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Chapter 1. Introduction

Large quantities of sewage sludge are produced in sludge treatment plants (STPs) and require adequate treatment to reduce the environmental impact of wastewater discharge. The activated sludge process is a widely used technology that helps in achieving the necessary effluent standards. However, the sewage sludge also contains useful materials such as lipids (triglycerides) that can be recovered and used as raw material to produce biodiesel. Utilizing this renewable fuel could reduce the use of natural resources and subsequent carbon dioxide (CO_2) emissions helping in realizing a circular economy. The potential recovery of this material has not been exploited much in North-West Europe (NWE). Accumulation of lipids for biodiesel production has only been investigated at lab and pilot scales (Wupperverband 2019). Generally, the sludge containing all the materials is used in anaerobic digestion to produce biogas. Anaerobic digestion is a mature technology used for the valorization of sewage, however, studies have shown the significance of exploring other technologies to produce higher-value end products such as biodiesel from lipids (Chen et al. 2018; Mondala et al. 2009; Patiño et al. 2018).

Biodiesel is a renewable fuel that has similar heating value and properties as fossil diesel. Thus, it can be directly used in engines or in applications where diesel is used (Siddiquee and Rohani 2011). It is also biodegradable and less toxic to the environment. It is the fatty acids methyl ester (FAME) and is mainly produced from edible vegetable oils (Olkiewicz et al. 2016). Due to the high cost of edible oils, the biodiesel production cost is mainly the feedstock cost, about 70 – 85% (Mondala et al. 2009). Cultivating oil seeds for biodiesel raises concerns about food shortages and food versus fuel competition. However, lipids in sewage sludge can be an alternate feedstock and are gaining more attention due to their availability in large quantities (Olkiewicz et al. 2014).

Lipids are basically fat, oil, and grease (FOG) found in wastewater. FOG represents about 30% of COD in the municipal wastewater which corresponds to 36 g/PE·d of a total 120 g COD/PE·d (Wupperverband 2019). FOG presents a problem by blocking the sewers and requiring cleaning that costs around €1 per population equivalent (PE) (SevernTrent 2016; Wupperverband 2019; Frkova et al. 2020). The larger FOG particles (>45 µm) can be easily collected at the inlet using sieves and grease traps. However, the smaller particles impose problems in the downstream treatment by limiting the oxygen transfer to the microorganisms, resulting in a decline of microbial activity (Henkel 2010). The amount of lipids found in the primary sludge is in the range of 15-30 wt.% while in the secondary sludge, 2-12 wt.% (Siddiquee and Rohani 2011). Since the sludge is already available in the STPs in large quantities, it can be considered to be a feedstock of low costs. Waste activated sludge (WAS) contains aerobic microorganisms that grow by feeding on the soluble and suspended organic substances in the wastewater (Fortela et al. 2018). The lipids in the WAS can be converted into biodiesel by transesterification. Generally, in this process, the lipids which are mainly triglycerides react with methanol at slightly elevated temperatures (about 70-80 °C) for a certain time (about 2 hours) in the presence of a catalyst (Revellame et al. 2011). Several oleaginous microorganisms are capable of accumulating lipids in the sludge. Therefore, cultivating these microorganisms for lipid production would also reduce the biodiesel production cost (Chen et al. 2018). However, if the wastewater is pre-treated separately for lipids accumulation especially for biodiesel production then those costs are also included in the biodiesel production.

The valorization of sewage sludge by biodiesel production has been investigated by several researchers. However, the economic potential of the whole value chain is missing in the literature. In the WOW project, the value chain consists of several steps including wastewater homogenization, lipid accumulation, growth of lipid accumulating bacteria, dewatering, drying, lipid extraction, transesterification, separation, and purification. The partners involved in developing and demonstrating the biodiesel value chain are the University of Luxembourg (UniLux), Luxembourg, and Remondis, Germany. The lipids pilot plant until the dewatering step was developed by UniLux whereas Remondis was responsible for dewatering, drying, extraction, transesterification, and purification. 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. Firstly, the overall methodology, the process adopted in the WOW project to accumulate, extract and convert the lipids into biodiesel are described, including the process flow diagram and the mass and energy balances. The mass flowrate data for the lipids pilot had been provided by UniLux. This report was written at the time when the sludge from the pilot plant was transported for further processing. Therefore, the data for the downstream steps (starting from dewatering) was obtained from existing literature (Gholami, Pourfayaz, and Maleki 2021; Crutchik et al. 2020; Chen et al. 2018). In the subsequent section, the techno-economic assessment methodology adopted to estimate the production cost also known as the minimum selling price (MSP) of biodiesel is presented. Then the results, key parameters, and their effect on the MSP are discussed. Lastly, the conclusions and the ideas for future research are presented.

Chapter 2. Methodology

In this chapter, the methodology used for the techno-economic assessment, the process flow diagram of the pilot and large-scale plants, and the data used to calculate the mass and energy balances, as well as the economics, are described.

2.1. Techno-Economic Assessment

When developing innovative technologies, such as the production of biodiesel from sewage sludge, 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).

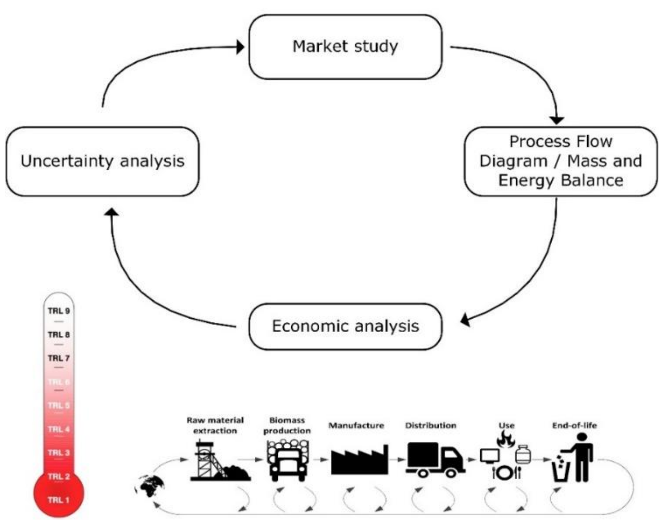

Figure 1. Techno-economic assessment

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 Wupperverband GmbH as the lead partner is available, as well as a factsheet per product (Wupperverband 2020). The state-of-the-art of legal framework is also separately available (Wupperverband 2019). The documents can be found on the project website[1]. A review article on the overall assessment of biodiesel production from sewage water-derived lipids was also written within this project (Frkova et al. 2020).

2.3. Process description and process flow diagram

2.3.1. Pilot plant

The pilot plant was designed for a wastewater inflow of 0.1 m^3/h with the layout shown in Figure 2. The plant consisted of mixing, anoxic and aerobic tanks, and a separation unit. The wastewater just after the screen at the STP was introduced into a mixing tank and continuously stirred to create homogeneity. The mixture was pumped to an anoxic tank where the biomass from the sedimentation tank was also recirculated. The biomass mixture at the anoxic tank outlet was pumped into an aerobic tank where the microorganisms that accumulate lipids were allowed to grow. The biomass mixture was then pumped into a sedimentation tank where the think foam formed was skimmed from the top continuously and recirculated to the anoxic tank. In case of lack of foam formation, surplus sedimented sludge could also be harvested. Recirculation was important to keep the biomass in the tanks. As it was a continuous process (not a batch with a sedimentation mid-step), there was a constant inflow and outflow. The inflow was just the inlet wastewater without activated sludge microorganisms while the outflow was including the

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

microorganisms. However, microorganisms were barely found in the microscopic counts and by mixed liquor suspended solids characterization. The pilot effluent water was visually clearer than the inlet. As both tanks were also continuously stirred, it was necessary to keep a certain amount of biomass in the bioreactors (anoxic and aerobic tanks). Eventually, it was the biomass that needed to be harvested. Samples were taken on average twice per week to check the biomass and weekly to characterize the inlet/outlet water composition and lipid content in inlet/outlet water and individual tanks (anoxic, aerobic, and sedimentation).

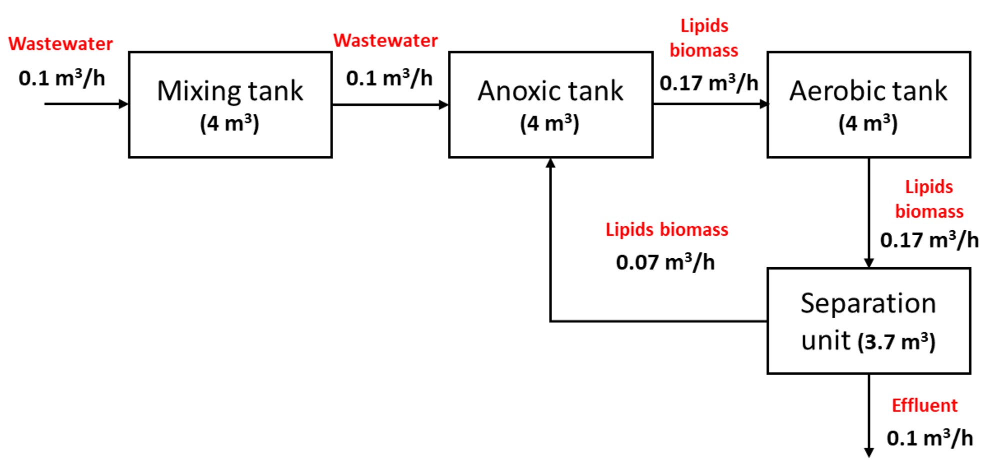

Figure 2. Pilot plant layout

The lipid production and transesterification part was not finalized at the time of writing this report. Therefore, the conventional method based on the literature has been used for the TEA as explained in the next section. Nevertheless, the plan was to use the in-situ transesterification method which was selected due to low lipid content and low amount of available material in the sludge obtained from the pilot. In this method, direct conversion of lipids from the sludge to biodiesel happens without intermediate lipid extraction. For the overall process, only methanol and HCl would be necessary. The in-situ transesterification can be done in one glass reactor at 70 °C to have a little overpressure. Thereafter, methanol is evaporated (can be reused), and the final product is purified. This method is expected to reduce the cost of biodiesel production further.

