Annotation sheet

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Annotation - Czech: Vyhodnoťě potenciál využití celulózových vláken z odpadů jako suroviny pro výrobu bioplastů a biokompozitů. Zpracujte rešerši zaměřenou na technologie extrakce celulózových vláken z lignocelulózových odpadů a proveďtě jejich kritické technicko-ekonomicky-environmentální posouzení. Navrhněte PFD a PID schémata ekologicky šetrné technologie pro extrakci celulózových vláken z lignocelulózových odpadů, zpracujte ekonomickou studii z hlediska investičních nákladů, provozních nákladů a návratnosti.

Annotation – English: Evaluate a potential of cellulosic fibers to be a raw material for production of bioplastics or biocomposites. Review technologies of cellulosic fiber extraction from cellulosic wastes and perform a critical techno-economically-environmental study. Design

PFD and PID charts for environmental friendly technology for cellulosic fiber extraction for biorefinery including economical study of investment and productions costs, and payback.

Keywords: Cellulosic fiber, green composite, bio based reinforced polymer, cellulosic biomaterial

Utilization: Designing of technology.

Declaration

I confirm that the diploma work was disposed by myself and independently, under leading of my thesis supervisor. I stated all sources of documents and literature

In Prague ……………………. …………………….

Name and Surname

"If you can't explain it simply, you don't understand it well enough."

Albert Einstein (1879 – 1955)

CONTENT

THEORETICAL PART

1 INTRODUCTION

Cellulosic Fibers make up a significant part of huge family of natural fibers. Generally, the term "natural fibers" is used for all types of fibers coming from plant material produced because of photosynthesis.[1] Green lignocellulosic raw materials such as cotton, flax, jute, sisal, kenaf and fibers of allied plants have served mankind for primitive tools, construction, goods for everyday life, or clothes manufacturing since more than 8000 BC. Flax and hemp fibers were used for fabric manufacturing in Europe about 4000 BC. (Czerniak et al. 1998) (Fig.1.1), and as reinforcement of ceramics as early as 6500 BC. (Kozlovski and Mackiewicz Talarezyk 2005). Ramie was used as a mummy clothes in Egypt during the period 5000-3300 BC. Hemp fiber implants have been found in over 10,000 years old pottery shards in China and Taiwan.

Fig.1.1 Images of flax threads dated to ap.4000 BC.
Found in Poland (Czerniak et al. 1998) [1].

Nowadays, despite huge development of completely new fibrous raw materials – man-made fibers in the twentieth century – natural fibers still play an important role in world textile market. Analysis of the world fibers supply since 1970 has showed that all fibers types suffered from demand reduction (Fig 1.2) [2]. The established fibers like polyester, polyamide, polypropylene, and acrylic were down in volumes. The usage of cotton, wool, and silk also decreased by 10.1% to 25.2 million tons, and man-made fibers fell 4.5% to 42.2 million tones.

Only the vegetable fibers section with kapok, ramie, flax, hemp, jute, sisal, and coir is anticipated to have stagnated at 5.9 million tons. World production of three major fibers, flax hemp, and ramie have kept the steady level since 2003 [2] in time of growing concern for environment protection and counteracting global warming, the value of natural fibers

significantly increased. As a renewable resource, natural process, causing reduction of carbon emission and waste minimizing.
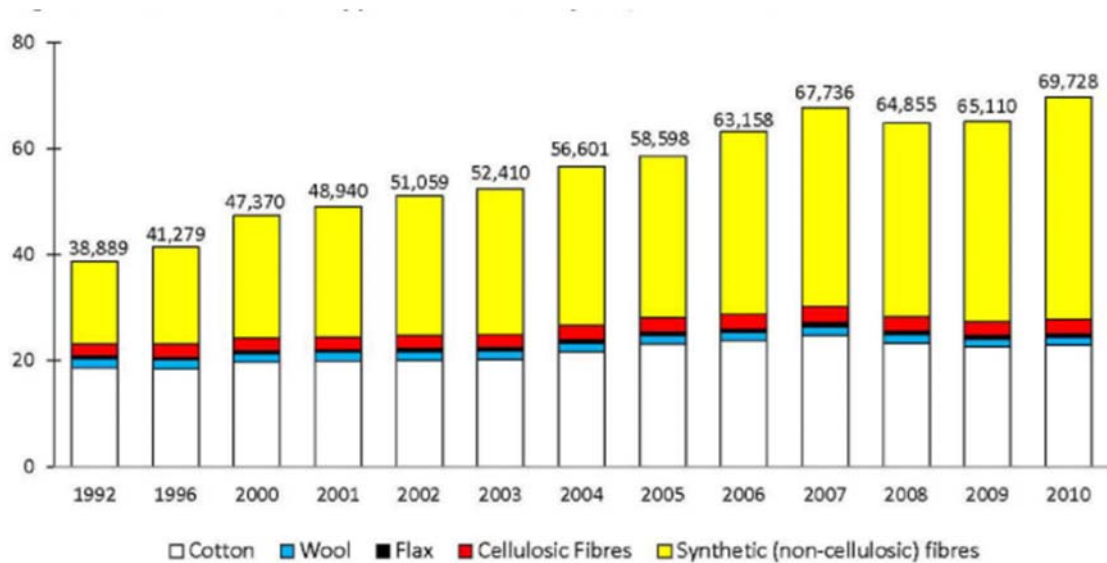

Fig.1.2 World fibers supplies (Oerlikon Textile The Fiber Year 2008/9) [2].

Good example of action contributing to CO_2 and waste reduction is preparation of fibers from lignocellulosic wastes.

1	Cellulose	Hemicellulose	Lignin
1	*2*	*3*	*4*
Hardwoods stems	40 – 45	24 – 40	18 – 25
Softwood stems	45 – 50	25 – 35	25 – 35
Nut shells	15	25 – 30	30 – 40
Corn cobs	45	35	15
Grasses	25 – 40	35 – 50	10 – 30
Paper	85 – 99	0	0 – 15
Wheat straw	30	50	15
Sorted refuse	60	20	20
Leaves	15 – 20	80 – 85	0
Cotton seed hairs	85 – 95	5 – 20	0
Newspaper	40 – 55	25 – 40	18 – 30
Waste paper from Chemical pulps	60 – 70	10 – 20	5-10
Primary wastewater solids	8-15	N/A	24-29
Swine waste	60	28	N/A
Solid cattle manure	1.6 – 4.7	1.4 – 3.3	2.7 – 5.7
Coastal Bermuda grass	25	35.7	6.4

1	2	3	4
Switchgrass	45	31.4	12

Tab.1.1 Amount of cellulosic fibers in individual biomass
Lignocellulose (cellulose + hemicellulose + lignin) (wt. %) [3]

1.1 Advantages of Recycling

Recycling minimizes pollution

All forms of pollution of environment in the modern world emanate from industrial waste. Recycling of these industrial wastes such as plastics, cans, and chemicals go a long way towards considerably cutting back on levels of pollution because these waste products are reused instead than just being thrown away heatedly [4].

Protects the environment

The big benefit of recycling waste material is that it plays a big role in protecting Mother Nature in the most balanced way. While many trees are cut down every day, recycled paper production from specific trees is continually utilized to reduce deforestation. This good example shows that other natural resources can be recycled and made useful this way to protect the environment.

Recycling minimizes global warming

It is perfectly true that recycling minimizes global warming and its grave impacts. During waste disposal, huge amounts of waste are combusted that lead to emission of waste greenhouse gases such as carbon dioxide, sulfur, and nitrogen, which contribute to climate change and global warming.

Recycling cuts down amount of waste in landfill sites

Recycling of old and used materials into reusable products strongly reduces the possibility of pollution of landfill sites. This is beneficial because it helps to minimize land and water pollution while landfills contribute mightily to environmental degradation [4].

1.2 Disadvantages of Recycling

High upfront capital costs

Recycling is not always cost-effective. Construction of a new waste recycling plant takes up a lot of capital. The total costs include buying different kinds of utility vehicles, upgrading the recycling unit, and chemical disposal and schooling the locals by initiating useful programs and seminars.

Recycling sites are always unhygienic, unsafe and unsightly

In many waste recycle plants you will almost always stumble upon unhygienic, unhealthy and unsightly conditions. Position where every manner of waste is piled gives a nice ground for the formation of debris and spread of infectious diseases. The harmful chemicals from these wastes can be also very dangerous.

On the top of reasons of massive pollution, the whole recycling process positions health risks for dedicated individuals responsible for recycling these waste products. Also, if such waste products come into contact with water, for example , results in the formation of leachate that ends up polluting water bodies, not to mention drinking water. [5]

Products from recycled waste may not be durable

The quality of products manufactured from recycled waste may not be on par regarding quality. These kinds of products are almost always made of trashed waste material that have been overmuch utilized and brittle. This makes products of recycled waste less durable and low priced.

Recycling is not widespread on large scale

Although recycling plays a significant role in reducing the rate of pollution, the process has not been widely spread and developed. Unfortunately recycling still is just a very small part of long-term success. Recycling is mostly common in schools and universities and has not hit a bigger milestone, as example, it has not been wholly used at local industries at a global stage. Conservation of trees at school is incomparable to the massive destruction of trees and oil spills happening at industrial levels.

After juggling the advantages and disadvantages of recycling, an individual can wisely take significant steps involved in recycling process. Knowing the effects of recycling is vital to

a higher degree that if carried out effectively, it can bring uncountable benefits to the environment and humans. Therefore, in this master thesis considered a method of obtaining cellulose fibers from waste material as wooden chips as a raw material.

1.3 Application of fibers as a renewable bio composites

Fibers have many purposes in concrete countertops [6]. They can be used either for reinforcing or can be used to prevent cracking and shrinkage of concrete. When fibers are used for structural reinforcing this is known as primary reinforcing. However, if they are used for shrinkage control it is known as secondary reinforcing. See Fig.1.4.

Fig.1.3 Cellulosic fibers as reinforcement material in concrete [39].

Fibers can play a valuable role in both reinforcing types. However, the type of fibers and the methods used will vary depending on which type of reinforcing you're after.

At the same time, cellulosic fibers can be used as insulation material [7]. Cellulose insulation is used in both new and existing structures, as loose-fill in open attic installations and dense packed in building cavities such as walls and cathedral ceilings.

Although cellulosic fibers can be used in furniture, automotive, pharmacy, electronics and cosmetics. For companies, which produce electroacoustic devices, cellulose is used as a membrane for high quality sound systems. In addition, cellulose is used in membrane for combustible cells (hydrogen); additives for high quality electronic paper (e-paper); ultra-filtrating membranes (water purification); membranes (Fig.1.5) used to retrieve mineral and oils [8].
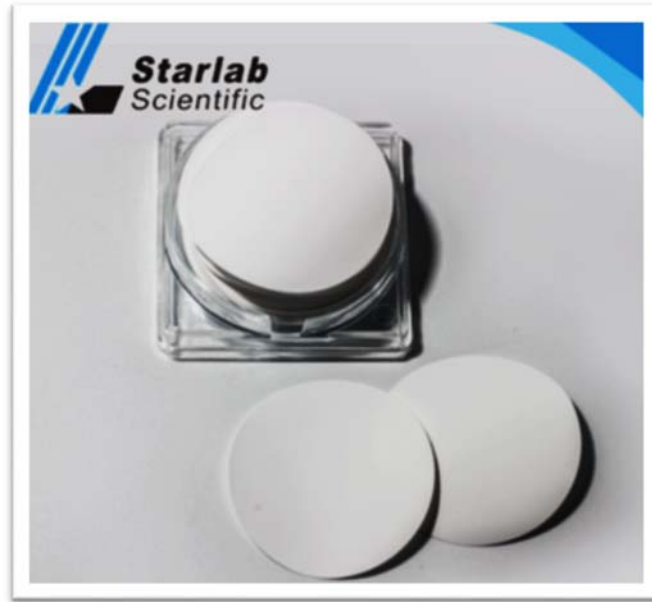
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Fig.1.4 Cellulose filter [9].

Nowadays, cellulose has been greatly discussed and researched in a huge variety of applications. The high strength and stiffness as well as the small dimensions of it reinforced with these fibers, which could afterwards be used in big range of applications.

2 CRITICAL LITERATURE SEARCH

All the countries in the international community face enormous challenges with regard to the issues of global population growth, dwindling fossil fuel resources, and the ever-advancing climate change [10]. The central task will be to provide a growing world population with adequate food, energy and raw materials, while taking care not to impact the natural environment, and to actively reduce climate-damaging greenhouse gases. To these ends, it will be necessary to develop intelligent solutions that are in keeping with a resource-efficient and sustainable economy. Having set out these objectives, biorefinery concepts – as central elements of a bio-based economy, and promising largely waste-free use of biomass, efficient conversion routes, and pathways for the energetic and material use of biomass – could play an important role for a future bio economy in the utilization and conversion of biogenic raw materials and residues [10].

