income from raw glycerol sales it gets more difficult to run a profitable biofuel business. To keep profitability stable, an efficient use of this waste product is necessary (Hirschmann *et al.*, 2005).

In this chapter we will look at some integration options to increase cost competitiveness of the biodiesel production by co-producing added-value products out of glycerol.

3.2 Reference case

Based on a mapping of the existing biodiesel producing complexes in the partner-related countries, including France (in that way covering >25% of the total EU27 biodiesel production in 2007), it was found that the majority of the plants starts from the vegetable oil as feedstock. Table 3-1. summarises the number of biodiesel plants in the partner-related countries (including France) and the main feedstock used. As can be seen, on a total of 108 biodiesel plants, the major feedstock appears to be the vegetable oil, especially rapeseed oil, rather than the seeds themselves. Therefore, the reference case used in this chapter has been defined as a plant producing biodiesel out of rapeseed oil, as this is representative for the majority of biodiesel plants in Europe. An extension to this reference case can be made by including the pressing of the rapeseed into rapeseed oil, leaving rapeseed cake as a by-product that can offer additional opportunities for valorisation.

Table 3-1 *Survey biodiesel sector*

Country	Number of plants	Main feedstock
Belgium	4	Rapeseed oil Soybean oil
Finland	2	Palm oil
Netherlands	20	Rapeseed oil Oil residue Animal fat Palm oil
Spain	30	Rapeseed oil Soybean oil Sunflower oil Used oil
Sweden	12	Rapeseed Tall oil
United Kingdom	18	Rapeseed oil Cooking oil
France	22	Rapeseed Sunflower Animal fat
Total	108	

A block diagram for the complete process is represented in Figure 3-1.

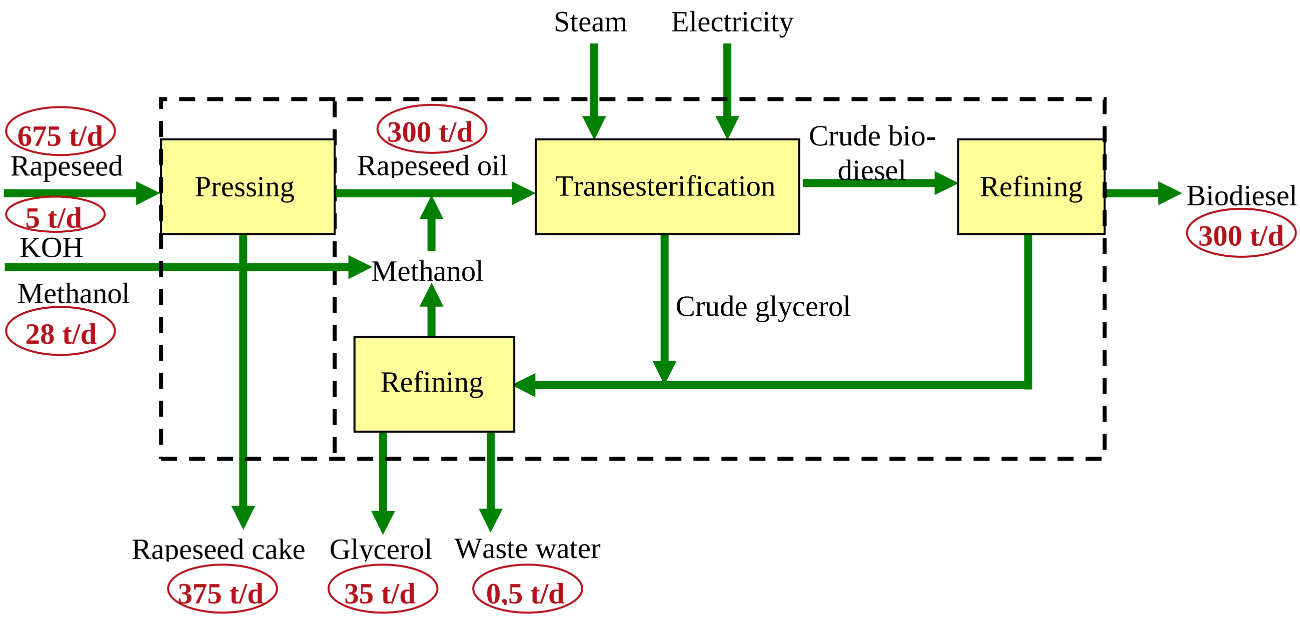

Figure 3-1 *Block diagram for the complete process for biodiesel production from rapeseed; the reference case for the biodiesel sector is based on rapeseed oil*

Pressing of the rapeseed

The process of the rapeseed pressing is schematically drawn in Figure 3-2. Prior to delivery to the extraction plant, the rapeseed is cleaned to remove dust, small particles and large refuse material which are normally part of harvested seeds. This is usually obtained by a combination of sieves and aspiration. The cleaning is followed by an extra drying of 1 to 2% and a resting period of 24 hours in order to be prepared for further processing.

The following step is the preconditioning of the seeds, consisting of preheating of the whole seed (to about 30-40°C) prior to processing by indirect heating or direct hot air contact. This process improves flaking, screw pressing capacity, cake formation and extractability.

The preheated rapeseed is then flaked between two rolling surfaces. This results in a rupture of the cell walls, allowing the lipid particles to migrate to the surface of the flakes. The flaked seeds are transferred directly to the cookers where they are heated to about 75-85°C.

The cooked flakes are transferred to the expellers where 60–70% of the oil is removed by pressing the flakes, leaving a more dense and durable cake with improved solvent extractability and percolation properties. The removed oil is further purified/dewatered by decantation, resulting in crude rapeseed oil.

The cake undergoes additional extraction with hexane to remove the remaining oil. The hexane is recovered from the crude rapeseed oil by distillation. Further toasting and drying/cooling is done to remove the hexane solvent from the extracted cake to produce rapeseed meal.

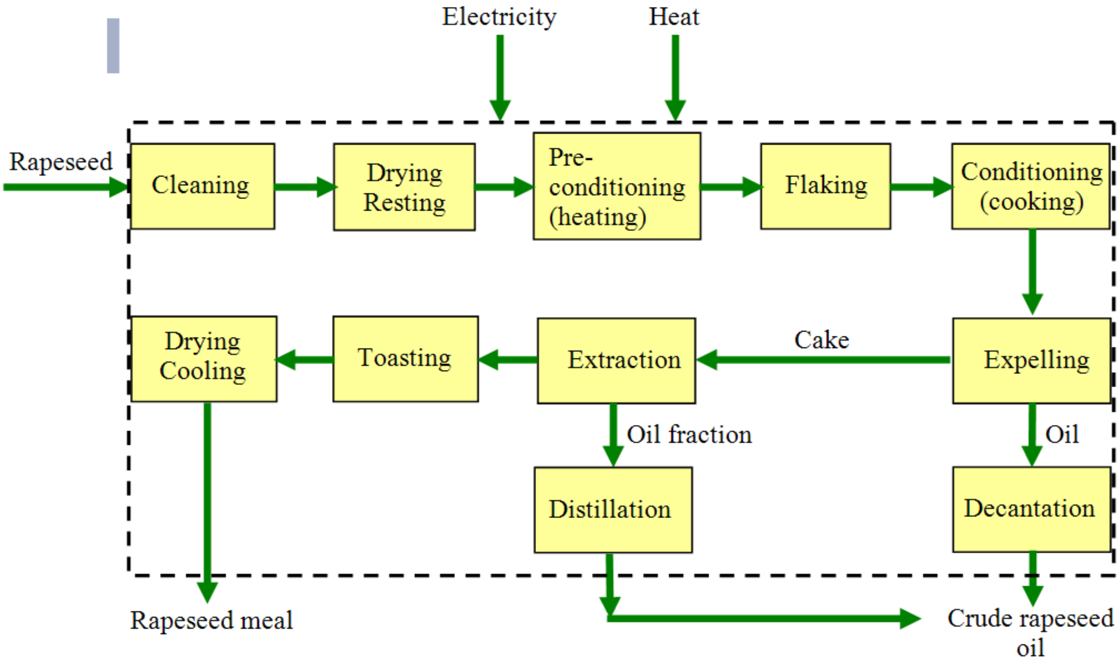

Figure 3-2 *Block diagram for rapeseed processing to crude rapeseed oil and rapeseed meal*

Biodiesel production

The rapeseed oil is filtered and pre-processed to remove water, free fatty acids and contaminants and fed to the transesterification process. The catalyst, potassium hydroxide, is dissolved in methanol and then mixed with the pre-treated oil. The mixture is heated (typically 50°C) for several hours (4 to 8 typically) to allow the transesterification to proceed. Figure 3-3 shows the reaction taking place during the transesterification.

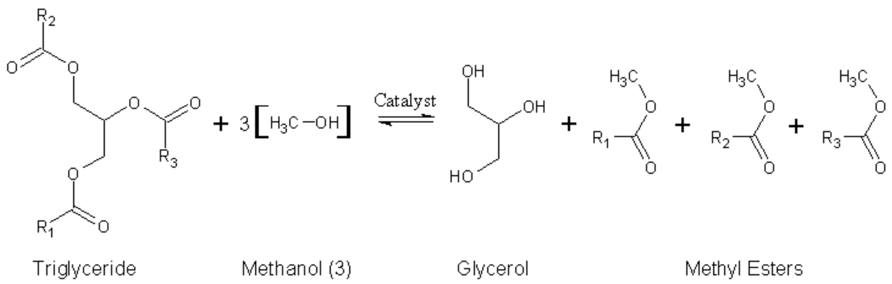

Figure 3-3 *Transesterification reaction (Source: Wikipedia, http://en.wikipedia.org/wiki/Biodiesel_production)*

Once the reaction is complete, the major co-products, biodiesel and glycerol, are separated into two layers. The lower layer of the process is composed primarily of glycerol and other waste products (methanol, sodium methoxide, soaps). The top layer, the ester phase containing biodiesel, unreacted oil, methanol and soaps, is decanted. Once separated from the glycerol, the biodiesel goes through a clean-up or purification process to remove excess alcohol, residual catalyst and soaps. This consists of one or more washings with clean water after which the remaining aqueous phase is separated from the biodiesel in settler tanks. The biodiesel is then dried to remove any trace amounts of moisture, after which it is stored.

The resulting waste stream is collected for methanol recovery. It is combined with the glycerol stream and heated to the normal boiling point of methanol (65°C), followed by stripping of the methanol and distillation to recover pure methanol that is recycled back to the beginning of the process.

Bottoms of the distillation columns contain the glycerol and other impurities such as unreacted catalyst and soaps that are neutralised with an acid (HCl). The impurities are separated from the glycerol using a decanter, producing 50%-80% crude glycerol. The remaining contaminants include unreacted fats and oils. In large biodiesel plants, the glycerol can be further purified, to 99% or higher purity, for sale to the pharmaceutical and cosmetic industries.

Some of the main parameters for the biodiesel production are listed in Tables A-5 and A-6.

3.3 Integrated biorefinery schemes

Two new technologies that have been developed based on glycerol have been investigated and integrated with the reference case. These two are:

- 1,3- propanediol production from crude glycerol (fermentation process);
- Epichlorohydrin production from crude glycerol (chemical conversion process).

The following text describes the cases and presents the mass balances.

3.3.1 1,3- propanediol production from crude glycerol

One way to valorise glycerol from biodiesel industry is the conversion into a high-price chemical, such as 1,3-propanediol (PDO). PDO has various applications mainly in polyester, but also in cosmetics, foods, lubricants, and medicines. Industrial PDO production has attracted attention as an important monomer to synthesise a new type of polyester, polytrimethylene terephthalate (PTT, Zeng and Biebl, 2002).

Glycerol can be converted to PDO by either chemical or biochemical methods. In this integrated biorefinery case PDO is produced through microbial fermentation by the natural PDO producer *Clostridium butyricum*. Microbial conversion of glycerol to 1,3-propanediol is particularly attractive, as the process is relatively easy, does not generate toxic by-products, has a low energy requirement and

higher yield than PDO derived via chemical reaction (Jun *et al.*, 2009). *C. butyricum* is considered one of the best "natural producers" because of its appreciable substrate tolerance *(Clostridium* species were found to be responding best to non-refined substrate sources), yield and productivity (Gonzalez-Pajuelo *et al.*, 2006). The production of 1,3-propanediol by natural organisms is shown in Figure 3-4. The main products from glycerol metabolism are 1,3-propanediol, butyric acid and acetic acid.

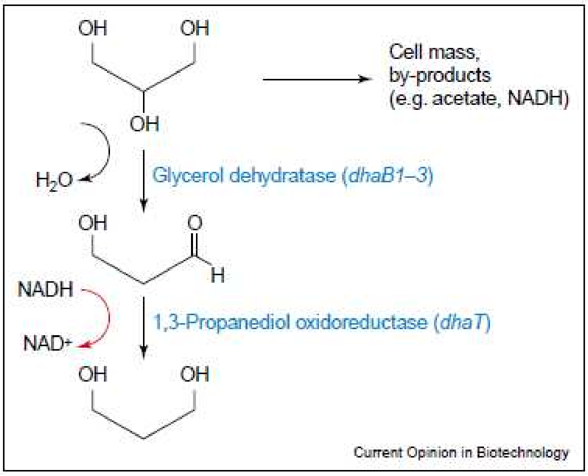

Figure 3-4 *1,3-propanediol production by natural organisms (Nakamura and Whited, 2003).*

After the PDO has been produced, the PDO has to be separated from the cellular broth that comes out of the bioreactor. Since the product shall be used mainly in polymer chemistry, the grade of purification has to be from 95% up to over 99%, depending on the type of impurities and the demanded product properties. As the product concentration of the fermentation broth is rather low, all recovery approaches need to include a prior step of water removal e.g. by evaporation (Willke and Vorlop, 2008). The separation scheme proposed by DuPont follows the following steps: microfiltration and ultra filtration, ion exchange, flash evaporation, and distillation (http://en.wikipedia.org/wiki/Bioseparation_of_1,3-propanediol).

The block diagram for the integrated biorefinery case producing 1,3-propanediol from glycerol is given in Figure 3-5. The mass balance for 1,3–propanediol production from glycerol is given in Table A-7.

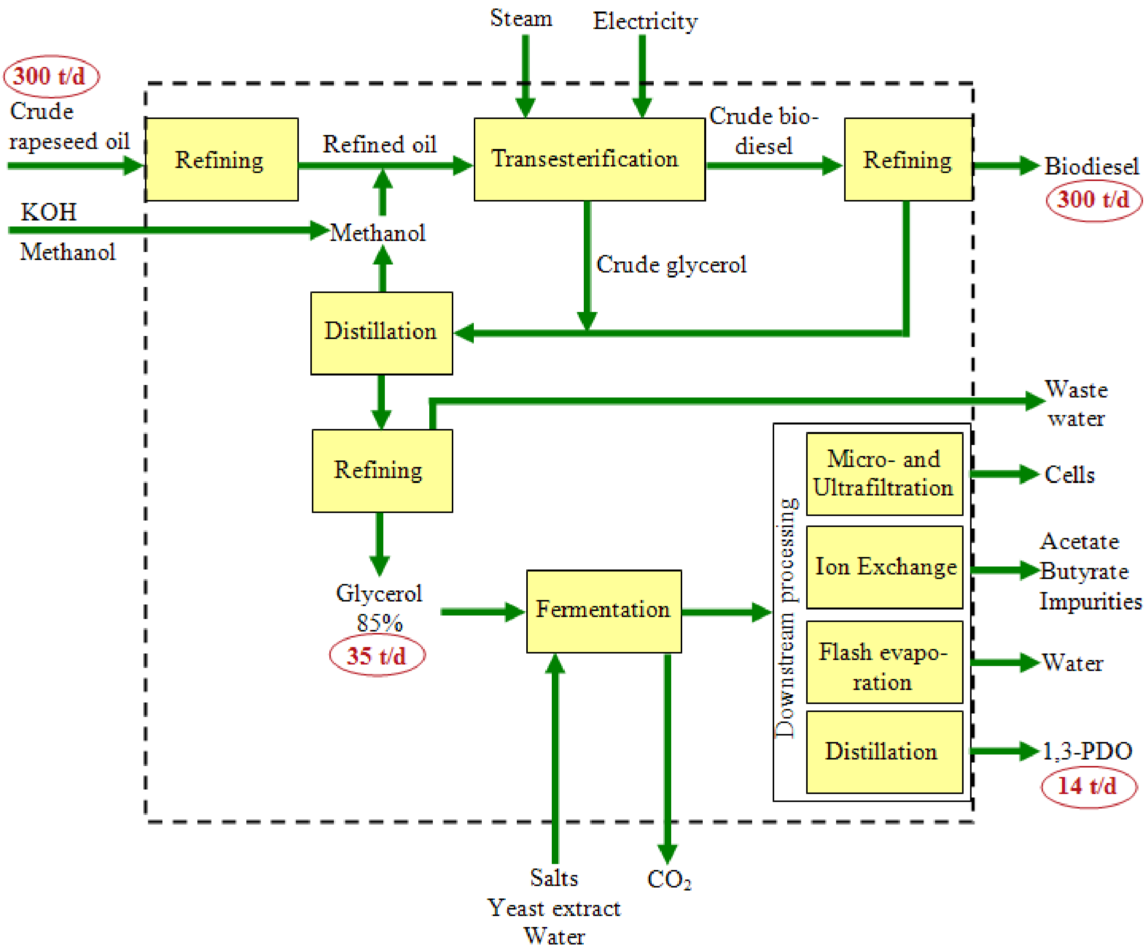

Figure 3-5 *Process block diagram for the integrated biorefinery case producing 1,3-propanediol from glycerol*

3.3.2 Epichlorohydrin production from crude glycerol

Epichlorohydrin is a high volume commodity chemical used largely in epoxy resins. Several routes are known for epichlorohydrin manufacture, however most is made from propylene and chlorine as primary raw materials in a multi-step process. Although practiced on a very large scale, this process suffers from some undesirable features, particularly the low chlorine atom efficiency (Bell *et al.*, 2008).

The process for the production of epichlorohydrin starting from glycerol was published earlier in scientific literature (Carius, 1862; Boschan and Winstein, 1956; Gibson, 1931), but the historically high cost of glycerol has prevented its development as a commercial process so far. Recently, however, glycerol has become increasingly available as a by-product of the manufacture of biodiesel, particularly in Europe. As a result, the available volume of renewable glycerol has risen, and the price has declined to a point where its use in the manufacture of commodity chemicals, such as epichlorohydrin, has become feasible. Several companies have announced plans to commercialise technology to manufacture epichlorohydrin from glycerol (Solvay www.solvaypress.com/pressreleases/0,52477-2-0,00.htm; Dow Chemical, *C&E News*, August 14, 2006, p. 3; Spolchemie www.spolchemie.cz/dwn/factsheet12.pdf). One such route is based on the conversion of glycerol through dichlorohydrins to epichlorohydrin. This two-step process is shown in Figure 3-6 and appears significantly simpler than the traditional process. The process can be run either batch-wise or continuously.

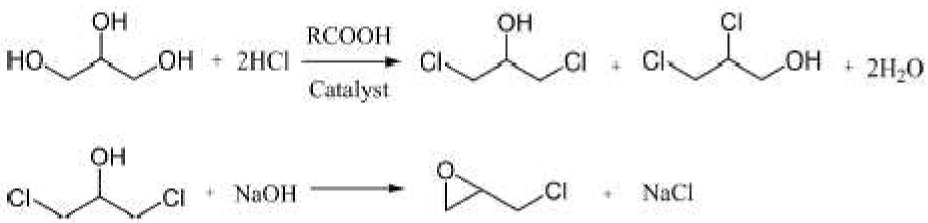

Figure 3-6 *Two-step process for the production of epichlorohydrin that employs renewable glycerol as feedstock. Only one equivalent of waste chloride is produced (Bell et al., 2008)*

The process developed by DOW Chemical Company is called the glycerol-to-epichlorohydrin (GTE) process (Bell *et al.*, 2008), the process developed by Solvay is called EPICEROL®. Solvay, a traditional glycerol and epichlorohydrin manufacturer, was the first to start production of epichlorohydrin from glycerol at their 10 ktonnes plant in France in 2007 (Pagliaro and Rossi, 2008).

For the integrated biorefinery case described here the EPICEROL® Process was used as an example. However, because of confidentiality reasons, the data presented here are based on patent and literature survey and own calculations. The block diagram for the integrated biorefinery case producing epichlorohydrin from glycerol is given in Figure 3-7. The mass balance for epichlorohydrin production from glycerol is given in Table A-8.

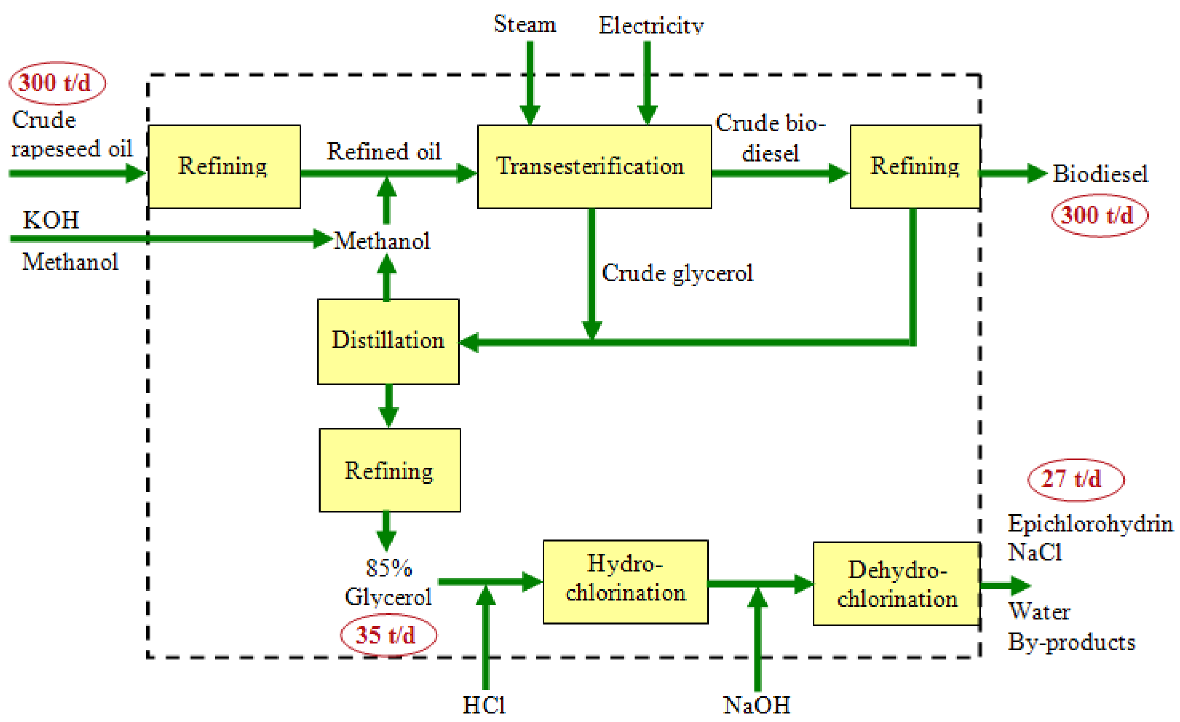

Figure 3-7 *Process block diagram for the integrated biorefinery case producing epichlorohydrin from glycerol*

3.4 Techno-economic assessment

3.4.1 Reference case

The economic assessment of the current biodiesel industry shows that the average market price for biodiesel (700 €/T) is lower than the estimated production cost (726 €/T). No subsidies were taken into account in these evaluations. The production costs were evaluated for new plants. From the data in Table B-1 it is clear that subsidies are needed to support the production.

3.4.2 1,3- propanediol production from crude glycerol

The economic assessment of the integrated biodiesel case producing PDO is given in Table B-2. Also in this case the estimated production cost for the biodiesel (732 €/T) is still higher than the average market price for biodiesel (700 €/T). Again, no subsidies were taken into account and the production costs were evaluated for new plants.

3.4.3 Epichlorohydrin production from crude glycerol

Table B-3 shows the economic assessment of the integrated biodiesel case producing Epichlorohydrin out of glycerol. In this case the estimated production cost for the biodiesel (668 €/T) drops below the average market price for biodiesel (700 €/T), making it profitable.

3.5 Technical and commercial feasibility

3.5.1 Technical feasibility

The technical feasibility has been evaluated by a panel of experts. In Table C-3 the technical feasibility of both integrated biorefinery cases is compared to the project average (= average of all biorefinery schemes considered in the Bioref-Integ project). Main deviations from average are highlighted (orange for below average; green for above average) and briefly commented.

Glycerol to1,3-propanediol (PDO)
Considered merely as an average case. The technology (fermentation) is considered as rather mature and benign. Main penalty comes from the significant downstream processing. This would mean that especially the complex downstream processing is challenging, not the fermentation process itself.

Glycerol to Epichlorohydrin (ECH)
Glycerol to ECH is well above average. This seems logic, as this is already an industrial process. This is clearly reflected in the high scores for the process feasibility. Worries mainly about safety issues (epichlorohydrin is toxic) and waste treatment.

3.5.2 Commercial feasibility

Also the commercial feasibility has been evaluated by a panel of experts. In Table C-4 the commercial feasibility of both integrated biorefinery cases is compared to the project average (= average of all biorefinery schemes considered in the Bioref-Integ project). Main deviations from average are highlighted (orange for below average; green for above average) and briefly commented.

Glycerol to 1,3-propanediol (PDO)
Commercially attractive project, especially regarding integration benefits and functional attributes (functionality of PDO-based polyesters). Some concerns related to water needs.

Glycerol to Epichlorohydrin (ECH)
Slightly above average, driven by integration benefits and slightly better score on other statements.

3.5.3 SWOT analysis

SWOT analyses for the two integrated cases have been carried out and is shown in Appendix D2. Especially the production of PDO out of glycerol shows some technical weaknesses, as, although proven at laboratory scale, production of PDO out of glycerol has not been proven at industrial scale yet. For the rest both integrated cases share similar characteristics: a large scale is needed to be economical advantageous, they both offer potential for product diversification but are limited by 1 or 2 big players that dominate the market and the technology, leaving little freedom to operate for new players.

3.6 Summary and conclusions

The high costs surrounding biodiesel production remains the main problem in making it competitive in the fuel market either as a blend or as a neat fuel. In this chapter we looked at valorisation options for glycerol, the by-product of biodiesel production, to increase cost competitiveness of the biodiesel production by co-producing added-value products.

The production of 1,3-propanediol and epichlorohydrin out of glycerol both have good technical and commercial feasibility, meaning that they show potential to improve the cost competitiveness of biodiesel production. As seen from Table 3-2 mainly the further conversion of glycerol into epichlorohydrin can make biodiesel production more profitable. In the other cases, subsidies are needed to support the production.

Furthermore, a larger scale could make production more profitable. The DuPont Tate & Lyle Bio Products facility in Loudon (Tennessee) produces around 45,000 tonnes/year of bio-PDO. Solvay has built a first industrial unit for the production of epichlorohydrin in Tavaux, with an initial capacity of 10,000 tonnes/year, and is currently preparing the construction of a new Epichlorohydrin plant in Thailand, scheduled to be operational in the first quarter of 2012, with an annual production capacity of 100,000 tonnes per year. The volumes produced in the integrated cases studied here are 5000 tonnes of PDO and 9000 tonnes of epichlorohydrin.

However, as could be seen from the techno-economic assessment, more than 80% of the production cost is associated with the feedstock itself and consequently, if one wants to lower biodiesel production cost, efforts should be focused on developing technologies capable of using lower-cost feedstock, such as recycled cooking oils and wastes from animal or vegetable oil processing operations.

Table 3-2 *Overview of production cost for the different cases*

Case	**Production cost of biodiesel €/t**
Reference case – Biodiesel production	726
Integrated case – glycerol to 1,3-propanediol	732
Integrated case – glycerol to Epichlorohydrin	668
Product value Biodiesel	**700**

4. Evaluation of innovative biorefinery concepts entering the pulp & paper industry

4.1 Introduction

Today's modern pulp mills have the possibility to generate surplus energy and have a great potential to be energy suppliers to other industries and society. Pulp mills are well suitable for becoming large scale biorefineries, because they have the infrastructure for handling large amounts of biomass, both raw material and products, and the industry has a lot of competence in running a plant with biomass as a raw material. Integration with the pulp mill and achieving synergy effects are often possible.

Pulp mills have experienced an increased competition from the energy sector for wood which has pushed up the biomass prices. On the other hand the demand for paper has declined, so that the price of the products has stayed low. Therefore, it is important to find new products to increase the revenues, or to decrease the production costs and thus increase competiveness. Pulp mills often have an energy surplus, being used to produce heat and electricity. This is performed in a rather inefficient recovery boiler. Utilising this energy surplus in another way could increase the efficiency of the mill.

4.2 Reference case

The reference mill is producing bleached market pulp through the Kraft Process and is a hypothetical pulp mill representing existing best available commercially proven Nordic technology in 2004. The raw material is softwood, 50% spruce and 50% pine and the production is 1800 dry tonnes pulp per day. The mill is equipped with a condensing turbine for maximising electricity production. The electricity not used in the process is sold. Other by-products sold are bark and tall oil. Figure 4-1 presents the pulping process and a block diagram for the reference case is shown in Figure 4-2.

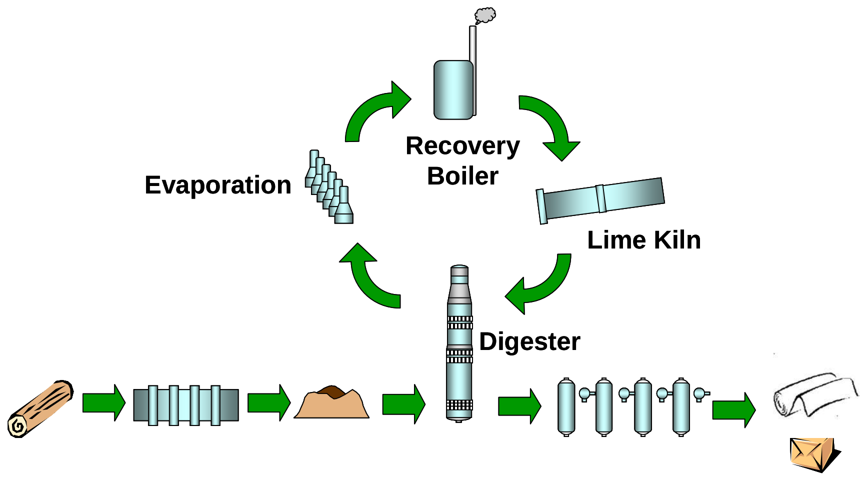

Figure 4-1 *A schematically process diagram of the pulping process*

Round wood and sawmill chips are fed to the digester. Using cooking chemicals, the cellulose and lignin are separated. The cellulose is sent to the fibre line, where it is washed and bleached using bleaching chemicals to produce bleached market pulp. The pulp is then used to manufacture paper, packing material, kraftliner, etc. The black liquor, containing the dissolved lignin, extractives, and residual cooking chemicals, is first evaporated and then combusted in the recovery boiler. At the bottom of the boiler, a smelt is formed which consists of the cooking chemicals. The generated steam is used in a turbine to generate steam, to be used in the process and also to generate electricity. It is here that

the energy surplus in the mill is created. The smelt from the recovery boiler is then further treated, with the main goal of transforming Na_2CO_3 to NaOH. This is done by adding lime (CaO), which forms NaOH and $CaCO_3$. $CaCO_3$ is then burned in the lime kiln to generate CaO which is used again to generate NaOH. This is called the lime cycle. The lime kiln is in many pulp mills the last consumer of fossil fuel and research is carried out to be able to replace it with a renewable fuel, for example lignin. The generated cooking chemicals, white liquor, are circulated back to the digester.

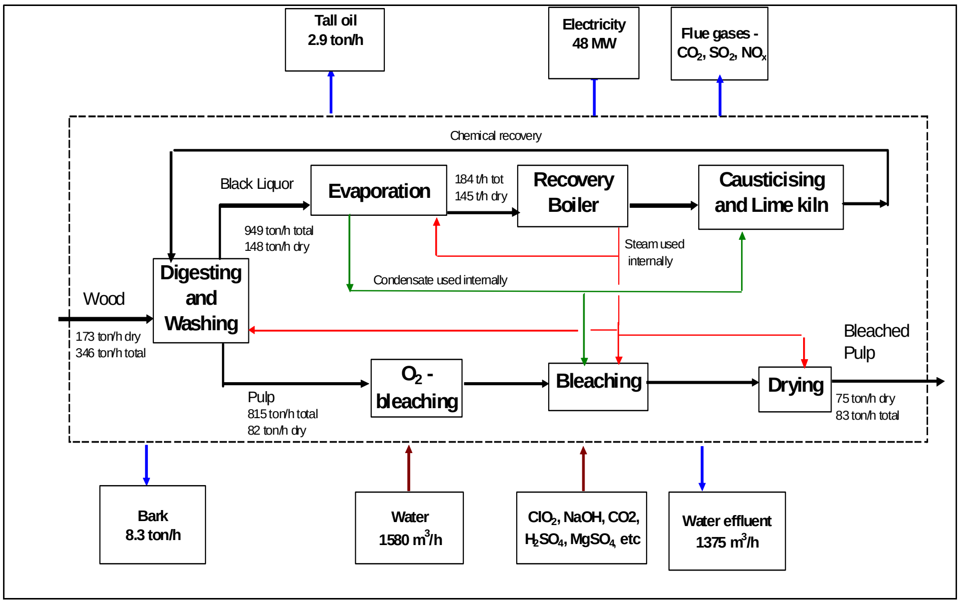

Figure 4-2 *Block diagram reference case (softwood) for pulp & paper sector*

Data and information on the reference case are found in Table 4-1, and the mass and energy balances are found in Table A-9 and Table A-10.