2.3.2. Large-scale plant

Within the WOW project, a techno-economic assessment of the whole value chain consisting of biodiesel production from sewage sludge was performed. The process flow diagram of the entire value chain for a large-scale plant developed for the current assessment is shown in Figure 3. The connections to the classical STP are depicted by the red-bordered boxes in the figure. When compared to the pilot plant, the key difference was that about 90% of the biomass was recirculated while the rest (10%) was sent to the biodiesel production process. The sedimentation tank was also replaced by a centrifuge for dewatering the biomass mixture. The downstream steps in the biodiesel production value chain (drying, extraction, transesterification, and purification) are completely based on the literature data.

The wastewater passed through the screens to remove large solids, rags, debris, etc. A mixing tank was used to homogenize the wastewater and reduce the large differences in its composition. The homogenized wastewater was sent to an anoxic tank where the accumulation of lipids occurs with the aid of activated sludge microorganisms. The wastewater along with the microbial biomass was then transferred to an aerobic tank where the replication or growth of lipid accumulating bacteria occurred. The wastewater with the lipids biomass was then sent to a centrifuge for separating and dewatering the biomass for further processing. The effluent was sent to be fully treated by conventional sewage treatment processes. For removing the moisture from the lipids biomass, a vacuum dryer was considered because of low power consumption. The dried lipids biomass was sent to an extraction column where the lipids were extracted from the microorganisms with the help of solvents. The solvent with dissolved lipids was separated in a centrifuge and sent to an evaporator column for solvent recovery. The waste biomass from the centrifuge was sent to a digester for biogas production. The lipids were subjected to transesterification where they reacted with methanol in the presence of a catalyst to produce fatty acids of methyl ester (FAME). The catalyst could either be a base or an acid and is dependent on the amount of water and free fatty acids. In this assessment, sodium hydroxide ($NaOH$) was assumed as a catalyst based on the literature data. The unused methanol was recovered in an evaporator. The FAME was washed with warm water and separated from other components in a decanter. The lighter component (biodiesel) was removed from the top and purified in a distillation column. The heavier component (glycerol) was sent to a neutralization reactor where the catalyst ($NaOH$) is neutralized using hydrochloric acid (HCl). The glycerol was separated in a decanter from sodium chloride ($NaCl$) that was formed in the neutralization reactor while the glycerol was removed from the bottom and further purified in a distillation column. The aqueous $NaCl$ was removed from the top and was considered a by-product of the process.

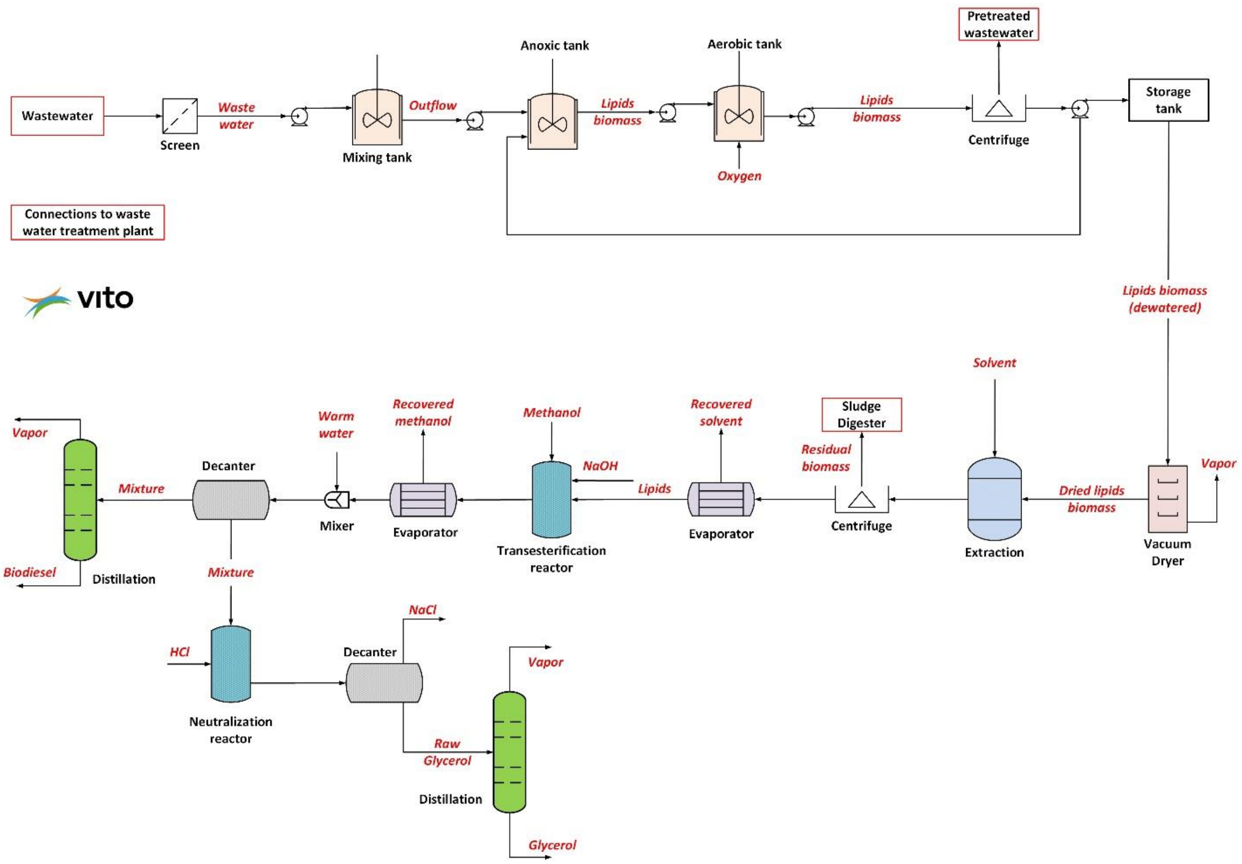

Figure 3. Process flow diagram of the producing biodiesel from sewage

2.4. Technical details of large sale plant – Mass and energy balance

The downstream process for lipids extraction and transesterification was designed based on the data from the literature (Chen et al. 2018). The mass and energy assumptions used for all the equipment which were not obtained from the pilot plant are listed in Table 1. Five pumps were considered to transfer wastewater and sludge from one equipment to another. The electricity required for pumping was about 0.1 kWh/m^3. The mixing, anoxic and aerobic tanks were continuously mixed to keep the mixture homogeneous. The power consumption for mixing in these tanks was about 0.1 kWh/m^3. The aeration required in the aerobic tank was 1.1 m^3/m^3 biomass and the power consumption was 1 kWh/kg$_{O2}$. As mentioned earlier, the sedimentation tank in the pilot plant was replaced by a centrifuge and it consumed 1.9 kWh/m^3 of electricity. Here, it is also assumed that about 10% of biomass was sent further to the biodiesel production process and the rest (90%) was recirculated to the anoxic tank. A vacuum evaporator was considered for drying the lipids biomass with moisture loss of up to 80% and power consumption of 200 kWh/m^3 biomass. The lipid extraction process was assumed to occur at 90 °C and takes 1 hour. The solvent was a mixture of chloroform and methanol in the ratio 2:1 and the requirement was 5.7 t/t dried lipids biomass. The steam required to provide heat during the extraction process was calculated based on the specific heat of the solvent mixture and was 0.33 t/t of dried lipids biomass. It was assumed that mixing was required in the extraction reactor which consumed 0.01 kW/m^3 of electricity. The outlet of the extraction step was sent to a centrifuge where it was assumed that the residual biomass was about 61.6% of the dried lipids biomass from the vacuum dryer. This means that 38.4% of the dried lipids biomass was dissolved in the solvent as lipids (triglycerides). About 99.5% of the solvent was recovered in the evaporator and the steam required in the evaporator was 0.05 t/t input. In the transesterification reactor, the methanol and the NaOH requirement was about 0.21 and 0.02 kg/kg lipids whereas the steam requirement to provide the heat was 14.4 kJ/kg input. The unreacted methanol was recovered in the evaporator column which had a steam requirement of 4607 kJ/kg input. The FAME produced was washed with warm water (0.001 kg/kg FAME). The mixture was sent to a decanter where 88 wt.% of the stream was removed from the top as raw biodiesel and further purified in a distillation column. The thermal energy required in the purification process was 1668 kJ/kg input. The heavier mixture was sent to a neutralization reactor where HCl in the quantity 0.1 kg/kg input was used to neutralize the catalyst. It was then separated from the heavier component, glycerol, in the second decanter. The raw glycerol was further purified in a distillation column which required 1668 kJ/kg input of thermal energy.

