Biobased Chemistry and Technology

BSc Thesis Biobased Chemistry and Technology

Biorefining of duckweed at ECOFERM!

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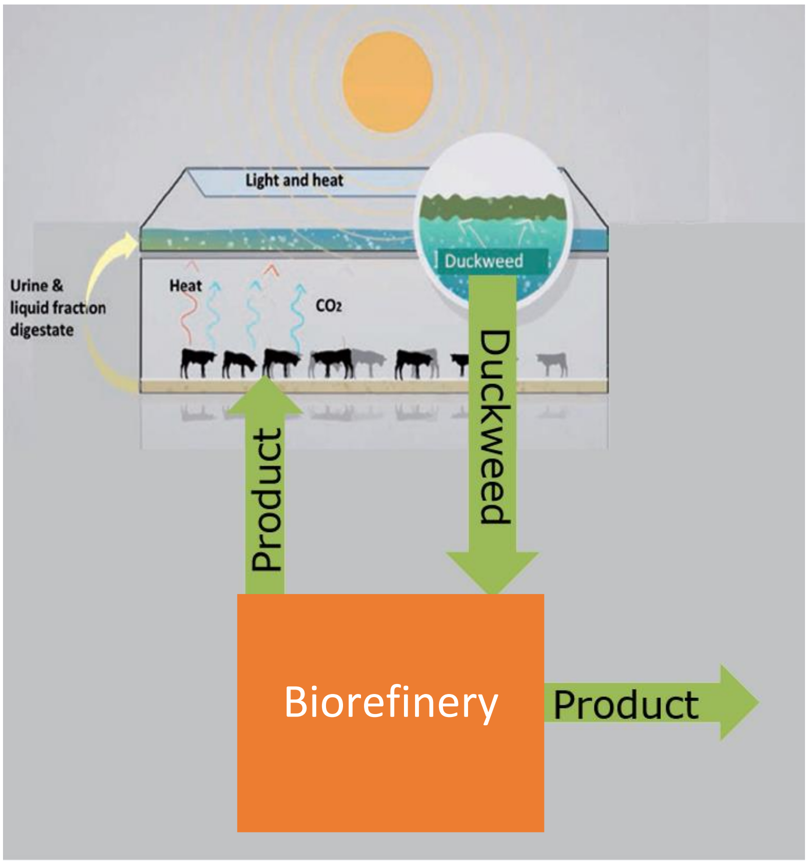

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Biorefining of duckweed at ECOFERM!

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Abstract

Europe produces 14% of the worldwide meat resulting in a high demand for protein rich feed sources like soy. Soy cannot grow in the European climate and the major part is imported from outside Europe which is costly and gives an extra load to the environment. Duckweed is considered as an alternative protein feed source, able to grow in the European climate.

In ECOFERM!, duckweed was fed to the calves to limit the amount soy used. ECOFERM! is a closed-cycle farm in which by-products from rosé calf farming are used to produce duckweed and biogas. ECOFERM! is tackling problems with manure regulations and reduces soy import. However, the production of duckweed turned out to be too expensive for the extra value direct feeding created. Duckweed is used inefficiently when fed directly to calves. Processing of duckweed in a biorefinery can solve this problem trying to maximize all the chemical compounds in duckweed.

This thesis will mainly focus on designing, modelling and identifying bottlenecks for a protein biorefinery of duckweed on ECOFERM!. The knowledge found in the literature is used to design this refinery process. Two different scenarios of the most promising processes are created. A refinery based on grass processing and a refinery based on green tea residues (GTR) processing are modelled to see which one is the most promising and suitable for ECOFERM!.

The chemical composition of the protein product, cake product and waste water created in both process is calculated in the model. The value of those products is based on the price of comparable products. The model also calculates the costs involved with certain model settings like heat exchanger used, heating temperature, extraction pH, steam injection system used, capacity, process size and pressing once or twice. With this data, the processes and the design choices of these processes are evaluated before measuring.

The reference income generated by normal feeding of duckweed is 0,014 € per kilogram fresh weight (FW). To generate this income for the grass based process a fractionation percentage, which is an adaptable factor in the model, should be greater than 20 percent. If the capacity and process size increase the costs per dry matter will decrease largely. But the extra costs for refining duckweed will remain too high to make a profit in the end.

In the GTR based system, most income is generated with a high purity and a low protein yield. The total income is always higher than the reference income independent from the purity and yield. In this system, the extraction temperature has a great influence on the costs and equipment needed. It is possible under specific conditions to turn a profit with the GTR based system.

The most critical process step for the proof of concept of the grass based system is the coagulation. It is the process step with the highest energy consumption and high investment costs are involved. The coagulation in this system results in a low recovery compared to the alkali based system. In the alkali based system, the extraction conditions of the alkali extraction step are the most critical in the proof of concept. A major costs reduction can be realised and the extraction conditions can be greatly optimised for the total process.

In the refinery based on alkaline extraction, a higher crude protein content in the protein product is realised, the dry matter in the cake is higher too. With this refinery, less valuable components end up in the waste water compared to the system based on grass processing. Therefore, the total revenue of the system based on alkaline extraction is greater than the system based on grass processing. Alkaline extraction is better applicable at small scale since the costs per dry matter are less influenced by the capacity and process size. Alkaline extraction has the potential to be a better alternative for direct duckweed feeding on ECOFERM!

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1. Introduction

1.1 Background

The world population is growing to an estimated 9.7 billion people in 2050 (DESA, 2015). Developing countries get richer, which will result in an increasing global meat demand with 85% from 2005 to 2050 (Bruinsma, 2009). To meet the future demand for meat technologies that enhance the productivity and sustainable management of natural resources are required (FAO, 2009).

Europe produces 14% of the worldwide meat (Eurostat, 2013), resulting in a high demand for protein rich feed sources. Soy is the most used protein source to grow cattle, but cannot grow in the European climate. Therefore, the major part is imported from outside Europe (Gelder & Herder, 2012), which is costly and gives an extra load to the environment (Brown, 2009). Duckweed is considered as an alternative protein feed source and able to grow in the European climate (Leng, Stambolie, & Bell, 1995). Cultivated under the right growing conditions, duckweed can have a protein content of 45% per dry matter (Landolt & Kandeler, 1987), which is comparable to the protein content of soy with 43.8% protein per dry matter (Cromwell, 2012).

Moreover, the livestock sector produces a lot of manure which is partly used to fertilize the land. Fertilization of agricultural land is regulated strictly and cannot exceed maximum amounts of nitrogen and phosphate which are in animal manure (RVO, 2017). If farmers exceed the norm, they need to transport the manure to farmers or regions without a manure surplus or process the manure on their site.

In 2011 the ECOFERM! concept was introduced and used to utilize waste streams (manure, heat and CO_2) of a rosé calves farm. ECOFERM! is tackling problems with manure regulations and reduces soy import, in order to produce calve meat in an efficient manner. It is an example of a circular farm in which waste streams are used to create more added value. Manure is used to fertilize duckweed and to produce biogas in a mono-digester, duckweed is then used as a protein source for calves. The closed cycle and an overview of ECOFERM! can be seen in Figure 1. Some thesis work is done on the ECOFERM! project. First, a dynamic model was designed for the production of duckweed on ECOFERM! by van den Top (2014). The production of duckweed was modelled in combination with economic possibilities by van Marrewijk (2017).

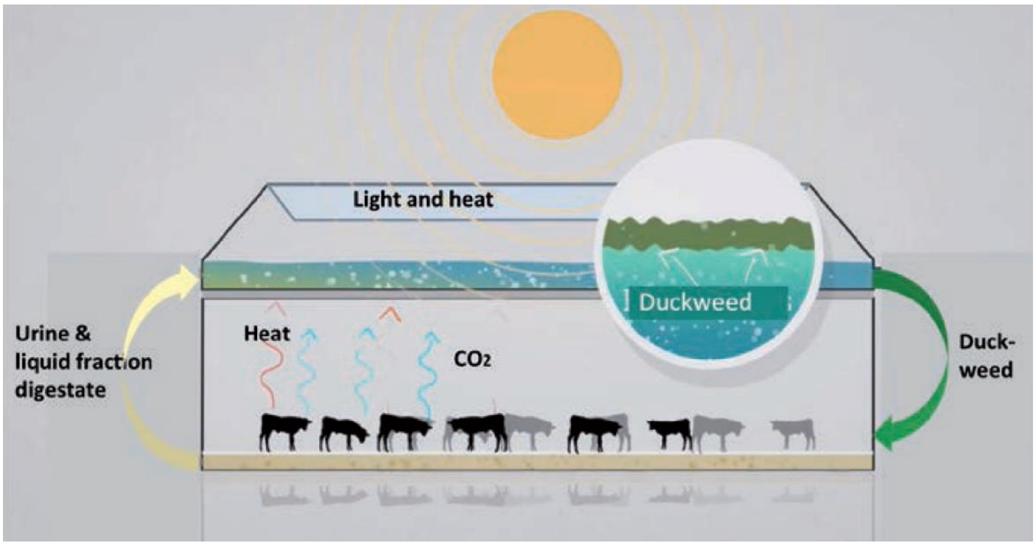

Figure 1 - Overview of an ECOFERM! farm (de Wilt et al., 2016)

The ECOFERM! principle was applied on a farm in Uddel. However, the production of duckweed turned out to be too expensive and labour intensive for the extra value it created. So, the farm stopped the production of duckweed as a protein source for the calves since it was not profitable.

Feeding fresh duckweed to calves is not a perfect feedstock and has some disadvantages. Feed intake decreases when fresh duckweed with a high water content is fed (Hoving, Holshof, & Timmerman, 2012). It is also difficult to match the calves' feed requirement to the fresh duckweed supply. These factors limit the value of fresh duckweed for calves.

To increase the value of duckweed, van Marrewijk (2017) suggested feeding fresh duckweed to pigs. Pigs have less strict feed requirements than claves which make it is easier to meet supply and demand. Another advantage is that duckweed could replace 50% of soy in the current pig feed composition (Le thi Men, Chinh, & Preston, 1997). However, feeding duckweed to pigs has some major drawbacks as well. Duckweed has a phosphor content which is too high to be feasible for pig feed (van Marrewijk, 2017). Duckweed is moderately digestible for pigs, in this way protein is not used to its maximum potential. Ruminants, like cows, are more effective in isolating duckweed protein. Rumen bacteria ensure the protein is released and available for uptake in the intestines. In short, fresh duckweed as a feed source has drawbacks for both calves and pigs.

Another alternative to increase the value of duckweed is to refine it in a biorefinery. Duckweed has a promising chemical composition but is inefficiently used when fed to cattle directly (de Wilt et al., 2016). Processing of duckweed in a biorefinery can solve this problem by trying to maximize the use of all chemical compounds like protein, fibre and minerals. High priced and high-quality products can be produced to make the cultivation of duckweed pay off, creating more value on ECOFERM!.

Grass is already used in biorefineries. The Grassa! project focused on adding value to plant flows by means of biorefinery, producing a high-quality protein product and a fibre product. It turned out that grass could be economically attractive as a feedstock in a biorefinery (Honkoop & Aarts, 2015). Grass has some analogies with duckweed. The big difference is that duckweed contains less dry matter, but a higher amount of protein per dry weight (de Wilt et al., 2016).

Within Grassa!, protein was separated out of the grass using a screw-press, creating two fractions: a juicy fraction containing 65% of the total protein content and a fibre fraction with 35% of the total protein content (Bongen, 2014).

Another way of extracting protein is with alkaline extraction, an integrated biorefinery was designed by Zhang (2016). Alkaline extraction disrupts the cell walls and at the same time extracts protein. The duckweed must be separated in two fractions after this extraction step. This technique is very promising since a high protein yield and recovery can be obtained in an economic way (Zhang, Sanders, & Bruins, 2014).

Regarding the results from Grassa! and Zhang the major challenge is to develop a protein refinery which can be successfully applied within ECOFERM!. Therefore, the biorefinery for ECOFERM! has to process duckweed, in a way the most profitable compounds can be isolated and used to its highest potential. Also, by-streams have to be used in a smart way, which contributes to more added value with minimal impact on the environment. Manure produced by calves is processed on the farm, reusing minerals and reducing mineral emission. In short, the preferred situation is a biorefinery for duckweed that makes the ECOFERM! principle lucrative while using a closed cycle.

1.2 Research questions

The main research question:

How to refine duckweed in sustainable products with added value for ECOFERM!?

Sub questions:

1. *Which refining techniques can be used to refine duckweed, in order to produce valuable and sustainable products?*
2. *What is the most suitable (with respect to financial and environmental aspects) biorefinery for ECOFERM!?*
3. *What process steps in the designed process are the most relevant for the proof of concept?*

1.3 Approach

The starting point of this thesis is to design, simulate and identify bottlenecks for a biorefinery on an ECOFERM! farm. The main goal is to design a small-scale refinery for duckweed which closes the cycle. If a closed cycle is not possible a semi-closed cycle with minimized transportation is also an option. The designed biorefinery can use the opportunities of ECOFERM!. Like, the mono-digester, the cogeneration and the possibility to feed a waste stream back to the calves. It broadens the possibilities in the designing process.

The knowledge found in the literature is used to design a refinery process. Different scenarios of the most promising processes are created since at this stage it is not clear which process performs the best. These different processes are modelled using Excel to quantify the performance of each process. The financial aspect and the yield of different components are evaluated. The costs of the new machines, energy, fuel and chemical consumption are important for the economic analysis and will be included. However, the labour costs are not concerned and will be excluded. Since the extra labour needed to operate the biorefinery is part of the operational management of the farmer.

Final research question will point out what processes are most relevant to the proof of concept but does not concern the practical execution of the proof of concept. What processes have the highest potential to be further optimised or the highest chance to be wrong, is also discussed in this chapter. This sub question will give insight in how the designed processes should be tested, to prove if the process also works in practice.

2. Process description

This chapter gives an overview of the possible refinery techniques for duckweed. Duckweed can be refined in two different fundamental methods. Within these methods, the process steps are fixed but how the process step is executed differs and is a design choice. This choice depends on different aspects like costs, profit, quality of the end product and the extent to which the output product is suitable for further processing in the system. The designed processes have to fit within the existing structure of ECOFERM!. Therefore, some variations on the process are better but not suitable for ECOFERM!. Each individual process step has to be optimised, but also the process chain as a whole (Gool & Bitter, 2015). The final design can be one of these fundamental processes or a combination.

System 1 is a system in which the processing route of grass is applied on duckweed. System 2 is a system based on alkaline extraction with green tea residues as a model crop. Each system is first described in a general scheme. Each process step is described individually and an overall scheme with all the suitable process steps for ECOFERM! is presented in Appendix A. These schemes are a guideline for the modelling in the next chapter.

Process 1: System for duckweed based on grass processing

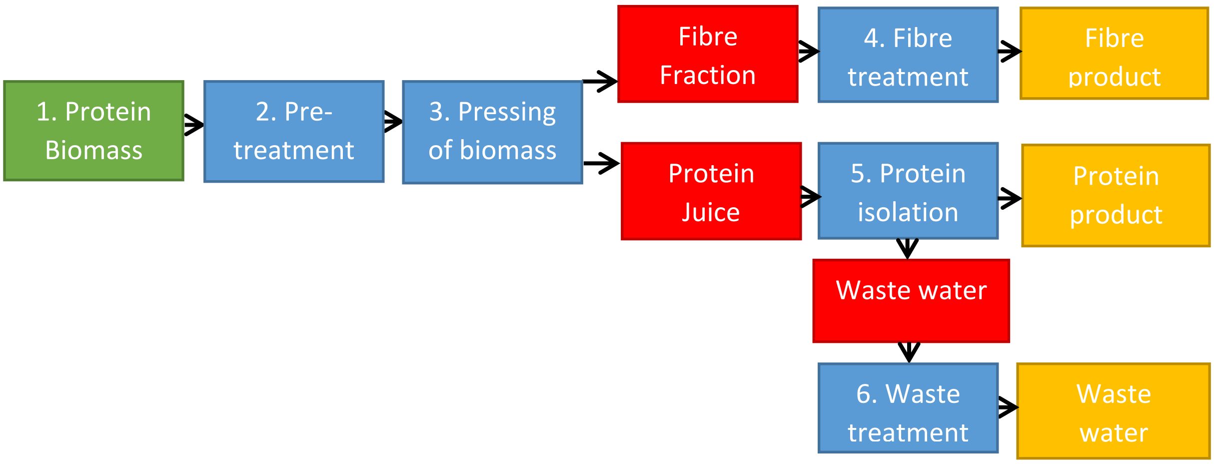

Figure 2 - General scheme based on green refinery

The general scheme of a green biorefinery has been displayed in Figure 2. Protein is the main valorising component extracted from grass. The extracted protein can be used for food and feed purposes. Food purposes are possible, but are regulated strictly and should be produced under very clean circumstances. Therefore, the focus will be on feed applications, which is better suitable for the small-scale refinery on ECOFERM!.

2.1.1 Protein Biomass

In 2015 ECOFERM! yielded a total of 14500 kg fresh duckweed, with a dry matter content of 5.4%. Duckweed grows slowly during the winter months, it is assumed that all the production is realised and processed in 6 (summer) months. This means that in the duckweed season the installation should be able to process around 80-kilogram fresh weight (FW) of duckweed a day.

A model requirement is that the maximum capacity per batch should be adaptable independently from the size of the input stream. There are many situations in which the capacity of the process should be larger than the amount of duckweed processed by the installation. By implementing this requirement the process can handle, for example, seasonal fluctuation, change in growing conditions or the choice to skip the processing on Sundays.

In Table 1 the start composition of 1000 kg just harvested duckweed is presented. The data is taken from the final report of ECOFERM! (de Wilt et al., 2016). Combined with data taken from (Landolt & Kandeler, 1987) a feed composition is derived.

The protein content of duckweed depends on the nutrient content of the water and the prevailing climatic conditions (Leng et al., 1995). A high protein content with a high yield is most favourable as a biomass source. A high carbohydrate content is less important since the carbohydrates only have a dietary value and are not used in this process. The carbohydrates can become valuable, when integrated with other processes, such as fermenting.

Table 1 - Start composition of 1000 kilogram fresh duckweed based on (de Wilt et al., 2016) and (Landolt & Kandeler, 1987)

Duckweed		Weight (kg)	Weight (kg)
Total weight		1000	
Liquid		945.6	
Dry matter		54.3	
	Crude protein		24.7
	Crude fibre		6.0
	Crude ash		7.4
	Crude fat		2.9
	Total Carbohydrates		12.2
	Polyphenol		1.1

2.1.2 Pretreatment

Duckweed would require little or no mechanical pretreatment since it has a green, hydrated biomass and a small size (Cheng & Stomp, 2009). Grass, on the other hand, must be severely pretreated since in its original form the material is too big, firm and rigid. Grass is pretreated by fiberizing it between two grinding plates, which meshes up the grass and opens up the cells. As a result, a major part of the proteins is made accessible for pressing. Fiberizing is a process with a high-energy demand (O'Keeffe, Schulte, Sanders, & Struik, 2011). Eliminating such severe and energy consuming grinding step can save substantial amounts of energy and is preferred for duckweed. Blade milling or directly press duckweed can serve as options, both can save energy and costs.

What exact pretreatment is best for duckweed is not known, since there is no public knowledge about this subject. In the model, the assumption is made that the pretreatment does not affect further process steps. The best pretreatment for duckweed processing should be further examined.

2.1.3 Pressing

Pressing is used to separate duckweed into two fractions, a fibre fraction and a juice fraction containing the proteins. Pressing can be executed once or twice. Pressing twice is common for grass or grass silage. The first pressing separates the two fractions. The second pressing only presses the press cake to ensure that a major part of the protein is in the liquid fraction.

In a batch process, a single screw-press can be used to perform both pressings. On ECOFERM! batch processing of duckweed is more logic than continuous processing, because of the small scale.

The fractionation percentage is used to determine what amount of duckweed entering the system ends up in the liquid fraction and what amount ends up in the fibre fraction. O'Keeffe et al. (2011) states for grass that 30 to 50 percent of the weight ends up in the cake fraction, while 50 to 70 percent ends up in the press juice. In other words, if the fractionation percentage of grass cake is 30 percent, one kilogram of grass results in 0.3 kilograms of cake and 0.7 kilograms of juice. It is assumed that duckweed has a different fractionation percentage since duckweed contains more water which will result in a bigger juice fraction. Therefore, a ratio of 0.3:0.7 is taken as the upper limit of the fractionation percentage for duckweed. The exact fractionation ration is unknown, therefore it should be adaptable in the model.

The chemical composition of duckweed press cake and centrifuged press juice is known. These data are obtained by contacting ABC Kroos. The most important data is presented in Table 2 and Table 3. The crude protein content of the juice is higher than the crude protein content in the cake.

Table 2 - The chemical compositions of press cake by ABC Kroos

Press cake	g/kg	g/kg
Liquid	891	
Dry matter	109	
	Crude protein	25
	Crude fibre	21
	Crude ash	19
	Crude fat	3
	Total Carbohydrates	40.7
	Polyphenol	0.3

Table 3 - The composition of centrifuged press juice by ABC Kroos

Press Juice	g/kg	g/kg
Liquid	907	
Dry matter	93	
	Crude protein	69
	Crude fibre	0
	Crude ash	7.7
	Crude fat	7.7
	Total Carbohydrates	7.8
	Polyphenol	0.8

2.1.4 Fibre treatment

This fraction contains the major part of fibres. The chemical composition of press cake is comparable with the chemical composition of brewer's grains and can be used as a feed source. Fibres can be further processed using alkaline extraction, to extract even more protein. However, the fibre or cake flow is relatively small, so the investment costs for this operation are likely too high to be feasible.

Grass fibres are used in industrial applications as insulation material, which can only be profitable if there is an assumed high value and high volume (O'Keeffe, 2010). Therefore, the small-scale production of insulation material is inadvisable since a high volume cannot be achieved. The fibres are also used as packaging material in the paper industry. However, this application is expensive. The production of packaging material in this way is difficult and can only be profitable with a high volume (Bongen, 2014). Fibre fraction can also be transported to be processed elsewhere, but this does not result in a closed cycle, which is preferred in ECOFERM!.

Co-digestion in the biogas plant is possible but not attractive since the value of the fibres as a feed source is higher than the value of biogas. Using the press cake as feed is the easiest and promising option.

2.1.5 Fibre product

The fibre fraction is good digestible for calves. It was hypothesized that pressing duckweed increases digestibility of the cake (Bongen, 2014). Cake fraction of duckweed still contains 15 percent of the initial protein content in duckweed which is 22 percent per dry matter cake. A calf is better suited than a pig to extract protein out of this green biomass. The fibres improve the stability of a calves' rumen (de Wilt et al., 2016) while pigs cannot use these fibres at all.

2.1.6 Protein isolation

The isolation of the protein fraction is executed in three steps of which the centrifuge step is optional. First, the protein juice is centrifuged or not, then coagulated, after this step the proteins are separated. At the end of this step, the waste water and final product are yielded.

Centrifuge

In the model, an option to use a centrifuge is implemented, the main goal of the centrifuge is to remove water out of the protein juice, to make the heating step of heat precipitation cheaper. Since less water is heated. A drawback of a centrifuge is the high investment costs. To be applicable in this situation, centrifugation must save a great amount of energy in the following steps.

Coagulation

Press juice is coagulated using heat, acid or a combination. Acid precipitation is a method in which a low amount of energy is consumed and a high protein recovery can be achieved (Zhang, 2016). However, it is not an ideal option, since the waste water and the protein product should be neutralized. Otherwise, the waste and end products are not useful for ECOFERM!.

The pH of the waste water is too low to have directly function. The waste water cannot be directly fed into the duckweed pond since the optimal pH is 6.2 (Top, 2014).

Heat precipitation is the most suitable and applied option for this process. Proteins coagulate, are separated and the protein feed is yielded (Sanders, Liere, & de Wilt, 2016). The protein feed can be made rumen resistant, in this way the proteins are better digestible for calves, increasing the value (Bongen, 2014). Other contents of the grass protein juice, like cellulose, cell membranes and chlorophyll, will also coagulate (Paping, van de Ven, & Wohl, 2014). This product cannot be used as food protein, because of these impurities. Clearing those impurities is costly and better suitable for an industrial application.

Heat coagulation can be executed with a combination of a heat exchanger and superheated steam. The juice is preheated to 45 ^{o}C and then injected with super-heated steam to increase the temperature of the juice to 75-85 ^{o}C (Kamm, Hille, Schönicke, & Dautzenberg, 2010). Steam heating has a big advantage over normal heating to 85 ^{o}C, the steam bubbles lead to larger agglomerates that will push the protein clot to the juice's surface (Kamm et al., 2010). This makes it easier to process in the next step. An option to change between steam heating and no steam heating should be implemented in the model to see the effect on the energy usage and investment cost. Information about the coagulation with normal heating is unknown, so the same characteristics as for steam heating are used.

2.1.7 Separation

The wet protein is floating on top of the juice, therefore skimming is an energy efficient and effective option (Kamm, Schönicke, & Kamm, 2009). It is easy applicable at small scale and in batch operations, ideal for ECOFERM!.

Filtration has the same advantages; however, skimming seems a more logical alternative since the coagulant is already floating on top of the press juice.

In the industry, decanter centrifugation is the most commonly used method to separate juice and clot. A centrifuge can process large amounts of product continuously. This is not necessary for ECOFERM! since small batches are processed every day. A decanter centrifuge is expensive, uses a lot of energy compared to skimming and is not the best option for this situation.

2.1.8 Protein product

The obtained protein product is suitable for feed applications in monogastric diets. While the press cake, as mentioned earlier, is still valuable as feed for ruminants like calves. Pigs are not efficient in taking up protein out of fresh duckweed. In the protein product, the proteins are better available for pig uptake. The phosphor content of this feed is also minimal since most phosphor ends up in the juice fraction. In this way, pig manure is less emissive, which increases the value.

As stated in chapter 1, duckweed is not an optimal feed source for both pigs and cows. By splitting duckweed into two fractions, both products can be fed in a far more optimal way. The cake and protein feed both increase in value.

For an industrial application, the coagulated protein should be dried. Without drying the feed will spoil quicker and transportation costs are higher. Transportation costs are not a concern in ECOFERM!, the protein product can be sold in the region and the product stream is small resulting in minimal transportation costs. The protein product is such a small flow that the feed can be fed immediately to the pigs. This will save a substantial amount of money since drying is an energy consuming operation (O'Keeffe, 2010).