2.1 Biorefinery concept

Biorefinery – technological concept, in which wastes and non – food biomass is transformed to bio composites, biomaterials and biofuel of second generation with additional production of electric and heat energy [11]. Standard VDI 6310 [12] defines this term as a dedicated integrative, multifunctional concept which use biomass from a range of a raw material sources for sustainable generation of a range of different products and intermediate products while exploiting the biomass to the fullest extent possible, see Fig 2.1.
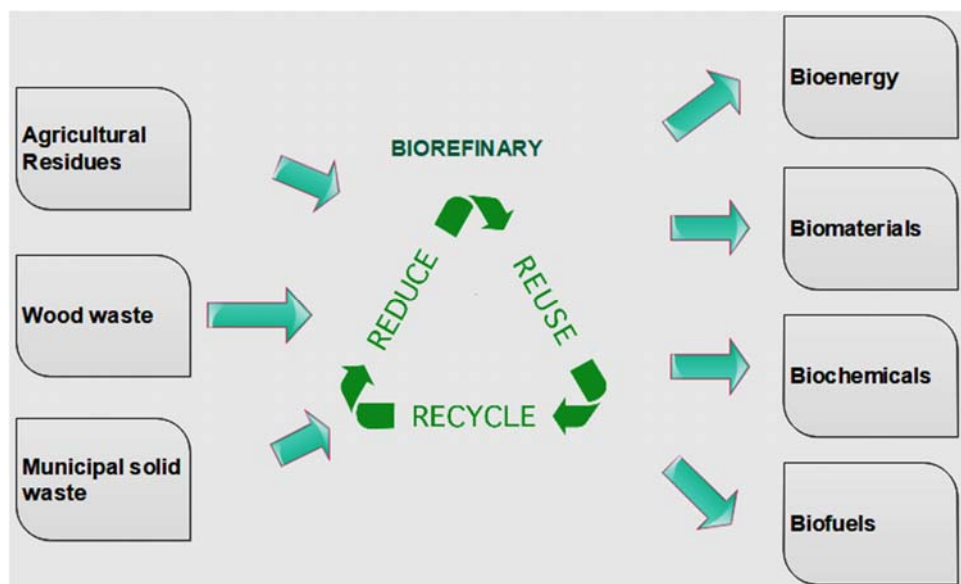

Fig. 2.1 Biorefinery concept [13]

Nevertheless, such definition is not exact because it doesn't distinguish biorefinery categories depending on type of raw material, so for this purpose should be prepared more precise and individual block diagram (Fig 2.2 and Fig. 2.3)

In such concept, we can produce cellulosic fiber which can be used as insulation material, reinforcement composite etc. and at the same time produce biogas, which can provide our plant with heat and electricity. Such production will have less operation cost, and in its tern, it will provide higher benefit to investors. But nowadays such technology is still far from realizing because of economical and some technical aspects (Fig 2.2).
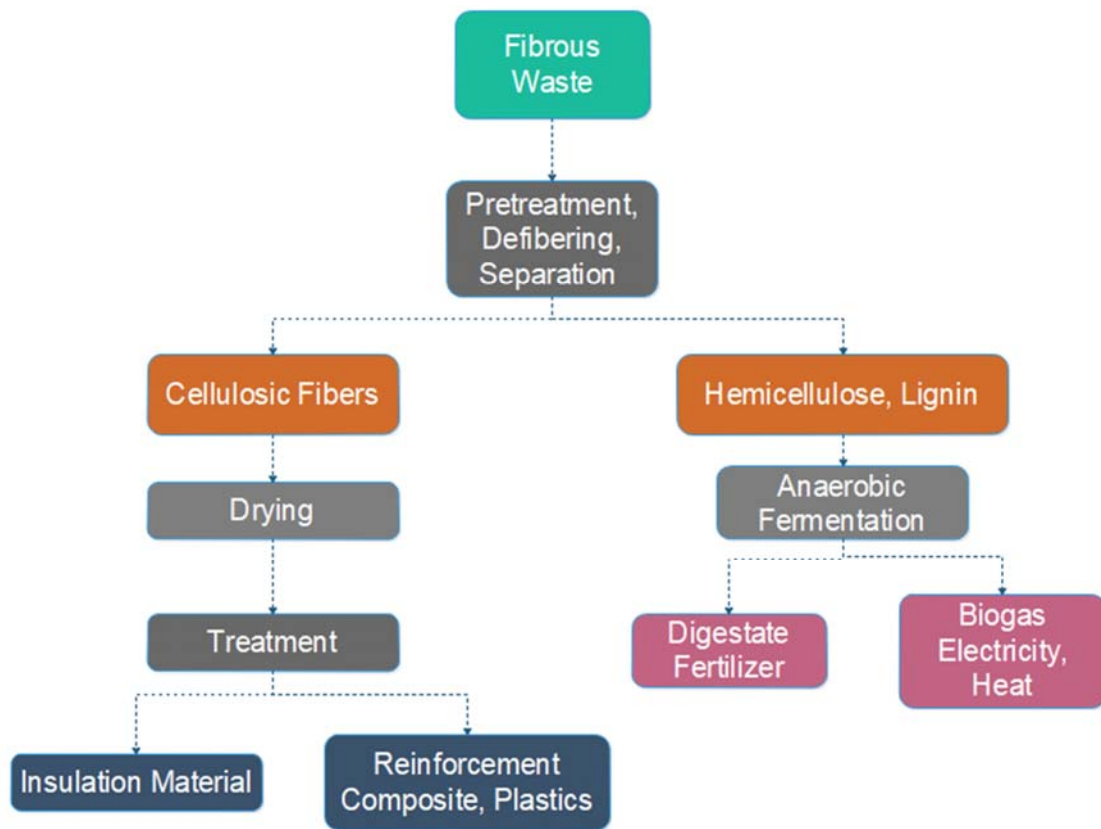

Fig. 2.2 Biorefinery concept [10]

Next concept (Fig 2.3) has similar steps with previous concept but the biggest difference between them is that in the 2nd concept lignocellulosic biomass firstly by hydrolysis and some treatment steps terns into saccharides.
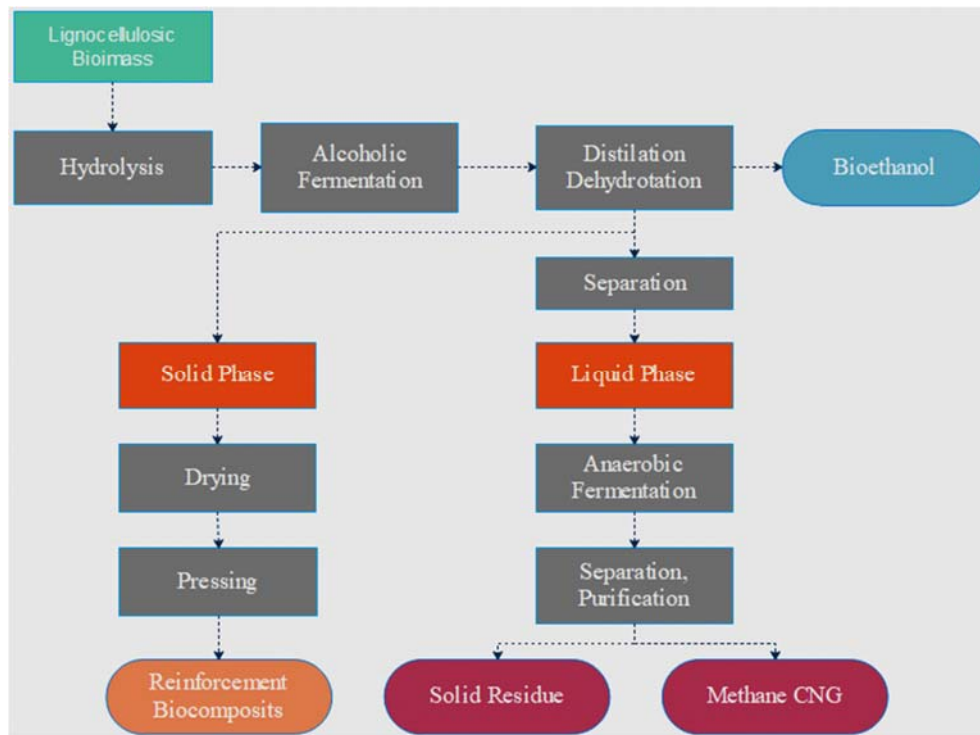
Fig.2.3 Bio refinery concept [10]

Then by Alcoholic fermentation we are able to separate pulp from liquid solution which in its turn are full of biodegradable elements which can be transformed into biogas.

Such Biorefinery concepts, operating in pilot plant or industrial scale, are still under developing.

2.2 Critical technical aspects.

Mechanical processing (MP) is widely spread in preparation of biomass for specific processing technologies. An alternative or additional objective of it is to optimize the supply chain and minimize factory gate raw material costs. Almost in all cases, the physical and mechanical properties of the biomass will be changed (density, size distribution etc.). MP covers a range of different methods, including comminution (size reduction), separation and compaction, sorting or sieving. The processing of biomass typically uses technologies of removing unwanted components, to stich the size of the particles (make them more uniform and easier to handle) by fractionation step, and to modify particles (if it is necessary) by simple and effective chemical or enzymatic means, to improve the efficiency of downstream processing. Both wet and dry technologies can be used in production of particles of different

materials for different applications. After shredding and chopping, intensive dry milling technologies can be applied combined with air classification, for getting a fraction with controlled particle size distribution. Modern technologies include dry milling performed either at room temperature or under cryogenic conditions, or wet milling (e.g. agitated pearl milling in water or in organic solvent). For more effective production of bio based materials, the powders or pulps produced must be classified either in solution or in the air. Challenge here is to create such technologies and processes which will minimize the energy requirement for mechanical pre-treatment (which are often large)

Based on previous concept (Fig.2.2, 2.3) we showed several steps of such technology. There are many experimental works according to which can be created such system (Fig.2.4) which will provide ideal case for this concept. Nevertheless, all the processes which are inside such technology like hydrolysis, anaerobic fermentation, gas purification, were mentioned separately and demand of each of them on other ones are unknown and that create difficulties of realizing such system in industrial scale.

Another technical problem as for direct implementation of laboratory results to our system is that laboratory experiments and technologies based on them such as extraction, purification, thermal treatment and etc. were conducted only for pure raw materials. That's why in the case of waste treatment, it is always necessary to take in to account their high level of contamination.

Therefore, suitable technology for biorefinery concept is such a processing that will allow effective waste conversation and purification in individual steps, with a required level of interconnection to subsequent processing. From the technical point of view and industrial realization, by author recommended to take in to account such the most important requirements for the technology design and operation that must be fulfilled at least as follows [14]:

– High efficiency of material treatment;
– Ability of system to work with various materials;
– Minimal waste generation;
– Avoiding degradation of products and intermediates;
– Minimizing energy demand;
– Increase usage of secondary energy (withdraw heat on batch cooling, steam condensate heat and etc.);
– Minimize usage of chemicals;
– Financial low cost of technology in terms of operating and investment cost;
– Friendly economic balance of technology.

Apparatuses as Boilers, separators, storage vessels, dryers, heat exchangers, crushers, and etc. form main part of machinery in biorefinery concept. Their right choice design and their price depends on their process (parameters such as working volume, temperature, pressure batch concentration), accessories (mixing system, insulation), Type of process (continual, batch, semi continual) and their service. Mostly this apparatus working as pressure vessels and they classify as pressure vessels. There for during choosing such apparatuses we should take in to account following aspects:

- User friendly design.
- Proper material choosing.
- Minimize usage of expensive materials and parts.
- Finding of some compromise in working volumes of apparatuses inside plant [14].

2.3 Fundamental Pricing

Economical (investment cost, production cost, payback time, raw material price, demand) and technological (yield, process conditions, conversion factor) aspects of biorefinery concept are the main part for investors to decide whether to invest money to such project or not. Nevertheless, economical tasks ply major role during making decisions from the point of profit. Typical lifetime of such project is around 25-30 years, and payback time of good realized project is up to 6-8 years [15]. Simple payback time (SPT) can be roughly calculated as total investment cost to the technology (CAPEX) divided by average annual cash flow, i.e. difference between income (AI) and sum of total production cost, depreciations and taxes (SPC), equation 1. From it follow, lower investment cost, the lower simple payback time:

$$ \text{SPT} = \frac{\text{CAPEX}}{\text{AI} - \text{SPC}} . \qquad (2.1) $$

Total investment cost CAEPX is a package of inner battery limits (ISBL) investment, contingency charges (CC), engineering cost (EC) and office costs (OSBL) as well. ISBL cost shows the plant cost (sum of individual prices for procuring and installing of all apparatuses and equipment in main process streams. OSBL cost [lk9] represent the cost of additions that must be made inside the plant, engineering networks, laboratories, pipelines, etc., and 40% of OSBL is often used as an initial estimation of OSBL. On its tern, EC cost [15] consist of design and other engineering services and 30% of ISBL plus OSBL is used as an initial estimation of it. CC cost [15] is a financial reserve which is calculated as 10% of sum of ISBL and OSBL.

Total investment cost strongly depends on a price of individual machines and equipment inside the plant. Using Factorial method (equation 2) of calculation of price, rough price of each apparatus can be found:

$$C_e = a + b \cdot S^n \qquad (2.2)$$

where S – process parameter; n – index; a, b – table data; Ce – price.

That's why the cost of apparatuses strongly depends on overall optimization of system or optimization of each equipment. Choosing of material has huge demand on price to. If carbon steel is used as a base material, alloyed steel is by 1.1x, stainless steel 1.5x, hastelloy by 1.65x and nickel alloys by 1.7x more expensive in comparison to base one [15]. So, it means that we should find some compromise and balance between corrosion resistance, erosion, abrasion, smart design and equipment price. From this follows that good design and choosing of equipment is a key for improving total investment cost.

2.4 Annual Income

The level of annual income depends on product and its purchase price in relation to local and global demand. It is necessary to take in to account not only production cost but also to a purchase price of the product. Nowadays bioproduct portfolio is mainly covered by liquid and gaseous biofuels that are used for decentralized heat and power generation. Such products have low purchase price – low economical value.

