TECHNO-ECONOMIC ASSESSMENT OF AN INTEGRATED ALGAL BIOREFINERY

by

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TECHNO-ECONOMIC ASSESSMENT OF AN INTEGRATED ALGAL BIOREFINERY

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In dedication to my beloved parents
who have been my source of inspiration, strength and support.

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ABSTRACT

TECHNO-ECONOMIC ASSESSMENT OF AN INTEGRATED ALGAL BIOREFINERY

There is an urgent global need to access sustainable energy sources as the supply-demand imbalance of non-renewable energy resources is one of the most critical issues of humankind. All alternate solutions offered to replace fossil-based non-renewables must be both economically viable and environmentally sustainable. In this respect, techno-economic assessments play crucial roles in achieving economic viability while covering the whole production pipeline of the offered product. Algae-based biofuels are strong candidates compared to other biofuels concerning their higher biomass yield, shorter growth cycle and the capability of year-round cultivation in marine and brackish water. Despite these advantages, high energy requirements and costly equipment increase both capital and operational expenses, weakening the viability of commercialization of algae-based biofuels. To address this issue, integrated algal biorefineries have become prominent; implementing production of multi-valorized, value-added products, while optimizing the usage of resources from different feedstocks. To assess the viability, this study conducts a techno-economic assessment of a full-scale carbon-negative integrated algal biorefinery for bio-jet fuel, astaxanthin, beta-carotene and Spirulina powder production. Viable prices for bio-jet fuel commercialization were calculated to be 3.227-9.011$/ton for 50 % blend (with commercial Jet A-1 fuel), 866-1.444$/ton for 5 % blend, 656-771$/ton for 1 % blend without carbon credit. With the addition of carbon credit, the prices were found to decrease to 3.199-8.807$/ton for 50 % blend, 838-1.240$/ton for 5 % blend and 567-628$/ton for 1 % blend. Minimum viable prices for astaxanthin, beta-carotene and Spirulina powder were calculated as 850$/kg, 43,50$/kg, and 307$/kg, respectively.

ÖZET

ENTEGRE ALG BİYORAFİNERİSİNİN TEKNO-EKONOMİK ANALİZİ

Yenilenemeyen enerji kaynaklarının arz-talep dengesizliği insanlığın en kritik sorunlarından biri olup, sürdürülebilir enerji kaynaklarına erişim sağlanması küresel ölçekte acil bir ihtiyaçtır. Fosil tabanlı yenilenemeyen kaynakların yerini almak için sunulan tüm alternatif çözümler hem ekonomik olarak uygulanabilir hem de çevresel olarak sürdürülebilir olmalıdır. Bu bağlamda, tekno-ekonomik analizler, sunulan ürünün tüm üretim hattını kapsamakta ve ekonomik uygulanabilirliğin sağlanmasında önemli rol oynamaktadır. Yosun bazlı biyoyakıtlar, daha yüksek biyokütle verimi, daha kısa büyüme döngüsü, tuzlu veya acı sularda yıl boyunca yetiştirilme olanakları açısından diğer biyoyakıtlara kıyasla güçlü adaylardır. Bu avantajlara rağmen, yüksek enerji ve pahalı ekipman gereksinimleri hem sermaye hem de işletme giderlerini artırarak yosun bazlı biyoyakıtların ticarileştirilmesinin uygulanabilirliğini zayıflatır. Bu sorunu çözmek için strateji olarak entegre alg biyorafinerileri öne çıkmaktadır. Entegre biyorafinerilerde farklı hammaddelerden gelen kaynakların kullanımı optimize edilmekte ve yüksek katma değerli ürünler üretilmektedir. Bu çalışma, biyo-jet yakıtı, astaksantin, beta-karoten ve Spirulina tozu üretmekte olan tam ölçekli, karbon negatif, entegre bir alg biyorafinerisinin uygulanabilirliğini değerlendirmek amacı ile tekno-ekonomik analizini kapsamaktadır. Biyojet yakıtının ticarileştirilmesi için karbon kredisi içermeyen uygulanabilir fiyatlar % 50 harman (ticari Jet A-1 yakıtı ile) için 3.227-9.011$/ton, % 5 harman için 866-1.444$/ton ve % 1 harman için 656-771$/ton olarak hesaplanmıştır. Karbon kredisi ilavesiyle birlikte fiyatlar % 50 harman için 3.199-8.807$/ton, % 5 harman için 838-1.240$/ton ve % 1 harman için 567-628$/ton'a düşmektedir. Astaksantin, beta-karoten ve Spirulina tozu için minimum geçerli fiyatlar ise sırasıyla 850$/kg, 43,50$/kg ve 307$/kg olarak hesaplanmıştır.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	Explanation	Unit
A	Annual Cost for Payback of the Investment	$
a	Annuity Factor	
Afdw	Ash Free Dry Weight	mg
ASTM	American Society for Testing Materials	
B_{tot}	Total Benefit	$
CAPEX	Capital Expenditure	$
CCMP	Culture Collection of Marine Phytoplankton	
C_{inv}	Total Capital Cost of the Investment	$
C_{op}	Total Operating Cost of the Facility	$
C_{tot}	Total Cost	$
d	Discount Rate	
DHA	Docosahexaenoic Acid	
DOC	Direct Operating Cost	$
EPA	Eicosapentaenoic Acid	
FCI	Fixed Capital Investment	$
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene	
GHG	Greenhouse Gas	
HEFA	Hydroprocessed Esters and Fatty Acids	
HEFA-HRJ	Hydroprocessed Esters and Fatty Acids Hydrotreated Renewable Jet	
HEFA-SPK	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic kerosene	
HTL	Hydrothermal Liquefaction	