2.1.9 Waste water treatment

Waste water after separation of protein, contains the major part of carbohydrates, phosphate, potassium, protein residues, amino and organic acid (Sanders et al., 2016). A process to precipitate phosphate is a possibility. The phosphate in this wastewater can precipitate by adding chemicals. Phosphate is then isolated and sold as a fertilizer. These steps are expensive and not necessary since the waste water can be processed directly on site.

In the waste water stream, there is a low amount of dry matter. If used in a digester or fermenter it should be filtered first. This will yield a minimum amount of dry matter and would not significantly contribute to extra biogas or bio ethanol production, only leading to extra costs.

2.1.10 Waste water

This waste stream can be used as a fertilizer on the land or as a substrate to grow duckweed on. Duckweed is able to grow under conditions with high amount of nutrients. Duckweed is also excellent in removing those nutrients, accumulation of nutrients in the pond is therefore not a concern. In this way, all the nutrients can be recycled or processed on site by using a closed cycle. After coagulation, the waste water still contains a lot of heat since it is heated to 85 ^{o}C. Since a small amount of duckweed processed in a batch process, the hot waste water cannot be used to preheat the protein juice. The water can be directly spread on the land but the temperature is too high to be fed into the duckweed pond directly and should cool down first to 25 ^{o}C.

Process 2: System for duckweed based on green tea residues processing

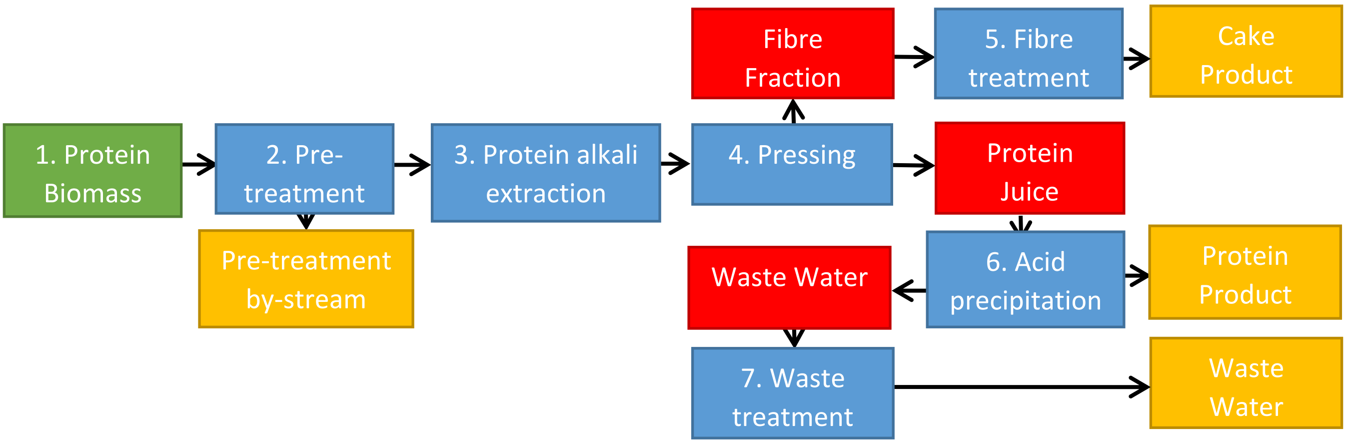

Figure 3 - General scheme based on alkaline extraction of green tea residues

Figure 3 represents a process based on alkaline extraction, which is a promising technique for green biomass sources since a high protein yield and recovery can be obtained in an economically feasible way (Zhang, Sanders, et al., 2014). Therefore, this process is modelled as an alternative for process 1. Zhang designed an integrated biorefinery using this alkaline extraction technique for green tea residues (GTR). It was stated that alkaline treatment can be universally applied on other leaf species like duckweed. However, very limited information about this extraction technique is known for other biomass sources and the technique was only tested on lab scale for GTR. Since there is little knowledge on the alkaline extraction of duckweed, a lot of assumptions must be made. The assumptions made are based on the study Zhang (2016) performed.

2.2.1 Protein biomass

GTR is a waste stream of the tea lemonade production. A water extraction is performed on fresh tea leaves to extract tea. After this, the GTR is sun-dried, ground into powder and then burned. However, GTR has a high protein and carbohydrate content (see Table 4) and a lot more value can be generated when these components are extracted and used for: feed, food and chemicals.

Duckweed and GTR have a significantly different composition which has an influence on the pretreatment steps needed to effectively refine these types of biomass. The biggest difference is in dry matter and liquid content. Duckweed has a dry matter content of 5.4 percent while GTR has a dry matter content of 93.2 percent.

Table 4. Chemical composition of green tea residues Zhang (2016)

Press cake	Fresh Weight (kg)	Dry matter weight (kg)
Liquid	68	
Dry matter	932	
	Crude protein	248
	Crude fibre	231
	Crude ash	41
	Crude fat	18
	Total Carbohydrates	316
	Polyphenol	78

2.2.2 Pretreatment

GTR is severely pretreated to reduce the amount of alkali used, increase the purity and reduce amino acid degradation. The pretreatments needed to process GTR are first explained, then the differences with duckweed are pointed out.

GTR pretreatment

GTR is pretreated to remove buffering components, such as pectin and polyphenols. When these components are not removed, extra alkali will be consumed and the protein extraction will be costly and yield less protein. The extraction of buffering components for GTR can be effectively done in a two-step chemical extraction.

The first step is an ethanol pretreatment were pigments and polyphenols are removed. The pretreated solid fraction has to be separated from the ethanol fraction containing the polyphenols. This solution is distilled or frozen to recover the ethanol and separate the polyphenols. These polyphenols are food grade and can be used as an anti-oxidant in food (Zhang, van Krimpen, Sanders, & Bruins, 2016a). A drawback of an ethanol pretreatment is that it is costly since ethanol is flammable therefore extra safety measures are necessary.

In GTR, pectin is extracted with a Viscozyme® L treatment. Viscozyme® L degrades cell wall carbohydrates, like pectin, hemi-cellulose and cellulose. In this process, protein extraction yield is enhanced, while removing carbohydrates (Zhang et al., 2016a). This is done by hydrolysis of pectin by Viscozyme® L into galacturonic acid (GA). After pectin extraction with Viscozyme® L, the solid fraction containing the protein has to be separated from the liquid fraction containing GA, glucose and remaining part of polyphenols. The liquid fraction is transported to a factory for further processing since it contains components which are valuable as bulk chemicals (Su, Qiu, Kong, Mi, & Han, 2015).

Difference in pretreatments for duckweed

Pectin and polyphenols are extracted in GTR to improve the process by removing buffering components and creating extra value by transporting the waste streams to factories. The extra costs of the treatments are compensated by the higher product yield and the value of these waste streams. However, the same is not the case for duckweed. Duckweed contains 70 times less polyphenol and 25 times fewer carbohydrates (see Table 1 and Table 4). As a result, pretreating duckweed with the same pretreatments as for GTR will create by-streams without value. Therefore, GTR pretreatments are left out in the final design, which completely simplifies the process and makes it better compatible for ECOFERM!

It is not known how these pretreatments influence the protein yield and the quality of the end product in duckweed. But it is assumed that the effect on the end product will be limited since there is a low amount of pectin and polyphenol in duckweed. It is hypnotised that pretreating duckweed with the same pretreatments as GTR does not improve the protein extraction and will create very limited extra value with the by-streams. Two extra process steps, more consumables and extra equipment is needed, leading to extra costs. Those extensive pretreatments are not suitable for duckweed or for small scale operation such as ECOFERM!. Therefore, in this designed process GTR pretreatments are left out and not modelled for duckweed.

2.2.3 Protein alkali extraction

Without needing a pretreatment, the alkaline extraction itself becomes the first treatment. Alkaline extraction can be considered an effective pretreatment since it simultaneously disrupts the cell wall and extracts protein (Zhang, Bruins, & Sanders, 2014). Therefore, a mechanical pretreatment is not necessary anymore.

Fresh duckweed is directly added to a reaction vessel. In the reaction vessel, the pH is raised to a range from 12.3 to 13.5 with a temperature ranging from 70 to 150 ^oC (Zhang, Bruins, et al., 2014). For GTR the reaction conditions were optimised at a pH of 13, with a temperature of 95 ^oC. The duckweed was mixed and extracted for four hours (Zhang, Sanders, Xiao, & Bruins, 2015). To reach a pH of 13, NaOH was used. A drawback of NaOH is that it generates large amounts of sodium salts, which cannot be effectively recycled, resulting in a less sustainable process (Zhang, 2016).

Potassium hydroxide can be used as an alternative for NaOH. KOH can extract over 90% protein and can be readily integrated with the processes designed for NaOH protein extraction (Zhang, 2016). After protein extraction with KOH, the residual water containing potassium salts may be used as K-fertilizer for duckweed production (Hasler, Bröring, Omta, & Olfs, 2015), making the process more sustainable and to create added value for ECOFERM!. In this way, the extra costs for the higher price of KOH are compensated while creating a more sustainable process (Zhang, 2016).

According to the patent of Zhang, Bruins, et al. (2014) for biomass with a very high moisture content, like duckweed, exceeding a liquid fraction with a mass of 0.8, a solid alkaline compound can be used without addition of water.

The extraction is performed at a pH of 13, most information is known about this pH so it is taken as standard value in the model. Protein can also be extracted at lower pH, lower temperatures and shorter extraction times (F. Farnoosh, personal communication, June 19, 2017). The protein extraction in Zhang's project was performed under extreme conditions and not tested under milder conditions.

Under milder pH conditions (pH around 10) fewer proteins are extracted, however, it can save a substantial amount of alkali. Fewer salts are formed which cannot be effectively used in the process. Also, less HCL is needed to neutralize the cake fraction and waste streams. These factors make it possible that a lower protein yield caused by a lower pH can pay off since the usage of consumables will drop drastically. If the pH changes from 13 to 12, the total costs and consumables needed will decrease by factor ten. A decrease from pH 13 to pH 10 will lead to a decrease in consumable usage and costs by a factor of three hundred. To give an indication, 1 kilogram of NaOH is needed to reach pH 13 in 211 kilograms of duckweed.

The pH at which the extraction is performed must be optimised in the total process. In a way that the costs of consumables are balanced with the yield of the protein and fibre product. In the model, there is an option to change the pH to lower values, with a minimum of pH 10. This option only gives an indication of the alkali usage and costs. The extraction efficiency does not decrease when the pH decreases since no data is available.

Also, the extraction temperature and extraction time should be optimised for the total process. Lower temperatures will influence the amount of protein extracted, energy used and investments needed. For the process designed by Zhang, the duckweed must be heated to 95 ^oC for 4 hours. Extract for so long at this temperature is a drawback of the system. Because the heating contributes up to 85 percent of the total energy used in the process.

In ECOFERM! it is possible to use waste heat of the cogeneration to preheat the substance to 45 ^oC with a heat exchanger or a coil. The extra heating to 95 ^oC is done with a heating tank. If the extraction can be performed at temperatures below 45 ^oC, this heating tank is not necessary and a simple heat exchanger can heat up the solution out of waste heat. If this extraction is performed at room temperature, even a heat exchanger is unnecessary. Which saves extra investment costs.

An option to change the temperature in the model should be implemented to see the effect on the costs. To see the effect of the heat exchanger on the cost and energy used a "No heat exchanger" design is should also be modelled. In which no heat exchanger is used to preheat the water, the water must be heated with a heating tank from the start to its desired temperature.

2.2.4 Pressing

The cake and the extractant should be separated after extraction. Pressing once or twice is used as separation technique in the model. Some data about the pressing of duckweed is known, see Table 2 and Table 3, while data of other separation techniques like filtration, centrifugation and settling are unknown. Pressing is chosen since it will give the most reliable model with the information available.

2.2.5 Fibre treatment

The cake is most efficiently processed by means of pH adaptation for applications as cow feed. Neutralizing the pH for feed applications is a simple operation, with just one process step. HCL is added to the fibre fraction to realise a pH around 7. As mention in process 1, co-digesting and fermenting are less optimal, since the value of the products created by those processes are lower than the value of calve feed. No information about the value as a calves feed of alkaline extracted duckweed cake is known. The value of this cake should be determined using a comparable feed source.

2.2.6 Acid precipitation

The proteins in the protein juice can be isolated by means of acid precipitation. The pH is lowered with the addition of HCL to a pH in a range of 3.5 to 4 at a temperature of 4 °C (Zhang, van Krimpen, Sanders, & Bruins, 2016b) (Zhang, Bruins, et al., 2014). The substance with a lowered pH is put in a refrigerator, these conditions were kept the same overnight. It is possible that the usage of a refrigerator is only a lab method not adapted to a semi industrial application. In the proof of concept, it should be tested if the usage of a refrigerator can be left out. This simplifies the process by eliminating waiting times, saves investment costs and energy.

At these conditions, the protein precipitates and is then easily separable by means of filtration, centrifugation, settling or skimming. 85% of these proteins can be recovered by acid precipitation (Zhang, 2016).

Skimming is the easiest and best applicable for the small-scale operation in ECOFERM!, other operations have greater advantages when the scale increases.

2.2.7 Protein product

The protein product has a pH which is too low for cow consumption, the rumen of a cow operates at a pH of 6 to 7 (Webster, 2017). To be applicable for cows the protein product must be neutralized, which is an extra process step. For pigs, a pH of around 4 is normal (personal communication, H. Hellegers, July 8, 2017). No extra neutralizing step should be executed. The feed can be directly fed which is an advantage over feeding it to cows.

2.2.8 Waste water treatment

A simple waste water treatment is needed for the processing on ECOFERM!. The waste water has a pH of 3.5 which is too low to be fed directly into the duckweed pond, since the ideal pH is around 6.2 (van den Top, 2014). Waste water should be neutralized by raising the pH with the addition of NaOH.

2.2.9 Waste water

The waste water is cooled down to 4°C in the acid precipitation step, which can be used as an advantage. The temperature of the pond can reach temperatures up to 40 °C in the summer months, so adding cold water positively influence the temperature. Since the pond temperature should be around 25^oC (van den Top, 2014). The cold waste water can be used as a control mechanism to maintain the right pond temperature. The waste water also contains sodium or potassium salts depending on the alkali used. It is not yet clear how duckweed reacts on the higher concentrations of salt. However, the waste water stream is very small compared to the pond volume, so the effect of those extra salts are in this stage neglected.

3. Model

The chapter is divided in three parts. The first part discusses the expressions used to determine the chemical composition of protein product, cake fraction and waste water stream. The second part calculates the income generated out of the cake and protein product. The third part is about the energy used and the costs involved in the process. A complete overview of all the expressions used in the model including a nomenclature of all the symbols used can be found in Appendix C and D.

3.1 Chemical composition of products and waste streams

3.1.1 Process 1: System for duckweed based on grass processing

Start

$$Fin,i = Fin * Cin,i \qquad for\ each\ component\ of\ i \qquad [kg] \qquad (1.1)$$

Equation 1.1 represents the start composition of duckweed. Fin is the amount of duckweed processed per batch. Cin,i is start concentration of different components i, respectively: crude protein (CP), fat (Fa), fibre (Fi), ash (Ash), total carbohydrates (TC), polyphenol (PP), water ($water$) and dry matter content (DM). The dry matter in this model is composed out of components j: crude protein, fat, fibre, ash, total carbohydrates and polyphenol. Fin,i is the weight of each component in the start composition.

Press cake

$$Fpc1,i = Fin * \frac{FraFibre}{100} * \frac{Cpress,i}{1000} \qquad for\ each\ component\ of\ i \qquad [kg] \qquad (1.2)$$

$Fpc1,i$ represents the weight of the chemical component in the press cake of duckweed. $Cpress,i$ is the concentration of the press cake for the different components i in g/kg. Information about the chemical composition of the press cake and press juice were received from ABC Kroos. $FraFibre$ is the fractionation percentage. It has a great influence on the amount and chemical composition of the fibre and juice fraction. Duckweed contains more water and less fibre compared to grass, a fractionation percentage in the range of 15-20 percent is most likely.

$$Fpc1,DM,j = Fpc2,DM,j = Fpc\#,DM,j \qquad for\ each\ dry\ matter\ component\ of\ j \qquad [kg] \qquad (1.3)$$

The press cake can be pressed twice, for both pressings 100 percent recovery of the components is assumed. This assumption results in a second pressing that only removes water. Using this assumption Equation 1.3 holds. The weight of the press cake fraction is denoted with pc. DM,j is the total dry matter content of the dry matter components j in the press cake, $1\ or\ 2$ represents if the duckweed is pressed once or twice. # is a placeholder to indicate that the substance is pressed, either once or twice.

$$Fpc2,water = Fin * \frac{FraFibre}{100} * \frac{Fpc1,DM}{1000} * \frac{Cpress2,water}{1000 - Cpress2,water} \qquad [kg] \qquad (1.4)$$

To calculate the water content after the second pressing Equation 1.4 is used.

$Cpress2,water$ is the liquid content of the press cake, this is an adaptable factor for in the model. Ranging from 890 g/kg to 750 g/kg. The upper value of 890 was taken from the ABC Kroos data on pressing, in conversation with my supervisor 750 g/kg water was taken as lower limit (T. van Boxtel, personal communication). The extra water which is pressed out when the value is smaller than 890 g/kg will be added to the protein juice, to make sure the protein is in solution.

Press juice

$$Fin,DM,j - Fpc,DM,j = Fj,DM,j \qquad for\ each\ dry\ matter\ component\ of\ j \qquad [kg] \qquad (1.5)$$

$$Fj,DM,j = Fjuice,DM,j \qquad for\ each\ dry\ matter\ component\ of\ j \qquad [kg] \qquad (1.6)$$

The chemical composition of the dry matter components in the juice can be determined by Equation 1.5. Fin, DM, j is the dry matter weight of the inflow and Fj, DM, j is the dry matter in the juice.

ABC Kroos used a centrifugation step to lower the amount of water in the juice, it is assumed that only water was centrifuged. More details about the calculations of centrifugation are presented in Appendix D.

Coagulation

$$Fraction,k = \frac{Grassjuice,k}{Product,k} \qquad k\ for\ water,fibre,protein,ash \qquad [-] \qquad (1.7)$$

It is assumed that the coagulation of duckweed protein behaves in a similar way as the coagulation of grass protein. In Equation 1.7 the data from (O'Keeffe et al., 2011) is used to calculate the fractions ($Fraction, k$) ending up in the protein product. $Grassjuice, k$ is the amount of each component in the press juice, while $Product, k$ is the amount which finally ends up in the product. O'Keeffe however did not supply any good data on the total carbohydrate, fats or polyphenols ending up in the protein product. Therefore, the fraction of these components is assumed to be 0.05.

$$Fjuice,i * Fraction,i = Fproduct,i \qquad i\ for\ each\ component \qquad [kg] \qquad (1.8)$$

With these fractions, the amount of a specific component can be calculated, Equation 1.8. The sum of the dry matter components results in the total dry matter in the product.

Total

$$Fwaste,i = Fjuice,i - Fproduct,i \qquad for\ each\ component\ of\ i \qquad [kg] \qquad (1.9)$$

$$Fin,i = Fwaste,i + Fjuice,i + Fproduct,i \qquad [kg] \qquad (1.10)$$

With this method, the total chemical composition of the waste water can be calculated with a simple computation, Equation 1.9. Using the model, the chemical composition of all the produced streams can be calculated, see Equation 1.10.

3.2.1 Process 2: System for duckweed based on GTR processing

Extraction

$$Ex,CP = Fin,CP * \frac{PY}{1000} \qquad [kg] \qquad (2.1)$$

$$Ex,DM = \frac{Ex,CP * 1000}{purity} \qquad [kg] \qquad (2.2)$$

The start composition is the same as the start composition in Equation 1.1. The protein yield (PY) of alkaline treatment on GTR is known and is set as a changeable factor in the model. As for duckweed, the protein yield is not known. The range in which this factor can be changed is based on GTR. The protein yield is used to calculated Ex, CP the extracted protein out of the starting material.

The purity with this treatment is also known for GTR, but not for duckweed. Therefore, this is also a changeable factor within a range based on GTR. With purity, the total dry matter content of the extractant is calculated, using Equation 2.2.

$$Ex,i = (Ex,DM - Ex,CP) * \frac{Fin,i}{\sum Fin,i} \qquad i\ for\ TC,PP,Fa,Fi,Ash \qquad [kg] \qquad (2.3)$$

$$NEx,j = Fin,j - Ex,j \qquad j\ for\ CP,TC,PP,Fa,Fi,Ash,DM \qquad [kg] \qquad (2.4)$$

An estimate of all the individual components in the extractant and cake is important to be able to estimate the price of the created products. Therefore, fractions are used to determine the amount of each individual component in the juice and cake. With those fractions, the weight of each individual component is calculated by Equation 2.3. With this data, the chemical composition of the not extracted substance NEx,j in Equation 2.4 is calculated.

Pressing

$$NEx,j = FFibre\#,j \qquad \#\ is\ the\ number\ of\ pressings\ 1\ or\ 2 \qquad j\ for\ CP,CT,PP,Fa,Fi,Ash,DM \qquad [kg] \qquad (2.5)$$

$$Ex,j = FJuice\#,j \qquad \#\ is\ the\ number\ of\ pressings\ 1\ or\ 2 \qquad j\ for\ CP,CT,PP,Fa,Fi,Ash,DM \qquad [kg] \qquad (2.6)$$

Pressing has only influence on the amount of water in $FFibre\#,water$. Therefore, it has also influence on $FJuice\#,water$.

$$FFibre\#,water = FFibre\#,DM * \frac{Cpress\#,water}{1000 - Cpress\#,water} \qquad \#\ is\ the\ number\ of\ pressings\ 1\ or\ 2 \qquad [kg] \qquad (2.7)$$

In Equation 2.7 the same method as in equation 1.4 is used to calculate the amount of water in the fibre $FFibre\#,water$. A ratio between water content and dry matter content after pressing is used to transform in $FFibre\#,DM$.

$$FFibre\# = FFibre\#,DM + FFibre\#,water \qquad [kg] \qquad (2.8)$$

$$Fjuice,water = Fin,water - FFibre\#,water \qquad [kg] \qquad (2.9)$$

$$Fjuice = Fin - FFibre\# \qquad [kg] \qquad (2.10)$$

Using the water content in the fibre fraction the total fibre flow $FFibre\#$, the water content of the juice $Fjuice,water$ and total juice flow are calculated $Fjuice$, see Equation 2.8 to 2.10.

Mass balance acid precipitation

$$AFJuice,DM,i = FJuice,DM,i \qquad i\ for\ CT,CP,PP,Fa,Fi,Ash \qquad [kg] \qquad (2.11)$$

$$AFJuice\#,water = Juice\#,water + Formed,water \qquad [kg] \qquad (2.12)$$

The dry matter does not change when the acid is added. $AFJuice$ is the chemical composition of the protein juice after the acid precipitation is performed. The effect of the addition of NaOH and HCL and the formulas used can be found in Appendix D. When an acid-alkali reaction is performed extra water is formed which contributes to extra water in the juice.

Separate juice and waste water

$$End,CP = AFJuice,CP * \frac{Recovery}{100} \qquad [kg] \qquad (2.13)$$

$$EndPurity = purity + 180 \qquad [\frac{g}{kg\ DM}] \qquad (2.14)$$

$$End,DM = \frac{End,CP * 1000}{EndPurity} \qquad [kg] \qquad (2.15)$$

It was stated in (Zhang, 2016) that the acid precipitation had a $Recovery$ of 85 percent of the protein. In GTR the purity after acid precipitation increased with 180 $g/kg\ DM$, for duckweed the same increase in purity for the end product is used.

$$End,i = (End,DM - End,CP) * Fraction,i \qquad i\ for\ CT,PP,Fa,Fi,Ash \qquad [kg] \qquad (2.16)$$

$$WW,j = AFJuice,j - End,j \qquad j\ for\ CP,CT,PP,Fa,Fi,Ash,DM \qquad [kg] \qquad (2.17)$$

The method for calculating the exact chemical composition of the waste water is executed in Equation 2.17.

$$End,water = End,DM * (\frac{100 - \alpha DM}{\alpha DM}) \qquad [kg] \qquad (2.18)$$

The amount of water in the product after skimming was unknown, α in Equation 2.18 is the percentage of dry matter in the end product. It was set on 30 percent. This setting is not important for the rest of the model. The value of the product was determined by the amount of protein, not the amount of water in it. So, αDM gives only an indication in the size of the waste water stream.

$$Fin,i = WW,i + End,i + FFibre\#,i \qquad [kg] \qquad (2.19)$$

The total balance is presented in Equation 2.19.

3.2 Income

The chemical composition of comparable products is used to determine the income generated out of the fibre product and protein product. For the prices of the comparable products used, see Appendix B about the model data.

3.2.1 Fibre

$$PDM = \left(\frac{BGp}{10 * bg,DM}\right) * FFA \qquad [\frac{€}{kg\ DM}] \qquad (1.11)$$

The press cake of duckweed in process 1 has a comparable chemical composition as brewers grain. The price of brewers grain BGp in $€/ton$ is used as a reference to give an indication of the value of the fibres. In feed products, mainly the dry matter has value. The price of fresh brewer grains is known in euro per ton fresh weight ($€/ton\ FW$) This price must be transformed to $€/kg\ DM$ to be applicable for duckweed. This price transformation can be done with Equation 1.11. bg,DM is the dry matter percentage of the brewers grain.

The chemical composition of process 2 fibres are different than those of process 1. Therefore, the price per dry matter is compensated for this difference using factor FFA. The protein content of the process 2 fibres is twice as high as the protein content of process 1 fibres. However, the fibres in this fibre product are totally disrupted and are likely to have a lower value. Therefore, the value of FFA is estimated to be 1.5 in process 2 and 1 in process 1.

$$IC = \frac{Fpc,DM * PDM}{Fin} \qquad [\frac{€}{kg\ FW}] \qquad (1.12)$$

IC is the income created in € by the press cake per kilogram fresh duckweed.

