TO2 Advanced pre-treatment of biomass

Task A3. Modelling chains and economic evaluation (WUR-FBR)

K.P.H. Meesters, E. Annevelink & E.R.P. Keijsers

Report 1648

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Author(s)	K.P.H. Meesters, E. Annevelink & E.R.P. Keijsers
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Wageningen UR Food & Biobased Research
P.O. Box 17
NL-6700 AA Wageningen
Tel: +31 (0)317 480 084
E-mail: info.fbr@wur.nl
Internet: www.wur.nl

Summary

The overall objective of the TO2 project 'Advanced pre-treatment of biomass' was to design optimal energy-driven refinery chains for the sustainable valorization of non-woody biomass to biobased commodities. Therefore optimal combinations need to be found of upstream biorefining and the production of high-quality (solid) energy carriers from a broad spectrum of non-woody biomass streams. Task A3. within this TO2 project focused on modelling chains and performing an economic evaluation of these chains. Three cases of biomass chains were modelled and evaluated in this report.

Case 1: Production of press cake and protein from fresh culture grass

Case 2: Production of press cake, protein and phosphate from fresh culture grass

Case 3: Production of fibre for torrefaction and PHA polymer from silaged verge grass

Case 1: Production of press cake and protein from fresh culture grass
A small scale biorefinery is assumed that will be temporarily installed at a certain farm. All the fields near that farm will be mowed and the grass will immediately be processed in the equipment of the small scale biorefinery. After a few days, when all the grass in the neighbourhood of the farm is processed, the biorefinery is moved to another farm and the process is repeated. In the biorefinery fresh culture grass from pastures is first pressed, resulting in a press cake and a juice. The press cake is then sold as cattle feed. The juice is heated to coagulate proteins. The coagulated proteins are separated from the juice in a decanter centrifuge. The proteins are sold as pork feed. They have a composition comparable to soy bean meal, and can therefore be sold at the same price. The remaining supernatant is spread over the land of farmers in the neighbourhood.

Case 2: Production of press cake, protein and phosphate from fresh culture grass
This case is almost identical to case 1. However, in case 2 the supernatant is further treated with lime to precipitate phosphate. The precipitate is recovered as a phosphate rich sludge that may be sold as fertilizer. The low phosphate supernatant is again spread over the land of farmers in the neighbourhood. The costs of spreading the supernatant will be lower in this case because the farmers will not ask for a phosphate fee.

Case 3: Production of fibre for torrefaction and PHA polymer from silaged verge grass
Silaged verge grass (originating e.g. from road maintenance) is first put into an acidification reactor. Volatile fatty acids (mainly acetic acid and propionic acid) are then produced. These fatty acids are fed to a reactor with PHA accumulating bacteria. When the bacteria are filled with PHA, a centrifuge is used to harvest the bacteria containing the PHA. The PHA filled bacteria

are sold then to a PHA manufacturer. The liquid from this process is largely recycled to the acidification reactor in order to overcome product inhibition in the acidification reactor. A small bleed stream is treated with lime to recover phosphate. After a few weeks, all easily degradable material will be removed and cellulose and lignin will remain. These are then treated in a composting facility.

Results

The cases 1 and 2 with fresh culture grass from pastures had a long payback time. Removal of the phosphate did not really influence the overall result positively. However, case 3 with the verge grass biorefinery, showed a better perspective. This case however was mainly based on many uncertain assumptions, whereas the two pasture grass cases were based on achieved laboratory scale results. Therefore, considerable laboratory research and process development will be needed to obtain the correct data to get this process going.

Residue streams from cases 1 and 2 will not be suitable for further treatment in the Torwash process. However the residues of case 3 do offer this possibility.

Content

1 Introduction

The overall objective of the TO2 project ‘Advanced pre-treatment of biomass’ was to design optimal energy-driven refinery chains for the sustainable valorization of non-woody biomass to biobased commodities. Therefore optimal combinations need to be found of upstream biorefining and the production of high-quality (solid) energy carriers from a broad spectrum of non-woody biomass streams.

Task A3. within this TO2 project focused on modelling chains and performing an economic evaluation of these chains. Based on the experience of previous projects first a general scheme was designed for a complete fresh grass biorefinery chain (see Figure 1). The scheme shows possible connections with the Torwash technology. Subsequently the first part of the value chain was used as a starting point for the three cases that were modelled in SuperPro Designer.

This report describes the set-up of these three cases in Chapter 2. Appendix A gives all the modelling assumptions. In Chapter 3 the results of the calculations with SuperPro Designer are given and finally conclusions are given in Chapter 4.