Table 1. Mass and energy assumptions for the large-scale plant

Equipment	Item	Value	Source
Pump	Wastewater density (kg/m^3)	1000	-
	Electricity (kWh/m^3)	0.1	(Crutchik et al. 2020)
Mixing tank	Electricity use (kWh/m^3)	0.1	(Crutchik et al. 2020)
	Retention time (h)	40	Pilot plant
Anoxic reactor	Electricity use (kWh/m^3)	0.1	(Crutchik et al. 2020)
	Retention time (h)	24	Pilot plant
Aerobic reactor	Aeration air (m^3/m^3)	1.1	(Henze et al. 2008)
	Electricity mixing (kWh/m^3)	0.1	(Crutchik et al. 2020)
	Electricity aeration (kWh/kgO_2)	1	(Crutchik et al. 2020)
	Retention time (h)	24	Pilot plant
Centrifuge 1	Sludge to anoxic reactor (wt.%)	90%	Assumption
	Electricity use (kWh/m^3)	1.9	(Crutchik et al. 2020)
Storage tank	Retention time (h)	168	Assumption
Dryer	Density (kg/m^3)	1000	Assumption
	Moisture loss (wt.%)	80%	(Chen et al. 2018)

	Electricity (kWh/m^3)	200	(Aquadest 2021)
Lipid extraction	Dried lipids biomass (% of input)	15%	(Chen et al. 2018)
	Solvent (C:M - 2:1) (% of input)	85%	
	Chloroform (% of solvent)	67%	
	Chloroform density (kg/m^3)	1490	
	Chloroform specific heat (kJ/kg-K)	1.1	
	Methanol (% of solvent)	0.3	
	Methanol density (kg/m^3)	792	
	Methanol specific heat (kJ/kg-K)	3.6	
	Solvent density (kg/m^3)	1257	
	Solvent specific heat (kJ/kg-K)	1.9	
	Electricity (kW/m^3)	0.01	(Crutchik et al. 2020)
	Extraction time (h)	1	(Olkiewicz et al. 2014)
	Temperature (°C)	90	Assumption
Centrifuge 2	Residual biomass (% of dried lipids)	61.6%	(Chen et al. 2018)
	Electricity use (kWh/m^3)	1.9	(Crutchik et al. 2020)
Evaporator 1	Lipids out (% of dried lipids)	38%	(Chen et al. 2018)
	Solvent recovery (wt.%)	99.5%	
	Steam requirement (kJ/kg)	4607	(Gholami, Pourfayaz, and Maleki 2021)
	Steam temperature (°C)	136	
	Steam pressure (bar)	3.24	
	Steam latent enthalpy (kJ/kg)	2,127	
Transesterification reactor	Methanol (kg/kg-lipids)	0.21	(Chen et al. 2018)
	NaOH (kg/kg-lipids)	0.02	
	Lipids conversion (wt.%)	99%	
	Steam requirement (kJ/kg input)	14.4	(Gholami, Pourfayaz, and Maleki 2021)
Evaporator 2	Recovered methanol (kg/kg input)	0.09	(Chen et al. 2018)
	Mixture (kg/kg input)	0.91	
	Steam requirement (kJ/kg)	4607	(Gholami, Pourfayaz, and Maleki 2021)
Water wash	Warm water (50 °C) (kg/kg input)	0.001	(Chen et al. 2018)
Decanter 1	Raw biodiesel (% of input)	88%	(Chen et al. 2018)
	Mixture to neutralization (% of input)	12%	
Distillation 1	Biodiesel out (% of input)	99.96%	(Chen et al. 2018)
	Vapor out (% of input)	0.001	
	Steam requirement (kJ/kg input)	1668	(Gholami, Pourfayaz, and Maleki 2021)
Neutralization reactor	Hydrochloric acid (kg/kg-input)	0.1	(Chen et al. 2018)
	Density of mixture (kg/m^3)	1260	
	Electricity mixing (kWh/m^3)	0.1	(Crutchik et al. 2020)
Decanter 2	Sodium chloride (% of input)	19%	(Chen et al. 2018)
	Raw glycerol (% of input)	81%	
Distillation 2	Glycerol out (% of input)	79%	(Chen et al. 2018)

Vapor out (% of input)	21%	
Steam requirement (kJ/kg input)	1668	(Gholami, Pourfayaz, and Maleki 2021)

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 plant were obtained from the literature or the vendors and are listed for each equipment in Table 2. It is to be noted that the cost of a sequencing batch reactor was assumed for the anoxic and aerobic tanks. To scale up the plant to larger flows the reference capacities as shown in Table 3 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.

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

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 15 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 8000 h/y. 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. This values is based on equity ratio = 20%, debt ratio = 80%, discount rate = 7.84%, tax rate = 29.58% (Belgium), and interest rate = 4.5%.

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

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

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.

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

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 biodiesel minimum selling price (MSP). The MSP is the total production cost, including annualized CAPEX and OPEX, per amount of product. 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 2. Equipment cost and operating labor assumptions

Plant equipment	Capital cost (€)	Scale factor	Personnel (per shift)
Pump	1,333	0.67	0.1
Mixing tank	55,147	0.57	0.2

Anoxic reactor	263,947	0.78	0.5
Aerobic reactor	263,947	0.78	0.5
Centrifuge	235,000	0.6	0.35
Storage tank	128	0.57	0.2
Dryer	180,000	0.6	0.5
Extraction reactor	105,432	0.78	0.35
Evaporator	74,520	0.78	0.35
Transesterification reactor	278,760	0.53	0.5
Water wash	105,432	0.78	0.35
Decanter	30,377	0.6	0.35
Distillation column	164,772	0.78	0.35
Neuralization reactor	22,724	0.53	0.5

Table 3. Biodiesel plant equipment and reference capacity

Plant equipment	Type	Reference capacity	Source
Pump	Centrifugal	10 m^3/h	(Axflow 2017)
Mixing tank	Polyester buffer tank	60 m^3/d	(VITO 2010b)
Anoxic reactor	Sequencing batch	30 m^3/d	(VITO 2010a)
Aerobic reactor	Sequencing batch	30 m^3/d	(VITO 2010a)
Centrifuge	Continuous	4 m^3/h	(Evodos 2019)
Storage tank	Horizontal vessel	1.1 m^3	(Mudliar et al. 2008)
Dryer	Vacuum evaporator	0.13 m^3/h	(Aquadest 2021)
Extraction reactor	Column	6705 kg/h	(Gholami, Pourfayaz, and Maleki 2021)
Evaporator	Distillation column	8122 kg/h	
Transesterification reactor	Heated	8122 kg/h	
Water wash	Column	6705 kg/h	
Decanter	Separator	6705 kg/h	
Distillation column	Distillation column	6659 kg/h	
Neutralization reactor	Agitated	772 kg/h	

Table 4 lists the assumptions used for estimating the capital and operating and maintenance (O&M) costs. The economic life of the plant is assumed as 15 years and all the values are presented in 2019 euros. The equipment costs obtained from the literature and the vendors are increased by 96% of the purchase cost to account for the installation and other costs (piping, instrumentation, electrical, engineering costs, civil works, and start-up). For labor estimation, the number of personnel required per equipment per shift is estimated using the methodology by Peter and Timmerhaus (Peters, Timmerhaus, and West 2003). The personnel per shift were taken from the same reference and are listed in Table 2. An average labor wage rate of €31.2/h was assumed for plant operators and maintenance workers in Europe ("Eurostat - Data Explorer" 2019). The assumptions used for estimating the overall labor costs are the labor burden (30% of base labor), overhead charge rate (25% of total labor), insurance (1% of CAPEX) (Crutchik et al. 2020), and maintenance (2% of CAPEX). For scaling labor requirement along with the plant scale, a scaling exponent of 0.25 was assumed based on the recommendations given by Peter et al. (Peters, Timmerhaus, and West 2003). Furthermore, the variable O&M costs for the electricity, steam, water, solvent, and chemicals were estimated based on the unit prices given in Table 4.

Since a part of the wastewater is directed towards biodiesel production, there would be savings in energy, personnel, and sludge disposal costs. These OPEX savings can offset some of the biodiesel production costs to some extent. However, these savings are expected to be small and are not considered in the current assessment. Moreover, these savings are not present when a standalone production plant is built for lipids accumulation and biodiesel production.