I	Total Investment Cost	$
i_a	Annual Administrative Cost	$
IATA	International Air Transport Association	
IC	Total Indirect Cost	$
IEA	International Energy Agency	
i_i	Periodical Cost for Infrastructure, Building (given as annual)	$
IRR	Internal Rate of Return	
L	Lipid wt%	
MB3N	Modified Bold 3N	
MFSP	Minimum Fuel Selling Price	$
N	Project Period	year
NPV	Net Present Value	$
O	Operational Cost	$
O_l	Labor Cost	$
O_m	Maintenance Cost	$
O_o	Other Operational Costs	$
OPEX	Operational Expenditure	$
ORP	Open Raceway Pond	
O_u	Utilities Cost	$
P	Interest Rate	
PBR	Photobioreactor	
PE	Purchased Equipment	$
PUFA	Polyunsaturated Fatty Acids	
q	Inflation Rate	
r	Annual Result of Cost-Benefit Assessment	$
ROI	Return on Investment	
SAG	The Culture Collection of Algae at the University of Göttingen, Germany	
T	Technical Lifetime	year
TC	Total Carbohydrate	g
TDC	Total Direct Cost	$
TEA	Techno-Economic Assessment	

TIC	Total Installed Cost	$
TL	Total Lipid	g
TP	Total Protein	g
UTEX	University of Texas	

1. INTRODUCTION

The global increase in population and continued usage of non-renewable sources such as petroleum-based transportation fuels create an urgent need for rapid progress and implementation of large-scale sustainable alternatives. Ever-increasing usage of limited resources led to circular economy to be offered as a solution to overcome some of the existing consumption and production demands. Incorporated with the biorefinery approach, sustainable ways of producing multiple bioproducts from biomass feedstock through relevant conversion techniques are possible within the bioproduct-based circular economy framework.

In a bioproduct-based economy, biomass resources are utilized for the production of energy, fuel, plastics, food and feed along with other high-value products (U.S. Energy Information Administration, 2013). Recently, numerous scientific research studies are directed on the production of biofuels from biomass feedstocks (Vertés et al., 2010; Gaurav et al., 2017).

Microalgae, considered as third-generation biomass feedstock, offer a viable alternative for the production of liquid drop-in biofuels and other value-added bioproducts due to their higher efficiency, biomass productivity and yield, and independence on arable lands compared to other energy crops. In addition to these operational advantages, algal biomass comprises various components to be extracted and processed as bioproducts, such as food components, supplements, nutraceuticals, cosmetics, bioplastics, and biofertilizers. Although utilization of microalgae biomass has gained acceleration during the last years, its commercialization is hindered by several economic constraints.