Table 4-1 *Reference mill configuration*

Characteristic key data	Unit	Softwood
mill capacity (pulp production)	Dry t/d	1800
raw material	Dry t/d	4150
composition raw material	%	50% pine and 50% spruce
black liquor processed by recovery boiler	tDS/d	3400
bark sold	Dry t/d	200
electricity exported	MW	48
tall oil sold	t/d	70
equipped with	-	back-pressure turbine, condensing turbine

4.3 Integrated biorefinery cases

Three new technologies entering the pulp and paper industry have been investigated and integrated with the reference cases. These technologies are:

- Lignin extraction from black liquor;
- Black liquor gasification, followed by dimethyl ether (DME) or methanol production;
- Ethanol production from wood pulp.

The following paragraphs describe these integrated cases and present the related mass and energy balances. Generally for all cases, water entering the process is the major input post while water effluent is the biggest output. Most of the heat input to the process is cooled away or released with the flue gases.

4.3.1 Lignin extraction

Lignin can be extracted from the black liquor in the evaporation plant at 30-45% dry solid consistency. The separation of lignin takes place by lowering the pH via CO_2 injection. Lignin is precipitated, and separated from the black liquor in a filter press. It is then re-suspended in an H_2SO_4 solution and washed. The remaining black liquor and the filtrate from the washing are recycled back to the evaporation plant. The produced lignin has a very low content of ash (<1.5%) and sulphur.

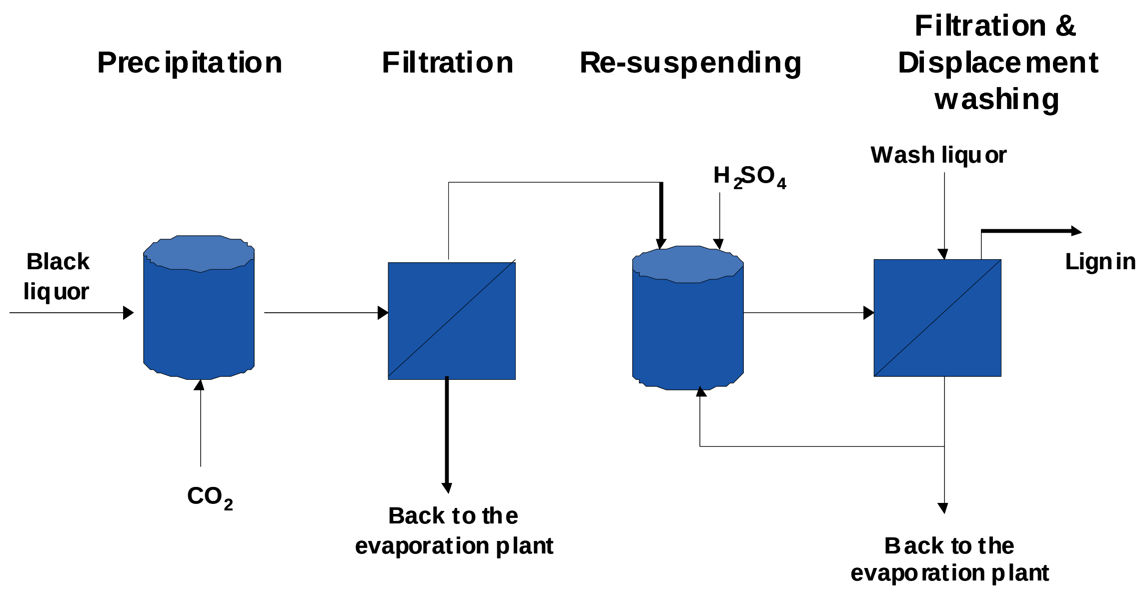

Figure 4-3 *A schematically diagram of LignoBoost Process*

When lignin is precipitated, the heating value of the black liquor will decrease and the recovery boiler will generate less high pressure steam. As the recovery boiler is often the bottleneck of the pulp mill, lowering its load will create a potential to increase the pulp production with approximately 25%. Increasing the pulp production is of course only possible if all other equipment can handle with it.

The integrated case is outlined in Figure 4-4.

Many pulp mills use heavy fuel oil or natural gas in the lime kiln, which is the last big consumer of fossil fuel in the pulp industry sector. The extracted lignin is an excellent fuel to be used in the lime kiln and it can replace fuel oil also in other pulp mills, or sold as a solid biofuel. The lime kiln in the reference case and in the biorefinery cases uses fuel gas generated by gasification of bark. The mass and energy balances for the lignin extraction case are shown in Table A-11 and Table A-12.

The major post in the mass balance is the water entering and exiting the system. In the energy balance the entering raw material is the major input and the most of the energy then ends up in the products, flue gases or cooled away.

4.3.2 Black liquor gasification and DME production

In a black liquor gasification (BLG), the recovery boiler is replaced with a gasifier. The evaporated black liquor is gasified in a pressurised reactor under reducing conditions. The generated gas is separated from the inorganic smelt and ash and is cooled. The smelt falls into the quench bath below the gasifier, where it dissolves to form green liquor in a manner similar to the dissolving tank of a recovery boiler.

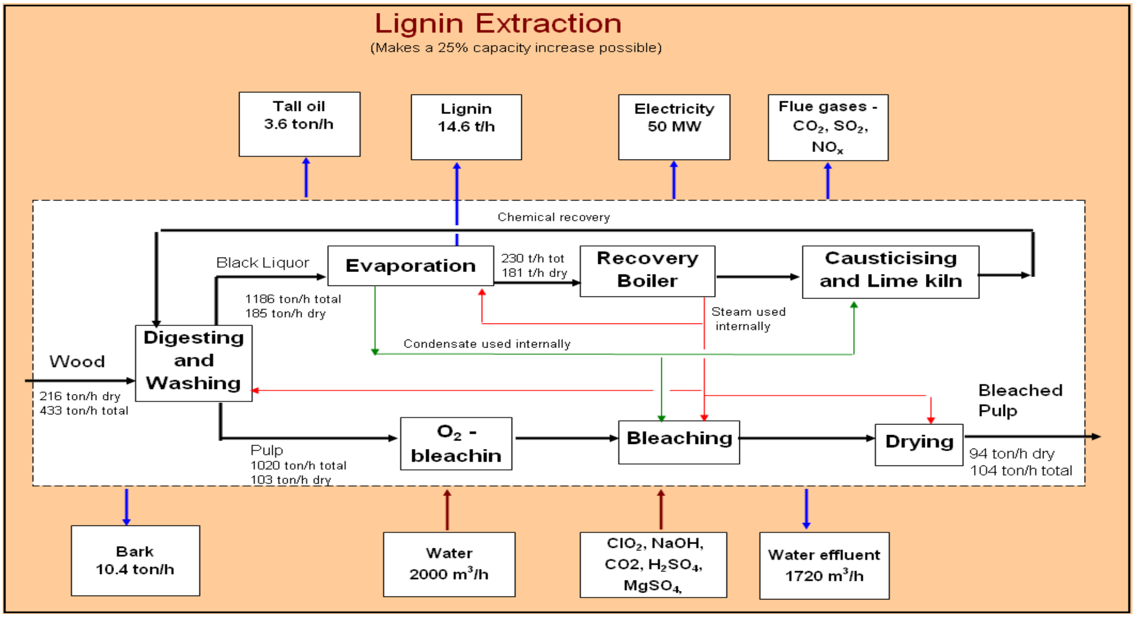

Figure 4-4 *Block diagram for lignin extraction case*

The raw fuel gas from the gasifier exits the quench and is further cooled in a counter current condenser. Water vapour in the fuel gas is condensed, releasing heat to be used in steam generation. Hydrogen sulphide is removed from the cooled and dried fuel gas in a pressurised absorption stage. The resulting gas is a nearly sulphur-free synthesis gas consisting of mainly carbon monoxide, hydrogen and carbon dioxide. The purified synthesis gas is used for dimethyl ether (DME) synthesis. The DME is a biofuel which potentially can replace diesel in heavy vehicles.

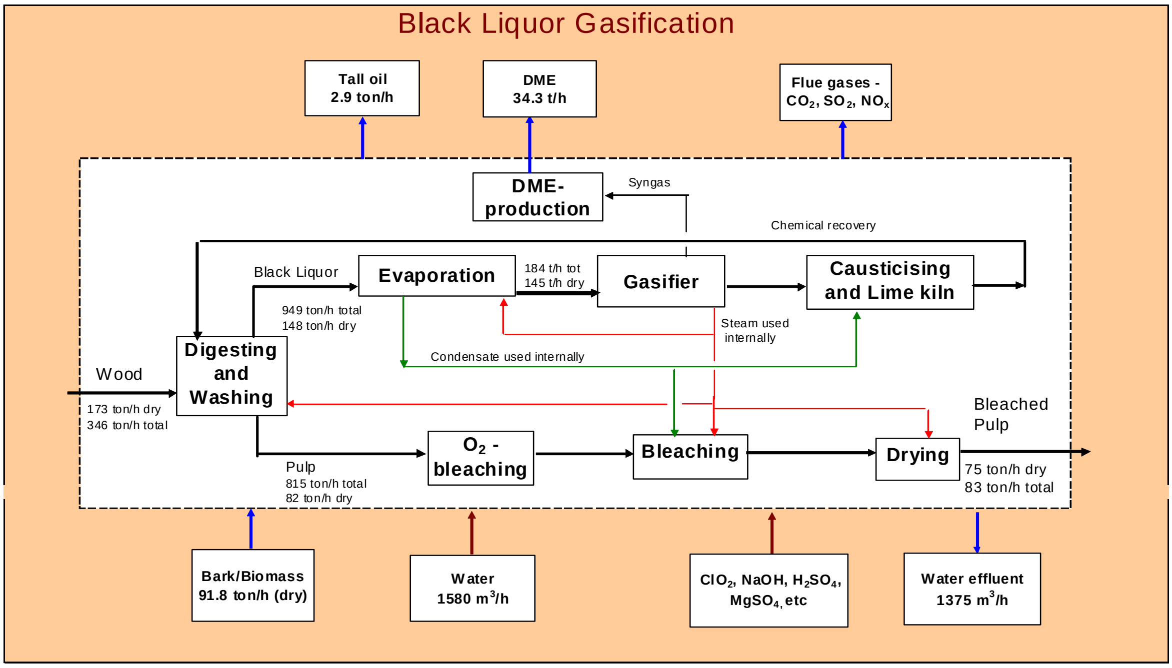

Figure 4-5 *Block diagram for black liquor gasification case*

In this integrated case 824 t/d of pure DME is produced. Biomass should be imported to cover up the steam and electricity demand. The mass and energy balances are outlined in Tables A-13 and A-14. The integrated case is outlined in Figure 4-5.

The major post in the mass balance is the water entering and exiting the system. In the energy balance the entering raw material is the major input and the most of the energy then ends up in the pulp, DME, flue gases, or cooled away.

4.3.3 Ethanol production in a pulp mill

Since the current worldwide production capacity of pulp is larger than the demand, it may be beneficial to convert a pulp mill to produce ethanol instead of pulp. Some mills also have several pulp production lines and one option is to convert one of these lines to ethanol production. The chemical recovery line is intact, but the fibre line is replaced with new units. The ethanol production is carried out by enzymatic hydrolysis, fermentation and distillation. The soluble hemicellulose and cellulose from the digester are sent to the SSF (Simultaneous Saccharification and Fermentation) unit. The hydrolysis and fermentation are carried out continuously in tanks coupled in series. A cellulose enzyme preparation is added to the hydrolysis tanks that are maintained at a temperature of approximately 65°C. After fermentation, the raw ethanol is fed to a distillation column and concentrated to 96%. A block diagram for this concept is shown in Figure 4-6.

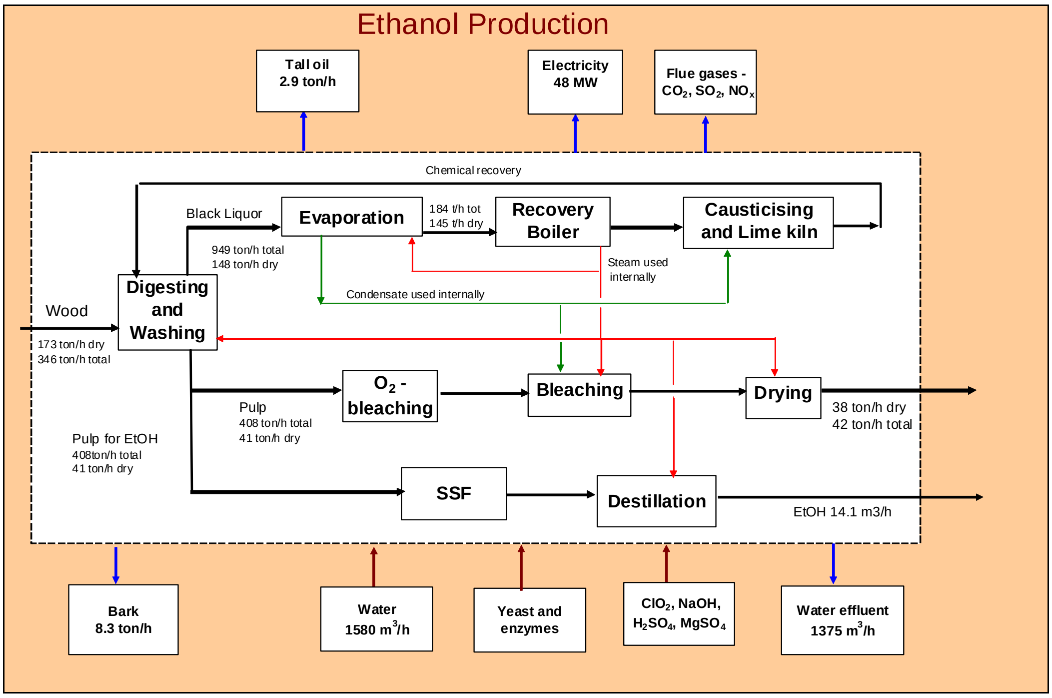

Figure 4-6 *Block diagram for ethanol production case*

In the investigated case one fibre line is converted to an ethanol production unit. The pulp production will then be halved, but in addition ethanol will be produced. Much of the current equipment from the pulp mill can be used for the ethanol production, which will result in a rather low investment cost. The mass balance for this process is shown in Table A-15 and the energy balance is shown in Table A-16.

The major post in the mass balance is the water entering and exiting the system. In the energy balance the entering raw material is the major input and most of the energy ends up in pulp, ethanol, flue gases, or cooled away.

4.4 Techno-economic assessment

The production costs of softwood pulp are calculated for reference case, as well as for biorefinery cases. No subsidies are taken into account in these calculations. The production costs are based on new greenfield pulp mills.

Economic assessments carried out for the reference case and the integrated biorefinery cases are presented in Tables B-4, B-5, B-6, and B-7.

The investment cost of the reference case has been estimated at 715 M€ (Table B-4). The production cost of pulp is very dependent on the wood price. Here a wood price of 75 €/tonne is assumed. The calculated production cost for bleached softwood pulp is 398 €/tonne (90% dry).

In the lignin extraction case, the capacity is increased with 25% due to the debottlenecking of the recovery boiler. The investment cost is estimated at 795 M€, and the calculated production cost for pulp is 347 €/tonne (Table B-5). For lignin a price of 200 €/tonne is considered. If lignin can be used for producing carbon fibres or chemicals, the lignin price will increase and the concept would score much better.

In the BLG/DME case the pulp production capacity is the same as in the reference case. Additional biomass is required to produce steam and electricity, but DME is also produced at large quantities. Compared to the reference case, much higher investment (1065 M€) and operating costs are needed, the latter due to the need of importing biomass to produce the required steam and electricity. The pulp production cost is lower than in the reference case, 367 €/tonne (Table B-6).

Work has been carried out to find solutions to integrate the mill and the gasifier better and to decrease steam and electricity demand and thus the need to import biomass. This is however, not taken into account in this study. With increased integration and energy efficiency, and potentially a higher price for DME, this case would score much better.

Finally, in case of ethanol production from pulp, the pulp production is halved compared to the reference case. The investment cost (620 M€) is lower, compared to the reference case (Table B-7). This case doesn’t show good economics. The pulp production cost is 586 €/tonne, much higher than the reference case. This is due to the high investment cost in combination with lower pulp production. The case is in practice only interesting when converting an existing mill, not building a new one like in this study. The investment costs for the modification when converting an existing plant are much lower, and this is especially interesting when a mill is about to close down or need to shift production from pulp.

4.5 Technical and commercial feasibility

4.5.1 Technical feasibility

All subjective scores for the technical feasibility are presented in Table C-5 and summarised in Table 4-2.

Table 4-2 *Technical feasibility of pulp & paper biorefinery cases*

	Lignin extraction	**BLG / DME**	**Ethanol**	**Project average**
Technical feasibility	79.8	62.0	72.3	70.7

For the technical feasibility, the lignin extraction case is better than the project average. This process exists as a demonstration facility which is reflected in a good score for the process definition and maturity. The LignoBoost demonstration plant in Bäckhammar, Sweden opened in January 2007 (Figure 4-7). The demo plant can produce up to 4000 tonnes of lignin per year, which is used for large scale tests. For example, lignin has been used in long term trials to replace coal at a combined cycle heat and power plant. Another example is full-scale trials in a lime kiln in Sweden, where the replacement of fossil fuel was evaluated. The LignoBoost Process is owned and developed by Metso Corporation.

Figure 4-7 *Lignin produced in Bäckhammar*

Black liquor gasification scores below the project average: although well defined, the process is not yet proven (black liquor to DME). DME is not fully accepted as a biofuel which is a drawback, and a big reason for the low score. If methanol (which is an intermediate in the DME production) would be produced instead, the score would have been higher. The black liquor gasification step is proven and the Chemrec BLG Process is under active development, and a pilot plant exists in Piteå, Sweden (Figure 4-8). The design capacity of the Chemrec gasifier is 20 tonnes/day. In the beginning of 2010 the gasifier was operated over 12,000 hours, and the process has shown to be stable, achieving good results. A DME production facility is under construction (Figure 4-8) next to the pilot plant. According to the planning, it will be in operation in September 2010. A larger demonstration plant with a capacity of 500 tonnes/day has been planned.

Figure 4-8 *Volvo DME-truck and the DME plant under construction in Piteå, Spring 2010*

The ethanol case is on average. Positive is that the required process is well identified; negative are the challenges linked to lignocellulosic ethanol (second generation), and the required complex downstream processing. The concept of producing cellulose to be used for ethanol production in a pulp mill has been verified in a full scale test. There is a pilot plant for production of ethanol from wood in Örnsköldsvik, Sweden, operated by SEKAB. The plan is to build a larger demonstration plant within a few years.

4.5.2 Commercial feasibility

All subjective scores for the commercial feasibility are presented in Table C-6 and summarised in Table 4-3.

Table 4-3 *Commercial feasibility of pulp & paper biorefinery cases*

	Lignin extraction	**BLG / DME**	**Ethanol**	**Project average**
Commercial feasibility	83.3	82.8	74.0	71.0

The lignin extraction case scores high and shows to be an attractive project. Strong points are found on two main commercial drivers: tangible competitive advantages and a positive image: renewable energy (solid fuel) without competition with food. The black liquor gasification to DME is highly attractive project from a commercial perspective. Strong points are found on two main commercial drivers: tangible competitive advantages and a positive image: renewable energy (liquid fuel) without competition with food. The pulp mill would have two valuable products to stand on, pulp and DME. The ethanol case is a commercially rather neutral case. Positive legislative impact, but no real benefit on the main issues: competitive advantage and social & environmental (= perception) impact. Question remains whether it is interesting to produce ethanol instead of pulp, seen the lower market price of ethanol. The relatively high investment cost also affects this process, and it looks more attractive to convert an old mill.

4.5.3 SWOT analysis

SWOT analysis for the three biorefinery cases has been carried out and is shown in Appendix D3. All three cases are more or less proven technically; a demonstration plant exists for the lignin case and pilot plants exists for the BLG and ethanol case. However, some gaps need to be closed and improvements need to be done before the concepts become fully commercially viable. The LignoBoost technology for lignin extraction is closest of the three concepts to be built in full scale; the plan is to have a plant built in 2011. The commercial potential of the black liquor gasification is very large, and the industry considers it as an attractive alternative. The ethanol case may be a good option in older mills, however, some technical gaps still exist for full scale implementation.

4.6 Summary and conclusions

The pulp and paper sector has a great potential for producing bio-based transportation fuels to replace gasoline or diesel, biofuels to replace fossil fuel use in lime kilns, or in combined cycle heat and power plants, or in the production of biochemicals. This market sector uses also wood, origin from non-food sources, as a raw material. The economics in non subsidised production is also good as well as the technical development stage of the processes studied. Table 4-4 shows the cost of pulp production in the reference case, as well as in the biorefinery cases.

Table 4-4 *Cost of pulp production in reference case and biorefinery cases*

Case	**Production cost of softwood pulp (90% dry) (€/t)**
Reference case - pulp from softwood	398
Biorefinery case - lignin extraction	347
Biorefinery case - black liquor gasification/DME	367
Biorefinery case - ethanol in a pulp mill	586

All three cases are more or less proven technically; a demonstration plant exists for the lignin case and pilot plants exists for the BLG and ethanol case. However, some gaps need to be closed and improvements need to be done before the concepts are fully commercially viable. The LignoBoost technology for lignin extraction is closest of the three concepts to be built in full scale; the first full scale unit is planned to be built in 2011. Black liquor gasification is considered as an attractive biorefinery

case. With the construction of a DME plant to utilise the syngas from a black liquor gasifier in Sweden, the concept will be fully proven. There is a high investment cost; however, with a combination of grants and economic incentives, it is an attractive case. The ethanol case may be a good option in older mills and in places where the cost of raw material is low. However, some technology gaps remains like the enzymes to hydrolyse wood isn't fully developed. The yield of wood-to-ethanol is not that good, but better utilisation of by-products and integrating it with for example a lignin extraction unit (which could use the CO_2 produced in the ethanol plant) would increase the economics.

The lignin extraction case shows good scores in both technical and commercial feasibility. The concept has promising economics, mainly due to a potential capacity increase. Lignin can today be used in combustion applications, but research is carried out to use it as a raw material for more advanced applications as carbon fibre. This would increase the lignin price radically.

The black liquor gasification with DME production shows good commercial scores but lower technical score, mainly due to the unsecure market around DME. Much work has been carried out the last couple of years to integrate the gasifier and DME unit even more with the pulp mill. If this can be implemented in a mill, the concept would show much better economics. A higher DME price, which is possible if DME is fully accepted as a biofuel, would also result in a better score for this case.

Ethanol is on average both commercially and technically. Investment cost is high in this case, but in practice this case wouldn't be built as a new mill, but to be retrofitted in an existing mill. The investment cost would then be much lower and the economics would be better. Increased utilisation of by-products (CO_2) and producing biogas from the effluent would further improve this case. The production of ethanol from wood on larger scales still needs to be proven.

Today's modern pulp mills have the possibility to generate surplus energy and have a great potential to be energy suppliers to other industries and society. Pulp mills are well suitable for becoming large scale biorefineries and the industry has a lot of competence in running a plant with biomass as a raw material. Integration with the pulp mill and achieving synergy effects are often possible. This work has shown that it is possible to decrease the pulp production cost by implementing different biorefinery concepts.

5. Co-production of biofuels in existing refinery units

5.1 Introduction

Nowadays, there is a growing interest for biofuels in the European Union for two main reasons:

- Road transport sector has been one of the main responsibles for the increase of greenhouse gases emissions in the last years. Substitution of fossil fuels by biofuels can contribute to the reduction of these emissions.
- Primary energy consumption is mainly based on fossil sources, i.e. coal, gas and oil. Furthermore, oil consumption in Europe depends mainly on import. The use of biofuels can contribute to reduce the global dependency on the use of traditional fossil-based energy.

To face these two important problems, the European Union has introduced measures to promote a greater use of more environmentally-friendly fuels in road transport.

One example of these measures is the EU Directive 2003/30/EC, that promotes the mandatory incorporation of a minimum amount of biofuels in road transport fuels (gasoline and diesel), 5.75% in energy basis in 2010. This European Directive has been translated to the particular legislation of the different countries. In case of Spain, the minimum participation of biofuels has been increased up to 5.83% in energy basis. Furthermore, in the Spanish case a flexible scenario has been created, in which a minimum amount of 3.9% must be incorporated in one of the two fuels (gasoline or diesel) with the condition to incorporate a higher percentage of biofuels in the other, in order to achieve 5.83% of participation in the global amount of gasoline and diesel put into the market.

By 2020, the proposal is to increase this participation of biofuels in transport up to 10% (with the following distribution: 6% from liquid biofuels, 2% from bio-hydrogen and 2% from bio-electricity).

Other Directive promoted by the European Union, that reviews and extends the previously commented, is the 2009/30/EC (“Fuel Quality Directive”). This Directive promotes the mandatory monitoring and reporting of "lifecycle greenhouse emissions" from fuels as of 2009, and an obligation for fuel suppliers to ensure that greenhouse gases produced by their fuels throughout their life-cycle (i.e. production, transport and use) are cut by 1% per year between 2011 and 2020.

Beside incorporating a minimum amount of biofuels, road transport fuels must comply with the European quality standards, EN-228 for gasoline and EN-590 for diesel. Some specifications included in these standards limit the incorporation of high volumes of conventional biofuels (bioethanol and biodiesel):

- In EN-228 for gasoline there is a limit in the maximum vapour pressure (60 kPa), maximum oxygenated compounds (3.7 wt.%) with maximum limits for some specific compounds (10 vol% ethanol and 15 vol% of ETBE, for example) and distillation curve in gasoline. These are some of the parameters that prevent the incorporation of high quantities of bioethanol in gasoline.
- In EN-590 for diesel there is a limit for incorporation of FAME (7 vol%). There is also a limitation in the maximum density allowed in diesel. Due to the high density of FAME, this is a property that also could limit the incorporation of high amounts of biodiesel.

Such measures pose barriers to a higher participation of conventional biofuels, bioethanol and biodiesel, that are nowadays the only ones present in the market at significant commercial amounts. For these reasons, it is neccesary to develop new processes and ways to produce biofuels more compatible with fossil fuels than conventional oxygenated ones.

5.2 Reference cases

A conventional oil refinery is a facility in which fuels and chemicals are produced from petroleum. The flow diagram of a refinery is vary complicated, consisting of atmospheric and vacuum distillation of oil, followed by downstream processing and conversion of the main streams generated during the distillation. There is a high interrrelation between the different process units. Each one of the final fuels are composed of a mixture of different streams, coming from several processes.

Two different units of a conventional oil refinery, FCC and HDS, have been chosen as reference cases for this sector.

5.2.1 Fluid Catalytic Cracking (FCC) unit

The block diagram for the Fluid Catalytic Cracking (FCC) and gas concentration units is shown in Figure 5-1. The mass balance is given in Table A-17.

In the FCC unit a heavy fraction of petroleum (vacuum gasoil) is processed at low pressure (1-3 bar) and high temperature (490-550ºC) in the presence of a circulating acid catalyst. In these conditions, vacuum gasoil heavy molecules are cracked into lighter molecules, upgrading this low-value feedstock into high-value products (LPG, naphtha, gasoil and heavy oil). In the cracking reactions, some by-products are also produced: fuel gas, which is used as internal fuel in refinery furnaces, coke, which deactivates temporarily the catalyst and is burned in the regenerator (generating in this way most part of the heat demand by the process) and H_2S, which is converted in a unit downstream in solid sulphur.

The FCC unit has two main reaction vessels:

- Reactor, in which the cracking reactions take place. During cracking reactions, coke is produced, deactivating the catalyst by depositing on its active sites.
- Regenerator, where the coke produced in the reactor is burnt off in the presence of air, regenerating the catalyst.

The gas concentration unit consists of a group of fractionation columns where the reaction products are separated. In the gas concentration unit, besides fractionation columns, there are also other processes (amine plant) to eliminate impurities present in some of the product streams (eliminate H_2S from fuel gas).

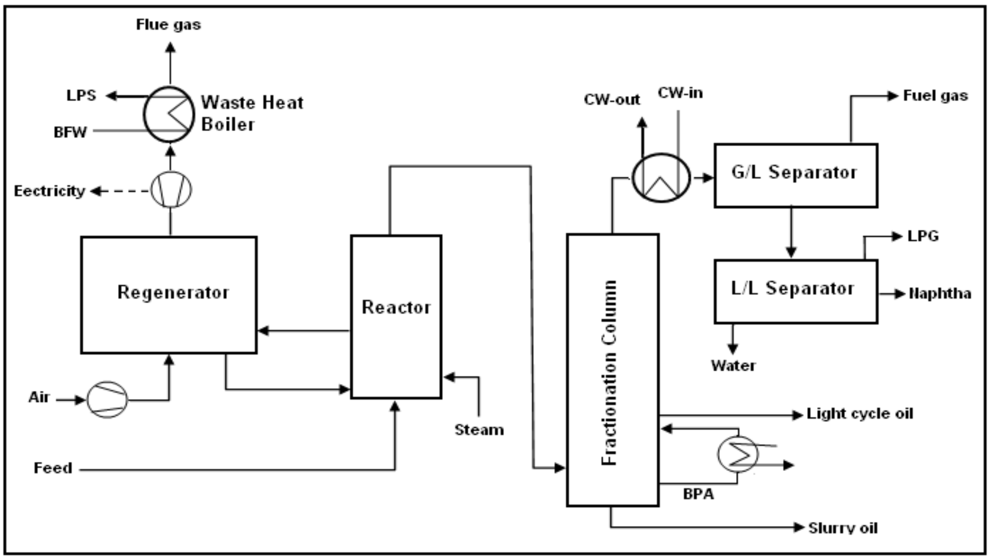

Figure 5-1 *Block diagram for FCC and gas concentration units*

The mass yield of the main product (liquefied petroleum gas, naphtha, diesel and heavy oil) is 93.8 wt.%.

5.2.2 Hydrodesulphurisation (HDS) unit

In the Hydrodesulphurisation unit (HDS), a blend of middle distillates (kerosene and diesel) reacts with hydrogen at high pressure and high temperature, in the presence of a fix-bed metal catalyst (sulfidised Co-Mo or Ni-Mo catalyst). The objective of the process is to eliminate the sulphur compounds present in the feed, in order to fulfil the maximum amount of sulphur allowed in the end product. Sulphur compounds are selectively cracked to hydrocarbons and H_2S. In these cracking reactions, a low amount of fuel gas is also produced. The H_2S generated is absorbed with an amine-type compound in an absorber, and converted to solid sulphur in a downstream processing unit (sulphur recovery unit).

The block diagram for the hydrodesulphurisation process is shown in Figure 5-2. The mass balance is given in Table A-18.

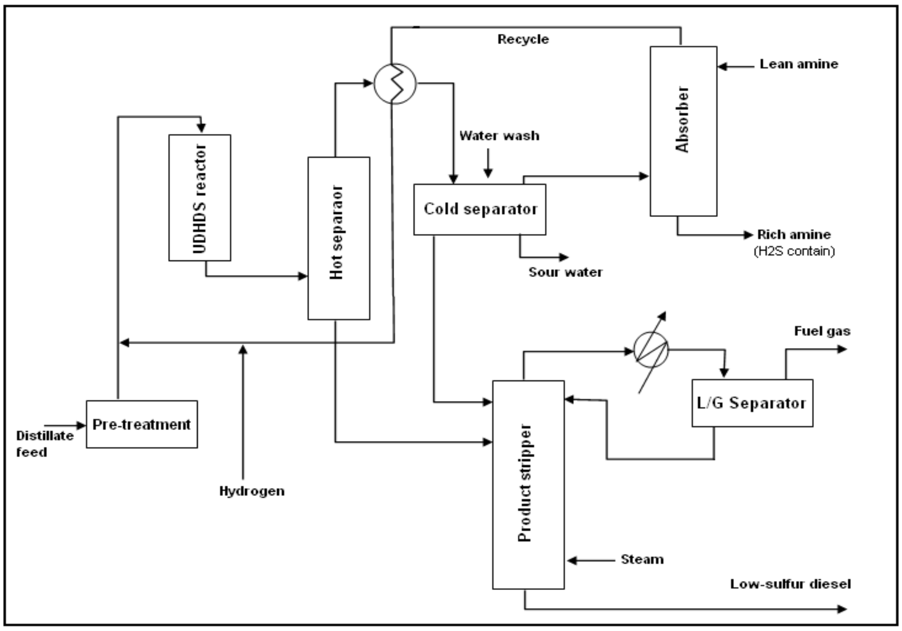

Figure 5-2 *Block diagram for HDS unit*

The mass yield of hydro treated middle distillates is 97.8 wt.%.