Table 4. General capital (CAPEX) and operational cost (OPEX) assumptions

Item	Unit	Value
Plant lifetime	y	15
Base year	-	2019
Piping	% CAPEX	15%
Instrumentation/Electrical	% CAPEX	25%
Engineering costs	% CAPEX	10%
Civil works	% CAPEX	34%
Start-up	% CAPEX	12%
Operating hours	h/y	8000

Insurance	% CAPEX	1%
Labor wage rate (base labor)	€/h	31.2
Labor burden	%base labor	30%
Overhead charge rate	% total labor	25%
Maintenance labor	%CAPEX	2%
Electricity	€/MWh	93
Steam	€/t	24.6
Warm water (50 °C)	€/m^3	1.2
Chloroform	€/kg	0.61
Methanol	€/kg	0.39
Sodium hydroxide	€/kg	0.39
Hydrochloric acid	€/kg	0.03

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 of a large-scale plant are described. Firstly, the results for the base case when biodiesel is produced are discussed. In the next section, the outcomes from a sensitivity analysis are presented where the key parameters that affect the biodiesel MSP are identified.

3.1. Production of biodiesel

3.1.1. Mass and Energy Balances

The mass and energy balances of the large-scale biodiesel production plant are illustrated in Figure 4. The mass balance until the centrifuge is based on the pilot plant data and was provided by the University of Luxembourg (UniLux). The energy requirement for pumping and mixing in these process steps was taken from the literature. The mass and energy balance for the rest of the plant (starting from the dryer) was also developed based on the literature data. The plant was designed for a wastewater flow of 200 m^3/h, which was pumped into a mixing tank for creating homogeneity. The outlet of the mixing tank was pumped into the anoxic tank where the lipids were accumulated by the microorganisms. Here, most of the lipids biomass (117.8 m^3/h) from the centrifuge was recirculated to keep the biomass balance in the tanks. The outlet of the anoxic tank (317.8 m^3/h) was pumped into an aerobic tank where the growth of the lipids accumulating bacteria was aided by aeration. The lipids biomass from the aerobic tank outlet was dewatered using a centrifuge. About 186.9 m^3/h of effluent was separated and sent to the STP for further treatment. Only 10% of the lipids biomass which corresponds to 13.1 m^3/h was sent to a vacuum dryer while the rest was recirculated to the anoxic tank to maintain the microorganism balance. In the dryer, 10.5 t/h of water was removed as vapor (80% of the moisture) and 2.6 t/h of the dried lipids biomass was forwarded to an extraction reactor. Chloroform and methanol mixture was used as a solvent and were required in the quantities of 11.7 and 3.1 t/h, respectively. In the extraction process, the lipids were recovered from the microorganisms by breaking their cell wall. The lipids-rich solvent was separated from 1.6 t/h of residual biomass in a centrifuge (not shown in the figure). About 14.7 t/h of the solvent mixture was recovered from the evaporator with a loss of just 0.1 t/h. The amount of the triglycerides obtained was ~1 t/h and was sent to the transesterification reactor. Methanol and NaOH were supplied to this reactor in the quantities of 0.2 t/h and 0.02 t/h, respectively. The outlet mixture (1.1 t/h) was further sent for separation and purification. A single block is used in the figure to combine the processes of separation, purification, and neutralization. For neutralizing the NaOH, ~0.02 t/h of HCl was consumed to form NaCl.

The products obtained were biodiesel, glycerol, and NaCl in the quantities of 1 t/h, 0.1 t/h, and 0.03 t/h, respectively.

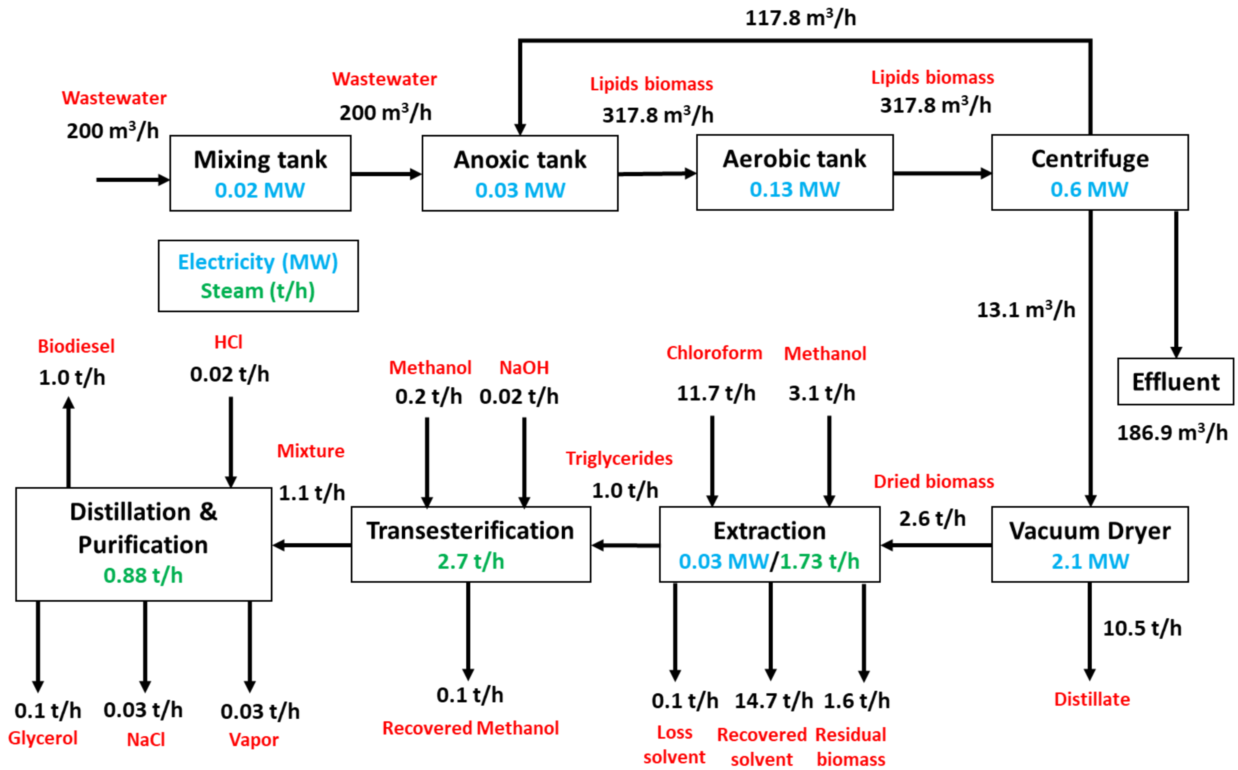

Figure 4. Mass and energy balance of biodiesel production

3.1.2. Economic analysis

The economic assessment results for the base case are discussed in this section. Figure 5 shows the breakdown of capital costs (CAPEX) and O&M costs (OPEX). For the base case, annualized CAPEX and OPEX were € 5,731,581 and € 7,588,580, respectively. The major contribution to CAPEX comes from the anoxic (40%) and aerobic tanks (40%) since these tanks were fed with large inflows of wastewater and recirculated lipids biomass and thus required a larger volume. It is to be noted that these two tanks constitute 80% of the overall CAPEX. Therefore, a cheaper alternative reactor configuration that provides similar performance could lower biodiesel production costs. The cost of a sequencing batch reactor (SBR) is assumed for these tanks as it is known that these reactors can be modified to suit the requirements (Quan and Gogina 2019). A sensitivity analysis was performed in the later section to estimate the effect of CAPEX on the biodiesel MSP. The centrifuge and the storage tank constitute about 10% of the overall CAPEX. Since the sludge was dewatered in the centrifuge, the volume required in the storage tank was relatively lower. The vacuum dryer alone contributed about 6% while the extraction equipment (reactor, centrifuge, and evaporator) and mixing tank about 3% and 1%, respectively. The transesterification reactor (0.3%), separation/purification equipment (0.3%) and the pumps (0.2%) have very small contribution to the overall CAPEX.

The OPEX breakdown in Figure 5(b) shows that the largest contribution is from electricity (30%) which was mainly required in the drying process. It consumed about 69% of the overall electricity consumption. The steam requirement during the extraction and purification processes had a share of 14%. Thus, a significant part of the OPEX was due to the energy requirement of the plant (44%). The fixed OPEX including labor, maintenance, and insurance contributed 10%, 12%, and 25% to the total OPEX, respectively. The final 10% of OPEX contribution came from solvents and chemicals required in the process.

