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Chapter 1. Introduction

The activated sludge process for treating wastewater is a widely used technology for reducing the environmental impact of wastewater discharge. However, wastewater contains a lot of useful carbon-based materials (~121 g COD/(PE·d)) such as cellulose, polyhydroxyalkanoates (PHA), lipids, and fatty acids that could be recovered and used as a raw material to produce several bio-based products. This in turn minimizes the net energy consumption of the wastewater treatment plant (WWTP). The potential recovery of these materials has not been exploited much in North-West Europe (NWE). Generally, all these materials are used in anaerobic digestion to produce biogas. Currently, very few plants are in operation such as a full-scale plant for cellulose recovery at the WWTP Aarle-Rixtel in the Netherlands (Cirtec BV 2020) and a pilot-scale plant for recovery of polyhydroxyalkanoates (PHA) at WWTP Manresa, Spain (SMART-Plant 2020). Utilizing each of these valuable materials could reduce the use of natural resources and subsequent carbon dioxide (CO_2) emissions helping in realizing a circular economy. Of these materials, cellulose fibers are the major constituent due to the increased usage of toilet paper. In western Europe, the per capita annual toilet paper consumption was reported to be about 14 kg/capita (Ruiken et al. 2013). Cellulose fibers constitute 25%-30% of the particulate fraction (i.e. COD fraction) of the wastewater (Ruiken et al. 2013).

In typical wastewater treatment, the cellulose is first hydrolyzed followed by metabolization. This depends on the temperature and sludge retention time which ultimately affects the oxygen demand, sludge production, and nutrient removal (Ruiken et al. 2013). Furthermore, the degradation efficiency of cellulose fibers ranged from 6.7% to 100% at contact time ranging from 3 days to 20 days, respectively, at a lab-scale (Ahmed et al. 2019). Therefore, cellulose fibers are mainly biodegraded in the secondary treatment of wastewater treatment plants and as a result, the aeration energy consumption of the plant increases. Alternatively, the cellulose fibers can be recovered from wastewater before the primary sludge stage by using a sieve. Fine mesh has been in use as a mechanical treatment option (Rusten and Ødegaard 2006) as an alternative to the primary treatment of wastewater. It has also been observed that the cellulose fibers are the major fraction of chemical oxygen demand (COD) removed by the sieve and have a consistency similar to paper mache indicating the presence of toilet paper in the wastewater (Ruiken et al. 2013).

The recovered cellulose could be used in many applications such as in mortar mix in the building sector (Cipolletta et al. 2019). Mixing the cellulose fibers was found to increase the performance of mortar in terms of lightness, flexural strength, and hygrometric properties. However, since the recovered cellulose is a carbon-based element, it can also be used to produce bio-based products using processes such as pyrolysis. In the pyrolysis process, the carbon-based material is subjected to heat in an oxygen-deficient environment such that it removes the volatiles from the material as gas and converts the rest to biochar. The volatiles can be condensed to separate the stream into liquid and pyrolysis gas. The liquid fraction from condensation constitutes bio-oil and pyroligneous acid and some other minor components. A fast pyrolysis process occurs in a temperature range of 300-1000 °C and has a residence time of fewer than 2 seconds (Miltcon Services Limited 2018). This process is used if more bio-oil is desired in the products. On the other hand, a slow pyrolysis process occurs in a similar temperature range (100-1000 °C) but with a residence time ranging from minutes to hours (Miltcon Services Limited 2018). This process is adopted whenever the desired product is biochar.

Biochar produced from pyrolysis has limited direct applications. It is mainly used as a solid fuel for combustion or to enhance the soil quality in agriculture. To increase the number of applications, biochar can be activated. Activation results in an increased surface area allowing numerous applications such as in water purification, wastewater treatment, as adsorbent, etc. Physical activation is performed by using steam or inert gas at 800 – 1000 °C to remove the volatile components and oxidize the solid carbon residues (Hagemann et al. 2018). The surface area is increased by removing the partially combusted compounds that have been formed in the pores during carbonization. This in turn increases the available pores and their volume, consequently, increasing the adsorption capacity of the activated biochar (Mohammad-Khah and Ansari 2009). Another activation method is chemical activation in which the biochar is permeated with a liquid activation agent such as $ZnCl_2$, KOH, or H_3PO_4 (Hagemann et al. 2018). When the biochar is soaked in the inorganic liquid activation agent, the organic molecules are degraded and prevented from depositing in the pores. After soaking, the activation agent is flushed with water and recovered (Mohammad-Khah and Ansari 2009). The chemical activation process generates a higher surface area and has higher activation efficiency than the physical activation process. However, it imposes additional costs such as chemicals and their recovery and reduces the equipment's life by corrosion (Cha et al. 2016).

In the WOW project, the use of the screened cellulose material from wastewater to produce bio-based products via a fast pyrolysis process was evaluated. In the WOW! project, the cellulose pyrolysis pilot plant was developed by the partners Cirtec and PulsedHeat. Cirtec was responsible for designing the cellulose screens whereas PulsedHeat was responsible for the rest of the plant consisting of dewatering, drying, and pyrolysis section. In this report, the results of the techno-economic evaluation are discussed and strategies to optimize the process from an economic point of view are presented. In the next section the overall methodology, the process adopted in the WOW project to recover cellulose and turn it into useful products are described, including the process flow diagram and the mass and the energy balances. The data had been provided by the partners PulsedHeat and Cirtec unless mentioned otherwise. Next, the techno-economic assessment methodology adopted to estimate the minimum selling price (MSP) of the products is presented. Finally, the results obtained and the key parameters, and their effect on the key performance indicators are discussed. Lastly, the conclusions and recommendations for future research are reported.

Chapter 2. Methodology

In this chapter, the methodology used for the techno-economic assessment, the process flow diagram of the full plant, and the data used to calculate the mass and energy balance, as well as the economic results, are described.

2.1. Techno-Economic Assessment

When developing innovative technologies, such as the recovery from cellulose from wastewater and its conversion into bio-oil, (activated) biochar, and pyroligneous acid, it is important to have a clear idea of the economic performance of the process. A techno-economic analysis (TEA) helps to optimize the development of a process and to determine the most important parameters. Consistently applying the methodology will enhance chances of success when introducing (innovative) processes on the market. A TEA considers the entire value chain and can be applied during every technology readiness level (TRL). The methodology can be divided into four different phases. First, a market study is performed. Second, a preliminary process design is defined and translated into a simplified process flow diagram (PFD) and mass and energy balance. Third, this information is directly integrated into a dynamic cost-benefit analysis (CBA) (i.e. economic evaluation). From this analysis, profitability is identified. Fourth, an uncertainty analysis is performed to identify the potential barriers. As information gathering is expensive, a TEA is performed iteratively with a go/no-go decision after every iteration. A graphical representation of the methodology is provided in Figure 1. A detailed description of the methodology can be found in (Van Dael et al. 2015).

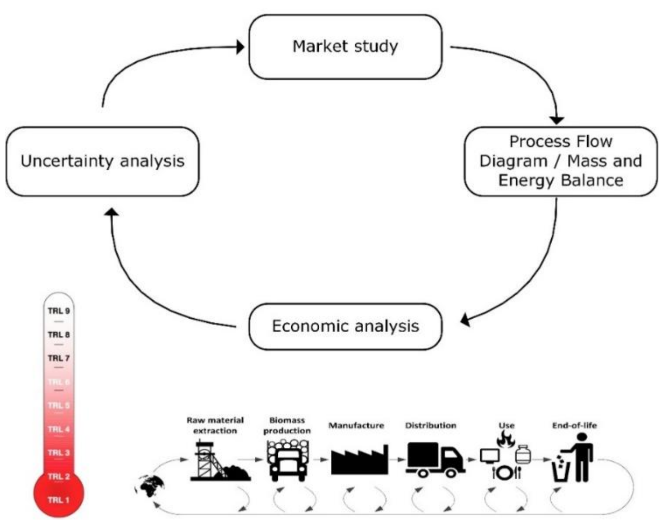


Figure 1. Techno-economic assessment

2.2. Market study

The market study allows the researcher to identify the competitors and customers. It also provides information concerning the size of the market, the needs of the market, and the alternatives on the market. Furthermore, it will also provide information concerning the costs and revenues. Moreover, a market study contains a study of the legislation that is in place. Finally, market research provides insight into market trends. However, the latter is more difficult to estimate when working with innovative technologies. Within the WOW project, the market study was performed by the project partners and reported in separate documents. For the products a market potential study by Wupperverbandsgesellschaft für integrale Wasserwirtschaft mbH is available, as well as a factsheet per product. The state-of-the-art of legal framework is separately available in a report from Avans Hogeschool. The documents can be found on the project website[1].

2.3. Process description and process flow diagram

Within the WOW project, a techno-economic assessment for the cellulose recovery and pyrolysis unit, as well as for two subsequent biochar activation methods was performed. The process flow diagram of the cellulose recovery and the pyrolysis unit is shown in Figure 2. The connections to the classical WWTP are depicted by the red-bordered boxes in the figure. The wastewater coming into the treatment plant was sent through the screens specially designed to recover cellulose fibers. The cellulose fibers collected were sent to the dewatering press and the effluent was sent back to the WWTP as primary effluent. In the dewatering press, the surplus water was pressed out and also sent to the WWTP as primary effluent. The pressed cake was dried in a dryer by using the hot flue gas from an after/co-burner. The outlet flue gas from the dryer was washed with water in a cyclone to remove any particulate matter. The washed flue gas was split into three streams, two of the streams were sent to the after/co-burner and burner, respectively and the rest was sent to the stack. The dried cellulose was made into small pellets in a pellet press and sent for further drying in a deep dryer. Some part of the flue gas from the after/co-burner was used in the deep dryer. The outlet flue gas was washed with water in a cyclone to remove any particulate matter

[1] https://www.nweurope.eu/projects/project-search/wow-wider-business-opportunities-for-raw-materials-from-wastewater/

before releasing the flue gas to the stack. The washed water from both the cyclones was mixed with the primary effluent and sent to the WWTP. The dried pellets from the deep dryer were sent to the pyrolysis reactor.

In the WOW project, a fast pyrolysis process was adopted which ensured increased production of volatiles, especially bio-oil. The heat required for pyrolysis was provided by the flue gas from the propane-fired burner. The temperature is kept constant by varying the propane mass flow to the burner. The amount of recycled flue gas is determined by the heat demand of the process. The biochar produced was removed continuously from the reactor while the volatiles were collected and quenched to remove the pyroligneous acid fraction followed by bio-oil separation. The outlet from the oil separator was then subjected to condensation. Water was used as a coolant in the heat exchanger (condensation) unit. After removing the pyroligneous acid by using a knock-out drum, the pyrolysis gas was obtained at the cyclone top. The pyrolysis gas was then recirculated to be used in the after/co-burner along with propane to produce the heat required in the dryers. The liquid fractions of pyroligneous acid obtained after quenching and from the knock-out drum and the cyclone are collected.

The biochar was further sent for activation depending upon the requirement. Two types of biochar activation processes were adopted in this assessment namely (1) physical activation which was done by using steam and (2) chemical activation which was done by heating the biochar with an acid. Figure 3 represents the physical activation process of biochar by using steam. In this process, a boiler was used to generate the required saturated steam which was then supplied to the activation reactors where biochar was placed in the form of a bed. The activated biochar with the increased surface area was removed from the bottom of the reactors and packed for distribution while the saturated water at the exit was reused after treatment. Figure 4 represents the chemical activation process by using a liquid activation agent phosphoric acid (H_3PO_4). In this process, the biochar was mixed or soaked with H_3PO_4 in a rotary mixer followed by heating at high temperatures in a rotary kiln. The mixture was then cooled in a rotary cooler followed by washing of H_3PO_4 with water. The synthesized activated carbon was dried in a rotary dryer and packed for distribution. The flushed H_3PO_4 with water was separated and was stored for recycling.