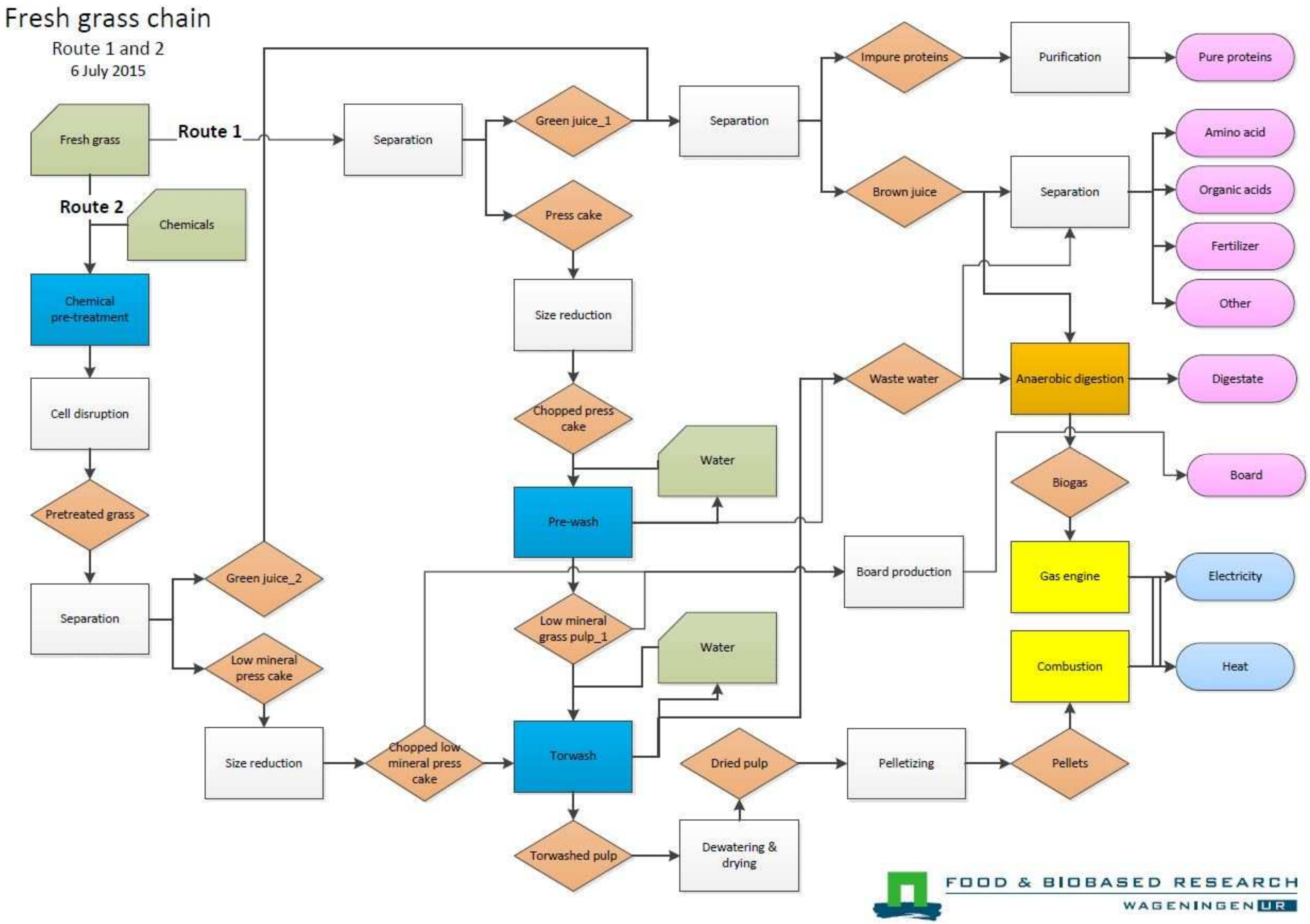

Figure 1 Two possible routes for a fresh grass biorefinery chain.

2 Set-up of the three case studies

Grass has several components of economic interest: fibres, proteins, amino acids, sugars, phosphate. Depending on the quality of the grass (culture grass, verge grass, silage grass), different process schemes will be needed. Based on the model data and assumptions presented in Appendix A, three different cases were studied:

Case 1: Production of press cake and protein from fresh culture grass

Case 2: Production of press cake, protein and phosphate from fresh culture grass

Case 3: Production of fibre for torrefaction and PHA polymer from silaged verge grass

2.1 Case 1: Production of press cake and protein from fresh culture grass

A small scale biorefinery is assumed that will be temporarily installed at a certain farm. All the fields near that farm will be mowed and the grass will immediately be processed in the equipment of the small scale biorefinery. After a few days, when all the grass in the neighbourhood of the farm is processed, the biorefinery is moved to another farm and the process is repeated. In the biorefinery fresh culture grass from pastures is first pressed, resulting in a press cake and a juice. The press cake is then sold as cattle feed. The juice is heated to coagulate proteins. The coagulated proteins are separated from the juice in a decanter centrifuge. The proteins are sold as pork feed. They have a composition comparable to soy bean meal, and can therefore be sold at the same price. The remaining supernatant is spread over the land of farmers in the neighbourhood.

This is modelled in SuperPro Designer as follows (Figure 1): fresh culture grass (S-101) is pressed in a filter press (P-1) to separate the material into two fractions i) fibres in the press cake (S-103) and ii) juice (S-104). The juice is heated to 70 ^{o}C (P-2, P-3) to coagulate dissolved proteins (P-4). The proteins (S-111) are separated from the liquid in a decanter centrifuge (P-5), which leaves a rest fluid (S-110) that is assumed to be applied as fertilizer.