3.2.2 Product

$$PCP = 100 * \frac{Sp}{DMsoy * CPsoy} \qquad [\frac{€}{kg\ CP}] \qquad (1.13)$$

Soy is used as a product to price the protein product produced in this biorefinery. It is assumed that only protein in soy creates value. In other words, the value of other components is neglected, protein is the primary valorizing component. In Equation 1.13, Sp is the price of soy in $€/ton$, $DMsoy$ is the percentage of dry matter and $CPsoy$ is the concentration of crude protein with a unit of $g/kg\ DM$. The price per fresh weight is transformed to price per kilogram protein which is used to determine the price of the protein product.

$$IP = \frac{PCP * Fproduct, CP}{Fin} \qquad [\frac{€}{kg\ FW}] \qquad (1.14)$$

$$ITotal = IP + IC \qquad [\frac{€}{kg\ FW}] \qquad (1.15)$$

$$IYear = Fin * ITotal\ or\ IRef * \frac{365}{2} \qquad [\frac{€}{year}] \qquad (1.16)$$

IP is the income created in € by the protein product per kilogram duckweed. Together with the IC it generates the total income of the biorefinery independent from the amount of duckweed processed. For the yearly income, it is assumed that during half a year all the duckweed is processed and that a batch (Fin) with the same size is processed each day. The yearly income is mainly to give an indication and to compare the yearly income with the yearly costs, discussed later in this chapter.

3.2.3 Reference income

$$IRef = \frac{Fin}{Fin, DM} * DWp \qquad [\frac{€}{kg\ FW}] \qquad (1.17)$$

As a reference to test the income from refining duckweed using one of the systems, the value of duckweed as a feed source for calves is used. The price was determined by de (de Wilt et al., 2016). Duckweed as a direct feed source for calves has a value of 0.25 euro per kilogram dry matter (DWp). With this data the income per kg fresh duckweed is calculated, by using Equation 1.17. The $IRef$ is important to put $ITotal$ into perspective.

3.3 Costs

In each system, design dependent costs are involved which are different for both systems. Data about the costs used can be found in Appendix B. In process 1, there are four design factors. These design factors are: centrifuging, steam heating, preheating and pressing. In system 2, there are three design factors that change the design of the system. Which are two factors that influence the heating, namely the heating temperature and the use of a heating coil. And one factor that influences the energy cost of pressing.

To show the effects on the investment and energy costs decision trees are made. The decision tree of heating is coupled, which means that the need of a heating tank is dependent on the choices made. How the costs of these different design factors are calculated is discussed in this part with the use of these decision trees.

3.3.1 Centrifuge

$$CostEnergy = Energy * EP \qquad [€] \qquad (1.18)$$

Adding a centrifuge affects both the energy costs and investment costs, as illustrated in Figure 4. EWc in kWh/kg, is an abbreviation for energy of a centrifuge used per weight processed. Only the amount of juice centrifuged is needed to calculate the energy consumption of centrifugation. With the price per kilowatt, EP, set on 0.10 $€/kWh$, the energy costs of centrifuging the juice is calculated. A general formula for converting energy to cost is displayed in Equation 1.18.

$$Costs1 = Costref * \left(\frac{Cap1}{Capref}\right)^{0.6} \quad [€] \quad (1.19)$$

$$For\ a\ centrifuge: \quad Cap1 = Fjuice \quad [kg] \quad (1.20)$$

The investment costs are dependent on the size of a centrifuge. Equation 1.19 is used for all the size dependent cost calculations. To make these calculations a piece of equipment with known costs ($Costref$) and known capacity ($Capref$) is used. $Cap1$ is the desired capacity of the system. This is, in case of the centrifuge, the size of $Fjuice$. The unit of $Cap1$ does not matter as long as it has the same unit as $Capref$.

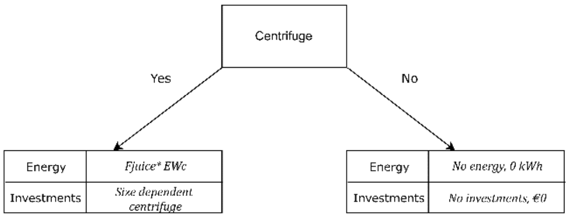

Figure 4 - Decision tree of centrifuging involving energy and investment costs

3.3.2 Pressing

$$For\ a\ press: \quad Cap1 = Fin \quad [kg] \quad (1.21)$$

The investment costs of a press are independent of the number of pressings, a press is needed anyway. The costs of the press can be calculated using Equation 1.19 and 1.21. When pressed once the energy is calculated by simply multiplying the inflow with EWp the energy consumption of a press per weight processed. When the fibre is pressed a second time, the total weight which has to be pressed increases with the amount of fibres.

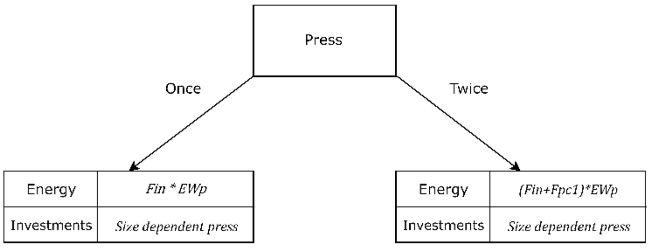

Figure 5 - Decision tree of pressing involving energy and investment costs

3.3.3 Heating – grass based system

$$Level\ 1 \quad For\ a\ coil: \quad Cap1 = Acoil \quad [m^2] \quad (1.22)$$

$$Level\ 2 \quad For\ a\ heating\ tank: \quad Cap1 = Fjuice \quad [kg] \quad (1.23)$$

The decision tree for heating is different in process 1 than in process 2, see Figure 6 and Figure 7. For the grass based system when coil preheating is used it is assumed that no extra energy is required to preheat the juice. A steam heater has a fixed investment price and is not size dependent. Energy can be transformed to costs with Equation 1.18.

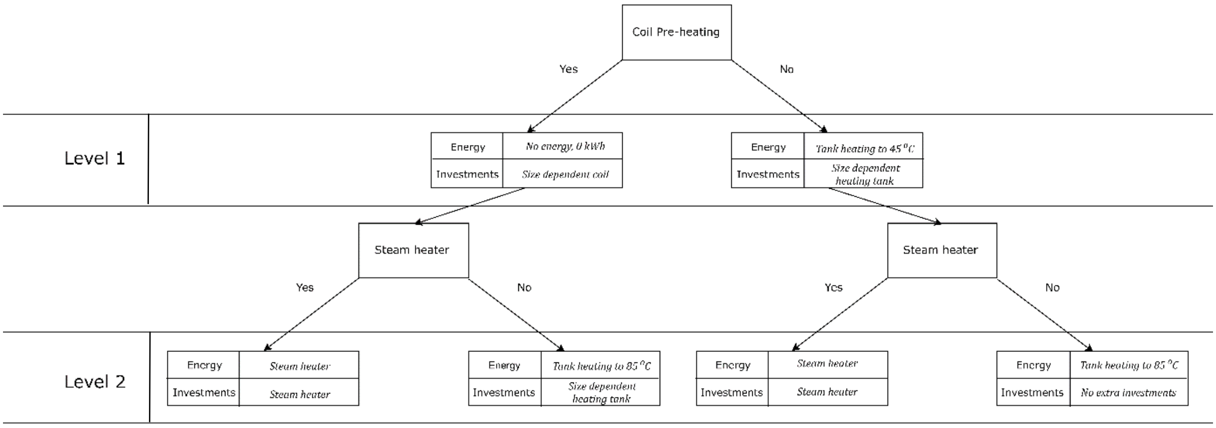

Figure 6 - Decision tree of heating duckweed in the grass based system involving energy and investment costs

$$DTh,c = Level1,c + Level2,c \qquad c\ for\ costs\ of\ energy\ and\ investment \qquad [€] \qquad (1.24)$$

With Equation 1.24 the costs of the decision tree of heating DTh can be calculated. $Level\ 1\ or\ 2$ are the result of the choices made in each level.

3.3.4 Heating – alkali based system

A decision tree about heating in this system is presented in Figure 7. Level 1 concerns heating or no heating. Level 2 concerns preheating or no preheating with a coil. No extra heating happens when the temperature is set on 25 °C. If the temperature is higher, heating is needed with either a heating tank or a preheating coil. What investments are needed and what equipment uses the energy depends on the path taken in the decision tree.

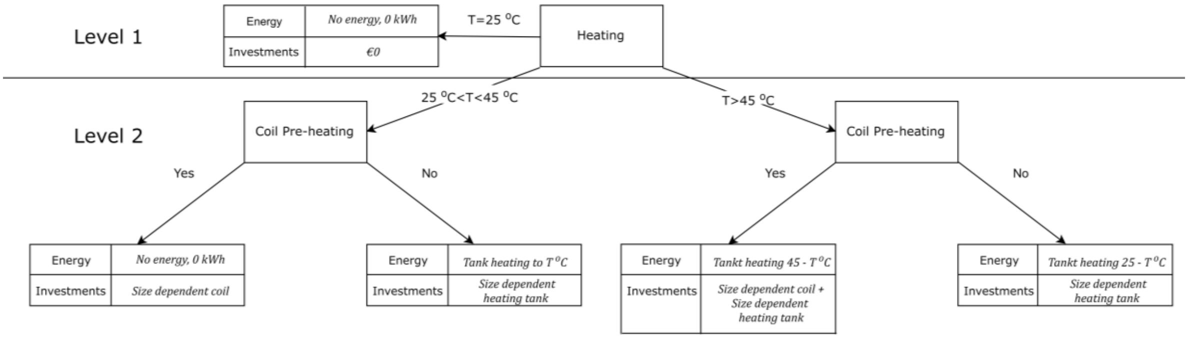

Figure 7 - Decision tree of heating duckweed in the alkali based system involving energy and investment costs

3.3.5 Total system- grass based

$$DSCost,c = DTc,c + DTp,c + DTh,c \qquad c\ for\ energy\ and\ investment \qquad [€] \qquad (1.25)$$

To calculate the design specific costs $DSCost,c$, the choices made in all the decision tress must be added, resulting in Equation 1.25. DTc is the decision tree for centrifuging, DTp is the decision tree for pressing and DTh is the decision tree for heating.

3.3.6 Total system- alkali based

$$DSCost,c = DTh,c + DTp,c + Refrigerator,c \qquad for\ c\ energy\ and\ investment \qquad [€] \qquad (2.20)$$

Equation 1.25 is comparable to Equation 2.20. There is no centrifuge in the GTR process but there is a size dependent $Refrigerator$ needed in the process that consumes energy and needs investments. Information about the energy usage of a refrigerator is known in $kWh/year$ and transformded to $kWh/batch$.

$$CCost = (DSCost, investment + FCost) \qquad [€] \qquad (1.26)$$

$$ICost = CCost * LANG \qquad [€] \qquad (1.27)$$

The system has also some fixed costs ($FCost$) which are needed in every design and are the same for every design. $CCost$ are the total costs of all the major components without $LANG$. $LANG$ is a ratio of the total cost of installing a process to the cost of the total equipment needed in a process. The costs after $LANG$ will give a good indication of the actual installation cost of a working biorefinery. This $LANG$ factor is set on 2 (personal communication T. van Boxtel).

$$Maintainance = ICosts * 5\ \% \qquad [\frac{€}{year}] \qquad (1.28)$$

$$Interest = ICosts * 6\% \qquad [\frac{€}{year}] \qquad (1.29)$$

To keep the biorefinery running an extra yearly expense of 5 percent of the costs after $LANG$ is needed for maintenance. Within ECOFERM! 6 percent a year is needed for interest.

3.3.7 Consumables

$$HCLCosts = \sum added\ HCL * pHCL \qquad [\frac{€}{batch}] \qquad (2.21)$$

$$NaOHCosts = \sum WNaOH * pNaOH \qquad [\frac{€}{batch}] \qquad (2.22)$$

HCL is needed twice in the system for acid precipitation and neutralization of the fibre. $NaOH$ is also needed twice, for the alkali treatment and neutralization of the waste water. $pHCL$ and $pNaOH$ are the prices per litre or kilo of the consumables, these are used to calculate the costs in Equation 2.21 and 2.22.

3.3.8 Cost per DM product

$$CDM = \frac{DSCost, energy + Maintainance + Interest}{Fproduct, DM + Fpc, DM * \frac{365}{2}} \qquad [\frac{€}{kg\ DM}] \qquad (1.30)$$

An important factor in the feasibility analysis is the cost per dry matter of product. The amount of dry matter produced in a year is divided over the costs per year. Resulting in the costs per dry matter. The protein product and fibre product toghether create the total dry matter with value. If not done so the protein product sponsors the fibre product, in this way that is not the case. Both products have value and both contribute to the costs made.

3.3.9 Energy of heating

Energy used by other process steps is already covered in the previous cost section. This part concerns about the heating used in both processes. As displayed in Figure 6 and Figure 7 several situations in which heating is necessary are possible involving a heat exchanger, a steam heater or a heating tank.

A comprehensive description about the formulas used to calculate the energy used by those specific pieces of equipment can be found in the Appendix. Also, characteristics of those pieces of equipment, for example, the tank size or the temperature of the outflow after heat exchanging, can be found in this Appendix. The calculation of the energy used by a heating tank is displayed in this part, the heating tank leads to a most influential contribution of the total energy consumed.

Heating juice and tank

$$Qtank = Mtank * \frac{Cpsteel}{1000} * (Tend - Tamb) \qquad [kJ] \qquad (1.31)$$

$$Qjuice = Fjuice * \frac{Cp}{1000} * (Tend - Tcout) \qquad [kJ] \qquad (1.32)$$

$$Qtot = Qtank + Qjuice \qquad [kJ] \qquad (1.33)$$

All the data to solve equation 1.31 to 1.33 is available and calculated in the Appendix D. $Tamb$ is set on 20 °C, $Cpsteel$ is 502 J/kg. The temperature of $Tend$ and $Tcout$ is situation dependent and process dependent, presented in Table 5. Situation 4 can also be considered as a combination of situation 2 and 3.

Table 5 - End temperatures of preheating (Tcout) and coagulation (Tend)

Situation 2	$Tend = 85$ ℃ $process\ 1\ or\ 95$ ℃ $process\ 2$	$Tcout = 45$ ℃
Situation 3	$Tend = 45$ ℃	$Tcout = 25$ ℃
Situation 4	$Tend = 85$ ℃ $process\ 1\ or\ 95$ ℃ $process\ 2$	$Tcout = 25$ ℃

Power of heating

$$Wtank = Utank * Atank * \left(\frac{Tamb + Tend}{2} - Tamb\right) \qquad \left[\frac{J}{s}\right] \qquad (1.34)$$

$$Wtot = Wheater - Wtank \qquad \left[\frac{J}{s}\right] \qquad (1.35)$$

The temperatures $Tamb$ and $Tend$ are needed to calculate the heat loss through the tank sides in equation 1.34. $Utank$ for the tank is set on 1 W/m^2°C. The power of the heating component $Wheater$ in the tank is 35 kW this power is used to heat up the juice and the tank. Some energy is lost via the sides of the tank, therefore the minus sign in equation 1.35.

Energy used

$$th = \frac{Qtot}{3600 * Wtot} \qquad [h] \qquad (1.36)$$

$$Wmaintain = Utank * Atank * (Tend - Tamb) \qquad \left[\frac{J}{s}\right] \qquad (1.37)$$

$$E = Wheater * th + Wmaintain * tm \qquad [kWh] \qquad (1.38)$$

After heating the juice to 85 or 95 °C in th hours, the temperature is maintained for time tm in hours. Equation 1.38 is the total energy needed to heat up the solution.

4. Method

The equations of both processes are modelled in Excel, the same structure is used for every process step. An example of the structure is given in Figure 8. The input is on the left side, coloured in blue. System characteristics are on top, calculations are done under the system characteristics. The cells are linked to the output, which can be easily further linked to other processes in the system.

The most useful information of both processes is presented on a single tab. On this overview tab, several model settings can be changed.

In Table 6 an overview of the changeable model setting is given. When these settings are changed they can influence several factors in the model, like investment costs, energy consumption, income, amount or chemical composition of product, cake or waste water. All processes are influencing the costs dry matter product. If a model setting changes the investment costs also maintenance and costs of interest will change.

These settings can be adapted with switches, also shown in Figure 8. There are three types of switches, switches that specify a yes/no, switches that specify a range and switches that specify a yes range/no.

		System Characteristics						
		Duckweed Start Concentration						
		Liquid	Wcin	945,67	g/kg			
		Dry Matter	Dmin	54,33	g/kg			
		Crude Protein	Cpin	24,70	g/kg			
		Crude Fa	Fain	2,86	g/kg			
		Crude Fibers	Fiin	5,96	g/kg			
		Crude ASH	Ashin	7,41	g/kg			
		Total Carbohydrates	Tcin	12,26	g/kg			
Input		Polyphenol	Ppin	1,14	g/kg	**Output**		
Fin	80 kg	PT_Watercontent		76	kg	PT_Watercontent	75,7	kg
		PT_DM_OUT		4	kg	PT_DM_OUT	4,3	kg
		PT_CP_OUT		2	kg	PT_CP_OUT	2,0	kg
		PT_Fa		0	kg	PT_Fa	0,2	kg
		PT_Fiber		0	kg	PT_Fiber	0,5	kg
		PT_Ash		1	kg	PT_Ash	0,6	kg
		PT_TC		1	kg	PT_TC	1,0	kg
		PT_PP		0	kg	PT_PP	0,1	kg

Figure 8 - Modelling structure used in the Excel file

Figure 9 gives an overview of the main Excel sheet with all the relevant data. Left and right are the control panels for both systems. They have different inputs as stated earlier and can be both adapted using the switches. These switches are set in a specific range. The system characteristics can be adapted using a similar input box. If a setting is changed in this box, the settings of both systems are changed. This makes it easier to manually compare both systems.

To collect all the data different macros are programmed to automatically collect data. 3D-plots require a lot of data, making those plots by hand was not an option. A macro could change the model settings, collect the data and even formatted the figure.

Under system characteristics is the start composition of duckweed with data about the income it would generate when directly fed in euro per year and euro per fresh weight. All the other information about the costs and revenues of both systems is also present, as well as the chemical composition of all the products.

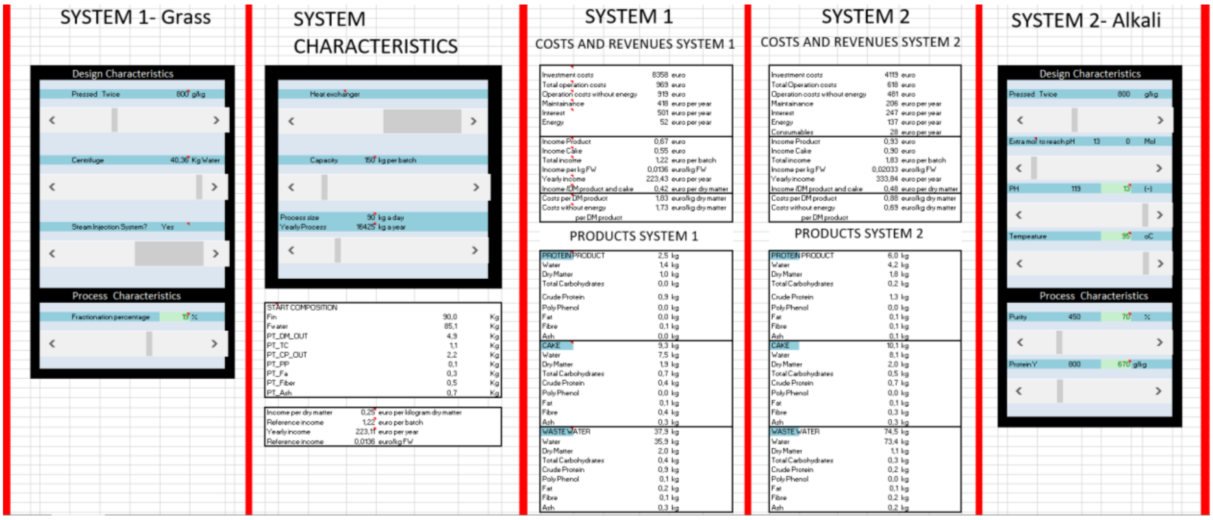

Figure 9 - Overview of the main Excel sheet

Table 6- Summary of the changeable model settings

System Characteristics		
Changeable model setting	Influences	Type of switch
Heat exchanger	Energy and investment costs both systems	Yes/No
Capacity	Energy and investment costs both systems	Range
Process size	Energy used, income, amount of product, cake and waste water	Range
System 1 – Grass - Design Characteristics		
Changeable model setting	Influences	Type of switch
Pressing	Energy, operation costs, water in cake fraction and product	Range
Centrifuge	Water in product and waste water, investment costs, energy	Yes range/No
Steam injection system	Investment costs, energy	Yes/No
System 1 – Grass - Process Characteristic		
Changeable model setting	Influences	Type of switch
Fractionation percentage	Investment costs, energy, chemical composition of product, cake and waste water, income	Range
System 2 – Alkali - Design Characteristics		
Changeable model setting	Influences	Type of switch
Pressing	Energy, operation costs, water in cake fraction	Range
Extra Mol added	Costs of consumables	Yes range/No
pH	Costs of consumables	Range
Temperature	Energy consumption	Range
System 2 – Alkali - Process Characteristics		
Changeable model setting	Influences	Type of switch
Purity	Chemical composition of product, cake and waste water, income	Range
Protein Yield	Chemical composition of product, cake and waste water, income	Range

5. Results

This chapter is divided into two parts, the first part describes the results of the grass based system and the second part describes the results of the GTR based system. Both systems have different inputs, since both systems function in a slighly different way. The outputs, however, are the same and are comparable. Since there is an opportunity to adapt a lot of specific settings a standard ECOFERM! situation or scenario is created. This scenario has fixed values for all the changeable model settings. The standard conditions differ from both systems and are displayed in Table 7 and Table 8.

Process 1: System for duckweed based on grass processing

5.1.1 Standard Scenario

This standard scenario is mainly used to test the effect of each factor in the model. If one factor is tested, the other factors are fixed.

The process size of 80 kilograms per day results in the same amount of duckweed produced in 2015 on ECOFERM!. The capacity of this case is set on 150 kilograms per batch, with this capacity it is possible for the farmer to harvest 3 or 4 times a week instead of 7 times a week. In this way, the farmer has extra flexibility. Also, seasonal fluctuations should not be a problem with an overcapacity of 53 percent.

There is a lot of residual heat in ECOFERM!, so a heat exchanger seems to be a logical option. Within industrial applications a steam injector is used with good results, data about coagulation without steam injector is not known. Therefore, the steam injector is included in the standard scenario.

Table 7 - Standard scenario process 1

Changeable model factor	Set on	Unit
Pressing	800	g/kg
Centrifuge	No	
Steam injection	Yes	
Fractionation percentage	15	Percent
Heat exchanger	Yes	
Capacity	150	kg
Process size	53,33	Percent
	80	kg

5.1.2 Effect of fractionation percentage on chemical composition and income

The fractionation percentage has a large influence on the crude protein content of the cake. It influences the cake crude protein content positive, but the protein product and waste water are negatively influenced.

In Figure 10 and Figure 11 the y-axis represents the chemical composition in kg/kg, while the fractionation percentage is on the x-axis. Crude protein and dry matter out of the starting duckweed ends up in either one of the three fractions. When these three concentrations are added the concentration of the starting material is the result.

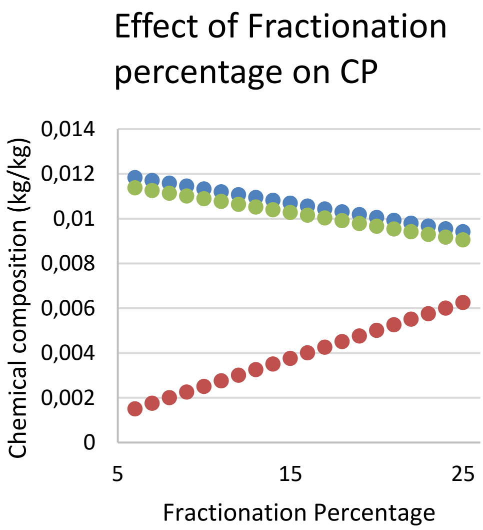

Figure 10- The effect of the fractionation percentage on the Crude Protein in the products formed

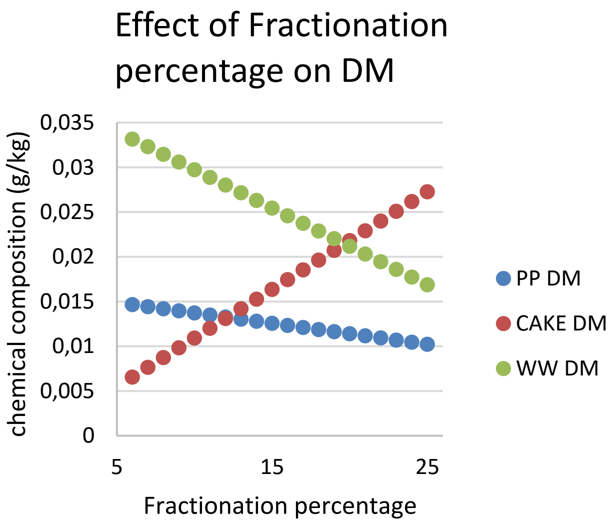

Figure 11- The effect of the fractionation percentage on the DM in the products formed

The fractionation percentage has also an influence on the dry matter and crude protein. The dry matter content of the cake is positively influenced. The dry matter content of the protein product shows a minimal decrease. As a result, with an increasing fractionation percentage dry matter of the waste water ends up in the cake.

This characteristic has also its influence on the income of both products, see Figure 12. The price of the cake is determined by the total dry matter, while the price of the protein product is only influenced by the crude protein content. A lower income out the protein product is compensated by a higher cake income. This results in a positive relation between the fractionation percentage and the income in $€/kg$. Note that the fractionation percentage in this model is range, while in practice it is a fixed value.

5.1.3 Reference income

The reference income is the income that would be generated when the duckweed is directly fed to the calves. Therefore, the fresh weight of the duckweed is used. It does not concern costs involved in

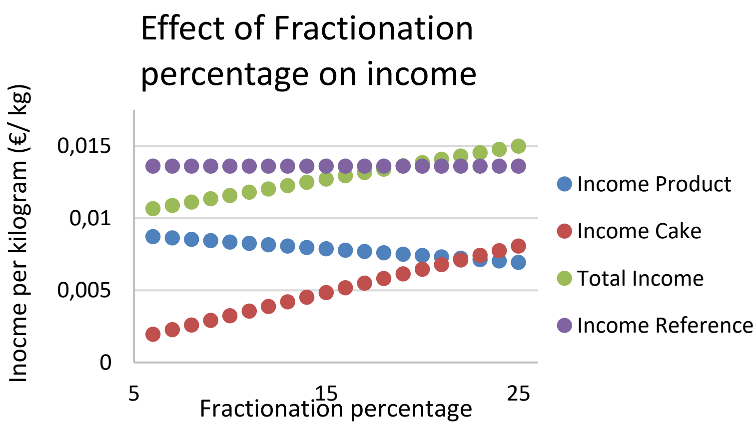

Figure 12- The effect of the fractionation percentage on the income

the production of duckweed. The reference income is 0,01358 $€/kg\ FW$. Calculated by Equation 1.17 if the income of a product is below this limit, feeding directly generates more income. No extra costs are involved in this application, while refining costs extra money to create a lower income. When the fractionation percentage is greater than 20 percent the balance without costs is positive. However, when the operation costs are concerned it lead to a negative total balance of around 720 euro a year. The underlying data for investment and energy consumption, which are needed to compute the operation costs, can be found in Appendix B.