Particularly, high production costs caused by the intensive energy requirements during biomass harvesting are one of the main components that affect the economic viability of the algal biotechnology field. Accordingly, algae-based production of bioproducts is reconstructed under the circular economy concept and the integrated biorefinery approach, where multiple products besides biofuels are produced, residual biomass is utilized, and the amount of overall waste is minimized (Thomassen et al., 2016). Although the environmental sustainability of algal biomass is well-established, techno-economic assessments (TEA) are performed to prove economic viability and provide guidelines for the realization of large-scale integrated biorefineries.

1.1. Integrated Biorefinery Concept

The integrated biorefinery concept is defined as “the sustainable processing of biomass into a spectrum of marketable products and energy” (IEA Bioenergy Task 42, 2007; Triverdi et al., 2015). The main focus of the concept is to maximize the utilization of biomass and to minimize the waste material and emissions from the conversion of bioenergy products by maximizing the recovery of energy and material. The algal biorefinery concept integrates the production of high-value products, biofuels and bioenergy while optimizing the use of resources from different feedstocks. In addition, the concept maximizes efficiency, profitability and benefits while minimizing the environmental impact such as greenhouse gas (GHG) emissions and overall ecological footprint by adopting the zero-waste principle. As an example, after extracting primary products such as lipids for biofuel applications, the remaining residual algal biomass can be used as animal feed, biofertilizer, or influent for anaerobic digestion processes to generate biogas. To capture the full potential of an integrated biorefinery, it is essential to optimize the combination of biomass feedstocks and products along with by-products. In a biorefinery, different biomass feedstocks undergo different production routes and are converted into a wide spectrum of bio-based products meeting the demand as a sustainable substitute in the market. In addition, integrating high-value products to the product range increases the chances to be able to become a viable substitute, and compete with the prices of the non-bio-based products by increasing the market value and compensating the high operational costs.

The most important barrier between algal biorefineries and the commercialization of its bio-based products is the high operational expenses (OPEX) (Acien et al., 2012; Taylor et al., 2013; Brownbridge et al., 2014; Barlow et al., 2016; Dong et al., 2016; Giwa et al., 2016). Harvesting and processing of microorganisms such as microalgae require high energy demand which eventually leads to higher upstream costs and creates obstacles for the viability of algal biorefineries. Another major problem emerges when the energy required for the conversion processes is supplied by fossil fuels leading to increases in the amount of GHG emissions. Though biorefineries aim to eliminate the fossil economy by being environmentally sustainable, they are not always economically feasible.

To address these challenges, this thesis study focuses on a large-scale algal biorefinery built at Boğaziçi University Sarıtepe Campus (located in Kilyos, Istanbul, Turkey). The biorefinery, operates under Istanbul Microalgae Biotechnologies Research and Development Unit (IMBIYOTAB), uses the integrated biorefinery concept and produces multiple value-added bioproducts along with bio-jet fuel to be blended with commercial Jet A-1. Uniquely, the power requirements for the biorefinery

operations are supplied by renewable energy generated by the wind turbine located within the university campus, making the production process thoroughly sustainable.

1.2. Istanbul Microalgae Biotechnologies Research and Development Unit

The TEA in this study has been conducted through Istanbul Microalgae Biotechnologies Research and Development Center (IMBIYOTAB), being one of the pioneering research and development (R&D) centers in algal biotechnology in Turkey, aiming to expand usage of algae as sustainable bio-based feedstock in food, health, energy, agricultural and environmental sectors. IMBIYOTAB (presented in Figure 1.1) conducts high throughput systems biology-based analyses including genomic, transcriptomic, metabolic and proteomic characterization on several different algae species to develop high-value bioproducts and applications on various algae species for above-mentioned sectors.



Figure 1.1. IMBIYOTAB biorefinery facility, Istanbul, Turkey.

It is an indispensable requirement that the solutions found and the products produced are environmentally sustainable as well as economically viable. IMBIYOTAB provides high-quality, reproducible data to develop algal feedstock as environmentally sustainable and economically feasible solutions for food, water, and energy issues. The development of high-value commodity products from algal biomass through high-technology to contribute to the planetary resources is the top priority of IMBIYOTAB. Techno-economic assessment plays a crucial role to be able to fulfill these goals and create accessible solutions.