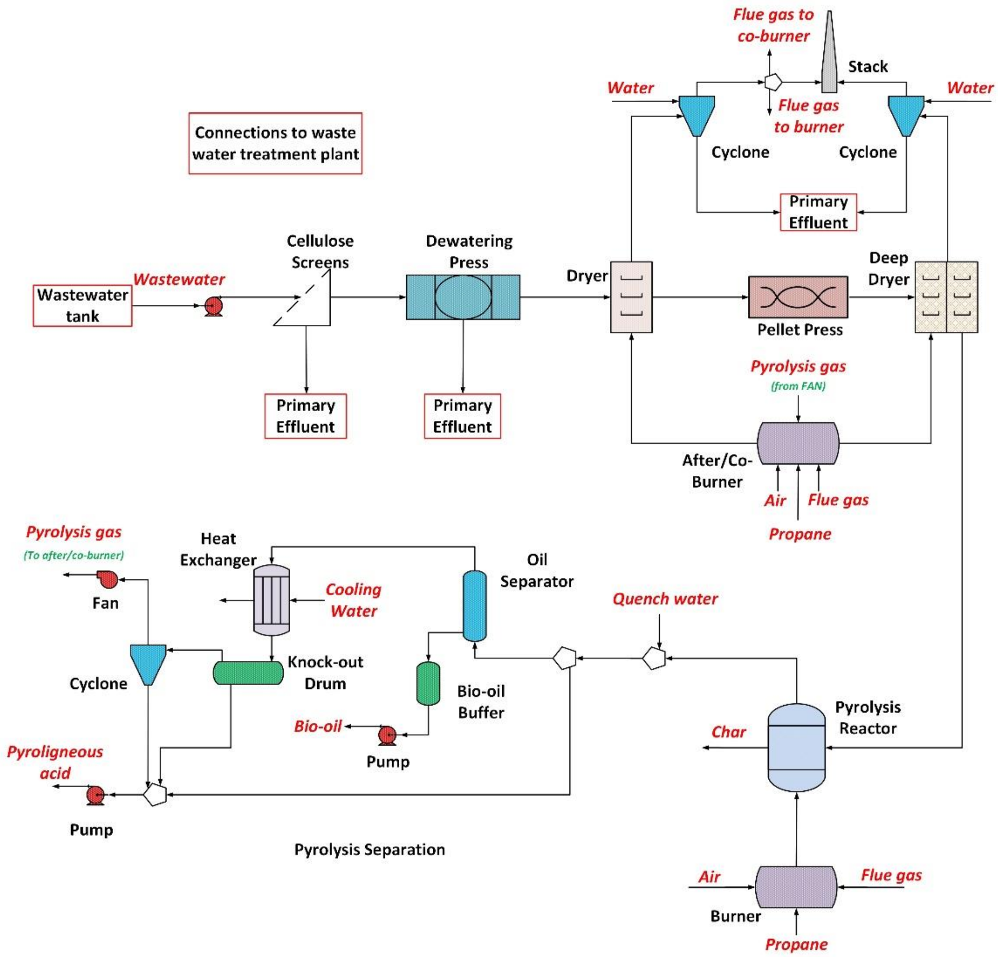


Figure 2. Process flow diagram of the cellulose recovery and pyrolysis unit

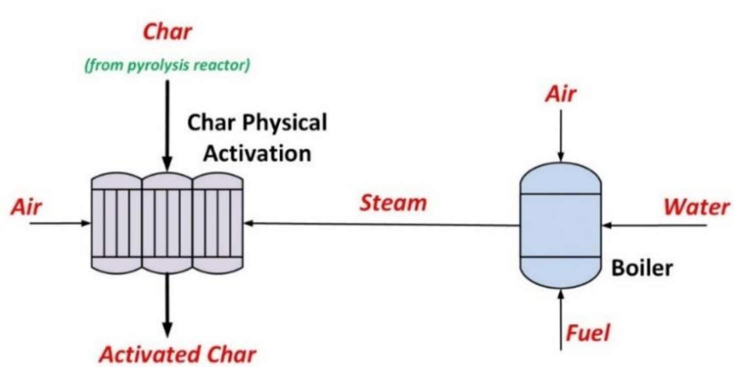


Figure 3. Physical char activation by steam

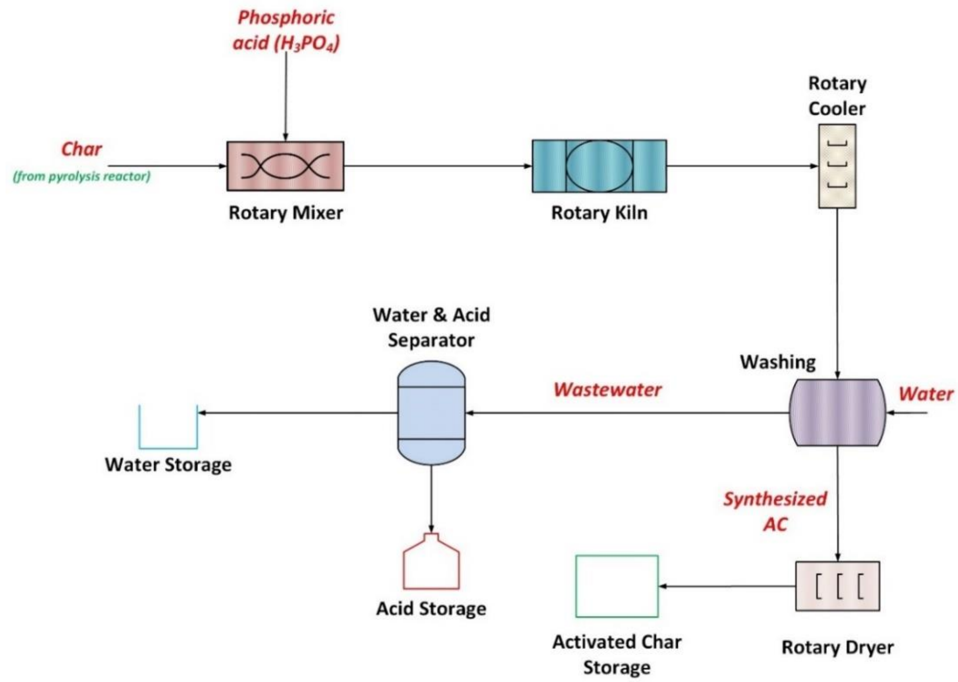


Figure 4. Chemical char activation by phosphoric acid

2.4. Technical details – Mass and energy balance

The pilot plant was designed at a scale of 75 kgDM/hr. An overview of the type of equipment used is provided in Table 1. After the initial wastewater screening to remove larger solids (<6mm), two cellulose screens with a pore size of 350 µm were used for a flow of 500 m^3/h and consumed 0.032 kWh/m^3 of electricity. The dewatering press was a screw-type press with a capacity of 50.5 kgDM/hr and consumed about 0.03 kW/kgDM. The pressed cellulose screenings were dried in a falling curtain dryer called DryFall® specially designed for these types of operations by Pulsed Heat (Pulsed Heat 2020). The heat required by the dryer was 1 kW/kgDM which was supplied by the flue gases at 850 °C from the after/co-burner whereas the electricity requirement was 0.11 kW/kgDM. The flue gas from the dryer was washed in a cyclone with spring water pumped locally to extract the bulk of the dust from the gas stream. The washed flue gas was then split and recycled to the burners for temperature control. Spring water was used for washing in the cyclones and each cyclone used in this process consumed 0.01 kW/kgDM. The washed water was sent for treatment along with primary effluent. Pulsed Heat had done a dust cyclone test and collected about 3 kg/hr of dust, measured for a wet input of 308 kg/h. Thus, the dust was about 1% ± 2% on a wet basis. The collected dust fraction was relatively small. Therefore, to catch additional dust, a wet cyclone was also tested in the pilot plant and injected the spring water in the co-current direction to the gas stream from the dryer. The outlet suspension could be reintroduced before dewatering press and as a cellulose fiber recycle stream (minimizing the cellulose back to the WWTP). However, it was also concluded that it would be better to use a dry cyclone at the dryer exit since the dust captured was already dried and was close to 90% dry matter because of cellulose fibers. Furthermore, on a rough estimate, 5% of the thermal input would be saved by using a dry cyclone compared to a wet cyclone.

The dried cellulose was made into pellets using a flat die pellet press with a capacity of 73 kg/hr and electricity consumption of 0.13 kW/kgDM. The pellets from the pellet press had a temperature of approximately 60 – 70 °C. These pre-heated pellets saved about 5% in thermal input. The specific heat (Cp) for the mineral and organic fraction of the pellets and water was 2 kJ/kg·K and 4.18 kJ/kg·K, respectively. When compared with the evaporation enthalpy of water 2200 kJ/kg, this is marginal. The pellets are further dried in a deep dryer at 120 °C by using the flue gas from the after/co-burner. The dryer had a capacity of 50.5 kgDM/hr with heat and electricity requirements of 1.05 and 0.05 kW/kgDM, respectively. For drying the pellets, Pulsed Heat designed a column dryer for this project. It had a pellet bed that slowly sinks, through which flue gases diluted with air go through. For a larger-scale installation, a part of the residual heat from the DryFall® dryer could be used to heat air for the pellet dryer. The outlet flue gas was washed with spring water and released to the stack.

The dried pellets were introduced into the pyrolysis reactor as a bed and the hot flue gas at a temperature of 850 °C was introduced from the bottom. It was assumed that the residual oxygen in the flue gas reacts with the char in the reactor. In this project, a fast pyrolysis process was adopted which occurs at very high temperatures (~900 °C) and at very small residence times (< 1 sec). Fast pyrolysis also ensures increased bio-oil yield as opposed to slow pyrolysis which is used for increased biochar production. The heat and electricity required in the reactor were 0.27 and 0.02 kW/kgDM, respectively. The biochar contains a significant amount of ash. The sieved cellulose material would contain around 7% of inorganic material on a dry basis (PulsedHeat 2020). The reactor was heated with flue gases, instead of burning biochar by introducing air to be able to better regulate the gas temperature. This leads to a lower temperature of 900 °C as opposed to 1400 °C. Furthermore, combusting less carbon leads to less ash per kilogram of sieved material. For the quality of the effluent, it is better if it contains fewer heavy metals.

A propane burner was used to supply the heat required in the fast pyrolysis process with a capacity of 12.6 kW and required an electricity input of 0.01 kW/kgDM. As mentioned earlier, the reactor heat demand was controlled by recycling the washed flue gas from the cyclones. The gas after/co-burner was a combi-post burner with a capacity of 27.2 kW, in which the pyrolysis gas was burnt along with propane. For a full-scale installation, biogas would be preferred, as it is considered a green fuel. Propane was used due to the relatively low demand, which makes it suitable for a refillable (7 m^3) tank. The combi-post burner utilizes a high-speed propane flame with a tangential geometry. The pyrolysis gas is introduced via a ceramic pipe, in co-current with air, and mixed inside the combustion chamber. The pyrolysis gas is burnt with an excess of oxygen and is ignited by a high-temperature gas (> 850 °C) in the combustion chamber.

The bio-oil separation process adopted was fractionated condensation involving several steps in which the bio-oil was extracted first followed by pyroligneous acid in three steps. The pyroligneous acid produced was not entirely pure but diluted with water and impurities. The capacity of the pyrolysis separation was 73 m^3/hr and the electricity requirement was 0.06 kW/kgDM. The quench and the condenser water requirements were 0.001 and ~1 m^3/hr, respectively.

For the physical char activation, the steam requirement was assumed to be 0.225 kg-steam/kg-char (Kim et al. 2019). The activated char yield assumed was 50% with heat and electricity requirements of 66 and 12.3 kWh/ton respectively (Kim et al. 2019). The activation was performed at a temperature of 900 °C, the residence time of 4 h, and the resultant activated char assumed to have a surface area of 900 m^2/g (Stavropoulos and Zabaniotou 2009). The reference activation and boiler capacities assumed were 208 kg/hr (Asadi-Sangachini et al. 2019) and 3781 kg/hr (Vanreppelen 2016), respectively. Finally, the sieve losses of 5% were assumed during grinding and packaging. On the other hand, the chemical activation process required 1 liter of H_3PO_4 per kg of biochar (Ng et al. 2003) and yielded 75% of activated char (Kim et al. 2019). The activation was done at 550 °C temperature with a residence time of 2.5 hours. The surface area of the activated char obtained was assumed twice that of physical activation, about 2000 m^2/g (Stavropoulos and Zabaniotou 2009). The electricity consumption was 36.9 kWh/ton input while the heat requirement, capacity, and sieve losses were assumed the same as that of the physical activation.

2.5. Economic analysis

To check whether the process is economically feasible and thus worthwhile of investigating from an investor's point of view the mass and energy balance calculations are directly coupled with the economic analysis. The economic analysis should give a clear idea of the capital expenditures (CAPEX) and operational expenditures (OPEX) of the technology. The combination of both provides the total production cost and can be translated into the minimum selling price (MSP). In addition, the revenues are calculated by using the assumed market prices in this study. Using this information, the net present value (NPV), internal rate of return (IRR), and discounted payback period (DPBP) were calculated.

Equipment costs were obtained from the partners, the literature, and/or quoted by the vendors for a certain cost basis. This basis may be a land area, capacity in terms of volume or flow rate, operating pressure, etc. When the values used in the analysis differ from these cost bases, those equipment prices need to be scaled to reflect the new data. One methodology to do this is called the 'six-tenth rule'. It is mainly used for an order-of-magnitude estimation. The rule relates the fixed capital investment cost of a new process to the fixed capital investment cost of a similar previously constructed plant with a known capacity by an exponential ratio relying on the nonlinear relationship between plant capacity and plant cost. This is done using equation [1] by applying a scaling exponential specific to each equipment. The investment costs for the pilot plant were provided by Pulsed Heat/Cirtec and are listed for each equipment in Table 2. The listed costs also include installation, license, taxes, and overheads. To scale up the plant to larger flows of dry matter the reference capacities as shown in Table 1 were used. The general scaling exponent used is 0.6, hence the name 'six-tenth rule', however, the exponents are different for different equipment and are listed in Table 2.

$$Cost\ of\ equipment\ A = (cost\ of\ equipment\ B) \times \left(\frac{Capacity\ of\ A}{Capacity\ of\ B}\right)^{exponent} \qquad [1]$$

One problem that might arise with the previous method is that the estimates are based on historical data and that these need to be updated to current prices and economic conditions. The prices that are not up-to-date can be adjusted using the Chemical Engineering Plant Cost Indices (CEPCI) according to equation [2] (CEPCI 2011). Something to consider is that this method is accurate for cost estimates based on data not older than 10 years. If data is older, one needs to be careful with using this index. In this report, the plant lifetime assumed is 20 years and all the costs were estimated based on the year 2019 or converted into 2019 euros using the CEPCI. The operating hours for the plant were assumed to be 6570 hr/yr. The pilot plant could have operated 24 hours a day, but in the beginning, it was operated only during the day shift. It was expected that with the startup, there would certainly be several things that would need adjustment. The process, however, was developed to run continuously but for such a new technology and new design, the actual running hours would be different. Therefore, the assumption in the current assessment seems valid.

$$Present\ cost = Original\ cost \times \left(\frac{CEPCI_{present}}{CEPCI_{original\ year}}\right) \quad [2]$$

The capital costs were annualized using the equation [3]. The formula for the weighted average cost of capital (WACC) is described in equation [4]. The WACC is the average cost of capital, taking into account the different sources of capital that a firm uses. In this report, a WACC of 4.1% was assumed.

$$Annualized\ cost = \frac{Total\ capital\ cost\ over\ plant\ lifetime}{\frac{1-(1+WACC)^{-Plant\ lifetime}}{WACC}} \quad [3]$$

$$WACC = (Equity\ ratio \times Discount\ rate) + (Debt\ ratio \times (1 - Tax\ rate) \times Interest\ rate) \quad [4]$$

The NPV indicates the profitability of the technology using equation [5], where *T* is the life span of the investment, CF_n is the difference between revenues and costs in year *n*, I_0 is the initial investment in year 0, and *i* is the discount rate. A technology is considered interesting when the NPV is positive (Levy and Sarnat 1994). The NPV compares the amount of money invested in a project today to the present value of the future cash receipts from the investment. In other words, the amount invested is compared to the future cash amounts after they are discounted by a specified rate of return (i.e. discount rate). The NPV considers the investment today and the revenues and expenses from each year of the lifetime of a project. The riskier an investment, the higher the estimated discount rate must be. Typical discount rates are (i) 10% for cost improvement of conventional technologies, (ii) 15% for the expansion of conventional technologies, (iii) 20% for product development, and (iv) 30% for speculative venture (Mercken 2004). However, in most articles, a discount rate of 10-15% was opted in combination with a life span of 10-15-20 years.

$$NPV = \sum_{n=1}^{T} \frac{CF_n}{(1+i)^n} - I_0 \quad [5]$$

Other popular measures for evaluating whether an investment is financially worthwhile are the DPBP and the IRR. The payback period is defined as the point in time when the initial investment is paid back by the net incoming cash flows, but it has the disadvantage of not taking into account the time value of money. Therefore, one can use the DPBP that does take into account the time value of money. The DPBP can be calculated using the equation [6]. In the equation *CF* is the difference between revenues and costs, *i* is the discount rate and I_0 is the initial investment cost. The shorter the DPBP the more attractive the investment is. The IRR is the discount rate at which the NPV is zero. It thus equates the present value of the future cash flows of an investment with the initial investment and provides the effective interest rate being earned on a project after taking into consideration the time periods when the various cash amounts are flowing in or out. For an IRR to be attractive for an investor it must be higher than the return rate that can be generated in lower-risk markets or investments than the project, e.g. saving the investment money in a bank or investing in safe, low-risk bonds. Because the IRR is a percentage, it can only be used as a decision rule for selecting projects when there is only one alternative to a status quo and should certainly not be used to select one project from a group of mutually exclusive projects that differ in size (Boardman et al. 2006). Therefore, when one has to choose between more than one technology or process (i.e. alternatives), the NPV ranking is mostly preferred over the IRR ranking (Lorie and Savage 1955).

$$DPBP = \frac{ln\left(\frac{CF}{CF - iI_0}\right)}{\ln(1+i)} \qquad [6]$$

The performance indicator for this economic assessment is chosen as the minimum selling price (MSP) of the three pyrolysis products (i.e. bio-oil, pyroligneous acid, and (activated) biochar). The MSP is the total production cost, including annualized CAPEX and OPEX, per amount of product. For the calculation of the MSP, the respective market prices of the other products (i.e. coproducts) that are valorized were taken into account. The formula for the calculation of the MSP is provided in the equation [7].

$$MSP = \frac{Annualized\ CAPEX + OPEX - Revenues\ coproducts\ (€/yr)}{Product\ (kg/yr)} \qquad [7]$$

Table 1. Pyrolysis plant equipment and reference capacity

Plant equipment	Type	Reference capacity	Units
Cellulose screens	Mesh - 350 µm	500	m^3/hr
Dewatering press	Screw press	50.5	kgDM/hr
Dryer	Falling curtain	50.5	kgDM/hr
Cyclone 1	Centrifugal	252	m^3/hr
Pellet press	Flat die	73	kg/hr
Deep dryer	Column dryer	50.5	kgDM/hr
Cyclone 2	Centrifugal	396	m^3/hr
Propane burner	Combi-post burner	12.6	kW
Pyrolysis reactor	Fast pyrolysis	0.04	m^3

Pyrolysis separation	Fractionated condensation	73	m^3/hr
Gas after/co-burner	Combi-post burner	27.2	kW
Char physical activation	Steam	208	kg/hr
Char chemical activation	Phosphoric acid	208	kg/hr

Table 2. Capital cost and operating labor assumptions

Plant equipment	Capital cost (€)	Scale factor	Personnel (per shift)
Cellulose screens	185,000	0.75	0.02
Dewatering press	25,000	0.6	0.35
Dryer	118,000	0.48	0.5
Cyclone 1	45,600	0.6	0.15
Pellet press	35,400	0.72	0.2
Deep dryer	62,200	0.48	0.5
Cyclone 2	50,000	0.6	0.15
Propane burner	30,200	0.78	0.1
Pyrolysis reactor	86,500	0.53	0.5
Pyrolysis separation	86,600	0.67	0.1
Gas after/co-burner	64,200	0.78	0.1
Char physical activation	376,940	0.53	0.2
Char chemical activation	423,604	0.53	0.2

Table 3 lists the assumptions used for estimating the operating and maintenance (O&M) costs. The estimation of labor required was based on the number of personnel required per equipment per shift similar to the methodology by Peter and Timmerhaus (Peters, Timmerhaus, and West 2003). The personnel per shift were taken from the same reference (Peters, Timmerhaus, and West 2003) and are listed in Table 2. For the pilot plant, it was estimated that 3 operating personnel were required. An average labor cost of €31.2/hr was assumed for plant operators and maintenance workers in Europe ("Eurostat - Data Explorer" 2019). The assumptions used for estimating the labor burden, overhead charge rate, and maintenance (Wright et al. 2010) are also listed in Table 3. Furthermore, the variable O&M costs for the electricity, fuel, water, steam, and acid were estimated based on the unit prices given in Table 3. The current market prices of the products are given in Table 4.