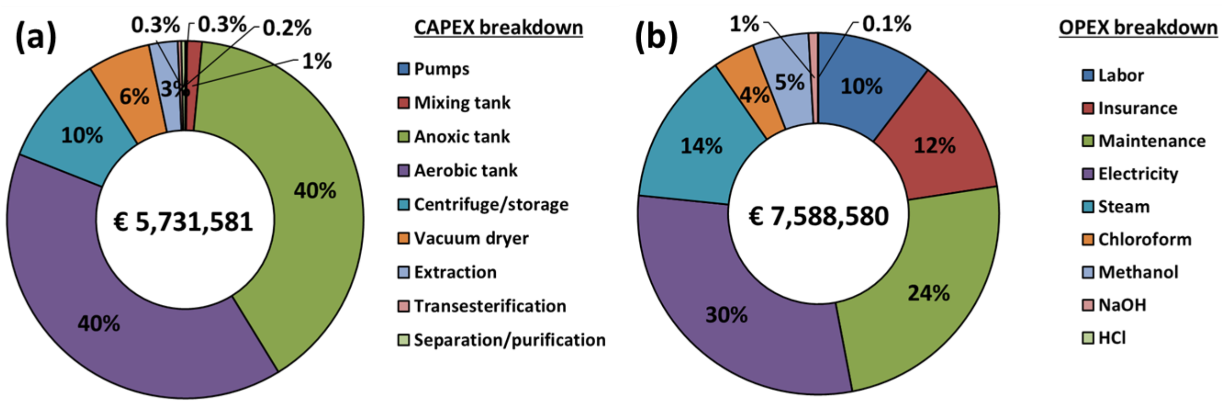

Figure 5. Biodiesel production (a) Capital cost and (b) Operating cost breakdown

The overall breakdown of biodiesel MSP or the production cost is shown in Figure 6. The biodiesel MSP estimated in this assessment is €1.59 /kg biodiesel which is higher than the market price (€0.92 /kg) and the prices reported in the literature (see Table 5). The production costs using sewage sludge as the feedstock are reported to be ~€1 /kg. Compared with the literature studies in which other feedstocks were used, the production cost estimated in the current assessment is relatively higher. A complete comparison cannot be made since these studies did not provide details on the economic assessment methodology used and thus the results cannot be verified. Moreover, these studies were mainly based on the regions outside Europe and it is expected that the cost estimations will differ considerably. The commercial company KFS Biodiesel GmbH[2] in Germany produces biodiesel from used cooking oil and rapeseed oil and estimated the market price to be €0.8 /kg. Furthermore, a market potential study conducted in the WOW project estimated the biodiesel market price to be in the range of € 0.8 – 1.04 /kg (Wupperverband 2020), which is lower than that estimated in the current assessment. Figure 6 shows that the CAPEX has the largest contribution to the biodiesel MSP. It contributed about 43% to the overall biodiesel production cost. As mentioned earlier, CAPEX is dominated by the investments required in building anoxic and aerobic tanks. Therefore, identifying and developing alternative reactor configurations would bring down the biodiesel price significantly. Since the maintenance cost is dependent on the CAPEX (2% of CAPEX), its contribution was nearly 15%. The electricity consumption contributed about 17%, which is mainly dominated by the electricity required in drying operation. The drying of lipids biomass is an important step in the biodiesel production process where a lot of energy is consumed. If an alternative drying process is developed which consumes less electrical power, then MSP can be reduced further. The current assessment considered a vacuum evaporation method. This method requires low electricity consumption when compared to other traditional technologies based on thermal energy (Aquadest 2021). The only drawback is that these types of evaporators can accommodate only semi-solid state material. So, the lipids biomass has to be dewatered as much as possible before sending it to the vacuum dryer. The contribution from the chemicals (mainly solvents) was 6% and can be further reduced by using a cheaper solvent with less requirement per ton of dried lipids biomass during the extraction process. This will also reduce the overall steam requirement during the extraction and solvent recovery steps and will also reduce the equipment size.

2 https://kfs-biodiesel.de/en/

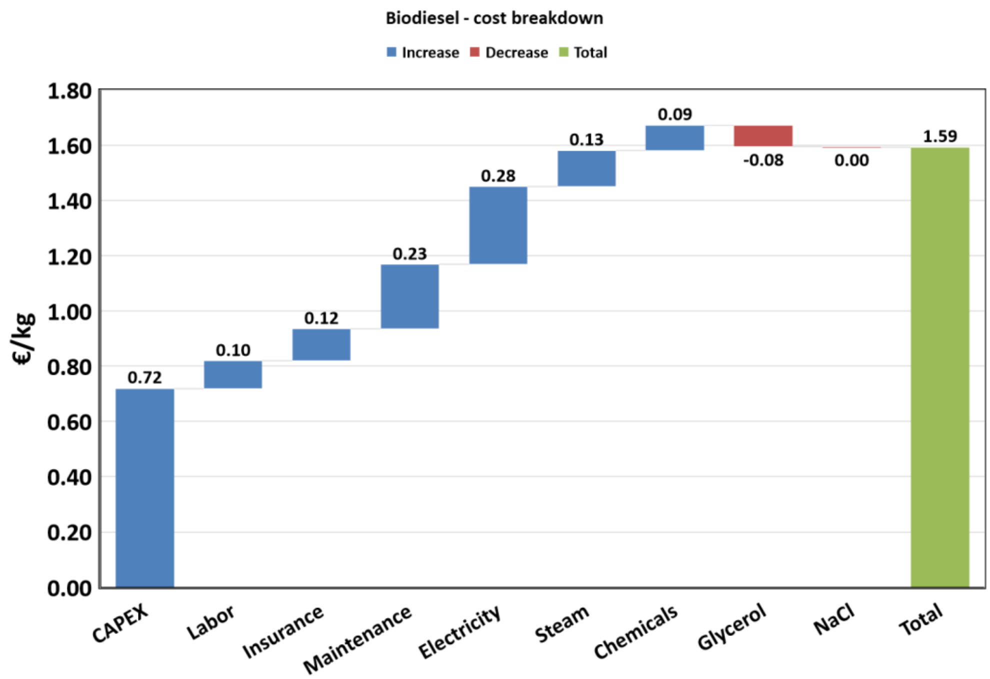

Figure 6. Biodiesel MSP breakdown

Table 5. Biodiesel production price

Source	Price, €/kg (2019)	Reference
Sewage sludge	0.94	(Chen et al. 2018)
Sewage sludge	0.98	(Mondala et al. 2009)
Grease trap	1.2	(Tran et al. 2018)
Sewage sludge	1.1	(Olkiewicz et al. 2016)
Acidic oil	0.9	(Gebremariam and Marchetti 2018)
Calophyllum oil	0.6	(Naveenkumar and Baskar 2020)
Sunflower oil	1.6	(Tasić, Stamenković, and Veljković 2014)
Microalgal biomass	16.2	(Lee et al. 2019)
Jatropha curcas oil	0.7	(Yusuf and Kamarudin 2013)
Palm oil	0.7	(Sakdasri, Sawangkeaw, and Ngamprasertsith 2018)
Used cooking/rapeseed oil	0.8	Survey report – KFS Biodiesel GmbH

In addition to the main product (biodiesel), the by-products glycerol and NaCl also have economic value. Though not significant, the revenue obtained by selling the by-products could offset some of the biodiesel production costs. The product yield and the revenues obtained by selling at the market price are shown in Figure 7. This assessment was performed to find the net present value (NPV) of the biodiesel plant and identify whether the plant would be profitable under current data and assumptions. The total amount of products were 8990 t/y in which the biodiesel was about 89 wt.% whereas glycerol and NaCl were about 9 wt.% and 3 wt.%, respectively. Using the market prices of the biodiesel (0.92 €/kg), glycerol (0.79 €/kg) and NaCl (0.05 €/kg), the revenues estimated were €7,957,179 /y. About 92% of the revenues were from biodiesel and 8% were from glycerol while revenue by selling NaCl was insignificant.

Table 6 compares the current results with that available in the literature (Chen et al. 2018). The CAPEX estimated in the current assessment is ~2.6 times higher than that in the literature. The large difference is because Chen et al. had used the primary sludge as the feedstock directly without considering the lipids accumulation and microbial growth in the anoxic and aerobic tanks, respectively. The large differences in the biodiesel production capacity and also the region where the studies were performed also contributed to the differences in CAPEX. The biodiesel production capacity is 4.1 times smaller because the plant scale considered in this assessment was based on the fact that only about 10-15% of the wastewater from an STP of size 200,000 PE was directed towards the biodiesel production plant. The OPEX estimated in this assessment is also ~1.25 times higher. Consequently, the biodiesel MSP estimated is ~1.7 times higher than that reported by Chen et al. Similarly, the economic indicators such as NPV, IRR, and DPBP estimated in the current assessment are undesirable and showed that this plant is not profitable under current assumptions. Therefore, the key parameters that can reduce the biodiesel production cost were identified and the possible improvement strategies were discussed in section 3.2.

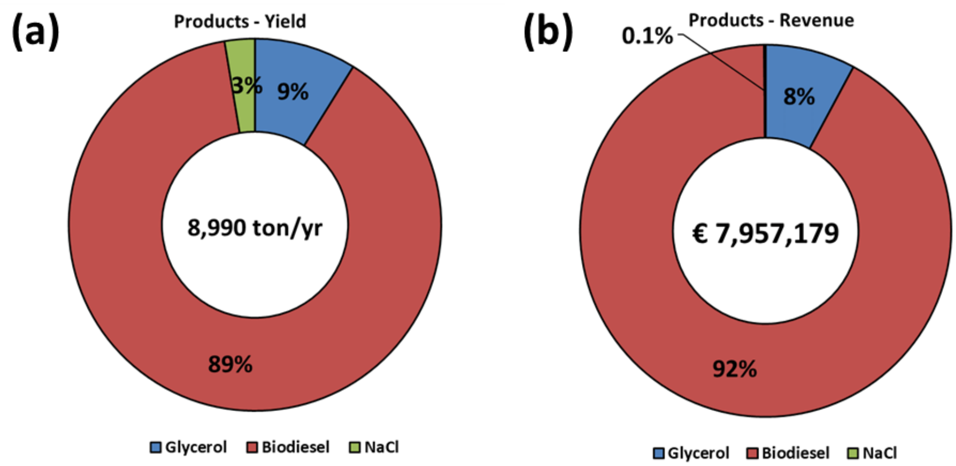

Figure 7. Product yield and revenue based on current market prices

Table 6. Comparison with literature results

	Current study	(Chen et al. 2018)
Feedstock	Primary sludge	Primary sludge
Normalized CAPEX (€/t biodiesel)	720	278
Normalized OPEX (€/t biodiesel)	954	760
Biodiesel output (t/y)	7959	32617
Biodiesel MSP (€/t)	1594	937
Net present value (€)	-90,496,934	-
Internal rate of return (%)	-	-
Discounted payback period (y)	>30	-

3.2. Sensitivity analysis

In this section, the impact of changes in four technical parameters (plant scale, biomass recirculation, drying energy, and lipids conversion) and five economic parameters (CAPEX, labor requirement, prices of glycerol, chloroform, and methanol) on the economic feasibility of biodiesel production are discussed. Then the most influential parameters are investigated separately for their effect on the biodiesel MSP using a local sensitivity analysis.