IMBIYOTAB facilities consist of a dedicated R&D center, algal biomass cultivation and biomass processing in a biorefinery concept. Algal biomass is produced with 80.000 L-capacity outdoor open raceway ponds (ORP), in addition to 30.000 L of indoor photobioreactor (PBR) (presented in Figure 1.2) capacity totaling approximately 2.400 tons/year wet algae processing capacity. Open raceway ponds consist of 4 types of ponds as 100L, 1.000L, 10.000 L and 15.000 L (presented in Figure 1.3).



Figure 1.2. Photobioreactors and downstream processing equipment at IMBIYOTAB.



Figure 1.3. Open raceway ponds at IMBIYOTAB.

The R&D center mainly works on improving algae usage in energy, food and health sectors for a sustainable future. The R&D center and laboratory work collaboratively on designating optimal strains and conditions for algae to be used in these sectors. The product range of IMBIYOTAB and the most common products produced within IMBIYOTAB with their estimated market values and global market volumes are presented in Figure 1.4. and Table 1.1 respectively.

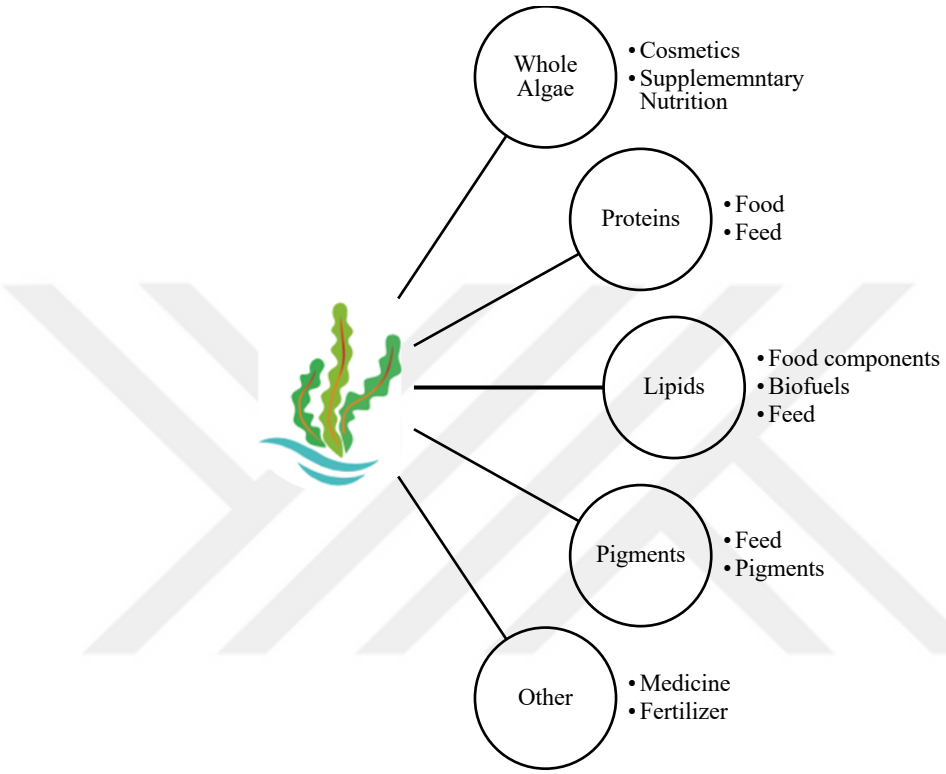


Figure 1.4. Algae-based biorefinery product applications (adopted from Slegers et al., 2013).

Table 1.1. Estimated market prices and global volumes of algae-based products.