As mentioned earlier, by removing the cellulose, the energy for aeration in the next step of the wastewater treatment system, as well as the costs for sludge disposal after digestion are reduced. The savings in aeration energy and the reduction in sludge disposal was calculated as an OPEX saving and considered as revenue in this study. The savings in energy and sludge disposal are in the range of 10-15% each (Marcelis and Wessels 2019). For the current economic assessment, 10% of savings in both were considered and the effect of increasing the savings was estimated in the sensitivity analysis. The average cost of energy consumption and sludge disposal was taken as €6.4 and €3.2/PE·yr (PE – Population equivalent), respectively (Fatone 2020). Next to the savings in costs, the removal of the cellulose also results in a loss of biogas from the secondary sludge. The biogas potential of sludge amounts to 300 Nm^3/tonDM (Marcelis and Wessels 2019). The loss in revenues due to biogas loss was subtracted from the OPEX savings by assuming a biogas price of €0.06/m^3 (Som Gupta 2020). The final value of the OPEX savings obtained was €0.9/PE·yr. Note that these savings are realized at the level of the wastewater treatment facility and it was assumed that the owner from the wastewater facility was also the owner of the pyrolysis unit or that the owner of the wastewater facility transfers these savings to the owner of the pyrolysis unit as a revenue.

Table 3. General plant and operational cost (OPEX) assumptions

Item	Unit	Value
Plant lifetime	yr	20
Base year	-	2019
Operating hours	hr/yr	6570
Insurance	%Investment	1%
Site preparation	%Investment	10%
Wage rate	€/hr	31.2
Shifts per day	#	3
Operating labor burden	% base labor	30%
Labor overhead charge rate	% total labor	25%
Maintenance	% CAPEX	2%

Electricity	€/MWh	93
Natural gas	€/MWh	34
Steam	€/ton	24.5
Water	€/m^3	0.1
Propane	€/kg	0.29
Phosphoric acid	€/kg	0.16
OPEX saving	€/PE.yr	0.9

Table 4. Pyrolysis products market prices

Item	Unit	Value	Range	References
Biochar	€/kg	1.4	1-1.4	(a), (b)
Physically activated char	€/kg	2	1.5-2	(c), (d)
Chemically activated char	€/kg	4	4-6	(e), (f)
Bio-oil	€/kg	0.5	0.33 - 0.56	(d), (g)
Acetic acid	€/kg	0.8	0.5-0.8	(d), (h)
Pyroligneous acid (diluted)	€/kg	0.1		Assumed due to low purity

(a) (Biosorb 2016)
(b) Survey report - Donau Carbon GmbH
(c) (Kuppens et al. 2015)
(d) (WiW mbH 2020)
(e) (Stavropoulos and Zabaniotou 2009)
(f) Survey report - ETC-GmbH
(g) (EUBIA 2017)
(h) (Spekreijse et al. 2019)

2.6. Sensitivity analysis

As the values used for the calculations were uncertain, a sensitivity analysis was performed. The prediction of the values was often based on literature and checked with expert opinion. The values are therefore deterministic rather than stochastic. A Monte Carlo simulation (5000 trials) was performed to identify the parameters that had the highest influence on economic feasibility. Within this analysis, the variables (technical as well as economic) were varied following a triangular distribution over specified ranges depending on the variable. The goal of this kind of quick scan is to determine the parameters that have the highest impact on the variance of MSP. The analysis searches for the parameters that should be investigated in more detail. For these parameters, a local sensitivity using what-if analysis was performed to see how changes in these parameters influence the economic feasibility.

Chapter 3. Results and discussion

In this chapter the results of each step of the techno-economic assessment for the three cases are described, i.e. (1) base case with cellulose screening and pyrolysis unit, (2) activation case with the description of the full plant, including the physical biochar activation, and (3) activation case with the description of the full plant, including the chemical biochar activation. Firstly, the results for the base case are described. Next, the results for the activation cases are described and each of the three cases is compared with the similar processes reported in the literature. In the third section of this chapter, the three cases are compared together in detail using a sensitivity analysis.

3.1. Base Case – cellulose screening and pyrolysis unit

3.1.1. Mass and Energy Balances

The pilot plant mass and energy data was provided by Pulsed Heat and is adapted in Figure 5. In the figure, the black arrows indicate the material flow, the red arrows indicate the energy/power supply and the green indicates the pyrolysis products. The whole plant was designed for the wastewater flow of 540 m^3/h containing 75 kgDM/hr. After the cellulose screens, the fibrous mass contains about 5% of dry solids which was increased to 45% by the dewatering press. In the dryer, most of the moisture content was evaporated by the hot flue gases from the after/co-burner and increased the dry solid content to 65%. At this consistency, the pellets were produced in a pellet press followed by further drying. In the deep dryer, the dry solid content was increased to 90% by evaporating additional water. The dried pellets in the reactor were subjected to pyrolysis in an oxygen-deficient environment that produced biochar and volatiles. Out of the 75 kgDM/hr, about 13.6 kg/hr biochar, 18.3 kg/hr of bio-oil, and 22.7 kg/h pyroligneous acid were produced. The rest was recovered as pyrolysis gas with considerable energy content. The flue gas from the dryer was split and about 14% and 43% was recirculated to the propane burner and after/co-burner, respectively, while the rest was sent to the stack. The heat required in the dryers and the reactor was generated in the burners. The total electricity consumption of the plant was estimated at 67.3 kW.

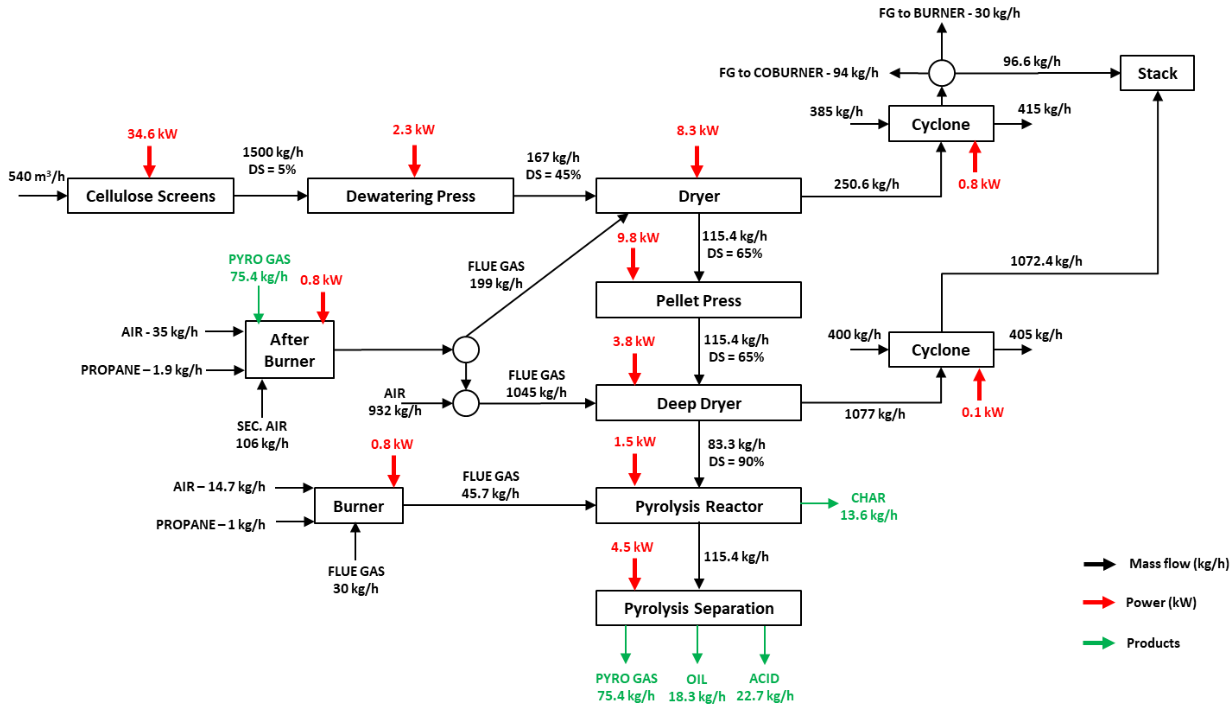


Figure 5. Mass and energy balance of base case
DS = Dry Solids

3.1.2. Economic analysis

The economic assessment results for the base case are discussed in this section. Figure 6 shows the cost breakdown of capital costs (CAPEX) and O&M costs (OPEX). For the base case, annualized CAPEX and OPEX were €87,860 and €172,303, respectively. The major contribution to CAPEX comes from the cellulose screens (17%) since these screens were fed with large inflows of wastewater and required a larger surface area. The gas after/co-burner contributed about 16% to the CAPEX as it burns both propane and pyrolysis gas to produce a large amount of flue gases for the dryers. Furthermore, the dryer and pyrolysis separation contributed 12% and 11% to the CAPEX, respectively. The dryer handled a relatively larger amount of cellulose screenings than the downstream equipment. The pyrolysis separation consisted of several processing units to separate bio-oil, pyroligneous acid, and pyrolysis gas as shown in Figure 2. The OPEX breakdown in Figure 6(b) shows that the largest contribution was from personnel cost (46%) followed by electricity (24%). A total of 3 operators were required to operate the entire plant and additional personnel was required for maintenance and administrative work. The maintenance costs contributed about 7% to the overall OPEX while the rest of the operating costs were insignificant to the overall OPEX.

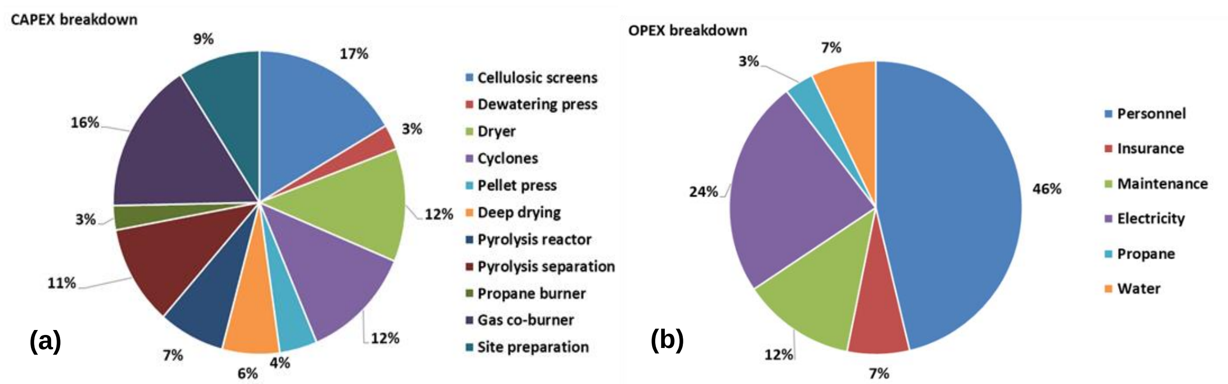


Figure 6. Base case (a) capital cost breakdown and (b) operating cost breakdown

The products yield and their corresponding share in the revenues are shown in Figure 7. It can be observed that in terms of mass, the largest amount of product was the pyroligneous acid mixture followed by bio-oil and biochar in that order. It is to be noted that the pyroligneous acid would not be pure and would contain water and impurities. Thus the market prices would be less than that of pure pyroligneous acid. Therefore, in the current assessment, the market price of pure pyroligneous acid (€0.5/kg) was not assumed, however, it is reduced to €0.1/kg. Later in the sensitivity analysis (section 3.1.3), this price is varied and the effect on the MSP of the other two products was observed. In terms of revenue, biochar contributed the largest amount since it had a higher market price than the other two products. For ease of comparison, the savings in OPEX were also considered as revenue and it was about 31% of the overall revenue.

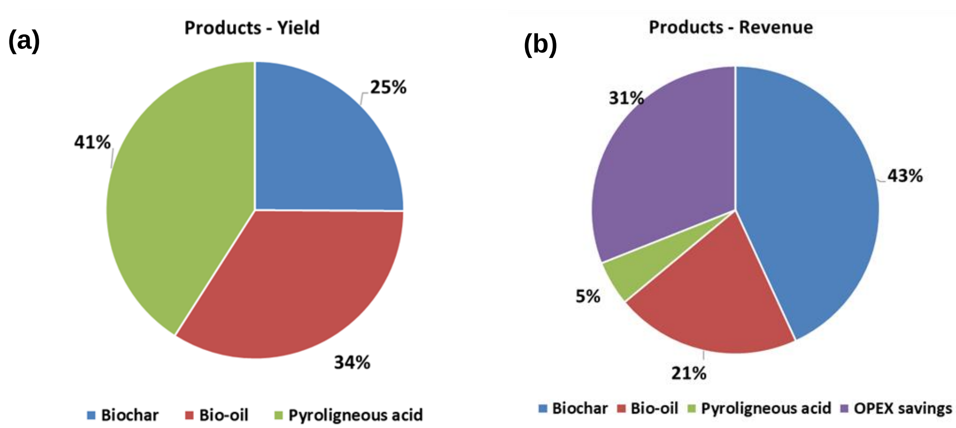


Figure 7. Base case (a) product yield and (b) product revenue

Figure 8 shows the MSP of each product. Note that the market price of the other co-products and OPEX savings were taken into account in this assessment. As mentioned earlier, the fixed cost of personnel had the largest contribution followed by investment and electricity for all three products. Compared to the assumed market price of biochar, the MSP in this study was 24% lower. The main reason was that the biochar market price is to a large extent determined by the price of the biomass feedstock. In this case, the cellulose is the feedstock and the cost of the cellulose with other feedstock costs are compared below. Similar to the MSP for biochar, the MSP of bio-oil and pyroligneous acid was 50% and 206% lower than the assumed market prices, respectively. This was mainly due to the large biochar revenue and also the low feedstock cost. The MSP of the pyroligneous acid was -€0.11 /kg meaning that the production costs of the pyroligneous acid are already recovered by selling the biochar and the bio-oil at assumed market prices. It also generates an additional profit of €0.11 /kg of pyroligneous acid. Furthermore, if this pyroligneous acid was sold at market price (€0.1 /kg), then the total profit would be €0.21 /kg of pyroligneous acid (0.11+0.1). To give more clarity on how the MSP of the products was estimated, a waterfall chart for biochar is presented in Figure 9. It consists of the contributions from all the cost elements including revenues and OPEX savings normalized by dividing by the amount of biochar. It is evident from the results that savings in OPEX contributed significantly towards the revenue and it canceled out the investment costs completely (OPEX savings, €1.01 /kg vs. investment, €0.98 /kg). It is important to note here that the OPEX savings considered were at the lower range mentioned by (Marcelis and Wessels 2019). If the OPEX savings were in the higher range (~15% reductions in both energy and sludge), then a further reduction in the MSP could be expected. The combined revenue by selling bio-oil and pyroligneous acid at the assumed market prices almost offset the costs associated with labor.