5.1.4 Effect of centrifugation on investment and energy costs

The assumption was made that the centrifuge only removes water and water does not have value in the model. Therefore, it has only influence on the investment costs and energy costs. A centrifuge is an expensive piece of equipment, but when used for 100 percent it can save almost half of the energy costs per year. Also, it can win back some of the investment costs. When a centrifuge is applied less water has to be heated, which saves energy. Also, smaller heating tanks are needed which saves investment costs. However, not using a centrifuge is still a lot cheaper since the investment costs are just too high. Figures about the effect of a centrifuge can be found in the Appendix E.

5.1.5 Effect of pressing on energy and investment costs

Pressing once (between 821-890 g/kg) costs less energy and less investment costs. The same press is used twice, but pressing twice generates more water in the juice. Therefore, the heating cost more energy and a larger heating tank is needed too. Between 810 and 830 g/kg is a leap, that is explained by the extra energy needed to press the firbes a second time. Pressing more water in the juice influences also the size of a heating tank. Figures about the effect of a pressing can be found in the Appendix E.

5.1.6 Effect of heat injector and heat exchanger

This part is the result of the decision tree in Figure 6 and Figure 7. The figure of this result can be found in the Appendix. Steam heating with a heat exchanger is cheaper than steam heating without a preheating coil since an extra preheating tank is needed to preheat the juice.

With no steam heating, a heating tank is needed anyway. The investment costs are higher when the additional heat exchanger is applied. In that situation, the no heat exchanger option is cheaper.

Steam heating and no steam heating have the same energy cost per year. The energy costs of a heat exchanger are 30 euro per year cheaper than without a heat exchanger. This difference is relatively small and the higher investment costs of a preheating coil have a payback time over 10 years. When the scale and the capacity percentage increase the investment win back time may be halved.

5.1.7 Effect of capacity and capacity percentage on the operation costs

The capacity percentage is the percentage in which the available capacity is used, resulting in the final process size. In the standard scenario, a capacity of 150 kilograms and a capacity percentage of 53 percent leads to a process size of 80 kilograms a day. The capacity affects directly the investment costs, a larger installation will cost more money. The capacity percentage influences the process size, consequently influencing the amount of energy used and the amount of inflow. In this way, it also influences the amount of products formed. These two factors can be independently adapted. When the capacity is larger instead of processing, for example, seven times a week the process can be executed two times a week resulting in more freedom for the farmer.

To get full insight into the effect of the capacity and process size 3D plots are made. Capacity and capacity percentage are on the x and y-axis while the operation costs or cost per dry matter are on the z-axis. The operation costs are the costs per year, composed out of maintenance, interest and energy.

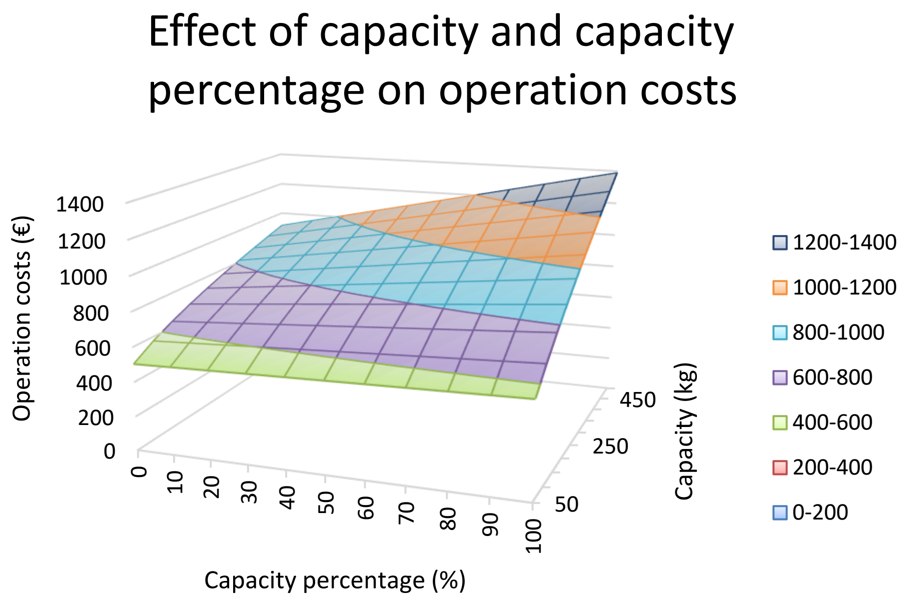

Figure 13 - Effect of capacity and capacity percentage on the operation costs

Figure 13 is an example of the situation in Table 7. When the capacity percentage is 0 percent, no energy is used since no duckweed is processed in the system. This gives an indication of the investment costs, since at zero percent only the investment cost contributes to the operation costs, in the form of maintenance and interest.

When the capacity percentage is larger than zero, energy consumption starts to play a role. Maintenance and interest for a certain capacity are fixed, so the change of operation costs is caused by the energy consumption for capacity percentages larger than zero. In the lower range of the capacities, a small increase in operation costs is observed when the capacity percentage increases. This makes sense because an increase in the capacity percentage does lead to a small increase in duckweed processed. Which leads to a small increase in energy consumed. In larger capacities this is different, a small increase in the capacity percentage leads to a larger increase of duckweed processed and energy costs.

5.1.8 Effect of capacity and size on cost per dry matter

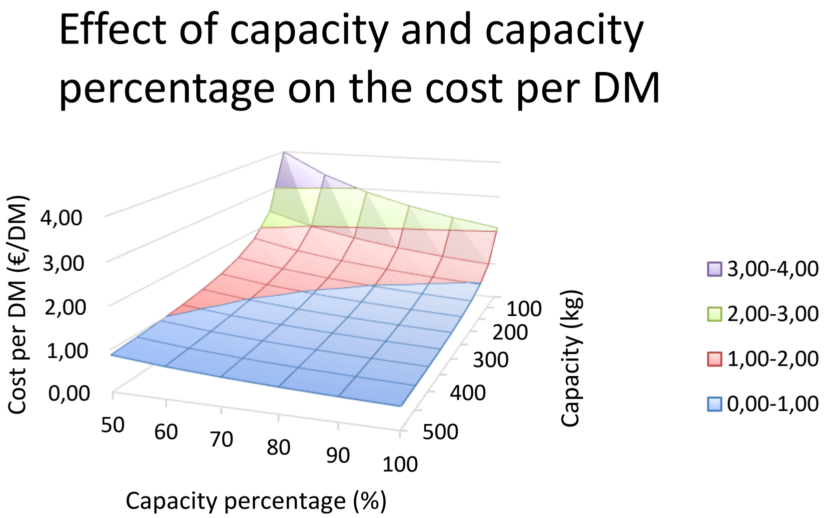

Figure 14- Effect of capacity and capacity percentage on the cost per DM

In Figure 13 the capacity percentage has only an influence on the energy used, but in Figure 14 this is not the case. The capacity percentage also influences the amount of product formed. In other words, the amount of dry matter and crude protein that ends up in the two products. At small scale, an increase in the capacity percentage results in a large decrease in costs per dry matter. At a larger scale, this effect is much less. At low capacity percentages, an increase in capacity can lead to a big decrease in cost per dry matter, this effect is much less when the capacity percentage is higher. In other words, in the steep part of the graph (low capacity and low capacity percentage) is it easier to lower the cost per dry matter with small adaptations. In the flat part of the graph (high capacity and high capacity percentage) a small decrease of the cost per dry matter is harder to realise.

In Appendix F the same graphs with different model settings are presented. This Appendix will give an idea of the effect of certain settings on the shape of these graphs.

Process 2: System for duckweed based on GTR processing

5.2.1 Standard Scenario

The temperature and pH are set on the same conditions as in the experiments of Zhang. Since the buffering capacity of duckweed is not known an extra 20% Mol is added to the solution. It is an extra margin to be in the right range for consumable costs. Note that this factor is a rough estimate and that the effect of this factor on the operation cost is releatively small. A heat exchanger, the same capacity and process size are used for system 2 just like system 1. The standard protein purity and yield for duckweed are not known and are roughly estimated using the data of GTR.

Table 8 - Standard scenario process 2

Changeable model factor	Set on	Unit
Pressing	800	g/kg
Extra mol added	20	%
pH	13	
Temperature	95	°C
Protein purity	70	%
Protein yield	670	g/kg
Heat exchanger	Yes	
Capacity	150	kg
Process size	53,33	Percent
	80	kg

5.2.2 Effect of temperature on investment and cost per dry matter

When the temperature increases both energy and investment costs increase too. In the model, the heating coil can heat or preheat the duckweed to 45 ^{O}C, if extraction is performed below this value a heat exchanger is a better option than heating in a tank.

At the standard scenario with higher temperatures, there is no difference in operation costs when a heat exchanger is used. This can be explained by the fact that with a preheating coil the investment costs are higher but the energy costs are lower. The effect on the extra interest and maintenance is as big as the effect of less energy consumed. This means that in total the operation costs are the same.

However, this when the scale increases, more energy is saved with a heat exchanger than the extra interest and maintenance costs. In other words, at large scale a heat exchanger is always a cheaper option but at small scale this does not hold. The operation costs are equally expensive as without a heat exchanger.

5.2.3 Effect of pressing on energy and investment costs

Pressing once or twice has a minimal effect on both the energy costs and the investment costs. There are some differences between system 1 and 2. In system 1 the pressing is performed at the beginning of the refinery, before the heat coagulation step. In system 2 the pressing is performed after the heating. Therefore, the pressing has no influence on the amount of juice which needs heating.

5.2.4 Effect of pH and consumables cost

The costs of consumables are strongly affected by the pH. The extraction is performed at pH 13, an extraction of pH 12 or 11 is much cheaper and an additional effect is that fewer salts are formed. The consumable costs of pH 13 are between 25 and 40 euro per year. A pH decrease from 13 to 12 saves approximately a factor 10 in the consumable costs, a decrease from 13 to 11 saves a factor of around 100, because of the logarithmic scale of pH.

5.2.5 Effect of the purity on dry matter and crude protein content

The protein purity can be adapted in this model, it has an effect on the chemical composition of all the products. Figure 15 is the balance between the dry matter content of all the products. When the purity increases the dry matter content of the protein product decreases. The crude protein content stays the same since it is another adaptable factor in the model. This means that other dry matter components than crude protein lead to an increase in the dry matter of the cake. The protein content is purity independent. The purity has an influence on the other components in the protein product, cake product and waste water.

When the purity is high, it means that the product mainly contains crude protein, which means the other components in duckweed must be in the cake or waste water. Figure 15 shows that most of these other components end up in the cake.

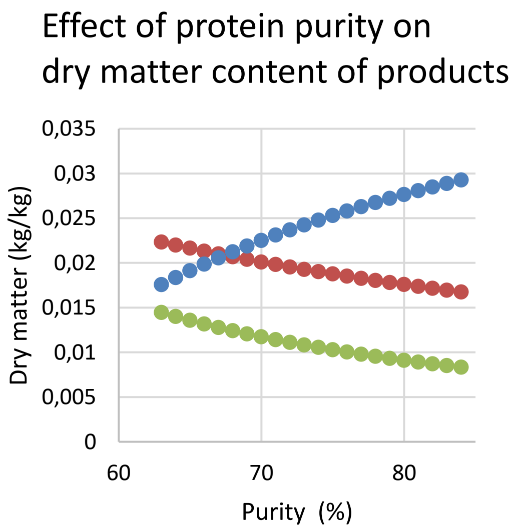

Figure 15 - Effect of the purity on the dry matter of the products

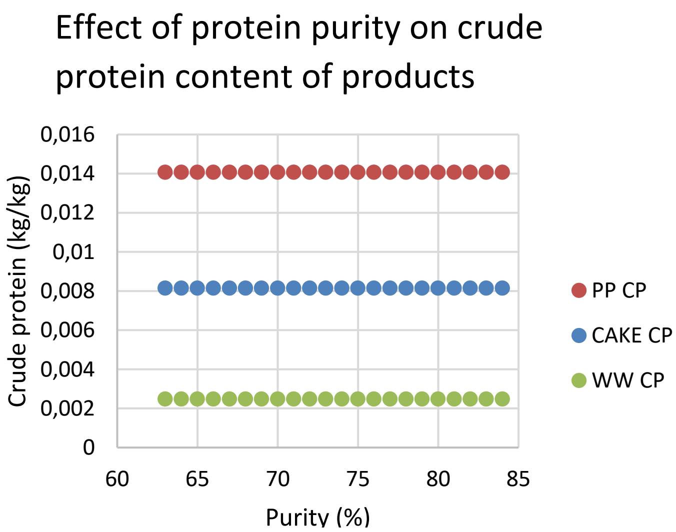

Figure 16 - Effect of the purity on the crude protein content of the products

5.2.6 Effect of the protein yield on dry matter and crude protein content

An increasing protein yield leads to a decrease in the cake dry matter but a slight increase in the waste water dry matter. If the protein yield increases, the protein is extracted out of the cake. At lower protein yields most of the dry matter ends up in either one of the products. If the protein yield increases the crude protein content of the cake decreases. The waste water has a slight increase in the protein content and dry matter content when extra protein is extracted in the protein product. This is because more protein and dry matter is extracted by the alkaline extraction but not did not end up in the product when acid precipitated. In other words, the protein and dry matter is extracted but did not end up in the final product.

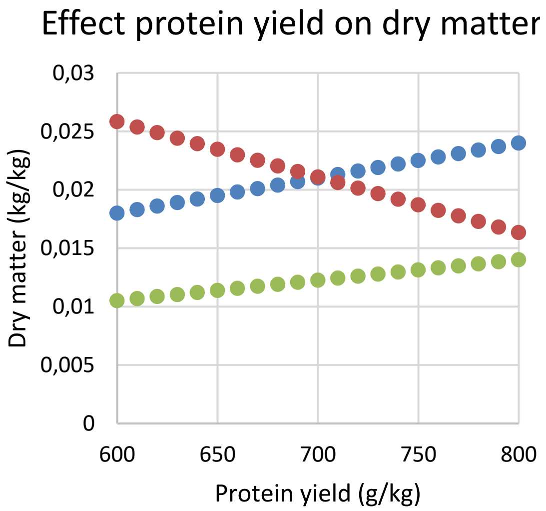

Figure 17- Effect of protein yield on dry matter

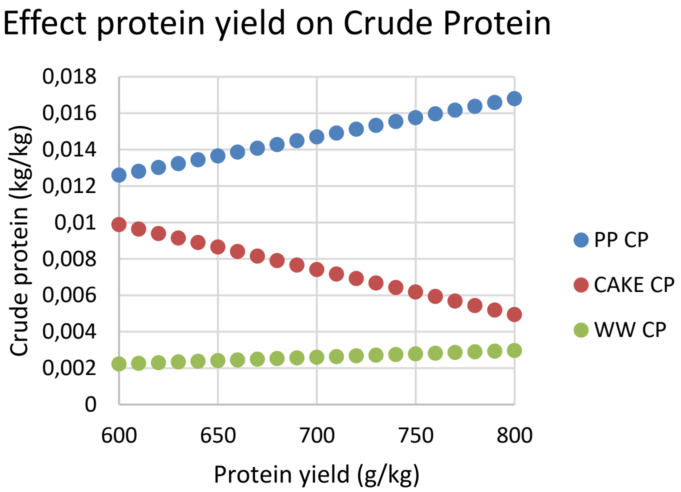

Figure 18 - Effect of protein yield on crude protein

5.2.7 Effect of purity and yield on the cake

To give an overview of both effects, a 3D plot of the purity and yield of the cake is made. A plot of the crude protein content of the product is not made. The amount of protein is not affected by the purity. Protein yield can be set as a changeable factor in the model. This will result in a plot with values that are set as inputs in the model. This plot is therefore irrelevant.Protein yield negatively influences the amount of dry matter in the cake. But the purity positively influences the amount of dry matter in the cake. As a consequence, a protein product with high protein yield and low purity will result in minimal dry matter for the cake.

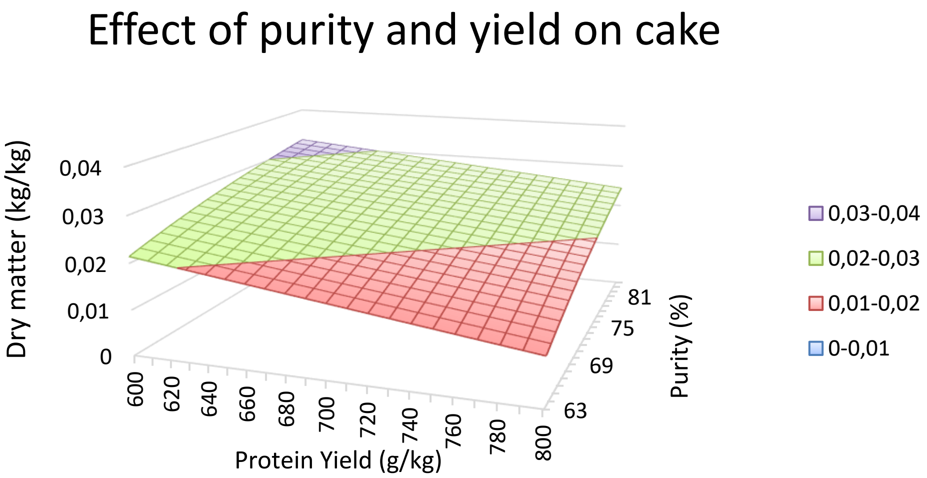

Figure 19 - Effect of the purity and yield on the dry matter in the cake

5.2.8 Effect of purity and protein yield on the total income

The plot in Figure 20 gives insight into the best extraction characteristics. The cake has a larger influence on the income at a low purity. A high protein yield results in a high price for the protein product, but this is totally canceled out by the lower price for the cake product. It even results in a negative relation when the protein yield increases. If the protein purity increases this effect declines. At high purities, the protein yield has hardly effect on the price. An increase in the protein yield does not directly mean more income, an increase in the purity does. The gray surface on the bottom of

Figure 20 is the reference income. For every setting of purity or yield, a higher income than the reference income is realised. The income balance is positive for all situations.

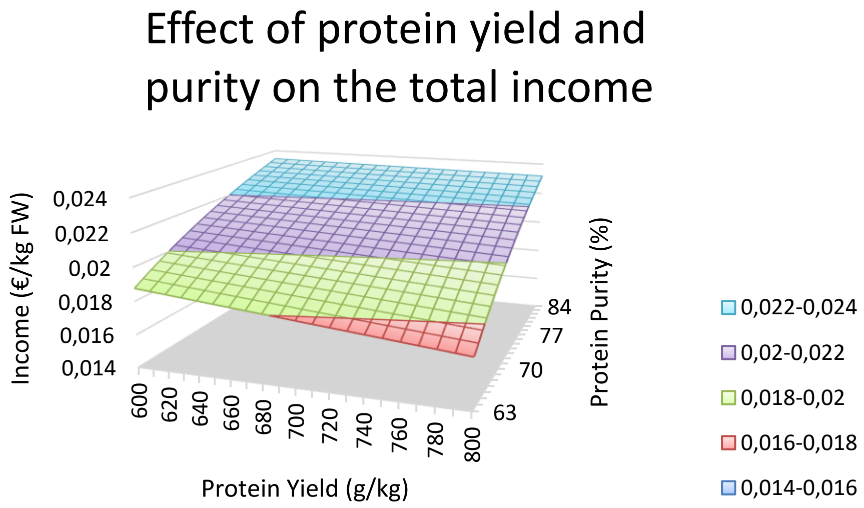

Figure 20 - Effect of protein yield and purity on the total income

5.2.9 Effect of capacity and size on operation costs and costs per dry matter

The effect of the capacity and capacity percentage under standard conditions for the operation costs results is a figure with comparable shape as system 1, see Figure 13. Since duckweed is heated to 95 °C for 4 hours, energy costs play a larger role in this system. Therefore, the operation costs are higher at a larger scale. Also, extra costs for consumables result in higher operation costs. Without energy used, when the capacity percentage is 0, the operation costs are comparable to system 1.

The shape of the costs per dry matter Figure 21 is different from system 1. An increase in the capacity percentage or capacity leads to a smaller decrease of the costs per dry matter than in system 1. The scale of the system is less influential for the costs per dry matter than in system 1. Also, the costs per dry matter of this system are lower, but the operation costs are generally higher. In system 2, more dry matter ends up in the products and less in the waste water fraction. Therefore, the costs per dry matter can be lower with higher operation costs. For this system, other settings are also tested on the behaviour of capacity percentage and capacity. The results of these different settings are displayed in Appendix F.

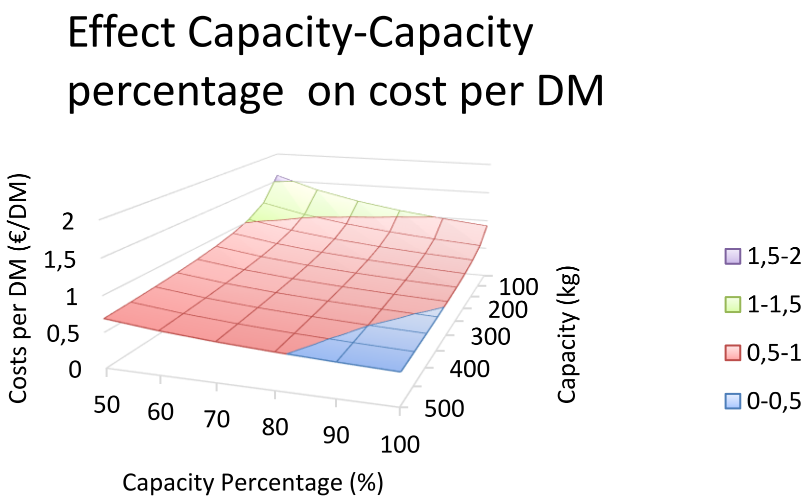

Figure 21- Effect of the capacity and capacity percentage on the costs per dry matter

6. Discussion

In the model, a lot of assumptions are made without measuring. The philosophy behind this approach is to identify bottle necks in the process and gather knowledge before measuring. With this approach, it is already clear which factors are most influential on the processes and how the process functions without measuring a single parameter. This is a different approach of what is normally used but realise that in this way it is possible to visualise the opportunities and identify pitfalls before running into those pitfalls when started measuring directly.

Income

The income of ECOFERM! for process 1 is around 0.015 euro per kilogram duckweed and for process 2 around 0.020 euro per kilogram duckweed. Which will result in a turnover of respectively 1.20 or 1.60 euro a day. 80-kilogram fresh duckweed will result in 4.3-kilogram dry matter. A turnover of 1.46 euro is realised a day with the value of duckweed determined by the (de Wilt et al., 2016). These small amounts wouldn't make a different in the amount of feed it replaces. The scale must increase, so duckweed can make a significant contribution to the feed ration on ECOFERM!

Overcapacity

The capacity of the system in the ECOFERM! the scenario was set on 150 kilogram a day to have the capacity to handle with seasonal fluctuations and days off. However, overcapacity is expensive, a larger installation is installed but in practice this extra capacity is barely used. Since a batch system is used for duckweed a smaller capacity can be used twice or even more often to coop with peaks in the growing season or a peak after a free day. In this way, the capacity is used more intensively and a smaller installation can do the job. The effect of this action is for example that a larger refrigerator in system 2 is installed to handle the extra product streams. Not the total installation has to increase in size, only some equipment to make multiple batches possible. This is not an option in the model but would be a good way of bringing back the overcapacity. A drawback of multiple batches is that it is more labour intensive. The system should run a couple of times which costs more time and effort than running a big system once.

Heat exchanger

In the designed system, a simple heating coil is used to preheat the substances. A more efficient heat exchanger can heat the substance with an instream temperature of 80 ^{o}C to higher temperatures than 45 ^{o}C. The effect of a heat exchanger without a heating tank was big. In this case, the possibility for higher extraction temperatures without high costs is created. A heating tank would be unnecessary and the heating costs would be minimal.

It is not known how much the extraction conditions are influencing the quality of the product as mentioned earlier. There are more opportunities for other extraction temperatures combined with a heat exchanger.

Pressing

In the model, pressing is a controllable factor and when pressed a second time only extra water is removed. In practice, this is different. It is unknown how duckweed reacts on the pressings but as observed for grass when pressed twice some extra dry matter will end up in the juice fraction (O'Keeffe et al., 2011). This amount is minimal and was neglected in this model.

How duckweed reacts on pressing once or pressings twice is a characteristic of duckweed and cannot be that easily changed. The amount of pressing has its influence on the water content in the fibres and juice. In the model, it is possible to set the pressing on every possible water concentration. However, this is a lot harder to realise in practice.

Note, that the water concentration of 820 g/kg is only for this model a characteristic associated with a two-time pressing. If pressed twice generally the fibres will be dryer than pressed once. In the model, the concentration of 820 g/kg is taken as a boundary. It is possible for the cake fraction to hold more or less water if pressed twice.

pH

How duckweed reacts on the addition of alkali is unknown. As mentioned before, the extra Mol function is built in to make sure the consumables costs are in the right order of magnitude.

Centrifuge

The data of ABC Kroos was used to calculate the maximum amount of water centrifuge. There is a possibility that the centrifuge can seperate more water out of duckweed. This will lead to a further decrease in the investment costs and energy costs as displayed in the figures in Appendix E. Even if this is the caste the investment costs of a centrifuge are a big drawback for ECOFERM!. If the centrifuge would be used a second time in the system for example in the separation of protein product and juice and it would lead to significantly more value, then a centrifuge should be reconsidered.