Economically sustainable biorefinery concept has to produce products with the highest economic value include commodities for the production of composite materials with bio-components or bioplastics (Fig.2.4). Extracted cellulosic fiber have a potential to be reinforcement of bio composites and it can reach very high purchase prices from 500 up to 1000 Euro per ton of dry fibers with application in composites and insulation [17]. On the other hand, production price must be also taken into account in economical balance of biorefinery concept. The higher total annual production cost, the lower annual cash flow, and the higher simple payback time. The highest impact on production cost is mainly price of raw material, yield, efficiency, and lifetime if technology, amount of raw material and a chance of modernization of technology.
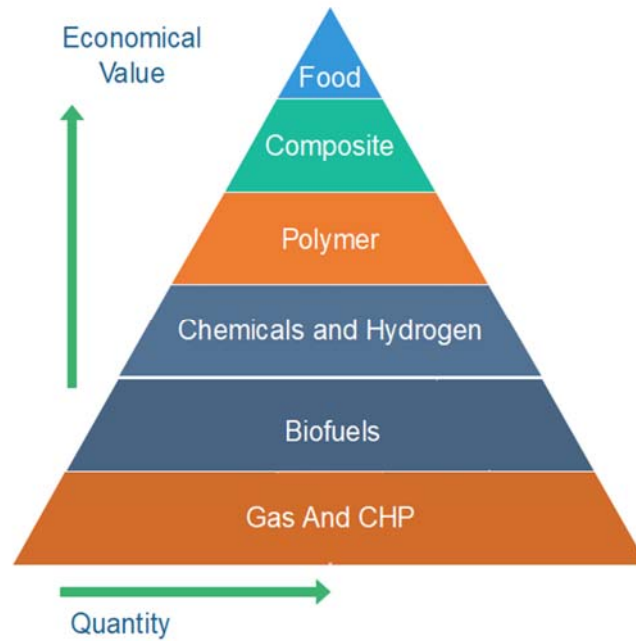
Fig.2.4 Economical value of product in relation to its quantity [11]

The economic viability of bio refineries depends largely on the availability of a reliable supply of appropriate quality biomass at fair prices. An important research area is therefore more precise estimation of current European biomass production potential. For this, qualitative (type of biomass) and quantitative (amount, yield) statistical databases of cultivated biomass should be compiled and updated regularly.

Further development of mapping systems will provide us a more complete picture of the distribution of potential of biomass production. Such data will allow industry to assess the potential of different areas to deliver biomass in the appropriate volumes and quality for bio refinery applications [17].

Total production cost can be estimated by using Fig.2.5, where you can find plot between price and concentration.
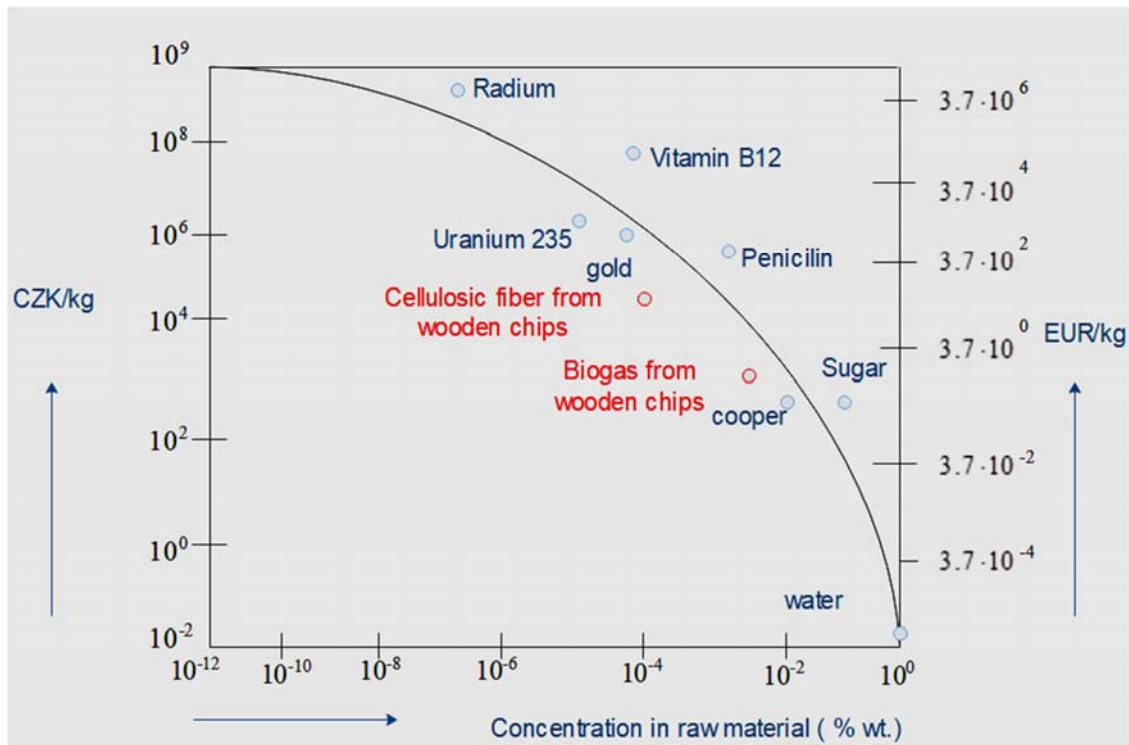
Fig.2.5 Total production cost / product concentration in raw material [18]

After all, bio refinery concept looks like an effective, environmental friendly and economical perspective waste treatment technology, which need for applying in reality more researches and laboratory experiments.

2.5 Biochemical process of anaerobic digestion

Anaerobic digestion (AD) is microbiological process, where organic matter is processing in the non-availability of oxygen. Using engineering approach and special design, the AD process is applied to process organic biodegradable matters in airproof reactor tanks, commonly named digesters, for production of biogas. Position in the production chain showed in the Fig.2.6. Different groups of microorganisms are involved in the AD process which provides two main products: energy-rich biogas and a nutritious fertilizer.

AD of waste biomass provides many benefits -- production of renewable energy, reduction of greenhouse gases and etc. It transforms organic waste material into resources and at the same time this process reduce solid waste volumes and thus waste disposal price. Biogas as a renewable energy source can not only improves the energy balance of a country but also can make environmental protection by reducing pollution from waste and decrease usage of fossil fuels [19].
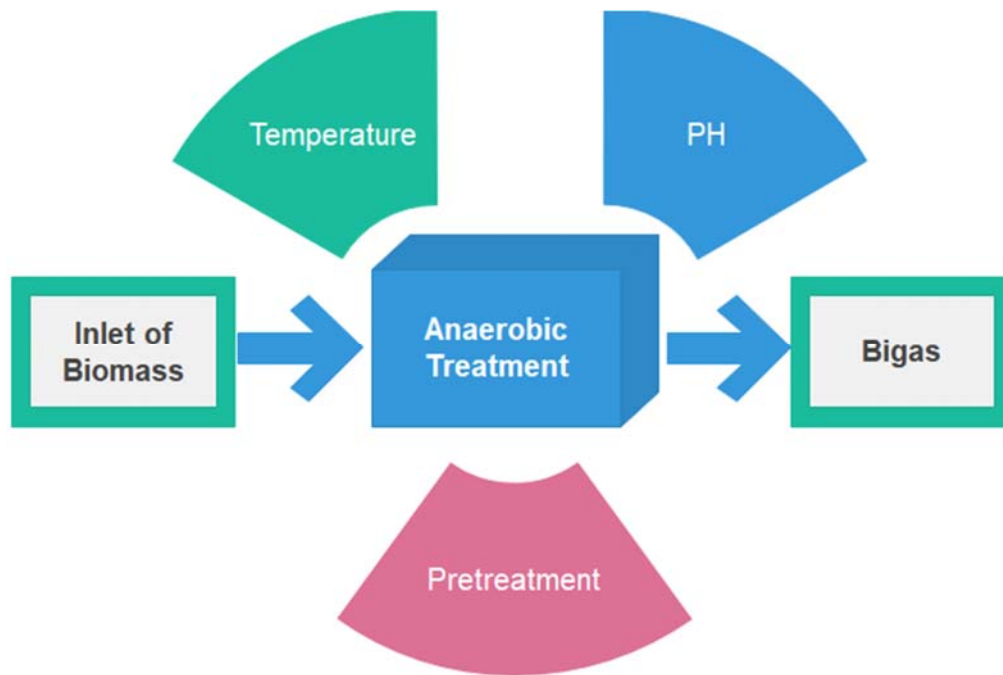
Fig.2.6 Anaerobic treatment flowsheet [20]

The calorific value of biogas is between $6.0 – 6.5$ kWh/Nm^3 and it depends on concentration of methane, average value of it is in the range of $55 – 70$ % vol. [21]. The net calorific value depends on the efficiency cogeneration units or other appliances used to process the biogas. For example, a gas generator, can convert about $2 – 2.2$ kWh into usable electricity, while the remaining energy released as heat.

The anaerobic decomposition of organic matter occurs in four – step process (Fig.2.7).

2.5.1 Hydrolysis

Hydrolysis is usually the slowest of the four degradation steps. The bacteria transform complex organic materials into liquefied monomers and polymers, for example, proteins, carbohydrates and lipids (fats) are transformed to amino acids, monosaccharides and fatty acids respectively [22]. This extracellular enzyme-mediated transformation of higher mass organic molecules into basic structural building blocks is very important as particulate organic materials are simply too large to be directly absorbed and used by microorganisms as substrate.
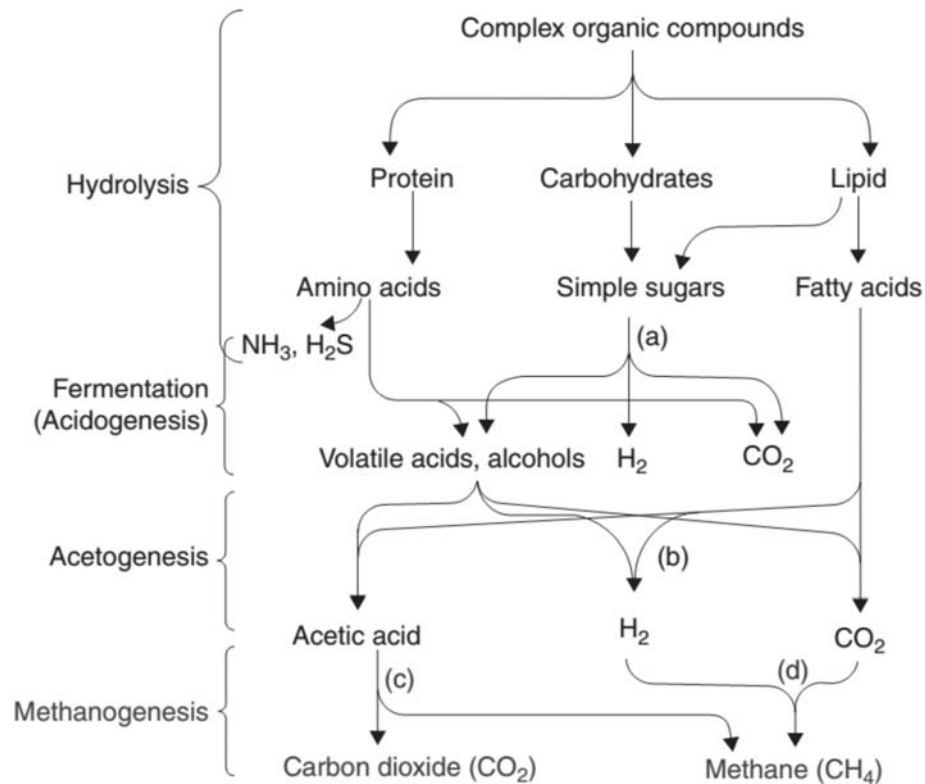
Fig.2.7 Biodegradation steps [23]

The hydrolysis of carbohydrates takes place within a few hours and the hydrolysis of proteins and lipids within a few days. Lignocellulose and lignin are degraded only slowly and incompletely [21].

2.5.2 Acidogenesis

The monomers formed in the hydrolytic phase are taken up by different facultative and obligatorily anaerobic bacteria and are degraded in the second, acidogenic, phase to short-chain organic acids, C_1-C_5 molecules, alcohols, nitrogen oxide, hydrogen sulfide, hydrogen and carbon dioxide. The concentration of the intermediately formed hydrogen ions affects the kind of fermentation products. The higher the partial pressure of the hydrogen, the fewer reduced compounds, such as acetate, are produced. The degradation of amino acid also leads to production of ammonia [21].

2.5.3 Acetogenesis

At this point long chain fatty acids and volatile fatty acids and alcohols are transformed by acetogenic bacteria into hydrogen, carbon dioxide and acetic acid. During this reaction, the

BOD and the COD are both reduced and the pH decreased [24]. Hydrogen plays an important intermediary role in this process, as the reaction will only occur if the partial pressure is low enough to thermodynamically allow the conversion of all the acids. Hydrogen scavenging bacteria lead to a lower partial pressure. Thus, the hydrogen concentration in a digester is an indicator of its "health" [25].

2.5.4 Methanogenesis

In the last stage, methanogenic bacteria convert the hydrogen and acetic acid to methane gas and carbon dioxide. Methanogenesis is affected by conditions in the reactor such as temperature, feed composition and organic loading rate [26].