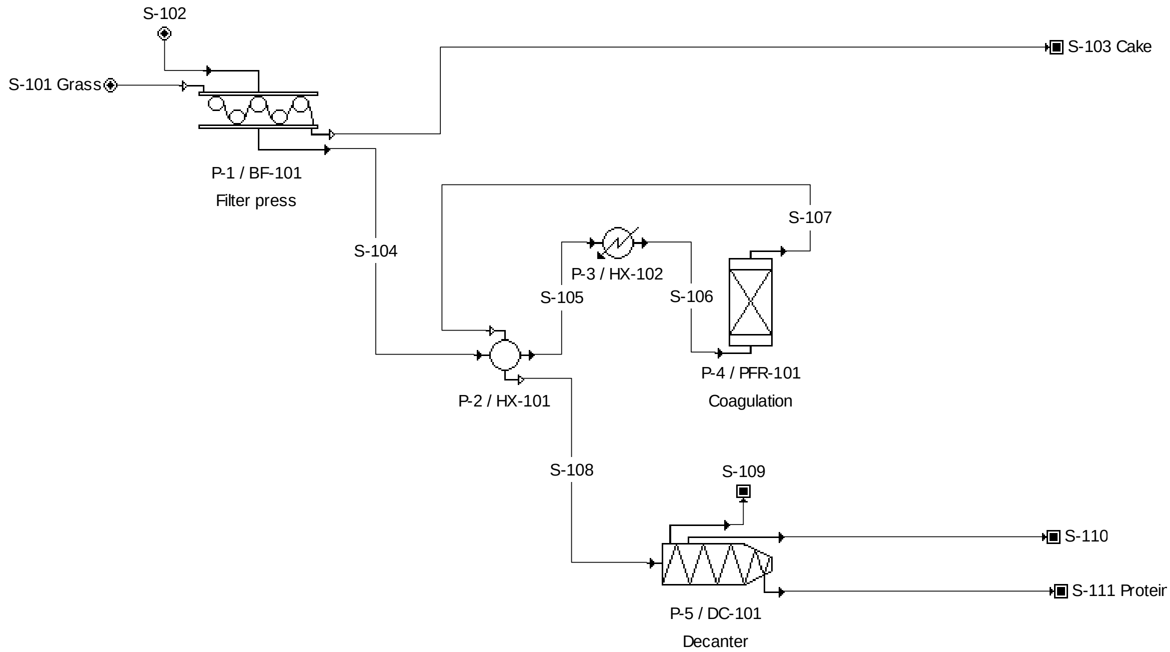

Figure 2 Process scheme Case 1: Production of press cake and protein from fresh culture grass.

2.2 Case 2: Production of press cake, protein and phosphate from fresh culture grass

This case is almost identical to case 1. However, in case 2 the supernatant is further treated with lime to precipitate phosphate. The precipitate is recovered as a phosphate rich sludge that may be sold as fertilizer. The low phosphate supernatant is again spread over the land of farmers in the neighbourhood. The costs of spreading the supernatant will be lower in this case because the farmers will not ask for a phosphate fee.

This is modelled in SuperPro Designer as follows (Figure 2): in case 2 the scheme of case 1 is extended with a P-recovery unit. Phosphates are precipitated by addition of lime (P-6) and then separated in a clarifier (P-7).

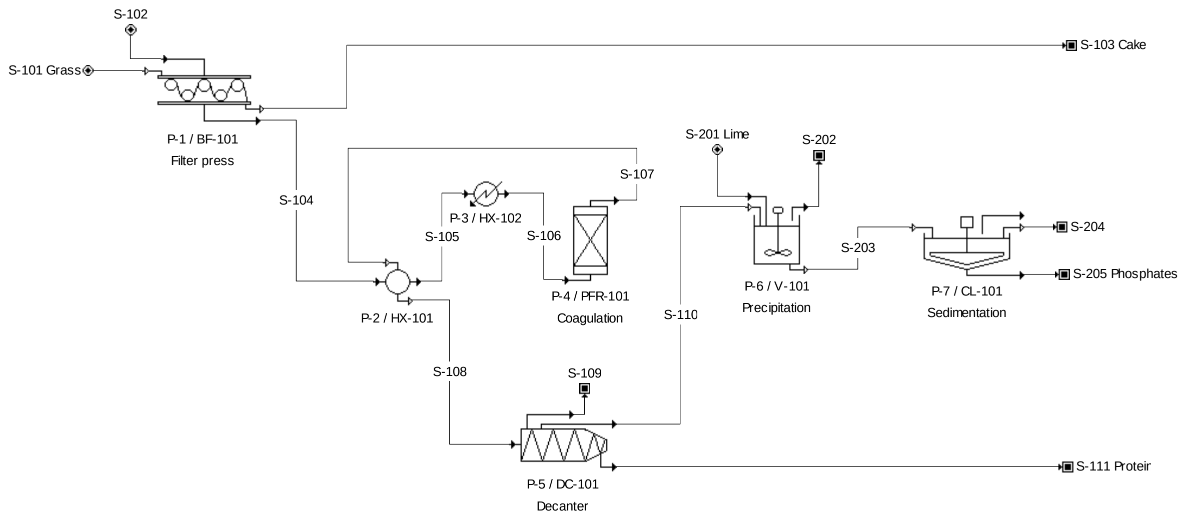

Figure 3 Process scheme Case 2: Production of press cake, protein and phosphate from fresh culture grass.