Chemical composition of the inflow duckweed

In this model, the inflow of duckweed has a fixed chemical composition. In practice, this is never the case. The chemical composition of duckweed fluctuates and is dependent on the prevailing conditions. The effect of a different biomass composition was not experimentally tested. With a small adaptation in the model different duckweed compositions can be reviewed. The sensitivity of the certain factors like costs and chemical composition of processes can be reviewed and lead to insightful data. The chemical composition of the inflow of duckweed has a direct influence on all the important outputs, like chemical composition of products, costs of energy and investment, income, reference income and costs per dry matter. Note that for the data of the start composition of duckweed the real data of ECOFERM! is used which fits ECOFERM!. A sensitivity analysis for different compositions of duckweed would create more insight into the functioning of the process but it would not contribute to extra results for the ECOFERM! case.

Determination of the cake value

The determination of the value of the system 2 press cake has an uncertainty. There is a big difference between the press cakes of the two processes. The proteins in system 1 are in native shape while the system 2 press cake the proteins are denatured. This has its influence on the price, but it is unknown by how much. Also, the fibres lose their value when totally disrupted which happens in system 2. They cannot serve as a stabilizer for the rumen. On the other side, the chemical composition of system 2 press cake is far more promising than the composition of system 1 press cake. Which largely increases the value. FFa is an uncertain factor in Equation 1.11 The price of the system 1 press cake can be determined more accurately. Because the chemical composition of the brewer's grains fits the chemical composition of pressed duckweed in system 1.

Total balance of system

When the fractionation percentage is below 20, value of duckweed is lost, the income balance is then negative. Which result ultimately in a final balance which is negative too. In other words, the extra costs for refining cannot make a profit. Even if the energy costs are not a concern it is impossible to turn a profit. It is This process can only be feasible if there is less overcapacity, scale increases and the coagulation is much more effective. For more information about the coagulation see 7.1.1.

The income balance for process 2 is always positive independent from the characteristics about purity and protein yield. But then again, the total balance in negative. The extra costs can result in extra value but not enough to cover all the operation costs. For this process, if the scale increase, the purity is high, overcapacity decreases and mainly the temperature is below 45 ^{o}C it is possible to reach a positive total balance. 45 ^{o}C is a limit since the need of a heating tank is then superfluous, which save investment costs. Under these favourable and most ideal conditions, it is possible to turn a total profit, unlike in system 1 in which this is not possible even under the most favourable conditions.

7. Critical points proof of concept

The next step in the design process is the proof of concept, this is not performed in this thesis. The critical points in the proof of concept are discussed. The most relevant process steps to test in the proof of concept give insight in the performance of both systems. In this work, knowledge gaps were identified about certain process steps. Assumptions were made to be able to model both processes. The goal of this chapter is to discuss these process steps with knowledge gaps and identify what critical points are most important for the proof of concept. First, the proof of concept of process 1 is discussed, then process 2 and finally some comments on the total system.

Process 1: Proof of concept grass based system

This system was first specifically designed for grass and now adapted for duckweed. The results of this model will give a clear indication of its performance. However, the model does need verification.

In the proof of concept, there are four factors that are relevant to the proof of concept. Which are in order of relevance: coagulation, pretreatment, pressing and waste water usage.

7.1.1 Coagulation

The coagulation step in the process is very important since it yields the actual product. It is the process step that uses the most energy and when steam heating is applied would require high investment costs. There is notable room to cut the costs so to say. Steam heating is used in the industry with good results but is not ideal for small scale operations. In the proof of concept, the focus should be on alternatives of steam heating. A major advantage of steam heating was that the steam leads to larger agglomerates (Kamm et al., 2010). Heating with a heating tank was used as an alternative in the model, but does not have this advantage.

Flotation can serve as a cheap alternative to force the protein product to the top. However, it is unknown how effective this is in combination with tank heating.

Also, the effect of pH on the coagulation is interesting to test. In system 2, only pH and residual heat are used to separate protein and the rest. The protein recovery in system 2 is significantly higher than in system 1. A recovery of 51 percent in system 1 and a recovery of 85 percent in system 2 is achieved. A possible explanation of this difference is the addition of acid. Another explanation could be that the prior process steps lead to a higher recovery with acid. The fact remains that the protein recovery in system 2 is higher than in system 1. If this recovery could be improved, ideally with a method consuming less energy the feasibility of this process 1 would greatly increase.

7.1.2 Pretreatment

The model does not provide any information about the effect of pretreatment on the quality of the products. For grass, the pretreatment is vital for a good extraction and severe pretreatments are necessary. However, it was stated that duckweed would require little or no mechanical pretreatment. It would be interesting to see the effect of pretreating on the product quality and chemical components ending up in the products. A less severe pretreatment can be used on duckweed but what pretreatment exactly is not known and interesting to research. Pressing itself can also serve as a cell disruption method. Meaning that pressing simultaneously separates the fraction and opens the cells for protein coagulation. The effect of pressing on the cell disruption of duckweed is unknown. But there is a possibility that a pretreatment would not be necessary unless extra cell disruption by an unknown pretreatment would lead to significantly better products. The design of the process can be improved when the effect of the pretreatment is clear.

7.1.3 Pressing

Fractionation percentage is a factor in the model which has a great influence on the amount of products and quality of the products formed. Since the concentrations after pressing are known, but the percentage ending up in each fraction is not known. This factor got a great influence on the system. The fractionation percentage can be tested by pressing duckweed and measure the weight of both fractions. This data can then be used as a fixed value in the model. It would be even better to test the chemical composition of duckweed or the fractions before and after pressing. To verify the data gotten and used from ABC Kroos. With this test, the real effect of pressing can be understood.

7.1.4 Waste water usage

Coagulation optimisation should have priority over this part in the proof of concept. When the coagulation step is not optimised a lot of crude protein and a major part of the dry matter ends up in the waste water. This is lost in the process as fertilizer in the current design. Feeding the waste water should be considered. The waste water can be mixed with the drinking water of the cows. In this way, the waste water would increase in value and it can result in more income on ECOFERM!. The chemical composition should be tested to predict the value. A point to note is that the waste water contains a high amount of phosphate. Duckweed used the phosphate out of the cow manure to grow and a major part of this phosphate ends up in the waste water. The phosphate content of the urine will increase when this waste water is fed. On ECOFERM! this is no problem since the urine is used in the duckweed pond. It has no effect on the phosphate rights or phosphate regulation. The cow takes up the useful components out of the water and separates the phosphate which is then again used by the duckweed. Creating a closed phosphate cycle.

Process 2: Proof of concept GTR based system

There is a great difference between duckweed and GTR in chemical composition. A lot of processes should be optimised for the specific use of duckweed. In GTR the waste fraction did not have any value while in the case of duckweed the cake can create a considerable amount of value. This aspect is new for alkali extraction.

In the proof of concept for system 2, there are three factors important. Which are in order of relevance: extraction conditions, pressing and acid precipitation.

7.2.1 Extraction conditions

The most important aspect in the proof of concept are the conditions for alkali extraction. A major cost reduction can be realised when the extraction conditions are changed to a lower temperature. The effect of the extraction on the protein purity and yield for both the protein product and cake is vital for the process optimisation. The effect of the extraction conditions on duckweed is based on assumptions in the model. The chemical composition is not changed with different conditions, which would probably happen in practice. The validation of different extraction conditions with experiments will make it clear if system 2 has really the potential to be an alternative for direct feeding.

7.2.2 Pressing

Pressing is effectively used for the system of grass which is the main reason this method is also applied as a separation method in system 2. Yet again, the effect of pressing or separation in this case of unknown. It is possible that another separation technique will lead to better results and is preferred for that reason. Also, the influence on pressing once or twice is unknown, this should be tested with experiments.

7.2.3 Acid precipitation

The acid precipitation gives good results on GTR. The same is assumed for duckweed. In process 1, skimming could be used as an efficient way of separating the juice and precipitated protein. For GTR centrifuging was used to separate those fractions. It should be verified if skimming leads to comparable results. In short, the acid precipitation conditions and separation methods need optimisation and model validation.

7.2.4 Refrigerator

In the work of Zhang, a refrigerator was used to complete the acid precipitation. In his work, it was not described why this specific step was needed. The effectiveness and importance of this process step is unknown and should be tested. If the coagulation is further optimised this is a process step that must be investigated.

Total

7.3.1 Value of product

In the model, the performance of both systems is tested by means of product price, costs per product, reference income and total costs made. The value of the products is determined by comparing the chemical composition with other feed sources with a known price. In reality, the real value will be determined by the amount of feed the products replace. The nutrition value should first be tested in the lab and finally on the animals to see the effect of feeding the product on the animal. This is the final step in the proof of concept since optimising the yield, the process and the chemical composition are easier and more important in this development stage. To test the effect of nutrition on animals is an expensive and long-lasting trajectory (Sebec, L. Personal communication, 06-28-17). Therefore, the designed process should be final and extensively tested. Because of the costs, there is no room for error in nutrition research.

7.3.2 Evaluation

It is important in the proof of concept to keep evaluating the performance. The model shows that system 2 is most promising. However, system 1 is already effectively tested for grass. Therefore, system 1 remains important in the proof of concept to compare the performance of system 2. In other words, system 1 serves as a standard to put the output of system 2 into perspective. Both processes should also be compared to direct feeding because this is the current situation on ECOFERM!.

8. Conclusion

Process 1: System for duckweed based on grass processing

When duckweed is refined in the same way as grass processing, the protein is divided over three fractions. A protein product, a cake product and waste water is produced. The cake contains the lowest amount of crude protein, while the protein product contains slightly more crude protein than the waste water. The fractionation percentage is a factor in the model that is used to determine what amount of duckweed entering the system ends up in the liquid fraction and what amount ends up in the fibre fraction. With an increasing fractionation percentage, the crude protein in the cake increases while the crude protein in the waste water and protein product decreases. The fractionation percentage strongly influences the amount of dry matter in the cake and waste water. The dry matter of the protein product is less influenced by this percentage.

The fractionation percentage has a positive influence on the income generated by the products. A fractionation percentage higher than 20 percent is most desired as the income per kilogram fresh duckweed exceeds the reference income. When the fractionation percentage is lower more value for ECOFERM! is created when the duckweed is directly fed to the calves.

A centrifuge leads to a large increase in investment cost accompanied with a relatively small decrease of energy costs. A centrifuge which is used to remove only water is too expensive in this small-scale operation. Removing water does not contribute to any extra value in the total system.

Pressing twice results in higher energy and investment costs. However, this difference is small. In practice, a farmer will always press the duckweed twice to assure the two fractions are separated and maximum protein recovery is realised. Because the extra costs involved are very minimal.

If a steam heater is necessary cannot be determined, the influence of heating with a tank on the final quality of the protein product is unknown. A steam heater should be applied in combination with a heat exchanger, without a steam heater a heat exchanger is a bad choice.

An increase in capacity leads to a large decrease in cost per dry matter, the same holds for capacity percentage. For ECOFERM!, an increase in the scale and a more efficient use of this capacity will lead to a large decrease in costs per dry matter.

With the grass based system, the extra costs for refining cannot make a profit, even if the energy costs are not a concern. Therefore, the grass based process is not a feasible process within ECOFERM!.

Process 2: System for duckweed based on green tea residues processing

When duckweed is refined with the system based on green tea residues (GTR) processing, also a protein product, a cake product and waste water are produced. When the protein purity of the product increases, more dry matter ends up in the press cake, while dry matter in the protein product and the waste water decreases. There is always more dry matter in the cake and protein product than dry matter in the waste water.

An increasing protein yield has a positive effect on the amount of protein in the juice but it negatively influences the dry matter amount in the cake. The crude protein in the waste water is hardly affected by a change in the protein yield.

An extraction temperature of 95 ^{o}C contributes 50 percent to the operation costs. When the extraction can be executed at lower temperatures the investment costs, as well as the energy costs, will largely decrease.

At small scale, the costs for a heat exchanger are comparable to the absence of a heat exchanger. When the scale increases a heat exchanger becomes a better option. A heat exchanger gives the possibility to perform the extraction at temperatures up to 45 ^{o}C with significantly fewer operation costs. The effect of the temperature on the extraction efficiency is not known but can be largely optimised for the total process.

pH has a smaller influence on the costs than the temperature but a decrease from pH 13 to 12 leads to a cost reduction of a factor approximately ten. While a pH reduction of 13 to 11 leads to a consumable costs reduction of almost a factor 100. For pH, the same holds as for temperature, this factor should be optimised for the total process.

The protein purity has a positive relation to the income while an increase in protein yield has a negative influence on the income. The extraction should be focussed on extracting a pure protein product, not a high protein yield.

There is a moderate effect on the cost per dry matter when the capacity or process size is increased. The GTR based system is applicable for small scale operations, since an increase in scale or a decrease in overcapacity does lead to a small decrease in costs.

It is possible to turn a profit with the GTR based system. However, only under specific conditions. the process size should be equal to the capacity and the extraction temperature should be lower, resulting in the same quality products. It is important for the proof of concept that the extraction conditions are optimised for the total process in ECOFERM!.

Total conclusion both systems

In the system based on GTR, a higher crude protein content in the protein product is realised, the dry matter in the cake is higher too. In other words, less valuable components end up in the waste water. As a result, the total revenue of GTR based system is greater than grass based system.

The investment costs of both systems are in the same order of magnitude. However, when the extraction of the GTR based system is performed at 95 ^{o}C and the extraction pH is at 13 the operation costs are higher than in the grass based system. When the extraction temperature is lowered the energy costs become significantly cheaper.

In general, better products with the comparable investment costs are formed in the GTR based system. The energy and the consumable costs in this process lead to higher operation costs but it generates more income.

Costs per dry matter are strongly influenced by scale in the grass based system but less in the GTR based system. To rephrase, the GTR based system is better applicable at small scale than the grass system.

To conclude, the GTR based process is more promising than the grass based process and has the potential to be a better alternative for direct duckweed feeding on ECOFERM!.

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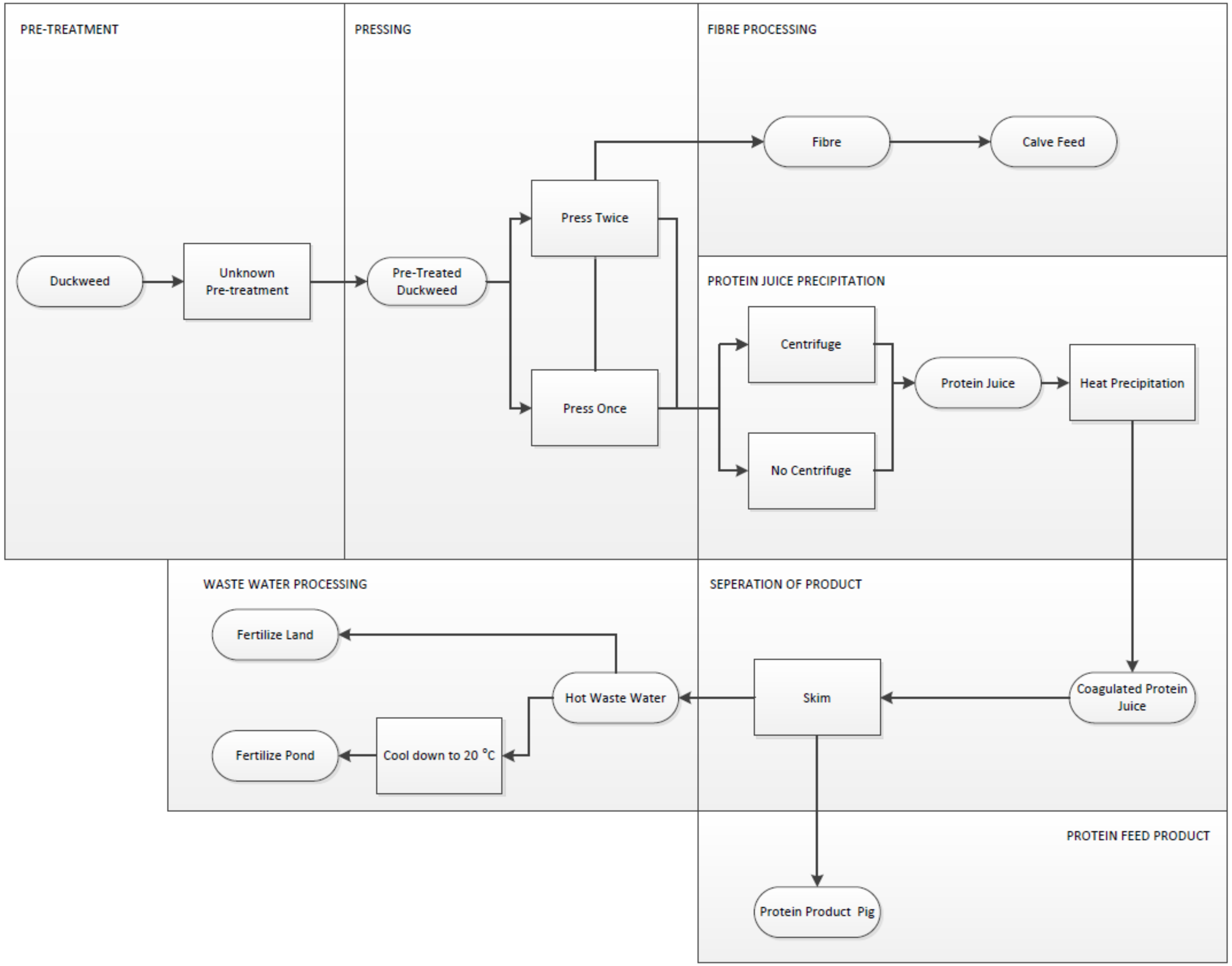
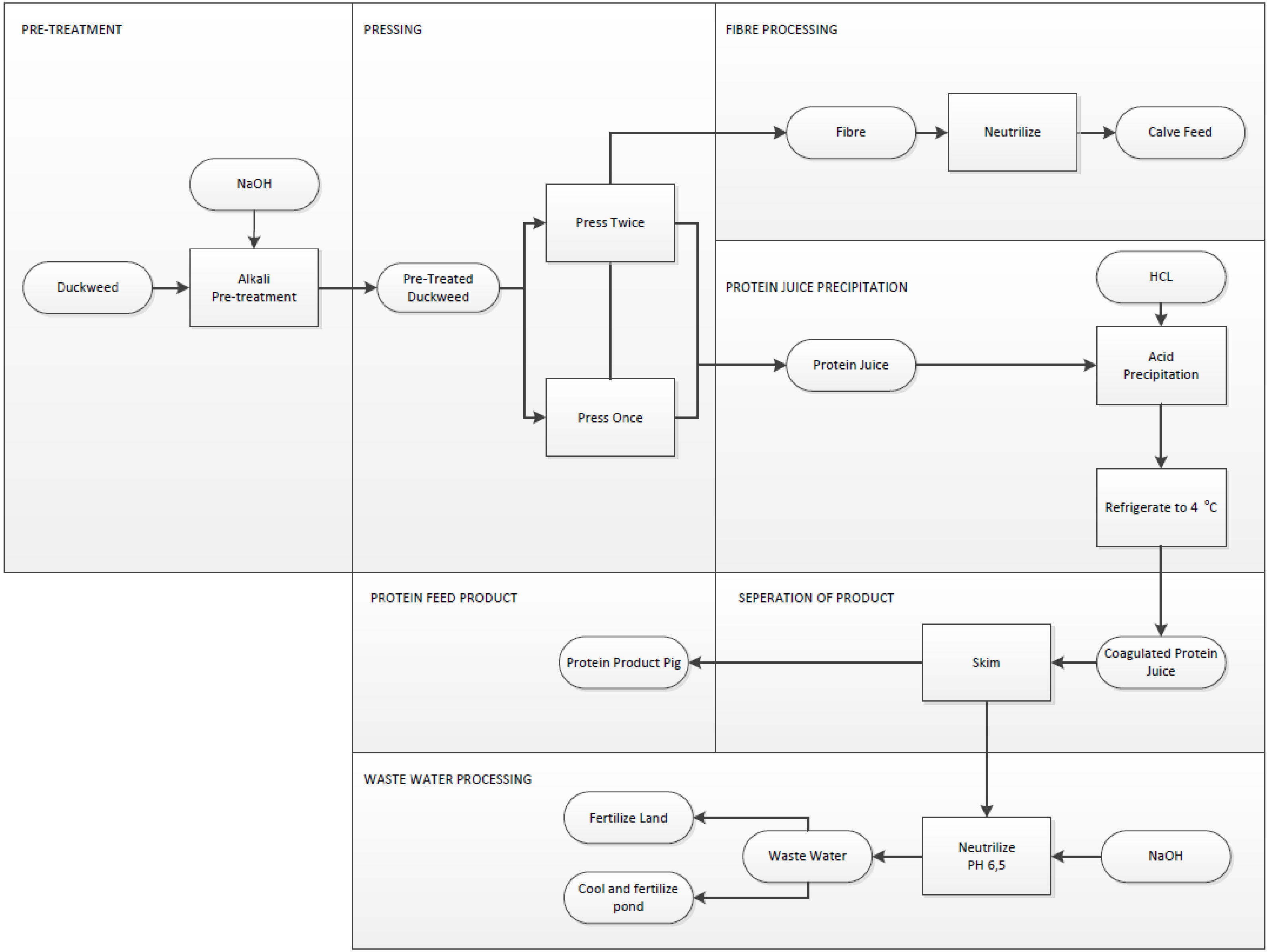
Appendix A - Process schemes

Process 1: System for duckweed based on grass processing



Process 2: System for duckweed based on GTR processing



Appendix B - Model data

Consumables				
HCL			0.1	$€/L$
NaOH			0.2	$€/kg$
Product prices				
Brewers grains	65	$€/ton\ FW$	0.30	$€/kg\ DM$
Soy	370	$€/ton\ FW$	0.74	$€/kg\ CP$
Duckweed	14	$€/ton\ FW$	0.25	$€/kg\ DM$
Energy characteristics				
Energy cost			0.1	$€/kWh$
Screw press	energy usage		0.0049	kWh/kg
Centrifuge	energy usage		0.0044	kWh/kg
Refrigerator	energy usage		160	$kWh/year$
Refrigerator	energy usage		0.88	$kWh/batch$
Size dependent equipment				
	$Capref$		$Costref$	
Screw press	500	kg/h	3000	€
Preheating coil	0.46	m^2	500	€
Centrifuge	500	kg/h	7500	€
Tank	1000	L	2000	€
Tank with heating	500	L	3000	€
Refrigerator	1000	L	1000	€
Size independent equipment				
Skimmer			50	€
Skim bucket			50	€
Press juice container			150	€
IBC			150	€
Injector			1000	€
Boiler and pump			2000	€

Appendix C- Nomenclature

Process 1: System for duckweed based on grass processing

Chemical composition

Symbol	Description	Unit
Fin	Total inflow of duckweed	kg
Fin, i	Inflow of duckweed of certain component	kg
Cin	Concentration of certain component in the start composition of duckweed	$\frac{g}{kg}$
$Fpc1, i$	Weight of certain component after a single pressing in the press cake of duckweed	kg
$FraFibre$	Fractionation percentage	%
$Cpress\#, i$	Concentration of the press cake for different components after either one or two pressings	g/kg
DM, j	The total dry matter content of the dry matter components j in the press cake	kg
$Fpc1$	The total outflow of the press cake after pressing once	kg
$Fpc2$	The total outflow of the press cake after pressing twice	kg
$Fpc\#, DM, j$	The total outflow of a specific dry matter component of the press cake after either one or two pressings.	kg
$Fpc\#, water$	The water content of the press cake after pressing	kg
Fj	The total juice flow before centrifuging	kg
$Fjuice, i$	The total juice flow after centrifuging of each component	kg
$CjuiceABC, i$	Concentration of the press juice for different components according to ABC Kroos data	g/kg
$Fcent$	The total juice flow of the centrifuged juice	kg
$Fmaxcent$	Maximum amount of water which is centrifuged out of the juice	kg
$\alpha Cent$	A percentage of the maximum amount of water centrifuged	$\%$
$Fraction, k$	Fraction of the chemical component ending up in the product	$-$
$Grassjuice, k$	Amount of each component in the press juice	kg
$Product, k$	Amount of each component in the product	kg
$Fproduct, i$	The total flow of each component in the product	kg
$Fwaste, i$	The total flow of each component in the waste water	kg

Income

PDM	The price per kilogram dry matter of brewer's grains	$\frac{€}{kg\ DM}$
BGp	The price of brewer's grains	$\frac{€}{ton}$
Pbg, DM	The dry matter percentage of the brewer's grain	$\%$
IC	Income generated by the fibre product	$\frac{€}{kg\ FW}$
PCP	The price of crude protein derived from soy	$\frac{€}{kg\ CP}$
Sp	Price of soy	$\frac{€}{ton}$
$DMsoy$	the soy dry matter percentage	$\%$
$CPsoy$	the concentration of crude protein in soy	$\frac{g}{kg\ DM}$
IP	Income generated by the protein product	$\frac{€}{kg\ FW}$

$ITotal$	The total income generated by the biorefinery system	$\frac{€}{kg\ FW}$
$IYear$	The total income generated by the biorefinery system in a year	$\frac{€}{year}$
$IRef$	Reference income generated by direct feeding the duckweed	$\frac{€}{kg\ FW}$
DWp	The price of duckweed as a direct feeding sources	$\frac{€}{kg\ DM}$

Energy

$Fcogeneration$	The amount of cogeneration waste water needed to preheat the juice	kg
Cp	Specific heat capacity of water	$\frac{J}{kg°C}$
$Thout$	The temperature of duckweed press juice after preheating	°C
$Thin$	Temperature of the cogeneration waste water before preheating	°C
$Tcout$	The temperature of duckweed press juice after preheating	°C
$Tcin$	The temperature of duckweed press juice before preheating	°C
$\Delta \log(T)$	Logarithmic mean temperature difference	°C
HL	Heat loss during preheating	%
$Qheat$	Energy needed to preheat	kJ
t	Time needed to preheat the juice.	h
$Wcoil$	Required power which needs to be supplied by the heating coil	$\frac{J}{s}$
$Ucoil$	Overall heat transmission coefficient for a water to water heat exchanger with copper as transmission material	$\frac{W}{m^2°C}$
$Acoil$	Heat exchange area	m^2
$hout$	Specific enthalpy of the press juice at 85 °C	$\frac{kJ}{kg}$
hin	Specific enthalpy at 45 °C	$\frac{kJ}{kg}$
$hstoom250$	Specific enthalpy needed to heat the cogeneration water to steam of 250 °C	$\frac{kJ}{kg}$
$Fsteam$	Amount of steam needed to reach a certain temperature	kg
$Part1$	Energy needed to heat water to 100 °C	kJ
$Part2$	Energy needed to evaporate all the water	kJ
$Part3$	Energy needed to heat the steam to 250 °C	kJ
Hv	The heat of evaporation of water	$\frac{kJ}{kg}$
$Cpsteam$	The specific heat capacity of steam	$\frac{J}{kg°C}$
$Tsteam$	End temperature of the steam	°C
$Vtank$	Volume of the tank	m^3
TF	Tank factor, extra factor to make sure the tank is a fraction larger than the volume of the juice	-
ρ	Density of water	$\frac{kg}{m^3}$
h	Height of the tank	m
d	Diameter of the tank	m
$Atank$	Outer surface of the tank	m^2