The gaseous product, biogas, consists mainly of methane and carbon dioxide, but also contains several gaseous "contaminants" such as hydrogen sulphide (easily detected by it smell of rotten eggs), nitrogen, oxygen and hydrogen. See the Table 2.1. Biogas with methane content higher than 45 % is flammable; the higher the CH_4 content the higher the energy value of the gas [21].

Components	Symbol	Concentration [vol. %]
Methane	CH_4	55 – 70
Carbon dioxide	CO_2	35 – 40
Water	H_2O	2 (20°C) – 7 (40°C)
Hydrogen sulphide	H_2S	20 – 20000 ppm (2%)
Nitrogen	N_2	<2
Oxygen	O_2	<2
Hydrogen	H_2	<1
Ammonia	NH_3	<0.05

Tab.2.1 Composition of biogas created from bio-waste [27]

2.6 Process parameters

2.6.1 Temperature

According to the Lab. Results was found that temperature of boiling in first reactor should be not more than 200°C because of biodegradation of wooden chips. Otherwise quality of final product will decrease and the final price will be lower. °

Temperature in 2nd reactor (Fermentation tank) should be in the range 30 – 40 °C. because mesophilic microorganisms which will be used in our fermenter prefer such temperatures and will give highest yield in biogas production [20]. On the other hand, influence of unneeded components like free ammonia is lower at lower temperatures. On the following Fig.2.8 you could find fermentation time for various microorganisms.
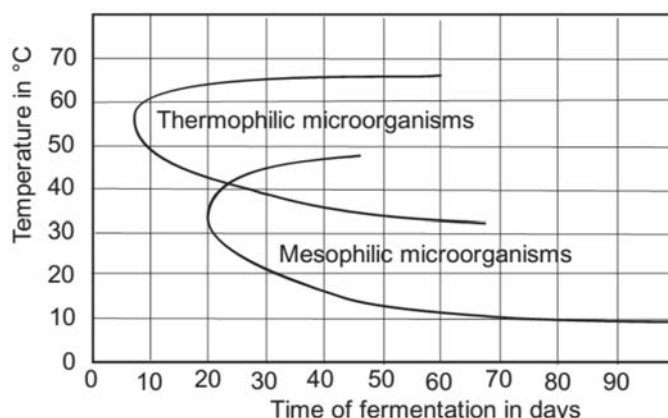

Fig.2.8 Influence of Temperature on fermentation time [21]

2.6.2 Specific surface area of material

For biochemical reaction in Fermenter surface area of biomass should be kept as large as possible. To increase the surface area of material comminution or milling are preferred before processing [28].

2.6.3 pH value

The situation with pH value is similar as for temperature. Microorganisms involved in the different stages of decomposition, require different pH value. The pH optimum for hydrolysis and acid-forming bacteria is in a range from 5.2 to 6.3. They are not fully reliable on this, however, and are still capable of converting substrates at a slightly higher pH value. The only problem is that their activity is slightly reduced. In contrast, the pH value in the neutral

range from 6.5 to 8 is essential for acetogenesis and methanogenesis. Thus, if the fermentation process occurs in a single digester, this pH range must be maintained [29].

2.6.4 Comparison of substrate pretreatments

The main effect of pretreatment on different types of substrate are Particle size, solubilization, biodegrability improvement, formation of refractory compounds and loss of organic material.

Based on Carllson and co-workers [30] the amount of substrate of wastes used in production of biofuels are represented in Fig 2.9:
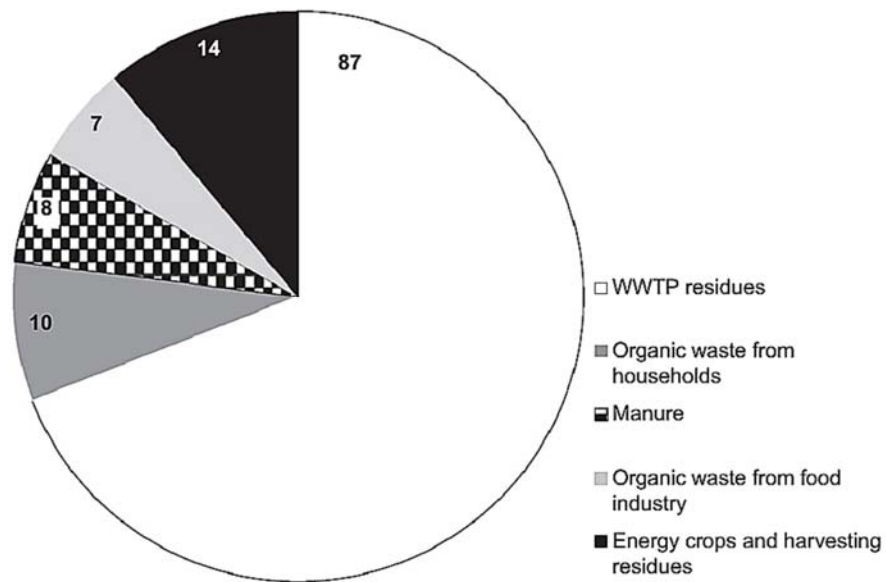

Fig.2.9 Various substrate types [30]

The most important part is WW, because the water used in enormous amounts on our planet. The 2nd one is agricultural products and residuals, and the 3rd is organic wastes. It is obvious that every other type of substrate going to have different data for treatment. Nevertheless, the Fig. 2.11 was obtained during Carlsson and co-workers work [30].
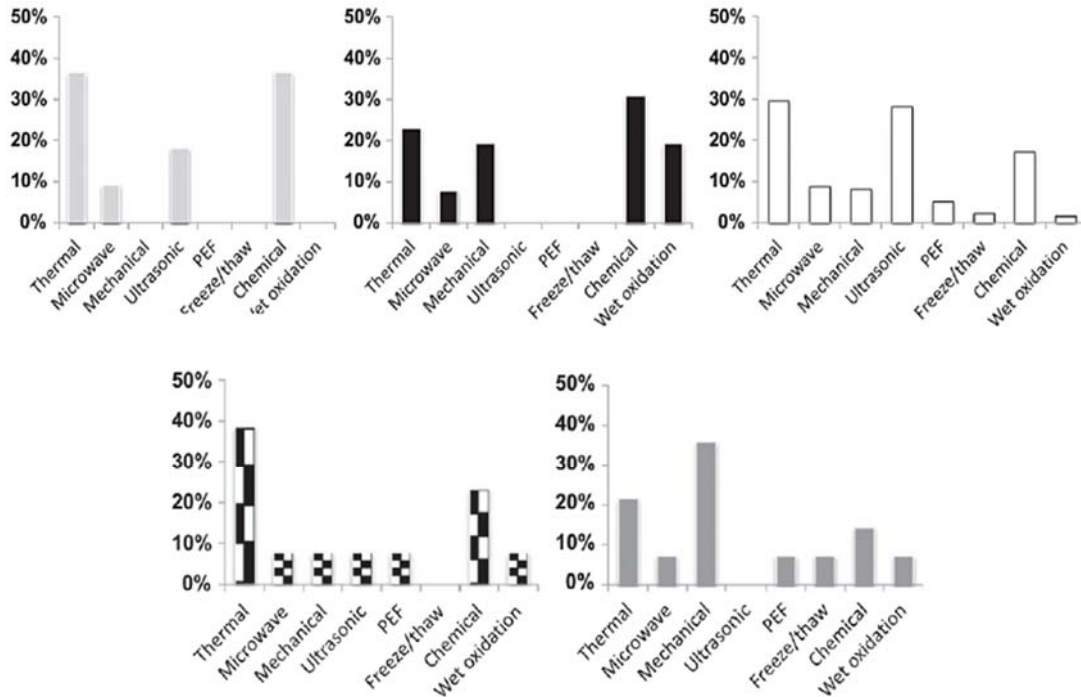
Fig.2.10 Different pretreatments on different substrates.
Vertical – the preferred treatment for the plant; Horizontal – types of treatments [30].

From the Fig. 2.10 is clear that mainly physical (thermal, mechanical, ultrasonic) and chemical pretreatments are the most effective. Considering these two methods, we can say that the physical pretreatment is more effective. Additionally, the chemical pretreatment needs extra step and extra invests for eliminating of chemicals after treatment and such method can't be environmental friendly.

2.7 Thermal – expansionary pretreatment

Thermal – expansionary pretreatment was used in batch mode, see the. The experiment was done by Kratky and Jirout [31]. Briefly, the hydrolyser is batch double-jacketed pressure vessel, which could be filled maximum by 8 l. Wheat straw is heated by oil (O) in double-jacketed vessel. Lab scale vessels and apparatuses can be found in Fig.2.11 and Fig.2.12.
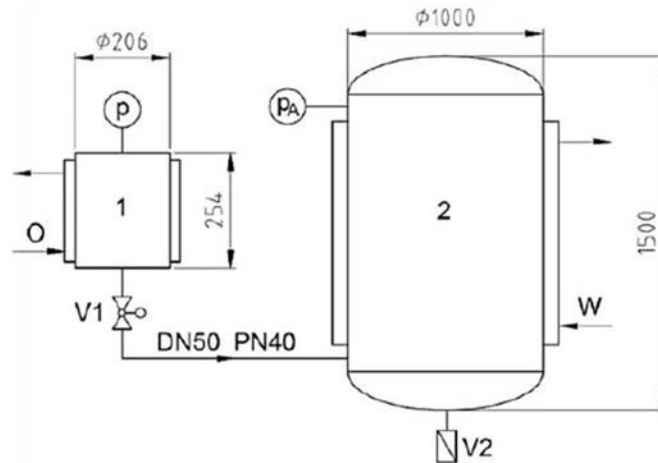
Fig. 2.11 Unit for thermal-expansionary pretreatment TEP
1–hydrolyser, 2–expansion vessel, V1–ball valve with pneumatic actuator,
V2–dump valve, O–heating oil, W–water cooling [31].

Fig. 2.12 Unit for thermal-expansionary pretreatment TEP [31].

2.7.1 Lab scale of Cellulosic fiber production

Thermal – expansionary pretreatment is modern technology that can be used with different types of lignocellulosic biomasses. During this pretreatment, lignocellulosic biomass is held in the reactor, where high temperature steam and pressure is applied for a few minutes. When residence time is over, the batch is quickly depressurized. Liquid, which is sucked into biomass pores, changes its phase from liquid to vapor and the associated volumetric change causes a sudden disruption of the lignocellulosic bonds. The effectiveness of a steam explosion/ expansion particularly depends on the particle size, its humidity and composition, on steam temperature and on residence time. The equivalent hemicellulose removal can be obtained at a

high steam temperature with a short residence time (270° C, 1 min) or at low temperature with a long residence time (190° C, 10 min) [31]. Nevertheless, it was found that the treatment at low temperature with a long residence time is preferable [32].

TEP – a novel trend in processing of lignocellulosic biomass in industrial biofuel technology. This double-stage process combines the boiling of an aqueous biomass suspension within the high pressure followed by rapid decompression. Until now, there were no information about the effectiveness of the pretreatment. This work will show the effectiveness of usage of the following pretreatment on the plant-scale. The expansion vessel (2) is used to keep the expanded substrate. The dump valve (V2) is used to discharge the hydrolysate (expanded substrate). Expansion vessel is equipped with water (W) cooling system. The ball valve (V1) keeps the pressure in hydrolyser, which is gained during heating. Firstly, the hydrolyser is filled with the mixture of substrate and water (95 wt. %). The mixture is heated by oil up to some desired temperature, as the hydrolyser is closed, the pressure is increased. The ball valve opens and the mixture is expanded in expansion vessel due to different pressure difference in both vessels. The products of sudden expansion are vapor and hydrolysate.

As we heat the mixture up to some desired temperature and pressure, we process it for some residence time after the depressurizing the temperature is rapidly decreased. The dependence of P, T parameters to time could be seen on the Fig.2.13.
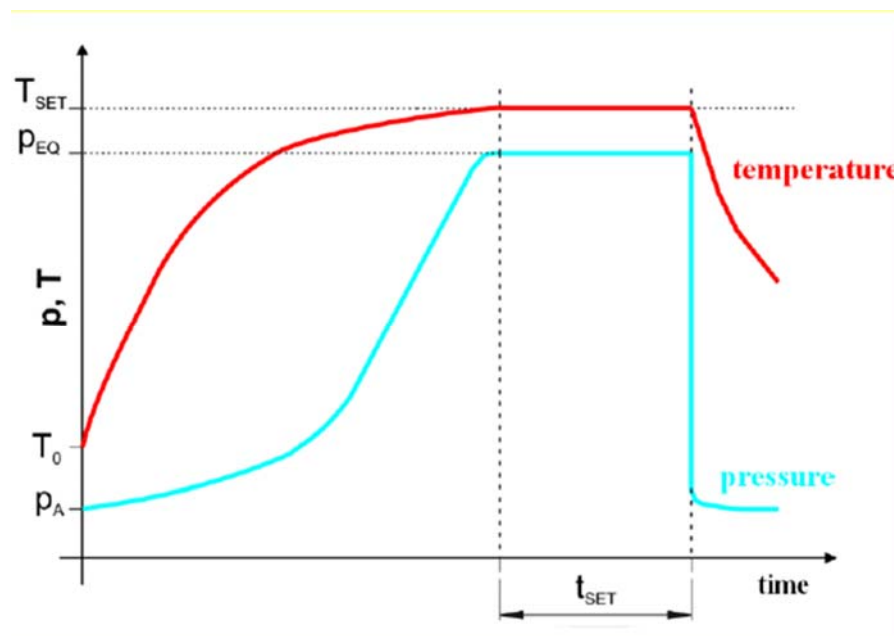

Fig.2.13 Dependence of Pressure and Temperature on time [31].