2.3 Case 3: Production of fibre for torrefaction and PHA polymer from silaged verge grass

Silaged verge grass (originating e.g. from road maintenance) is first put into an acidification reactor. Volatile fatty acids (mainly acetic acid and propionic acid) are then produced. These fatty acids are fed to a reactor with PHA accumulating bacteria. When the bacteria are filled with PHA, a centrifuge is used to harvest the bacteria containing the PHA. The PHA filled bacteria are sold then to a PHA manufacturer. The liquid from this process is largely recycled to the acidification reactor in order to overcome product inhibition in the acidification reactor. A small bleed stream is treated with lime to recover phosphate. After a few weeks, all easily degradable material will be removed and cellulose and lignin will remain. These are then treated in a composting facility.

This is modelled in SuperPro Designer as follows (Figure 3): Verge grass is silaged (P-1). C6 polymers, C5 polymers, oligo saccharides, saccharides and protein are largely converted to organic acids in an acidification process. The inert solid fraction (S-106) is removed in a filter press (P-2). The extract (S-103) and press liquid (S-107) are sent to the fermenter (P-3), where PHA accumulating bacteria are grown. Due to the uptake of organic acids in the fermenter, the pH will rise and phosphates will precipitate. Via addition of acetic acid, these phosphates are re-dissolved (P-4). The biomass with accumulated PHA is recovered in a decanter centrifuge (P-5). The remaining liquid (S-306) is largely recycled to P-1 via a flow splitter (P-6). A small bleed stream removes excess water from the process. This water is treated with lime (S-402) to precipitate phosphates (P-7). The phosphates are recovered in a clarifier (P-8).

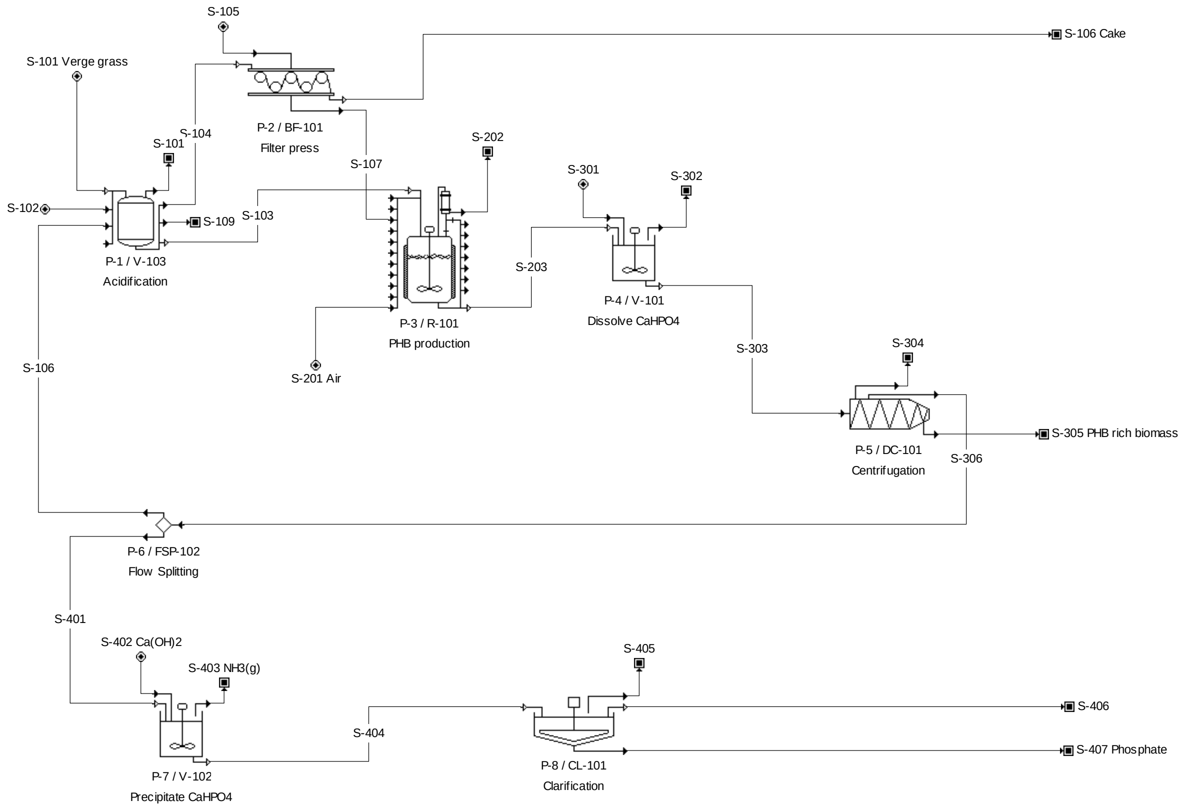

Figure 4 Process scheme Case 3: Production of fibre for torrefaction and PHA polymer from silaged verge grass.