$Mtank$	Mass of the tank	kg
TS	Thickness of the steel tank	m
$Tamb$	Ambient temperature	°C
$Qtank$	Energy required to heat the tank	kJ
$Qjuice$	Energy required to heat up to juice	kJ
$Qtot$	Total energy required for the heat coagulation	kJ
Tm	Mean temperature	°C
ΔTm	Mean temperature difference	°C
$Wtank$	Energy transfer loss of the tank	J/s
$Wheater$	Heating capacity of the heater	J/s
$Wtot$	Effective total heat transfer of the heating tank	J/s
$Wmaintain$	Energy transfer needed to maintain the temperature	J/s
$Utank$	Overall heat transmission coefficient the heating tank	$\frac{W}{m^2 °C}$
E	Energy used by heating with a heating tank	kWh
tm	Time the temperature in is maintained to make sure all the proteins are coagulated	h
th	Time needed to reach the coagulation temperature.	h

Costs

$CostEnergy$	Costs involved with the energy consumed	€
$Energy$	Energy consumption	kWh
EP	Energy price	$\frac{€}{kWh}$
$Costs1$	The costs of a size dependent piece of equipment	€
$Cap1$	The desired size of a piece of equipment	-
$Costref$	The costs of a reference sized piece of equipment	€
$Capref$	The size of a piece of equipment with known costs	-
EWc	The energy consumption of a centrifuge per weight processed	$\frac{kWh}{kg}$
$Ecentrifuge$	Energy consumption of a centrifuge	kWh
$Epress1$	Energy consumption of single pressed fibre	kWh
$Epress2$	Energy consumption of two pressed fibre	kWh
EWp	The energy consumption of a press per weight processed	$\frac{kWh}{kg}$
$DSCost, c$	Design specific costs	€
DTc	Result of the decision tree of centrifuging for both energy and investment costs	-
DTp	Result of the decision tree of pressing for both energy and investment costs	-
DTh	Result of the decision tree of heating for both energy and investment costs	-
$CCost$	Total investment costs before LANG	€
$LANG$	A ratio of the total cost of installing a process to the cost of the total equipment needed in a process	-
$ICost$	Investment costs	€
$Maintainance$	Total costs for maintenance a year	€
$Interest$	Total costs of interest a year	€
CDM	Cost per dry matter of both products	$\frac{€}{kg\ DM}$

Process 2: System for duckweed based on GTR processing

Ex, CP	Amount of crude protein ending up in the extractant	kg
PY	Protein yield	$\frac{g}{kg}$
Ex, DM	Amount of dry matter ending up in the extractant	kg
$purity$	The purity of the protein product	%
$\sum Ex, i$	Sum of the dry matter components excluding crude protein	kg
$Fraction, i$	The fraction of the dry matter components excluding crude protein	-
Ex, i	Amount of component ending up in the extractant	kg
NEx, j	Amount of component not ending up in the extractant	kg
C_OH	Concentration OH^- needed to reach a certain pH	$\frac{Mol}{L}$
$MINNaOH$	Minimum amount of Mol needed to reach a certain pH	Mol
BF	Buffering factor	$-$
$MAXNaOH$	Maximum amount of Mol needed to reach a certain pH	Mol
$Consumption$	Actual consumption of moles to reach a certain pH	Mol
$WNaoh$	Weight of NaOH added to reach a certain pH	kg
$Mw, NaOH$	The molar mass of NaOH	$\frac{g}{mol}$
CA_OH	Actual concentration of NaOH after adding extra mol to compensate for the buffering in duckweed	$\frac{Mol}{L}$
$Fibre, OH$	The amount of OH^- which ends up in the fibre fraction	Mol
$OHpressed$	The amount of OH^- that is pressed out by the second pressing and ends up in the juice fraction	Mol
$Juice, OH$	The amount of OH^- which ends up in the final juice fraction	Mol
$FNFibre$	Flow of the neutralized fibre	kg
HCL	Hydrogen chloride	-
$NaOH$	Sodium hydroxide	-
H_2O	Water	-
$NaCL$	Sodium chloride	-
$FNFibre, HCL$	Amount of Mol HCl needed to neutrilize the fibre	Mol
$FFibre, OH$	Amount of Mol OH^- in the fibres	Mol
$mol, Water$	Moles $Water$ formed	Mol
$mol, NaCL$	Moles $NaCL$ formed	Mol
$AddedHCL$	The amount of HCl solution that needs to be added to neutralize	L
$MxHCL$	Concentration of the HCl solution	$\frac{Mol}{L}$
$AddedWater$	The amount of water added to the juice when the HCl solution is added	kg
$Formed, n$	Amount of component n formed during reaction	kg
Mw, n	Molar mass of component n	$\frac{g}{mol}$
C_H	H^+ concentration needed to reach pH of 3.5	$\frac{Mol}{L}$
$FNJuice$	Total neutralized juice flow	kg
$FNJuice, HCL3.5$	Amount of HCL needed to lower the pH to 3.5 after neutralization	Mol
AP	the amount of moles HCL needed to perform the acid precipitation	Mol
$AFJuice$	Acid precipitated juice	kg
End	Final protein product flow	kg
$EndPurity$	Final purity of the end product	$\frac{g}{kg\ DM}$

$Recovery$	The amount of protein recovered after acid precipitation	%
WW	Total waste water flow	kg
αDM	Dry matter percentage in the end product	%
$Fproduct$	Total product flow	kg
FFA	Factor to adapt the price of brewer's grains to the better chemical composition of system 2 press cake	-
$Refrigirator, c$	The energy and investment costs of a size dependent refrigerator	-
$HCLCosts$	The costs of the consumable HCL	$\frac{€}{batch}$
$NaOHCosts$	The costs of the consumable $NaOH$	$\frac{€}{batch}$
$pHCL$	Prices per liter of HCl	€
$pNaOH$	Price per kilogram $NaOH$	€

Appendix D – Expressions

Process 1: System for duckweed based on grass processing

Chemical composition

$$Fin,i = Fin * Cin,i \qquad for\ each\ component\ of\ i \qquad [kg] \quad (1.1)$$

i for component:	Symbol used
Crude protein	CP
Fat	Fa
Fibre	Fi
Ash	Ash
Total carbohydrates	TC
Polyphenol	PP
Water	$water$
Dry matter content	DM

$$Fpc1,i = Fin * \frac{FraFibre}{100} * \frac{Cpress,i}{1000} \qquad for\ each\ component\ of\ i \qquad [kg] \quad (1.2)$$

$$Fpc1,DM,j = Fpc2,DM,j = Fpc\#,DM,j \qquad [kg] \quad (1.3)$$

j for component:	Symbol used
Crude protein	CP
Fat	Fa
Fibre	Fi
Ash	Ash
Total carbohydrates	TC
Polyphenol	PP
#	Number of pressings $1\ or\ 2$

$$Fpc2, water = Fin * \frac{FraFibre}{100} * \frac{Fpc1, DM}{1000} * \frac{Cpress2, water}{1000 - Cpress2, water} \quad [kg] \quad (1.4)$$

$$Fin, DM, j - Fpc, DM, j = Fj, DM, j \quad [kg] \quad (1.5)$$

$$Fj, DM, i = Fjuice, DM, i \quad [kg] \quad (1.6)$$

$$Fin * \frac{100 - FraFibre}{100} = Fj \quad [kg] \quad (1.7)$$

$$Fj = Fj, DM, j + Fj, water \quad [kg] \quad (1.8)$$

$$Fcent, water = \frac{Fj, DM * CjuiceABC, water}{CjuiceABC, DM} \quad [kg] \quad (1.9)$$

$$Fcent = Fcent, water + Fj, DM \quad [kg] \quad (1.10)$$

$$Fmaxcent = Fj - Fcent \quad [kg] \quad (1.11)$$

$$Fjuice = Fj - \frac{\alpha Cent}{100} * Fmaxcent \quad [kg] \quad (1.12)$$

$$Fraction, k = \frac{Grassjuice, k}{Product, k} \quad [-] \quad (1.13)$$

k for component:	Symbol used
Water	$water$
Crude protein	CP
Fibre	Fi
Ash	Ash

$$Fjuice, i * Fraction, i = Fproduct, i \quad [kg] \quad (1.14)$$

$$\sum Fproduct, DM, j = Fproduct, DM \quad [kg] \quad (1.15)$$

$$Fwaste, i = Fjuice, i - Fproduct, i \quad [kg] \quad (1.16)$$

Income

$$PDM = \frac{BGp}{10 * bg, DM} \quad [\frac{€}{kg\ DM}] \quad (1.17)$$

$$IC = \frac{Fpc, DM * PDM}{Fin} \quad [\frac{€}{kg\ FW}] \quad (1.18)$$

$$PCP = 100 * \frac{Sp}{DMsoy * CPsoy} \quad [\frac{€}{kg\ CP}] \quad (1.19)$$

$$IP = \frac{PCP * Fproduct, CP}{Fin} \quad [\frac{€}{kg\ FW}] \quad (1.20)$$

$$ITotal = IP + IC \quad [\frac{€}{kg\ FW}] \quad (1.21)$$

$$IYear = Fin * ITotal \text{ or } IRef * \frac{365}{2} \quad [\frac{€}{year}] \quad (1.22)$$

$$IRef = \frac{Fin}{Fin, DM} * DWp \quad [\frac{€}{kg\ FW}] \quad (1.23)$$

Energy

$$Fcogeneration = Fjuice * 1.5 \quad [kg] \quad (1.24)$$

$$Thout = \frac{(Fin * Cp * (Tcout - Tcin)) - (Fcogeneration * Cp * Thin)}{Fcogeneration * Cp} \quad [°C] \quad (1.25)$$

$$\Delta \log(T) = \frac{(Thin - Tcin) - (Thout - Tcout)}{LN\left(\frac{Thin - Tcin}{Thout - Tcout}\right)} \quad [°C] \quad (1.26)$$

$$Qheat = Fjuice * \frac{Cp}{1000} * (Tcout - Tcin) * \left(\frac{100 + HL}{100}\right) \quad [kJ] \quad (1.27)$$

$$Wcoil = 1000 * \frac{Qheat}{t} \quad [\frac{J}{s}] \quad (1.28)$$

$$Wcoil = Ucoil * Acoil * \Delta \log(T) \quad [\frac{J}{s}] \quad (1.29)$$

$$Acoil = \frac{Q}{t * U * \Delta logT} \quad [m^2] \quad (1.30)$$

$$\frac{(Fjuice * hout) - (Fjuice * hin)}{(hstoom250 - hout)} = Fsteam \quad [kg] \quad (1.31)$$

Heating water to 100 °C

$$Part1 = \frac{Fsteam * Cp}{1000 * (100 - Thin)} \quad [kJ] \quad (1.32)$$

Evaporating water

$$Part2 = Fsteam * Hv \quad [kJ] \quad (1.33)$$

Heating steam to 250 °C

$$Part3 = (Tsteam - 100) * \frac{Cpsteam}{1000} * Fsteam \quad [kJ] \quad (1.34)$$

$$Total\ energy\ heating \qquad Qsteam = Part1 + Part2 + Part3 \qquad [kJ] \qquad (1.35)$$

$$Vtank = TF * \frac{Fjuice}{\rho} \qquad [m^3] \qquad (1.36)$$

$$h = d = \frac{Vtank}{(0.25 * \pi)^{\frac{1}{3}}} \qquad [m] \qquad (1.37)$$

$$Atank = 2 * \left(\frac{1}{4} * \pi * h^2\right) + \pi * h * d \qquad [m] \qquad (1.38)$$

$$Mtank = Atank * TS * \rho \qquad [kg] \qquad (1.39)$$

$$Qtank = Mtank * \frac{Cpsteel}{1000} * (Tend - Tamb) \qquad [kJ] \qquad (1.40)$$

$$Qjuice = Fjuice * \frac{Cp}{1000} * (Tend - Tcout) \qquad [kJ] \qquad (1.41)$$

$$Qtot = Qtank + Qjuice \qquad [kJ] \qquad (1.42)$$

$$Tm = \frac{Tamb + Tend}{2} \qquad [°C] \qquad (1.43)$$

$$\Delta Tm = Tm - Tamb \qquad [°C] \qquad (1.44)$$

$$Wtank = Utank * Atank * \Delta Tm \qquad \left[\frac{J}{s}\right] \qquad (1.45)$$

$$Wtot = Wheater - Wtank \qquad \left[\frac{J}{s}\right] \qquad (1.46)$$

$$th = \frac{Qtot}{3600 * Wtot} \qquad [h] \qquad (1.47)$$

$$Wmaintain = Utank * Atank * (Tend - Tamb) \qquad \left[\frac{J}{s}\right] \qquad (1.48)$$

$$E = Wheater * th + Wmaintain * tm \qquad [kWh] \qquad (1.49)$$

Costs

$$CostEnergy = Energy * EP \qquad [€] \qquad (1.50)$$

$$Costs1 = Costref * \left(\frac{Cap1}{Capref}\right)^{0.6} \qquad [€] \qquad (1.51)$$

$For\ a\ centrifuge:$ $$Cap1 = Fjuice \qquad [kg] \qquad (1.52)$$

$$Ecentrifuge = Fjuice * EWc \qquad [kg] \qquad (1.53)$$

$For\ a\ press:$ $$Cap1 = Fin \qquad [kg] \qquad (1.54)$$

$$Epress1 = Fin * EWp \qquad [kWh] \qquad (1.55)$$

$$Epress2 = (Fin + Fpc1) * EWp \qquad [kWh] \qquad (1.56)$$

$Level\ 1$ $For\ a\ coil:$ $$Cap1 = Acoil \qquad [m^2] \qquad (1.57)$$

$Level\ 2$ $For\ a\ heating\ tank:$ $$Cap1 = Fjuice \qquad [kg] \qquad (1.58)$$

c for cost component:	Symbol used
Energy	$Energy$
Investment	$Investment$

$$DSCost, c = DTc, c + DTp, c + DTh, c \qquad [€] \qquad (1.59)$$

$$CCost = (DSCost, investment + FCost) \qquad [€] \qquad (1.60)$$

$$ICost = CCost * LANG \qquad [€] \qquad (1.61)$$

$$Maintainance = ICosts * 5\ \% \qquad [\frac{€}{year}] \qquad (1.62)$$

$$Interest = ICosts * 6\% \qquad [\frac{€}{year}] \qquad (1.63)$$

$$CDM = \frac{DSCost, energy + Maintainance + Interest}{Fproduct, DM + Fpc, DM * \frac{365}{2}} \qquad [\frac{€}{kg\ DM}] \qquad (1.64)$$

$$DSCost, c = DTc, c + DTp, c + DTh, c \qquad [€] \qquad (1.65)$$

Process 2: System for duckweed based on GTR processing

$$Ex,CP = Fin,CP * \frac{PY}{1000} \quad [kg] \quad (2.1)$$

$$Ex,DM = \frac{Ex,CP * 1000}{purity} \quad [kg] \quad (2.2)$$

$$\sum Ex,i = Ex,DM - Ex,CP \quad [kg] \quad (2.3)$$

$$Fraction,i = \frac{Fin,i}{\sum Fin,i} \quad [-] \quad (2.4)$$

$$Ex,i = \sum Ex,i * Fraction,i \quad [kg] \quad (2.5)$$

$$NEx,j = Fin,j - Ex,j \quad [kg] \quad (2.6)$$

i for component:	Symbol used
Fat	Fa
Fibre	Fi
Ash	Ash
Total carbohydrates	TC
Polyphenol	PP
j for component:	Symbol used
Crude protein	CP
Fat	Fa
Fibre	Fi
Ash	Ash
Total carbohydrates	TC
Polyphenol	PP
Dry matter content	DM

$$NEx,j = FFibre\#,j \quad \text{for each component of } j \qquad [kg] \qquad (2.7)$$

$$Ex,j = FJuice\#,j \quad \text{for each component of } j \qquad [kg] \qquad (2.8)$$

$$FFibre\#,water = FFibre\#,DM * \frac{Cpress\#,water}{1000 - Cpress\#,water} \qquad [kg] \qquad (2.9)$$

$$FFibre\# = FFibre\#,DM + FFibre\#,water \qquad [kg] \qquad (2.10)$$

$$Fjuice,water = Fin,water - FFibre\#,water \qquad [kg] \qquad (2.11)$$

$$Fjuice = Fin - FFibre\# \qquad [kg] \qquad (2.12)$$

$$C\_OH = 10^{14-pH} \qquad [\frac{Mol}{L}] \qquad (2.13)$$

$$MINNaOH = Fin,water * \rho * C\_OH \qquad [Mol] \qquad (2.14)$$

$$MAXNaOH = MINNaOH * BF \qquad [Mol] \qquad (2.15)$$

$$MINNaOH \leq Consumption \leq MAXNaOH \qquad [Mol] \qquad (2.16)$$

$$WNaOH = Consumption * \frac{Mw,NaOH}{1000} \qquad [kg] \qquad (2.17)$$

$$CA\_OH = \frac{Consumption}{Fin,Water} \qquad [\frac{Mol}{L}] \qquad (2.18)$$

$$Fibre,OH = FFibre\#,water * CA\_OH \qquad [Mol] \qquad (2.19)$$

$$OHpressed = FFibre1,water * CA\_OH * -Fibre2,water * CA\_OH \quad \text{if } \# = 1 \; OHpressed = 0 \qquad [Mol] \qquad (2.20)$$

$$Juice,OH = FJuice,water * CA\_OH + OHpressed \qquad [Mol] \qquad (2.21)$$

$$FFibre,DM,l = FNFibre,DM,l \quad \text{for each component of } l \qquad [kg] \qquad (2.22)$$

l for component:	Symbol used
Crude protein	CP
Fat	Fa
Fibre	Fi
Ash	Ash
Total carbohydrates	TC
Polyphenol	PP

$$HCL + NaOH \rightarrow H_2O + NaCL \quad (2.23)$$

$$Fibre \quad FNFibre, HCL = FFibre, OH \quad Juice \quad FNJuice, HCL = FJuice, OH \quad [Mol] \quad (2.24)$$

$$General \quad FN, p, HCL = F, p, OH \quad [Mol] \quad (2.25)$$

$$for\ each\ product\ of\ p$$

$$FNFibre, HCL = mol, Water\# = mol, NaCL\# \quad [Mol] \quad (2.26)$$

p for component:	Symbol used
Juice	$Juice$
Fibre	$Fibre$

$$AddedHCL = \frac{FN, p, HCL}{MxHCL} \quad [L] \quad (2.27)$$

$$x\ dependent\ on\ fibre\ or\ juice$$

$$AddedWater = AddedHCL * \frac{\alpha Water}{100} \quad [L] \quad (2.28)$$

$$diffent\ \alpha Water\ for\ product\ of\ p$$

$$Formed, n = mol, n\# * \frac{Mw, n}{1000} \quad [kg] \quad (2.29)$$

$$FNFibre\#, water = FFibre\#, water + Formed, water \quad [kg] \quad (2.30)$$

$$FNFibre\# = FNFibre\#, water + FNFibre, DM \qquad [kg] \qquad (2.31)$$

n for component:	Symbol used
Water	$Water$
HCL	HCL

$$C\_H = 10^{-pH} \qquad [\frac{Mol}{L}] \qquad (2.32)$$

$$FNJuice, HCL3.5 = FNJuice, water * C\_H \qquad [Mol] \qquad (2.33)$$

$$AP = FNJuice, HCL + FNJuice, HCL3.5 \qquad [Mol] \qquad (2.34)$$

$$added\ HCL = \frac{AP}{M32HCL} \qquad [L] \qquad (2.35)$$

$$AFJuice, DM, l = FJuice, DM, l \quad for\ each\ component\ of\ l \qquad [kg] \qquad (2.36)$$

$$AFJuice\#, water = Juice\#, water + Formed, water \qquad [kg] \qquad (2.37)$$

$$End, CP = AFJuice, CP * \frac{Recovery}{100} \qquad [kg] \qquad (2.38)$$

$$EndPurity = purity + 180 \qquad [\frac{g}{kg\ DM}] \qquad (2.39)$$

$$End, DM = \frac{End, CP * 1000}{EndPurity} \qquad [kg] \qquad (2.40)$$

$$\sum End, i = End, DM - End, CP \quad for\ each\ component\ of\ i \qquad [kg] \qquad (2.41)$$

$$End, i = \sum End, i * Fraction, i \quad for\ each\ component\ of\ i \qquad [kg] \qquad (2.42)$$

$$WW, j = AFJuice, j - End, j \quad for\ each\ component\ of\ j \qquad [kg] \qquad (2.43)$$

$$End, water = End, DM * (\frac{100 - \alpha DM}{\alpha DM}) \qquad [kg] \qquad (2.44)$$

$$WW, water = FNJuice, water - End, water \qquad [kg] \qquad (2.45)$$

$$WW = WW, water + WW, DM \qquad [kg] \qquad (2.46)$$

$$Fproduct = End, DM + End, water \quad [kg] \quad (2.47)$$

$$PDM = \left(\frac{Pbg}{10 * bg, DM}\right) * FFA \quad [€] \quad (2.48)$$

$$DSCost, c = DTh, c + DTp, c + Refrigerator, c$$
$$for\ c\ energy\ and\ investment \quad [€] \quad (2.49)$$

$$HCLCosts = \sum added\ HCL * pHCL \quad [€] \quad (2.50)$$

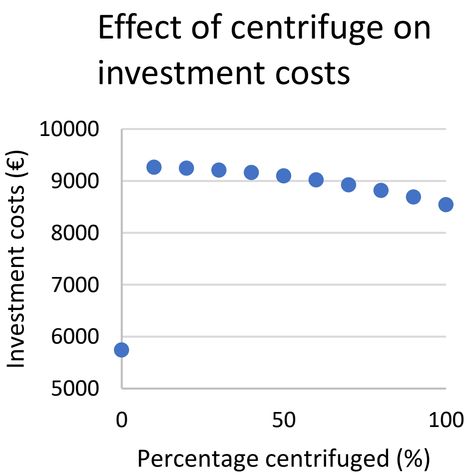
$$NaOHCosts = \sum WNaOH * pNaOH \quad [€] \quad (2.51)$$

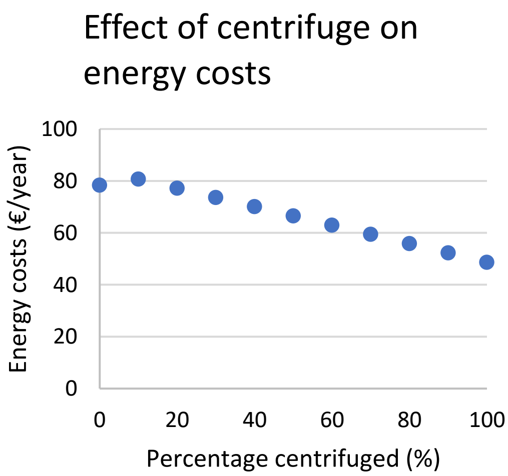
Appendix E - Extra result figures

Changeable model factor	Process 1		Process 2	
	Set on	Unit	Set on	Unit
Pressing	800	g/kg	800	g/kg
Centrifuge	No		-	-
Steam injection	Yes		-	-
Fractionation percentage	15	Percent	-	-
Heat exchanger	Yes		Yes	
Protein purity	-	-	70	%
Protein yield	-	-	670	g/kg
Extra mol added	-	-	20	%
pH	-	-	13	
Temperature	85	ºC	95	ºC
Capacity	150	kg	150	kg
Process size	53,33	Percent	53,33	Percent
	80	kg	80	kg

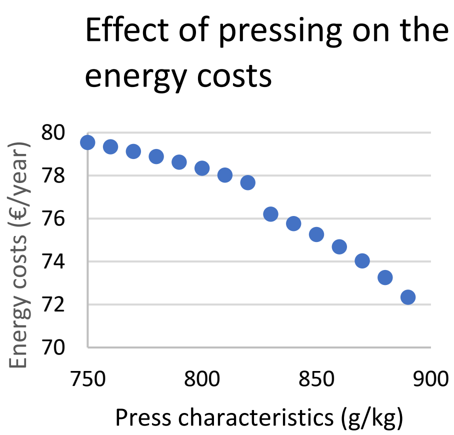
Process 1: System for duckweed based on grass processing

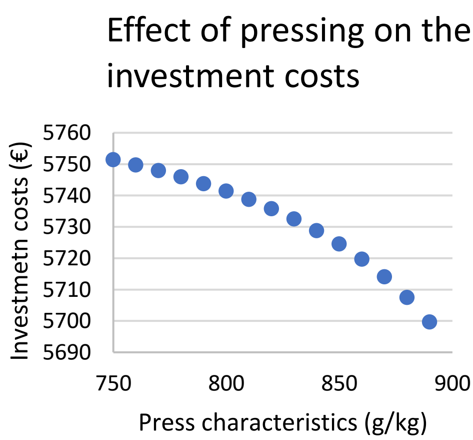
Effect of centrifugation on the investment and yearly costs





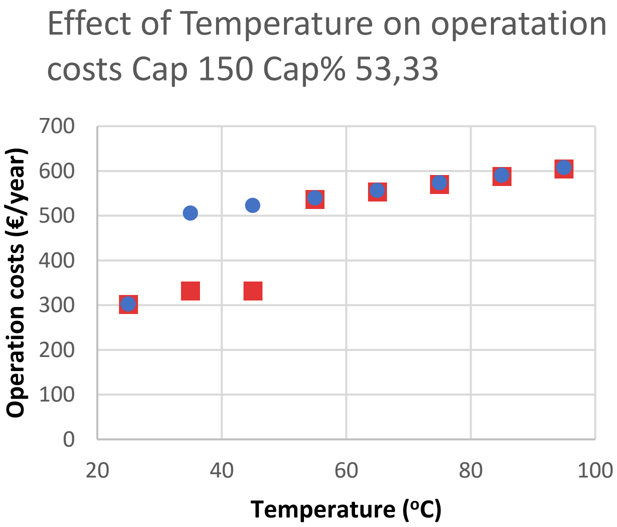
Effect of pressing on the energy and investment costs