3.2.1. Monte-Carlo analysis

The Monte-Carlo simulation was performed for the 9 selected variables. Since the process under study is quite new, not much information on the key variables 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. The selected variables were varied over certain ranges. The variables are plant scale (represented by wastewater flowrate in m^3/h), biomass recirculation (%), drying energy requirement (%), lipids conversion (%), CAPEX (% increase or decrease), labor requirement (% increase or decrease), and prices of glycerol, chloroform, and methanol (€/kg).

The lower boundary for the plant scale was set at 40 m^3/h (-80% of reference value) while the maximum scale was set at 400 m^3/h (+100% of reference value). This was done to take into account the large variations in the scale of STPs. The selected range is based on the assumption that only 10-15% of the wastewater is directed towards biodiesel production. 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 biomass recirculation to the anoxic tank was important to maintain an optimum amount of biomass in the tanks. Therefore, the lower boundary of the biomass recirculation was set at 50% while the upper boundary was set at 90% (reference value). It cannot be 100% since some biomass is required in the downstream processes for biodiesel production. For the drying energy requirement, the maximum was kept the same as the reference value and a lower boundary was set at -40% of the reference value. The goal is to reduce the energy consumption in the drying process. The lipids conversion to FAME considered for this assessment was 99% but in reality, it might be lower due to practical challenges. Thus, it was varied from 80% to 100% to cover the uncertainty in the conversion. The CAPEX is highly uncertain because of differences in available data. Therefore, the CAPEX was varied from -60% to +20% of the reference value to accommodate a large range of CAPEX. The labor requirement was lowered to -50% of the reference value. 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. The by-product glycerol brings revenue that could offset some production costs. Therefore, it was varied from -20% to +20% of the reference value (0.63 – 0.95 €/kg). The price of solvents (chloroform and methanol) was also varied from -20% to +20% of their reference values (chloroform: 0.49 – 0.73 €/kg and methanol: 0.31 – 0.47 €/kg).

Figure 8 shows the contribution of each selected variable towards the variance in biodiesel MSP 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. Six variables (drying energy, labor requirement, glycerol price, lipids conversion, methanol, and chloroform) have very low sensitivity and thus were not investigated using a local sensitivity. The most influential variable is biomass recirculation (79.5%) and has positive sensitivity. The variables, CAPEX also has positive sensitivity (10.4%) whereas the wastewater inflow has negative sensitivity (-6.3%). The impact of these variables on the MSP is further investigated in the following subsections.

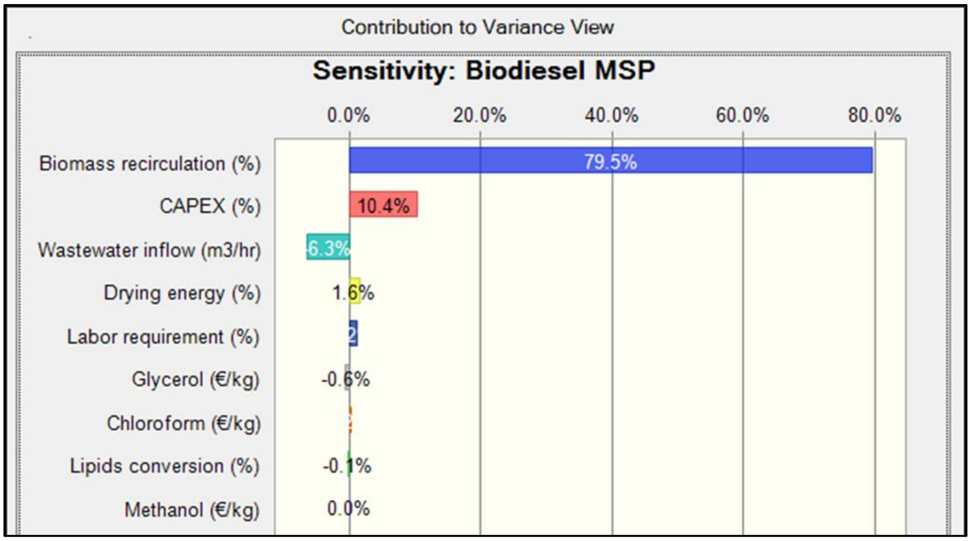

Figure 8. Relative contribution of the variables' range to the variance in biodiesel MSP

3.2.2. Impact of plant scale (wastewater inflow)

The wastewater flow rate determines the scale or size of the STP which is measured in terms of population equivalent (PE). As mentioned earlier, the plant considered in the current assessment was designed for a wastewater flow of 200 m^3/h and was based on the assumption that only about 10-15% of the wastewater flow would be directed towards the biodiesel production plant. The STP considered was of the size 200,000 PE (largest plant operational in Luxembourg). The wastewater flow for this plant considering the average flow of 0.2 $m^3/PE \cdot d$ would be 1666.67 m^3/h. A side stream of 12% flow would be 200 m^3/h, which was the inflow to the biodiesel production plant. The plant scale ranges from 40 m^3/h to 400 m^3/h which corresponds to 40,000 PE and 400,000 PE, respectively. The variation in the wastewater inflow can also be seen as the variation in the percentage of flow from the same STP. If a plant of size 200,000 PE is considered, then 40 m^3/h represents 2.4% whereas 400 m^3/h represents 24% of the wastewater inflow.

The effect of the plant scale on the biodiesel MSP is shown in Figure 9. The biodiesel MSP decrease as the scale goes from lower to the upper limit. 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 scale factor. The reduction in biodiesel MSP was 32.4% as the scale was varied from lower to the upper limit. Moreover, when compared to the market price (0.92 €/kg), the biodiesel production cost is 36% higher even at the upper scale limit.

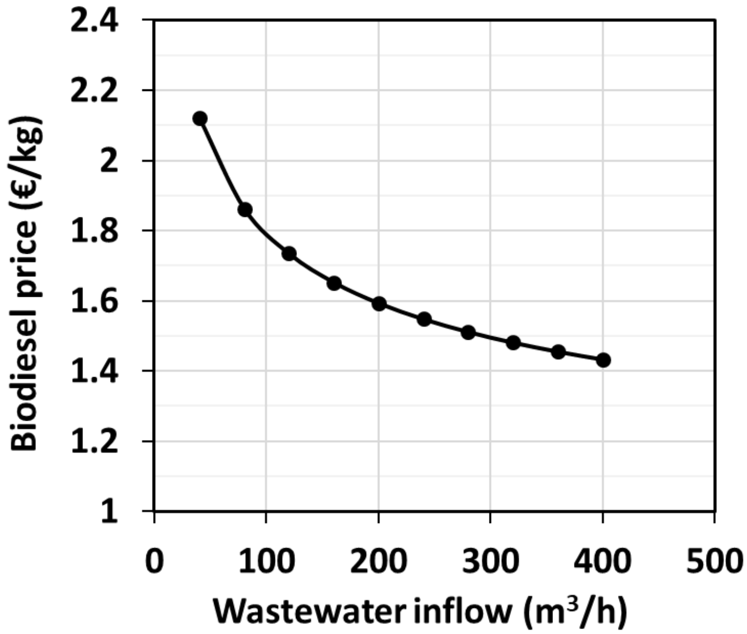

Figure 9. Impact of plant scale on biodiesel MSP

3.2.3. Impact of biomass recirculation

As discussed in section 3.2.1, the Monte-Carlo analysis showed that biomass recirculation is the most significant parameter. The biomass was recirculated back to the anoxic tank and was important to maintain the biomass level in the tanks. As it is a continuous process (not a batch with a sedimentation mid-step), there was a constant inflow and outflow. The inflow was just the inlet wastewater without activated sludge microorganisms while the outflow was including the microorganisms. As both reactors were also continuously stirred, a certain amount of biomass had to be kept in the bioreactors since it was the only thing that was harvested. Since there are no set rules for the amount to be recirculated, it was assumed that 90% of the lipids biomass needs to be recirculated for optimum balance of the biomass. However, it depends on the biomass quality and the other available biomass sources. It is to be noted that less recirculation means that more biomass will be directed towards biodiesel production. The biomass recirculation was varied from 90% to 50% and the effect of this variation on biodiesel MSP is shown in Figure 10. As the biomass recirculation is reduced to 50%, the biodiesel MSP reduced from 1.59 to 0.74

€/kg, a 53% reduction. The lowest biodiesel price obtained is about 19% lower than the market price indicating that the biodiesel production from such a plant is economically feasible if the biomass recirculation is controlled. The biodiesel MSP matched the market price at about 72.5% biomass recirculation. Therefore, the optimum recirculation should be below the aforementioned percentage for economic feasibility. The main purpose of recirculation was to provide sufficient microorganisms for lipids accumulation. An alternate biomass source can also provide the required microorganisms. Since only about 10-15% of wastewater is considered to be directed towards biodiesel production, the activated sludge from the existing STP can be an alternate biomass source.