2.7.2 Laboratory results

By Jirout and Kratky [31] were found that, the best yield in according to degradation of raw material, was reached at 200 C and 20 minutes of residence time. The following Fig.2.14 and Fig.2.15 shows how pretreatment influence on wooden chips, and at the same time you could see the results of the experiment, which are very important for further calculations.

Fig.2.14 Untreated wooden chips on the left, treated (200° C) on the right [31].

Fig 2.15 Treated wooden
chips at different Temperatures (135° 160° 180° C) [31].

3 OBJECTIVES

Until now, there were no public accessible work, where you can find technology in industrial scale of cellulosic fiber production with integrated biogas production, its mass, energy balances and economic analysis of such plant. The aim of these work is to show the detailed calculation of the plant.

3.1 General objective

– Design of cellulosic fiber production with integrated biogas production – Techno-economical study.

3.2 Specific objectives

– To review of plant working principle.
– To make a critical literature search about utilization of biomass in the past and nowadays substrate pretreatments.
– To create based on literature search, a flowsheet of cellulosic fiber production plants. In the same way to create the best heat regeneration cycle of the plant.
– To create PFD and PID of the process.
– To perform the economical calculations of total investment costs and operating costs.
– To calculate based on economical calculation, the payback period.

4   PRACTICAL PART

After analyzing previous concepts, by author was created block diagram (Fig.4.1and 4.2) and process flow diagram in which you can find almost all processes that should be taken in to account during production of cellulosic fibers.
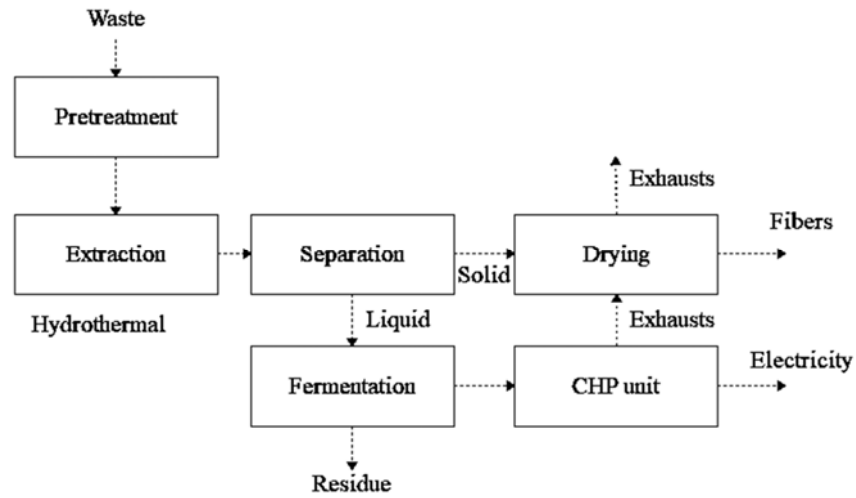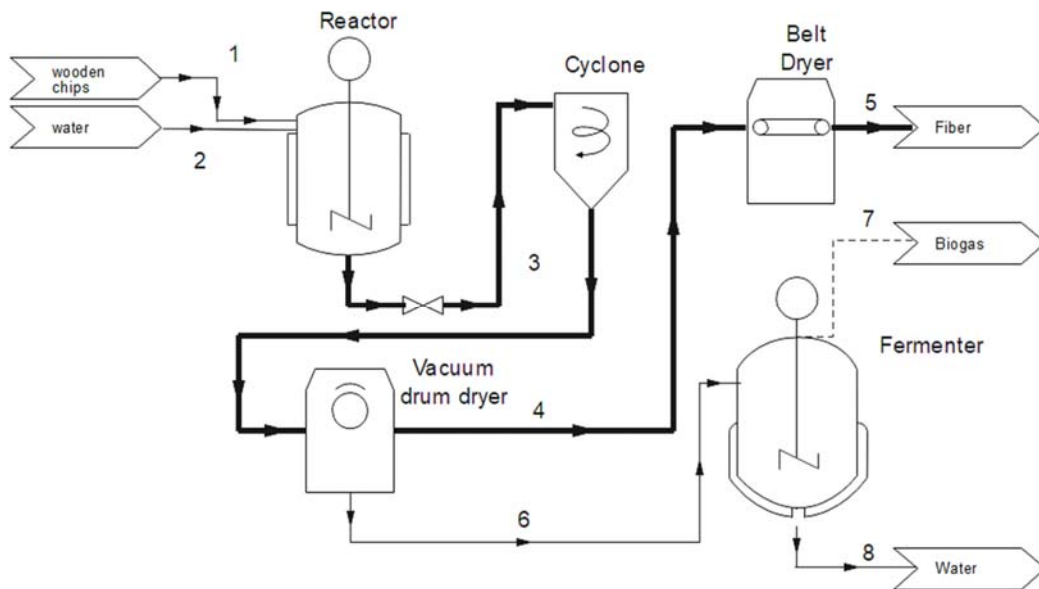

Fig.4.1 Block diagram of preferred concept

Fig.4.2 Main processes in conceptual project.

The whole process consists of following steps:

— Thermal treatment followed by rapid batch decompression;

— Separation;

— Fermentation;

— Drying of cellulosic fiber.

4.1 Thermal treatment followed by rapid batch decompression

In previous chapter, we discussed about lab-scale and lab-results of hydrothermal treatment of wooden chips. The idea is to create the flowsheet of production of cellulosic fiber, which is efficient and has regeneration of energy within the system.

After studying Kratky's lab. results [31] by us were proposed own mass and energy balanced flowsheet of thermal treatment followed by rapid batch decompression and flowsheet of it is represented below in Fig.4.3:
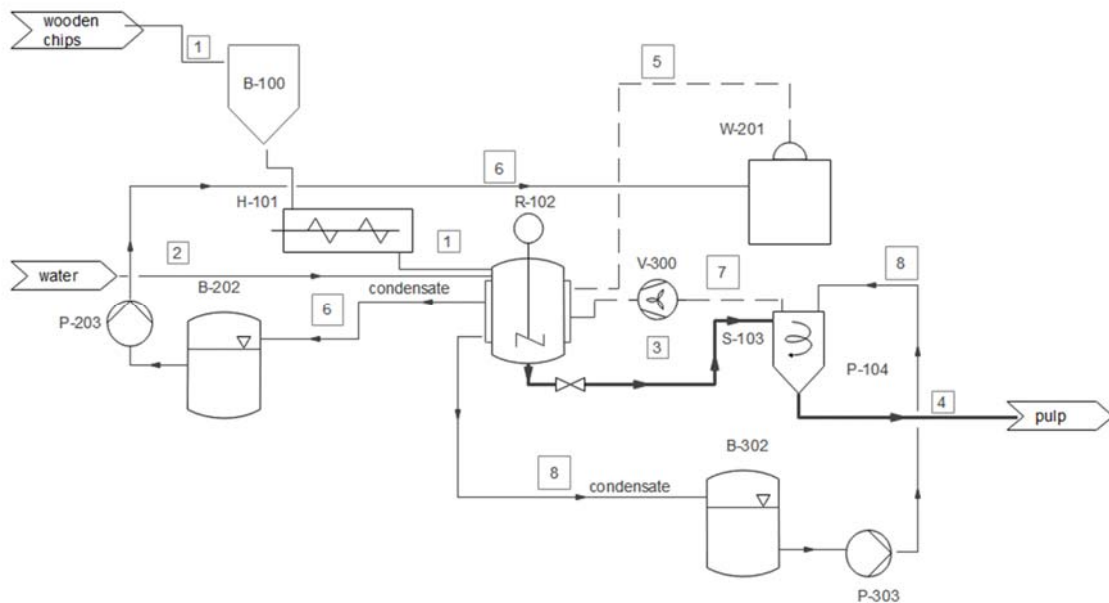
Fig.4.3. Thermal treatment followed
by rapid batch decompression.

The stream 1 (substrate) is sent to storage vessel (B-100) from which it moves to screw conveyor (H-101) and send to reactor (R-102) where it mix with water from stream 2. The mass flow rate of both streams (1, 2) is established, so the mass fraction of water in reactor is equal to 90%. Reactor take significant part in this technology. Temperature inside should be 200 °C and residence time equal to 20 min [31]. The mixture inside reactor is pressurized from 1.0 to 2.2 bar. At the same time it is heated by compressed steam by jacket system which is heated by

2 loops (stream 5 and stream 7). 1st is the outlet from expansion vessel (S-103) (stream 7) and 2nd loop generated by steam generator (W-201) (stream 5). The system should by settled in such condition where both loops will keep temperature inside the reactor(R-103) at 200 °C [31]. Finally, after all, the stream 5 rapidly expanded inside the expansion vessel-cyclone (S-103), where the soaked water by the substrate immediately evaporated, due to difference of pressure. Such system give opportunity for good treatment of wooden chips according to its specific construction. The fibers of substrate disrupted to the powder level, due to evaporation of water which was inside the substrate. The treated substrate is now ready for subsequent processing.

After analyzing lab. scale results [31] of boiling and using expansion method for disintegration of wooden chips by us was decided to use both method of pretreatment of wooden chips. For making this process simpler and less costly, can be used some chemicals but in this case future step of fermentation can be much harder and project will not be environmental friendly.

4.2 Separation

From previous flow sheet was clarified step of pretreatment of substrate. Next step should be separation of cellulose from lignin and hemicellulose which are separated from each other and are in water solution. See Fig.4.4:
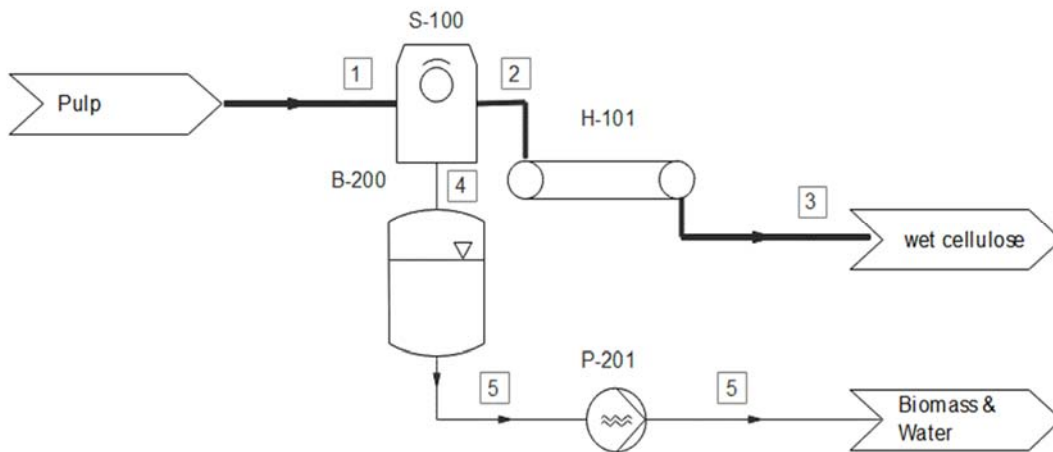

Fig.4.4 Separation of cellulose from rest bio residues.

For this purpose, stream 1 goes to vacuum drum drier (S-100). Author used this apparatus which can separate bigger cellulose particles from rest biomass. During this process was assumed total dissolving of hemicellulose and lignin in water on previous strep. Stream 2

connect Vacuum drum drier with conveyor (H-101). In its tern, stream 3 provide connection of conveyor and next process of cellulose drying. Stream 4 flows into vessel (B-200) which provide proper functioning of screw pump (P-201) which was placed on stream 5 to give needed flow rate for next step of treatment of biomass and water mixture.

4.3 Fermentation

On the Fig.4.5 you can see the fermentation process which includes maintaining a certain temperature in fermentation vessel. Substance which content Biomass and water by stream 1 flows into Heat Exchanger (W-100) for decreasing temperature of it while after previous steps temperature in it is close to 200 °C. On the other hand, this heat Exchanger (W-100) provide heating of the Reactor (R-104) in which fermentation process take place. This process will take 35 days at temperature 30°C.
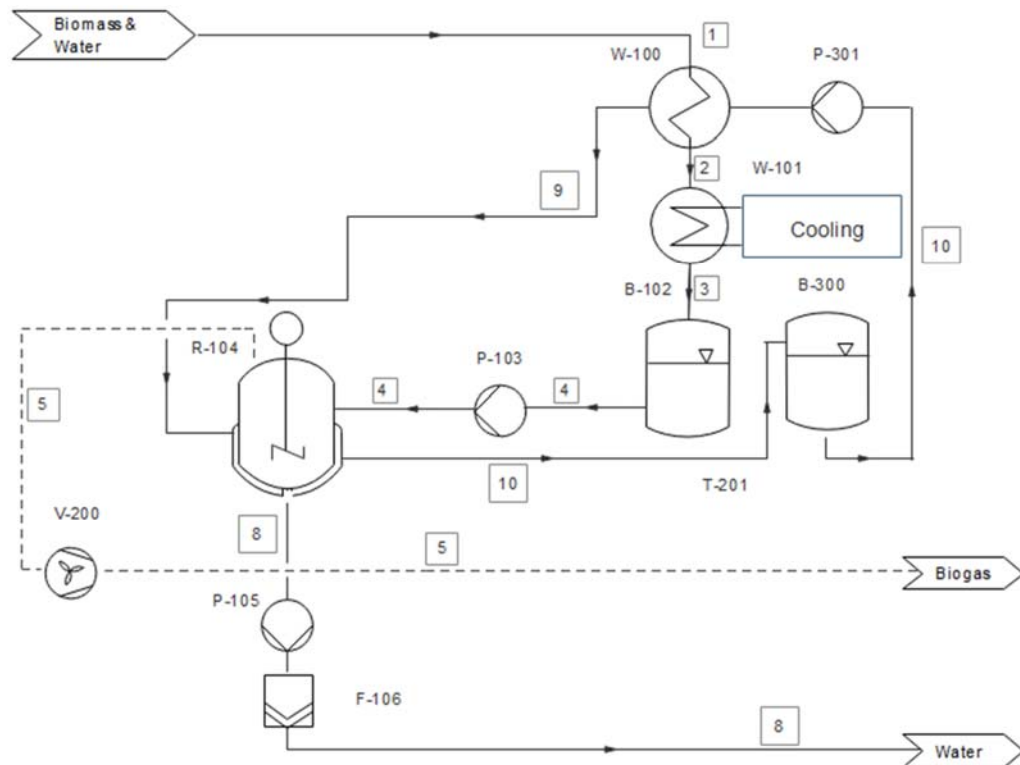
Fig.4.5 Fermentation of cellulosic fiber residues.