3 Results

The results of the three cases are discussed in this Chapter. This is divided in a section on fresh culture grass biorefining and a section on silaged verge grass biorefining. The overall results are given in Table 1 and in Figure 4.

3.1 Fresh culture grass biorefining (case 1 and 2)

Case 1 – Protein removal
The total investment (incl. installation, working capital and start-up costs) of case 1 will be 1,978 k€. The biorefinery process in case 1 only has are very small positive difference between total revenues and operating cost per year of (1,158 – 1,017 =) 141 k€/year. However, the return on investment (ROI) of 11.6% and the internal rate of return (IRR) of 6.6% are not convincing for investors. Also the payback time (PBT) of 8.6 year is too close to the plant expected life time of 10 year. Finally the net present value (NPV) at 7% interest of the investments and revenues is negative, being -34 k€.

Case 2 - Protein removal with P recovery
The total investment of case 2 is 2,236 k€, which is a bit higher than in case 1. The addition of phosphate recovery in case 2 does not really improve the overall biorefinery process from an economic point of view. The biorefinery process in case 2 only also has a small positive difference between total revenues and operating cost per year of (1,163 – 992 =) 171 k€/year, although it is slightly higher than in case 1. Again, the ROI of 12.4% and the IRR of 7.3% are not convincing for investors. And also the PBT of 8.1 year is still too close to the plant expected life of 10 year. The NPV has improved a bit to 28 k€.

Further improvement to Case 1 - Higher protein yield & 50% sharing of equipment
If the yield percentage of the protein recovery in the press could improved from 65% to 85% (e.g. by repeated pressing or soaking in alkaline), both the protein yield and the protein purity will increase. This will allow for a higher product price (a 20% increase is assumed). This will then increase the profitability of case 1 to ROI = 16.3% and IRR = 13.4%, which is a significant improvement, but still not enough to convince investors.

Further improvement to Case 1 - 50% sharing of equipment
The mobile biorefinery unit will only be running during the spring and summer period of the of the year when fresh grass is available. It is assumed that this is 50% of the year. However, during the fall and winter period both the press and the decanter centrifuge could also be used for other processes, for example for manure treatment. the total capital investment is again 1,978 k€, but only 1,416 k€ is charged to the project. In that case only half of the capital costs of the press and

decanter have to be allocated to the biorefinery process, the total capital investment is again 1,978 k€, but only 1,416 k€ is charged to the project. This improves the ROI to 15.9% and the IRR to 14.0%. The payback time will also decrease to 6.3 years. This will now be more convincing for a potential investor.

Further improvement to Case 1 - all improvements together (including P recovery of Case 2)
All improvement measures together (phosphate removal, higher protein yield and capital costs allocated to other processes) will yield a biorefinery process with a ROI of 21.7%, an IRR of 21.0% and a payback time of 4.6 years. For an investor this could be an attractive investment.

So a summary of the conclusions for case 1 and 2 is:

- low profitability;
- case 2 with P removal is a little more profitable;
- more refinery needed, but how can this be achieved;
- if the protein yield could be increased and if the equipment could be share this will improve the profitability
- no possibility for delivery of residues to the Torwash process.

3.2 Silaged verge grass biorefining (case 3)

The total investment (incl. installation, working capital and start-up costs) of case 3 is 20,648 k€. The biorefinery process in case 3 has a substantial difference between total revenues and operating cost per year of (12,015 – 6,256 =) 5,759 k€/year. So this has a positive economic result with a ROI of 25.7%, an IRR of 24.1% and a PBT of 3.9 year). The NPV is 18,206 k€. However, some of the assumptions in the calculations have a high uncertainty (e.g. the yield of acids from verge grass acidification, the yield of PHA and the PHA price). Therefore these assumptions should first be researched in more detail before building a pilot or a demonstration plant.

So the overall conclusions are:

- a high added value product (PHB) seems more profitable;
- there are no actual data to support the assumed yield yet, so the results are uncertain;
- the quality of the produced PHB is unknown;
- in this case there is a possibility of delivery a residual streams to the Torwash process.

Table 1 Summary of the economic results (2015 prices) obtained from the SuperPro Designer calculations for the three cases, including further improvements to case 1.

Value	Case 1 protein	Case 2 P recovery	Case 1 more protein	Case 1 50% sharing	Case 1 plus all improvements	Case 3 PHA
Total Capital Investment (k€)	1,978	2,236	1,982	1,978	2,240	20,648
Capital Investment charged to project (k€)	1,978	2,236	1,982	1,416	1,678	20,648
Equipment purchase cost (k€)	766	914	769	766	916	3,234
Operating Cost (k€/year)	1,017	992	1,016	936	910	6,256
Total revenues (k€/year)	1,158	1,163	1,311	1,158	1,316	12,015
Gross margin (%)	12.18	14.77	22.53	19.22	30.89	47.71
Return on Investment (ROI) (%)	11.64	12.38	16.31	15.94	21.73	25.71
Payback Time (PBT) (year)	8.59	8.08	6.13	6.27	4.60	3.89
IRR (after taxes) (%)	6.64	7.27	13.36	13.98	21.02	24.14
NPV at 7% Interest (k€)	-34	28	616	483	1,189	18,206