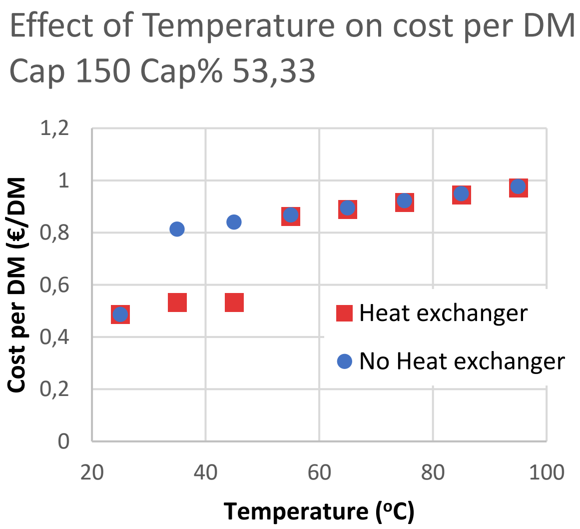




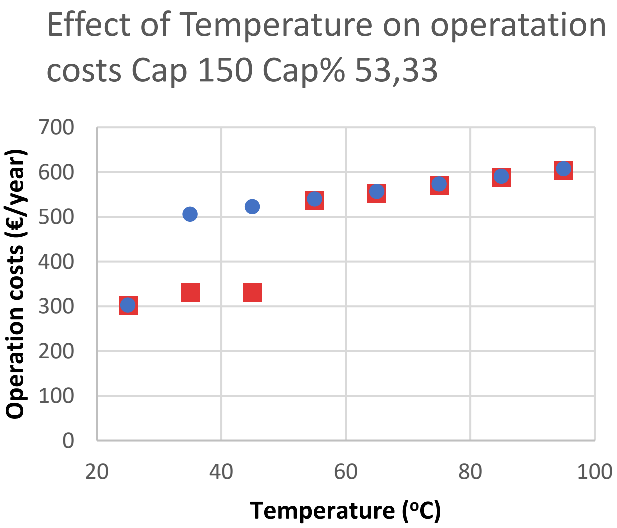
Process 2: System for duckweed based on GTR processing

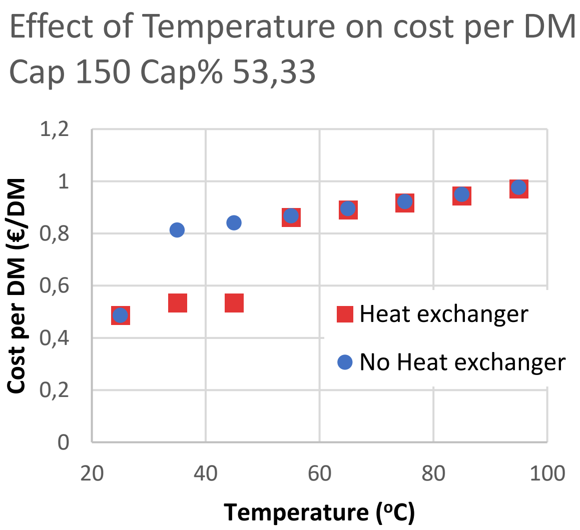
Effect of temperature on the operation costs and costs per dry matter on ECOFERM! scale



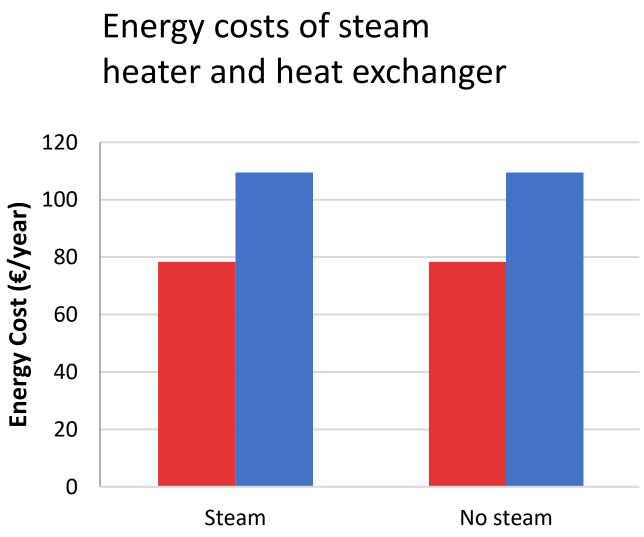


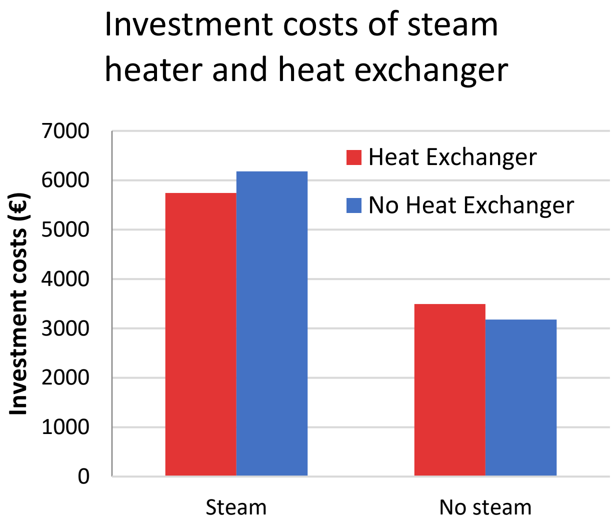
Effect of temperature on the operation costs and costs per dry matter on a larger scale



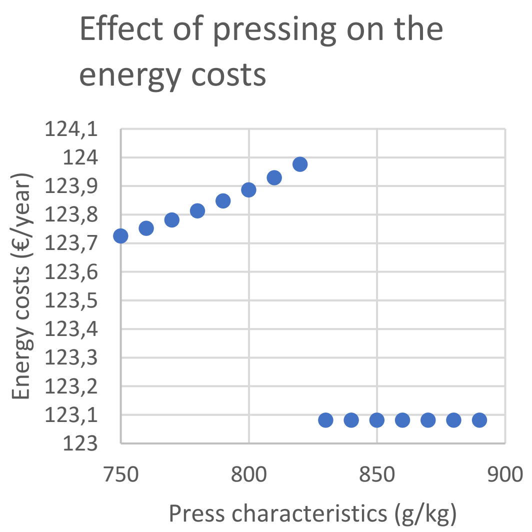


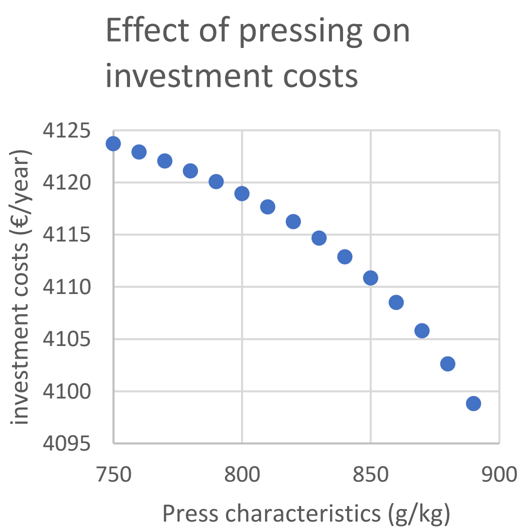
Effect of a steam heater or a heat exchanger on energy and investment costs



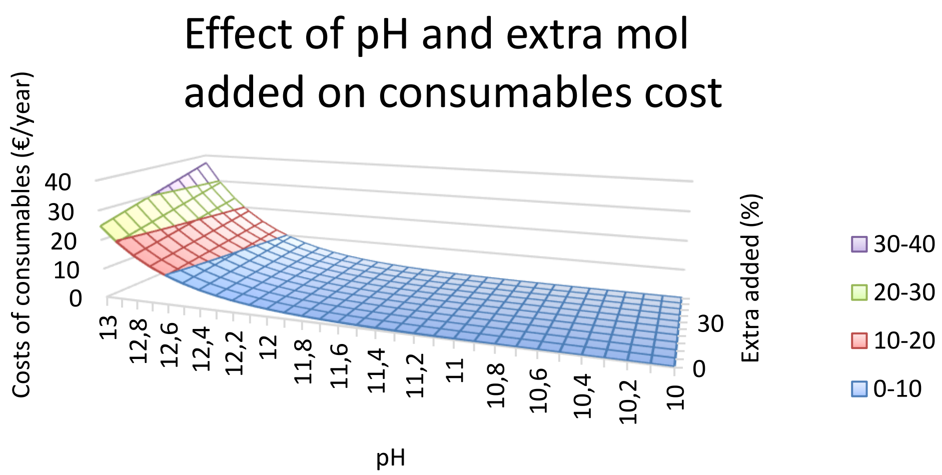


Effect of pressing on the investment and energy costs

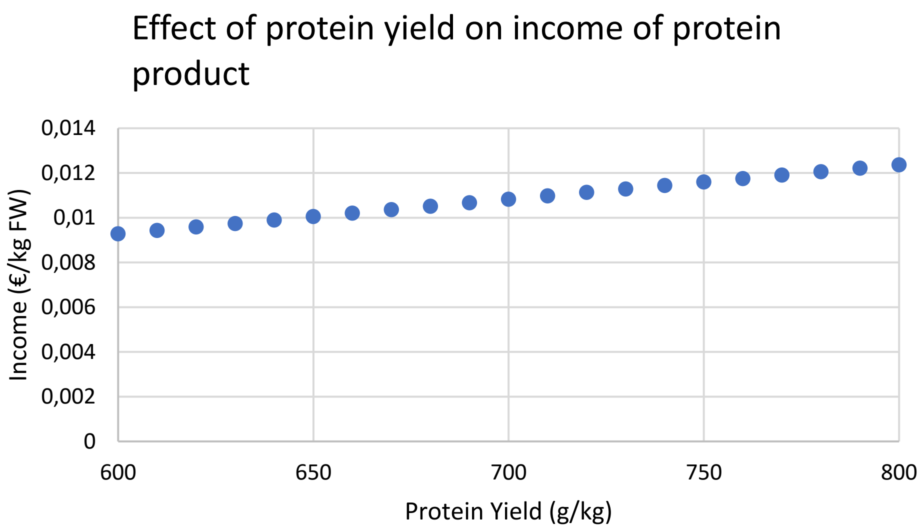




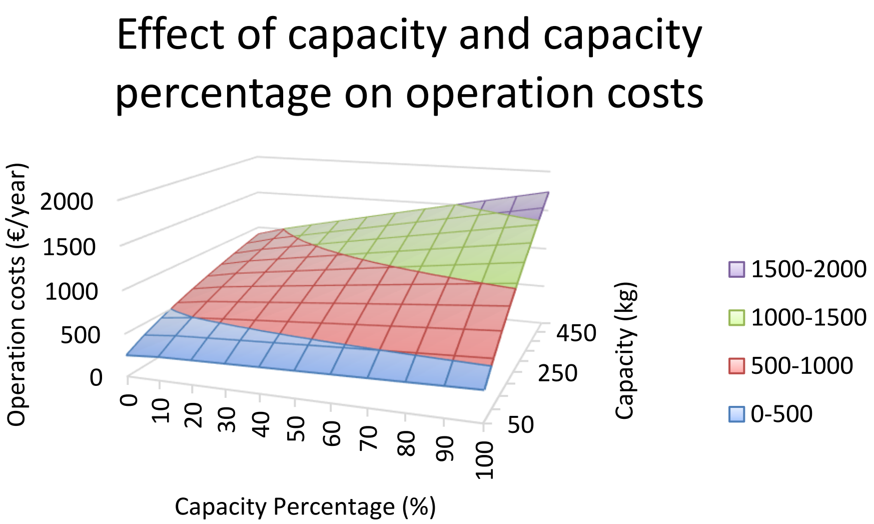
Effect of pH and extra Mol added on the consumables costs



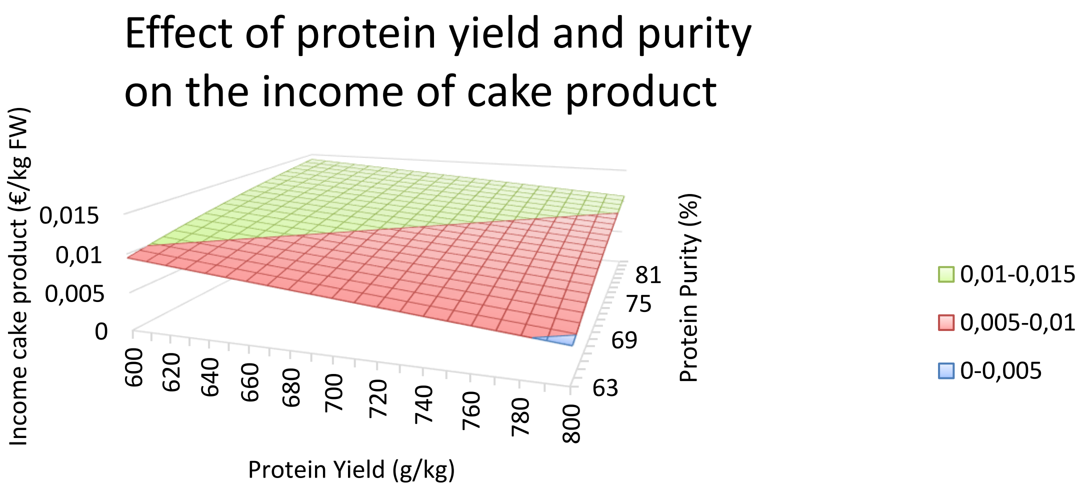
Effect of protein yield on income of protein product



Effect of the capacity and capacity percentage on the operation costs



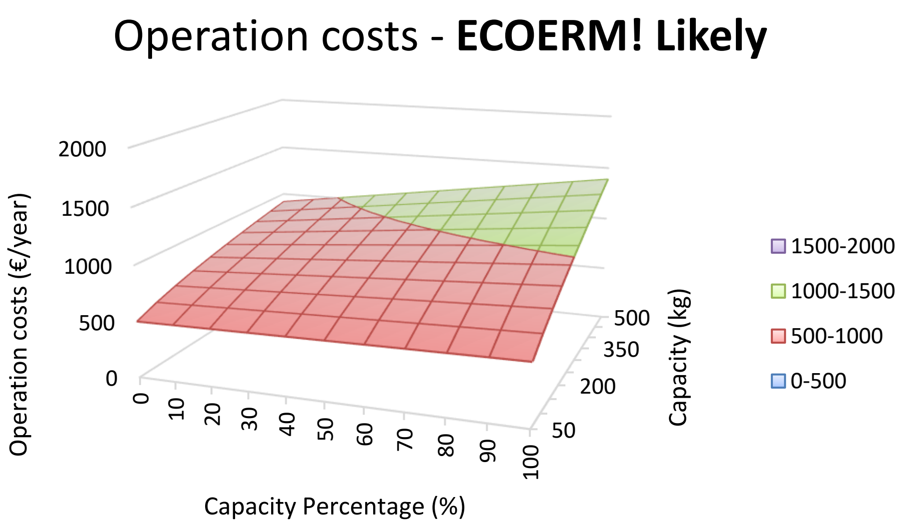
Effect of protein yield and purity on the income of the cake

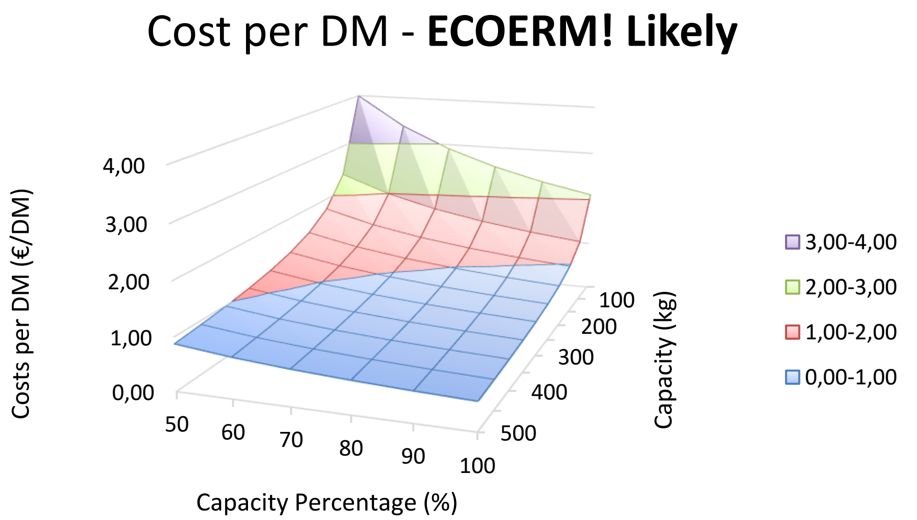


Appendix F – Figures of capacity and capacity percentage from different scenarios

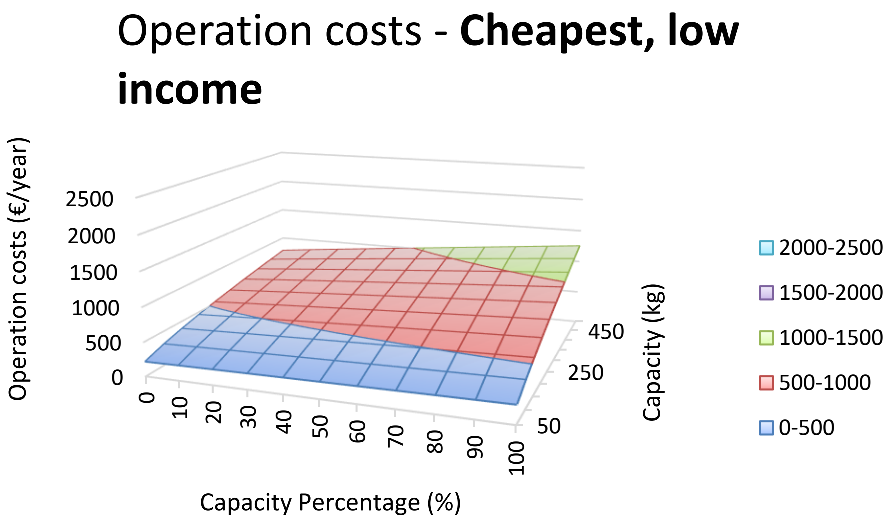
Process 1: System for duckweed based on grass processing

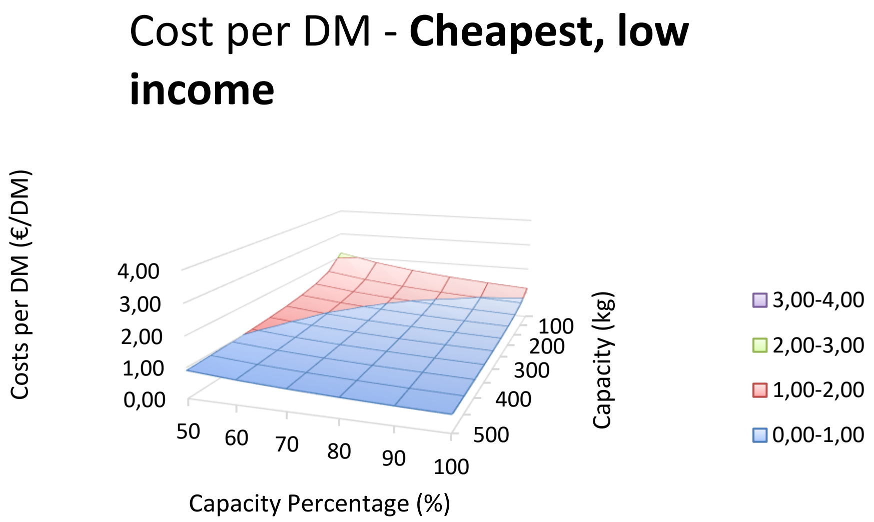
Scenario title	Standard conditions model (ECOFERM!! Likely)		
Changeable model factor		Set on	Unit
Pressing		800	g/kg
Centrifuge		No	
Steam injection		Yes	
Fractionation percentage		15	Percent
Heat exchanger		Yes	



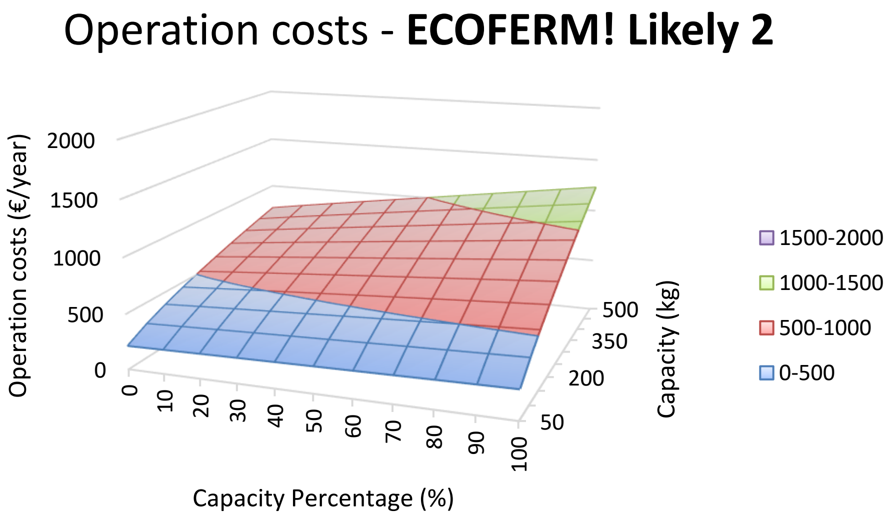


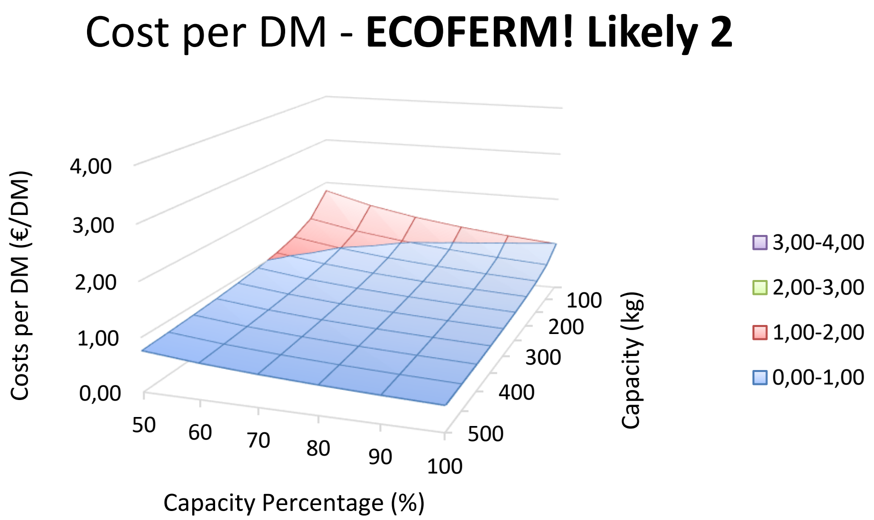
Scenario title	Cheapest, low income		
Changeable model factor		Set on	Unit
Pressing		800	g/kg
Centrifuge		No	
Steam injection		No	
Fractionation percentage		10	Percent
Heat exchanger		No	



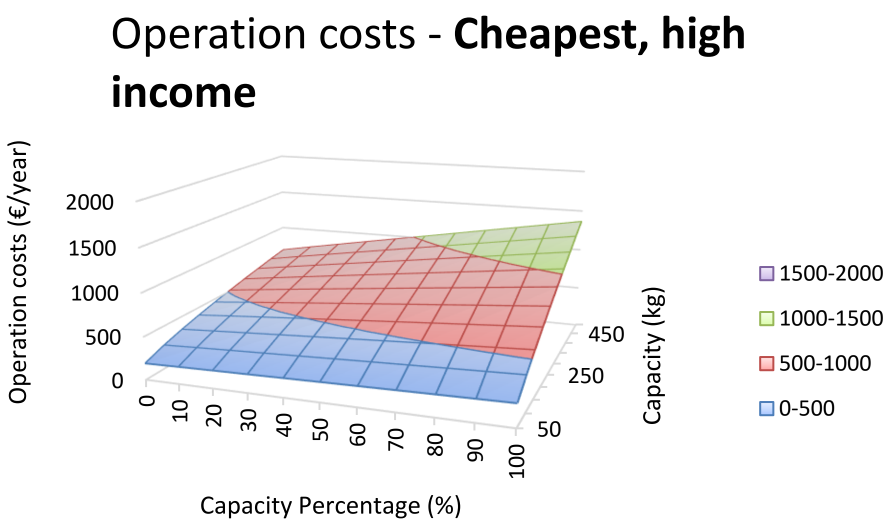


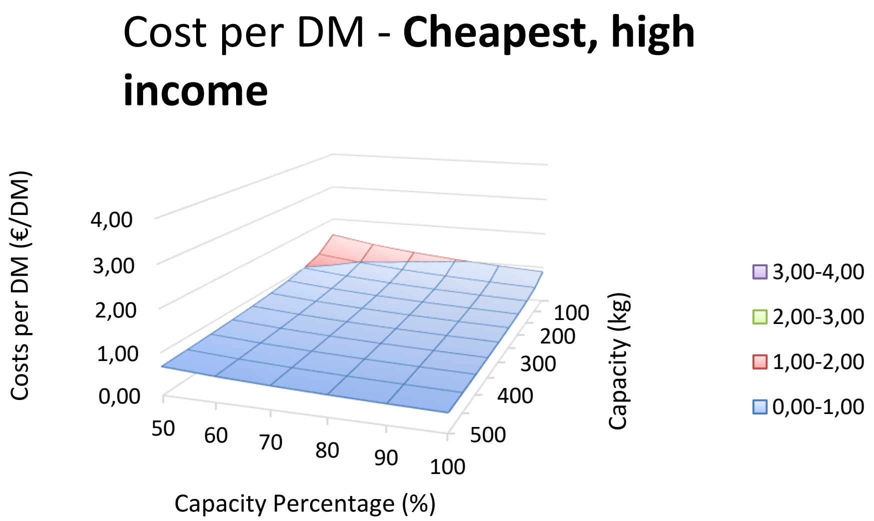
Scenario title	ECOFERM! Likely 2		
Changeable model factor		Set on	Unit
Pressing		800	g/kg
Centrifuge		No	
Steam injection		No	
Fractionation percentage		15	Percent
Heat exchanger		Yes	