Calculation of Heat balance of the Reactor (R-104) shows that temperature on inlet to it in stream 4 will be too high, that can cause some problems during fermentation process, that's why by author was decided to cool stream 2 by additional cooling system (W-101) for decreasing the temperature inside the stream 3. After cooling stream 3 flows into Vessel (B-102) which gives opportunity for proper functioning of pump (P-103) which in its turn pumps

stream 4 into reactor (R-104). Stream 5 forced by Fan (V-200). For simplifying the process by author was assumed that almost all amount of biomass transfer to biogas in the reactor(R-104). Stream 8 consist of water with some negligible amount of biomass which runs through the filter (F-106) and after this procedure goes to again to the beginning of the process. Firstly, it will go to balance vessel which prevent pump of soaking the air while that can cause damaging of it and then again to 1st reactor where Thermal treatment followed by rapid batch decompression runs.

4.4 Drying of cellulosic fiber

This process is very sensitive according to the structure of our material, too high temperature can cause destroying of the cellulosic fiber structure but on the other hand law temperatures can give us unready product which will spoil after some period (see Fig.4.6). During designing of the system these specifications should be taken in to account. Stream 1 enter belt dryer (T100) where cellulosic fiber is dried by stream 8 which comes from heat exchanger (W-201). Steam 2 runs through crusher (Z-101) and fiber obtain needed shape. Biogas in stream 3 enter cogeneration unit (D-200) burns inside generate electricity and produced hot exhaust gases heat exchanger (W-201) which heat air from stream 7 forced by fan(F-300) and take direction to belt dryer (T-100). Steam 6 take exhaust gases from heat exchanger (W-201) to atmosphere.
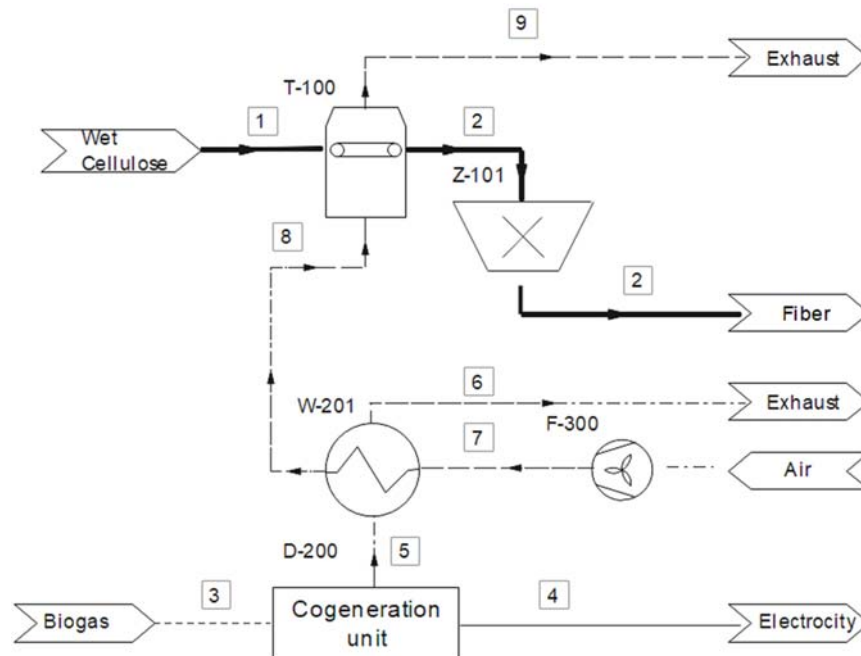

Fig.4.6. Drying of cellulosic fiber

4.5. Mass and Energy balances

4.5.1 Mass balance

Before describing all streams, we need to assume inlet of wooden chips. based on information of existing fiber production factories flow rate of raw material was fixed at 500 kg/h. or 0.14 kg/s Lab. results (Tab. 4.1) give us exact content of soft wood chips according to which mass balance can be calculated. That is concept technology that's why need to take in to account many assumptions.

Let's assume that softwood which author will use as a raw material in his project have 47% of cellulose. For better understanding the whole process by was created from PFD which can be found in Appendix K.

Lignocellulosic Biomass		Cellulose (%)	Hemicellulose (%)	Lignin (%)
Hardwood	Poplar	50.8-53.3	26.2-28.7	15.5-16.3
	Oak	40.4	35.9	24.1
	Eucalyptus	54.1	18.4	21.5
Softwood	Pine	42.0-50.0	24.0-27.0	20.0
	Douglas fir	44.0	11.0	27.0
	Spruce	45.5	22.9	27.9
Agricultural Waste	Wheat Straw	35.0-39.0	23.0-30.0	12.0-16.0
	Barley Hull	34.0	36.0	13.8-19.0
	Barley Straw	36.0-43.0	24.0-33.0	6.3-9.8
	Rice Straw	29.2-34.7	23.0-25.9	17.0-19.0
	Rice Husks	28.7-35.6	12.0-29.3	15.4-20.0
	Oat Straw	31.0-35.0	20.0-26.0	10.0-15.0
	Ray Straw	36.2-47.0	19.0-24.5	9.9-24.0
	Corn Cobs	33.7-41.2	31.9-36.0	6.1-15.9
	Corn Stalks	35.0-39.6	16.8-35.0	7.0-18.4
	Sugarcane Bagasse	25.0-45.0	28.0-32.0	15.0-25.0
	Sorghum Straw	32.0-35.0	24.0-27.0	15.0-21.0
Grasses	Grasses	25.0-40.0	25.0-50.0	10.0-30.0
	Switchgrass	35.0-40.0	25.0-30.0	15.0-20.0

Tab. 4.1 Cellulose Hemicellulose and lignin content in different raw materials in wt. % [37]

According to previous researches of concentration of cellulose $\dot{m}_c$ and other compounds of wooden chips and taking in to account assumptions mentioned before calculation in stream 4 can be calculated according to following equation:

$$\dot{m}_c = \dot{m}_{w.ch} \times 0.47 = 0.14 \times 0.47 = 0.03 \text{ kg/s.} \tag{4.1}$$

where $\dot{m}_{w.ch}$ is mass of wooden chips.

From Lab. researches we know that for treatment of soft wooden chips we should use proportion 10% w.ch. and 90% of water. From this proportion, we can calculate flow rate of mixture $\dot{m}_{mix.}$:

$$\dot{m}_{mix.} = \dot{m}_{w.ch.} \times \frac{90}{10} + \dot{m}_{w.ch.} = 0.14 \times 9 + 0.14 = 1.39 \, \text{kg/s} \qquad (4.2)$$

According to assumptions that cellulose can absorb 2.47 [31] times more water that its own weight, the flow rate of wet fiber cellulose $\dot{m}_{w.f.c}$ in the stream 4 equal to:

$$\dot{m}_{w.f.c} = \dot{m}_c \times 2.47 + \dot{m}_c = 0.03 \times 2.47 + 0.03 = 0.23 \, \text{kg/s} \qquad (4.3)$$

Knowing the value of $\dot{m}_{w.f.c}$ we can easily find the value of rest biomass and water $\dot{m}_{b\&w}$, which flows in stream 7 to the fermenter(R-506):

$$\dot{m}_{b\&w} = \dot{m}_{mix.} - \dot{m}_{w.f.c} = 1.39 - 0.23 = 1.16 \, \text{kg/s} \qquad (4.4)$$

Considering assumption that all biomass will be transferred to biogas we are able to calculate biogas yield $Y^{BG}_{CH_4+CO_2}$ which will be created in our fermenter (R-503):

$$Y^{BG}_{CH_4+CO_2} = Y^{BG} \times m_b = 0.1 \cdot 265 = 26.5 \, \text{Nm}^3/\text{h} \qquad . \qquad (4.5)$$

This value will be useful for choosing cogeneration unit, which will provide heat for drying of cellulose fiber and some electricity for the plant.

Taking in to account that water content in final product should be around 3% (based on Jirout and Kratky lab. results) [31] flow rate in the stream 5 equal to:

$$m_{r.f.c.} = \dot{m}_c \times 1.03 = 0.03 \times 1.03 = 0.07 \, \text{kg/h} \qquad (4.6)$$

That means that belt drier (T-107) should take out 0.16 kg/s of water from wet cellulose.

Next Tab.4.2 represent mass balances in main streams. More balance details can be found in appendix 1, 2, 5.

In the following table number, which is standing first after letter "m" refers to stream number, and second number refers to wooden chips (index "1"), water (index "2"), pulp (index "3"), lignin + hemicellulose (index "4"), cellulose fiber (index "5") and biogas (index "6").

Table of mass balance		
stream	value	unit
m1;1	0.13889	kg/s
m2.2	1.25000	kg/s
m3;3	0.13924	kg/s
m4;2	0.00004	kg/s
m4;5	0.06528	kg/s
m5;2	0.00196	kg/s
m5;5	0.00002	kg/s
m6;2	1.08876	kg/s
m6;4	0.07361	kg/s
m7;2	0.00405	kg/s
m7;6	0.00002	kg/s
m8;2	1.08472	kg/s

Tab.4.2 Mass flow rates of main streams

4.5.2 Energy balance

Energy balance take big part in process calculations. Finding amount of generated and absorbed heat in one place and we are able to use it in another one. Such heating or cooling systems will decrease amount of investment which will be needed for heating or cooling of the system. Unfortunately, such 1st reactor need too much heat that's why external heat suppliers were used for heating of it.

The calculation of energy balance based on: temperatures of outlet and inlet streams, mass flow rates, and properties of the fluid.

Let's calculate energy balance for first reactor (R-102). For finding amount of heat which should be provided from steam generator firstly we need to calculate heat which will be generate by cyclone (S-103)

$$Q_{(S-103)} = \dot{m}_{mix} \times C_p \times \Delta T = 1.39 \times 4200 \times (100-35) = 379160 \text{ W=379.16 kW} \quad (4.7)$$

where $\dot{m}_{mix}$ mass flow rate of mixture of wooden chips and water, ΔT temperature difference on inlet and outlet, C_p specific heat capacity of water.

The following equation represent amount of overall heat which should be added to the reactor (R-102).

$$Q_{t(R-102)} = \dot{m}_{mix} \times C_p \times \Delta T = 1.39 \times 4200 \times (200-35) = 962500 \text{ W=962.5kW} \quad (4.8)$$

Rest heat will be providing by steam generator (W-201):

$$Q_{(W-201)} = Q_{(R-102)} - Q_{(S-103)} = 96250 - 379160 = 583340 = 583.3 \, \text{kW} \qquad (4.9)$$

Based on proportion of mix inside the Reactor (R-102) we can assume density of mixture as 1000 kg/m³ and considering residence time t_{res} as 24 hours we can calculate volume ($V_{(R-102)}$) of it:

$$V_{(R-102)} = \frac{\dot{m}_{mix}}{\rho_{water}} \times t_{res} = \frac{1.39}{1000} \times 24 * 3600 = 120 \, \text{m}^3. \qquad (4.10)$$

Next step will be calculation of Heat in 2ⁿᵈ reactor (R-506). We assume that the temperature after drum dryer (S-105) felt till 100 °C. The Reactor will be supplied by heat of the stream 7 and the rest amount of unnecessary heat we be cooled by cooling system (W-503). After discussion with my supervisor, we fix the residence time — t_{res} of the reactor (R-506) on the value 25 days. Having this parameters and mass flow rate in stream 7 we can calculate volume of the Reactor (R-506).

$$V_{(R-506)} = \frac{\dot{m}_{b\&w}}{\rho_{water}} \times t_{res} = \frac{1.16}{1000} \times 25 \times 24 \times 3600 = 2511 \, \text{m}^3 \qquad (4.11)$$

where $\dot{m}_{b\&w}$ mass flow of biomass and water separated from cellulosic fiber, ρ_{water} density of water.

It was found that energy loss is around $q = 12.5$ W/m³ [35,36]. Using volume and Energy loss we can calculate $Q_{f(R-506)}$:

$$Q_{f(R-506)} = q \times V = 12.5 \times 2511 = 31384 \text{W} = 31.4 \, \text{kW}. \qquad (4.12)$$

For supplying heat to the reactor by author was created a loop which include heat exchanger (W-502) (Fig.4.7) and will cover heat loss during residence time of fermentation process. The rest amount of unnecessary heat we be cooled by cooling system (W-503). Because of conceptuality of that process was estimated that temperature at the input has 40 °C and mass flow is equal to 720 kg/h.