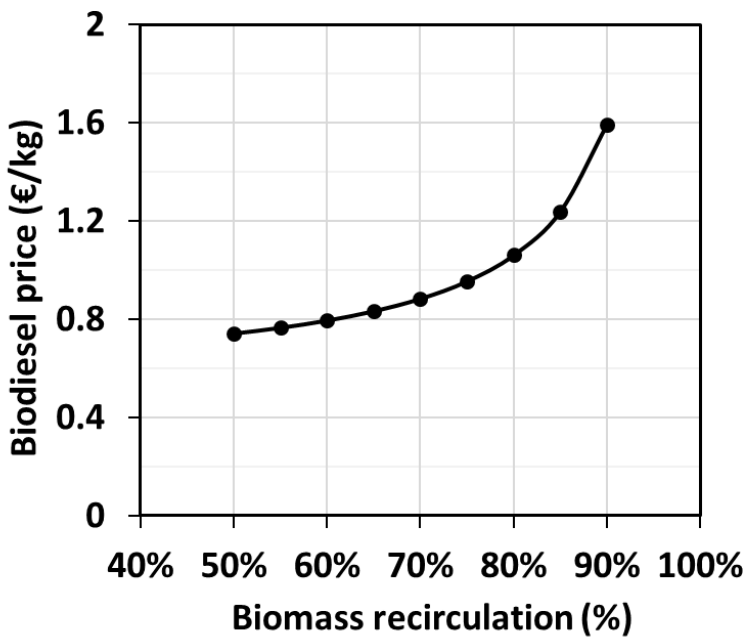

Figure 10. Impact of biomass recirculation on biodiesel MSP

3.2.4. Impact of capital expenditure (CAPEX)

As mentioned earlier in section 3.1.2, the CAPEX estimated in the current assessment is ~2.6 times that estimated in the literature (Chen et al. 2018). For the anoxic and aerobic tank, the cost data were acquired from the literature and it constituted 80% of the total CAPEX. The reason is the large inflows of wastewater and recirculated biomass and thus required larger volumes. Once the lipids biomass was dewatered, the equipment size required was relatively small. The current capital cost estimation can be considered overestimated and this was due to the lack of details available on the construction of a large-scale plant and the type of bioreactor suitable for such operations. In this assessment, the cost of an SBR was considered for both anoxic and aerobic tanks. However, an alternate scenario would be to build simple and specialized tank configurations suitable for lipids accumulation and microbial growth. The CAPEX was varied from -60% to +20% of the reference value and the results obtained are shown in Figure 11. By reducing the CAPEX by 50%, the reduction in the biodiesel MSP was 23%. Therefore, it can be concluded that CAPEX is also an influential factor which is also evident in the Monte-Carlo analysis. However, at 50% CAPEX reduction, the biodiesel price was still 25% higher than the market price. Thus, a reduction in CAPEX alone is not sufficient to make the biodiesel production plant economically feasible.

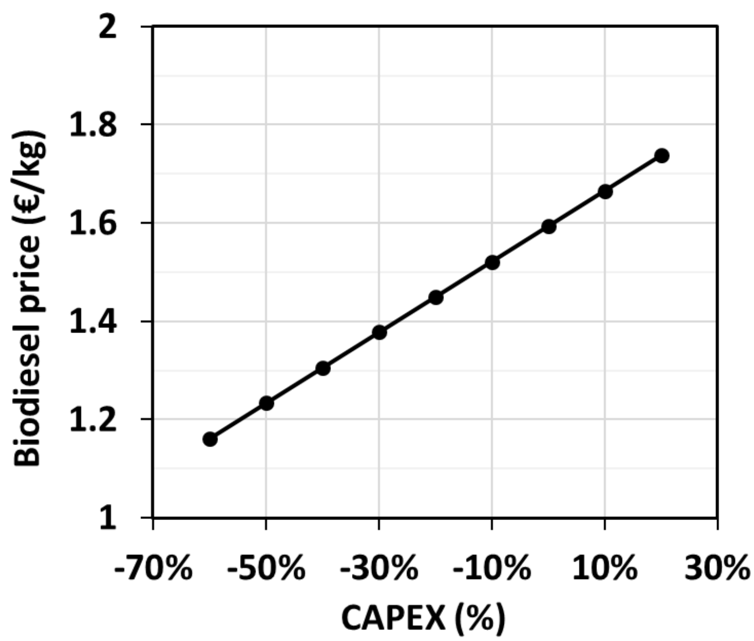

Figure 11. Impact of CAPEX on biodiesel MSP

Chapter 4. Conclusions and future work

Wastewater contains a lot of valuable materials such as fat, oil, and grease (FOG) that can be further processed to produce useful fuels such as biodiesel. Utilizing these valuable materials could reduce the use of natural resources and subsequent carbon dioxide (CO_2) emissions and hence, realize a circular economy. In this report, a techno-economic assessment on a biodiesel production plant from wastewater sludge as substrate was performed. In the WOW project, the biodiesel production value chain consisted of several steps including mixing, lipids accumulation and microbial growth, separation, drying, extraction, transesterification, separation, and purification of products. The lipids pilot plant until the separation step was developed by the University of Luxembourg (UniLux) and the lipids biomass was sent to Remondis

(Germany) who are responsible for lipids extraction and transesterification. The biodiesel MSP estimated in this assessment was € 1.59 /kg which is higher than the market price and also to that reported in the literature. Further comparison with the literature using other feedstocks also shows that the estimated MSP is relatively higher. A market potential study conducted in the WOW project estimated the biodiesel market price to be in the range of € 0.8 – 1.04 /kg (Wupperverband 2020), which is significantly lower than the current assessment.

Several technical and economic parameters affect the overall performance of the plant. The biomass recirculation back to the anoxic tank is the most influential variable. Lowering the recirculation from 90% to about 72% will result in the biodiesel MSP similar to the average market price. An optimum recirculation strategy should be developed without compromising the biomass requirement in the anoxic tank. An alternate biomass source can also provide the required biomass. This source can be from either the primary or secondary sludge of the STP. The next influential variable is the plant CAPEX in which the anoxic and aerobic tanks constitute 80% of the total CAPEX. Therefore, a lot of reduction in the CAPEX can be expected if these tanks are optimally designed or an alternate reactor configuration is employed. A 50% reduction in the CAPEX can reduce the biodiesel production cost by 23%. The plant scale represented by the wastewater inflow is also considered an influential variable. It can be observed that the biodiesel MSP decrease as the scale goes from small to large. 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. Factoring in the savings in the OPEX of STP when a part of the wastewater stream is directed towards the biodiesel production plant will also reduce the costs to some extent.

It is evident from the results that several parameters are needed to be improved together to make biodiesel production from sewage economically feasible. The pilot plant developed in this project is innovative and has a new design. Thus, there will be deviations of 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 biodiesel production plants indicate its future potential. Given the key variables and improvement strategies discussed above, a positive business case is possible. It would be interesting to investigate further since it has the potential for reducing the MSP by optimizing plant operation and efficient energy consumption.

References

Aquadest. 2021. “AQUADEST - KR - Vacuum Evaporator.” 2021. https://aquadest.cz/en/aquadest-kr.

Axflow. 2017. “MAF Pump for Algal Slurry.” https://www.axflow.com/nl-nl/catalogus/producten/pompen.

Boardman, Anthony E., David H. Greenberg, Aidan R. Vining, and David L. Weimer. 2006. *Cost-Benefit Analysis: Concepts and Practice*. New Jersey: Pearson Education. http://testbankmango.eu/Test-bank-for-Cost-Benefit-Analysis-4-9780137002696.

CEPCI. 2011. “Chemical Engineering Plant Cost Index.” *Chem Eng* 121 (1): 60.

Chen, Jiaxin, Rajeshwar Dayal Tyagi, Ji Li, Xiaolei Zhang, Patrick Drogui, and Feiyun Sun. 2018. “Economic Assessment of Biodiesel Production from Wastewater Sludge.” *Bioresource Technology* 253 (April): 41–48. https://doi.org/10.1016/j.biortech.2018.01.016.

Crutchik, Dafne, Oscar Franchi, Luis Caminos, David Jeison, Marisol Belmonte, Alba Pedrouso, Angeles Val del Rio, Anuska Mosquera-Corral, and José Luis Campos. 2020. “Polyhydroxyalkanoates (PHAs) Production: A Feasible Economic Option for the Treatment of Sewage Sludge in Municipal Wastewater Treatment Plants?” *Water (Switzerland)* 12 (4): 1118. https://doi.org/10.3390/W12041118.

Dael, Miet Van, Tom Kuppens, Sebastien Lizin, and Steven Van Passel. 2015. “Techno-Economic Assessment Methodology for Ultrasonic Production of Biofuels.” In , 317–45. Springer, Dordrecht. https://doi.org/10.1007/978-94-017-9624-8_12.