Product	**Market price**	**Global market volume (Million $)**
Astaxanthin	4.840-12.555,5 $/kg	60.500
Omega-3 fatty acids	699,3-1.300 $/kg	3.993
Spirulina	140 $/kg	394
Beta-carotene	35-65,5 $/kg	605
Bio-jet fuel	629,2 $/ton	66
Bio-methane	0,5 $/m3	3.146
Biofertilizer	600-1.000 $/ton	2.420
Fish and shellfish feed	1.149,5 $/ton	121
Cattle feed	314,6 $/ton	72.600

While developing solutions for sustainability, IMBIYOTAB also focuses on the sustainability of the production. The electricity used within the facility is supplied by the wind turbine installed on campus (presented in Figure 1.5) allowing renewable energy to be utilized year-round. With the 1 MW wind turbine, 140% of the annual electricity consumption of the campus is covered, in addition to saving approximately 900 tons of carbon and 1.000.000 kWh of energy.



Figure 1.5. Wind turbine in the facility.

In addition, IMBIYOTAB aims to establish carbon-negative production by the carbon dioxide captured through algal photosynthesis. Below, Figure 1.6 is a scheme of the general layout of IMBIYOTAB.

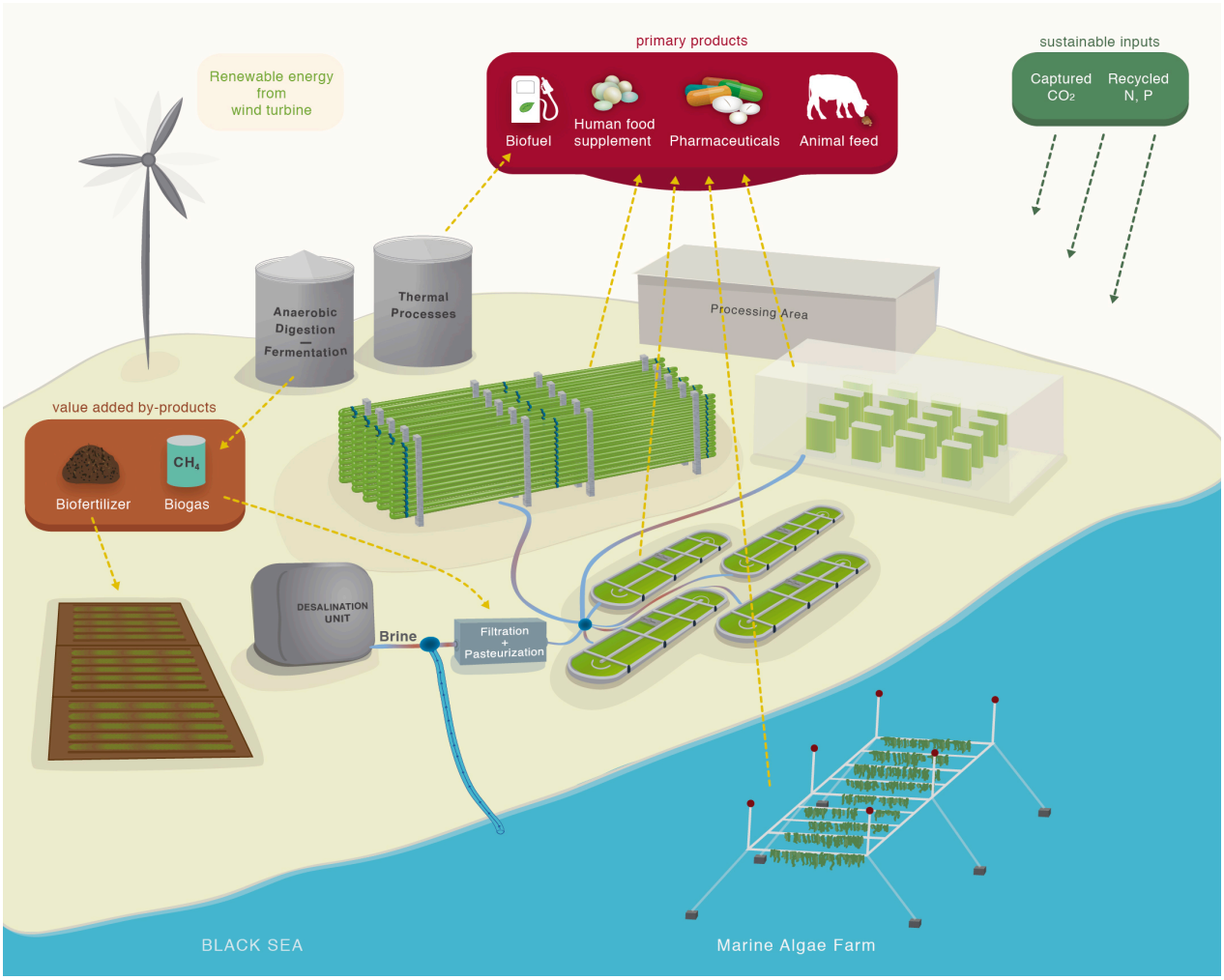


Figure 1.6. Carbon negative integrated algae biorefinery concept of IMBIYOTAB.

1.3. Conversion of Biomass to Bioproducts

The feasibility of an algal biorefinery depends on the entire processes of the algae cradle-to-gate, which includes cultivation, harvesting, and conversion to main products and by-products. The processes starting from the very beginning up to the production of the main ingredient of the product, in this case wet algal biomass, are referred to as upstream processes and the processes from harvesting of the algae up to the final product, for example algae oil, are referred as downstream processes of algae oil production. The components obtained from the downstream processes are then processed to form the final products; bio-jet fuel, astaxanthin, beta-carotene, Spirulina powder, and, the residual biomass utilized as by-products.

1.3.1. Upstream Processes

1.3.1.1. Research and Development. Algae with more than 70,000 species outspread worldwide have extensive biodiversity along with their high-efficiency photosynthesis and carbon absorption capacities (Eberhard et al., 2008; Lin et al., 2014). About 300 of these species can accumulate high oil contents and are subject to R&D studies for biofuel production (Sheehan et al., 2016). R&D processes to improve biomass productivity and yield before production are the key points of integrated biorefineries. During R&D, specialists focus on strain/species research, selection of suitable species for the geographical conditions and optimization of the species.