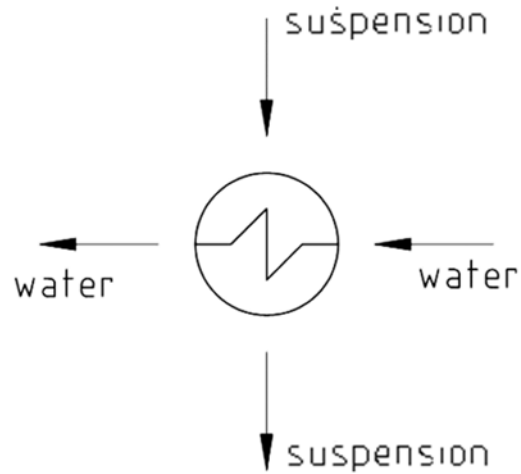For more information, please bourse appendix 1, 2.

Fig.4.7 Heat Exchanger (W-502).

Knowing these parameters and using balance, we can calculate temperature on the output from heat exchanger (W-502).

$$Q_{(R-506)} = Q_{(W-502)} = \dot{m}_{b\&w} \times C_{p.water} \times (T_{in7} - T_{out8})$$

$$T_{out8} = \frac{(Q_{(W-502)} + T_{in7})}{\dot{m}_{b\&w} \times C_p} = \frac{31400 + 40}{1.16 \times 4200} = 77\,°C. \qquad (4.13)$$

After calculation of output temperature of the Reactor (R-506) we can calculate heat which should be removed from the stream 7 by cooling system (W-503). For this firstly we need to find output temperature of stream 7 from heat exchanger W-502 (Fig.4.8):

$$Q_{(R-506)} = Q_{(W-502)} = \dot{m}_{b\&w} \times C_{p.water} \times (T_{in12} - T_{out11}) \qquad (4.14)$$

$$T_{out11} = T_{in12} - \frac{(Q_{(W-502)})}{\dot{m}_{b\&w} \times C_p} = 100 - \frac{31400}{1.16 \times 4200} = 93.6\,°C.$$
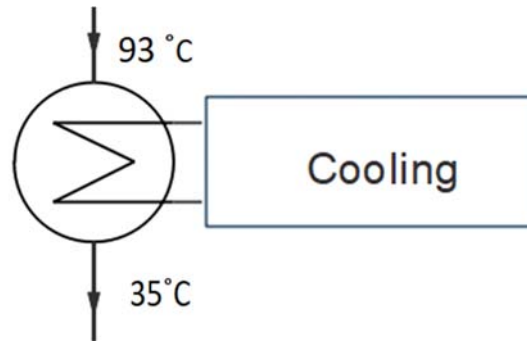
Fig.4.8 Cooling System (W-503).

This temperature can be assumed as temperature of input to cooling system and according to it can be calculated amount of heat, which should be removed from the stream 8.

$$Q_{(W-503)} = \dot{m}_{b\&w} \times C_p \times \Delta T = 1.16 \times 4200 \times (93.6 - 35) = 286000 \text{ W} = 286 \text{ kW.} \quad (4.15)$$

It is necessary to calculate energy balance for drying of cellulose fiber. This process takes place in the Belt Dryer (Fig.4.9):
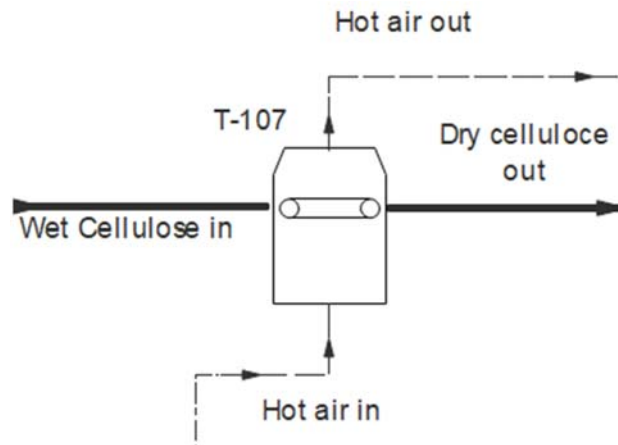

Fig.4.9 Belt Dryer

This calculation was made by using Mollier diagram [38] that shows ability of air to capture and take out unneeded amount of water. By author was chosen exhaust gases from cogeneration unit (D-509) as a source of heat for heating air which in its turn will dry wet cellulose fiber passing through the belt conveyor (T-107).

Using Mollier diagram was found that for ambient temperature air which has 50% humidity content 7.25 g/kg of water. Based on this value and with future heating of air till 80 °C we can estimate that air at that temperature can absorb ΔX = 0.538 kg/kg of air.

According to this value it is possible to calculate which flow rate of air $\dot{m}_{air}$ we should run through the belt dryer (T-107):

$$\dot{m}_{air} = \frac{\dot{m}_{u.water}}{\Delta X} = \frac{580.45}{0.538} = 0.3 \text{ kg/s} \tag{4.16}$$

After calculation of $\dot{m}_{air}$ we can calculate $Q_{(T-107)}$:

$$Q_{(T-107)} = \dot{m}_{air} \times C_p \times (T_{16} - T_{15}) = 0.3 \times 1000 \times (80 - 20) = 17742W = 17.74kW \tag{4.17}$$

From the analysis of cogeneration unit, we know that temperature of exhaust gases is close to 550 °C. This value will be inlet temperature to heat exchanger, which will heat air from 20°C to 80°C. Flow rate of exhaust gases was calculated by using special calculator which calculate it according to amount of inlet of biogas to cogeneration unit and it is equal to 366.5 kg/h. For more information, please visit appendix 2.

Knowing these parameters, we can calculate heat which is necessary to transfer from exhaust gases to the air trough heat exchanger (W-701) in stream 24.

$$Q_{(W-701)} = Q_{(T-107)} = \dot{m}_{exhausts} \times C_p \times (T_{17} - T_{18}) \tag{4.18}$$

$$T_{18} = T_{17} - \frac{\dot{m}_{exhausts} \times C_p}{Q_{(W-701)}} = 550 - \frac{0.1 \times 1000}{17740366.5 \times 1000} = 376\,°C$$

Where $\dot{m}_{exhausts}$ mass flow rate of exhaust gases.

Furthermore, these values represent that amount of exhaust gases are sufficient for heating of air for future dewatering of wet cellulosic fiber (stream 4).

4.6 Shredding

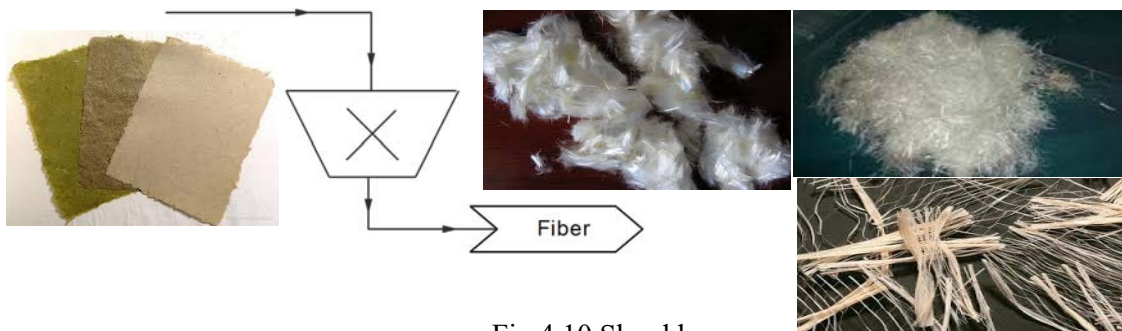Shredder (Fig. 4.10) is necessary for giving proper shape for final product (Z-108).

Fig.4.10 Shredder

Based on consultations with supervisor we use $\varepsilon = 50$ kWh/ton as a usage of electricity of it. Now we can calculate energy consumption of it per hour:

$$Q_g == \dot{m}_{r.f.c.} \times \varepsilon = 50 \times 0.247 = 12 \text{ kWh} \tag{4.19}$$

4.7 Power of cogeneration unit

Based on previous calculations of methane yield by author was chosen cogeneration unit CP5WN which is enough to burn 13.25 Nm^3/h of biogas. From the researches was found that [21 and Appendix B]:

$$q_{CH_4} = 9.94 \text{ kWh/Nm}^3.$$

$$Q_{cu(D-509)} = q_{CH4} \times \eta_{cu} \times Y_{CH4} = 9.94 \times 0.84 \times 13.25 = 110.6 \text{ kW} \tag{4.20}$$

According to its specification [Appendix B] can be calculated amount of electricity and heat which it will generate:

$$Q_{el} = Q_{cu} \times \eta_e = 110.6 \times 0.28 = 36.87 \text{ kW} \tag{4.21}$$

Rest of heat that will not be necessary in the processing line can be used for administrative works.

4.8 Economic analysis

Even after understanding whole process, realizing its potential, it is necessary to make economical study, for estimation how much such project need to invest and which payback period it will have.

4.8.1 Capital cost

The capital cost of a plan is calculated according to factorial method, which has an error ± 30%. This method base on purchased equipment cost and that's why require good analyzing for apparatuses cost. In this thesis estimation and calculation of prices was made by some correlations and formula [34]:

$$C_e = a + b \cdot S^n \tag{4.22}$$

It would be long to place here all calculation of prices of each apparatus, that's why you can find the example and important calculations bellow and wrest of calculations in following table and in appendix 4.

– **Pump (P-400).**

In the calculation of Fermenter (R-506) it was found the mass flow rate in the stream 14. Using the previous formula and defining mass flow rate as the key parameter we can calculate capital cost.

$$C_e = 3300 + 48 \times 1.08^{1.2} = 3353\$$$

– **Fermentation reactor (R-506)**

Unfortunately, this reactor cannot be calculated using previous formula. However, price of it was based on literature search.

Deublin and Steinhauser [21] mentioned, that investment price can be calculated from some characteristics of fermenter such as volume. From their study, it is necessary to take in to account that 1 m³ of fermenter cost from 300 to 500$. But after analyzing the market by author was found that in average alone price of the reactor is 120$ per m³.

$$C_e = 2511 + \times 120 = 31320\$$$

Such way of calculation can give better result in fermenter price calculation and error in calculation decrease by 10-12% (Tab.4.3).

Some prices were taken from existed biogas plants while it is impossible to use factorial method of calculation on them. They are mentioned as reference (ref.) in the Tab.4.3.

Apparatuses as conveyors filters water condensation system and belt dryer were searched on the market one by one and in appendix D mentioned their prices.

Sum of all prices gave us total capital cost (TCC) of our plant. For calculating total investment cost (TIC) we should add construction (40%) + project and engineering (30%) [21] consumptions from total capital cost:

$$TIC = TCC + 0.7 \times TCC = 1.48 + 1.48 \times 0.7 = 2.51 \text{ mln. \$.} \tag{4.23}$$

Part No.	Type	Unit for size	S	a	b	n	Cost
P-203	Liquid pump	l/s	0.27	3300	48	1.2	3300.00
B-202	Balance vessel	m³	0.16	5700	700	0.7	5900.00
R-102	Reactor	m³	120.00	14000	15400	0.7	453500.00
S-103	Cyclone separator	m³	2.90	5700	700	0.7	7200.00
R-506	Fermenter	m³	2510.73	14000	15400	0.7	301300.00
S-105	Drum separator	m²		-7400	4350	0.9	20000.00
V-300	Fan	m³/h	265.00	4200	27	0.8	6500.00
H-106	Conveer	m	2.00	21000	340	1.0	3000.00
T-107	Belt dryer	m²	13.00				100000.00
Z-108	Grinder	kg/h	0.07	3000	390	0.5	3100.00
W-503	Cooler	kW	285.94	61000	650	0.9	166600.00
D-509	Cogen unit	kW	36.88	1200		$/kWe	44300.00
B-100	Storage vessle	m³	31.58	3300	48	1.2	6300.00
H-101	Screw conveyor	m					8000.00
P-104	Screw pump	kg/s					4100.00
B-500	Balance vessel	m³	0.70	5700	700	0.7	6200.00
P-501	Screw pump	kg/s					4100.00
W-502	Heat exchanger	m²	0	1100	850	1.0	1100.00
B-504	Storage vessle	m³	2510.73	3300	48	0.7	14800.00
P-505	Screw pump	kg/s					4100.00
P-400	Liquid pump	l/s	1.08	3300	48	1.2	3400.00
F-401	Filter	m²	20.00	-45000	56000	0.3	92600.00
B-402	Balance vessel	m³	2.25	5700	700	0.7	6900.00
P-403	Liquid pump	l/s	1.25	3300	48	1.2	3400.00
V-507	Fan	m³/h	13.25	4200	27	0.8	4400.00
W-701	Heat exchanger	m²	26.38	1100	850	1.0	23500.00
V-700	Fan	m³/h	0.30	4200	27	0.8	4200.00
D-510	Burner	duty,MW			180000		9000.00
B-600	Balance vessel	m³	1.00	5700	700	0.7	6400.00
P-601	Liquid pump	l/s	0.20	3300	48	1.2	3300.00
B-302	Balance vessel	m³	0.21	5700	700	0.7	5900.00
P-303	Liquid pump	l/s	0.17	3300	48	1.2	3300.00
W-201	Steam generator	ref					150000.00
					Capital Cost in mln $		1.48

Tab.4.3 Total Capital Cost

Also, we should take in to account energy consumption of the plant (Q). From previous calculations was found that energy which is required for apparatuses each apparatus in plant. Summarizing these values and consider 20% heat loses (based on consultations) and also energy which is generated by cogeneration unit Q_e we will get:

$$Q = (Q_g + Q_f + Q_t) \times 1.2 - Qe$$

$$Q = (12102 + 31384 + 962500) \times 1.2 - 36877 = 1170000000 \text{ Wh=1170 MWh} \quad (4.24)$$

The price of electricity per year mentioned in the following Tab 4.4 as Energy cost and its calculations can be found in Appendix B and I.