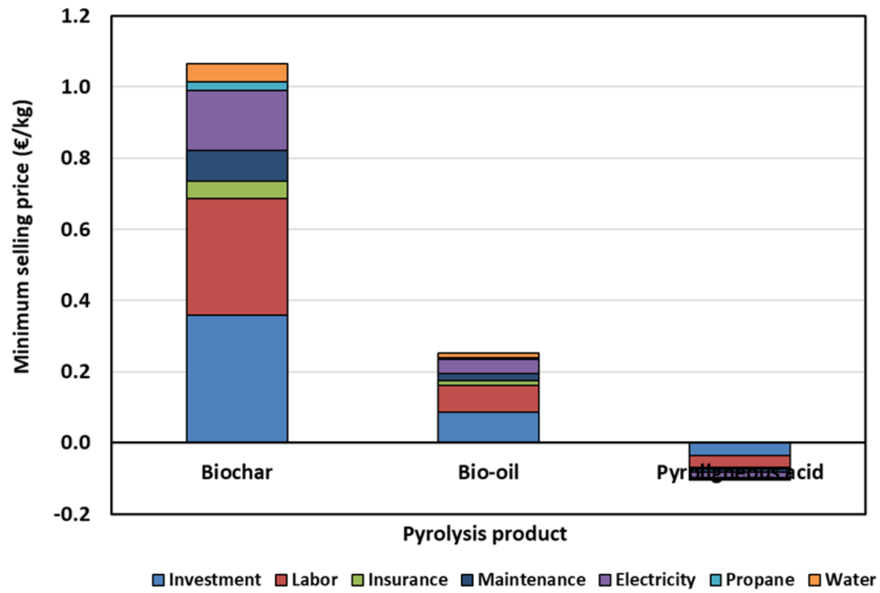


Figure 8. Minimum selling price of the individual products in the base case

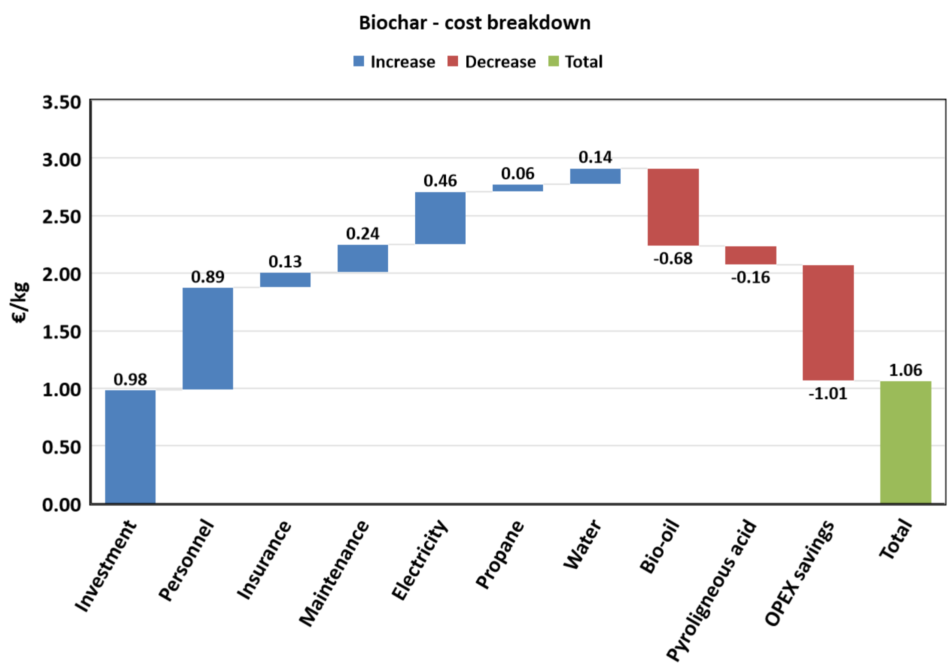


Figure 9. Waterfall chart for the biochar cost breakdown

Feedstock price was the main factor in determining the final product price. In our assessment no direct feedstock cost was taken into account, however, the pre-treatment steps for the cellulose before entering into the pyrolysis unit, determine its cost. The feedstock cost estimation, therefore, included the cellulose screens, dewatering, drying, and two-third of the cost of gas co-/after burner since only two-thirds of the gas was used in the drying stage while the rest was used in the deep drying stage. The cellulose feedstock price breakdown with and without OPEX savings is presented in Figure 10(a). The cellulose feedstock price without OPEX savings was €208 /tonDM whereas with OPEX savings it was €25 /tonDM. The cellulose feedstock was cheaper compared to most of the virgin, clean biomass prices reported in the surveys and the literature as shown in Table 5. The negative values in the table indicate the gate fee, i.e. you would get money to process this feedstock.

Figure 10(b) also indicates the OPEX savings at which the cellulose price would be zero euro per ton. In the graph, it can be seen that this is around €1/PE·yr. At this point, the whole cost of the pretreatment processes is offset by the savings in the energy use in the WWTP and the lower costs for sludge disposal. Further increase in the OPEX savings made the feedstock price negative, similar to the negative values or gate fees listed in Table 5 for some feedstock materials.

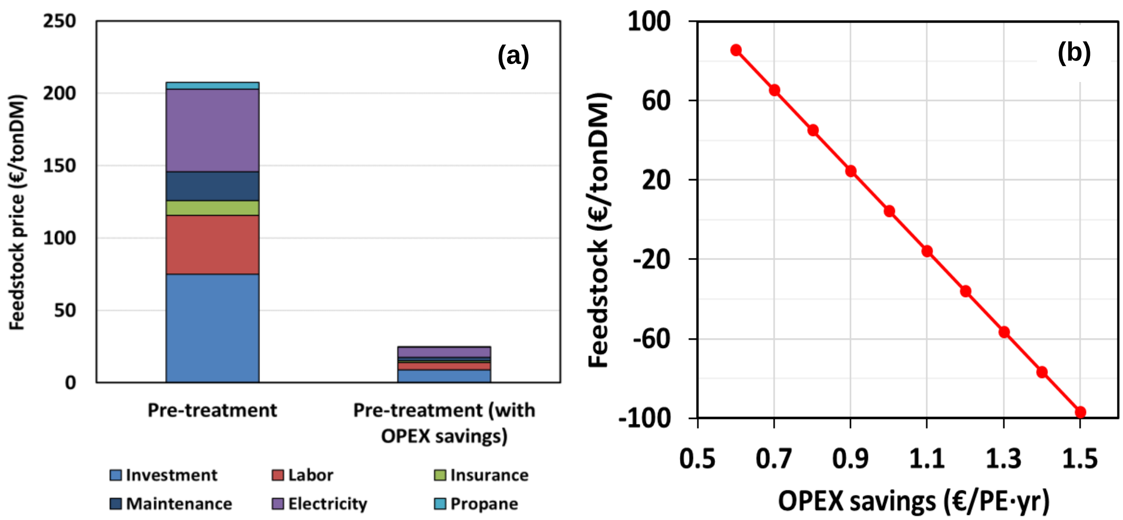


Figure 10. (a) Cellulose feedstock cost (b) Effect of OPEX savings

Table 5. Feedstock price

Material	Price (€/ton DM)	Reference
Willow tree	50	(Kuppens et al. 2015)
Wood chips	33	(Campbell et al. 2018)
Pulpwood	82	(Wu et al. 2019)
Coffee husks	-36.8	(Haeldermans et al. 2020)

Medium-density fiberboard	-7.5	(Haeldermans et al. 2020)
Palm date fronds	70	(Haeldermans et al. 2020)
Wood mix	-10	(Haeldermans et al. 2020)
Tree bark	11.2	(Haeldermans et al. 2020)
Olive stone kernels	67.8	(Haeldermans et al. 2020)
Coconut shells, wood, coal	200 €/t	Donau Carbon GmbH
Coal, coconut shell, peat	2000-3000 €/t	ETC GmbH

The results from the current study are compared to a pyrolysis plant reported in the literature by (Haeldermans et al. 2020). They used different type of feedstocks but the cost breakdown of only medium density fiberboard (MDF) were fully reported and are listed in Table 6. The MDF was considered as waste and thus had a gate fee of -€7.5 /ton which was treated as revenue. In this study, for the feedstock cost to be around the aforementioned value, the OPEX savings should be slightly higher than €1 /PE·yr as seen in Figure 10. The CAPEX and OPEX were normalized based on the biochar output and converted to 2019 euros to make it easier for comparison. It can be seen that the normalized CAPEX was higher for the current study due to additional equipment used for the processing of cellulose fibers before the pyrolysis step (cellulose screens, dewatering press, dryers, pelletizer) and for bio-oil separation in the downstream (separator and condensers). The MDF process had only a grinder and dryer before pyrolysis and a gas engine to produce electricity by using the pyrolysis gas. The electricity was sold to generate additional revenue which was subtracted from the OPEX, which is also lower than the current study. This was mainly due to lower electricity and heat consumption and less labor per ton of product. The CAPEX and the OPEX for the current study would reduce further if the economies of scale are accounted for. However, these types of plants using wastewater cellulose are not expected to be of the scale as large as the MDF plant due to limitations in the WWTP size. The MSP obtained in the current study was almost double that reported for the MDF plant. The reason for this in addition to the economies of scale was the lower biochar yield (18%) as opposed to 27% in the MDF case using a slow pyrolysis process.

Table 6. Comparison of physical activation case with literature (Haeldermans et al. 2020)

	Current study	(Haeldermans et al. 2020)
Feedstock	Cellulose	MDF*
Feedstock price (€/ton)	25	-7.5

Normalized CAPEX (€/ton product)	361	207
Normalized OPEX (€/ton product)	708	565
Biochar output (ton/yr)	89	6804
Biochar yield (%)	18.1	27
Biochar MSP (€/ton)	1060	573

*MDF – Medium-density fiberboard

3.1.3. Impact of market prices

The market prices of the three products will be highly dependent on the market demand and quality specifications. If the demand for a product is higher in the market then that product will be sold at a relatively higher market price and this will reduce the MSP of the other co-products. As mentioned earlier, the pyroligneous acid quality was very low which reduced its economic value. It cannot be used for applications where high quality was required rather it could be used as a feedstock in the digestor to produce biogas. Therefore, to estimate the MSP of each product, the market price of the co-products were varied within specified ranges based on the literature and market potential study as listed in Table 4. The bio-oil market price was varied from €0.1 /kg to €0.6 /kg. The exact price of pyroligneous acid is uncertain due to low quality, therefore the potential selling price was also varied from €0.1/kg up to €0.6/kg.

Figure 11 shows the effect of varying bio-oil and pyroligneous acid market prices on the MSP of biochar (y-axis). As the bio-oil price was increased, the MSP of biochar decreased significantly due to high bio-oil yield (34 wt.% as opposed to 25% wt.% of biochar). This was due to increased revenue from selling the bio-oil resulting in a bigger margin that sufficiently covers the production costs. The reduction in biochar MSP was 42% as the bio-oil price varied within the selected range for a constant pyroligneous acid price of €0.1/kg. This reduction increased to 86% for a pyroligneous acid price of €0.6/kg. This shows that high purity pyroligneous acid is more beneficial to the overall economics. Therefore, measures should be taken to obtain the pyroligneous acid as pure as possible or employ a purification process. This would probably increase the production costs but might get balanced by the higher market price of relatively pure pyroligneous acid. At a constant bio-oil price, an increase in the pyroligneous acid price from €0.1/kg to €0.6/kg resulted in a reduction of €0.82/kg in the biochar MSP.

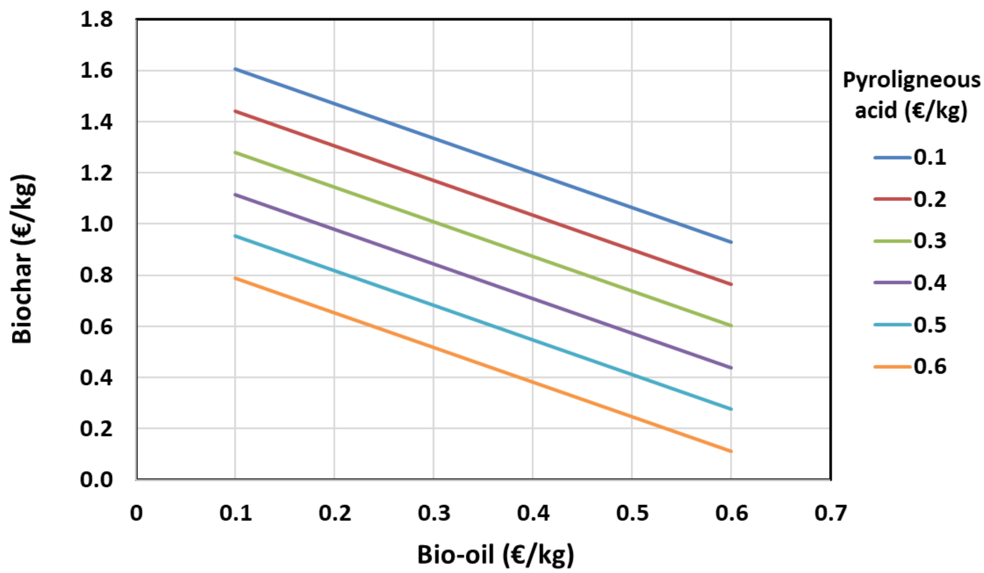


Figure 11. Biochar minimum selling price as a function of bio-oil and pyroligneous acid market prices

3.2. Activation case – Physical and Chemical activation

3.2.1. Mass and energy balance

The mass and energy balance of the physical activation process adopted in the current project is shown in Figure 12. For simplicity, only the mass and energy flows at the system boundaries of the process shown in Figure 3, are depicted here. The biochar from the pyrolysis process was activated using steam at a rate of 3.1 kg/h. About 50% of the biochar was converted to activated char while the rest was gasified and removed along with steam as off-gases (9.9 kg/h). After the activation process, the activated char had to be cooled using cooling water (14.5 kg/h) which was recycled. The loss in the activated char while sieving is also shown in the figure.

The mass and energy balance of the chemical activation process is shown in Figure 13. The whole process shown in Figure 4 is combined in a single block and only the mass and energy flows at the system boundaries are shown. As mentioned earlier, the activation yield assumed was 75% while the rest was assumed to be lost as fines during the process. The recovered phosphoric acid solution and the wash water always remained in the system. Therefore, only the acid solution (11.4 kg/h) and wash water makeup (0.13 kg/h) streams are shown in the figure. The power required for pumping and rotating the equipment was 0.5 kW while the heat required for drying was 0.9 kW. The activated char loss while sieving was 0.5 kg/h.