5.3 Integrated biorefinery cases

There are two biorefinery cases in the conventional oil refinery sector based on the reference case of FCC and HDS units:

- Vegetable oil as partial feed of FCC unit;
- Vegetable oil as partial feed of HDS unit.

5.3.1 Co-processing of vegetable oil as a partial feed for FCC unit

In the first biorefinery case a vegetable oil is used as partial feed for the Fluid Catalytic Cracking Process (FCC). The amount of vegetable oil is 10 wt.% of FCC feed.

The mass balance for this biorefinery case is given in Table A-19. The results have been obtained in previous research studies carried out by Repsol in an FCC pilot plant unit, which simulates the operating conditions of an industrial unit.

There are several factors that affect the mass balance: type of FCC catalyst used, operating conditions of the industrial unit, type of vegetable oil used and percentage of vegetable oil in the feed. The case presented corresponds to the specific conditions in one of the several industrial units of Repsol.

The mass yield of the main products (liquefied petroleum gas, naphtha, diesel and heavy oil) in the biorefinery case is 92.3 wt.%, which is somewhat lower, compared to the reference case. The production of by-products (fuel gas, coke, H_2S) is similar to the base case. There is a loss of production of valuable products, because part of the vegetable oil is cracked to non-commercial by-products (CO, CO_2 and water).

The need for energy and utilities is a little bit higher in the biorefinery case, compared to the reference case, so there is a slight increase in operating costs when vegetable oil is co-processed.

5.3.2 Co-processing of vegetable oil as a partial feed of HDS unit

In biorefinery case vegetable oil is used as a partial feed of hydrodesulphurisation process (HDS). The amount of vegetable oil is 10 wt.% of HDS feed.

The mass balance of HDS biorefinery case is given in Table A-20. The results have been obtained in previous research studies developed by Repsol in a HDS pilot plant unit, which simulates the operating conditions of an industrial unit.

There are several factors that could affect to the mass balance results: type of HDS catalyst used (CoMo or NiMo), operating conditions of the industrial unit, type of vegetable oil used and percentage of vegetable oil in the feed. The case presented corresponds to the specific conditions in one of the several industrial units of Repsol.

The mass yield of hydro treated middle distillates in the biorefinery case is 96.5 wt.%, which is somewhat lower, compared to the reference case. Production of by-products increase, mainly due to the additional production of propane, that comes from the hydro-deoxygenation of vegetable oil.

The need for energy and utilities in the biorefinery case is a little bit higher in the biorefinery case, compared to the reference case. It is also important to highlight that the hydrogen consumption also has a significant increase in the biorefinery alternative, because the vegetable oil consume more hydrogen in the process than the fossil feedstock.

5.4 Results techno-economic assessment

5.4.1 Co-processing of vegetable oil as a partial feed of FCC unit

In the first biorefinery case a vegetable oil is used as partial feed for the Fluid Catalytic Cracking Process. The amount of vegetable oil is 10 wt.% of FCC feed.

From a *technical point of view*, the following considerations must be taken into account:

- Refined vegetable oil acquired in the market can be used as biorefinery feedstock. In this way, potential impacts of contaminants (metals, free fatty acids, phospholipids, etc.) present in the crude vegetable oil on the catalyst and equipment (feed pre-heat exchangers and furnace, etc.) of the FCC unit are avoided. There is no need to modify equipment in use, or to install a pre-treatment stage.
- Other residual and low-price renewable feedstock could be used (animal fats, used cooking oil, etc), if they are properly pre-treated to eliminate impurities.

The vegetable oil that partly substitutes fossil vacuum gasoil is also upgraded into lighter products in the operating conditions of the unit. Due to the presence of oxygen in the vegetable oil, some oxygenated products are also produced. Most part of the oxygen is eliminated as non-value by-products like CO, CO_2 and water. The production of non-value by-products from the renewable feedstock has an economic impact in the margin. The CO, CO_2 and water produced must be treated in the units located downstream. CO and CO_2 end in the fuel gas stream. Water is separated from the produced naphtha (as sour water), and should be treated in the water treatment plant. This further treatment leads to an extra cost in auxiliaries/energy.

Due to the almost complete removal of oxygen during the cracking process, only a minimum amount of oxygenated compounds (at ppm levels) are finally present in the produced fuels. For this reason some of the undesirable properties of conventional biofuel (bioethanol and biodiesel) are avoided.

From a molecular point of view, the compounds obtained in the cracking of vegetable oil are very similar to those obtained from fossil fuels. Moreover, presence of some desirable compounds is higher in the biorefinery case, leading to improved properties in some of the main products: higher octane in FCC naphtha and lower density and higher cetane in FCC gasoil. In this way, a premium in quality could be considered for these biofuels.

The use of the biofuel produced by co-processing does not require any modification in the current gasoline and diesel motors, even at high percentage, due to the absence of oxygenated compounds and the similarity with conventional gasoline and diesel. For this reason, the automotive sector (car manufacturers) is very favourable to the use of this kind of biofuel.

From an ***economic point of view***, the following considerations must be taken into account:

- One of the main benefits is that there is no need for additional investment. Existing units could be used for biofuels production.
- However, there is a clear increase in production cost (loss of economic margin in the unit), that in the case of the FCC unit is between 10 and 20%, compared to the reference case, referred as €/tonne of total feed processed (fossil + renewable).

Two main factors affecting the production cost are:

- Differential price between cost of vacuum gasoil and vegetable oil: refined vegetable oil is more expensive;
- Vegetable oil is partially cracked to non-valuable products: CO, CO_2 and water (loss of production).

There is also an increase in operating costs, that is not significant compared to the feed cost (vegetable oil)

5.4.2 Co-processing of vegetable oil as a partial feed of HDS unit

In biorefinery case vegetable oil is used as a partial feed of hydrodesulphurisation process (HDS). The amount of vegetable oil is 10 wt.% of HDS feed.

From a ***technical point of view***, the following considerations must be taken into account:

- Refined vegetable oil acquired in the market can be used as biorefinery feedstock. In this way, potential impacts of contaminants (metals, free fatty acids, phospholipids, etc.) present in the crude vegetable oil on the catalyst and equipment (feed pre-heat exchangers and furnace, etc.) of the HDS unit are avoided. There is no need to modify equipment in use, or to install a pre-treatment stage.
- Other residual and low-price renewable feedstock could be used (animal fats, used cooking oil, etc), if they are properly pre-treated to eliminate impurities.

The vegetable oil that partly substitutes fossil middle distillates also reacts with hydrogen in the operating conditions of the unit. Vegetable oil is mainly constituted of triglycerides (saturated and unsaturated fatty acids of 14 to 22 carbon atoms, combined with a glycerol backbone). Under HDS process conditions, triglycerides are converted to propane and parrafins. Oxygen present in the vegetable oil is released as non-value by-products like CO, CO_2 and water. The production on non-value by-products from the renewable feedstock has an economic impact in the margin.

The CO, CO_2 and water produced must be treated in the units located downstream. CO and CO_2 end in the fuel gas stream. Water is separated from the produced naphtha (as sour water), and should be treated in the water treatment plant. This further treatment leads to an extra cost in auxiliaries/energy.

The oxygen present in the vegetable oil is completely removed by the reactions shown in Figure 5-3 (decarbonilation, descarboxylation and dehydratation). The hydrogen also reacts with the double bonds present in the unsaturated fatty acids. In this way, paraffin is the main product of the hydrogenation of vegetable oil. The hydrogen consumption increases for unsaturated vegetable oils.

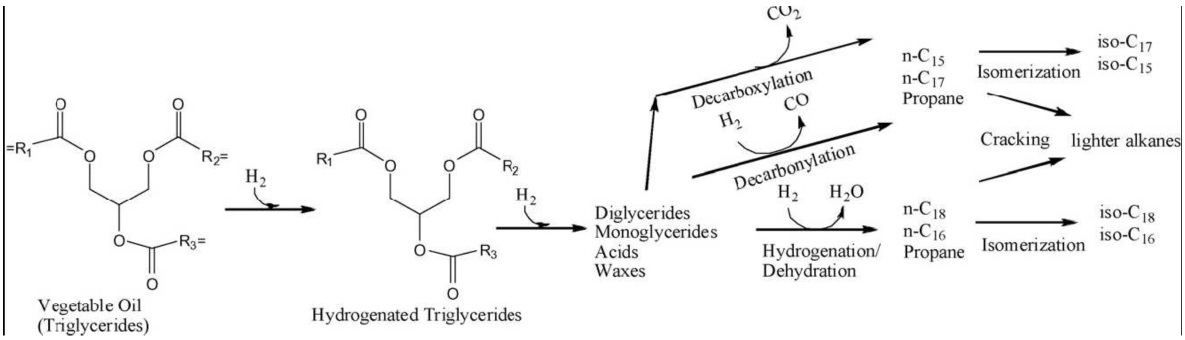

Figure 5-3 *Oxygen removal reactions of vegetable oil*

From a molecular point of view, the compounds obtained in the HDS of vegetable oil are very similar to those obtained from fossil fuels. Moreover, paraffin is the main product obtained in the HDS of vegetable oil, which are highly appreciated components for diesel. It leads to improved properties in the final product: lower density and higher cetane in diesel. In this way, a premium in quality could be considered for these biofuel.

Only cold flow properties are worse for some vegetable oils, compared to fossil diesel. The use of biofuels produced by co-processing does not require any modification in the current gasoline and diesel motors, even at high percentage, due to the absence of oxygenated compounds and to the similarity with conventional gasoline and diesel. For this reason the automotive sector (car manufacturers) is very favourable to the use of this kind of biofuel.

From an *economic point of view*, the conclusions are very similar to the previously indicated for the FCC biorefinery case. The following considerations must be taken into account:

- One of the main benefits of this alternative route of biofuels production is that there is no need for additional investment. Existing units could be used for biofuels production.
- However, there is a clear increase in production cost (loss of economic margin in the unit), that in the case of the HDS unit is slightly lower than in the FCC case: between 5 and 15%, compared to reference case, referred as €/tonne of total feed processed (fossil + renewable).

The main factors affecting production cost are:

- Differential price between cost of fossil feedstock and vegetable oil: refined vegetable oil is more expensive than fossil middle distillates, but in this case the difference is lower than in the FCC case.
- Vegetable oil is partially cracked to non-valuable products: CO, CO_2 and water (loss of production).

- There is an increase in hydrogen consumption in the HDS unit when vegetable oil is co-processed. Hydrogen is an expensive reactive.

Other point to highlight is that production of green diesel through this route is more expensive than biodiesel production (FAME) via the transesterification process.

5.5 Technical and commercial feasibility analysis

5.5.1 Technical feasibility analysis

In Table C-7 the results of the technical feasibility study of both biorefinery cases are presented.

Both biorefinery schemes have obtained the highest scores of all the biorefinery cases studied. Average technical feasibility is 71%, while in case of FCC it is 86% and in the HDS case 89%. This result is not surprising, because both alternatives have been demonstrated from a technical point of view.

Both processes are considered highly realistic: processes well defined, no major technological challenges and no need for additional downstream processing. Products are more or less referenced in the targeted (fuel) markets.

5.5.2 Commercial feasibility analysis

In Table C-8 the results of the commercial feasibility study of both biorefinery cases are presented.

Commercial feasibility is below par. Incorporation of vegetable oil in a conventional refinery is leading to a more expensive product. There is absolutely no integration benefit, and there may be concerns about using food grade oil for fuel.

Although not fully appreciated by all respondents, there are some technical benefits in these integrated schemes. The most important advantage is that biofuels produced from vegetable oil have improved qualities compared with the fossil ones: higher octane for "green gasoline" produced in FCC and higher cetane and lower density for "green diesel" produced in HDS. This fact could also result in an economic benefit (could result in a "premium" for quality of the produced biofuels). Although this quality premium will not compensate in any case the loss of margin in the unit.

The main drivers are the supportive legislation (blending in biofuels) and the production of renewable energy.

5.5.3 SWOT analysis

The results of the SWOT analysis carried out by different partners for each biorefinery scheme is presented in Appendix D4.

5.6 Summary and conclusions

The main conclusions obtained for the biorefinery cases are:

- The alternative for biofuels production is technically viable. From a technical point of view, there are some advantages for the produced biofuels:
    - Due to the almost complete deoxygenation achieved in the process, biofuels produced are very similar to fossil fuels.
    - Some of the properties of the biofuels are even better than the fossil fuels: in the FCC unit, the "green gasoline" has a higher octane number and the "green diesel" has better cetane and density. In the HDS unit, the "green diesel" has also lower density and higher cetane.

- From an economic point of view, the main advantage of this alternative is that there is no need for extra investment, because existing refinery units can be used. However, there is also an important disadvantage, which is the significant increase in the production cost.
- The main factors affecting the increase in the cost of production are:
  - Differential price between vegetable oil and fossil feedstock: both in the FCC and the HDS cases, the vegetable oil is more expensive than the fossil feedstock. In case of the HDS, the differential is lower than in case of the FCC unit.
  - There is a loss of production due to the removal of oxygen in vegetable oil as non-valuable products (CO, CO_2 and water).
  - Cost of production could be lower if "residual feedstock" is used (animal fat and used cooking oil).
- Nowadays, there is no mechanism to compensate the higher cost of production of this alternative. Tax exemptions should be applied to biofuels produced by this route, as it happens nowadays with conventional biofuels.
- Co-processing of vegetable oil in the HDS unit is preferred compared with the FCC unit by two main reasons:
  - Increase in production cost is lower.
  - It is more focused in diesel production (there is an important deficit of diesel production in Europe).
- This alternative does not compete with current biofuels. It is a complementary route:
  - Production of biodiesel (FAME) is more cost effective than co-processing vegetable oil in HDS unit, but limited by EN590.
  - Due to the similarity between the biofuels produced by this route and the fossil transport fuels, it is a way to achieve higher participation of biofuels without modifications in the current engines.

6. Evaluation of integrated biorefinery technologies in power industry

In the power sector two cases have been assessed: a biorefinery based on a combustion based Combined Heat and Power (=CHP) plant and a biorefinery based on a gasification based power plant. The combustion based plant is integrated with the production of pyrolysis oil from biomass. Since in the production of pyrolysis oil a combustion reactor is required, the integration of pyrolysis oil production with a combustion based power plant is expected to give advantages over stand-alone pyrolysis. The gasification based power plant is integrated with the production of transportation fuels and chemicals. The fuel gas produced by gasification contains a number of products that, with relative low additional investments, can be converted into high-value products. This concept is expected to give economic advantages over stand-alone power production.

6.1 Combustion based power production

Reference case

Combustion based technologies are state-of-the-art in power production from solid and liquid fuels in Europe. Different reactor technologies exist for combustion and different feedstocks are used. Nevertheless, basic principles are similar. The fuel used (coal, peat, biomass, waste and/or oil) is combusted. The heat released by combustion is used to generate steam that is expanded in a steam turbine to generate electricity. Residual heat, present in the expanded steam, can either be disposed or be utilised in district heating. The possibilities to use the residual heat depend on the local presence of heat users and infrastructure for distribution of heat. Dependent on infrastructure and heat demand in the neighbourhood of the plant, possibilities for CHP vary over Europe.

In the reference case a 67 MW_{th} circulating fluidised bed (=CFB) boiler is used as combustion technology. Peat is used as fuel for the combustion plant. In Finland peat is considered to be a renewable fuel, whereas in other European countries it is not. The differences in performance when using biomass as feedstock are considered to be minor. A simplified block diagram for the reference case is given in Figure 6-1. Peat is combusted with air and generates flue gas and ash. Heat is recovered from the flue gas to generate steam that is subsequently used to generate electricity.

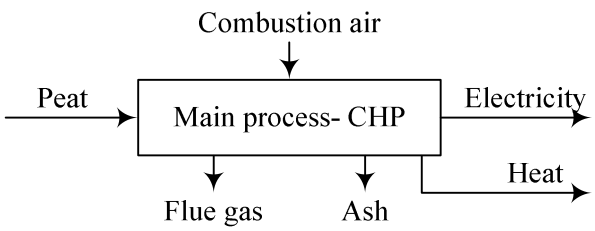

Figure 6-1 *Block diagram for CHP plant using peat*

Integrated biorefinery case

Fast or flash pyrolysis is a process that converts biomass into a liquid product that can be used for a wide range of different applications. Pyrolysis oil can be used for heat and power production, for recovery of high-value chemicals and for upgrading to transportation fuels. The pyrolysis liquid has the advantage of being a liquid that is stored easier than solids, that is used easier in decentralised applications, and that has a high energy density offering advantages in transportation.

In the pyrolysis process biomass is heated in an inert atmosphere to ~550 ^oC. Due to the temperature the biomass is thermally cracked and converted into vapours, gas and char. To achieve a high yield of vapours that can be condensed to a liquid, the residence time in the pyrolysis process has to be short, typically below 1 second. At a short residence time the maximum yield of liquid products is about 70

wt.%. Char and gas generated in the pyrolysis process are combusted to supply the heat required for pyrolysis.

VTT (Finland) has developed an integrated concept in which fast pyrolysis is integrated with a circulating fluidised bed boiler. By doing this a separate combustor, for combusting char and gases released by the pyrolysis process, is avoided. The integration offers a number of technical and economic advantages compared to stand-alone pyrolysis:

- A high overall efficiency compared to a stand-alone pyrolysis concepts;
- Lower investment costs since a dedicated combustor for the pyrolysis process is not required (effects on the costs of the main boiler are considered to be marginal);
- Lower operating costs than stand-alone pyrolysis due to reduced man-power;
- Operating flexibility due to full exploitation of by-products in the main boiler;
- Operation is easier, because there is no need to combust the by-product char in a small scale sub-optimal boiler.

The integrated concept is depicted in Figure 6-2. Forestry residues are dried and pyrolysed giving pyrolysis oil. Char and gas produced in the pyrolysis process are combusted in the CHP plant, together with peat. Heat produced in the CHP plant is used to heat the dryer and the pyrolysis process and for the production of electricity in a steam turbine and for district heating.

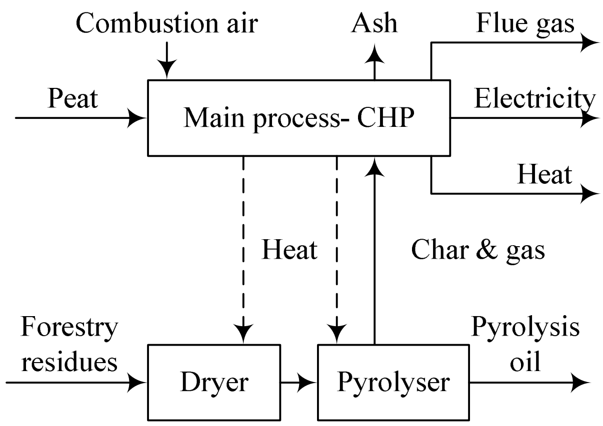

Figure 6-2 *Block diagram for fast pyrolysis process integrated with CHP plant using peat*

The integrated biorefinery concept has been tested by Metso Corporation in Tampere. A 2 MW_{th} pyrolysis unit producing 7 tonnes pyrolysis oil per day was integrated with a 4 MW_{th} circulating fluidised bed boiler. The integrated plant was successfully operated in 2009.

Techno-economic assessment

Mass- and energy balances for both the reference and the integrated case are given in Table A-21. In the reference case peat is used as the only fuel for the plant. The efficiency of electricity production is 25% and 60% of the input is converted to heat giving an overall energy efficiency of 85%.

In the integrated case forestry residues are used as additional input to the plant and converted to pyrolysis oil. The energy efficiency of pyrolysis oil production from the forestry residues is 70%. The pyrolysis oil represents 17% of the energy output of the whole biorefinery. When the whole plant is considered the efficiency of electricity production is 18% and for heat production 50%. The efficiency of electricity and heat production are lower than for the reference case since part of the input to the plant is converted into pyrolysis oil. The energy efficiency of the integrated biorefinery is 85%. This equals the energy efficiency of the reference case (the stand-alone CHP plant).

Electricity production costs

For both the reference case and the integrated biorefinery case the costs of electricity production have been determined, see Table 6-1 (as well as Tables B-8 and B-9). For both cases the operating time is 5500 hours/year, based on the heat demand in district heating. The costs of peat are 22 €/tonne and of forestry residues 43.5 €/tonne. The capital cost of the reference case, a 67 $MW_{th,input}$ CHP plant, is 34 M€. For the integrated case, the CHP plant and a 22 $MW_{th,input}$ pyrolysis plant, the capital investment is 45 M€. Capital costs are depreciated in 12 years. Operating and maintenance costs (O&M costs) have been set at 8% of the capital costs for the reference case and at 10% of the capital cost for the integrated case. For the integrated case a slightly higher percentage has been chosen due to increased complexity of the plant. Heat is sold at 15 €/MWh.

Table 6-1 *Cost of power production (€/MWh$_e$) for reference and integrated biorefinery cases for a combustion based biorefinery*

	Reference case	Integrated case
Feedstock costs		
- Peat	35.2	38.3
- Forestry residues		24.4
Capital costs	30.3	43.2
Operating and maintenance costs	30.4	49.3
Gross production costs	95.9	155.2
Co-products		
- Heat	36.0	48.0
- Pyrolysis oil		19.3
Total revenues co-products	36.0	67.3
Total power production costs	59.9	87.9

In the reference case, the gross production costs are 95.9 €/MWh$_e$, with feedstock costs, capital costs and O&M costs having about equal shares. Revenues from heat production are 36.0 €/MWh$_e$ giving a net cost of power production of 59.9 €/MWh.

In the integrated case, the gross costs of electricity production increase to 155.2 €/MWh. This is caused by additional costs for feedstock (wood residues), an increase in capital costs and a slight decrease in electricity production. Just like in the reference case, feedstock costs, capital costs and O&M costs have about the same share in gross costs of electricity production. Revenues from heat production increase in the integrated case due to an increase in the ratio between heat and power production. In the integrated case it is assumed that pyrolysis oil is sold at a value of 91 €/tonne. Per MWh of electricity produced this gives a revenue of 19.3 €. Total revenues from the sales of heat and pyrolysis oil are 67.3 €/MWh$_e$ giving net power production costs of 87.9 €/MWh. This is significantly higher than in the reference case. To arrive for the integrated case at power production costs of 59.9 €/MWh, just like in the reference case, pyrolysis oil has to be sold at 247 €/tonne.

Technical and commercial feasibility

The technical feasibility for the integrated case is scored at 64.6 (see Table C-9). This is lower than the project average technical feasibility of 70.7. The major positive point in the evaluation of the technical feasibility is that no significant downstream processing is required in the integrated process. The main process, CHP production, is relatively independent of the pyrolysis process added in the biorefinery case and only 2 unit operations are added in the biorefinery case: drying and pyrolysis. Major negative points in the evaluation are the immaturity of the pyrolysis process and the need to develop applications for the pyrolysis oil produced. The pyrolysis process has been demonstrated by several companies (e.g. VTT, BTG and Dynamotive) at (pre)commercial scale. Nevertheless, it can still not be considered to be an industrial mature process. Several applications are under development for the pyrolysis oil produced, with some of them already being demonstrated at considerable scale. However, pyrolysis oil is still not a commodity with an accompanying market.

The commercial feasibility for the integrated case is scored at 65.8 and hence also below the project average commercial feasibility of 71.0 (see Table C-10). The major positive point in the commercial feasibility is the generation of a renewable product with positive impacts for the environment. The major negative points are that there is not an existing market addressed and the introduction of the new product does not lead to economical benefits for the user.

SWOT analysis
The major comments by respondents in the SWOT analysis are given in Table 6-2. For a more detailed SWOT analysis see Appendix D.5.1. Similar remarks as in the technical and commercial feasibility assessment appear here. The fact that pyrolysis oil is a liquid is positively appreciated and recognised as strength of the concept. The liquid can be stored and later on used to meet peak demand in heat and electricity production either centralised or decentralised. Decentralised use of pyrolysis oil, instead of wood, is expected to give lower emissions. Opportunities are offered at high petroleum prices. The pyrolysis oil can replace fuel oil and at this improves the economic viability of the process with increasing petroleum prices. Furthermore, opportunities are in upgrading of the pyrolysis oil to replace fossil based transportation fuels. The immaturity of the process is considered as a weakness. Furthermore, the varying quality and the possible harmful properties of the pyrolysis oil are brought up as negative points. The latter points once again reflect that pyrolysis oil is not yet a commodity product accepted by society.

Table 6-2 *Major items in SWOT analysis for pyrolysis based biorefinery*

Strengths - Pyrolysis oil is liquid this has advantages in storage, transportation and use	Weaknesses - Unproven technology - Varying quality of oil
Opportunities - Increasing price of petroleum - Upgrading to 2nd generation transportation fuels	Threats - Pyrolysis oil might have unwanted properties - Competition with other bioliquids

6.2 Gasification based power production

Reference case
Power generation from natural gas with combined cycles is state-of-the-art technology. By gasification biomass can be converted into a fuel gas that can be used for power generation in combined cycles. The combination of biomass gasification and combined cycle technology has been demonstrated at the Varnamo plant in Sweden at a scale of 6 MW_e. The integrated technology is not considered to be technologically mature at the moment. A few biomass gasification demonstration plants have been built at small scale, some of them for power generation and some of them for Combined Heat and Power production. A few other gasification plants have been built for co-firing biomass in existing coal-fired power plants.

A simplified block diagram for the reference case is given in Figure 6-3. Biomass is dried to a moisture content of ~15 wt.% before gasification. After that, the biomass is gasified with preheated air in an atmospheric gasifier. The gas exiting the gasifier is cleaned before it is compressed and fed to the combined cycle section. Cleaning consists of dust removal, tar removal and removal of contaminants like H_2S and HCl. The (cleaned) gas is pressurised and fired in a gas turbine. Flue gas produced is expanded for electricity generation. Heat present in the fuel gas from the gasifier and the flue gas after expansion in the gas turbine is recovered in the Heat Recovery Steam Generator (HRSG) and steam produced by heat recovery is fed into the steam turbine (the combination of the gas turbine and steam turbine is the combined cycle) for additional electricity generation.

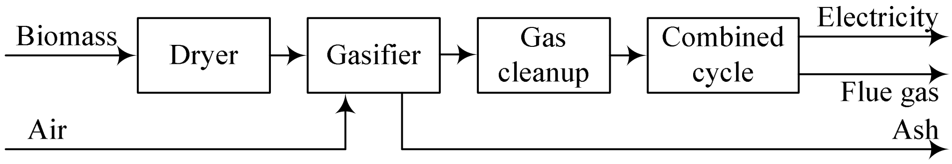

Figure 6-3 *Block diagram for biomass integrated gasification combined cycle plant*

Integrated biorefinery case
Gasification of biomass at temperatures below 900°C produces a mixture of gaseous components. The gas produced contains a number of valuable components like ethylene, BTX, tars and H_2 and CO. In the integrated biorefinery case these components are separated from the gas to generate additional income.

A simplified block diagram for the integrated biorefinery case is given in Figure 6-4. Biomass is gasified in an indirectly heated gasifier to produce a fuel gas. Heat required for the gasification is produced by combustion of char formed in the gasification. After cooling of the gas, a cyclone is used to remove the bulk of the dust from the gas. BTX[2] and tars are separated from the gas by the OLGA scrubbing process developed by ECN. BTX and tars are further separated by distillation. After tar removal, contaminants in the gas (chlorine, ammonia and sulphur) are removed by scrubbing processes and guard beds. CO_2 is removed from the fuel gas by scrubbing to enable cryogenic separation. In the cryogenic separation the fuel gas is split in ethylene, CH_4 and synthesis gas. The synthesis gas is converted into mixed alcohols by catalytic conversion. CH_4 from the cryogenic distillation is together with off-gas from the catalytic synthesis used for power generation in a combined cycle.

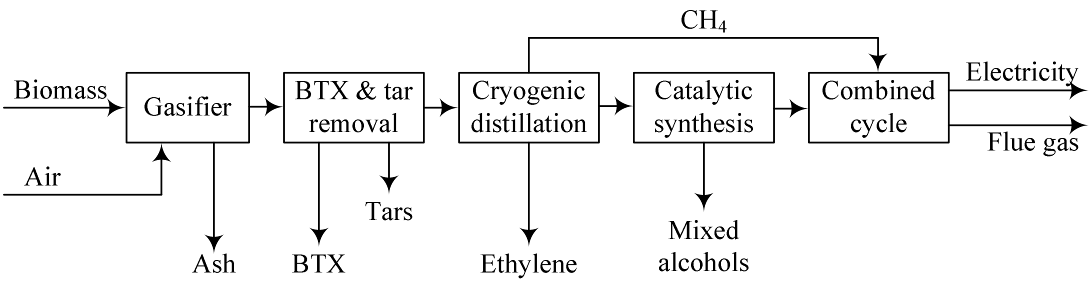

Figure 6-4 *Block diagram for gasification based biorefinery*

The combination of gasification and combined cycles is proven technology for coal. For biomass a 6 MW_e demonstration plant has been operated in Varnamo, Sweden. For coal, plants producing multiple products via gasification exist, e.g. the Great Plains synfuels plant in the USA. The Dakota gasification company produces with the Great Plains plant apart from the main product synthetic natural gas: ammonium sulphate, ammonia, cresylic acid, naphtha and phenol. Clearly, the development of such plants for biomass is challenging. Not only due to technology risks but also since reliable supply of biomass at large scale is required.

Techno-economic assessment
The mass and energy balances for both the reference and the integrated case are given in Table A-22. In the reference case the plant only produces electricity. The efficiency of electricity production is 46%.

In the integrated biorefinery case chemicals are separated from the fuel gas produced by gasification and part of the gas is converted by catalytic synthesis to mixed alcohols. The efficiency of electricity production in the biorefinery drops to 13% since a major part of the fuel gas is converted into chemicals and transportation fuel. On energy basis 22% of the biomass feedstock is converted into transpor-

[2] BTX = Benzene, toluene and xylenes

tation fuel (mixed alcohols) and 25% into chemical products (ethylene, BTX and tars). The total energy efficiency of the integrated biorefinery case is 60%.

Electricity production costs
The costs of electricity production have been calculated assuming an operating of 8000 hours/year. For the biomass feedstock a cost of 40 €/wet tonne has been assumed, or at 50 wt.% moisture a value of 80 €/dry tonne. The capital cost of the reference case a 157 MW_e biomass integrated gasification combined cycle plant has been estimated to be 230 M€. This cost estimate is based on the costs from literature for mature technology. For the integrated biorefinery case the additional investments, for separating the chemicals and converting gas to mixed alcohols, are estimated to be 62 M€. This gives a total investment for the integrated biorefinery of 292 M€. Capital costs are depreciated in 12 years and operating and maintenance costs (O&M costs) have been set at 10% of the capital investment. In the integrated biorefinery case it has been assumed that ethylene is sold at 1000 €/tonne, BTX at 750 €/tonne, tars at 250 €/tonne and mixed alcohols at 617 €/tonne. The sales price of the ethylene and BTX are typical market values. For the biomass tars no market values exist, a typical market value for coal tars has been used. The mixed alcohols are rated at typical market values of ethanol: 500 €/m^3 or 625 €/tonne.

Results of the calculation of the electricity production costs are given in Table 6-3 (see also Tables B-10 and B-11). In the reference case the cost of electricity production is 74 €/MWh, with biomass feedstock accounting for slightly more than half of the costs and capital costs and O&M costs having about equal shares. In the integrated biorefinery case the gross productions costs increased by about a factor 4 due to reduced power production (slightly less than a factor four) and an increase in capital cost by 25%. The increase in gross power production costs is compensated by income from the by-products. Per MWh of electricity produced the co-products give a revenue of 236.5 €. The majority of the revenues from the co-products are generated by mixed alcohols (~52%) and ethylene (~31%). The net power production costs decrease from 74.4 €/MWh in the reference case to 48.0 €/MWh in the integrated biorefinery case.

Table 6-3 *Cost of power production (€/MWh_e) for reference and integrated biorefinery cases for a gasification based biorefinery*

	Reference case	Integrated case
Feedstock costs		
- Biomass	40.8	139.1
Capital costs	15.3	66.1
Operating and maintenance costs	18.3	79.3
Gross production costs	74.4	284.5
Co-products		
- Ethylene		74.0
- BTX		27.8
- Tars		11.3
- Mixed alcohols		123.4
- Total revenues co-products		236.5
Total power production costs	74.4	48

Technical and commercial feasibility
The biorefinery concept for a gasification based biorefinery scored a technical feasibility of 53.4 (see Table C-9), this is clearly below the project average of 70.7 . The whole processing scheme is highly challenging with quite a number of successive process steps in the main process line. The process scheme for the biorefinery case is completely different from the process scheme of the reference case. Failure in one of the process steps will result in disturbance of the whole process. The process steps required are considered to be immature resulting in high technology risks. On top of that some of the products, ethylene and BTX, are commodities, but others, tars and mixed alcohols, require development of a product market. Biomass tars have the potential for a large market, just like for coal tar, but

the market doesn't exist yet. Mixed alcohols can in principle be used as a renewable transportation fuel, however there is no experience on large scale with use of mixed alcohols in the transportation sector yet.