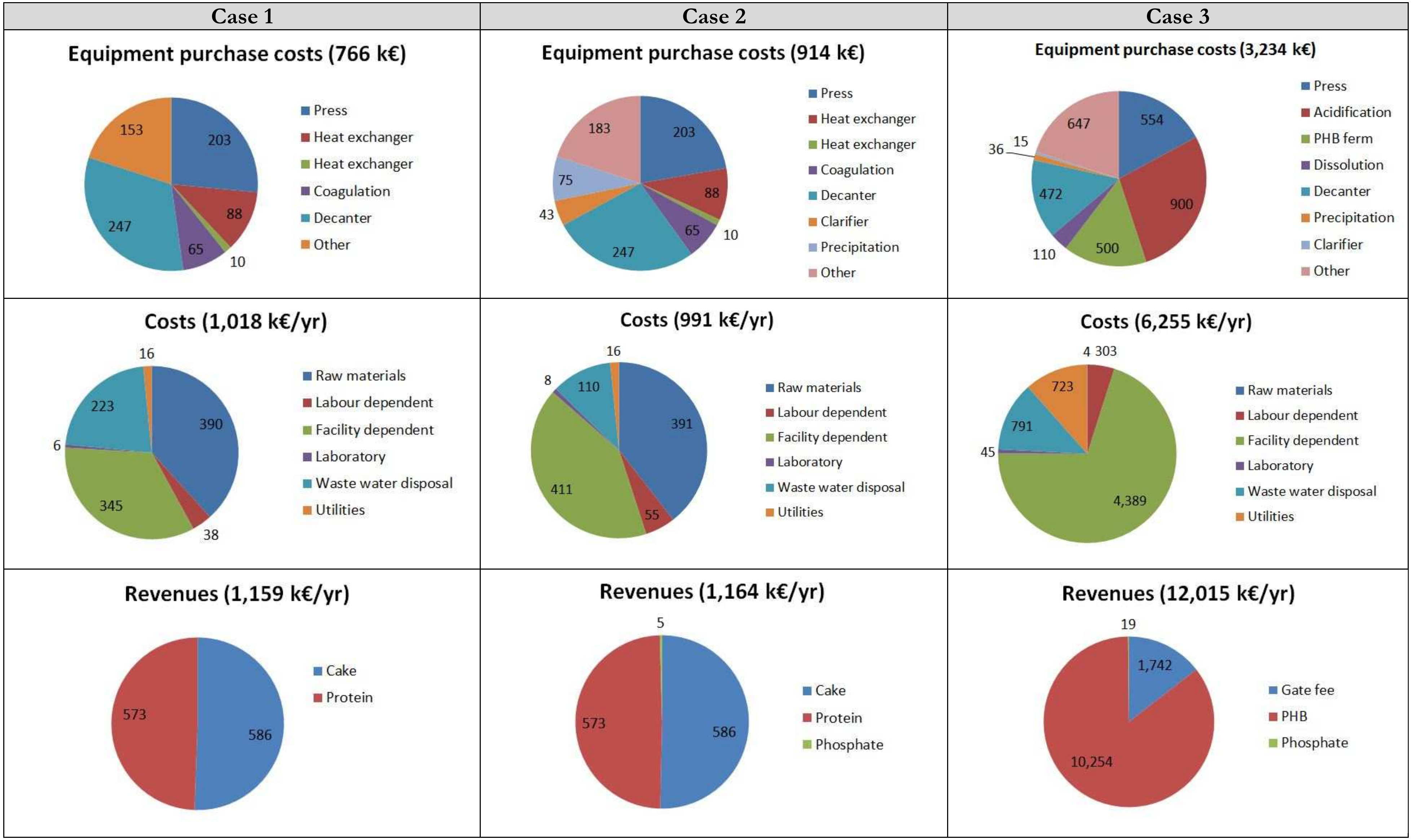

Figure 5 Results of the three cases.

4 Conclusions

The cases 1 and 2 with fresh culture grass from pastures had a long payback time. Removal of the phosphate did not really influence the overall result positively. However, case 3 with the verge grass biorefinery, showed a better perspective. This case however was mainly based on many uncertain assumptions, whereas the two pasture grass cases were based on achieved laboratory scale results. Therefore, considerable laboratory research and process development will be needed to obtain the correct data to get this process going.

Residue streams from cases 1 and 2 will not be suitable for further treatment in the Torwash process. However the residues of case 3 do offer this possibility.

Appendix A. Modelling assumptions for grass biorefinery

In this Appendix the model assumptions for a grass biorefinery are described. First the chemical reactions in the biorefinery are presented. Then the model assumptions for two different feedstocks being i) fresh culture grass and ii) verge grass.

A1. Reactions in the biorefinery

During processing of grass, several reactions will take place. In this paragraph the stoichiometry of these reactions is given. This paragraph provides detailed information on the model and is meant to secure the model data for later reference.