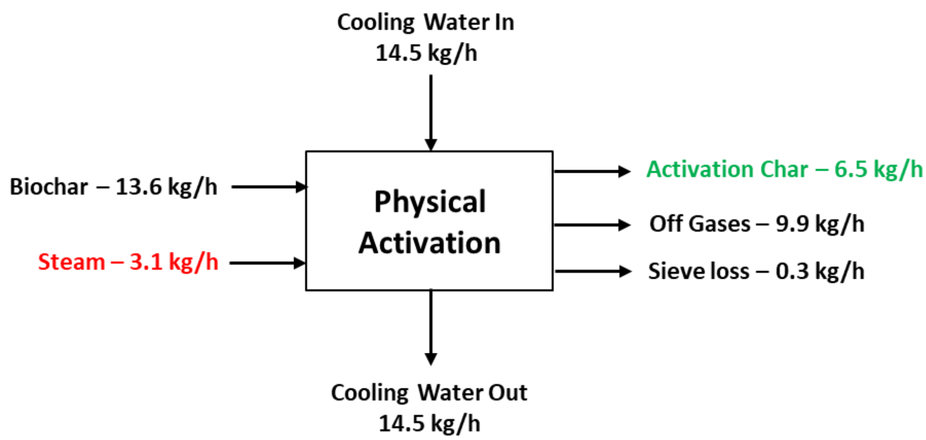


Figure 12. Mass and energy balance of the physical activation process

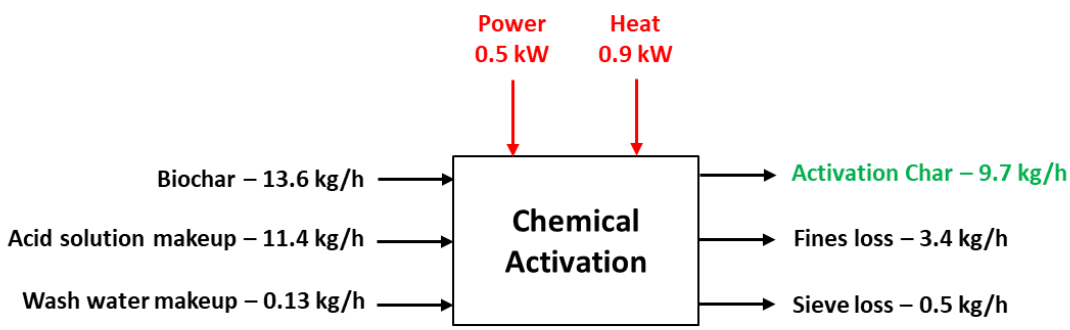


Figure 13. Mass and energy balance of the chemical activation process

3.2.2. Economic analysis – physical activation

The CAPEX and OPEX breakdown for the full plant with physical activation of the biochar is shown in Figure 14(a) and (b), respectively. For this case, the annualized CAPEX and OPEX were €95,810 and €181,004, respectively. The largest contribution to CAPEX was from cellulose screens and after/co-burner (each 15%) followed by dryer and cyclones (11% each). The physical char activation investment was about 8% of the total CAPEX. This included the activation reactor and the boiler for steam generation. Similar to the base case, the personnel cost (47%) was the largest operating costs followed by electricity (23%). Maintenance of the plant constituted about 13% of the overall OPEX followed by insurance and water (each 7%).

The product's yield differs considerably when compared to the base case as shown in Figure 15(a). The overall activated char yield was reduced to 14% due to a significant reduction during the activation process. Therefore, the share of the yield of bio-oil and pyroligneous acid increased to 39% and 47% of the overall products, respectively. The share of each product in the total revenues, generated by selling the products at market prices, is shown in Figure 15(b). The market price of physically activated char assumed in this study was €2/kg as the surface area is assumed to be increased to 900 m^2/g. The increased market price partly covers for the lower yield as the reduction in the share of the revenues (i.e. reduction with 9%-points) is lower compared with the reduced share in the overall product yield (i.e. 11%-points) when compared to the base case. The largest revenue share was still from OPEX savings (36%). The relative effect of physical activation in comparison to the base case without activation is shown in Table 10.

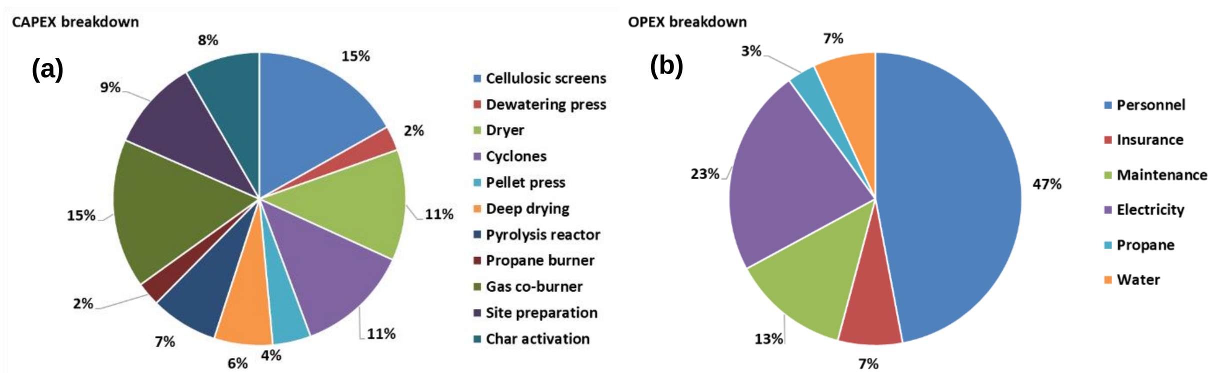


Figure 14. Physical activation case (a) capital cost breakdown and (b) operating cost breakdown

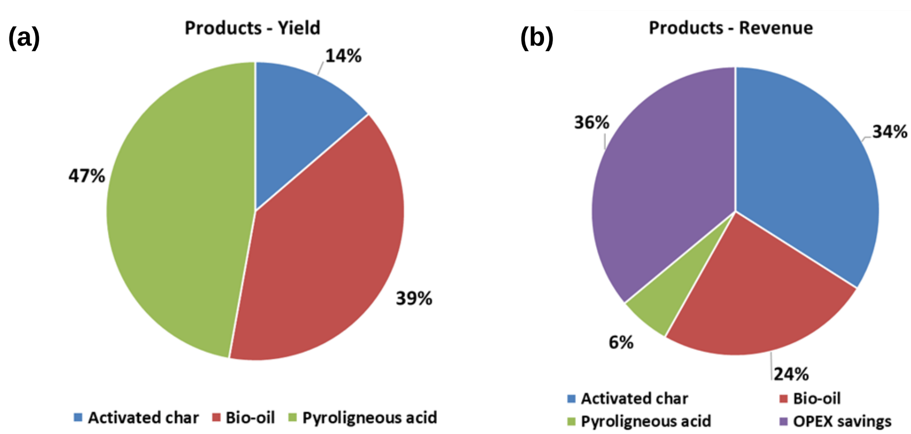


Figure 15. Physical activation case (a) product yield and (b) product revenue

The MSP for the individual products for the physical activation process is shown in Figure 18(a). It can be observed that the MSP of activated char estimated was beyond the assumed market price by €0.8/kg whereas the MSP of bio-oil and pyroligneous acid increased by €0.22/kg and €0.18/kg, respectively. The higher minimum selling prices compared to the base case are due to the additional CAPEX and OPEX for the physical activation and the lower biochar yield. The overall relative comparison with the base case can be seen in Table 10.

Table 7 compares the physical activation results of this study with those reported by (Vanreppelen 2016) converted to 2019 euros. Vanreppelen used various mixtures of particleboard and melamine formaldehyde as feedstock but for comparison, only the results of pure particleboard as feedstock were used. The particleboard was treated as a waste and provided an income of €70 /ton as a gate fee which was subtracted from the OPEX. For the current case, if the OPEX savings go beyond €1.4 /PE·yr then the feedstock price becomes negative (-€70/ton), representing the gate fee similar to the literature. The CAPEX required per ton of activated char for the current study was about 1.6 times that of the literature results. This is due to the additional equipment required at the upstream (cellulose screens, dewatering press, pelletizer, and dryers) and downstream (bio-oil and pyroligneous acid separator and condenser). The OPEX estimated in this study was almost doubled that in the literature. This was partly due to cellulose pretreatment costs (feedstock costs) and partly due to increased utilities (electricity, heat, and water) required by the additional equipment in the current study. The particleboard was subjected to slow pyrolysis as opposed to fast pyrolysis adopted in this project. As a result, the activated char yield reported was 25% as opposed to 8% in this project. The slow pyrolysis process adopted by Vanreppelen produced only biochar and the pyrolysis gases including the volatiles (bio-oil vapors) were used to provide process heat. The MSP obtained was lower (€1906 /ton) than that estimated in this study (€2803 /ton). However, if the OPEX savings in the current study were raised to €1.5 /PE·yr, representing the higher range in savings, then the MSP of the physically activated char would come down to €1390 /ton.

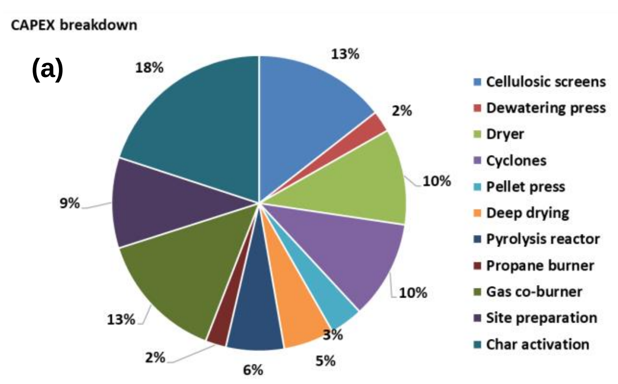
Table 7. Comparison of physical activation case with literature (Vanreppelen 2016)

	Current study	(Vanreppelen 2016)
Feedstock	Cellulose	Particleboard
Feedstock price (€/ton)	25	0
Normalized CAPEX (€/ton product)	911	579
Normalized OPEX (€/ton product)	1722	792
Activated char output (ton/yr)	42.5	1750
Activated char yield (%)	8%	25%
Physical activated char MSP (€/ton)	2803	1906

3.2.3. Economic analysis – chemical activation

The CAPEX breakdown for the full plant with chemical activation is shown in Figure 16(a). The annualized CAPEX and OPEX, in this case, were €109,974 and €202,596, respectively. The investment cost required for chemical activation was the largest contribution (i.e. 18%) to overall CAPEX due to additional equipment requirements as shown in Figure 4. The investment required for both cellulose screens and gas after/co-dryer was 13% each of the overall CAPEX followed by dryer and cyclones (each 10%). Similar to the previous cases, the personnel cost had the largest share in the operating costs (i.e. 50%) followed by electricity (21%) as can be seen in Figure 16b. The increase in the personnel cost was about 3%-points as more personnel time was required for chemical activation equipment.

The product yield and revenue are shown in Figure 17(a) and (b), respectively. In the chemical activation process, the activated char yield assumed was 75% and thus, the share of the activated biochar yield in the total product yield was 5%-points more than that from the physical activation process. Furthermore, the surface area obtained from chemical activation was assumed to be more than double (2000 m^2/g). Therefore, the price of chemically activated char would also be doubled to €4/kg as the price is directly related to the surface area (quality). Activated char with very high surface areas finds application in very sophisticated fields such as medical and for research purposes. However, due to the concerns regarding heavy metals and other contaminants, the use of carbon from a waste source in medical applications is uncertain. The share of the revenue from selling activated char from this process increased significantly to 61% of the overall revenue. The contribution to the overall revenue by selling bio-oil and pyroligneous acid was just 14% and 3%, respectively. The relative effect of chemical activation in comparison to the base case without activation is shown in Table 10.



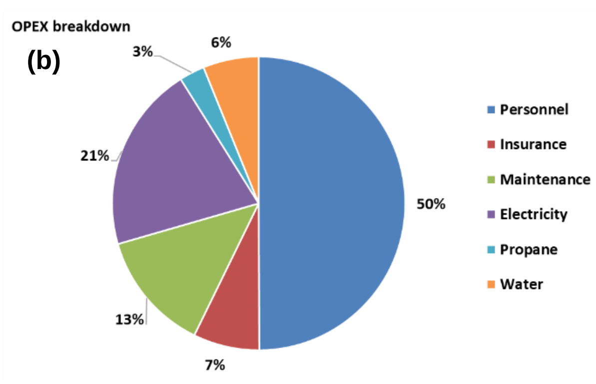


Figure 16. Chemical activation case (a) capital cost breakdown and (b) operating cost breakdown

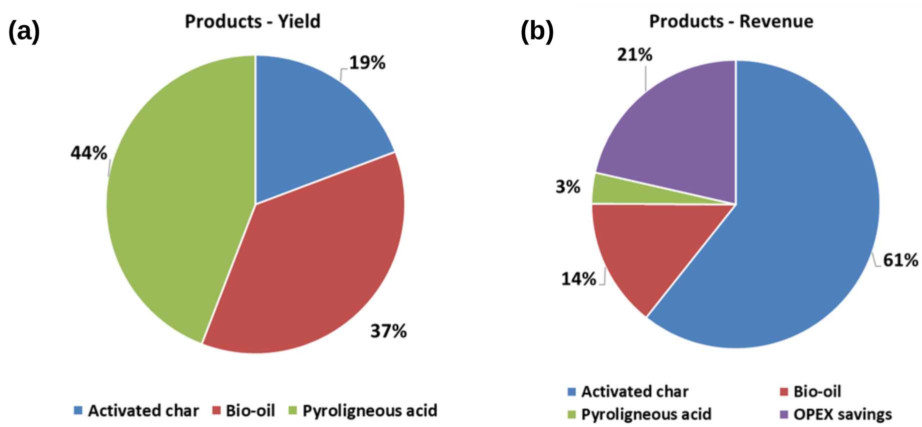


Figure 17. Chemical activation case (a) product yield and (b) product revenue

As can be seen in Figure 18(b), in chemical activation the MSP obtained for the three products is significantly lower than their assumed market prices. Though the CAPEX and OPEX increased when compared to the base case, the relatively higher activation yield (75%) and the high-quality activated biochar (~2000 m^2/g area) and corresponding high assumed market price resulted in a larger increase in the revenues. It can be observed from Figure 18(b) that the MSP of chemically activated char estimated was €2.63/kg which was about 34.3% lower than the market price (€4/kg). On the other hand, the MSP of bio-oil becomes negative (-€0.39/kg) when the activated biochar and pyroligneous acid were sold at assumed market prices. Thus, the revenue generated covered the total production costs and provided an additional profit of €0.39/kg of bio-oil produced. Further, additional profits were also generated when the bio-oil is sold at the market price (€0.5/kg), generating a net profit of 178% per kilogram of bio-oil (total €0.89/kg bio-oil). Similarly, if the activated char and the bio-oil were sold at market prices, the MSP of the pyroligneous acid becomes negative (-€0.63/kg), generating 730% of additional profit. The results indicate that the chemical activation process is more suitable and profitable than the physical activation process under the assumptions made. The relative comparison with the base case can be seen in Table 10.