The commercial feasibility of this biorefinery concept was scored at 68.4 (see Table C-10), or slightly lower than the project average of 71.0. Main negative deviations, compared to the project average, are the fact that for some of the products (tars and mixed alcohols) there is no existing product/market combination and the fact that the products produced do not lead to an economical advantage for the product user.

SWOT analysis

In Table 6-4 the major comments given by respondents in the SWOT analysis of the gasification based biorefinery are given. For a more detailed SWOT analysis see Appendix D.5.2. As clear strengths are recognised that the co-products have high value and that for some of the products (ethylene and BTX) there are already existing markets. The weaknesses of the concept are that concept is complex and that unproven technology is involved. In the gasification based biorefinery there are quite a number of processes to be integrated and all the products have to be managed. The complexity of the process and the required business development are therefore considerable. Some of the process steps are not commercially proven yet and those that are commercially proven have not been demonstrated in combination with the other process steps. The opportunities of this concept are an increase in the price of petroleum, since all by-products can potentially replace petroleum products (fuels as well as chemicals). An increasing petroleum price will result in an increased profitability of this concept. Furthermore, due to the production of ethylene and BTX the concept offers opportunities for integration with existing chemical industry. The threats for this biorefinery concept are the competition with biochemical biorefineries and registration and safety issues for the new products. This concept relies on extraction of products from a process not dedicated to the production of fuels and chemicals. This results in relatively low yields on a mass basis. Biochemical biorefineries are thought to be able to achieve higher product yields. Some of the products (tars and mixed alcohols) are new to the market. This might, especially for tars, result in registration and safety issues for these products.

Table 6-4 *Major comments in SWOT analysis for gasification based biorefinery*

Strengths	**Weaknesses**
- Existing markets for products - High value co-products	- Unproven technology - Complex concept
Opportunities	**Threats**
- Increasing price of petroleum - Integration with existing chemical industry	- Competition with biochemical biorefineries - Registration and safety issues for new chemical products

6.3 Summary and conclusions

For the power sector two biorefinery concepts have been modelled and assessed. For a combustion based CHP plant, integration with the production of pyrolysis oil has been analysed and for a gasification based power plant, integration with the production of chemicals and transportation fuels has been analysed.

For the combustion based biorefinery the advantage is in using the combustor present in the CHP plant for the combustion step required for pyrolysis process. This reduces the costs for pyrolysis oil production and makes operation of the pyrolysis process simpler. The pyrolysis process converts biomass into a liquid product that can be used for different applications. The biorefinery case has been modelled based on extra input of wood residues, for pyrolysis oil production. The integration results in pyrolysis oil production, from wood residues, with an efficiency of 70%. Electricity production of the CHP plant is decreased somewhat, whereas heat production increases somewhat. The overall energy efficiency of the stand-alone CHP plant and the biorefinery with integration of pyroly-

sis are both 85%. With the base case assumption on feedstock costs and revenues from the sales of pyrolysis oil (91 €/tonne), the cost of the electricity produced increases from 60 €/MWh for the stand-alone CHP plant to 88 €/MWh for the biorefinery with integration of pyrolysis. When the pyrolysis oil is sold at 247 €/tonne, the cost of electricity production for the biorefinery case drops to 60 €/MWh. This shows that opportunities for this concept might appear when the pyrolysis oil can be sold at higher prices. Both the technical and commercial feasibility of this concept scored below the project average. Major reasons for the relatively low score are the immaturity of the pyrolysis process and the fact that pyrolysis oil is not (yet) a commodity product with an established market. On top of these negative points mentioned in the SWOT analysis are that quality of the pyrolysis oil might vary and that the pyrolysis oil might have unwanted properties. Positive points mentioned in the SWOT analysis are the fact that pyrolysis oil is a liquid and the opportunities that will come up when the crude oil price increases. The fact that pyrolysis oil is a liquid offers advantages in transportation of this product and in the use of the product in e.g. decentralised applications. Since the pyrolysis oil competes with petroleum products, an increasing crude oil price will improve the economic profitability of this concept.

In the gasification based biorefinery high value chemicals are extracted from the gas and part of the gas is converted into transportation fuels. The co-production of these high-value products reduces the cost of electricity production. In the biorefinery concept part of the biomass in converted into products other than electricity, this results in a reduction of electricity production with almost a factor 4 (compared to stand-alone electricity production). The overall efficiency of the biorefinery concept is 60% and is significantly higher than for stand-alone power production (46%). The concept is clearly a product driven biorefinery, on energy basis 78% of the products of this biorefinery concept are chemicals and transportation fuels. In the biorefinery case the cost of electricity production is 48 €/MWh and significantly lower than for stand-alone power production (74 €/MWh). Also in the economics it is reflected that this concept is a product driven biorefinery. Electricity accounts for only 17% of the income, whereas the chemical products account for 40% of the income and the mixed alcohols for 43% of the income. The technical feasibility of the biorefinery concept scored clearly below the project average. The major reasons for the low score is that the process scheme is considered to be very complex and that required technologies are not all mature yet. Furthermore, the market for some of the products, tars and mixed alcohols, has to be developed. The commercial feasibility was assessed to be somewhat lower than the project average also here the fact that some of the products are not a commodity played a role. In the SWOT analysis the aforementioned arguments returned as negative point. Positive points in the SWOT analysis were that this concept offers opportunities for integration with existing chemical industry and will become more attractive at higher oil prices.

7. Evaluation of cheese whey biorefinery

7.1 Introduction

During the production of cheese, whey is produced as a side product. Whey is usually dried to produce whey powder. The energy demand of this process is considerable. Whey is sold as a protein rich side product. Yet, more than half of the whey is not protein but lactose. Through biorefinery, the whey proteins can be separated from the lactose via ultra filtration. The proteins can be dried in a spray drier to produce whey protein. This product will be very rich in protein and therefore it can be sold at a very good price. The lactose can be converted to lactic acid. Since the proteins are now removed, this stream can be concentrated via reverse osmosis. This saves the evaporation energy that is usually spent in the whey drying process. Lactic acid can be sold as food additive or for production of bioplastics (PLA).

7.2 Reference case

A block diagram for the cheese production process is shown in
Figure 7-1. The cheese factory has two sections: the cheese making section and the whey powder making section. In the cheese making section, cheese is produced from milk and whey is produced as a side product. In the whey powder making section, the whey is dried to produce whey powder.

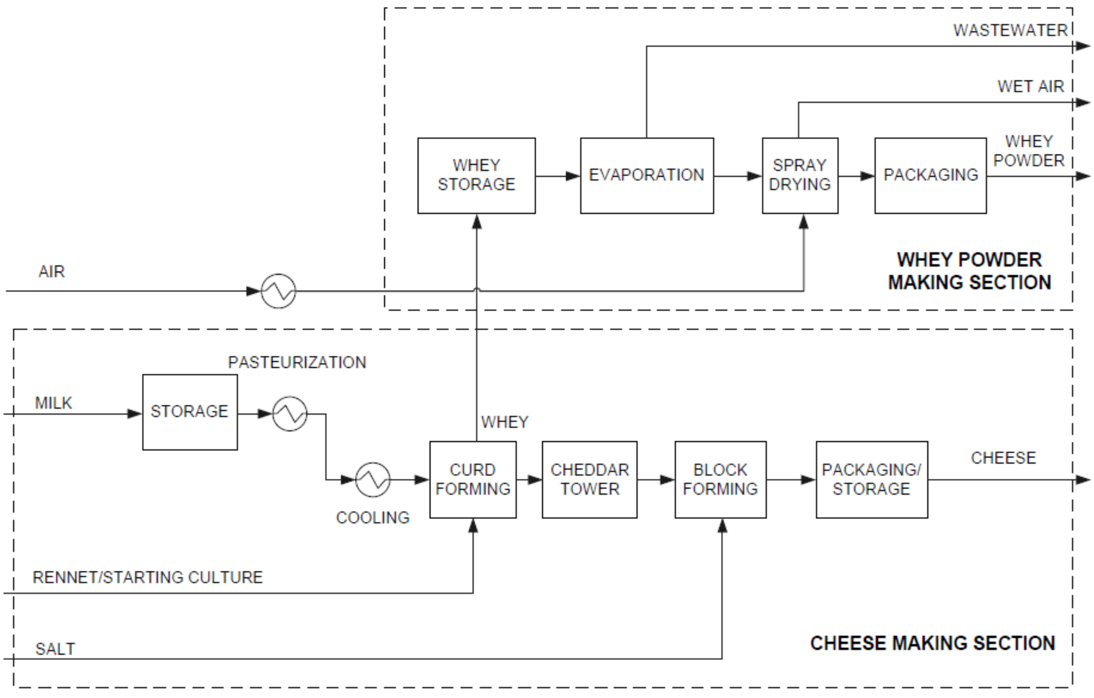

Figure 7-1 *Block diagram for a typical cheese production process*

7.2.1 Cheese making section

In the cheese making section, milk is pumped into storage tanks where the temperature is kept constant at 4°C. The milk then undergoes a cream separation process to provide a constant fat content throughout the year. Most of the cream goes back to the process and the remainder is sold for butter production.

The next step is the pasteurisation process, where milk is heated until 72°C for about half a minute, and then it is rapidly cooled down to 30°C. Milk is then sent to the vats where the fermentation takes place. Rennet and the starting culture are added in small proportions to the cheese vats, and the curd is formed. The curd is solidified in the cheddar tower, and an aqueous stream of whey is separated. The whey is composed of unconsumed proteins, fat, lactose, mineral salts, and water. After the cheddar tower curd blocks are shredded and mixed with salt in the mixer/tumbler. Blocks are formed by pressing the solids. After blocks forming cheese is sealed, cooled, and stored to mature. The yield of cheese is about 10 wt.% based on the milk basis.

The mass balance of the cheese making section is given in Table A-23, the energy consumption in Table A-24.

7.2.2 Whey powder production section

The whey removed during the curd forming is stored in a tank from where it flows to the multistage evaporator to concentrate the solids and remove most of the water (
Figure 7-1). After this first concentration step, the resulting slurry is spray-dried to remove almost all the water. Whey powder containing around 5 wt.% water is sent to the packaging unit. The amount of whey powder produced is about 7 wt.% on the milk basis.

The mass balance of the whey powder section is given in Table A-25, the energy consumption in Table A-26.

7.2.3 Overall cheese factory (reference case)

The overall mass and energy flows for cheese production process (including whey powder production) is given in Table A-27 and Table A-28. An overview is given in Figure 7-2.

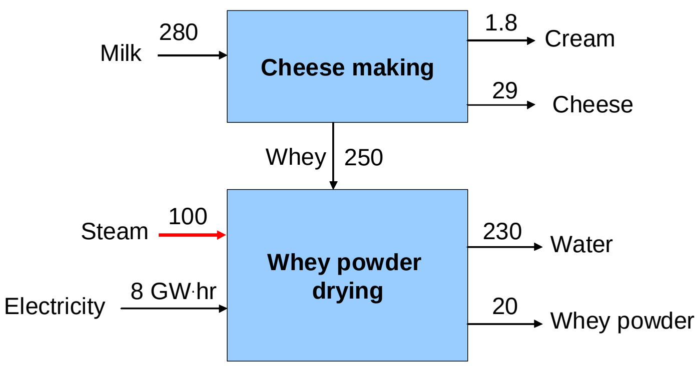

Figure 7-2 *Traditional cheese making process (mass flows in ktonnes/yr)*

7.3 Integrated biorefinery case

Whey powder is mainly sold for its protein content. Despite the fact that lactose, fats and minerals are present in higher quantities, they do not really add value to the whey powder. At the same time, whey powder production consumes a lot of heat for water evaporation. Through biorefinery of cheese whey, the protein, lactose, fats and minerals can be separated and sold at a higher value. At the same time, the energy demand of the process can be reduced. Lactose can be converted to lactic acid in order to add even more value. In the next paragraph this process will be described.

The cheese whey biorefinery was modelled after a detailed study by Börgardts *et al.* (1998) as shown in Figure 7-3. The process produces lactic acid from the lactose that is present in the whey. Before the fermentation, a large proportion of the fats and calcium is removed (S-01) to prevent membrane fouling in S-02. Ultra filtration (S-02) is then used to remove the whey proteins. The permeate is sent to the fermentor (R-01). In the fermentor, bacteria are grown that convert lactose to lactic acid. The bacteria cannot live at low pH values and therefore NaOH is added to neutralise the lactic acid in the

fermentor. The effluent from the reactor is first filtrated to remove the bacteria (S-03). The bacteria are recycled to the fermentor. The liquid from the micro filter is treated in an ion exchange column to remove divalent cations, mainly Mg^{2+} and Ca^{2+} (S-04).

The remaining solution of sodium lactate is sent to an electro dialysis unit where NaOH, lactic acid and effluent are produced (S-05). NaOH is recycled to the fermentor. Lactic acid is concentrated in a reverse osmosis unit to produce a 50% solution (S-06). The water from the reverse osmosis unit is sold as pure water.

The retentate of S-02 is split in two portions. A small part of the protein fraction is hydrolised (R-02) to produce amino acids that are used in the fermentor to grow the bacteria. A larger part is spray dried (S-07) and packaged (P-01) to be sold as whey protein concentrate (WPC).

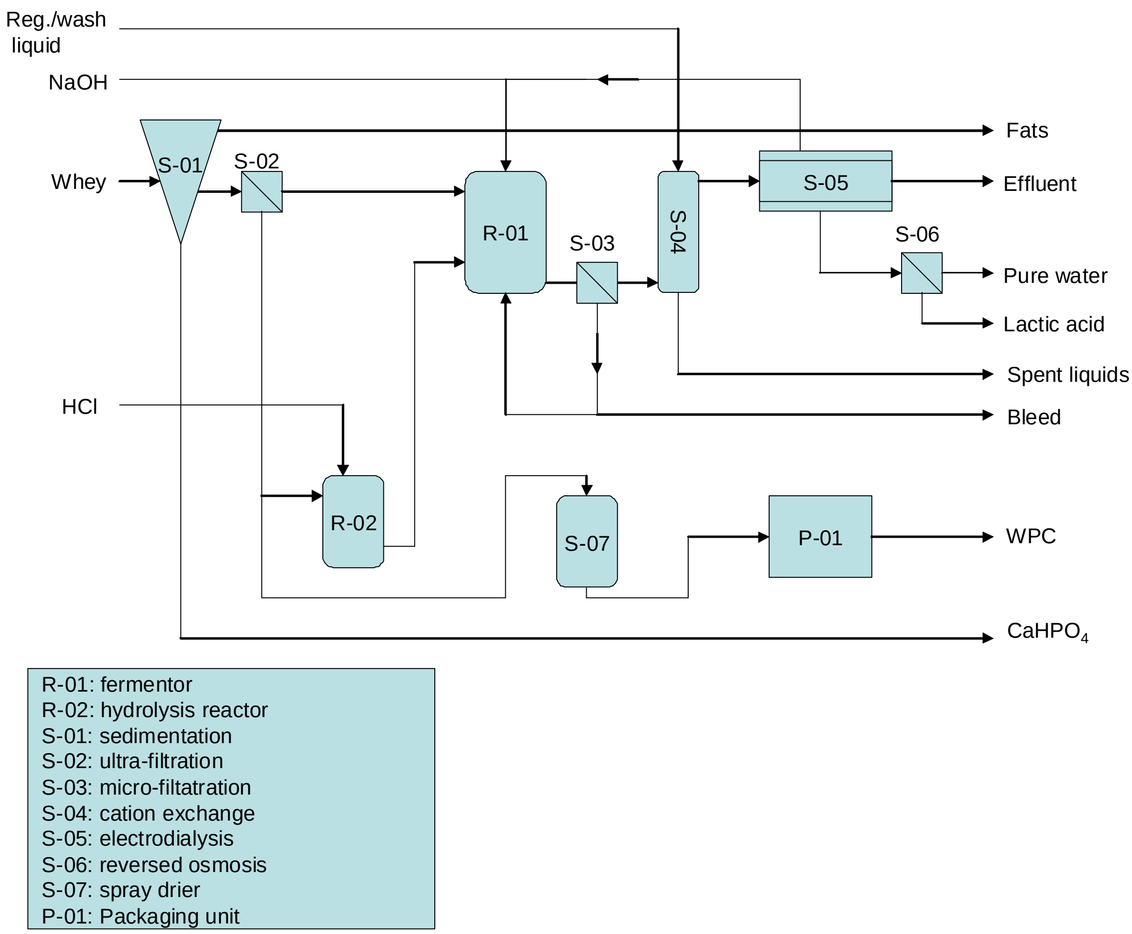

Figure 7-3 *Schematic overview of whey biorefinery*

The mass balance of the whey biorefinery is presented in Table A-29, the energy consumption for this process is given in Table A-30. The lactic acid case is also considered as an integrated case located within the premises of the cheese production process.

7.3.1 Overall cheese factory (integrated case)

The overall mass and energy balance for cheese production process (including integrated whey biorefinery) is given in Table A-31 and Table A-32. An overview is given in Figure 7-4.

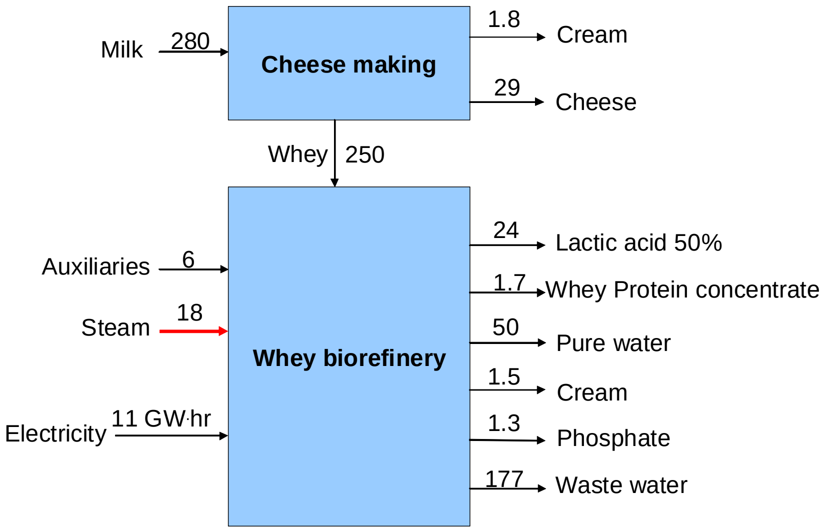

Figure 7-4 *Cheese making process with integrated whey biorefinery (mass flows in ktonnes/yr)*

7.4 Techno-economic and ecological assessment

7.4.1 Economic assessment

Economic assessments carried out for the reference case and the integrated biorefinery are presented in Table B-12 and Table B-13. A summary of the key economic parameters is given in Table 7-1.

Table 7-1 *Key economic parameters of reference case and integrated biorefinery*

	Reference	**Integrated case**
Products	Cheese Whey powder	Cheese Lactic acid Whey protein concentrate
Investment	51 M€	91 M€
Payback time	11 years	6 years
IRR	20%	26%
Cheese costs	1.9 €/kg	1.4 €/kg

7.4.2 Ecological assessment

The demand for electricity is higher in the integrated case due to the membrane filtrations and the electro dialysis. The demand for heat, however, is greatly reduced because there is no need for whey drying anymore. In the end, the integrated case needs less energy and produces less CO_2 (Table 7-2). On top of that, the integrated case also produces lactic acid that might be used to produce polymers that can replace fossil plastics such as polyethylene. This was not evaluated in this project.

Table 7-2 *Energy demand and CO_2 emission of reference case and integrated biorefinery*

	Energy (GJ/yr)		**CO_2 emission (tonnes/yr)**	
	Reference	**Integrated**	**Reference**	**Integrated**
Electricity	36000	46800	4176	5429
Steam	275400	51300	15300	2850
	311400	**98100**	**19476**	**8279**

7.5 Technical and commercial feasibility

7.5.1 Technical feasibility

The results of the technical feasibility are presented in Table C-11.

The technical feasibility score is below the project average. The significant downstream process (lactic acid fermentation and extraction plant) is accounted as a major penalty, together with the poor definition of the process design. Also the proof-of-concept is slightly below the project average.

Most of the challenge is not in the fermentation, but in the purification of lactic acid from the fermentation broth. Until now, lactic acid is precipitated by addition of lime. Lactic acid is produced from the precipitate by addition of sulphuric acid. Gypsum is produced here. The process that is proposed in this project uses electro dialysis instead. This prevents the large waste stream of gypsum. Therefore, the new process is more sustainable. But this sustainability is not rewarded in the evaluation method of this project (the use of lime rock and sulphur (originating from oil) is not regarded as the use of fossil feedstocks).

At the same time this new method introduces a complex downstream separation process with risks such as membrane fouling. This complexity and these risks are well elucidated and high weighted in the evaluation. This high complexity is well counterfeited by the very high profitability of the process.

7.5.2 Commercial feasibility

The results of the commercial feasibility are presented in Table C-12.

The commercial feasibility is slightly below the project average. The positive competitive advantages are counterbalanced by mainly legislative issues: novel food concerns for lactic acid from whey and no specific supportive legislation. Not mentioned here: the integrated case is saving on energy, as the evaporators are (partially) replaced by reverse osmosis.

Anyway, this is a rather surprising result, as lactic acid is an existing product, available in large quantities and referenced in several markets.

7.5.3 SWOT analysis

A SWOT analysis carried out for the integrated cheese biorefinery is presented in Appendix D.6, with some major points summarised in Table 7-3.

Table 7-3 *Some major points of the SWOT analysis*

Strengths • High value products • Existing markets • Lower non renewable energy usage	***Weaknesses*** • Complex downstream separation process ➔ High capital costs • Technical risks: membrane fouling
Opportunities • Shortage of phosphates • EU directive on renewable products	***Threats*** • Lactic acid and whey market unstable • Novel food application might be needed

7.6 Summary and conclusions

The integrated cheese biorefinery has several advantages:

- Lower energy demand (=lower CO_2 exhaust);
- Renewable products for biobased economy (PLA);
- High added value whey protein concentrate;
- High return on investment, short payback time;

- Phosphate production.

Some problems are foreseen:
- Complicated down stream processing with high capital costs;
- Technical risks with membrane fouling;
- Food application for whey protein concentrate due to alternative production method;
- Highly volatile market for whey protein concentrate and PLA;
- High dependency on sales of reverse osmosis water.

8. Evaluation of integrated biorefinery technologies in the sugar industry

8.1 Introduction

Currently, the European sugar is being reformed. This will lead to a reduction of the market price of sugar in the European Union. For the sugar industry it is essential to reduce the cost price of sugar in order to be competitive in the open world market. Until recently, the focus of the European sugar industry has been on sugar yield maximisation (due to the guaranteed high prices for sugar). But after the sugar reform, the focus will shift to total added value maximisation. Through biorefinery the total added value can be increased. In this chapter, the current practice will be compared with an integrated biorefinery approach of the sugar chain.

8.2 Reference case

A block diagram for the sugar beet process is given in Figure 8-1. This case represents the standard sugar industry production process using sugar beets to produce crystalline white sugar. Europe has seen a decrease in the number of sugar facilities, while increasing their average capacity as a way to reduce production costs. The reference case therefore refers to a large scale centralised process that is optimised for high sugar yield. Figure 8-1 provides an overview of the sugar process scheme with by-products. Farmers have consistently strived to increase the harvestable sucrose quantity from sugar beets to generate a larger portion of white sugar product. Based on data of the last five years (2004-2005) from IRS, the average yield of sugar beet is 67.1 tonnes/ha and the average sugar content is 16.8%. Following the current chemical composition, 70% of the product is white sugar, 12% is molasses and 18 % dry weight is pulp. The energy demand for the sugar plant is fully allocated to the main product white sugar. Despite this, a large amount of energy is required for the by-products, e.g. pulp drying (~23%) and molasses preparation (~15%). The energy use for sugar processing (including energy input for pulp drying) is 4.68 GJ/tonne white sugars (Corré and Langeveld, 2008).

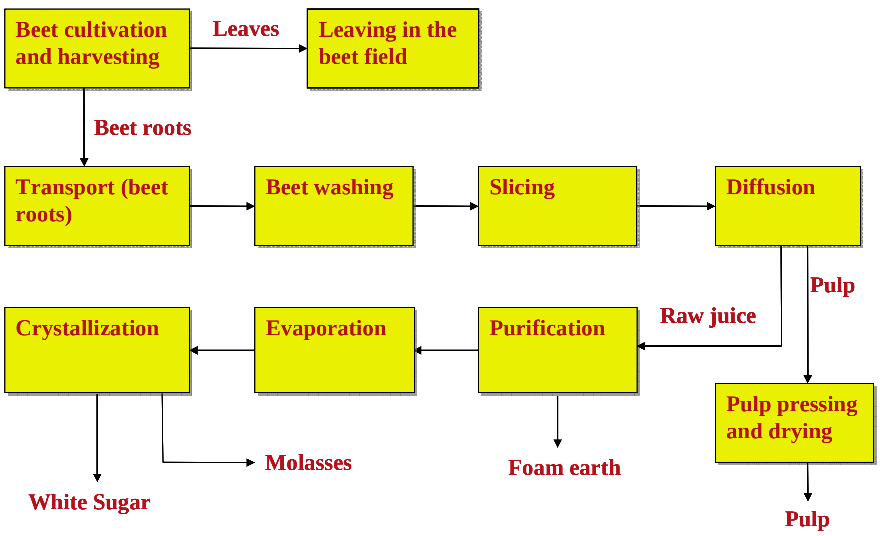

Figure 8-1 *Sugar beet process according to British Sugar (reference case)*

Table A-33 and Figure 8-2 show the mass balance of standard sugar processing in terms of input mass flows of feed streams and output mass flows of product streams. Lime requirement for adequate sugar purification depends on the beet quality; beet-sugar factory uses considerable amounts of 2-6% $CaCO_3$ on beet and this equates to 1-3% CaO on beet (Asadi, 2006). In this study, selected value of

lime (CaO) consumption rate is 2.5% of sugar beet or 25 kg/tonne of sugar beet, so the total required lime is 1.7 t/ha (67.1(wet basis) t/ha*2.5%). The CO_2 gas stream includes CO_2 from limestone ($CaCO_3$) and CO_2 from coke (9% of limestone).

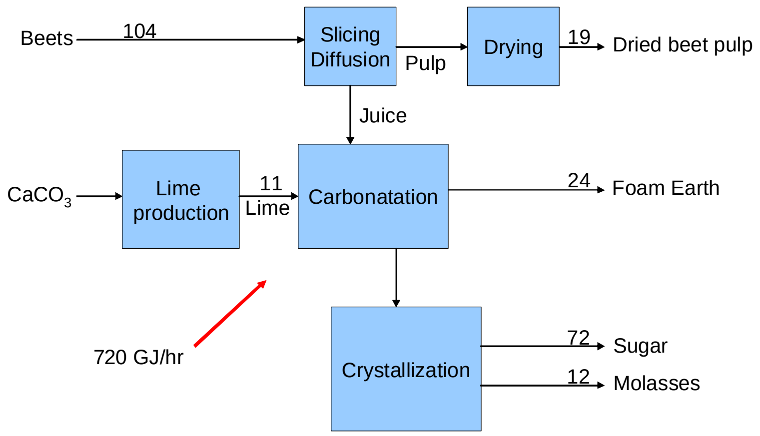

Figure 8-2 *Schematic representation of sugar beet processing (reference case), mass flows in tonne dry matter per hour*

Table A-34 gives the energy balance of a large scale sugar production plant.

8.3 Integrated biorefinery case

The decentralised sugar production process has a feedstock from sugar beet and includes catch crops & beet leaves. Several steps were simplified drastically compared to the reference case and it produces sugar, bioethanol and biogas. The biogas is used for electricity and heat production. A block diagram for the process is represented in **Error! Reference source not found.**.

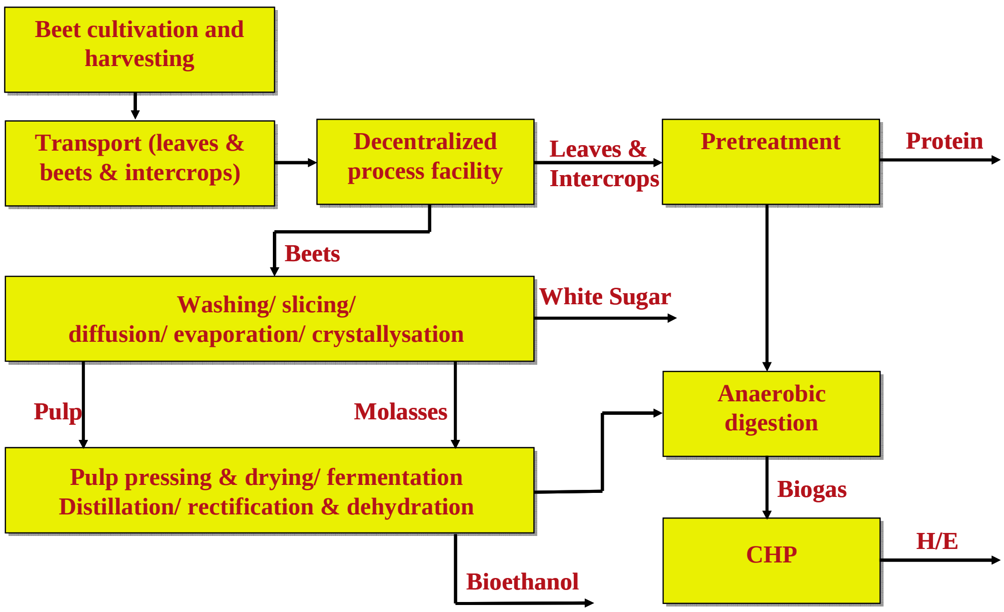

Figure 8-3 *Block diagram for biorefinery case of decentralised process chain for partial sugar, bioethanol and biogas production*

Firstly, both the roots and top portion of the beet, as well as the beet leaves and catch crops are harvested and processed. Catch crops are usually grown to maximise the land use, while minimising the nutrition loss and adding extra value for beet growers. In the Netherlands several crops are used like mustard seed, ramenas and other. Normally, the growth season before the beet is long enough to start growth of these catch crops from their seeds after the previous crop, potato has been harvested. When the processing of these leave drops is in place, after the beet harvest, small plants can be seeded that have been grown in parallel, starting in August from seeds. Normally these catch crops deliver some fertilisers that now are removed from the soil with the products. These fertilisers have to be compensated, but their economic value is much less than the products that can be recovered. The root structure of these plants remains to improve the soil fertility. 20% of dry weight of catch crops and beet leaves is protein. After pre-treatment, the protein product can be sold to the animal feed industry and residual organic wastes can be used for biogas digestion.

Secondly, despite white sugar still being the main product, it is produced in radically lower quantities due to process design alterations. The utilisation of the top portion of the sugar beet decreases the sucrose concentration and purity, whilst increasing the total quantity of sugars. As a result, in a traditional white sugar processing plant, higher operational demands on the juice clarification unit would occur, while the proportion of molasses would increase. To avoid this drawback it is envisioned, within the decentralised facility, to make a compromise between sugar production and ethanol production. The diffusion juices will not be exposed to the lime clarification step (also known as carbonatation) thereby reducing capital cost and energy requirement, but a new extraction step to isolate and recover a portion of the sucrose in the order of 60%; in an impure crystalline form compared to 95% previously. This crystalline sucrose half-product is subsequently sent to an existing large scale sugar plant and combined with the traditional process in the crude dilute sugar stream that is diffused from the beets.

An energy saving can be realised by circumventing the juice clarification unit. It has been calculated that the clarifier is responsible for 10.8% of the total energy input of sugar production (Tekin, 1998).

Residual streams from the extraction are treated as feedstock for ethanol fermentation and later for biogas digestion as it can be seen from **Error! Reference source not found.**. In the Netherlands, sugar beets are only available for processing during the season after harvest which is five months of a year; in the remaining period, the same factories can process grass or other agricultural productions.

The mass balance of sugar beet biorefinery process is given in Table A-35, the heat balance in Table A-36.