A1.1 Phosphate precipitation

$Ca^{2+}(aq) + 2H_2PO_4^-(aq) + Ca^{2+}(OH^-)_2(s) \text{ --> } 2Ca^{2+}(HPO_4^{2-})(s) + 2H_2O(l)$

A1.2 Phosphate dissolution

$Ca^{2+}(HPO_4^{2-})(s) + 2HAc(aq) \text{ --> } Ca^{2+}(aq) + H_2PO_4^-(aq) + Ac^-(aq)$

A1.3 Coagulation

Protein (aq) --> Protein(coag)

A1.4 Acidification

$C6p(s) + H_2O(l) \text{ --> } 3C_2H_4O_2(aq)$
$C5p(s) + H_2O(l) \text{ --> } 2.5C_2H_4O_2(aq)$
$Oligo(aq) + 5H_2O(l) \text{ --> } 15C_2H_4O_2(aq)$
$Protein + H_2O(l) \text{ --> } C_2H_4O_2(aq) + NH_3(aq)$

A1.5 Production of PHA accumulating organisms

$C_2H_4O_2(aq) + O_2(g) \text{ --> } CH_2O(s) + CO_2(g) + H_2O(l)$

A1.6 Losses

$C_2H_4O_2(aq) + 2O_2(g) \text{ --> } 2CO_2(g) + 2H_2O(l)$

A1.7 PHA production

$2.25C_2H_4O_2(aq) \rightarrow C_4H_6O_2(s) + 0.25CO_2(g)$

A1.8 Ammonia stripping

$NH_4^+(aq) + OH^-(aq) \rightarrow NH_3(g) + H_2O(l)$

A2. Model assumptions fresh culture grass

A2.1 General

Culture grass is a protein rich crop that is grown under optimal production circumstances, normally for animal feed. It will be harvested during 26 weeks/yr, 5 days per week, 10 hr/day = 1300 hr/yr. Culture grass will be processed in a mobile biorefinery unit that can process the harvest of 20 ha of grassland in one day. The yield of culture grass is 12.5 ton DM per year in 5 harvests. So one harvest will yield (12.5/5=) 2.5 ton DM per ha. The dry matter content of grass is estimated at 17%, so one harvest will yield 14.7 ton grass fresh weight per ha. The capacity of the mobile unit will be: (14.7 ton per harvest per ha * 20 ha of grass per day) / (10 hr/day) = 29.4 ton fresh weight/hr.

The unit will process 20 ha per day, 26 weeks per year, 5 days per week. In total 2,600 ha of grassland may be processed by one unit. The total grass land area in the Netherlands is 940,000 ha. So a total of 36 mobile units would be needed to visit each lot once a year.

A2.2 Raw material: fresh culture grass

The exact composition of fresh culture grass is not known and furthermore may fluctuate between fields, regions and moment of harvest. More than once the components of culture grass have been determined, but the results never add up to 100%. In order to set up a proper mass balance, a complete composition of grass is necessary. Based on earlier work and literature data, the following composition of fresh grass was derived. The price of culture grass was estimated at 60 €/ton DM (10.2 €/ton fresh weight).

Table A1. Composition of fresh culture grass (17% DM).

Component	% of DM	Elemental composition of component (mole/mole)					
		C	H	O	N	S	K
C5 polymer	14.0	5	8	4			
C6 polymer	28.0	6	10	5			
Lignin	3.0	31	34	11			0.09
Oligo sugars	12.0	30	52	26			
Sugars	5.0	6	12	6			
Organic acids	5.0	2	4	2			
Lipids	6.0	16	31	2			1
Protein	20.5	1,300	2,500	700	443	100	
KH_2PO_4	0.0		2				1
KCl	1.2						1
$Ca(H_2PO_4)_2$	2.0		4				
$CaCl_2$	0.7						
NaCl	2.6						
Total	**100.0**						

Table A2. Elemental composition of fresh culture grass expressed as mass percentage of total weight.

Element	Percentage (%)
C	41.3
H	6.0
O	39.5
N	3.3
S	1.7
Na	1.0
K	3.4
Ca	0.6
P	0.5
Cl	2.6
Total	**100.0**

A2.3 Additional materials: Lime

The costs of lime are estimated at 150 €/ton.

A2.4 Characteristics of the processes

Pressing
- Dissolved components divide with same ratio as water dividing ratio
- 70% of CaH_2PO_4: stays in solid, rest is removed with press water
- 35% of protein is removed with cake
- 55% of lipid is removed with cake
- 95% of solids (C6p, C5p, lignin) ends in press cake
- Dry matter content of solids in the press cake is 44%

Coagulation
- Heating to 70 ºC
- 70% of dissolved protein will coagulate

Decanter
- 95% of solids (C6p, C5p, lignin, lipid, coagulated protein) is removed with cake
- 80% of oligo saccharides is removed with coagulated protein
- Cake has a dry matter content of 200 g/l
- Dissolved components divide with water

Phosphate precipitation
- 5% excess $Ca(OH)_2$ is dosed
- Reaction is 100% complete

Clarification
- 90% of solids (C6p, C5p, lignin, coagulated protein, lipids) are removed
- 95% of $CaHPO_4$(s) is removed
- Phosphate sludge has total solids concentration of 200 g/l

A2.5 Products

- Fibre cake (feed) @44%DM, 66 €/ton
- Coagulated protein (feed) @24% DM, 81.6 €/ton (comparable to soy bean meal price)
- Press juice after protein coagulation: 10 €/ton to bring back to fields (case 1)
- Press juice after protein coagulation and phosphate removal: 5 €/ton to return it to fields (case 2)
- Phosphates are sold at 150 €/ton $CaHPO_4$

A2.6 Economy

The direct fixed capital costs are estimated from the purchased equipment cost. A factor of 2 was used to account for installation, piping, buildings etc. This is much lower than the standard factors (in Super Pro Designer these factors add up to 6). The mobile installation is a fairly simple machine that will use facilities at the farm that are already present (toilets, electrical connections, concrete floor, farmhouse as canteen, etc.). All together this makes the low factor realistic.