“Eurostat - Data Explorer.” 2019. 2019. http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=lc_lci_lev&lang=en.

Evodos. 2019. “Evodos 50.” https://www.evodos.eu/product/evodos-50/.

Fatone, Francesco. 2020. “SMART-Plant: Socio-Economic Assessment Including Life Cycle Costing (LCC) and Cost Benefit Analysis (CBA) Reports.” Ancona, Italy: SMART-Plant Consortium.

Fortela, Dhan Lord B, Ashley P Mikolajczyk, Rafael Hernandez, Emmanuel Revellame, William Holmes, and Mark Zappi. 2018. “Techno-Economic Potential of Integrated Anaerobic Digestion and Aerobic Lipid Accumulation for Fuels and Materials Recovery from Wastewater Treatment Plants.” *Journal of Fundamentals of Renewable Energy and Applications* 8 (4): 268. https://doi.org/10.4172/20904541.1000268.

Frkova, Zuzana, Silvia Venditti, Patrick Herr, and Joachim Hansen. 2020. “Assessment of the Production of Biodiesel from Urban Wastewater-Derived Lipids.” *Resources, Conservation & Recycling* 162: 105044. https://doi.org/10.1016/j.resconrec.2020.105044.

Gebremariam, S. N., and J. M. Marchetti. 2018. “Biodiesel Production through Sulfuric Acid Catalyzed Transesterification of Acidic Oil: Techno Economic Feasibility of Different Process Alternatives.” *Energy Conversion and Management* 174 (October): 639–48. https://doi.org/10.1016/J.ENCONMAN.2018.08.078.

Gholami, Ali, Fathollah Pourfayaz, and Akbar Maleki. 2021. “Techno-Economic Assessment of Biodiesel

Production from Canola Oil through Ultrasonic Cavitation." *Energy Reports* 7 (November): 266–77. https://doi.org/10.1016/j.egyr.2020.12.022.

Henkel, Jochen. 2010. "Oxygen Transfer Phenomena in Activated Sludge." Darmstadt: Technical University of Darmstadt. https://core.ac.uk/download/pdf/11681292.pdf.

Henze, M., M. C. M. van Loosdrecht, G.A. Ekama, and D. Brdjanovic. 2008. "Biological Wastewater Treatment: Principles, Modelling and Design." *Biological Wastewater Treatment: Principles, Modelling and Design*, September. https://doi.org/10.2166/9781780401867.

Lee, Jae Cheol, Boreum Lee, Juheon Heo, Hyun Woo Kim, and Hankwon Lim. 2019. "Techno-Economic Assessment of Conventional and Direct-Transesterification Processes for Microalgal Biomass to Biodiesel Conversion." *Bioresource Technology* 294 (December): 122173. https://doi.org/10.1016/J.BIORTECH.2019.122173.

Levy, H, and M Sarnat. 1994. *Capital Investment and Financial Decisions*. New Jersey: Prentice Hall. https://books.google.com/books?hl=en&lr=&id=YfYVZzeWNbEC&oi=fnd&pg=PR11&dq=Capital+investment+and+financial+decisions&ots=0QxxcDOL0E&sig=nCsOkgr8IfTmtPiFgZxwaByNWWQ.

Lorie, James H, and Leonard J Savage. 1955. "Three Problems in Rationing Capital." *The Journal of Business* 28 (4): 229–39. https://www.jstor.org/stable/2351049.

Mercken, R. 2004. *De Investeringsbeslissing. Een Beleidsgerichte Analyse*. Antwerpen: Garant. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=De+investeringsbeslissing.+Een+beleidsgerichte+analyse&btnG=.

Mondala, Andro, Kaiwen Liang, Hossein Toghiani, Rafael Hernandez, and Todd French. 2009. "Biodiesel Production by in Situ Transesterification of Municipal Primary and Secondary Sludges." *Bioresource Technology* 100 (3): 1203–10. https://doi.org/10.1016/j.biortech.2008.08.020.

Mudliar, S. N., A. N. Vaidya, M. Suresh Kumar, S. Dahikar, and T. Chakrabarti. 2008. "Techno-Economic Evaluation of PHB Production from Activated Sludge." *Clean Technologies and Environmental Policy* 10 (3): 255–62. https://doi.org/10.1007/s10098-007-0100-0.

Naveenkumar, Rajendiran, and Gurunathan Baskar. 2020. "Optimization and Techno-Economic Analysis of Biodiesel Production from Calophyllum Inophyllum Oil Using Heterogeneous Nanocatalyst." *Bioresource Technology* 315 (November): 123852. https://doi.org/10.1016/J.BIORTECH.2020.123852.

Olkiewicz, Magdalena, Martin Pablo Caporgno, Agustí Fortuny, Frank Stüber, Azael Fabregat, Josep Font, and Christophe Bengoa. 2014. "Direct Liquid-Liquid Extraction of Lipid from Municipal Sewage Sludge for Biodiesel Production." *Fuel Processing Technology* 128: 331–38. https://doi.org/10.1016/j.fuproc.2014.07.041.

Olkiewicz, Magdalena, Carmen M. Torres, Laureano Jiménez, Josep Font, and Christophe Bengoa. 2016. "Scale-up and Economic Analysis of Biodiesel Production from Municipal Primary Sewage Sludge." *Bioresource Technology* 214 (August): 122–31. https://doi.org/10.1016/J.BIORTECH.2016.04.098.

Patiño, Yolanda, Laura G. Mantecón, Sara Polo, Laura Faba, Eva Díaz, and Salvador Ordóñez. 2018.

"Effect of Sludge Features and Extraction-Esterification Technology on the Synthesis of Biodiesel from Secondary Wastewater Treatment Sludges." *Bioresource Technology* 247: 209–16. https://doi.org/10.1016/j.biortech.2017.09.058.

Peters, Max S., Klaus D. Timmerhaus, and Ronald E. West. 2003. *Plant Design and Economics for Chemical Engineers.* McGraw-Hill. http://highered.mheducation.com/sites/0072392665/index.html.

Quan, Tran Ha, and Elena Gogina. 2019. "Application of Anoxic Phase in SBR Reactor to Increase the Efficiency of Ammonia Removal in Vietnamese Municipal WWTPs." *E3S Web of Conferences* 97: 01017. https://doi.org/10.1051/e3sconf/20199701017.

Revellame, Emmanuel, Rafael Hernandez, William French, William Holmes, Earl Alley, and Robert Callahan II. 2011. "Production of Biodiesel from Wet Activated Sludge." *Journal of Chemical Technology & Biotechnology* 86 (1): 61–68. https://doi.org/10.1002/JCTB.2491.

Sakdasri, Winatta, Ruengwit Sawangkeaw, and Somkiat Ngamprasertsith. 2018. "Techno-Economic Analysis of Biodiesel Production from Palm Oil with Supercritical Methanol at a Low Molar Ratio." *Energy* 152 (June): 144–53. https://doi.org/10.1016/J.ENERGY.2018.03.125.

SevernTrent. 2016. "Bag It and Bin It | Environment | About Us | Severn Trent Water." 2016. https://www.stwater.co.uk/about-us/environment/bag-it-and-bin-it/.

Siddiquee, Muhammad N., and Sohrab Rohani. 2011. "Lipid Extraction and Biodiesel Production from Municipal Sewage Sludges: A Review." *Renewable and Sustainable Energy Reviews* 15 (2): 1067–72. https://doi.org/10.1016/j.rser.2010.11.029.

Tasić, Marija B., Olivera S. Stamenković, and Vlada B. Veljković. 2014. "Cost Analysis of Simulated Base-Catalyzed Biodiesel Production Processes." *Energy Conversion and Management* 84 (August): 405–13. https://doi.org/10.1016/J.ENCONMAN.2014.04.044.

Tran, Nghiep Nam, Marina Tišma, Sandra Budžaki, Edward J. McMurchie, Olivia Maria Morales Gonzalez, Volker Hessel, and Yung Ngothai. 2018. "Scale-up and Economic Analysis of Biodiesel Production from Recycled Grease Trap Waste." *Applied Energy* 229 (November): 142–50. https://doi.org/10.1016/J.APENERGY.2018.07.106.

VITO. 2010a. "Activated Sludge Systems | EMIS." 2010. https://emis.vito.be/nl/bbt/bbt-tools/selectiesystemen/wass/technieken/actief-slib-systemen.

———. 2010b. "Buffer Tanks | EMIS." 2010. https://emis.vito.be/en/bat/tools-overview/sheets/buffer-tanks.

Wupperverband. 2019. "Designing Value Chains for Carbon Based Elements from Wastewater - State of the Art Report." Wuppertal, Germany.

———. 2020. "Designing Value Chains for Carbon Based Elements from Sewage - Market Potential Study." Wuppertal, Germany.

Yusuf, N. N.A.N., and S. K. Kamarudin. 2013. "Techno-Economic Analysis of Biodiesel Production from Jatropha Curcas via a Supercritical Methanol Process." *Energy Conversion and Management* 75

(November): 710–17. https://doi.org/10.1016/J.ENCONMAN.2013.08.017.

Project partners

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