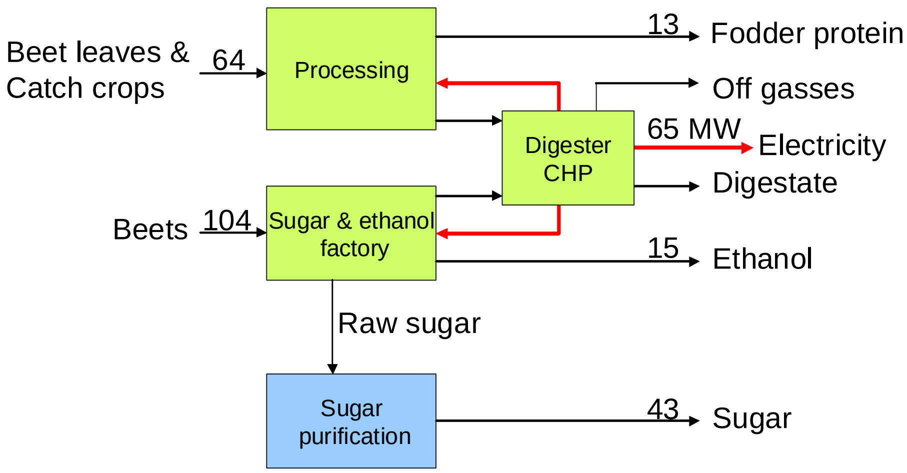

Figure 8-4 *Schematic representation of integrated sugar beet processing, mass flows in tonne dry matter per hour*

8.4 Techno-economic and ecological assessment

8.4.1 Economic assessment

The economic assessment of the current sugar industry shows (Table B-14) that the profitability is good at the current high sugar prices. After the sugar reform, however, the sugar price is expected to drop to 300 €/tonne.

The economic assessment of the integrated sugar biorefinery is given in Table B-15. The capital costs of the leave processing and the ethanol production are included as lump sum variable costs. The energy costs are cancelled out by the internal heat delivery from the CHP unit. The Internal rate of return (IRR) is considerably higher and the payback time is shorter, showing that the integrated biorefinery is economically more attractive. It could even produce sugar at the expected future market price.

A summary of the key economic parameters is given in Table 8-1.

Table 8-1 *Key economic parameters of reference case and integrated biorefinery*

	Reference	**Integrated case**
Products	Sugar	Sugar Ethanol Feed protein Electricity
Investment	168 M€	134 M€[3]
Payback time	7 years	5 years
IRR	7%	22%
Sugar costs	329 €/tonne	252 €/tonne

8.4.2 Ecological assessment

Table 8-2 shows that compared to the reference case, the energy demand of the integrated case is decreased, because no pulp drying and no carbonatation is needed. At the same time, the emission of green house gases is reduced due to the production of bioethanol and biogas. It is assumed that bioethanol replaces gasoline and that biogas is burnt in a CHP unit and replaces both heat and electricity. The CO_2 emission factors are given in Table 8-3.

Table 8-2 *Energy usage and CO_2 emission of reference and integrated sugar factory*

	Energy (TJ/yr)		CO_2 emission (ktonne/yr)	
	Reference	**Integrated**	**Reference**	**Integrated**
Heat	2691	*	164	
Ethanol		-1009		-68
Biogas		-2077		-154**
	2691	**-3086**	**164**	**-222**

* Heat is taken from CHP unit.
** Only electricity is rewarded for reduction of CO_2 emission, as the heat is used in the process.

Table 8-3 *CO_2 emission factors*

	ktonneCO_2/TJ
Heat	0.056
Ethanol	0.067
Electricity from biogas	0.074

[3] Capital costs of catch crop processing, ethanol production, and CHP are included as 'lump sum' variable costs.

8.5 Technical and commercial feasibility

8.5.1 Technical feasibility

The results of the technical feasibility are presented in Table C-13.

The integrated sugar biorefinery has an average feasibility score. There were no major hurdles identified, although this scheme is a significant change compared to the reference case. Basically, it is a combination of existing technologies. Some steps were abandoned, others outsourced. This explains the rather positive evaluation.

8.5.2 Commercial feasibility

The results of the commercial feasibility are presented in Table C-14.

The sugar beet biorefinery with decentralised beet processing plants has commercial feasibility score above average. Strong competitive benefits identified (cost impact, integration benefits), positive impact of extra renewable energy, but no functional benefits.

8.5.3 SWOT analysis

A SWOT analysis carried out for the integrated cheese biorefinery is presented in Appendix D.7, with some major points summarised in Table 8-4.

Table 8-4 *Some major points of the SWOT analysis*

Strengths • Value maximisation	***Weaknesses*** • Abandoning current capital
Opportunities • Other products possible (proteins)	***Threats*** • Independence of farmers

8.6 Summary and conclusions

The integrated biorefinery with decentralised beet processing is highly attractive for more than one reason:

- Far higher yield per acre of land;
- Cheaper process;
- Production of high quality feed;
- Production of renewable electricity;
- Production of biofuels;
- Lower energy demand;
- Lower CO_2 emissions.

Still the introduction could be hindered by several issues:

- Sugar companies might be concerned that farmers would go independent;
- Some process equipment at the sugar factory will become obsolete;
- Farmer will need a considerable amount of knowledge to run the process properly.

9. Evaluation of small scale power production vs. grass biorefinery

9.1 Introduction

Small scale power production from manure and other digestible materials (such as grass, maize, glycerol) via CHP is currently highly unprofitable. Large subsidies are rewarded to run such plants. The heat produced by small scale power production units is often not used, because there is little demand for heat in agricultural areas. At the same time, the production of grass is not very profitable. Grass biorefinery could increase the added value through production of fibres, feed protein and other products. The required heat for grass biorefinery can be taken from the small scale power production.

In this project the grass biorefinery will be integrated with the small scale power production, in order to improve the profitability of both the small scale power production and the grass producing farmer.

9.2 Reference case

The reference process for the grass biorefinery is the co-digestion of silage grass and manure to produce heat and electricity. A block diagram for the anaerobic digestion process is presented in Figure 9-1. Silage grass and manure are fed to the reactor where the anaerobic digestion takes place. Digestate, of which price is negative because of transportation cost, is sold for fertiliser use. Biogas (a natural occurring mixture of CH_4 and CO_2) is continuously produced. The biogas is used in a gas engine CHP unit to produce heat and electricity. A small proportion of the heat is used to heat the digester. The remaining heat is wasted to the atmosphere, as (usually) no compatible heat demanding process is present nearby the CHP unit.

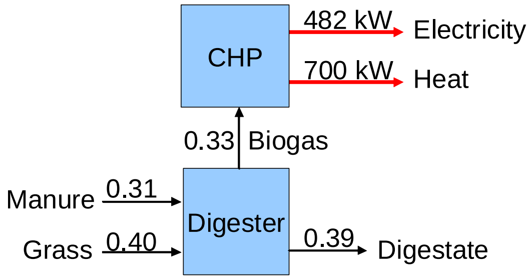

Figure 9-1 *Schematic representation of a digester and a CHP unit (reference case), mass flows in tonnes dry matter per hr*

Mass and energy balances on the digester are given in Table A-37 and Table A-38. The energy production by the CHP unit is given in Table A-39. Finally, Table A-40 shows the energy balance over the CHP unit.

9.3 Integrated biorefinery case

In the Netherlands several companies are currently developing a grass biorefinery based on fresh culture grass. The overall flow sheet of this process is given in Figure 9-2.

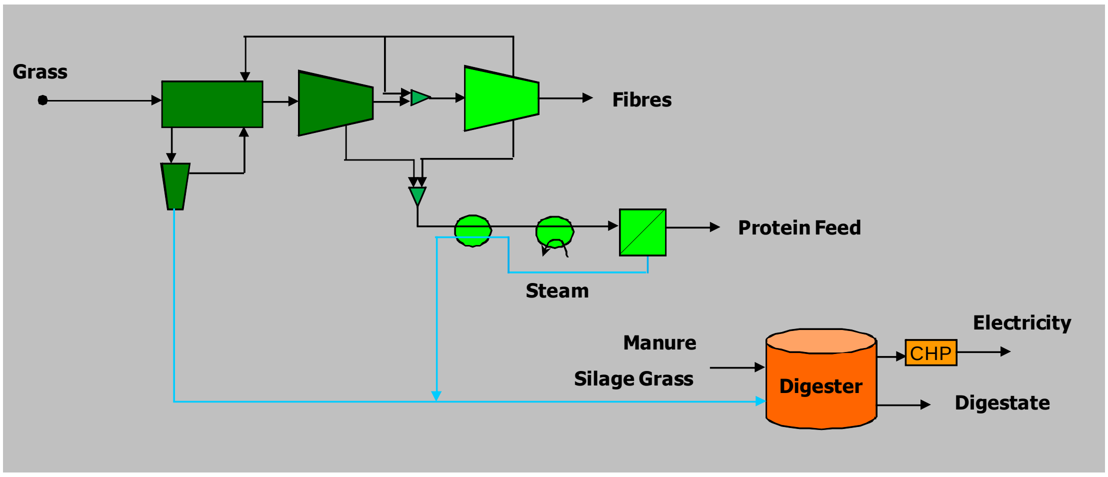

Figure 9-2 *Flow sheet Grass biorefinery*

The grass biorefinery consists of a primary and a secondary refining stage.

Primary refining stage (combination of washing, opening and pressing):

- Press cake;
- Press juice.

Secondary refining stage:

- Press cake upgraded into fibres for paper industry;
- Heat coagulation of grass juice;
    - Coagulated protein as feed (soya replacement);
    - Juice for co-digestion.

Fresh grass as a source for protein feed can only be harvested during 7 months every year. Possibilities to include sugar beet leaves and other green crops that are harvested during the winter are not included in this process, because the fibre quality and feed quality of these crops are still unknown. As digesters are processing year round, the other five months of the year the digester will not run on manure and juice from the grass biorefinery, but directly on manure and silage grass. The biorefinery will run for 2130 hours/year (7 months, 10 hours/day). The digester will run for 8000 hours/year.

In Table 9-1 an overview is given of the products that can be made from fresh grass.

Table 9-1 *Product overview Grass biorefinery*

	Amount [tonne]	Dry matter [%]	Dry matter [tonne]
Grass	1000	15	150
Fibre	118	40	47
Protein feed	191	20	38
Juice	691	9.4	65

The biogas yield of the juice is calculated based on the composition of the juice stream. The amount of biogas that can be formed is 32.1 Nm^3/tonne juice. The methane concentration is calculated at 59.2%. The efficiency of the conversion of biogas into electricity is 32.5%. In Table 9-2 the biogas and electricity production is given for 1000 tonnes of fresh grass.

Table 9-2 *Biogas and electricity yield*

Grass	Value	Unit
Amount	1000	tonne
Dry matter	15	wt.%
Dry matter	150	tonne
Juice	**Value**	**Unit**
Amount	690.98	tonne
Dry matter	9.37	wt.%
Dry matter	64.74	tonne
Biogas	**Value**	**Unit**
Production	32.1	Nm^3/tonne juice
Production	22.2	Nm^3/tonne grass
Production	22187	Nm^3/1000 tonnes grass
Electricity	**Value**	**Unit**
Production	60.5	kWh_e/tonne juice
Production	41.8	kWh_e/tonne grass
Production	41783	kWh_e/1000 tonnes grass

The ratio of manure and grass juice and grass silage is controlled both by maximum amount of dry matter in the digester, and by law. In order to use the digestate and manure on the field the ratio should not be less than 1:1 based on weight. Feeding the digester with silage grass is done with 28500 tonnes manure/year and 8000 tonnes silage/year. With grass juice the digester can be fed with 18250 tonnes manure/year and 18250 tonnes juice/year. In Table 9-3 the feeds of the digester are given.

Table 9-3 *Digester feed*

Grass season (7 months)	Value	Unit
manure	10646	tonnes
juice	10646	tonnes
harvest	15407	tonnes of fresh grass
Winter (5 months)	**Value**	**Unit**
manure	11875	tonnes
grass silage	3333	tonnes
harvest	9877	tonnes of fresh grass

The total amount of fresh grass harvested for the biorefinery (25284 tonnes) is therefore slightly higher than for the base case (23704 tonnes).

The amount of energy needed to operate the biorefinery is estimated at 150 kWh_e/tonne of dry matter during the grass season. This amounts to 346656 kWh_e per year.

The amount of steam necessary to heat up the juice in order to separate the protein feed amounts to 264 tonnes of low pressure steam of 1-2 bar.

The main mass and energy flows are given in Table A-41 and Table A-42. An overview is given in Figure 9-3.

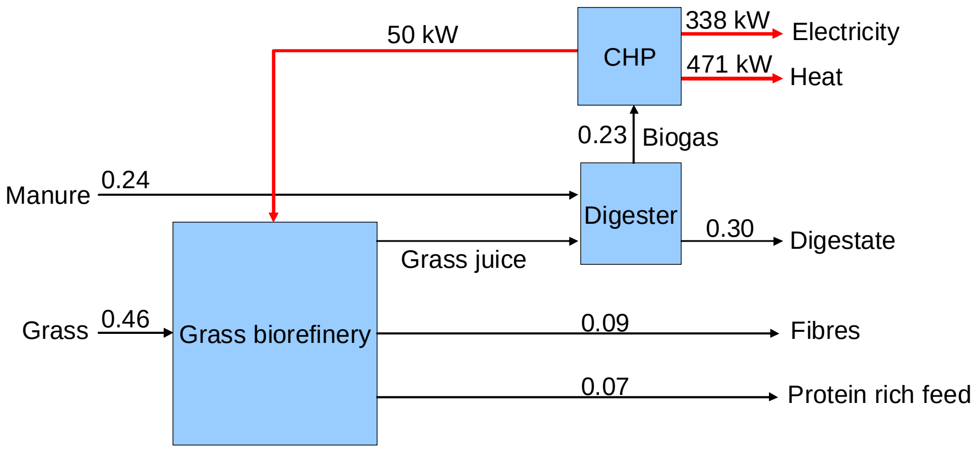

Figure 9-3 *Schematic representation of grass biorefinery integrated with digester and CHP units, mass flows in tonnes dry matter per hr*

The energy production of the CHP unit is given in Table A-43 and an energy balance is given in Table A-44.

9.4 Techno-economic and ecological assessment

9.4.1 Economic assessment

Table B-16 shows that small scale power production is not profitable. The calculated cost price difference (market value of electricity–cost price of small scale process) matches the current subsidy levels that are rewarded to run these processes quite closely.

Through the integration of a grass biorefinery with the small scale power plant the cost price of renewable electricity can be slightly reduced (see Table B-17). However, still a considerable amount of subsidy is needed to run the process.

A summary of the key economic parameters is given in Table 9-4.

Table 9-4 *Key economic parameters of reference case and integrated biorefinery*

	Reference	**Integrated case**
Products	Electricity	Electricity Protein feed Fibres
Investment	2.15 M€	2.27 M€
Electricity costs	0.177 €/kWh	0.170 €/kWh

9.4.2 Ecological assessment

Through the production of alternative products such as fibres and feed proteins, the production of renewable energy will drop. Therefore, also the reduction of the CO_2 emission will be lower for the integrated case (Table 9-5). However, the fibres produced in the integrated case might end up in waste incineration and thus generate renewable energy that is not accounted for in this project. Also, high quality feed proteins are produced. This will reduce the demand on feed proteins and therefore less agricultural land will be needed.

Table 9-5 *Renewable energy production and reduction of CO_2 emission*

	Energy (GJ/yr)		CO_2 emission (tonne/yr)	
	Reference	**Integrated**	**Reference**	**Integrated**
Electricity	14040	9720	1629	1128
Heat	20160	13680	1129	766
	34200	**23400**	**2758**	**1894**

9.5 Technical and commercial feasibility

9.5.1 Technical feasibility

The results of the technical feasibility are presented in Table C-13.
The grass biorefinery is a very challenging case, almost the most one of al projects investigated. There are two main weak points: the proof-of-concept is very week and the generated products are poorly referenced in the potential markets. The combination of these two aspects are leading to a very low technical feasibility. As the process is in an early stage of development, more research might help to overcome some of the apparent weaknesses (proof of concept).

9.5.2 Commercial feasibility

The results of the commercial feasibility are presented in Table C-14.

The grass biorefinery shows an average score on commercial feasibility. Mainly positive impact related to a better cost for electricity due to the refinery case. The lower amount of renewable energy and lack of supportive legislation for this concept is compensating this.

9.5.3 SWOT analysis

A SWOT analysis carried out for the integrated cheese biorefinery is presented in Appendix D.7, with some major points summarised in Table 9-6.

Table 9-6 *Some major points of the SWOT analysis*

Strengths • Cheap feedstock	***Weaknesses*** • Extraction plant idle 75% of time • No established markets or approvals
Opportunities • Purification of minerals (reducing mineral load on land)	***Threats*** • Cut down of subsidies • Dependent on weather conditions

9.6 Summary and conclusions

The integrated grass biorefinery has several advantages:

- Useful application of heat;
- Production of fibres;
- Production of high quality feed.

However, the problems with anaerobic digestion and combined heat and power generation are not solved:

- High costs and little income from electricity;
- Highly depending on current subsidy systems.

More refinery will be needed in order to produce more products and less electricity. Unfortunately, there are no incentives to do so with the current subsidy systems. Furthermore, the process has not been proven and the products (fibres and animal feed) have little or no approval or reference in market applications.

10. PortfolioScan of integrated biorefineries

10.1 Overall feasibility

Figure 10.1 shows the technical vs. commercial feasibility for all biorefinery schemes studied in Bio-ref-Integ. As explained in chapter 1, the top right quadrant groups the projects with both technical and commercial feasibility above average, the bottom left those below average. Above the diagonal are those projects with overall feasibility (technical x commercial feasibility) above average; close to the diagonal the 'average' projects.

The axes are set at average throughout all projects, being 71%, both for technical as commercial feasibility.

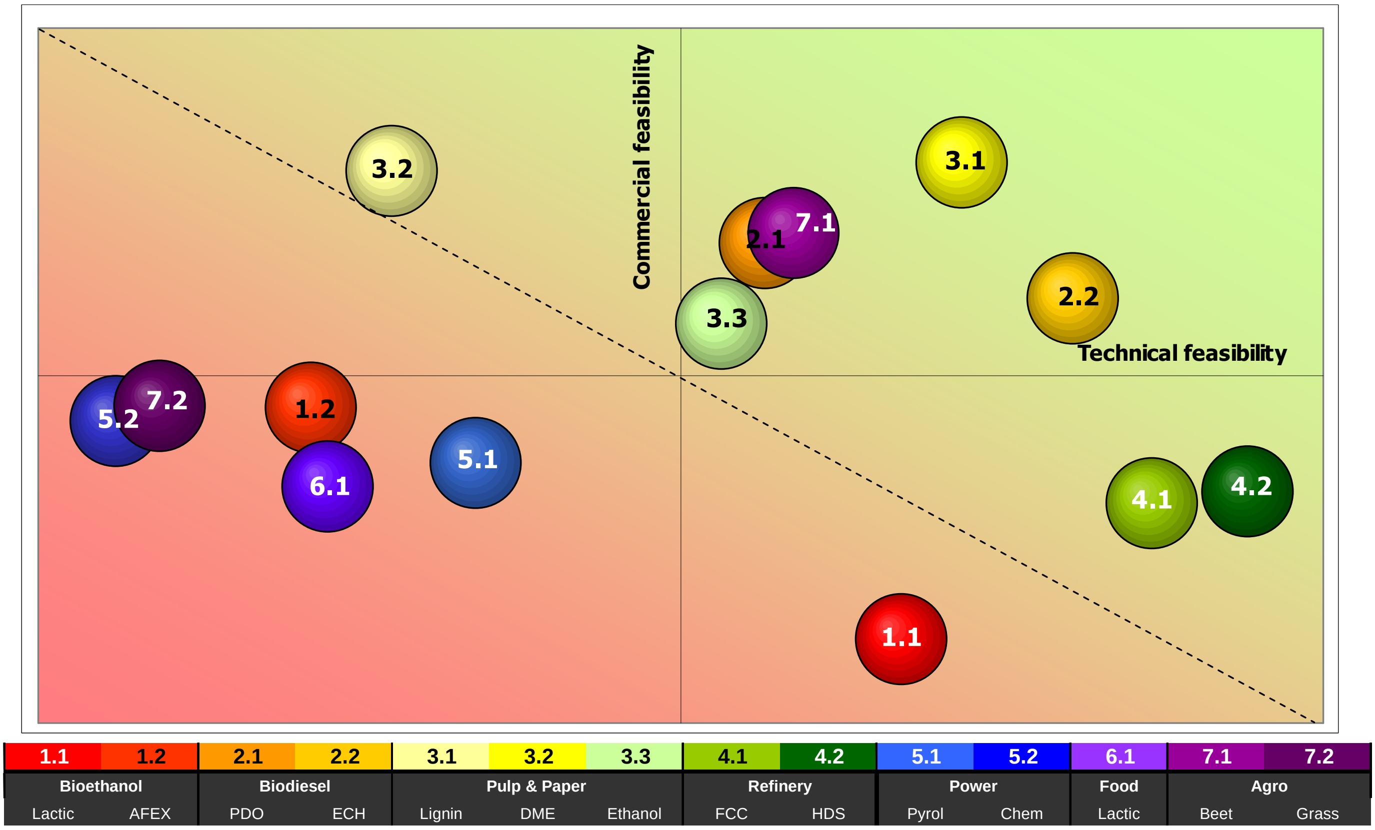

Figure 10-1 *Graphical representation of the technical, commercial and overall feasibility*

Out of this graph, the following conclusions can be made per sector:

- **Bioethanol:** both retained cases are overall below average feasibility;
- **Biodiesel:** the two cases are in the top right quadrant of high feasibility;
- **Pulp & Paper:** three cases from neutral to above average;
- **Conventional oil refinery:** both cases technically well feasible, but commercially borderline;
- **Power generation:** both cases are underperforming regarding both technical and commercial feasibility;
- **Food:** the retained biorefinery case is below average on both feasibilities;
- **Agro:** this is the only sector with a positive (decentralised beet plant) and negative (grass biorefinery) case.

10.2 Cross-sector analysis

The methodology used in this paragraph is described in chapter 1.

10.2.1 Impact level

Depending on the impact of the biorefinery case on the overall reference process, all biorefinery cases were clustered into three categories.

Low impact cases:

- Bioethanol, co-production of lactic acid;
- Biodiesel, glycerol to 1,3-PDO;
- Biodiesel, glycerol to epichlorohydrin;
- Pulp & Paper, lignin extraction;
- Food, lactic acid from whey.

Basically, most of these cases are dealing with a better use of a co-product of the reference case. Any problem occurring in running these projects has no impact on the production of the main product.

Medium impact cases:

- Bioethanol, AFEX treatment of DDGS;
- Pulp & Paper, DME production;
- Pulp & Paper, ethanol co-production.

These cases have some impact on the reference process, by changing the mass balances of the main feedstock-to-main product route or the reference co-product treatment. Problems in running these cases have some impact on the main product production.

High impact cases:

- Refinery, vegetable oil in FCC and HDS;
- Power generation, combined CHP and pyrolyser;
- Power generation, biomass gasification and chemical extraction;
- Agro, decentralised beet refineries;
- Agro, grass biorefinery.

These cases profoundly modify the reference case. Problems in operating these processes will have a huge to dramatic impact on the whole plant, possibly leading to production stop.

10.2.2 IRR=20%

In WP4, the IRR and payback time of the different projects (reference cases and biorefinery cases) have been computed (see Appendix B). Several cases had a negative IRR, with payback time exceeding 12 years, which made it difficult to discriminate such projects from each other.

Targeted investment analysis

In order to normalise the different projects to each other, the minimal sales price to reach a 20% IRR has been computed within WP5. This 20% IRR corresponds to an acceptable return on investment and a +/- 5 years payback time.

The required sales price can be considered as a target for sales teams or as a combination of the market price and possible subsidies (subsidies have been discarded in this project due to their regional specificity).

Table 10-1 *Calculation of required sales price for IRR = 20%*

IRR 20% analysis	Current market price	Required sales price increase	New target sales price	% change vs market price	Main product cost (WP4,2)
Bioethanol: reference	€800/T	-€25/T	€775/T	-3%	€628/T
Bioethanol: lactic	€800/T	-€255/T	€545/T	-32%	€368/T
Bioethanol AFEX 80	€800/T	-€90/T	€710/T	-11%	€577/T
Biodiesel: reference	€700/T	€65/T	€765/T	9%	€726/T
Biodiesel: PDO	€700/T	€115/T	€815/T	16%	€732/T
Biodiesel: ECH	€700/T	€35/T	€735/T	5%	€668/T
Pulp & Paper: reference	€500/T	€130/T	€630/T	26%	€398/T
Pulp & Paper: lignin	€500/T	€50/T	€550/T	10%	€347/T
Pulp & Paper: DME	€500/T	€210/T	€710/T	42%	€367/T
Pulp & Paper: ethanol	€500/T	€490/T	€990/T	98%	€586/T
Refinery: reference FCC	n.a.	n.a.	n.a.	n.a.	n.a.
Refinery: veg. oil in FCC	n.a.	n.a.	n.a.	n.a.	n.a.
Refinery: reference HDS	n.a.	n.a.	n.a.	n.a.	n.a.
Refinery: veg. oil in HDS	n.a.	n.a.	n.a.	n.a.	n.a.
Power: reference CHP	€50/MWh	€100/MWh	€150/MWh	200%	€60/MWh
Power: CHP/pyrolyse	€50/MWh	€135/MWh	€185/MWh	270%	€88/MWh
Power: reference gasification	€50/MWh	€60/MWh	€110/MWh	120%	€74/MWh
Power: gasification/chemicals	€50/MWh	€150/MWh	€200/MWh	300%	€48/MWh
Food: reference	€2.250/T	€0/T	€2.250/T	0%	€1.916/T
Food: lactic	€2.250/T	-€205/T	€2.045/T	-9%	€1.441/T
Agro: reference beet	€400/T	€30/T	€430/T	8%	€329/T
Agro: decentralised beet	€400/T	-€15/T	€385/T	-4%	€252/T
Agro: reference grass	€50/MWh	€230/MWh	€280/MWh	460%	€177/MWh
Agro: grass biorefinery	€50/MWh	€280/MWh	€330/MWh	560%	€171/MWh

Looking at the projects from this perspective gives a slightly different view than the product cost analysis as done in WP4 (right column in Table 10-1).

For a good understanding, colour codes used in Table 10-1 are:

- **Black** for reference cases;
- **Green** for improvement compared to reference;
- **Red** for worse compared to reference.

As mentioned earlier, IRR analysis could not be done for the refinery cases, as no extra investment was needed and the operating cost in all cases was higher than the reference case.

As first remark, and as validation of the whole calculation, it appears that the required additional price for electricity cases (Power generation / Agro, grass refinery) is quite in line with the subsidies granted for green electricity in the Netherlands.

Bioethanol:
Both bioethanol cases are an improvement compared to the reference case. This can give an edge to bioethanol producers, to preserve a sustainable profitability in case of fluctuations in feedstock price and crude oil benchmark.

Biodiesel:
For biodiesel, the cases are only dealing with a better –integrated- valorisation of glycerol. Depending on the case, this can improve the overall profitability of a biodiesel plant.

Pulp & Paper:
Here we have a first discrepancy between a simple cost calculation and a targeted investment analysis: the DME case reduces the pulp cost, but the profitability –with the current assumptions- is worse than the reference case. Probably that mixed solutions, including a recovery boiler and a gasifier, resulting in a debottlenecking of the pulp mill, with capacity increase as consequence (see lignin case) can improve the DME case.

Power generation:
None of the proposed biorefinery cases are improving the profitability of the reference cases. The targeted investment analysis revealed that even in the gasification/chemicals case, a lower product cost compared to reference case is not sufficient for a profitable process.

The message for thermal treatment of biomass seems to be double:

- Next to electricity, it is recommended to have a valuable outlet for heat;
- Keep it simple! Making the downstream complex does not improve the profitability.

Food:
Simple case, in correlation with the cost analysis.

Agro:
Especially for the grass biorefinery, we want to refer to the recommendations of the Power sector: simplicity is the message. Alternatively, increasing the amount of products extracted from grass at the expense of electricity can also improve the picture.

10.2.3 Correlation analysis

Finally, bringing all data together, both objective data as subjective ones (feasibility, SWOT), will complete the evaluation of the biorefinery cases and will allow for a ‘cross-sector’ analysis.

Table 10-2 is giving a complete overview of the discriminating criteria for each reference and corresponding biorefinery cases.

Colour code:	Subjective criteria;	**Green**: above average
		Orange: average
		Red: below average
	Objective criteria:	**Black**: reference cases
		Green: improvement compared to reference
		Red: worse compared to reference.

Table 10-2 *Subjective and objective criteria*

	Subjective criteria			Objective criteria	
	Impact level	Technical feasibility	Commercial feasibility	New target sales price (for IRR 20%)	% change vs market price (for IRR 20%)
Bioethanol: reference				€775/T ethanol	**-3%**
Bioethanol: lactic	Low	**78%**	**56%**	€545/T ethanol	**-32%**
Bioethanol AFEX 80	Medium	**60%**	**69%**	€710/T ethanol	**-11%**
Biodiesel: reference				€765/T biodiesel	**9%**
Biodiesel: PDO	Low	**74%**	**79%**	€815/T biodiesel	**16%**
Biodiesel: ECH	Low	**83%**	**75%**	€735/T biodiesel	**5%**
Pulp & Paper: reference				€630/T pulp	**26%**
Pulp & Paper: lignin	Low	**80%**	**83%**	€550/T pulp	**10%**
Pulp & Paper: DME	Medium	**62%**	**83%**	€710/T pulp	**42%**
Pulp & Paper: ethanol	Medium	**72%**	**74%**	€990/T pulp	**98%**
Refinery: reference FCC				n.a.	**n.a.**
Refinery: veg. oil in FCC	High	**86%**	**64%**	n.a.	**n.a.**
Refinery: reference HDS				n.a.	**n.a.**
Refinery: veg. oil in HDS	High	**89%**	**64%**	n.a.	**n.a.**
Power: reference CHP				€150/MWh	**200%**
Power: CHP/pyrolyse	High	**65%**	**66%**	€185/MWh	**270%**
Power: reference gasification				€110/MWh	**120%**
Power: gasification/chemicals	High	**53%**	**68%**	€200/MWh	**300%**
Food: reference				€2.250/T cheese	**0%**
Food: lactic	Low	**60%**	**65%**	€2.050/T cheese	**-9%**
Agro: reference beet				€430/T sugar	**8%**
Agro: decentralised beet	High	**75%**	**79%**	€385/T sugar	**-4%**
Agro: reference grass				€280/MWh	**460%**
Agro: grass biorefinery	High	**55%**	**69%**	€330/MWh	**560%**

Impact level and objective criteria

In many cases, there is some concordance between the impact level and the targeted investment analysis: a low impact project tends to be more profitable. Figure 10-2 plots the trend line between the impact level and the economical value (computed as % change in market price for reaching an IRR of 20% for the purpose of the graph).

Major exception to the trend is the decentralised beet case (highlighted). This is a high impact project, with positive economical value.

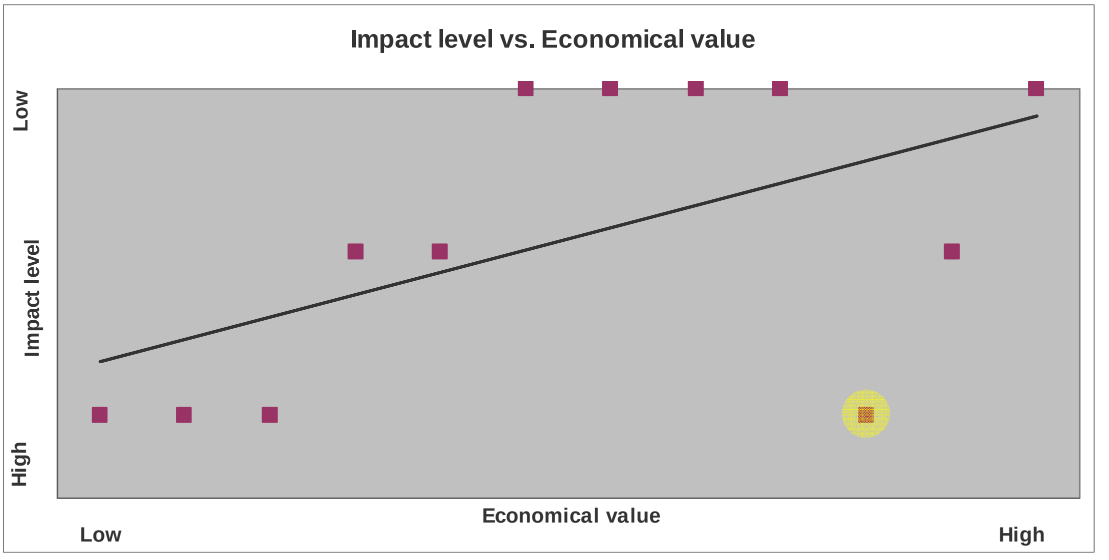

Figure 10-2 *Correlation between impact level and objective criteria*

Technical feasibility and objective criteria
Similarly, we found a reasonable correlation between the technical feasibility and the economical value, as shown in Figure 10-3. The main deviation here is the Food case (highlighted): the feasibility is considered rather low (60%) while the economical value is definitively positive.