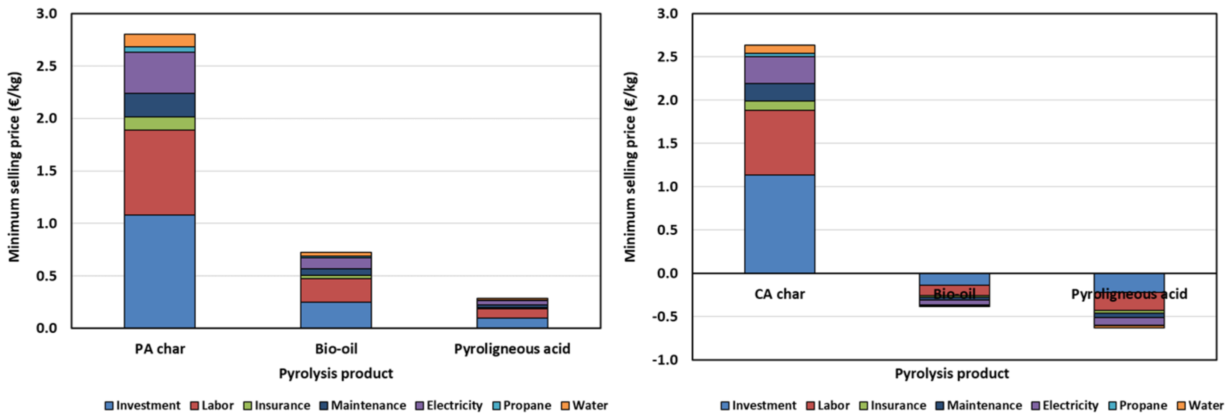


Figure 18. Minimum selling price – (a) Physical activation and (b) Chemical activation

Table 8 compares the chemical activation results of this study with those reported by (Asadi-Sangachini et al. 2019) converted to 2019 euros. The process and the cost data for the chemical activation case were taken from the same work. Asadi-Sangachini et al. used walnut shells as feedstock and reported the price as €109 /ton whereas the feedstock cost estimated in this study was €25 /ton, after taking into account the OPEX savings. The CAPEX required per ton of activated char for the current study was almost doubled due to the upstream equipment required to collect the cellulose fibers, dewater, pelletize and dry them. On the other hand, the OPEX estimated in this study was less than that in the literature, mainly due to the lower feedstock cost. The walnut shells were subjected to slow pyrolysis as opposed to fast pyrolysis adopted in this project. As a result, the activated char yield reported was 30% as opposed to 13.4% in this project. The slow pyrolysis process adopted by Asadi-Sangachini et al. produced only biochar and no other products were obtained. Thus, the MSP obtained was lower (€1684 /ton) than that estimated in this study (€2633 /ton). However, if the OPEX savings were raised to €1.5 /PE·yr, representing the higher range in savings, then the MSP would come down to €1690 /ton.

Table 8. Comparison of chemical activation case with literature (Asadi-Sangachini et al. 2019)

	Current study	(Asadi-Sangachini et al. 2019)
Feedstock	Cellulose	Walnut shells
Feedstock price(€/ton)	25	109
Normalized CAPEX (€/ton product)	815	456
Normalized OPEX (€/ton product)	1502	1948
Activated char output (ton/yr)	63.7	435

Activated char yield (%)	13.4	30
Chemical activated char MSP (€/ton)	2633	1684

3.3. Ideal business case

All the products from pyrolysis could be used within the WWTP. Biochar and activated char could be used for heat generation and purification, respectively. Bio-oil could also be used to generate heat whereas pyroligneous acid could be used as a carbon source and a disinfectant. Therefore, a business case can be defined in which the products are utilized within the treatment plant. It is termed as 'ideal business case' in this report as it is expected to make the net operating expenditure zero when pyrolysis and activation units are installed in the plant. Table 9 presents product quantities and the combined market value of these products per ton of dry matter.

Table 9. Product quantities obtained and market value per ton dry matter

	No activation	Physical activation	Chemical activation
Char (ton/tonDM)	0.18	0.09	0.13
Bio-oil (ton/tonDM)	0.25	0.25	0.25
Pyroligneous acid (ton/tonDM)	0.30	0.30	0.30
Market value (€/tonDM)	406	325	669

The purpose of this section is to investigate the amount of money that has to be paid still when all products are used within the plant. Ideally, it is expected to be zero but it depends mainly on the savings in the operating expenditure that resulted from not treating cellulose in the WWTP. The Waterschap Vallei en Veluwe estimates this cost to be around €500 /tonDM[2]. This cost includes thickening, dewatering, final sludge disposal, treatment, and incineration costs. As mentioned earlier in this report, a conservative value of €180 /tonDM (€0.9 /PE·yr) is considered as the base value based on the results from the SMART plant project (Fatone 2020). However, a sensitivity study is also carried out in section 3.4.6 to understand the influence of OPEX savings on the MSP. At a WWTP with primary sedimentation and anaerobic digestion,

[2] Private communication with Waterschap Vallei en Veluwe

the cellulose is degraded to produce biogas and thus the gains are limited. It is estimated that about 300 Nm^3 of biogas is produced per ton of dry matter (Marcelis and Wessels 2019) and with a biogas price of €0.06 /m^3 (Som Gupta 2020), the gain is about €18 /tonDM. But at a WWTP without primary sedimentation and digestion the advantages are quite high (lower loading of the aeration and less sludge production). If an existing WWTP is overloaded the installation of sieves will be even more beneficial. The sieves lower the loading and improves the effluent quality suitable to the requirements. However, the costs associated with disposal of sievings are quite high. Installing a pyrolysis unit along with an activation unit at the WWTP would be beneficial if the net OPEX is less than the disposal costs. The net OPEX is obtained by subtracting the annual OPEX savings (€500 /tonDM) from the overall annual costs. Figure 19 shows the net OPEX on the y-axis in thousand euros per year while the x-axis represents the variation in OPEX savings. The results are presented for the three cases with no activation, physical and chemical activations. The results show that the net OPEX is zero when the OPEX savings are €528, €562, and €634 /tonDM, respectively. If the OPEX savings (base value = €500 /tonDM) are subtracted then the WWTP has to pay only €28, €62 and €134 /tonDM, respectively, for the product quantities listed in Table 9. Another alternative is to dispose of the sievings to landfill rather than using them to produce useful products. If the costs associated with the disposal of sievings are higher than the OPEX savings shown in the figure, then the installation of the pyrolysis/activation units becomes attractive.

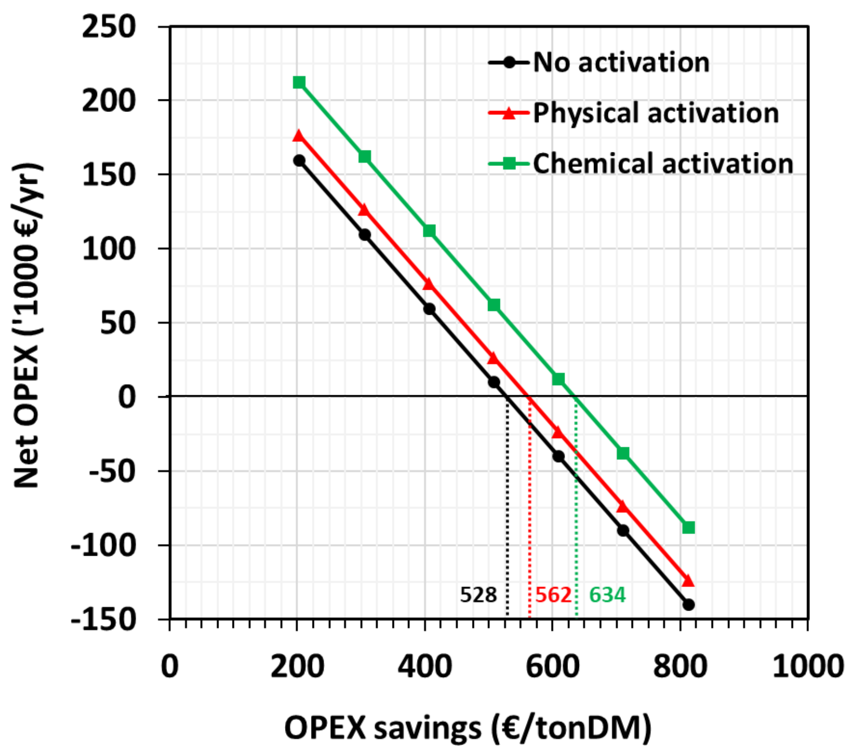


Figure 19. Net OPEX when all products are used within WWTP (business case zero)

3.4. Comparison of the three cases and sensitivity analysis

In this section, firstly the main outcomes from the TEA for the three cases are compared. Next, the impact of changes in five technical parameters (plant scale, cellulose screenings, drying heat, biochar output, and activation yield) and two economic parameters (labor requirement and OPEX savings) on the economic feasibility are discussed.

3.4.1. Comparison of the three cases

The economic indicators namely NPV and DPBP for the base case (biochar) and both the activation processes are shown in Table 10. It is clear that the base case and the chemical activation case are economically viable (NPV>0) under the assumptions made. Due to the low feedstock cost, assumed high quality, and yield of the chemically activated char, the NPV obtained for the chemical activation case was the highest. On the other hand, the physical activation case was not economically viable (NPV<0) due to assumed lower quality and low yield after activation. Similarly, the DPBP for the chemical activation process is the lowest (5.4 yrs) which meant that investment was expected to be recovered by the end of the fifth year. For the base case, the investment was recovered towards the end of the 15th year of the project. All these indicators pointed out that the pyrolysis plant in conjunction with the chemical activation process was more profitable than other cases. The only concern here was the quality of the activated char. The assumed quality is very high (~2000 m^2/g) which was not proven yet to be achieved by using cellulose from the wastewater as feedstock. Since the market price depends on the char quality and since the quality is uncertain, the assumed price in this study was chosen at the lower side of the price range obtained from the supplier ETC GmbH, Germany (€4-6/kg for 1000 m^2/g area).

Table 10. Comparison of TEA results for the three cases

	Base case	Physical activation	Chemical activation
Investment cost (€/yr)	87,860	95,810	109,974
Fixed operating cost (€/yr)	113,095	121,465	142,901
Variable operating cost (€/yr)	59,208	59,539	59,695
(Activated) Biochar production (ton/yr)	89	42	64
Bio-oil production (ton/yr)	121	121	121
Pyroligneous acid production (ton/yr)	146	146	146
Total revenue (€/yr)	290,161	249,945	419,747
Net present value (€)	118,861	-405,176	753,239
Internal rate of return (%)	7.9%	-	22.3%
Discounted payback period (yr)	14.5	>20	5.4

3.4.2. Monte-Carlo analysis

The Monte-Carlo simulation was done only for the base case where biochar was not activated. Since the process under study is innovative, not much information was available in the literature. Therefore, the variables selected for sensitivity were based on their contribution to the products' MSP and the opinion of the pilot plant owners. In total, 6 variables were considered and varied over specified ranges namely plant scale (represented by dry matter in kg/hr), cellulose concentration in wastewater (m^3/hr), drying heat requirement (%), biochar yield (kg/hr), labor requirement (represented as % increase or decrease) and OPEX savings (€/PE·yr).

The lower boundary for the plant scale was set at -60% (28 kgDM/hr) from the reference value while the maximum scale was set at +200% (153 kgDM/hr). This was done to take into account the large variations in the scale WWTPs. The lower value indicates the sources such as industries and small municipalities whereas the higher value indicates the bigger municipal sources such as towns or cities (Fatone 2020). The cellulose concentration was varied between ±40% (0.9 to 2.1 m^3/hr) of the reference value to take into account the variation in cellulose content in the wastewater (Ruiken et al. 2013). For the drying heat requirement, the maximum was kept the same as the reference value and a lower boundary was set at -50% of the reference value. The goal is to reduce the energy required for drying. The biochar yield depends on the type of pyrolysis process adopted (slow or fast). Fast pyrolysis results in higher bio-oil yield whereas slow pyrolysis results in a higher yield of biochar (Kuppens et al. 2015). Thus, it was varied from -20% to +20% of the reference value (10.9 to 16.3 kg/hr) to cover the uncertainty in the biochar yield. The labor wage rate was varied in the range ± 40% of the reference value (18.7 to 43.7 €/hr). A lower wage rate indicates less manual labor and high automation whereas a higher wage rate indicates more manual labor and less automation. This mainly depends on the plant design and thus the variation cannot be verified from the literature. OPEX savings are highly uncertain because of differences in available data. The range of savings in energy could be between 10-15% whereas the reduction in sludge disposal could be up to 20% (Marcelis and Wessels 2019). However, a 10% reduction was assumed for both reduction in energy and sludge disposal. Moreover, the cost data assumed for the energy and sludge disposal were also specific to a WWTP that was considered in SMART plant study (Fatone 2020). In this study, a minimum value of €0.6 /PE·yr (30% of reference value) and a maximum value of €1.5 /PE·yr (70% of the reference value) was considered.

Figure 20 shows the contribution of each selected variable towards the variance in MSP of biochar over selected ranges. A positive value in the figure indicates that an increase in the variable results in an increase in the MSP whereas the negative values indicate that MSP decreases with an increase in the variable. The variables having negative sensitivity are OPEX savings (-27.4%), dry matter (-18.6%) and cellulose concentration (-17.0%) whereas the variables having positive sensitivity are drying heat (+25.4%) and labor (+11.3%). The biochar yield was almost negligible relative to the other variables. The impact of these variables on the MSP is further investigated in the following subsections.

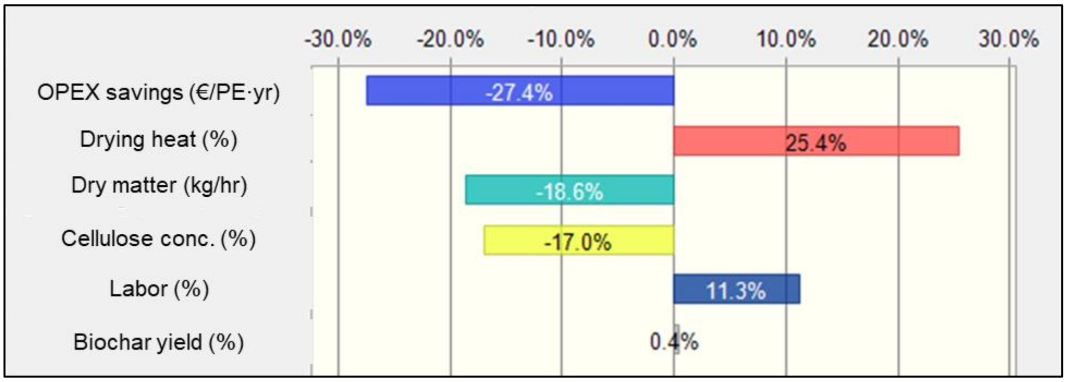


Figure 20. Relative contribution of the variables' range to the variance in biochar MSP

3.4.3. Impact of plant scale

The wastewater flow rate determines the scale or size of the WWTP which is measured in terms of population equivalent (PE). Assuming a constant dry matter, the cellulose concentration in the wastewater would also be constant for a particular size of the WWTP. In this analysis, the pyrolysis plant scale was represented in terms of dry matter of the cellulose screenings. The pilot plant was operated at 75 kgDM/hr (~150,000 PE) whereas the typical large-scale plants are generally operated at 150 kgDM/hr (~300,000 PE). The effect of the plant scale on the MSP of the three products for the base case is shown in Figure 21(a). It can be observed that the MSP of all three products decreases significantly as the scale goes from pilot to large scale. With an increase in the plant scale, the equipment size was also increased by a specific exponential relationship particular to each equipment. This resulted in lower operating expenses per unit plant capacity accounting for the economies of the scale factor. At a large scale, the reduction in MSP of the biochar and the bio-oil was 34% and 105%, respectively. The MSP of the pyroligneous acid mixture reduced from -€0.11 /kg at pilot-scale to -€0.32 /kg at large-scale. At a plant scale operating at 56 kgDM/hr, the pyroligneous acid MSP was zero indicating that all the cost of producing the pyroligneous acid mixture was offset by the revenue obtained by selling the biochar and the bio-oil at assumed market prices. Additional profits could be obtained by selling the pyroligneous acid mixture at the assumed market price (€0.1 /kg of pyroligneous acid sold).