4.8.2 Payback period

To estimate the payback time, we should calculate many parameters: direct operating cost (raw material, laboratory etc.), indirect operating cost (insurance, corporate directions), distribution cost (transport), income from sales (see Tab.4.4).

Parameter	Unit	Variant A
Profit from the sale of electricity &residuals (revenues from sales)	$/year	4,163,260
Operating costs excluding depreciation and interest payments	$/year	3,915,824
Direct operating costs	$/year	2,228,547
Raw materials	$/year	340,002
Personal costs of employees of the operation	$/year	149,299
Supervision	$/year	7,465
Maintenance costs	$/year	100,620
Consumables	$/year	12,577
Energy cost	$/year	1,596,298
Reserve	$/year	22,285
Indirect operating costs	$/year	87,277
Insurance	$/year	25,155
Corporate directions	$/year	62,122
Distributional costs	$/year	1,600,000
Transport	$/year	1,600,000
Taxable income	$/year	247,436

Tab.4.4 Expenses and revenues

However, to obtain such results, we should have project parameters. They and all the rest economical calculations could be found in appendix I.

Finally, after estimation of operating cost and other important parameters we can find payback period of the project. On the Fig 4.10 and Fig 4.11 mentioned these periods.
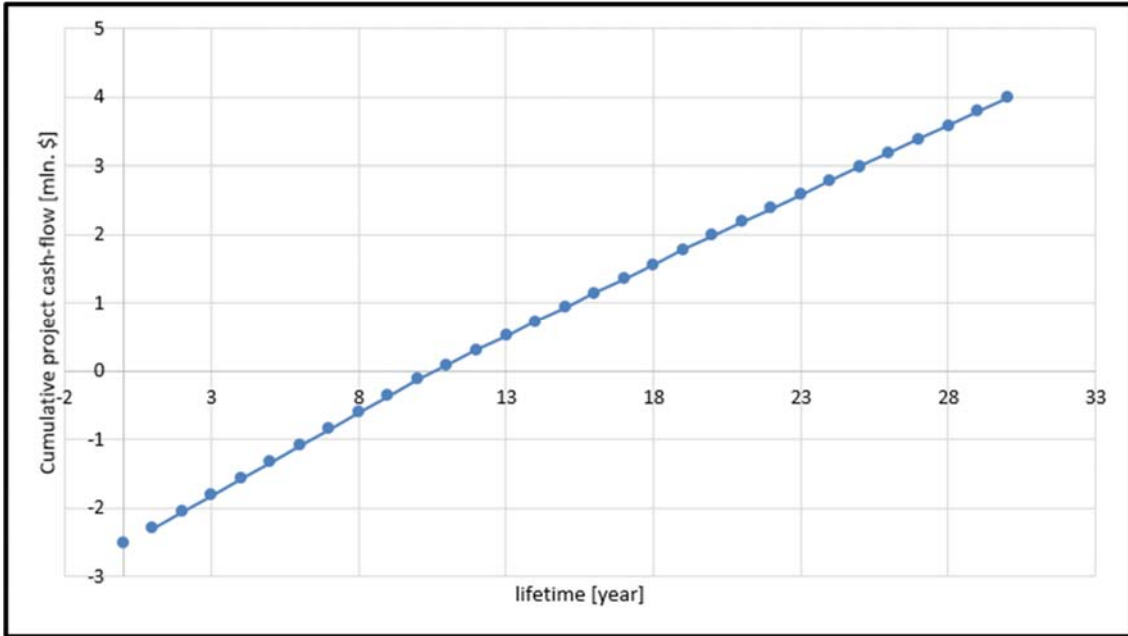
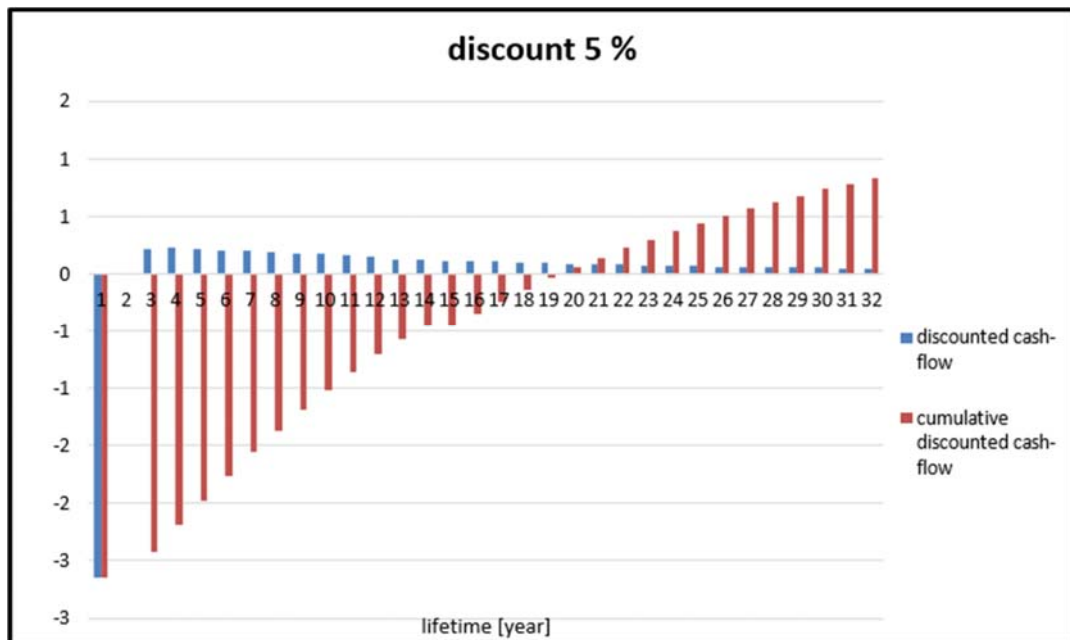Fig.4.11 Payback period for 0 % discount rate.

Fig.4.12 Payback period for 5 % discount rate.

Mainly, to get more realistic results, it is preferred to taking into account discount rate. The discount rate in discounted cash-flow analysis considers not only the time value of money, but also the unpredictable risks or uncertainty of future cash flow. So, for 0 % discount rate, or

in other words the ideal case, we will get our money back in approximately 13 years. However, for 5 % discount rate the payback period is approximately 24 years.

That is very good result according to estimation that 100% of investment will be bank credit. In developed countries, a government usually gives subsidies or discounts to build such innovated plants or other plants with processing different kinds of renewable energy sources, also subsidies for electricity profit. These subsidies could vary from 30 % to 60 % of total investment cost [33]. The electricity profit, with subsidies (green electricity), could increase electricity price from 2 to 4 times.

5 DISCUSSION

We tried to made estimation of mass, economic and energy balances and studies as precise as student access allows it. On the following Tab.5.1, you can find results of this work.

	Title	Results	
		C.F.P.+B.P.	C.F.P
Process	Substrate mass flow [kg.s^{-1}]	0.14	0.14
	Product mass flow [kg.s-1]	0.07	0.07
	Biogas yield [Nm$^{3.h-1}$]	26.50	-
	Electric power [kWh]	36.88	-
Economical analysis	Total Capital Cost (TCC) [mln.$]	1.48	0.92
	No. of equipment	33	22
	Reactor volume [m3]	120	120.00
	Reactor cost [mln.$]	0.45	0.45
	Fermenter volume [m3]	2511	-
	Fermenter cost [mln.$]	0.30	-
	Reactor percentage of TCC [%]	31	49
	Fermenter percentage of TCC [%]	20.36	-
	Total Investment Cost [mln.$]	2.52	1.56
	Profit [mln.$.year^{-1}]	0.247	0.257
	Payback period [year]	12	9
	Lifetime [year]	30	30
	Total profit of project [mln.$]	7.42	7.72

Tab. 5.1 Table of important outputs.

C.F.P.− Cellulosic Fiber Production

C.F.P.+B.P. − Cellulosic Fiber Production + Biogas production

As a repetition, input materials were wooden chips and water. Wooden chips are 10% wt. and the rest ,90% wt., is water. For some simplification after passing 1st reactor density of solution was assumed as water, because it mainly consists of water. We propose such flow sheet which can reuse unnecessary heat and energy to decrease operating cost of the plant.

After all calculations of mass and energy balances, finally, the economic analysis was calculated and was found the payback period.

Let's compare results from conceptual plant with Cellulosic Fiber Production plant without biogas production. As you can investment cost of plant with integrated biogas production is more expensive and its payback period is longer for 3-4 years. Take in to account that allowed error in such calculations are ± 30 %. Difference in investment cost is little bit less

than 1 million $. What we get from such production? Is it profitable in our life? It depends on many factors. From the point of pollution such project is much better than simple production, while almost all residuals can be transformed to biogas which can give us extra energy for supplying system itself. In the case of plant without biogas production we face another 2 problems. 1st with big number of residues which must be somehow utilized. And the 2nd we need to have additional source of heating for drying ready cellulose fiber. That situation exactly shows how innovations can help to protect nature and prevent pollution of nature. After small mathematical analysis, we can calculate that at the end of the life time of such project our biogas production can be applied for generation 8850 MWh of green energy. This value was calculating using efficiency of cogeneration unit of production electricity equal to 28%. With such small efficiency, even nowadays we are able to create plants which can open the new horizons for future technologies and better life of humanity. Payback period is one of the heaviest arguments for investors. On the other hand, even taking in to account TIC the total profit at the end of the lifetime period is quite close to 5 million $.

Such projects are great opportunity for mankind for protecting our planet and at the same time future generations.

6 CONCLUSION

During the work the following sections were accomplished:

- ✓ Literature search showed that thermal expansionary treatment has high potential and treated wooden chips are suitable for cellulosic fiber manufacturing. At the same time, residues of production can be used for production of biogas.
- ✓ Mass and energy balances were calculated for all streams, suitable machines and apparatuses were chosen for technology. Description of process streams, machines and apparatuses positioning are required part of flowsheet.
- ✓ Detailed flowsheet of a plant was designed. Amount of Electric Power which will be generated by Cogeneration unit was calculated. PFD was prepared in EDRAW software.
- ✓ Energy optimization of technology was done. Unnecessary heat was used for preheating the Fermenter. Hot exhaust gases from Cogeneration unit were used as drying media for dewatering wet cellulosic fiber.
- ✓ Based on Economic analysis, were found that Reactor price is 31 % and Fermenter price is 20% of total capital cost.
- ✓ Payback period of such plant is around 14-16 years.
- ✓ All calculations were programed and calculated in Microsoft Excel software. Modifying input data, mass, energy and economic balances of new technology are rapidly and easily counted.

SYMBOLS

Basic quantities

a, b, n	Correlation factors	$-$
Ce	Capital cost	$\$$
$\dot{m}$	Mass flow rate	$kg \cdot s^{-1}$
$\dot{m}_c$	Mass flow rate of cellulose	$kg \cdot s^{-1}$
$\dot{m}_{u.water}$	Mass flow rate of unneeded water	$kg \cdot s^{-1}$
$\dot{m}_{w.ch}$	Mass flow rate of wooden chips	$kg \cdot s^{-1}$
$\dot{m}_{w.f.c}$	Mass flow rate of wet cellulosic fibers	$kg \cdot s^{-1}$
$m_{r.f.c.}$	Mass flow rate of ready cellulosic fiber	$kg \cdot s^{-1}$
$\dot{m}_{b\&w}$	mass flow rate of biomass and water $kg.$	s^{-1}
Q	Power	kW
Q_{el}	Generated power by cogeneration unit	kW
Q_f	Heat loss of fermenter	kW
Q_{overal}	Overall power	kW
Q_g	Power of shredder	kW
ΔT	Temperature difference	$^{\circ}C$
C_p	Specific heat capacity	$kJ \cdot (kg \ K)^{-1}$
S	Heat transfer surface	m^2
V	Volume	m^3

T	Temperature	$°C$
q_{CH4}	Combustion heat	$kWh \cdot Nm^{-3}$
ρ	Density	kg/m^3
ε	Energy consumption	$kW \cdot ton^{-1}$
η_{cu}	Efficiency of cogeneration unit	-
η_e	Efficiency of electricity production	-
Y_{CH4}	Methane yield	$Nm^3 \cdot t\_TS^{-1}$
Y^{BG}	Biogas yield	$Nm^3 \cdot t\_TS^{-1}$
X	Parameter	-

Subscripts

CNG	Compressed natural gas
CHP	Combined heat and power
TIC	Total investment cost
TCC	Total capital cost
MP	Mechanical processing
SPT	Simple payback time
CAPEX	Capital expenditure
AI	Annual income
CC	Contingency charges
EC	Engineering cost

AD   Anaerobic digestion

COD   Chemical oxygen demand

BOD   Biological oxygen demand

CH_4 Methane

CO_2 Carbon dioxide

pH   Potential of hydrogen

WW   Waste water

TEP   Thermal expansionary pretreatment

C.F.P.   Cellulosic Fiber Production

C.F.P.+B.P.   Cellulosic Fiber Production + Biogas production

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