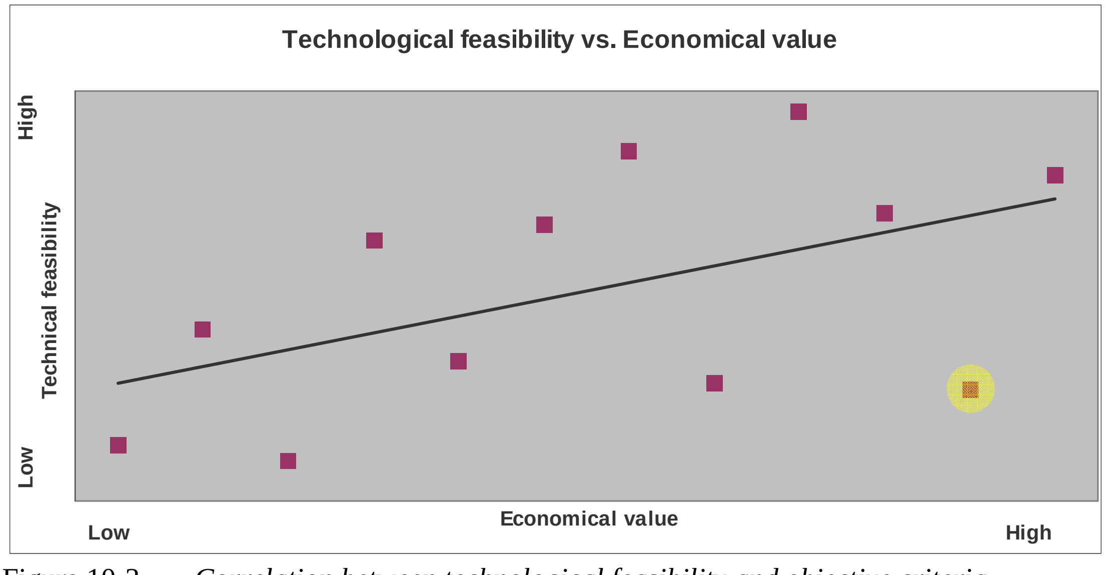

Figure 10-3 *Correlation between technological feasibility and objective criteria*

Commercial feasibility and objective criteria
As opposed to the more technical subjective factors, there is surprisingly no correlation between the commercial feasibility and the economical value.

How to understand this? Seemingly, the Consortium believes that economically attractive projects are not necessarily commercially feasible. Data may look attractive, but the challenge may be big. This tends to prove the added value to incorporate such a feasibility analysis to more conventional objective return on investment analysis.

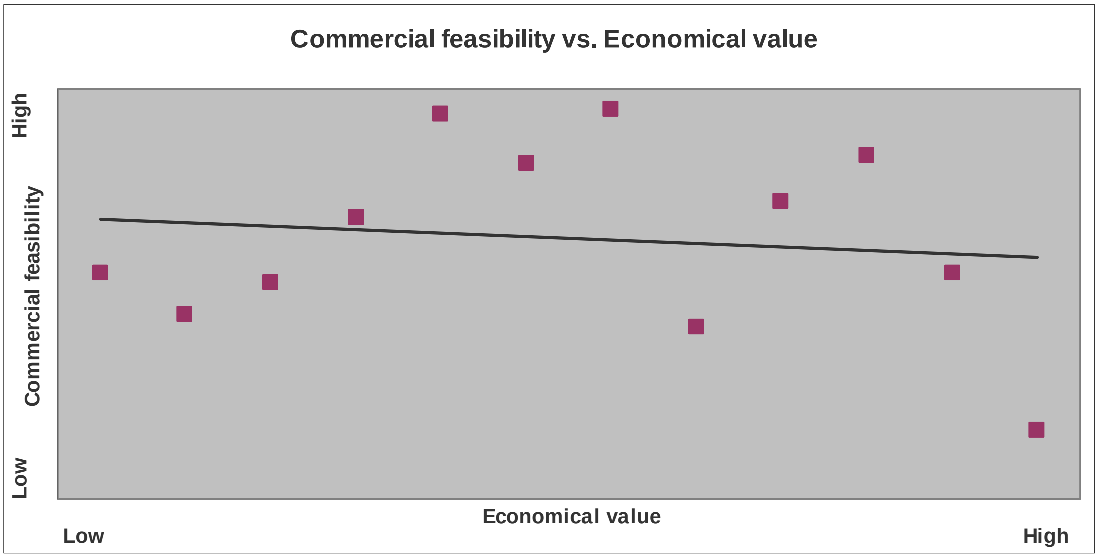

Figure 10-4 *Correlation between commercial feasibility and objective criteria*

Finally, some projects were clustered and compared to each other according to other attributes. These projects are selected out of all sectors.

Power generation projects
As a red wire throughout WP5, three biorefinery cases –Power, gasification / Power, CHP / Agro, grass-, respectively large, medium and small scale electricity production projects do show a similar trend:

- High impact projects;
- Below average technical feasibility;
- Average commercial feasibility;
- Very poor return on investment (one order of magnitude worse than other biorefinery cases), even for reference cases.

This explains why subsidies are needed to support such projects and highlights the complexity to define suitable biorefinery cases to improve the overall performance. As mentioned earlier, all efforts need to be oriented to a maximal valorisation of heat (co-product) and keeping a simple design.

Co-product valorisation projects
Projects focused on getting a better value for existing co-products have the best chances of success. These are typically the 'Low impact' projects.

Table 10-3 *Co-product valorisation projects*

	Subjective criteria			Objective criteria	
	Impact level	Technical feasibility	Commercial feasibility	New target sales price (for IRR 20%)	% change vs market price (for IRR 20%)
Biodiesel: PDO	Low	74%	79%	€815/T biodiesel	16%
Biodiesel: ECH	Low	83%	75%	€735/T biodiesel	5%
Pulp & Paper: lignin	Low	80%	83%	€550/T pulp	10%
Food: lactic	Low	60%	65%	€2.050/T cheese	-9%

All these projects are either considered as highly feasible, and/or have a good economical value.

Co-production projects

These are the projects where part of the main product of the reference case is replaced by (an)other product(s). There are three projects in this category.

Table 10-4 *Co-production projects*

	Subjective criteria			Objective criteria	
	Impact level	Technical feasibility	Commercial feasibility	New target sales price (for IRR 20%)	% change vs market price (for IRR 20%)
Bioethanol: lactic	Low	**78%**	**56%**	€545/T ethanol	**-32%**
Pulp & Paper: ethanol	Medium	**72%**	**74%**	€990/T pulp	**98%**
Agro: decentralised beet	High	**75%**	**79%**	€385/T sugar	**-4%**

These projects are considered as technically feasible and tend to be economically attractive.

Fermentation projects

These are the projects where the biorefinery cases include an additional fermentation step.

Table 10-5 *Fermentation projects*

	Impact level	Technical feasibility	Commercial feasibility	New target sales price (for IRR 20%)	% change vs market price (for IRR 20%)
Bioethanol: lactic	Low	**78%**	**56%**	€545/T ethanol	**-32%**
Bioethanol AFEX 80	Medium	**60%**	**69%**	€710/T ethanol	**-11%**
Biodiesel: PDO	Low	**74%**	**79%**	€815/T biodiesel	**16%**
Pulp & Paper: ethanol	Medium	**72%**	**74%**	€990/T pulp	**98%**
Food: lactic	Low	**60%**	**65%**	€2.050/T cheese	**-9%**
Agro: decentralised beet	High	**75%**	**79%**	€385/T sugar	**-4%**

Fermentation projects tend to improve the reference case, except for the co-production of ethanol in a pulp mill. The glycerol-to-PDO is also negative in economical value, but this can probably be improved by increasing the yield / productivity of the fermentation step. On the contrary to the other projects, all leading to ethanol or lactic acid, fermentation of glycerol to 1,3-PDO is not yet a mature technology, neither is PDO as a product.

Thermal treatment of biomass

This category is covering projects involving a thermal treatment of the incoming biomass.

Table 10-6 *Thermal treatment of biomass projects*

	Subjective criteria			Objective criteria	
	Impact level	Technical feasibility	Commercial feasibility	New target sales price (for IRR 20%)	% change vs market price (for IRR 20%)
Pulp & Paper: DME	Medium	**62%**	**83%**	€710/T pulp	**42%**
Power: reference CHP				€150/MWh	**200%**
Power: CHP/pyrolyse	High	**65%**	**66%**	€185/MWh	**270%**
Power: reference gasification				€110/MWh	**120%**
Power: gasification/chemicals	High	**53%**	**68%**	€200/MWh	**300%**

We exceptionally included two reference projects in this group, to better illustrate the comments. Seemingly, thermal treatment of biomass is still not a viable industrial option. Neither the reference cases nor the biorefinery cases are leading to a positive economical activity.

With the exception of the high commercial feasibility of DME (DME is indeed an interesting product with functional benefits, supplied in a demanding and regulatory supported market), all feasibility parameters are below average.

Legislation-driven projects
The final category is covering projects strongly supported by legislation.

Table 10-7 *Legislation-driven projects*

	Subjective criteria			Objective criteria	
	Impact level	Technical feasibility	Commercial feasibility	New target sales price (for IRR 20%)	% change vs market price (for IRR 20%)
Refinery: veg. oil in FCC	High	**86%**	**64%**	n.a.	**n.a.**
Refinery: veg. oil in HDS	High	**89%**	**64%**	n.a.	**n.a.**

Both selected projects have a high technical feasibility. Commercial feasibility however is below par, fully explained by the higher cost and the lack of technical benefits (as perceived by some respondents) compared to the respective reference cases.

This score has to be put into the right perspective: our model gives a lower weight to legislative support compared to price and technical benefits. Seen the directive character of the legislative support for these projects, this should be opposite.

10.3 Alternative improvement options

As explained in §10.2.2, sales price of the main product will have to increase substantially for several cases studied in this project in order to have a decent return on investment. This can be achieved by focussing on niches with potentially higher market price or by a subsidy mechanism (such as existing for green electricity).

Another option could be to reduce the processing cost or to further increase the value of the co-products. Some ideas (a.o. derived from WP3 and WP4) are mentioned here.

Bioethanol sector
Feedstock and steam are the most important cost factors in the bioethanol production, accounting resp. for 60% and 10% (excluding return on co-products). 2nd generation feedstocks (lignocellulosics) are obvious choices to reduce the feedstock cost, in combination with a higher conversion yield. This can be obtained in the '100% Bioethanol concept' in which part of the biomass is steam exploded, lignin extracted (used as solid fuel) and the remaining C5 and C6 fraction converted into ethanol. The rest of the biomass is gasified and transformed into ethanol by catalytic synthesis. The energy released in the gasification process is used to reduce the energy bill of the fermentation process.

This concept is focused on reducing the main cost drivers but is still immature (technological risk) and carries a high capex. This is an option for the future and a nice research challenge.

Biodiesel sector
Use of waste oil / fats as feedstock reduces the feedstock cost by 50%, only partially offset by a higher auxiliary and utility cost and extra investment cost. All in all, the production cost can be reduced by 20-25%, making a biodiesel production highly profitable (IRR of 40% at current sales price of €700/T).

Drawback is the limited availability of waste oil and fats and possibly technical problems on the long run due to accumulation of impurities and variability of incoming feedstock quality.

Pulp & Paper sector
As indicated in chapter 4, extracting lignin from the black liquor can significantly improve the profitability of pulp mills, mainly by debottlenecking the pulp mill. The hemicellulose fraction however remains in the liquor and is combusted.

A very attractive option is to consider a total valorisation of the incoming wood: cellulose to pulp, lignin to solid fuel and hemicellulose to ethanol and furfural. But this means that less energy will be available for operating the pulp mill. The solution is proposed by the AVAP^{tm} technology. Pulping is done by using ethanol (from hemicellulose) and sulphur dioxide in a closed system. In parallel, forest residues (and possibly lignin) are gasified supplying enough energy for the whole plant.

Another alternative process combines integrated cases studied in this project. Lignin removal debottlenecks the recovery boiler, allowing for a 25% capacity increase. This additional cellulose can be saccharified (as pulp market is rather saturated) and used as feedstock for fermentation (ethanol, lactic acid …).

Food sector
In the integrated case, lactose is converted into lactic acid by fermentation. A recent technology describes the fermentation of lactose to vitamin C (a.o. US patent 4259443). Vitamin C sells at €6/kg, compared to €0.8/kg for lactic acid. Assuming a 40-50% yield (realistic target) on lactose, this would reduce the production cost of cheese by 50%. The required sales price for cheese now drops to €1.620 for an IRR=20%, well below the cheese market price.

This example illustrates that a proper choice of the target product for co-product valorisation has a huge impact on the overall profitability.

Agro sector
In our grass biorefinery case, proteins are extracted from grass and sold as animal feed at €150/T dry. This concept is not profitable, as shown in Table 10-1, and subsequent discussion on Agro sector.

Seen the low volumes involved in such a grass biorefinery (<600 T dry proteins/a), it may be possible to further process these proteins into higher added value niche products such as hydrolysed vegetable proteins used as flavouring agents (sales price around €1,500/T, 10 times the feed value).

The effect on the cost for electricity (main product in this case) is spectacular, and makes such a grass refinery closer to reality.

This illustrates that the production of electricity out of biomass (in this case grass), can be profitable, providing a high value side stream. Basically, energy outlets can be considered as a co-product of the hydrolysed protein production.

11. Coclusions

- 366 existing industrial (fuel producing) complexes in partner-related countries have been identified, and 10 market-specific reference cases have been defined.
- Based on the results of WP1, WP2, and WP3, 14 integrated biorefinery cases for 7 considered biomass processing sectors have been defined within WP4.
- Integral technical and economic system assessments of defined biorefinery schemes have been performed within WP4.
- In WP5 the Consortium tried to analyse the different biorefinery cases according to both objective (profitability measurement) and subjective (technical and commercial feasibility; SWOT analysis) criteria.
- The technical and commercial feasibility, as well as the SWOT analysis were measured by a questionnaire filled in by experts within the Consortium.
- Regarding Technical Feasibility, major deviation from the average are related to process development (proof-of-concept, scalability…). Application development (referencing new products in the market) are mostly considered as less critical.
- Concerning the Commercial Feasibility, not surprising, the tangible competitive advantages (cost, price, technical benefits) are key success factors. The other key determinant, the perception of the products, processes… by the consumers is generally speaking scoring rather high for all projects. A good point for 'bio-based economy' projects as studied in Bioref-Integ! But this makes the perception criteria less discriminative for the different projects.
- The objective criteria used are related to investment analysis. In WP5 we proposed a 'targeted investment analysis'. In a similar IRR calculation model as used in WP4, we computed the required sales price for the main product to reach an IRR = 20%. This gives a better perspective to compare the different projects to each other.
- Another new parameter is the 'impact level': how deep will a biorefinery concept affect the reference process. We clustered the biorefinery projects in 3 groups: low, medium and high impact.
- Out of our study, there is a positive correlation between the technical feasibility and the economical value (measured as targeted sales price for IRR=20%). Low impact projects are also leading to a higher economical value.
- The commercial feasibility has no correlation with the economical value. It should be considered together with financial analysis to make an educated decision on biorefinery schemes.
- Projects involving thermal treatment of biomass (CHP, pyrolysis, gasification) are clearly still immature and not yet industrially feasible. This appears clearly in a low technical feasibility and a negative economic value.
- Power generation (electricity from biomass) projects also have a negative evaluation (subsidies were not taken into account!). This is of course in line with the comments on thermal treatment, as frequently the same technology is used. The message to electricity-from-biomass projects is: find a value application for heat and … keep it simple or … change focus and produce products from biomass.
- Biorefinery projects that have the potential to improve the economics of reference cases are low impact projects (no significant impact on the reference process), fermentation projects and co-product valorisation projects. These projects frequently also have an above average technical and commercial feasibility score.

- Finally, legislation is an important factor, driving the use of bio-based feedstock (see biofuel directive) or supporting directly biorefineries by several subsidy incentives.

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Appendix A Mass & energy flows

A.1 Bioethanol sector

Table A-1 *Overall mass balance of the Base Case*

Parameter	Grain meal	Ethanol	CO_2	DDGS
	Input	Output	Output	Output
Total mass flow* (t/h)	47	14	13	20

**Not all flows shown in the table*

Table A-2 *Mass balance of integrated case Ethanol + Lactic acid production*

Parameter	Grain meal	Wine alcohol	Ethanol	Lactic Acid	CO_2	DDGS
	Input	Input	Output	Output	Output	Output
Total mass flow (t/h)	47	5	17	3	11	20

**Not all flows shown in the table, which may lead to small differences between input and output*

Table A-3 *Overall mass balance for the 20% DDGS integrated concept*

Parameter	Grain meal	Wine alcohol	Ethanol	CO_2	DDGS	New DDGS
	Input	Input	Output	Output	Output	Output
Total mass flow* (t/h)	47	5	20	14	16	2

**Not all flows shown in the table, which may lead to small differences between input and output*

Table A-4 *Overall mass balance for the 80% DDGS integrated concept*

Parameter	Grain meal	Wine alcohol	Ethanol	CO_2	DDGS	New DDGS
	Input	Input	Output	Output	Output	Output
Total mass flow* (t/h)	47	5	22	16	4	12

**Not all flows shown in the table, which may lead to small differences between input and output*

A.2 Biodiesel sector

Table A-5 *Mass balance of biodiesel reference case*

Component	Inlet (Feed streams)	Outlet (Product streams)	Unit
Rapeseed oil	12.5		t/h
Potassium hydroxide	0.21		t/h
Methanol	1.17		
Total mass flow*	**13.88**		**t/h**
Biodiesel		12.5	t/h
Crude glycerol		1.46	t/h
Waste water		0.021	t/h
Total mass flow*		**13.98**	**t/h**

** Difference can be accounted to data inaccuracy*

Table A-6 *Energy balance of biodiesel reference case*

Component	Energy content MJ/kg	Enthalpy flow MJ/h Inlet	Enthalpy flow MJ/h Outlet
Rapeseed oil	37.6	470000	
Potassium hydroxide	n.a.	-	
Methanol	20	23400	
Biodiesel	37.5		468750
Crude glycerol	24.18		35302.8
Waste water	n.a.		-
Total flow*		**493400**	**504052.8**

** Difference can be accounted to unavailability of energy content of certain flows*

Table A-7 *Mass balance for 1,3- propanediol (PDO) production from glycerol*

Component	Inlet (Feed streams)	Outlet (Product streams)	Unit
Crude Glycerol	1.46		t/h
Mineral salts	0.17		t/h
Yeast extract	0.02		t/h
Total mass flow*	**1.65**		**t/h**
1,3-PDO		0.58	t/h
Acetate		0.05	t/h
Butyrate		0.12	t/h
Cells		0.06	t/h
CO_2		0.24	t/h
Impurities		0.13	t/h
Remaining waste (+ water)		0.45	t/h
Total mass flow*		**1.63**	**t/h**

** Difference can be accounted to data inaccuracy*

Table A-8 *Mass balance for Epichlorohydrin production from glycerol*

Component	Inlet (Feed streams)	Outlet (Product streams)	Unit
Glycerol	1.46		t/h
HCl	0.98		t/h
NaOH	0.54		t/h
Total mass flow	**2.98**		**t/h**
Epichlorohydrin		1.12	t/h
NaCl		0.79	t/h
Water		0.95	t/h
By-products		0.12	t/h
Total mass flow		**2.98**	**t/h**

A.3 Pulp & paper sector

Table A-9 *Mass balance of pulp and paper reference case (softwood)*

Component	**Inlet**	**Outlet**	**Unit**
Wood	346		t/h
Water	1580		t/h
Chemicals	8.0		t/h
Total	**1934**		t/h
Tall oil		2.9	t/h
Bark		8.3	t/h
Water effluent		1375	t/h
Bleached pulp		83	t/h
Flue gases		150	t/h
Misc. outputs and losses		315	t/h
Total		**1934**	t/h

Table A-10 *Energy balance of pulp and paper reference case (softwood)*

Component	**Energy content** (MJ/kg)	**Inlet** (GJ/h)	**Outlet** (GJ/h)
Wood	20	3460	
Water	0.1	166	
Chemicals	0.0	0,0	
Total		**3626**	
Tall oil	38		109
Bark	19		161
Water effluent	0.2		260
Bleached pulp	15		1125
Electricity			173
Flue gases	0.8		650
Cooled away			1153
Total			**3626**

Table A-11 *Mass balance of lignin extraction case*

Component	Inlet	Outlet	Unit
Wood	432		t/h
Water	2000		t/h
Chemicals	10		t/h
Total	**2442**		**t/h**
Tall oil		4	t/h
Bark		10	t/h
Lignin		15	t/h
Water effluent		1720	t/h
Bleached pulp		104	t/h
Flue gases		188	t/h
Misc. outputs and losses		401	t/h
Total		**2442**	**t/hr**

Table A-12 *Energy balance of lignin extraction case*

Component	**Energy content** (MJ/kg)	**Inlet** (GJ/h)	**Outlet** (GJ/h)
Wood	20	4325	
Water	0.1	210	
Chemicals	0.0	0.0	
Total		**4535**	
Tall oil	38		135
Bark	19		202
Lignin	26		380
Water effluent	0.2		326
Bleached pulp	15		1410
Electricity			180
Flue gases	0.8		743
Cooled away			1159
Total			**4535**

Table A-13 *Mass balance of black liquor gasification with DME production*

Component	Inlet	Outlet	Unit
Wood	346		t/h
Water	1580		t/h
Chemicals	57		t/h
Bark (85% dry)	108		t/h
Total	**2091**		**t/h**
DME		34	t/h
Tall oil		3	t/h
Water effluent		1375	t/h
Bleached pulp		83	t/h
Misc. outputs and losses		257	t/h
Flue gases		242	t/h
Total		**2091**	**t/h**

Tabel A-14 *Energy balance of black liquor gasification with DME production*

Component	**Energy content** (MJ/kg)	**Inlet** (GJ/h)	**Outlet** (GJ/h)
Wood	20	3460	
Water	0.1	166	
Chemicals	0.0	0.0	
Bark	19	1781	
Total		**5407**	
Tall oil	38		109
DME	29		989
Water effluent	0.2		260
Bleached pulp	15		1125
Flue gases	0.8		914
Cooled away			2010
Total			**5407**

Table A-15 *Mass balance of ethanol case*

Component	Inlet	Outlet	Unit
Wood	346		t/hr
Water	1580		t/hr
Chemicals	8		t/hr
Yeast & enzymes	11		t/hr
Total	**1945**		**t/hr**
Ethanol		11	t/hr
Tall oil		3	t/hr
Bark		8	t/hr
Water effluent		1375	t/hr
Bleached pulp		42	t/hr
Flue gases		150	t/h
Misc. outputs and losses		356	t/h
Total		**1945**	**t/h**

Table A-16 *Energy balance of ethanol case*

Component	**Energy content** (MJ/kg)	**Inlet** (GJ/hr)	**Outlet** (GJ/hr)
Wood	20	3460	
Water	0.1	166	
Chemicals	0.0	0,0	
Yeast & enzymes	0.16	2.0	
Total		**3628**	
Ethanol	28		308
Tall oil	38		109
Bark	19		161
Water effluent	0.2		260
Bleached pulp	15		563
Electricity Flue gases Cooled away	0.8		173 704 1398
Total			**3628**

A.4 Conventional oil refinery sector

Table A-17 *Mass balance of FCC and gas concentration units (main flows) for reference case*

Component	Input / output (t/h)
Feed	
Vacuum gasoil	200.0
Vegetable oil	0.0
Total feed	200.0
Products	
Liquefied petroleum gas (LPG)	187.6
Naphta (GLN)	
Diesel (gasoil)	
Heavy oil	
Total	187.6
By-products	
Fuel gas	12.4
Solid sulphur (from H_2S)	
Coke	
Water, CO, CO_2	0.0
Total by-products	12.4
Total products + by-products	200.0

Table A-18 *Mass balance of HDS unit (main flows) for reference case*

Component	Input / output (t/h)
Feed	
High sulphur gasoil	230.0
Vegetable oil	0.0
Hydrogen	1.6
Total feed	231.6
Products	
Hydrotreated middle distillates	226.6
By-products	
Fuel gas	5.0
LPG (C_3)	
Solid sulphur (H_2S)	
Warer, CO, CO_2	0.0
Total by-products	5.0
Total products + by-products	231.6

Table A-19 *Mass balance of FCC and gas concentration units (main flows) for biorefinery case*

Component	Input / output (t/h)
Feed	
Vacuum gasoil	180.0
Vegetable oil	20.0
Total feed	200.0
Products	
Liquefied petroleum gas (LPG)	184.6 (decrease in main products, compare to reference case)
Naphta (GLN)	
Diesel (gasoil)	
Heavy oil	
Total	184.6
By-products	
Fuel gas	12.3 (approx. same by-products as in reference case)
Solid sulphur (from H_2S)	
Coke	
Water, CO, CO_2	3.1
Total by-products	15.4
Total products + by-products	200.0

Table A-20 *Mass balance of HDS unit (main flows) for biorefinery case*

Component	Input / output (t/h)
Feed	
High sulphur gasoil	207.0
Vegetable oil	23.0
Hydrogen	2.1
Total feed	232.1
Products	
Hydrotreated middle distillates	222.4 (decrease in main products, compared to reference case)
By-products	
Fuel gas	6.1 (increase in C_3 production, compared to reference case)
LPG (C_3)	
Solid sulphur (H_2S)	
Warer, CO, CO_2	3.5
Total by-products	9.7
Total products + by-products	232.1

A.5 Power sector

Table A-21 *Mass and energy balance for reference and integrated biorefinery case for combustion based biorefinery*

Stream	Reference case		Integrated biorefinery case	
	Mass flow (t/h)	Energy flow (MW)	Mass flow (t/h)	Energy flow (MW)
Input				
Peat[4]	26.7	67	26.7	67
Forestry residues[5]			9.24	22
Air	130.75		152.22	
Total	157.45	67	188.16	89
Output				
Pyrolysis oil			3.31	15.5
Ash	0.4		0.41	
Flue gases	157.05		184.44	
Electricity		17.0		15.6
Heat		40.0		44.4
Total	157.45	57.0	188.16	75.5

Table A-22 *Mass- and energy balances for reference and integrated biorefinery case of gasification based biorefinery*

Stream	Reference case		Integrated biorefinery case	
	Mass flow (t/h)	Energy flow (MW)	Mass flow (t/h)	Energy flow (MW)
Input				
Biomass[6]	160	344	160	344
Air	1181		1181	
Total	1341	344	1341	
Output				
Flue gas	1341		1325	
Ash	0.1		0.1	
BTX			1.7	19
Tars			2.1	23
Ethylene			3.4	44
Mixed alcohols			9.2	74
Electricity		157		46
Total	1341	157	1341	206

[4] At 50 wt.% moisture
[5] At 50 wt.% moisture
[6] At 50 wt.% moisture

A.6 Food sector

Table A-23 *Mass balance of the cheese making section*

Component	Inlet (Feed streams)	Outlet (Product streams)	Unit
Milk	279652		t/yr
Salts	22		t/yr
Renin	253		t/yr
Starter	253		t/yr
Cheese		28781	t/yr
Whey		249586	t/yr
Cream		1812	t/yr
Total	**280180**	**280180**	**t/yr**

Cleaning water and resulting wastewater were excluded from this balance

Table A-24 *Annual energy consumption cheese making section*

Component	Value	Unit
Electricity	2105	MW.h/yr
Steam (low pressure 3 barg)	18460	t/yr

Table A-25 *Mass balance of whey powder section*

Component	Inlet (Feed streams)	Outlet (Product streams)	Unit
Whey	249585		t/yr
Air	135449		t/yr
Bags	85		t/yr
Whey powder		19292	t/yr
Stack		145868	t/yr
Waste water		219959	t/yr
Total	**385119**	**385119**	**t/yr**

Table A-26 *Annual energy consumption whey powder section*

Component	Value	Unit
Electricity	7893	MWh/yr
Steam (low pressure 3 barg)	83527	t/yr

Table A-27 *Overall mass balance of cheese production process*

Component	Input (kt/a)	Output (kt/a)
Milk	279.60	-
Rennet	0.25	-
Starting Culture	0.25	-
Salt	0.02	-
Air	135.60	-
Cheese	-	28.81
WP	-	19.21
Cream	-	1.80
Wastewater	-	220.00
Wet Air	-	145.90
Total	**415.72**	**415.72**

Table A-28 *Annual energy consumption of cheese production process*

Component	Value	Unit
Electricity	10	GW.h/yr
Steam (low pressure 3 barg)	102	kt/yr

Table A-29 *Mass balance of cheese whey biorefinery*

Component	Inlet (Feed streams)	Outlet (Product streams)	Unit
Whey	249587		t/yr
Regeneration	138		t/yr
Washing	5200		t/yr
HCl	44		t/yr
NaOH	476		t/yr
$MnSO_4$	10		t/yr
Lactic acid (50% solution)		23835	t/yr
Cream		1475	t/yr
$CaHPO_4$		1318	t/yr
WPC powder (80% protein)		1737	t/yr
Pure water		50275	t/yr
Waste water		176816	t/yr
Total	**255455**	**255455**	**t/yr**

Table A-30 *Annual energy consumption of cheese whey biorefinery*

Component	Value	Unit
Electricity	10788	MW.h/yr
Steam (low pressure 3 barg)	350	t/yr

Table A-31 *Mass balance of cheese production + whey biorefinery*

Component	Inlet (Feed streams)	Outlet (Product streams)	Unit
Milk	279,65		kt/yr
Salts	0,02		kt/yr
Rennin	0,25		kt/yr
Starter	0,25		kt/yr
Regeneration	0,14		kt/yr
Washing	5,20		kt/yr
HCl	0,04		kt/yr
NaOH	0,48		kt/yr
$MnSO_4$	0,01		kt/yr
Lactic acid		23,84	kt/yr
Cream		3,29	kt/yr
$CaHPO_4$		1,32	kt/yr
WPC powder		1,74	kt/yr
Pure water		50,27	kt/yr
Waste water		265,95	kt/yr
Total	**286,05**	**286,05**	**kt/yr**

Table A-32 *Annual energy consumption of cheese production + whey biorefinery*

Component	Value	Unit
Electricity	13000	MW.h/yr
Steam (low pressure 3 barg)	18800	t/yr

A.7 Agro sector

Table A-33 *Mass balance of sugar beet reference case*

Component	Inlet (dry basis)	Outlet (dry basis)	Unit
Sugar beets	103.50		t/h
Lime (CaO)	10.93		t/h
CO_2	16.71		t/h
White sugar		72.00	t/h
Foam earth (CaCO3)		24.43	t/h
Molasses		12.21	t/h
Pulp		18.64	t/h
Total*	**131.14**	**127.29**	**t/h**

* Difference accounted from data inaccuracy

Table A-34 *Energy balance of sugar beet reference case*

Component	Energy content (MJ/kg)	Inlet (GJ/h)	Outlet (GJ/h)
Sugar beet	17.00	1 760	
Sugar	15.00		1080
Molasses	15.00		183
Pulp	20.00		373
Total*		**1 760**	**1636**

* Difference (GJ/h) can be accounted from misc. losses and data inaccuracy

Table A-35 *Mass balance of sugar beet biorefinery case*

Component	Inlet (dry basis)	Outlet (dry basis)	Unit
Sugar beet	103.50		t/h
Catch crops & leaves	64.29		t/h
Sugar		43.07	t/h
Ethanol		14.53	t/h
CO2		15.04	t/h
Protein rich product		12.86	t/h
Biogas		45.00	t/h
Total*	**167.79**	**130.50**	**t/h**

* The difference in the mass balance is caused by the residues from the biogas fermentation (digestate) that contains un fermented components from the leaf and the catch crop

Table A-36 *Energy balance of sugar beet biorefinery case*

Component	Energy content (MJ/kg)	Inlet (GJ/h)	Outlet (GJ/h)
Sugar beet	17.00	1 760	
Catch crops & leaves	17.00	1 093	
Sugar	15.00		646
Ethanol	26.70		388
Protein rich product	15.00		193
Biogas	17.75		799
Total*		**2 853**	**2 160**

* Difference (GJ/h) can be accounted from digestate, misc. losses and data inaccuracy

Table A-37 *Mass flows of anaerobic digestion reference case*

Component	Feed streams		Product streams		Unit
	Moist	Dry	Moist	Dry	
Silage grass	1.00	0.40			t/h
Manure	3.56	0.31			t/h
Digestate			4.10	0.39	t/h
Biogas			0.33	0.33	t/h
Total	**4.56**	**0.71**	**4.43**	**0.72**	**t/h**

Table A-38 *Energy balance of anaerobic digestion reference case*

	Feed streams			Product stream		
	Dry	LHV	LHV	Dry	LHV	LHV
Component	tonne/hr	GJ/tonne	GJ/hr	tonne/hr	GJ/tonne	GJ/hr
Silage grass	0.40	18.00	7.20			
Manure	0.31	19.00	5.89			
Digestate				0.39	22.00	8.57
Biogas				0.33	13.33	4.40
Total			**13.09**			**12.97**