The effect of plant scale on the MSP of the products in both physical and chemical activation processes are shown in Figure 21(b) and (c), respectively. In the case of physical activation, at the pilot scale (75 kgDM/hr), the MSP of products obtained was higher than the market price. Thus, at this scale, physical activation was not profitable. However, as the scale was increased to a larger scale (125 kgDM/hr) the MSP for these products was similar to the market prices. Increasing the scale further, the physical activation plant becomes economically viable. Though the reduction in MSP was small, it could prove to be suitable for certain locations where cheaper steam for activation is available or where there are government regulations that prevent from using chemicals. The steam could be cheaply generated by recovering the waste heat from the flue gases. If this is taken into account then the MSP could reduce further proving it to be economically feasible. On the other hand, in the chemical activation process, the MSP of activated char was reduced by 28% when the plant scale was increased from pilot to large scale. The reduction in the price does not seem significant because the MSP of the products obtained in this process was already very low. It is interesting to note from the figures that the gap between the biochar and the co-products increased as the process changed from the base case to the chemical activation case. The MSP lines for the bio-oil and the pyroligneous acid moved towards negative values due to the higher market price of the chemically activated char (€4/kg). The revenues obtained covered the production costs of these co-products easily (representing zero price on the y-axis) and generated additional profits per kilogram of the co-products (representing negative prices on the y-axis). Further, additional profits would also be generated when these products were sold at their assumed market price. This indicated how the chemical activation process was more suitable and economically viable than physical activation. However, as mentioned earlier, this process requires several equipment and consequently more operating labor. It will not be suitable for locations where the space is limited or are regulated by the local laws preventing the use of chemicals.

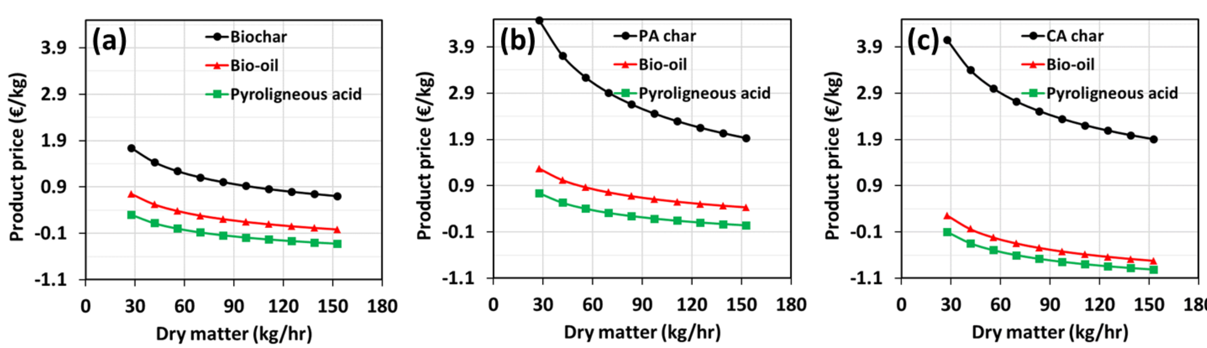


Figure 21. Product prices as a function of plant scale (input dry matter) (a) Base case, (b) Physical activation (PA), and (c) Chemical activation (CA)

3.4.1. Impact of cellulose concentration in wastewater

As the main source of cellulose in wastewater is toilet paper, the cellulose content represents the location of the WWTP. Some countries can have a similar flow per population equivalent per day but the toilet paper usage differs considerably. The cellulose content could also refer to the type of WWTP. For example, municipal wastewater has a certain concentration of cellulose whereas the industries that handle cellulosic materials such as paper can have higher concentrations of cellulose in their wastewater. Therefore, in this study, this effect was studied by varying the cellulose content in the wastewater. The reference value of cellulose screenings was 1.5 m^3/hr in a wastewater flow of 540 m^3/hr. By keeping the flow constant, the cellulose screenings were varied from -40% to +40% (0.9 to 2.1 m^3/hr) of the reference value. By doing this the size of the cellulose screens remained constant as it was scaled based on the wastewater flow whereas the size of the downstream equipment changed as they were scaled based on the cellulose content. The cellulose content could also vary depending on the seasonal changes. During dry weather, the water evaporation rate is higher and this would increase the cellulose concentration in the wastewater. On the other hand, during the rainy season, excess water dilutes the normal wastewater flow decreasing the cellulose concentration.

Figure 22 shows the variation of the cellulose feedstock price as a function of cellulose concentration in the wastewater. A steep variation from €97.2 to -€13.8 /tonDM in the feedstock price was observed when the cellulose concentration varied from -40% to +40% of the reference value. At about +30% cellulose screenings, the feedstock price becomes negative similar to the gate fee associated with some biomasses listed in Table 5. Due to an increase in the cellulose screenings, the scale of the pretreatment process (See Section 3.1.2) to produce cellulose feedstock also increases except for cellulose screens as they were scaled based on the wastewater flowrate. The cellulose feedstock price decreased partly due to the economies of scale factor. Moreover, the main reason was the increase in the OPEX savings in the WWTP due to higher cellulose concentration that does not pass through the WWTP. The OPEX savings increased from €54,000 /yr to €126,000 /yr with the increase in cellulose screenings over the specified range. The OPEX savings were dependent on the amount of dry solids in cellulose screenings and were upscaled accordingly in the model. This was reflected in the cellulose feedstock price estimated in this study and as shown in the figure.

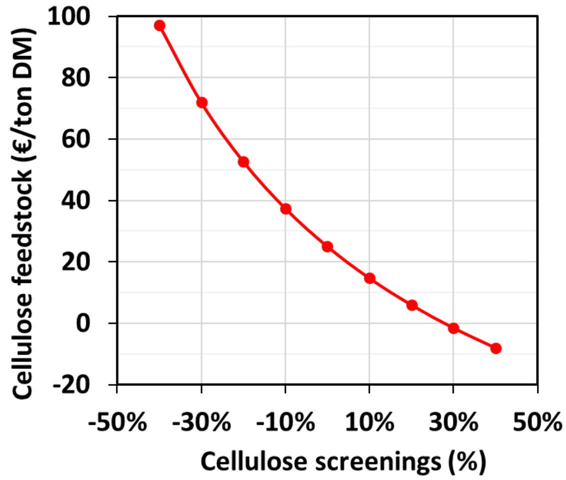


Figure 22. Cellulose feedstock price as a function of cellulose concentration

The results for MSP are plotted in Figure 23 for the three cases. The trends are similar to those discussed in the plant scale section. For the base case, if the cellulose content is below -20% of the reference value then the plant was not economically viable. The reduction in the MSP of biochar and bio-oil was 57% and 101%, respectively, as the cellulose content varies from -40% to 40% of the reference value. The pyroligneous acid mixture price could vary between €0.26/kg to -€0.32/kg. This was a significant variation that indicated that the cellulose content is also key to plant economics. This type of plant is not feasible at the locations where the toilet paper usage is not up to the reference value considered in this study unless there is another source of cellulose like the paper industry. It can also be inferred that this plant becomes unprofitable in wet weather when there are heavy flows but with the same cellulose content. The increase in the flow increases the size of the cellulose screens required. Thus, increasing the MSP of the products.

The MSP for the physical and chemical activation processes are shown in Figure 23(b) and Figure 23(c), respectively. The physical activation becomes economically viable at 2.25 m^3/hr cellulose screenings (50% of reference value), which is very rare unless the wastewater contains flow from both municipal sources and the paper industry. On the other hand, the chemical activation plant worked well economically, even at very low cellulose content. At -30% cellulose content, the MSP of the activated char was €~3.7/kg which was about 7% lower than the assumed market price.

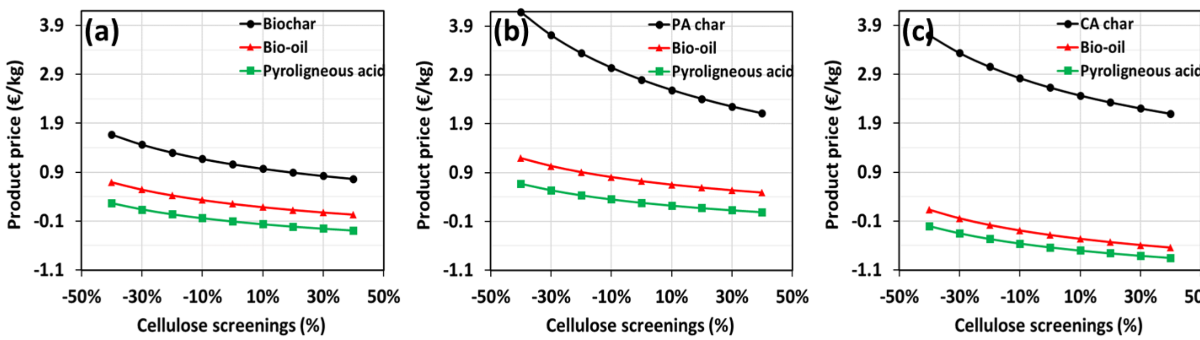


Figure 23. Product prices as a function of cellulose content in wastewater (a) Base case, (b) Physical activation (PA), and (c) Chemical activation (CA)

3.4.2. Impact of heat requirement in drying

Drying is an important step in the pyrolysis process where a lot of energy is consumed. The dewatered cellulose screenings with 45% DM were dried up to 65% DM in this step. It required about 1 kWh of heat per kilogram of dry matter per hour. The required heat was generated by burning the pyrolysis gas and propane in the gas co-/after burner. If the heat consumption is reduced, the burner size also gets reduced resulting in lower CAPEX. By doing this the pyrolysis gas that is saved could be sold or could also be used in a combined heat and power (CHP) plant, if available, to generate electricity. Generally, too many trace components are observed in the pyrolysis gas which makes it detrimental for direct electricity generation. Therefore, the gas could be used in a co-combustor to generate steam for biochar activation or to generate heat for the pyrolysis unit. For this assessment, it was assumed that the excess pyrolysis gas was sold to generate additional revenue. The drying heat was reduced to 45% of the reference value and the effect on the MSP is shown in Figure 24. For the base case, the MSP of the biochar reduced by 82% when drying heat is lowered to 45% of the reference value whereas for the bio-oil and the pyroligneous acid the MSP became negative. The MSP of the bio-oil at reference drying heat was €0.25 /kg and the corresponding MSP at 45% of the reference drying heat was -€0.39 /kg as shown in Figure 24(a). This means that the production costs of bio-oil is already recovered by selling the biochar and the pyroligneous acid at assumed market prices. It also generates an additional profit of €0.39 /kg of bio-oil. Furthermore, if this bio-oil was sold at market price (€0.5 /kg), then the total profit would be €0.89 /kg of bio-oil (0.39+0.5). Similar is the case with the pyroligneous acid where the total profit would be €0.74 /kg of bio-oil (0.64+0.1).

The results for the physical and chemical activation are shown in Figure 24(b) and Figure 24(c), respectively. It is interesting to note that if the heat requirement was reduced by just 20%, the MSPs in the physical activation case become equal to the market prices i.e. becomes economically viable. This will make this process feasible for the locations where chemical activation is not possible. As expected, the chemical activation process generated the highest profits of all three processes.

If an alternative drying process is developed which consumes less thermal energy, the MSP can be reduced further. The vacuum evaporation method could be used to remove the moisture from the cellulose screenings at low energy consumption. Due to vacuum pressures, the boiling point of water is lowered which requires a less intensive source of heating such as waste heat from the dryer or the deep dryer. The operating costs especially for energy in the current process can be significantly reduced by using the vacuum evaporation method. The energy requirement per kilogram of water evaporated was 1.45 kWh/kg in the current study. This can be reduced to as low as 0.2 kWh/kg by using the vacuum evaporation method (Aquadest 2021). The only drawback is that these types of evaporators can accommodate only semi-solid state material. Due to this reason, a hybrid drying process would be beneficial that has an energy consumption somewhere between the two extremes.

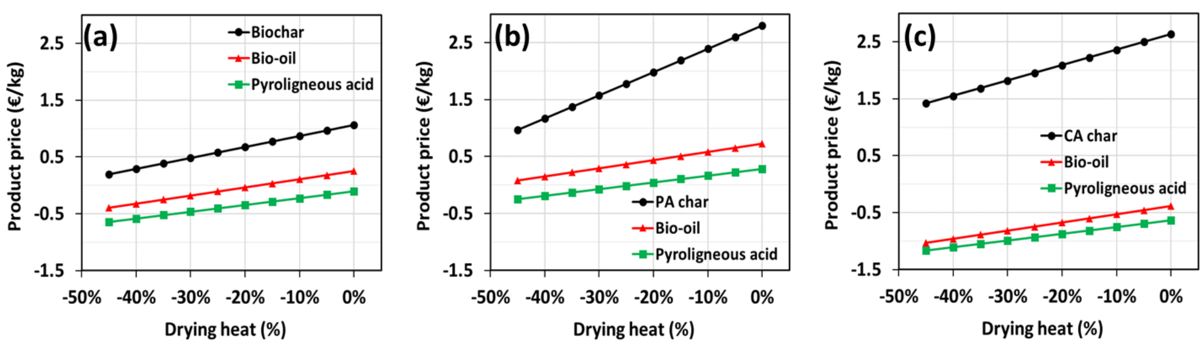


Figure 24. Product prices as a function of drying heat requirement (a) Base case, (b) Physical activation (PA), and (c) Chemical activation (CA)

3.4.3. Impact of biochar yield

It is evident from the Monte-Carlo results (Section 3.3.2) that the biochar yield is not the key parameter for the base case which can also be observed in Figure 25(a). However, when chemical activation is involved, the biochar yield becomes important as can be seen from the results in Figure 25(c). Generally, the slow pyrolysis process has a higher biochar yield as opposed to the fast pyrolysis process where bio-oil is the primary product (Barry 2018). In this study, since the fast pyrolysis process was adopted the primary product was the bio-oil but the previous results indicated the importance of the biochar in determining the MSP of the co-products. Therefore, the biochar yield was varied from -20% to 20% of the reference value considering the yield reported in previous studies (Haeldermans et al. 2020; Vanreppelen 2016; Asadi-Sangachini et al. 2019). Figure 25(b) shows that increase in the biochar yield even by 20% does not make the physical activation case economically feasible. In the chemical activation case, the increase in biochar yield directly affect the MSP due to a bigger margin available due to the high market price and was sufficient to compensate for the higher costs. The effect on the MSPs of bio-oil and pyroligneous acid was more pronounced indicating that the chemical activation process was more economically viable even if a slow pyrolysis process was adopted.

Biochar can also be used for producing thermal energy by combustion. The heating value of biochar obtained through slow pyrolysis is higher than that obtained in fast pyrolysis due to increased carbonization occurring during slow pyrolysis (Barry 2018). In terms of oxygen to carbon atomic ratio, the slow pyrolysis biochar reportedly showed a ratio of ~0.1 whereas the fast pyrolysis biochar showed a ratio above 0.15 (Barry 2018). These ratios are already less and can be expected to have a half-life of 1000 years or more (Barry 2018). Thus, the slow pyrolysis biochar is more suitable for long-term carbon sequestration. Another important difference is the leaching rate of the slow and fast pyrolysis biochar when the biochar is used in the soil or in combustion where the ash is disposed of at a landfill. Barry 2018 defined the leaching rate as the percentage of metals present in the biochar that is leached out through soxhlet extraction with deionized water (Barry 2018). His experiments showed a higher leaching rate in the fast pyrolysis biochar as opposed to a lower leaching rate in the case of slow pyrolysis biochar. If the cellulose screenings have higher heavy metal concentrations then slow pyrolysis would be desired due to less leaching rate. The fast pyrolysis would be desired more when the cellulose screenings have very low heavy metal concentrations where leaching is not a concern.