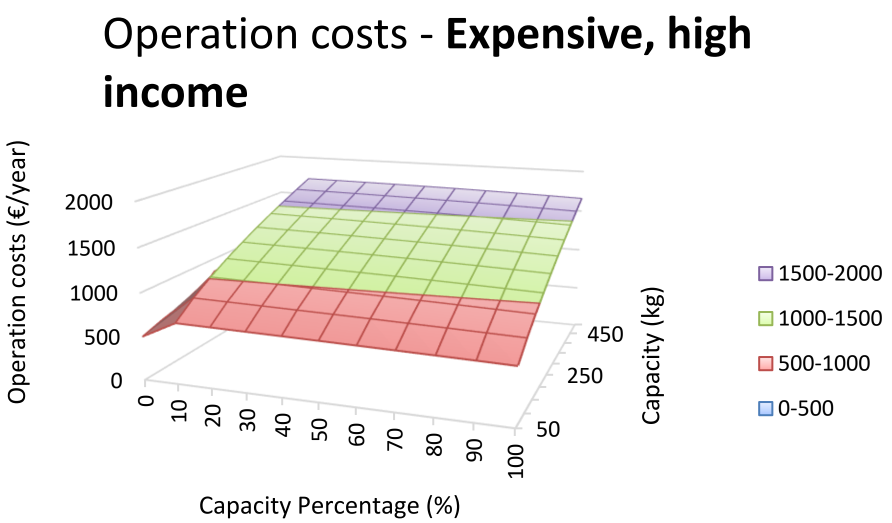


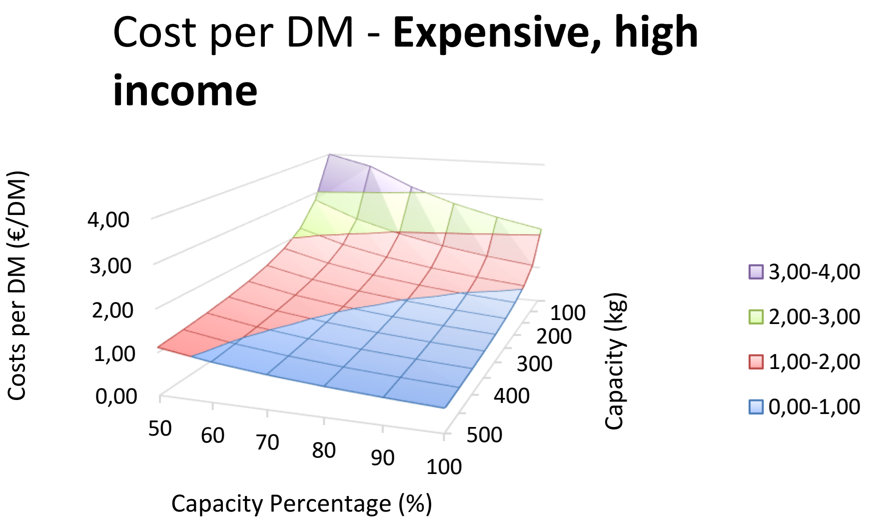
Scenario title	Cheapest, high income		
Changeable model factor		Set on	Unit
Pressing		800	g/kg
Centrifuge		No	
Steam injection		No	
Fractionation percentage		20	Percent
Heat exchanger		No	





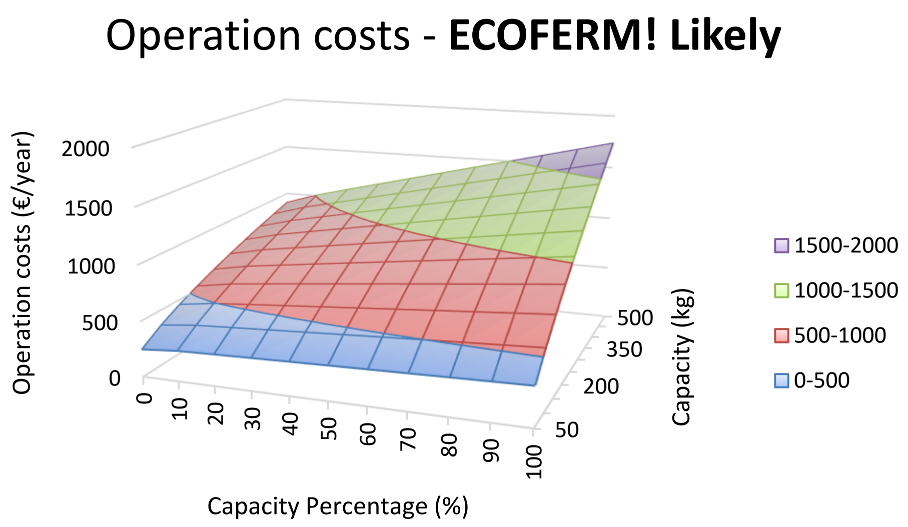
Scenario title	Expensive, high income		
Changeable model factor		Set on	Unit
Pressing		750	g/kg
Centrifuge		Yes	
Steam injection		Yes	
Fractionation percentage		20	Percent
Heat exchanger		Yes	

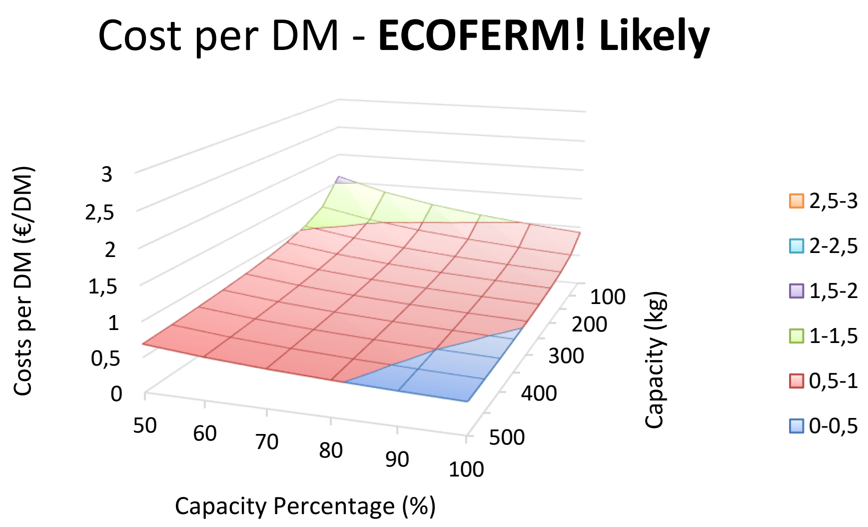




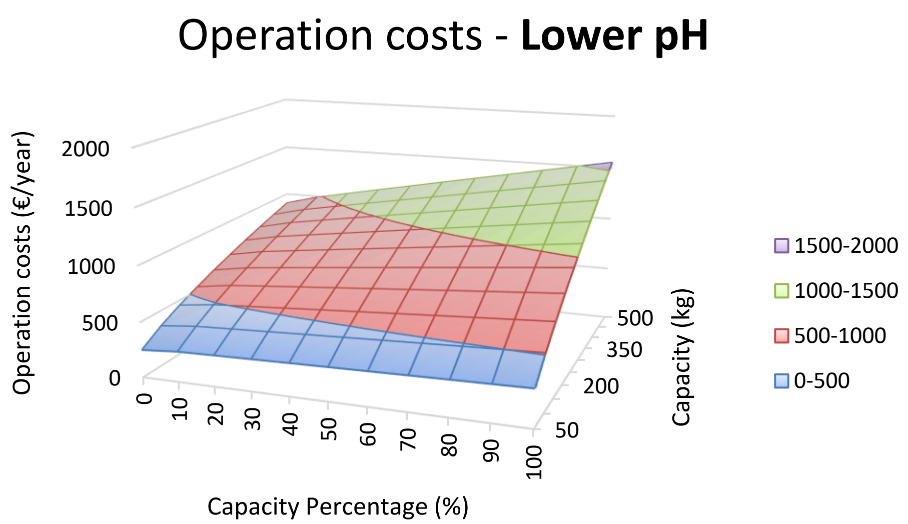
Process 2: System for duckweed based on GTR processing

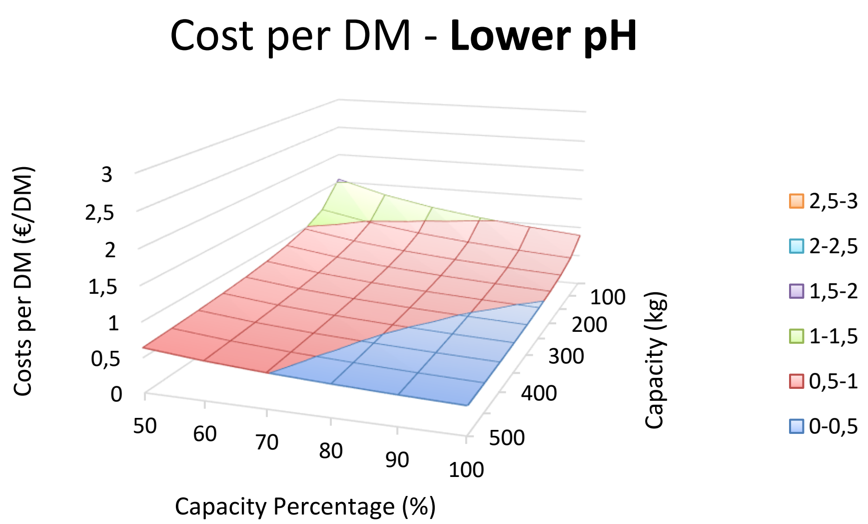
Scenario title	Standard conditions model (ECOFERM! Likely)		
Changeable model factor		Set on	Unit
Pressing		800	g/kg
Extra Mol added		20	%
pH		13	
Temperature		95	°C
Protein purity		70	%
Protein yield		670	g/kg
Heat exchanger		Yes	



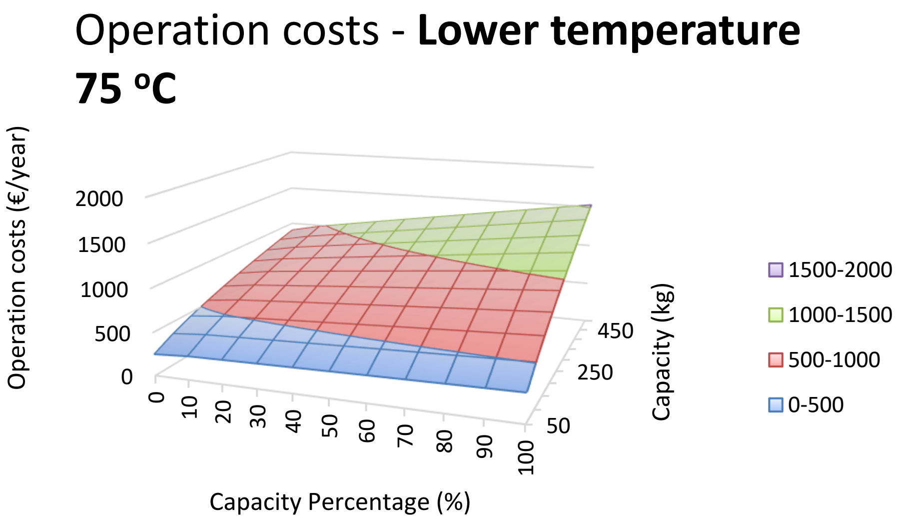


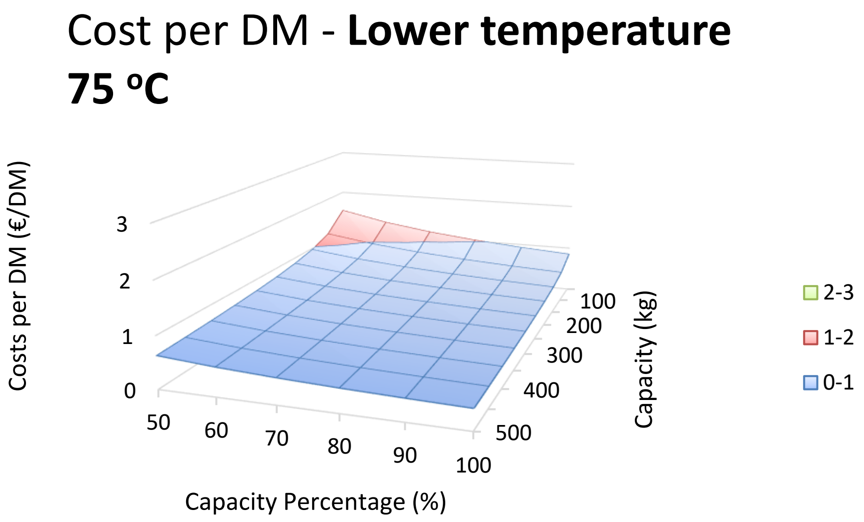
Scenario title	Lower pH		
Changeable model factor		Set on	Unit
Pressing		800	g/kg
Extra Mol added		0	%
pH		11	
Temperature		95	ºC
Protein purity		70	%
Protein yield		670	g/kg
Heat exchanger		Yes	



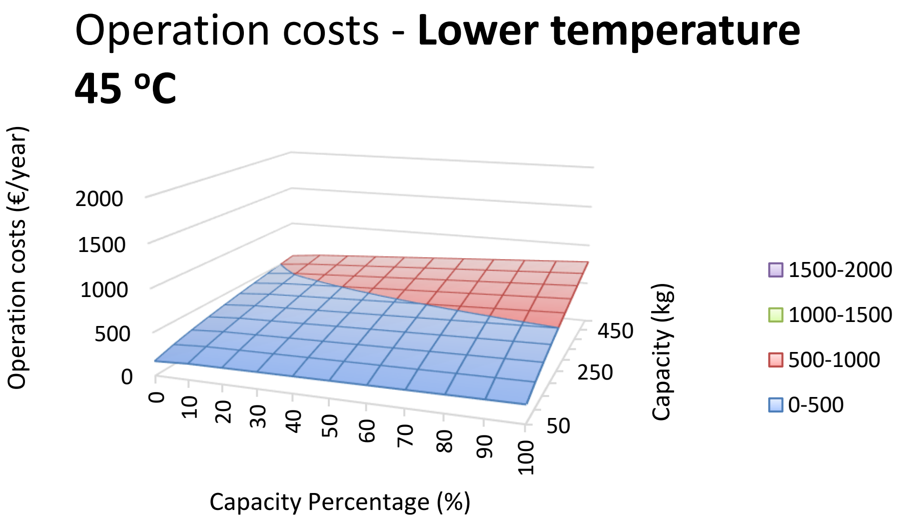


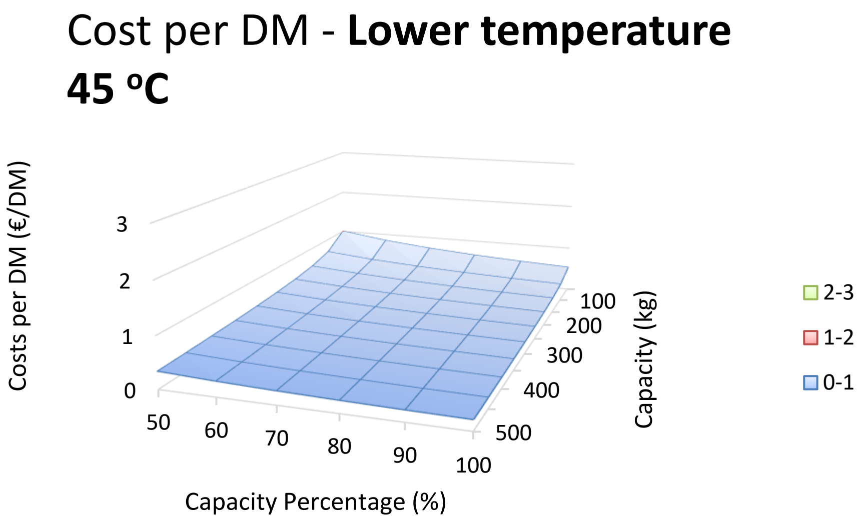
Scenario title	Lower temperature 75 ºC		
Changeable model factor		Set on	Unit
Pressing		800	g/kg
Extra Mol added		20	%
pH		13	
Temperature		75	ºC
Protein purity		70	%
Protein yield		670	g/kg
Heat exchanger		Yes	



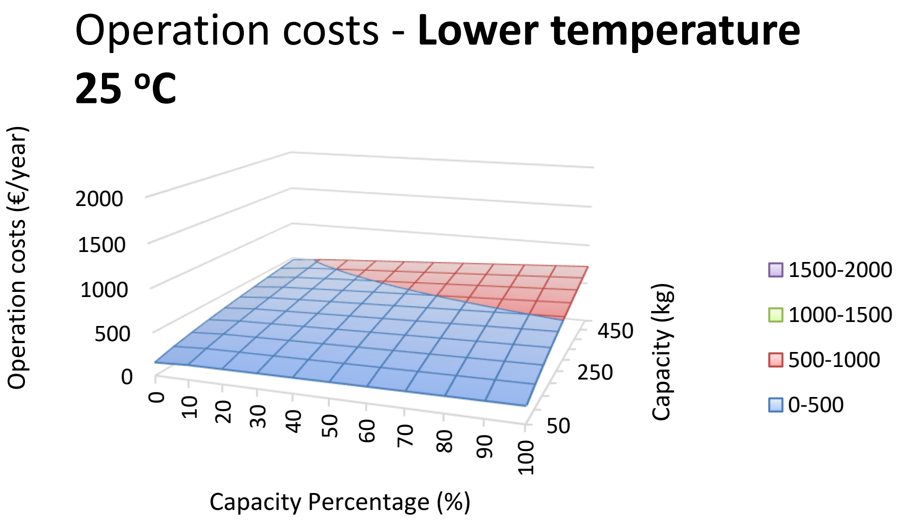


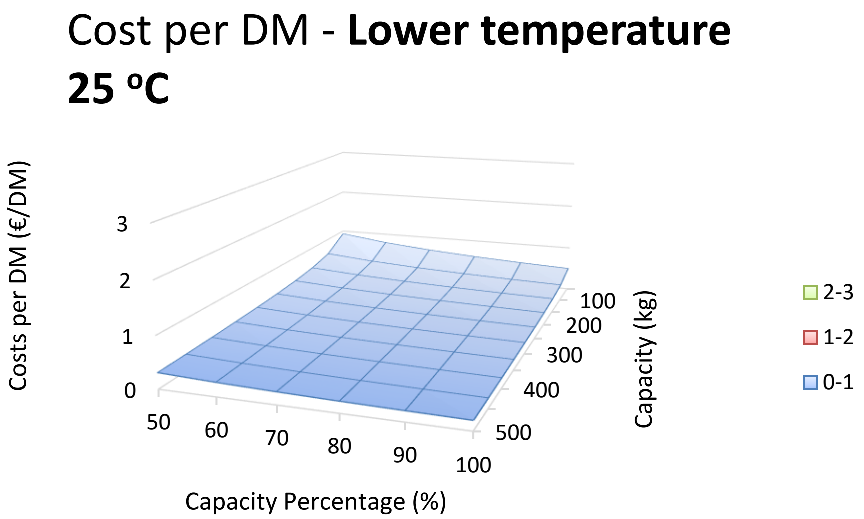
Scenario title	Lower temperature 45 ºC		
Changeable model factor		Set on	Unit
Pressing		800	g/kg
Extra Mol added		20	%
pH		13	
Temperature		45	ºC
Protein purity		70	%
Protein yield		670	g/kg
Heat exchanger		Yes	



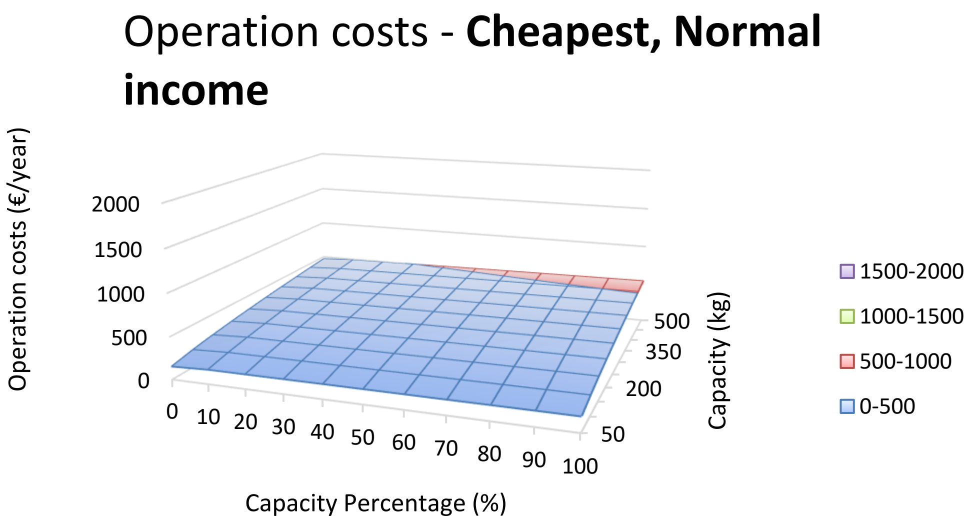


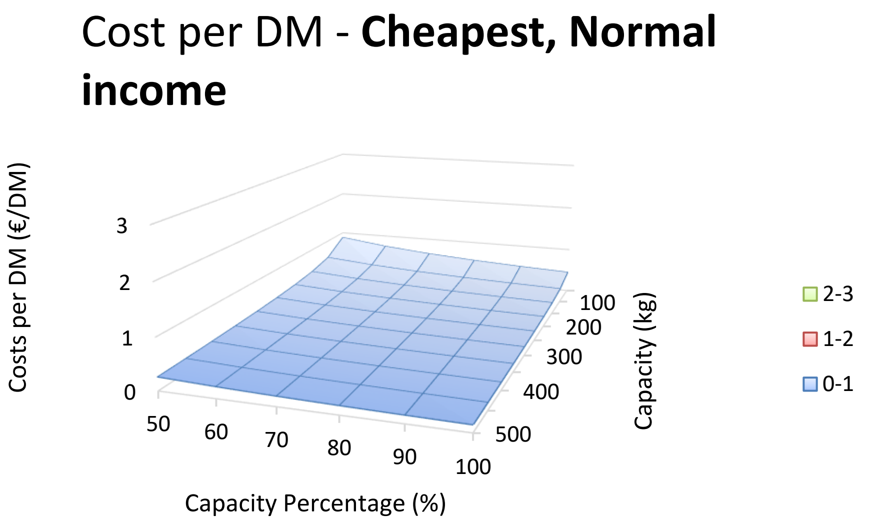
Scenario title	Lower temperature 25 °C		
Changeable model factor		Set on	Unit
Pressing		800	g/kg
Extra Mol added		20	%
pH		13	
Temperature		25	°C
Protein purity		70	%
Protein yield		670	g/kg
Heat exchanger		Yes	



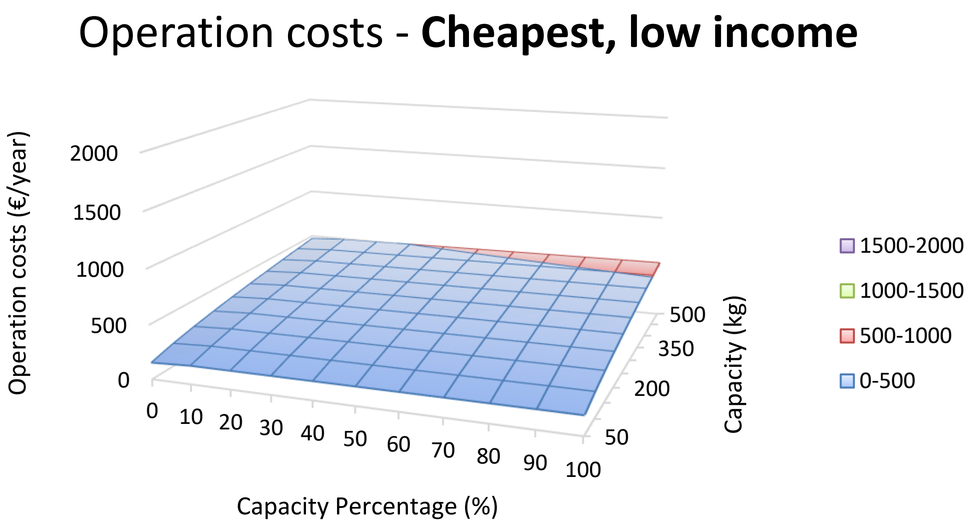


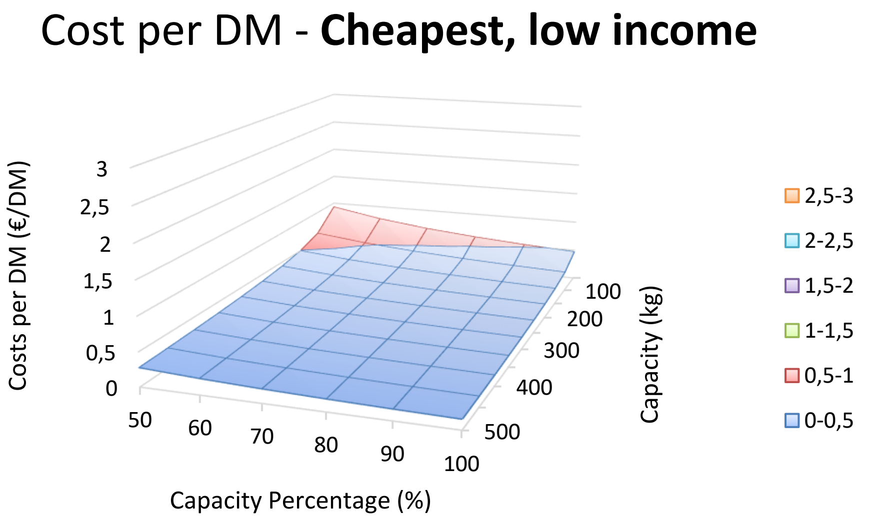
Scenario title	Cheapest, normal income		
Changeable model factor		Set on	Unit
Pressing		800	g/kg
Extra Mol added		0	%
pH		11	
Temperature		25	°C
Protein purity		70	%
Protein yield		670	g/kg
Heat exchanger		Yes	





Scenario title	Cheapest, low income		
Changeable model factor		Set on	Unit
Pressing		800	g/kg
Extra Mol added		0	%
pH		11	
Temperature		25	ºC
Protein purity		68	%
Protein yield		750	g/kg
Heat exchanger		Yes	





Scenario title	Cheapest, high income		
Changeable model factor		Set on	Unit
Pressing		800	g/kg
Extra Mol added		0	%
pH		11	
Temperature		25	ºC
Protein purity		78	%
Protein yield		650	g/kg
Heat exchanger		Yes