Table A-39 *Energy produced by CHP unit*

Heat	0.700	MW
Electricity	0.482	MWe

Table A-40 *Energy balance of CHP unit reference case*

		GJ/yr	
In	biogas	35200	
Out	electricity	13872	39%
Out	heat	20168	57%
Out	losses	1160	4%

Table A-41 *Mass flows of biogas biorefinery case (main flows)*

	Feed streams		Product streams		
Component	Moist	Dry	Moist	Dry	Unit
Fresh grass	1.93	0.29			t/h
Silage grass	0.42	0.17			t/h
Manure	2.82	0.24			t/h
Fibre			0.23	0.09	t/h
Coagulated protein			0.37	0.07	t/h
Digestate			4.29	0.30	t/h
Biogas			0.23	0.23	t/h
Total	**5.16**	**0.70**	**5.11**	**0.70**	t/h

Table A-42 *Energy balance anaerobic digestion of integrated biorefnery*

	Feed streams			Product streams		
Component	tonne dry/hr	GJ/tonne	GJ/hr	tonne dry/hr	GJ/tonne	GJ/hr
Fresh grass	0.29	18.00	5.20			
Silage grass	0.17	18.00	3.00			
Manure	0.24	19.00	4.60			
Fibre				0.09	16.00	1.46
Coagulated pro-tein				0.07	18.00	1.32
Digestate				0.30	22.00	6.60
Biogas				0.23	13.33	3.11
Total	**0.70**		**12.80**	**0.70**		**12.50**

Table A-43 *Energy produced by CHP unit*

Product streams		
Heat	0.471	MW
Electricity	0.338	MW_e

Table A-44 *Energy balance of CHP of integrated biorefinery*

		GJ/yr	
In	biogas	24919	
Out	electricity	9734	39%
Out	heat	13565	54%
Out	heat to process	748	3%
Out	loss	997	4%

Appendix B Economic assessment

Table B-1 *Economic assessment of Biodiesel*

Main product	**Biodiesel**		**Net Present Value**		**-€31.270.400**
Scale	**100.000**	**T/y**	**Internal Rate of Return**		**#DIV/0!**
			Payback time		**>12 years**
		Unit	**€/unit**	**Unit/T Biodiesel**	**€/T Biodiesel**
Raw material	Rapeseed oil	T	630,60	1,00	630,6
Chemicals	Methanol	T	220,00	0,09	20,6
	KOH	T	800,00	0,02	13,4
				Total auxliaries	34,0
Steam	3 barg steam	T	12,50	0,32	4,0
Electrcity		kWh	0,05	12,00	0,6
Water					0,0
Co-products	Glycerol	T	50,00	0,12	-5,8
					0,0
		kWh			0,0
					0,0
Variable cost					**663,4**
Capex	20.000.000	€			
Depreciation	12 years				16,7
Labour	28	#	100.000,00		28,0
Other costs	9%	of capex			18,0
Fixed costs					**62,7**
Total					**726,1**
Required subsidy					
Product value	**Biodiesel**				**700,0**

Table B-2 *Economic assessment of Biodiesel PDO*

Main product	**Biodiesel**		**Net Present Value**		**-€37.762.400**
Scale	**100.000**	**T/y**	**Internal Rate of Return**		**#DIV/0!**
			Payback time		**>12 years**
		Unit	**€/unit**	**Unit/T Biodiesel**	**€/T Biodiesel**
Raw material	Rapeseed oil	T	630,60	1,00	630,6
Chemicals	Methanol	T	220,00	0,09	20,6
	KOH	T	800,00	0,02	13,4
	Mineral salts	T	300,00	0,01	4,1
	Yeast extract	T	3.500,00	0,00	5,6
				Total auxliaries	43,7
Steam	3 barg steam	T	12,50	0,32	4,0
Electrcity		kWh	0,05	12,00	0,6
Water					0,0
Co-products	Glycerol	T	50,00	0,00	0,0
	PDO	T	1.300,00	0,05	-60,7
		kWh			0,0
Variable cost					**618,2**
Capex	44.000.000	€			
Depreciation	12 years				36,7
Labour	37	#	100.000,00		37,0
Other costs	9%	of capex			39,6
Fixed costs					**113,3**
Total					**731,5**
Required subsidy					
Product value	**Biodiesel**				**700,0**

Table B-3 *Economic assessment of Biodiesel EPI*

Main product	**Biodiesel**		**Net Present Value**	**€29.000.764**
Scale	**100.000**	**T/y**	**Internal Rate of Return**	**11%**
			Payback time	**9 years**

		Unit	**€/unit**	**Unit/T Biodiesel**	**€/T Biodiesel**
Raw material	Rapeseed oil	T	630,60	1,00	630,6
Chemicals	Methanol	T	220,00	0,09	20,6
	KOH	T	800,00	0,02	13,4
	HCL	T	80,00	0,08	6,3
	NaOH	T	200,00	0,04	8,6
				Total auxliaries	48,9
Steam	3 barg steam	T	12,50	0,32	4,0
Electrcity		kWh	0,05	12,00	0,6
Water					0,0
Co-products	Glycerol	T	50,00	0,00	0,0
	Epichlorohydrin	T	1.250,00	0,09	-112,3
		kWh			0,0
Variable cost					**571,9**
Capex	35.000.000	€			
Depreciation	12 years				29,2
Labour	35	#	100.000,00		35,0
Other costs	9%	of capex			31,5
Fixed costs					**95,7**
Total					**667,6**
Required subsidy					
Product value	**Biodiesel**				**700,0**

Table B-4 *Economic assessment of Softwood pulp*

Main product	**Bleached softwood pulp**		**Net Present Value**		**€538.390.461**
Scale	**588.000**	**T/y**	**Internal Rate of Return**		**10%**
			Payback time		**10 years**
		Unit	**€/unit**	**Unit/T BSP**	**€/T BSP**
Raw material	Pulp wood	T	75,00	2,30	172,5
Chemicals	Sodium hydroxide	T	400,00	0,03	10,8
	Magnesium sulphate	T	200,00	0,00	0,6
	Chlorine dioxide	T	700,00	0,01	5,6
	Hydrogen peroxide		400,00	0,02	6,0
	Oxygen		35,00	0,03	0,9
	Sulphuric acid	T	70,00	0,01	0,5
				Total auxliaries	25,4
Steam					
Electrcity		kWh			
Water			0,1	21,00	1,1
Co-products	Tall oil	T	200,00	0,04	-7,8
	Bark	T	70,00	0,11	-7,7
	Electricity	kWh	0,05	640,00	-32,0
					0,0
Variable cost					**150,4**
Capex	715.000.000	€			
Depreciation	12 years				101,3
Labour	500	#	100.000,00		85,0
Other costs	5%	of capex			60,8
Fixed costs					**247,2**
Total					**397,6**
Required subsidy					
Product value	**Bleached softwood pulp**				**500,0**

Table B-5 *Economic assessment of Lignin extraction*

Main product	**Bleached softwood pulp**		**Net Present Value**		**€1.008.733.502**
Scale	**737.000**	**T/y**	**Internal Rate of Return**		**16%**
			Payback time		**7 years**
		Unit	**€/unit**	**Unit/T BSP**	**€/T BSP**
Raw material	Pulp wood	T	75,00	2,30	172,5
Chemicals	Sodium hydroxide	T	400,00	0,03	12,0
	Magnesium sulphate	T	200,00	0,00	0,6
	Chlorine dioxide	T	700,00	0,01	5,6
	Hydrogen peroxide	T	400,00	0,02	6,0
	Oxygen	T	35,00	0,03	0,9
	Sulphuric acid	T	70,00	0,03	1,8
	CO2	T	35,00	0,02	0,7
				Total auxliaries	28,6
Steam					
Electrcity		kWh			
Water			0,1	21,00	1,1
Co-products	Tall oil	T	200,00	0,04	-7,8
	Bark	T	70,00	0,11	-7,7
	Lignin	T	200	0,155	-31,0
	Electricity	kWh	0,05	430,00	-21,5
Variable cost					**133,1**
Capex	795.000.000	€			
Depreciation	12 years				89,9
Labour	500	#	100.000,00		67,8
Other costs	5%	of capex			56,1
Fixed costs					**213,8**
Total					**346,9**
Required subsidy					
Product value	**Bleached softwood pulp**				**500,0**

Table B-6 *Economic assessment of BLG / DME*

Main product	**Bleached softwood pulp**		**Net Present Value**		**€695.503.213**
Scale	**588.000**	**T/y**	**Internal Rate of Return**		**9%**
			Payback time		**10 years**
		Unit	**€/unit**	**Unit/T BSP**	**€/T BSP**
Raw material	Pulp wood	T	75,00	2,30	172,5
Chemicals	Sodium hydroxide	T	400,00	0,03	10,8
	Magnesium sulphate	T	200,00	0,00	0,6
	Chlorine dioxide	T	700,00	0,01	5,6
	Hydrogen peroxide	T	400,00	0,02	6,0
	Oxygen	T	35,00	0,03	0,9
	Sulphuric acid	T	70,00	0,01	0,5
	Bark	T	70,00	1,22	85,4
				Total auxliaries	110,8
Steam					
Electrcity		kWh			
Water			0,1	21,00	1,1
Co-products	Tall oil	T	200,00	0,04	-7,8
	DME	T	600,00	0,46	-274,2
		kWh			0,0
					0,0
Variable cost					**1,3**
Capex	1.065.000.000	€			
Depreciation	12 years				150,9
Labour	500	#	100.000,00		85,0
Other costs	7%	of capex			130,4
Fixed costs					**366,4**
Total					367,7
Required subsidy					
Product value	**Bleached softwood pulp**				**500,0**

Table B-7 *Economic assessment of Ethanol production*

Main product	**Bleached softwood pulp**		**Net Present Value**		**-€302.364.920**
Scale	**294.000**	**T/y**	**Internal Rate of Return**		**-9%**
			Payback time	**>12 years**	
		Unit	**€/unit**	**Unit/T BSP**	**€/T BSP**
Raw material	Pulp wood	T	75,00	4,60	345,0
Chemicals	Sodium hydroxide	T	400,00	0,03	13,6
	Magnesium sulphate	T	200,00	0,00	0,6
	Chlorine dioxide	T	700,00	0,01	5,6
	Hydrogen peroxide	T	400,00	0,02	6,0
	Oxygen	T	35,00	0,03	0,9
	Sulphuric acid	T	70,00	0,01	0,8
	Yeast & Enzymes	T	100,00	0,37	37,0
				Total auxliaries	75,0
Steam					
Electrcity		kWh			
Water			0,5	21,00	10,5
Co-products	Tall oil	T	200,00	0,08	-15,6
	Bark	T	70,00	0,22	-15,4
	Ethanol	m3	800	0,37	-296,0
	Electricity	kWh	0,05	1.280,00	-64,0
Variable cost					**29,0**
Capex	620.000.000	€			
Depreciation	12 years				175,7
Labour	500	#	100.000,00		170,1
Other costs	10%	of capex			210,9
Fixed costs					**556,7**
Total					**585,7**
Required subsidy					
Product value	**Bleached softwood pulp**				**500,0**

Table B-8 *Economic assessment of power CHP*

Main product	**Electricity**		**Net Present Value**		**-€11.070.400**
Scale	**93.500**	**MWh/y**	**Internal Rate of Return**		**-6%**
			Payback time	**>12 years**	
		Unit	**€/unit**	**Unit/MWh**	**€/MWh**
Raw material	Peat	T	22,00	1,60	35,2
Chemicals		T			0,0
				Total auxliaries	0,0
Steam		GJ			0,0
Electrcity		kWh			0,0
Water					0,0
Co-products					0,0
	Heat	MWh	15,00	2,40	-36,0
Variable cost					**-0,8**
Capex	34.000.000	€			
Depreciation	12 years				30,3
Labour		#			0,0
Other costs	8%	of capex			30,4
Fixed costs					**60,7**
Total					**59,9**
Required subsidy					
Product value	**Electricity**				**50,0**

Table B-9 *Economic assessment of power CHP pyrolysis*

Main product	**Electricity**		**Net Present Value**		**-€38.979.267**
Scale	**85.800**	**MWh/y**	**Internal Rate of Return**		**#DIV/0!**
			Payback time	**>12 years**	
		Unit	**€/unit**	**Unit/MWh**	**€/MWh**
Raw material	Peat	T	22,00	1,74	38,3
	Forest residues	T	43,50	0,56	24,4
Chemicals		T			0,0
				Total auxliaries	0,0
Steam		GJ			0,0
Electrcity		kWh			0,0
Water					0,0
Co-products	Pyrolysis oil	t	90,75	0,21	-19,3
	Heat	MWh	15,00	3,20	-48,0
Variable cost					**-4,6**
Capex	44.491.200	€			
Depreciation	12 years				43,2
Labour		#			0,0
Other costs	10%	of capex			49,3
Fixed costs					**92,5**
Total					**87,9**
Required subsidy					
Product value	**Electricity**				**50,0**

Table B-10 *Economic assessment of power gasification*

Main product	**Electricity**		**Net Present Value**		**-€367.501.800**
Scale	**1.256.000**	**MWh/y**	**Internal Rate of Return**		**#DIV/0!**
			Payback time		**>12 years**
		Unit	**€/unit**	**Unit/MWh**	**€/MWh**
Raw material	Wood	T	40,00	1,02	40,8
Chemicals		T			0,0
				Total auxliaries	0,0
Steam		GJ			0,0
Electrcity		kWh			0,0
Water					0,0
Co-products					0,0
					0,0
Variable cost					**40,8**
Capex	230.319.000	€			
Depreciation	12 years				15,3
Labour		#			0,0
Other costs	10%	of capex			18,3
Fixed costs					**33,6**
Total					**74,4**
Required subsidy					
Product value	**Electricity**				**50,0**

Table B-11 *Economic assessment of power gasification + chemicals*

Main product	**Electricity**		**Net Present Value**		**€6.122.410**
Scale	**368.000**	**MWh/y**	**Internal Rate of Return**		**0%**
			Payback time		**12 years**
		Unit	**€/unit**	**Unit/MWh**	**€/MWh**
Raw material	Wood	T	40,00	3,48	139,1
Chemicals		T			0,0
				Total auxliaries	0,0
Steam		GJ			0,0
Electrcity		kWh			0,0
Water					0,0
Co-products	Ethylene	T	1.000,00	0,074	-73,9
	BTX	T	750,00	0,037	-27,7
	Tars	T	250,00	0,046	-11,4
	Mixed alcohols	T	617,00	0,200	-123,4
Variable cost					**-97,3**
Capex	291.962.000	€			
Depreciation	12 years				66,1
Labour		#			0,0
Other costs	10%	of capex			79,3
Fixed costs					**145,5**
Total					**48,1**
Required subsidy					
Product value	**Electricity**				**50,0**

Table B-12 *Economic assessment of cheese production*

Main product	**Cheese**		**Net Present Value**		**€26,791,034**
Scale	**28,815**	**T/y**	**Internal Rate of Return**		**20%**
			Payback time		**11 years**
		Unit	**€/unit**	**Unit/T cheese**	**€/T cheese**
Raw material	Milk	T	195.00	9.74	1899.3
Chemicals	Rennet	T	5,000.00	0.01	43.5
	Starter	T	820.00	0.01	7.1
	Salt	T	50.00	0.00	0.0
	Cleaning solvent	T	30.00	5.78	173.4
				Total auxliaries	224.1
Steam	3 barg steam	T	12.50	3.54	44.3
Electrcity		kWh	0.05	347.00	17.4
Co-products	Whey powder 10% protein	T	960.00	0.67	-643.2
	Cream	T	600.00	0.06	-37.8
Variable cost					**1504.0**
Capex	50,860,307	€			
Depreciation	12 years				147.1
Labour	0	#	100,000.00		0.0
Other costs	15%	of capex			264.8
Fixed costs					**411.8**
Total					**1915.8**
Product value	**Cheese**				**2250.0**

Table B-13 *Economic assessment of Milk biorefinery*

Main product	**Cheese**		**Net Present Value**		**€138,076,870**
Scale	**28,815**	**T/y**	**Internal Rate of Return**		**26%**
			Payback time		**6 years**
		Unit	**€/unit**	**Unit/T cheese**	**€/T cheese**
Raw material	Milk	T	195.00	9.74	1899.3
Chemicals	Rennet	T	5,000.00	0.01	43.5
	Starter	T	820.00	0.01	7.1
	Salt	T	50.00	0.00	0.0
	Cleaning solvent	T	30.00	5.78	173.4
				Total auxliaries	224.1
Steam	3 barg steam	T	12.50	0.65	8.1
Electrcity		kWh	0.05	448.00	22.4
Co-products	Whey powder 80% protein	T	3,500.00	0.14	-490.0
	Cream	T	600.00	0.06	-37.8
	Lactic acid	T	800.00	0.50	-400.0
	Pure water	T	300.00	1.75	-523.5
Variable cost					**702.6**
Capex	91,224,607	€			
Depreciation	12 years				*263.8*
Other costs	15%	of capex			474.9
Fixed costs					**738.7**
Total					**1441.3**
Product value	**Cheese**				**2250.0**

Table B-14 *Economic assessment of Sugar beet Process*

Main product	**Sugar**		**Net Present Value**			**€201,135,687**
Scale	**315,360**	**T/y**	**Internal Rate of Return**			**7%**
			Payback time			**7 years**
		Unit	**€/unit**	**Unit/T sugar**		**€/T sugar**
Raw material	Beets (dry weight)	T	112.52	1.44		161.8
Chemicals	CaCO3	T	59.29	0.15		9.0
Heat		GJ	3.00	10.00		30.0
Electrcity		kWh	0.05	0.00		0.0
Co-products	Molasses	T	90.00	0.17		-15.3
	Dried beet pulp	T	30.00	0.26		-7.8
	Foam Earth	T		0.34		0.0
Variable cost						**177.7**
Capex	168,000,000	€				
Depreciation	12 years					44.4
Other costs	20%	of capex				106.5
Fixed costs						**150.9**
Total						**328.7**
Product value	**Sugar**					**400.0**

Table B-15 *Economicassessment of decentralised sugar biorefinery*

Main product	**Sugar**		**Net Present Value**		**€184,490,028**
Scale	**189,216**	**T/y**	**Internal Rate of Return**		**22%**
			Payback time		**5 years**
		Unit	**€/unit**	**Unit/T BSP**	**€/T BSP**
Raw material	Beets (dry weight)	T	93.02	2.40	223.2
Chemicals	Processed leaves	T	110.00	1.49	163.9
	Ethanol factory (excl. raw materials	T	177.00	0.34	60.2
	An. Dig. & CHP (excl. raw materials)	kWh	0.08	1,545.00	129.0
Co-products	Ethanol	T	800.00	0.34	-269.6
	Protein rich	T	300.00	0.60	-179.1
	Renewable elektricity	kWh	0.05	1,545.00	-77.3
Variable cost					**50.4**
Capex	134,400,000	€			
Depreciation	12 years				59.2
Other costs	20%	of capex			142.1
Fixed costs					**201.3**
Total					**251.6**
Product value	**Sugar**				**400.0**

Table B-16 *Economic assesment of small scale power generation reference case*

Main product	**Electricity**		**Net Present Value**		**-€6,816,640**
Scale	**3,853**	**MWh/y**	**Internal Rate of Return**		**#DIV/0!**
			Payback time		**>12 years**

		Unit	€/unit	Unit/MWh	€/MWh
Raw material	Grass silage	T	10.00	2.08	20.8
	Manure (transport)	T	3.00	7.40	22.2
Co-products	Digestate (transport)	T	-3.00	8.52	25.6
Variable cost					**68.5**
Capex	2,150,000	€			
Depreciation	12 years				46.5
Labour	730	hr	35.00		6.6
Other costs	10%	of capex			55.8
Fixed costs					**108.9**
Total					**177.4**
Product value	**Electricity**				**50.0**

Table B-17 *Economic assessment of grass biorefinery integrated with small scale power plant*

Main product	**Electricity**		**Net Present Value**		**-€4,562,759**
Scale	**2,705**	**MWh/y**	**Internal Rate of Return**		**#DIV/0!**
			Payback time		**>12 years**

		Unit	€/unit	Unit/MWh	€/MWh
Raw material	Fresh grass	T	3.00	5.70	17.1
	Manure (transport)	T	3.00	8.33	25.0
	Grass silage	T	10.00	1.23	12.3
Co-products	Digestate (transport)	T	-3.00	12.68	38.0
	Coagulated protein	T	36.00	1.09	-39.1
	Fibres	T	80.00	0.68	-54.0
	Heat	MWhr/yr	0.00	1.39	0.0
Variable cost					**-0.7**
Capex	2,266,250	€			
Depreciation	12 years				69.8
Labour	1363	hr	35.00		17.6
Other costs	10%	of capex			83.8
Fixed costs					**171.2**
Total					**170.6**
Product value	**Electricity**				**50.0**

Appendix C Technical and commercial feasibility of selected biorefinery schemes

For each sector, the technical and commercial feasibility of the biorefinery cases have been compared to the project average (= average of all biorefinery schemes considered in the Bioref-Integ project), and the main deviations from average have been highlighted (orange for below average; green for above average).

Table C-1 *Technical feasibility of biorefinery cases for bioethanol sector*

Statement	Weight factor	Bioethanol Lactic Score	Bioethanol Lactic Weighted	Bioethanol AFEX Score	Bioethanol AFEX Weighted	Project average Score	Project average Weighted
Process development							
The integrated concept does not require significant downstream	7	0,3	2,3	1,2	8,2	0,8	5,8
All steps of the integrated concept are well identified	7	2,0	14,0	1,5	10,5	1,7	12,0
Required technologies are already developed	6	1,8	11,0	1,2	7,0	1,5	9,1
Required technologies are proven on industrial scale	6	1,7	10,0	0,2	1,0	0,9	5,5
Process does not require toxic or hazardous auxiliaries	4	1,5	6,0	0,8	3,3	1,6	6,2
The integrated concept does not generate additional waste	4	1,3	5,3	1,2	4,7	1,4	5,6
Application development							
Most of the selected applications are already existing	6	2,0	12,0	1,8	11,0	1,8	10,7
Products can be used in most of the selected applications	3	2,0	6,0	1,7	5,0	1,7	5,2
Products are referenced in most of the selected applications	4	1,7	6,7	1,3	5,3	1,6	6,3
Secondary products are referenced in the applications	3	1,5	4,5	1,2	3,5	1,4	4,3
Technical feasibility	50		77,8		59,5		70,7

Table C-2 *Commercial feasibility of biorefinery cases for bioethanol sector*

Statement	Weight factor	Bioethanol Lactic Score	Bioethanol Lactic Weighted	Bioethanol AFEX Score	Bioethanol AFEX Weighted	Project average Score	Project average Weighted
Project characteristics							
The integrated concept is leading to 1 new product	1	1,8	1,8	1,0	1,0	1,6	1,6
The product(s) can be used in several applications/markets	1	2,0	2,0	1,3	1,3	1,6	1,6
Market characteristics							
The integrated project addresses existing product/market combinations	4	2,0	8,0	1,7	6,7	1,8	7,3
The addressed markets are innovative (= open for new products/concepts)	2	1,5	3,0	1,2	2,3	1,4	2,7
The targeted markets are large enough to absorb the foreseen volumes	4	1,0	4,0	1,8	7,3	1,8	7,2
Competitive advantage							
Introduction of the new product(s) will lead to an economical benefit for the user	5	1,0	5,0	1,5	7,5	1,3	6,3
The new product(s) have functional benefits	5	1,0	5,0	1,5	7,5	1,1	5,4
There are specific benefits related to the integrated concept	4	1,0	4,0	1,5	6,0	1,2	4,7
Social & environmental impact							
The new product(s) is an alternative to fossil-based products	3	1,5	4,5	1,7	5,0	1,7	5,1
The integrated concept is not in competition with food supply	2	0,8	1,7	1,0	2,0	1,6	3,1
The integrated concept does not require large quantities of fresh water	2	1,0	2,0	1,5	3,0	1,5	3,1
The integrated concept is leading to additional renewable energy production	3	0,3	1,0	1,3	4,0	1,1	3,2
The integrated concept is 'LCA positive'	4	1,0	4,0	0,7	2,7	1,4	5,7
The integrated concept improves the European competitive position in a global market	3	1,3	4,0	1,5	4,5	1,6	4,8
Regulatory impact							
There are no regulatory barriers affecting the market introduction of the product(s)	3	1,5	4,5	1,0	3,0	1,4	4,1
There is a supporting EU directive promoting the integrated concept	4	0,3	1,3	1,3	5,3	1,3	5,0
Commercial feasibility	50		55,8		69,2		71,0

Table C-3 *Technical feasibility of biorefinery cases for biodiesel sector*

Statement	Weight factor	Biodiesel PDO Score	Biodiesel PDO Weighted	Biodiesel ECHi Score	Biodiesel ECHi Weighted	Project average Score	Project average Weighted
Process development							
The integrated concept does not require significant downstream processing	7	0,4	2,8	1,4	9,8	0,8	5,8
All steps of the integrated concept are well identified	7	1,8	12,6	1,8	12,6	1,7	12,0
Required technologies are already developed	6	1,8	10,8	2,0	12,0	1,5	9,1
Required technologies are proven on industrial scale	6	1,2	7,2	1,8	10,8	0,9	5,5
Process does not require toxic or hazardous auxiliaries	4	2,0	8,0	1,0	4,0	1,6	6,2
The integrated concept does not generate additional waste	4	1,0	4,0	0,8	3,2	1,4	5,6
Application development							
Most of the selected applications are already existing	6	1,8	10,8	2,0	12,0	1,8	10,7
Products can be used in most of the selected applications	3	2,0	6,0	2,0	6,0	1,7	5,2
Products are referenced in most of the selected applications	4	1,8	7,2	2,0	8,0	1,6	6,3
Secondary products are referenced in the applications	3	1,4	4,2	1,6	4,8	1,4	4,3
Technical feasibility	50		73,6		83,2		70,7

Table C-4 *Commercial feasibility of biorefinery cases for biodiesel sector*

Statement	Weight factor	Biodiesel PDO Score	Biodiesel PDO Weighted	Biodiesel ECH Score	Biodiesel ECH Weighted	Project average Score	Project average Weighted
Project characteristics							
The integrated concept is leading to 1 new product	1	1,6	1,6	2,0	2,0	1,6	1,6
The product(s) can be used in several applications/markets	1	1,4	1,4	2,0	2,0	1,6	1,6
Market characteristics							
The integrated project addresses existing product/market combinations	4	2,0	8,0	2,0	8,0	1,8	7,3
The addressed markets are innovative (= open for new products/concepts)	2	1,4	2,8	1,0	2,0	1,4	2,7
The targeted markets are large enough to absorb the foreseen volumes	4	2,0	8,0	2,0	8,0	1,8	7,2
Competitive advantage							
Introduction of the new product(s) will lead to an economical benefit for the user	5	1,4	7,0	1,2	6,0	1,3	6,3
The new product(s) have functional benefits	5	1,6	8,0	1,0	5,0	1,1	5,4
There are specific benefits related to the integrated concept	4	1,8	7,2	1,6	6,4	1,2	4,7
Social & environmental impact							
The new product(s) is an alternative to fossil-based products	3	2,0	6,0	2,0	6,0	1,7	5,1
The integrated concept is not in competition with food supply	2	2,0	4,0	2,0	4,0	1,6	3,1
The integrated concept does not require large quantities of fresh water	2	1,0	2,0	2,0	4,0	1,5	3,1
The integrated concept is leading to additional renewable energy production	3	0,4	1,2	0,4	1,2	1,1	3,2
The integrated concept is 'LCA positive'	4	1,6	6,4	1,6	6,4	1,4	5,7
The integrated concept improves the European competitive position in a global market	3	1,6	4,8	1,6	4,8	1,6	4,8
Regulatory impact							
There are no regulatory barriers affecting the market introduction of the product(s)	3	1,8	5,4	1,6	4,8	1,4	4,1
There is a supporting EU directive promoting the integrated concept	4	1,2	4,8	1,2	4,8	1,3	5,0
Commercial feasibility	50		78,6		75,4		71,0

Table C-5 *Technical feasibility of biorefinery cases for pulp & paper sector*

Statement	Weight factor	Pulp & Paper						Project average	
		Lignin		DME		Ethanol			
		Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Process development									
The integrated concept does not require significant downstream	7	0,8	5,3	0,0	0,0	0,3	1,8	0,8	5,8
All steps of the integrated concept are well identified	7	2,0	14,0	2,0	14,0	2,0	14,0	1,7	12,0
Required technologies are already developed	6	2,0	12,0	1,3	7,5	1,3	7,5	1,5	9,1
Required technologies are proven on industrial scale	6	1,0	6,0	0,8	4,5	0,8	4,5	0,9	5,5
Process does not require toxic or hazardous auxiliaries	4	1,5	6,0	1,8	7,0	1,8	7,0	1,6	6,2
The integrated concept does not generate additional waste	4	2,0	8,0	1,8	7,0	1,8	7,0	1,4	5,6
Application development									
Most of the selected applications are already existing	6	2,0	12,0	1,5	9,0	2,0	12,0	1,8	10,7
Products can be used in most of the selected applications	3	2,0	6,0	1,8	5,3	1,8	5,3	1,7	5,2
Products are referenced in most of the selected applications	4	1,5	6,0	1,0	4,0	2,0	8,0	1,6	6,3
Secondary products are referenced in the applications	3	1,5	4,5	1,3	3,8	1,8	5,3	1,4	4,3
Technical feasibility	**50**		**79,8**		**62,0**		**72,3**		**70,7**

Table C-6 *Commercial feasibility of biorefinery cases for pulp & paper sector*

Statement	Weight factor	Pulp & Paper						Project average	
		Lignin		DME		Ethanol			
		Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Project characteristics									
The integrated concept is leading to 1 new product	1	2,0	2,0	2,0	2,0	1,8	1,8	1,6	1,6
The product(s) can be used in several applications/markets	1	1,5	1,5	1,8	1,8	1,5	1,5	1,6	1,6
Market characteristics									
The integrated project addresses existing product/market combinations	4	2,0	8,0	1,8	7,0	2,0	8,0	1,8	7,3
The addressed markets are innovative (= open for new products/concepts)	2	1,8	3,5	1,0	2,0	1,3	2,5	1,4	2,7
The targeted markets are large enough to absorb the foreseen volumes	4	2,0	8,0	2,0	8,0	2,0	8,0	1,8	7,2
Competitive advantage									
Introduction of the new product(s) will lead to an economical benefit for the user	5	1,8	8,8	1,5	7,5	1,3	6,3	1,3	6,3
The new product(s) have functional benefits	5	1,0	5,0	1,5	7,5	1,0	5,0	1,1	5,4
There are specific benefits related to the integrated concept	4	1,5	6,0	1,5	6,0	0,5	2,0	1,2	4,7
Social & environmental impact									
The new product(s) is an alternative to fossil-based products	3	2,0	6,0	2,0	6,0	2,0	6,0	1,7	5,1
The integrated concept is not in competition with food supply	2	2,0	4,0	2,0	4,0	2,0	4,0	1,6	3,1
The integrated concept does not require large quantities of fresh water	2	1,5	3,0	1,5	3,0	1,3	2,5	1,5	3,1
The integrated concept is leading to additional renewable energy production	3	1,5	4,5	1,5	4,5	1,0	3,0	1,1	3,2
The integrated concept is 'LCA positive'	4	1,5	6,0	1,5	6,0	1,3	5,0	1,4	5,7
The integrated concept improves the European competitive position in a global market	3	2,0	6,0	2,0	6,0	1,5	4,5	1,6	4,8
Regulatory impact									
There are no regulatory barriers affecting the market introduction of the product(s)	3	2,0	6,0	1,5	4,5	2,0	6,0	1,4	4,1
There is a supporting EU directive promoting the integrated concept	4	1,3	5,0	1,8	7,0	2,0	8,0	1,3	5,0
Commercial feasibility	**50**		**83,3**		**82,8**		**74,0**		**71,0**

Table C-7 *Technical feasibility of biorefinery cases for conventional oil refinery sector*

Statement	Weight factor	Refinery FCC Score	Refinery FCC Weighted	Refinery HDS Score	Refinery HDS Weighted	Project average Score	Project average Weighted
Process development							
The integrated concept does not require significant downstream	7	2,0	14,0	2,0	14,0	0,8	5,8
All steps of the integrated concept are well identified	7	1,7	11,7	1,7	11,7	1,7	12,0
Required technologies are already developed	6	1,7	10,0	2,0	12,0	1,5	9,1
Required technologies are proven on industrial scale	6	1,0	6,0	1,3	8,0	0,9	5,5
Process does not require toxic or hazardous auxiliaries	4	1,7	6,7	1,7	6,7	1,6	6,2
The integrated concept does not generate additional waste	4	1,3	5,3	1,3	5,3	1,4	5,6
Application development							
Most of the selected applications are already existing	6	2,0	12,0	2,0	12,0	1,8	10,7
Products can be used in most of the selected applications	3	2,0	6,0	2,0	6,0	1,7	5,2
Products are referenced in most of the selected applications	4	2,0	8,0	2,0	8,0	1,6	6,3
Secondary products are referenced in the applications	3	2,0	6,0	1,7	5,0	1,4	4,3
Technical feasibility	**50**		**85,7**		**88,7**		**70,7**