A3. Model assumptions verge grass

A3.1 General

Verge grass is grass of much lower quality that is collected after mowing of road sides. Verge gras may be silaged so that it is accessible for processing full year around (7,920 hr/yr). In total 1,000 kton of verge grass is harvested each year in the Netherlands. It is assumed that ten processing units will be distributed over the country, that will each process one tenth of the available verge grass. The capacity of an individual unit should then be (1,000 kton/yr /10 units / 7,920 hr/yr =) 12.6 ton/hr. The harvested verge grass is assumed to have a dry matter content of 40%

A3.2 Raw materials: verge grass

Based on the composition of culture grass, the composition of verge grass (**Error! Reference source not found.**) was estimated (assuming a lower protein content and a higher C6 content).

Table A3. Composition of verge grass (40% dry matter).

Component	**% of DM**	**Elemental composition of component**					
		C	**H**	**O**	**N**	**S**	**K**
C5 polymer	14.0	5	8	4			
C6 polymer	32.5	6	10	5			
Lignin	3.0	31	34	11			0.09
Oligo sugars	12.0	30	52	26			
Sugars	5.0	6	12	6			
Organic acids	5.0	2	4	2			
Lipids	6.0	16	31	2			1
Protein	16.0	1,300	2,500	700	443	100	
KH_2PO_4	0.0		2				1
KCl	1.2						1
$Ca(H_2PO_4)_2$	2.0		4				
$CaCl_2$	0.7						
NaCl	2.6						
Total	100.0						

A3.3 Characteristics of the processes

Acidification of monomers and polymers

- 70% of protein is acidified
- 98% of free sugars is acidified
- 90% of oligo saccharides is acidified
- 70% of C5p is acidified
- 60% of C6p is acidified
- 90% of solids (C6p, C5p, lignin, lipids, biomass, PHA) is removed to press
- 30% of $Ca(H_2PO_4)_2$ is removed to press
- 10% of water and solubles is removed to press
- Rest is removed to fermentation

Press

- 95% of solids (C6p, C5p, lignin, lipids, biomass, PHA) is removed to press cake
- 70% of $Ca(H_2PO_4)_2$ is removed to press cake
- Rest is distributed according to water distribution ratio

Fermentation

- 20% of acetic acid used for production of PHA accumulating organisms
- 10% of acetic acid lost
- Rest of acetic acid used for PHA accumulation
- Glucose fully converted to PHA
- Potassium acetate fully converted to PHA
- Phosphate precipitation

Phosphate dissolution

- Full dissolution of phosphate
- Full titration of KOH formed in fermentation

Decanter centrifuge

- 83% removal of PHA and biomass
- Rest is distributed according to water distribution ratio

Phosphate precipitation

- Full precipitation of phosphate
- 90% of NH_4OH released as gas

Clarification

- 90% of phosphate recovered in sludge
- 70% removal of solids (C6p, C5p, lignin, biomass, PHA)

A3.4 Products

- Fibre cake (sent to torwash) @40% DM: -20 €/ton
- PHA rich biomass @37% DM: 1,000 €/ton PHA
- $CaHPO_4$ @100 g/liter: 150 €/ton $CaHPO_4$
- Wastewater disposal: 20 €/ton

A3.5 Economy

The direct fixed capital costs are estimated from the purchased equipment cost according to the standard factors in Super Pro Designer (altogether a factor of 6).

A4. Summary of the modelling assumptions

General assumptions:

- 10 years plant life time
- 10 months building time
- 2 months start-up time
- so in total 11 years
- equity finance (no bank loan)
- grass case:
- PHB case:

Assumptions for case 1 & 2:

- culture grass: 60 €/ton DM
- cost of lime: 150 €/ton
- grass cake: 150 €/ton DM
- protein: 360 €/ton DM (comparable to SBM)
- wastewater: 10 €/ton
- wastewater after P removal: 5 €/ton
- P sludge: 150 €/ton $CaHPO_4$

- low multiplier to calculate TI
- TI= 2 times purchased equipment cost

Assumptions for case 3:

- verge grass: -20 €/ton DM
- cost of lime: 150 €/ton
- PHB sludge: 1,000 €/ton PHB
- cake to torrefaction: -20 €/ton DM

- wastewater after P removal: 20 €/ton
- P sludge: 150 €/ton $CaHPO_4$

- normal multiplier to calculate TI
- TI = approx. 6.3 times purchased equipment cost