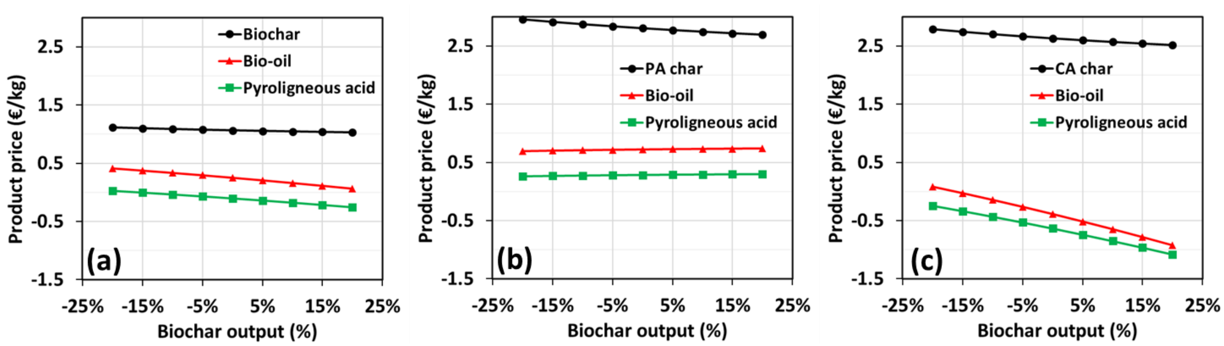


Figure 25. Product prices as a function of biochar yield (a) Base case, (b) Physical activation (PA), and (c) Chemical activation (CA)

3.4.4. Impact of biochar activation yield

Activation yield is the amount of activated char obtained after the process of activation. As mentioned earlier, the yield after physical activation was 50% due to gasification of the carbon by the steam whereas, in chemical activation, it was assumed 75%. Figure 26 shows the results for both physical and chemical activation processes. The activation yield for the physical process was varied from 30% to 75% and it can be observed that the MSPs of the three products decreased as the activation yield was increased. The physical process becomes economically viable, meaning the MSPs reach the market price at the activation yield of 70%. However, this activation yield is difficult to obtain due to the increased possibility of carbon gasification. This could be possible if the steam is replaced by other working fluids such as nitrogen or carbon dioxide but these working fluids are expensive and might increase the operating expenses resulting in a further increase in the MSPs. In the chemical activation process, even if the activation yield is reduced to 50%, the MSPs were slightly below the market prices indicating the exceptional performance of this process under current assumptions.

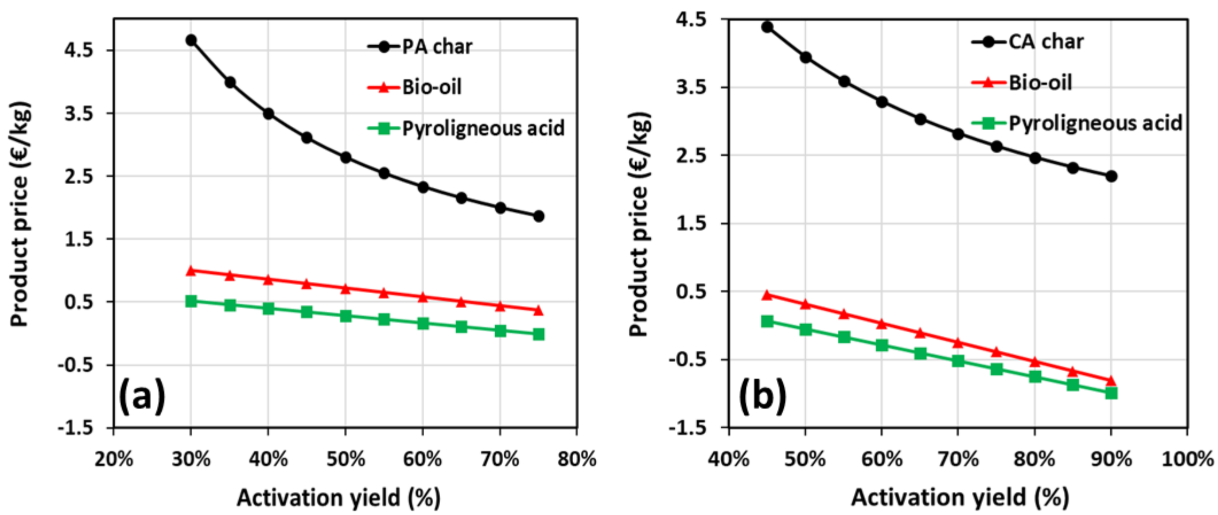


Figure 26. Product prices as a function of activation yield (a) Physical activated (PA), and (b) Chemical activated (CA) char

3.4.5. Impact of labor requirement

The labor requirement is a significant fixed operating cost. Therefore, if the plant is made automated as much as possible then the operating labor required can be reduced. The labor requirement in the current project was estimated based on the labor required for the standard pyrolysis plant (Vanreppelen 2016). However, due to advancements in technology, the plant operation can be made more automated requiring less human intervention. The downside is that it will increase the power consumption which might affect the overall plant costs. For the sake of simplicity, it had not been considered in this analysis. The decrease in labor requirement can also be expected with increasing plant operating experience.

The estimated MSPs for the three cases are shown in Figure 27. The labor requirement was varied from -40% to +40% of the reference value to have a broad overview of its effect. The biochar MSP at +40% labor was ~€1.4/kg which was equal to the market value whereas at -40% labor, it was about ~€0.7 /kg which was about half of the market value. This shows that by reducing the labor requirement the profit margin could be up to 50%. This was similar for the bio-oil and the pyroligneous acid except the profit margin would be up to 100% and 400%, respectively.

The results for the physical and chemical activation processes are shown in Figure 27(b) and Figure 27(c), respectively. The physical activation process becomes economically viable when the labor requirement was reduced by 40%. On the other hand, the chemical activation process remained economically viable even after the labor requirement was increased by 40%. This shows that at locations where cheap labor is available and the automation cannot be adopted then the chemical activation process is more suitable whereas at locations where manual labor is scarce, automating the plant is a more suitable option even with the physical activation process.

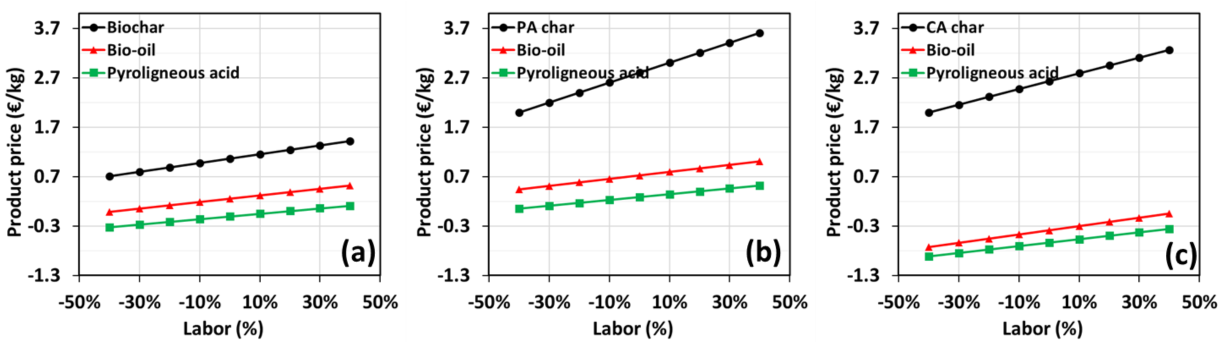


Figure 27. Product prices as a function of labor requirement (a) Base case, (b) Physical activation (PA), and (c) Chemical activation (CA)

3.4.6. Impact of OPEX savings

The savings in energy consumption and sludge disposal due to diverting the cellulose from the sludge treatment are significant. It could be anywhere between 10-15% for energy and 10-20% for sludge disposal. However, for this assessment, a lower value of 10% was assumed for both energy and sludge disposal which corresponded to €0.9 /PE·Y after subtracting the loss in biogas potential. If the upper limits were considered then the savings corresponded to ~€1.5 /PE·yr. If the cellulose is used as raw material, the OPEX savings will offset the costs for the additional pretreatment required when compared to other biomass. As it is clear from Section 3.1.2, that OPEX savings can bring the feedstock costs to negative values. Thus, cellulose from wastewater could also compete with other biomasses having a gate fee.

Therefore, the OPEX savings were varied in the range of €0.6 to €1.5 /PE·yr, and the results are shown in Figure 28. The biochar MSP reduced by 63% compared to the reference value when the OPEX savings were at the upper limit. Similarly, the bio-oil and the pyroligneous acid mixture MSP were -€0.24 /kg and -€0.52 /kg, respectively at the upper limit. If these products were sold at market prices, then the total profit would be €0.74 /kg of bio-oil and €0.62 /kg of pyroligneous acid, respectively.

The results for the physical and chemical activation processes are shown in Figure 28(b) and Figure 28(b), respectively. The physical activation process becomes economically viable when the OPEX savings were about €1.25 /PE·yr. This scenario was possible as the value lies in the OPEX savings range mentioned above. The OPEX savings was also a key factor to make this process feasible in addition to the space, availability of labor, and steam. On the other hand, the chemical activation process stayed economically viable even at the lower limit of the range.

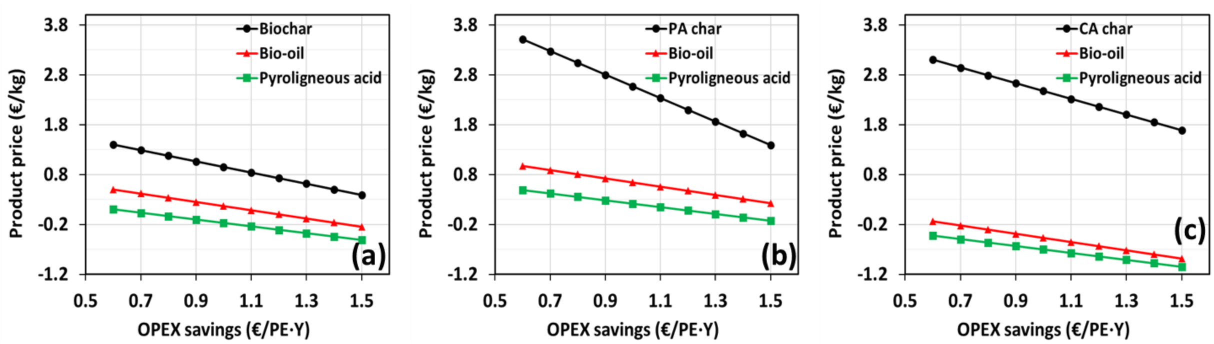


Figure 28. Product prices as a function of operating costs savings (a) Base case, (b) Physical activation (PA), and (c) Chemical activation (CA)

Chapter 4. Conclusions and future work

Wastewater contains a lot of carbon-based materials such as cellulose, lipids, and fatty acids. Utilizing these valuable materials could reduce the use of natural resources and subsequent carbon dioxide (CO_2) emissions and hence, realizing a circular economy. In this report, a techno-economic assessment on the pyrolysis plant at a pilot-scale (75 kgDM/hr) using the recovered cellulose fibers from wastewater as feedstock was performed. This feedstock was relatively cheaper compared to other biomass. It only required to be recovered, dewatered, dried, and formed into pellets. The savings in the operating expenditure (OPEX) due to reduction in aeration energy consumption and sludge disposal costs offset the pretreatment costs to a large extent. A fast pyrolysis process transformed the pellets into biochar and volatiles, which were separated into the bio-oil, the pyroligneous acid, and the pyrolysis gas. The pyrolysis gas was used up internally to provide the heat required for drying the cellulose fibers. The MSP estimated in this project for the biochar, the bio-oil, and the pyroligneous acid was 1.06, 0.25, and -0.11 €/kg, which is 24%, 50%, and 206% lower than the market prices assumed in this study, respectively. The market prices were key parameters that have a significant effect on the MSP. The MSP of biochar decreased significantly with an increase in the bio-oil and the pyroligneous acid market price. At higher market prices the MSP becomes negative which means that the production costs are recovered and additional profits are generated equal to the absolute value of the negative MSP per kilogram of the product. Further revenue could be generated by selling the products at market prices.

The biochar due to its limited application possibilities needs to be activated either by physical or chemical agents. Both the activation methods were assessed in this report. The physical activation process was done by steam and thus required just the activation reactor and boiler. However, the revenue from the activated char was low due to a low yield of 50% during activation. Compared to the base case, there was an increase in CAPEX and OPEX and a decrease in yield and revenues. The MSP obtained for all three products was above the assumed market prices.

The chemical activation method was done using a liquid activation agent, phosphoric acid in this case. It required more equipment and energy than the physical activation but had a higher yield (75%). Besides, the surface area obtained was assumed to almost double that of physical activation. It would expand the application possibilities to medical and research areas and could also be used as adsorbents. As a result, the market price of this activated char was also doubled. Compared to the base case, the CAPEX and the OPEX were increased, the yield decreased but the revenue increased significantly due to higher market price. The MSP estimated for activated char was about €2.63 /kg when the other two products were sold at market prices.

Several technical and economic parameters affect the overall performance of the plant. Plant scale (dry matter) was used to represent the WWTP size whereas cellulose content was used to represent the cellulose source and weather. It was observed that with an increase in plant scale and the cellulose content, the MSP of the products decreases. The heat required during drying also affects the MSP significantly. Much of the thermal energy used in this plant is for drying purposes. Thus, if an alternative drying technology such as a vacuum evaporator or a hybrid system is developed which consumes less thermal energy then there will be savings in fuel costs. Alternatively, a belt conveyor could be used to remove the moisture content by the action of gravity before the drying step. Moreover, the flue gases at the outlet were still at a relatively higher temperature that could be used to recover heat and use it to produce steam for physical activation or heat the feedstock for chemical activation. Alternatively, the quality of the heat can be enhanced by using a heat pump and used for the deep dryer. This will considerably reduce energy consumption. Furthermore, as the results indicated that having a higher activated char yield was more profitable then slow pyrolysis would be a better option since it will give a higher biochar yield. This would also lead to less products, and make the installation and operation less complex.

The economic parameters such as the labor requirement and the OPEX savings were the key parameters that affected the MSP significantly. The OPEX savings offset the cost of the pretreatment required to obtain the feedstock similar to the other biomass feedstock reported in the literature. The physical activation process was more suitable if there was easy access to steam and space whereas chemical activation was the most suitable activation method for all the parameter combinations. The pyroligneous acid produced during pyrolysis was diluted with water and impurities that will reduce its economic value. Therefore, a purification system should also be tested to understand the economic trade-offs between selling the impure pyroligneous acid or after purification. Lastly, the CAPEX also is the major contributor to the MSP. Therefore, if CAPEX is reduced then a considerable reduction in MSP can be expected.

The pilot plant developed in this project is innovative and has a new design. Thus, there will be deviations in the estimated results from the actual operation of the plant. There will be a learning curve that will help in utilizing the resources efficiently and optimizing the plant operation. The performance of this value chain compared to other pyrolysis plants is promising and results in a positive business case under the assumptions made. It would be interesting to investigate further since it has the potential for reducing the MSPs by optimizing plant operation and efficient energy consumption.

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