Table C-8 *Commercial feasibility of biorefinery cases for conventional oil refinery sector*

Statement	Weight factor	Refinery FCC Score	Refinery FCC Weighted	Refinery HDS Score	Refinery HDS Weighted	Project average Score	Project average Weighted
Project characteristics							
The integrated concept is leading to 1 new product	1	1,3	1,3	1,3	1,3	1,6	1,6
The product(s) can be used in several applications/markets	1	2,0	2,0	2,0	2,0	1,6	1,6
Market characteristics							
The integrated project addresses existing product/market combinations	4	2,0	8,0	2,0	8,0	1,8	7,3
The addressed markets are innovative (= open for new products/concepts)	2	1,0	2,0	1,3	2,7	1,4	2,7
The targeted markets are large enough to absorb the foreseen volumes	4	2,0	8,0	2,0	8,0	1,8	7,2
Competitive advantage							
Introduction of the new product(s) will lead to an economical benefit for the user	5	0,7	3,3	0,7	3,3	1,3	6,3
The new product(s) have functional benefits	5	0,7	3,3	0,7	3,3	1,1	5,4
There are specific benefits related to the integrated concept	4	0,0	0,0	0,0	0,0	1,2	4,7
Social & environmental impact							
The new product(s) is an alternative to fossil-based products	3	2,0	6,0	2,0	6,0	1,7	5,1
The integrated concept is not in competition with food supply	2	0,7	1,3	0,7	1,3	1,6	3,1
The integrated concept does not require large quantities of fresh water	2	1,7	3,3	1,7	3,3	1,5	3,1
The integrated concept is leading to additional renewable energy production	3	1,7	5,0	1,7	5,0	1,1	3,2
The integrated concept is 'LCA positive'	4	1,3	5,3	1,3	5,3	1,4	5,7
The integrated concept improves the European competitive position in a global market	3	1,7	5,0	1,7	5,0	1,6	4,8
Regulatory impact							
There are no regulatory barriers affecting the market introduction of the product(s)	3	1,0	3,0	1,0	3,0	1,4	4,1
There is a supporting EU directive promoting the integrated concept	4	1,7	6,7	1,7	6,7	1,3	5,0
Commercial feasibility	**50**		**63,7**		**64,3**		**71,0**

Table C-9 *Technical feasibility of biorefinery cases for power generation sector*

Statement	Weight factor	Power Pyrol Score	Power Pyrol Weighted	Power Chem Score	Power Chem Weighted	Project average Score	Project average Weighted
Process development							
The integrated concept does not require significant downstream	7	1,4	9,8	0,4	2,8	0,8	5,8
All steps of the integrated concept are well identified	7	1,4	9,8	1,4	9,8	1,7	12,0
Required technologies are already developed	6	1,2	7,2	1,2	7,2	1,5	9,1
Required technologies are proven on industrial scale	6	0,8	4,8	0,6	3,6	0,9	5,5
Process does not require toxic or hazardous auxiliaries	4	1,4	5,6	1,0	4,0	1,6	6,2
The integrated concept does not generate additional waste	4	1,4	5,6	1,2	4,8	1,4	5,6
Application development							
Most of the selected applications are already existing	6	1,4	8,4	1,2	7,2	1,8	10,7
Products can be used in most of the selected applications	3	1,6	4,8	1,4	4,2	1,7	5,2
Products are referenced in most of the selected applications	4	1,4	5,6	1,4	5,6	1,6	6,3
Secondary products are referenced in the applications	3	1,0	3,0	1,4	4,2	1,4	4,3
Technical feasibility	**50**		**64,6**		**53,4**		**70,7**

Table C-10 *Commercial feasibility of biorefinery cases for power generation sector*

Statement	Weight factor	Power Pyrol Score	Power Pyrol Weighted	Power Chem Score	Power Chem Weighted	Project average Score	Project average Weighted
Project characteristics							
The integrated concept is leading to 1 new product	1	1,6	1,6	1,2	1,2	1,6	1,6
The product(s) can be used in several applications/markets	1	1,0	1,0	1,2	1,2	1,6	1,6
Market characteristics							
The integrated project addresses existing product/market combinations	4	1,0	4,0	1,4	5,6	1,8	7,3
The addressed markets are innovative (= open for new products/concepts)	2	1,6	3,2	1,6	3,2	1,4	2,7
The targeted markets are large enough to absorb the foreseen volumes	4	1,6	6,4	1,6	6,4	1,8	7,2
Competitive advantage							
Introduction of the new product(s) will lead to an economical benefit for the user	5	0,8	4,0	0,8	4,0	1,3	6,3
The new product(s) have functional benefits	5	1,4	7,0	1,2	6,0	1,1	5,4
There are specific benefits related to the integrated concept	4	0,4	1,6	1,0	4,0	1,2	4,7
Social & environmental impact							
The new product(s) is an alternative to fossil-based products	3	1,4	4,2	1,6	4,8	1,7	5,1
The integrated concept is not in competition with food supply	2	2,0	4,0	2,0	4,0	1,6	3,1
The integrated concept does not require large quantities of fresh water	2	2,0	4,0	2,0	4,0	1,5	3,1
The integrated concept is leading to additional renewable energy production	3	1,6	4,8	1,2	3,6	1,1	3,2
The integrated concept is 'LCA positive'	4	2,0	8,0	1,8	7,2	1,4	5,7
The integrated concept improves the European competitive position in a global market	3	1,4	4,2	1,6	4,8	1,6	4,8
Regulatory impact							
There are no regulatory barriers affecting the market introduction of the product(s)	3	1,0	3,0	1,2	3,6	1,4	4,1
There is a supporting EU directive promoting the integrated concept	4	1,2	4,8	1,2	4,8	1,3	5,0
Commercial feasibility	**50**		**65,8**		**68,4**		**71,0**

Table C-11 *Technical feasibility of biorefinery case for food sector*

Statement	Weight factor	Food Lactic Score	Food Lactic Weighted	Project average Score	Project average Weighted
Process development					
The integrated concept does not require significant downstream	7	0,0	0,0	0,8	5,8
All steps of the integrated concept are well identified	7	1,3	9,3	1,7	12,0
Required technologies are already developed	6	1,3	8,0	1,5	9,1
Required technologies are proven on industrial scale	6	0,7	4,0	0,9	5,5
Process does not require toxic or hazardous auxiliaries	4	2,0	8,0	1,6	6,2
The integrated concept does not generate additional waste	4	1,3	5,3	1,4	5,6
Application development					
Most of the selected applications are already existing	6	1,7	10,0	1,8	10,7
Products can be used in most of the selected applications	3	1,7	5,0	1,7	5,2
Products are referenced in most of the selected applications	4	1,3	5,3	1,6	6,3
Secondary products are referenced in the applications	3	1,7	5,0	1,4	4,3
Technical feasibility	**50**		**60,0**		**70,7**

Table C-12 *Commercial feasibility of biorefinery case for food sector*

Statement	Weight factor	Food Lactic Score	Food Lactic Weighted	Project average Score	Project average Weighted
Project characteristics					
The integrated concept is leading to 1 new product	1	1,3	1,3	1,6	1,6
The product(s) can be used in several applications/markets	1	2,0	2,0	1,6	1,6
Market characteristics					
The integrated project addresses existing product/market combinations	4	2,0	8,0	1,8	7,3
The addressed markets are innovative (= open for new products/concepts)	2	1,7	3,3	1,4	2,7
The targeted markets are large enough to absorb the foreseen volumes	4	1,7	6,7	1,8	7,2
Competitive advantage					
Introduction of the new product(s) will lead to an economical benefit for the user	5	1,7	8,3	1,3	6,3
The new product(s) have functional benefits	5	1,0	5,0	1,1	5,4
There are specific benefits related to the integrated concept	4	2,0	8,0	1,2	4,7
Social & environmental impact					
The new product(s) is an alternative to fossil-based products	3	1,0	3,0	1,7	5,1
The integrated concept is not in competition with food supply	2	1,3	2,7	1,6	3,1
The integrated concept does not require large quantities of fresh water	2	1,3	2,7	1,5	3,1
The integrated concept is leading to additional renewable energy production	3	0,0	0,0	1,1	3,2
The integrated concept is 'LCA positive'	4	1,3	5,3	1,4	5,7
The integrated concept improves the European competitive position in a global market	3	1,3	4,0	1,6	4,8
Regulatory impact					
There are no regulatory barriers affecting the market introduction of the product(s)	3	1,0	3,0	1,4	4,1
There is a supporting EU directive promoting the integrated concept	4	0,3	1,3	1,3	5,0
Commercial feasibility	**50**		**64,7**		**71,0**

Table C-13 *Technical feasibility of biorefinery cases for agro sector*

Statement	Weight factor	Agro Beet Score	Agro Beet Weighted	Agro Grass Score	Agro Grass Weighted	Project average Score	Project average Weighted
Process development							
The integrated concept does not require significant downstream	7	0,8	5,3	0,8	5,3	0,8	5,8
All steps of the integrated concept are well identified	7	1,8	12,3	1,8	12,3	1,7	12,0
Required technologies are already developed	6	1,5	9,0	1,0	6,0	1,5	9,1
Required technologies are proven on industrial scale	6	1,0	6,0	0,0	0,0	0,9	5,5
Process does not require toxic or hazardous auxiliaries	4	2,0	8,0	1,8	7,0	1,6	6,2
The integrated concept does not generate additional waste	4	1,5	6,0	1,8	7,0	1,4	5,6
Application development							
Most of the selected applications are already existing	6	2,0	12,0	1,5	9,0	1,8	10,7
Products can be used in most of the selected applications	3	1,8	5,3	0,8	2,3	1,7	5,2
Products are referenced in most of the selected applications	4	1,8	7,0	0,8	3,0	1,6	6,3
Secondary products are referenced in the applications	3	1,3	3,8	1,0	3,0	1,4	4,3
Technical feasibility	50		74,5		54,8		70,7

Table C-14 *Commercial feasibility of biorefinery cases for agro sector*

Statement	Weight factor	Agro Beet Score	Agro Beet Weighted	Agro Grass Score	Agro Grass Weighted	Project average Score	Project average Weighted
Project characteristics							
The integrated concept is leading to 1 new product	1	1,5	1,5	1,5	1,5	1,6	1,6
The product(s) can be used in several applications/markets	1	1,5	1,5	1,5	1,5	1,6	1,6
Market characteristics							
The integrated project addresses existing product/market combinations	4	2,0	8,0	1,8	7,0	1,8	7,3
The addressed markets are innovative (= open for new products/concepts)	2	1,5	3,0	1,3	2,5	1,4	2,7
The targeted markets are large enough to absorb the foreseen volumes	4	1,8	7,0	1,8	7,0	1,8	7,2
Competitive advantage							
Introduction of the new product(s) will lead to an economical benefit for the user	5	1,8	8,8	1,8	8,8	1,3	6,3
The new product(s) have functional benefits	5	0,5	2,5	1,0	5,0	1,1	5,4
There are specific benefits related to the integrated concept	4	2,0	8,0	1,8	7,0	1,2	4,7
Social & environmental impact							
The new product(s) is an alternative to fossil-based products	3	1,8	5,3	1,0	3,0	1,7	5,1
The integrated concept is not in competition with food supply	2	1,3	2,5	2,0	4,0	1,6	3,1
The integrated concept does not require large quantities of fresh water	2	1,5	3,0	1,8	3,5	1,5	3,1
The integrated concept is leading to additional renewable energy production	3	1,5	4,5	1,0	3,0	1,1	3,2
The integrated concept is 'LCA positive'	4	1,5	6,0	1,5	6,0	1,4	5,7
The integrated concept improves the European competitive position in a global market	3	2,0	6,0	1,3	3,8	1,6	4,8
Regulatory impact							
There are no regulatory barriers affecting the market introduction of the product(s)	3	1,3	3,8	1,3	3,8	1,4	4,1
There is a supporting EU directive promoting the integrated concept	4	2,0	8,0	0,5	2,0	1,3	5,0
Commercial feasibility	50		79,3		69,3		71,0

Appendix D SWOT analysis of selected biorefinery schemes

D.1 Bioethanol sector

D.1.1 Ethanol + lactic

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- Economical value:
  - More added value driven out of feedstock
- Strategic value
  - Less dependent on EU directives
  - Possibility of product flexibility in response to market conditions i.e. to vary the relative amounts of lactic acid and ethanol produced
- Lower production cost of ethanol by co-producing lactic acid.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Technological challenge
  - Has the use of unrefined sugars for lactic acid production already been done at industrial scale? (normally refined sugars are used)
  - Utilities (e.g. waste water treatment) may be more complex with 2 products, process integration less obvious
  - More complexity
- Cost structure
  - Costs are potentially higher for a plant with 2 different fermentation sections and corresponding downstream processing sections
  - Increased operating cost of the integrated case in comparison with the reference case
  - Increased capital investment as well.

Opportunities: external; general trends affecting the integrated concept positively

- Increasing market for lactic acid, mainly driven by bioplastics
- Lactic acid market is not dependend on EU directives (it is a ‘natural’ market)
- On the other hand, a “Bioplastic directive” could boost lactic acid demand
- Possibility to extend technology to lignocellulose feedstock
- Lower sensitivity to world oil market prices
- Attractive concept for investors.

Threats: external; general trends affecting the integrated concept negatively

- Novel food directive (new process)
- Market growth for lactic acid mainly driven by bioplastic: still speculative
- Higher ethanol prices will increase profitability of competitors more than profitability of integrated refinery owners
- Underestimation of capital costs
- Traces of hazardous chemicals involved in lactic acid downstream processing might cause DDGS to be a waste instead of a product.

D.1.2 AFEX-DDGS

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- More value out of the feedstock material: more ethanol and higher DDGS price
- Contribution to meeting EU targets on biofuel consumption with less feedstock (less competition with food)
- Platform for other 2nd generation fermentations.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Technical feasibility
  - AFEX treatment not at industrial scale yet
  - Ethanol fermentation on other sugars than glucose, sucrose not yet developed on industrial scale
  - Safety issues with high pressure ammonia handling
- Expensive process
  - Potential high energy use and costs (for AFEX)
  - High investment.

Opportunities: external; general trends affecting the integrated concept positively

- Less competition with food supply
- Bio-ethanol from DDGS is 2nd generation ethanol which is much supported by EU
- EU Directive on biofuels
- Lower value for normal DDGS due to market saturation (this will be a problem for the competitor and to a lesser extent to the biorefinery owner, so it will increase competitiveness)
- New markets for higher quality DDGS in animal feed, possibly human food.

Threats: external; general trends affecting the integrated concept negatively

- Dependence on biofuel legislation
- AFEX DDGS not yet accepted in feed industry
- Underestimation of capital costs.

D.2 Biodiesel sector

D.2.1 1,3-PDO

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- High added value product out of glycerol leading to more competitive biodiesel operation
- New fermentation platform from glycerol.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Technical issues:
  - Fermentation based on glycerol not proven at industrial scale yet
  - Technical challenge to use crude glycerol
  - Lot of downstream processing
  - Lot of ‘waste’ / co-products
- Economical issues:
  - Investment cost: scale needs to be large enough to be economical advantageous
  - Market for 1,3-PDO is limited and depends on textile fibre development
- Strategic issues:
  - Application of PDO depends on Dupont (controls the fibre production)
  - Currently only 1 significant customer.

Opportunities: external; general trends affecting the integrated concept positively

- Low glycerol price (due to overproduction)
- Future product diversification possible (e.g. fatty acid esters of 1,3-PDO → lubricants)
- Replacing fossil-based chemicals by bio-based chemicals
- Second supplier of PDO.

Threats: external; general trends affecting the integrated concept negatively

- Dependence of Dupont patent restrictions
- Sustanability issues seed oils/palm oil
- Competition with advanced biofuels may reduce biodiesel production, hence glycerol availability
- Competition with PDO from sugars
- Success depends on acceptability of new fibre: non established target market).

D.2.2 Glycerol to epichlorohydrin

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- High added value product out of glycerol leading to more competitive biodiesel operation
- Stable outlet (price-wise) for glycerol towards ‘bulk’ chemical.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Epichlorohydrin is a toxic product
- Investment cost: large scale needed ideally
- Small scale epichlorohydrin production when integrated in (even a large) biodiesel plant
- Chemical process to implement (hazardous).

Opportunities: external; general trends affecting the integrated concept positively

- Replacing fossil-based chemicals by bio-based chemicals
- Low glycerol price (due to overproduction)
- Chemical modification of glycerol platform: further conversion potential to other products (glycidol, propylene oxide, 1,2-PG).

Threats: external; general trends affecting the integrated concept negatively

- Sustainability issues seed oils/palm oil
- Competition with advanced biofuels may reduce biodiesel production, hence glycerol availability
- Technology controlled by Solvay and Dow and operated at much larger scale.

D.3 Pulp & paper sector

D.3.1 Lignin

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- Technology:
  - Production of lignin in demonstration plant and end use experiments
  - Technology used is not very complicated
- Economy:
  - The economics for lignin production are promising
  - The investment costs are small
  - Pulp capacity may be increased with up to 25% by debottlenecking of the recovery boiler
- Strategy:
  - Reduction of heavy fuel oil consumption in pulp mills, where heavy oil is used. Lignin produced can be used as a lime kiln fuel.
  - The operator can export a solid biofuel (that can be stored and used when electricity price is high) or a raw material that may in the future be used for carbon fibres and chemicals.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Some technical risks possible in industrial production of lignin
- Less electricity export per tonne produced pulp (but balanced by solid fuel)
- Increased chemical costs
- Extra downstream processing.

Opportunities: external; general trends affecting the integrated concept positively

- Increasing oil price
- Trend towards bio-based energy
- This integrated concept does not compete with food resource
- Lignin may be used in other applications (carbon fibres or chemicals) which may increase the lignin price very much.

Threats: external; general trends affecting the integrated concept negatively

- Economical viability of the concept depends on the relative evolution of the price of electricity (as seller, incl. subsidies or as buyer), crude oil and solid fuel
- Pulp demand is decreasing which makes the capacity increase less relevant.

D.3.2 Black liquor gasification and DME production

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- Technology:
  - Gasification stage demonstrated in pilot scale (20 t/d BLG) and DME demonstration plant (500 t/d BLG) planned within a few years
  - DME is a better product than ethanol as alternative to fossil fuel
- Economy:
  - Economics of integrated concept is promising
  - Pulp capacity may be increased with up to 25% by debottlenecking of the recovery boiler
- Strategy:
  - Production of transportation fuel, and higher added value chemicals in pulp mills possible instead of only pulp and power.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Complex technology: more complicated process than lignin precipitation process and technical risks in industrial scale operation possible
- Large investment costs required and it may be even higher in the future
- Higher operating and maintenance costs
- Dependence on support from fuel industry.

Opportunities: external; general trends affecting the integrated concept positively

- Increasing oil price
- Trend towards bio-based energy
- This integrated concept does not compete with food resources
- Acceptance of DME by EU countries as biofuel (in addition to biodiesel and bioethanol).

Threats: external; general trends affecting the integrated concept negatively

- Economical viability of the concept depends on the relative evolution of the price of electricity (as seller, incl. subsidies or as buyer), biomass, crude oil and transport fuel
- Change in legislation on biofuels
- Hard to get someone to invest in the first plant due to the high investment cost
- Large amounts of biomass (bark) needs to be imported to keep the electricity balance, a high biomass price affects the concept’s economic outcome
- No acceptance of DME by EU countries as biofuel (in addition to biodiesel and bioethanol).

D.3.3 Ethanol production in a pulp mill

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- Technology:
  - A pilot plant is operated by SEKAB. The plan is to build a demonstration plant within 3 years that will produce 60 000 m^3 ethanol per year.
- Economy:
  - Economics of integrated concept is promising
- Strategy:
  - Production of transportation fuel in pulp mills possible instead of only pulp and power.
  - Platform for 2^{nd} generation fermentation
  - This concept can be applied to old pulp mills.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Economics of production is not very promising (yield pulp-to-ethanol; value of ethanol…)
- Dependence on support from oil industry
- Less efficient process, more by-products to take care of (CO_2, organic residues).

Opportunities: external; general trends affecting the integrated concept positively

- Increasing oil price
- Trend towards bio-based energy (EU directive on biofuels)
- This integrated concept does not compete with food resources
- Pulp demand is decreasing and instead of closing a mill down, this is a good option since the investment cost will be very low and much of the equipment from the pulp mill can be used in the ethanol plant.

Threats: external; general trends affecting the integrated concept negatively

- Economical viability of the concept depends on the relative evolution of the price of electricity (as seller, incl. subsidies or as buyer), crude oil and transport fuel.
- Change in biofuel legislation
- Enzymes to hydrolyse wood to sugars still are not commercially available
- Alternative routes to biofuels from wood: C5 fermentation of black liquor, gasification/FT of wood, DME from wood via gasification.

D.4 Conventional oil refinery sector

D.4.1 Vegetable oil in FCC

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- This route facilitates the refinery to comply with EU directives on mandatory incorporation of biofuels (2003/30/EC) and on reduction of greenhouse gases by 10% (Fuel Quality Directive)
- The existing unit operations can be used for renewable vegetable oil.
- The technical feasibility has been demonstrated on industrial scale
- Biofuels generated by the route proposed are more similar to conventional fossil fuels than the currently used biofuels (bioethanol and biodiesel).
- Some of the properties (quality) of the biofuels are improved compared to conventional fossil fuels (higher cetane and lower density for diesel and higher octane for gasoline)
- The use of the biofuels produced by co-processing does not require any modification in the current gasoline and diesel motors, even at high percentage. The automotive sector is favourable to the use of this kind of biofuels.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Production cost is higher:
  - The price of feedstock (vegetable oil) is generally higher than fossil fuel feedstock. Only if residual feedstock (animal fat or used cooking oil) is used, the price of the feedstock could be lower
  - The cost in auxiliaries is slightly higher when vegetable oil is co-processed, compared to the processing of conventional fossil feedstock
  - There can be unpredictable costs in long term operation in commercial unit (catalyst life etc).
- Oxygen compounds introduced in a refinery process which can be input in other processes and products where they can lead to problems
- Biofuels are introduced in products where they have no commercial benefit yet.

Opportunities:

- There is a supporting EU directive (Directive 2003/30/EC) promoting the mandatory incorporation of a certain amount of biofuels in road transport fuels (5.75% in energetic value in 2010)
- There is a supporting EU directive (Fuel Quality Directive) that obliges refiners to reduce by 10% the emission of greenhouse gases (GHG) between 2011 and 2020 (compared to the emission levels of 2010).
- Europe has an important energetic dependence. The biorefinery process proposed will allow European refiners to substitute part of the fossil feedstock by a renewable feedstock. In this way, dependence of external crude oil is reduced (which is highly appreciated and promoted). The exposure to highly volatile prices of crude oil would also be reduced in this way.
- In 2020 the EU aims to increase the share of biofuels in transport fuels from 5.75% to 10% (on energetic base). Due to differences in properties of bio-ethanol and FAME biodiesel compared to fossil fuels, this 10% incorporation level will be difficult to reach. The proposed concept, however, has no technical limitations in the incorporation level.

Threats:

- There is no mechanism to compensate the higher production costs due to the use of renewable vegetable oils to the oil refinery.
- Second generation biofuels may become cheaper and more competitive than blending in oil in a conventional refinery.

D.4.2 Vegetable oil in HDS

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- This route facilitates the refinery to comply with EU directives on mandatory incorporation of biofuels (2003/30/EC) and on reduction of greenhouse gases by 10% (Fuel Quality Directive)
- The existing unit operations can be used for renewable vegetable oil.
- The technical feasibility has been demonstrated on industrial scale
- Biofuels generated by the route proposed are more similar to conventional fossil fuels than the currently used biofuels (bioethanol and biodiesel).
- Some of the properties (quality) of the biofuels are improved compared to conventional fossil fuels (higher cetane and lower density for diesel and higher octane for gasoline)
- The use of the biofuels produced by co-processing does not require any modification in the current gasoline and diesel motors, even at high percentage. The automotive sector is favourable to the use of this kind of biofuels.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Production cost is higher:
  - The price of feedstock (vegetable oil) is generally higher than fossil fuel feedstock. Only if residual feedstock (animal fat or used cooking oil) is used, the price of the feedstock could be lower
  - The cost in auxiliaries is slightly higher when vegetable oil is co-processed, compared to the processing of conventional fossil feedstock
  - There can be unpredictable costs in long term operation in commercial unit (catalyst life etc.)
  - The production costs a lot of expensive hydrogen. The product may have a problem of being more expensive compared to FAME bio-diesel
- Oxygen compounds introduced in a refinery process which can be input in other processes and products where they can lead to problems
- Cold properties of “green diesel” are worse compared with fossil diesel
- Biofuels are introduced in products where they have no commercial benefit yet.

Opportunities:

- There is a supporting EU directive (Directive 2003/30/EC) promoting the mandatory incorporation of a certain amount of biofuels in road transport fuels (5.75% in energetic value in 2010)
- There is a supporting EU directive (Fuel Quality Directive) that obliges refiners to reduce by 10% the emission of greenhouse gases (GHG) between 2011 and 2020 (compared to the emission levels of 2010).
- Europe has an important energetic dependence. The biorefinery process proposed will allow European refiners to substitute part of the fossil feedstock by a renewable feedstock. In this way, dependence of external crude oil is reduced (which is highly appreciated and promoted). The exposure to highly volatile prices of crude oil would also be reduced in this way.
- In 2020 the EU aims to increase the share of biofuels in transport fuels from 5.75% to 10% (on energetic base). Due to differences in properties of bio-ethanol and FAME biodiesel compared to fossil fuels, this 10% incorporation level will be difficult to reach. The proposed concept, however, has no technical limitations in the incorporation level.

Threats:

- There is no mechanism to compensate the higher production costs due to the use of renewable vegetable oils to the oil refinery.
- Second generation of biofuels may become cheaper and more competitive than blending in oil in a conventional refinery.

D.5 Power generation sector

D.5.1 Fast pyrolysis

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- Remarkably smaller investment than for example in application producing Fischer-Tropsch products.
- Better product mix: liquid fuel (pyrolysis oil) in addition to heat and electricity
- Pyrolysis oil is a way to store heat and electricity ("storable heat" as invented by Vølund in the Harboøre plant) and follow the market demand in heat and electricity while maintaining full capacity
- Improved energy efficiency: flue gas and char from pyrolysis can be valorised
- Lower emissions from bio-oil compared to direct wood use in smaller-scale applications.
- Pyrolysis oil may be used as a raw material to a wide range of products with potentially high market value.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Upscaled process and long-term usage still to demonstrate: industrial-scale pyrolysis, use of bio-oil in fossil fuel boiler...
- More complex process
- Much higher CAPEX
- Less "green" electricity produced (but balanced by "stored energy")
- Production of instable pyrolysis oil
- The varying quality of pyrolysis oil produced is an important bottleneck to the development of applications
- Ash is a waste stream as it is not fully converted.

Opportunities: external; general trends affecting the integrated concept positively

- Increasing oil price
- Trend towards bio-based energy
- This integrated concept does not compete with food resource
- Can be used as second generation biofuel after refining (supported by EU).

Threats: external; general trends affecting the integrated concept negatively

- The demand for green electricity may increase in the future, while this concept produces less green electricity
- Competition with other bio-oil products, for example with rapeseed oil, palm oil or their derivatives
- Competition of alternative processes such as indirect gasification and combustion
- Pyrolysis oil is unstable and can be mutagenic and carcinogenic.

D.5.2 Chemical recovery

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- Increased return because of production of high added value chemicals
- Production of (bio-based) chemicals with already existing high market value
- Scalability
- Possibility to follow the market demand in heat and electricity while maintaining full capacity.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Unproven technology:
    - Combination of numerous individually proven, though integrated not yet proven, technologies
    - Combination of low pressure processes upstream and high pressure processes downstream
    - Many separation units needed
    - Even the reference case is not commercially proven technology. No demonstration of the whole process.
- Expensive infrastructure
- Chemical extraction at low yield and low volumes
- Complex concept: many products to manage, many processes to integrate.

Opportunities: external; general trends affecting the integrated concept positively

- Increasing oil price
- Trend towards bio-based energy and products/chemicals
- This integrated concept does not compete with food resource
- The mixed alcohols can be used as 2nd generation biofuels (supported by EU)
- Possibility for integration with existing chemical industries
- Development of pressurised gasification systems.

Threats: external; general trends affecting the integrated concept negatively

- The demand for green electricity may increase in the future, while this concept produce less green electricity
- Quality control of the chemicals
- Alternative processes: production of (fine) chemicals via biochemical biorefineries
- Possible issue with REACH.

D.6 Food sector

D.6.1 Lactic acid from whey

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- Mainly economical benefits: high value potential for lactose and whey proteins
- Products supplied to existing markets
- Lower non renewable heat demand.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- High CAPEX
- Complex downstream processing
- Technical risks: membrane processes will suffer from fouling problems. The degree of fouling is not yet known.
- High profitability depends largely on sales of reverse osmosis water: A buyer needs to be found

Opportunities: external; general trends affecting the integrated concept positively

- EU directive on renewable materials can drive demand for bioplastics / PLA / lactic acid
- Cheaper production of lactic acid?
- Worldwide shortage on phophates ($CaHPO_4$).

Threats: external; general trends affecting the integrated concept negatively

- High fluctuation in whey market
- Developments of world market on lactic acid
- Collapse of renewable material market due to sceptisism of consumer
- Regulatory status? New process may lead to Novel Food application.
- Buyer of reverse osmosis water might stop buying reverse osmosis water (process change, bankruptcy)

D.7 Agro sector

D.7.1 Decentralised beet refinery

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- Value maximisation, both in the plant as on the land
- Product diversification = risk spreading
- Additional 2nd generation feedstock supply; especially favourable for farming cooperatives operating beet sugar plants / refineries
- Process-related benefits:
  - Better utilisation of installations compared to only sugar beet processing leads to lower production costs/higher revenues
  - Less transport costs
  - Less downstream processing
  - Less waste.

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Technology:
  - Complex scheme, that has to be balanced
  - Ethanol production of sugars from beet pulp (pectin, hemicellulose…) is under development and has not been proven
  - Fractionation technology probably not proven at industrial scale yet; need further R&D
  - Increased operating cost
- Strategy:
  - Outsourcing of ethanol production and anaerobic digestion may form a commercial risk i.e. price to be paid for pulp, molasses may fluctuate
  - Less added value at the sugar plant, more added value at farm
  - Some current installations will be abandoned (very fast depreciation of equipment needed)
- Specification of protein meal and position in market not yet known
- Dependence on environmental conditions during cultivation.

Opportunities: external; general trends affecting the integrated concept positively

- Bio-energy, biofuels demand
- Ethanol from beet pulp may be considered as 2nd generation?
- Increasing demand for 'green' products
- Concept open to new application of products, especially proteins.

Threats: external; general trends affecting the integrated concept negatively

- Whole operation highly depending on legislation that can change
- Current outlet of beet pulp as animal feed product is reasonably good
- To some extent competition with food and/or feed production
- Farmers might become independent of central processing facility (intermediate products are more easily transported to alternative factories)
- Competition with conventional heat and power production
- Enough volume to enter the market?

D.7.2 Grass refinery

Strength: internal; what features are improving the competitive position of the operator (compared to operators sticking to reference case)?

- Economical factors:
    - Cheap feedstock
    - High added value potential
    - Plant might be profitable even without subsidies (whereas anaerobic digestion reference case will never be profitable)
- Strategic factors:
    - Platform towards non-energetic products (business development).

Weaknesses: internal; what features are threatening the competitive position of the operator (compared to operators sticking to reference case)?

- Technology and operation:
    - Technology not yet proven
    - Extraction plant idle 75% of the time
- Economy and market:
    - Logistic cost (supply of grass to the biorefinery)
    - Reduction of electricity per volume of anaerobic digester
    - Fibre prices are currently low
    - No established market for products protein meal and especially for fibres (the lack of outlet for fibres has proved to be critical in previous grass biorefinery commercialisation efforts e.g. by AVEBE)
- Regulatory:
    - Proteins need to be approved
    - Specification of protein meal and position in market not yet known
- Dependence on environmental conditions during cultivation and harvesting.

Opportunities: external; general trends affecting the integrated concept positively

- Cheap 2nd generation feedstock, no direct interference with food production
- Simple, sustainable concept that could be highly appealing to the general public
- Good environmental profile expected
- High future phosphate prices might increase profitability of further refinery
- Allowance for digestate instead of nitrogen/phosphate fertiliser would increase value of digestate
- Possibilities for purification of minerals from grass, thus decreasing mineral load on agricultural area.

Threats: external; general trends affecting the integrated concept negatively

- Cut down of subsidies
- Quality control of final product (proteins)
- Volume large enough to enter the market? (Electricity).