The species used in this study, in line with literature and experience gained in microalgae biotechnology within the IMBIYOTAB at Boğaziçi University, were selected according to the suitable lipid accumulation rates by applying system biology tools, optimization and up-scaling studies for the final product bio-jet fuel.

1.3.1.2. Species Cultivation. Each microalga species has optimal growth conditions and requires specific culture media to support their optimal growth. In addition, each species contains different amounts of lipids, proteins and carbohydrates. Although the amounts of components mostly depend on the species of the microalgae, cultivation conditions such as nutrients, gas supply, pH, temperature and light play a great role.

For species cultivation, cultures are prepared with certain recipes and optimal abiotic parameters such as lighting, temperature, pH, dissolved oxygen level and carbon dioxide level. The cultivation could be carried in various forms of reactors. In IMBIYOTAB, species are cultivated in ORPs and PBRs in accordance with the requirements of the species and the final products. The chosen species to be processed to produce various products, their strain numbers and the media to be cultivated in are listed in Table 1.2 below.

1.3.1.2.1. Open Raceway Pond. Commercial-scale microalgae productions are mostly carried in open raceway ORPs and PBRs. ORPs are the cheapest and simplest cultivation systems used for algae production generally for bulk, lower-value applications. A schematic representation of algae processing in ORP is presented in Figure 1.7 below. The cost of investment for these systems ranges from 0,13 to 0,37 (M€/ha) at 100 ha scale where 1.000 to 5.000 m^2 reactors are used for commercial scale. These reactors are operated with a concentration of 0,5g/L for ensuring the penetration of light

through the water which makes the harvesting process more difficult (Fernandez et al., 2013). ORP yields less amounts of microalgal biomass (1-5 g/L) compared with other bioreactors. Although ORPs are simple and cheaper, the reactors carry the risk of contamination with the excreta of birds or any foreign materials that could fall into the ponds and are susceptible to other microorganisms, such as weedy species, grazers and predators. Thus, these reactors are only suitable for a strain of microalgae that are tolerant to robust conditions and have low risk to culture collapse (Fernandez et al., 2013).

Table 1.2. Species to be cultivated, their strain numbers, reactors and medias to be cultivated in.

Species	Strain #	Class	Reactor	Liquid Medium
Ettlia oleoabundans	UTEX 1185	Green microalgae	ORP	Modified Bold 3
Nannochloropsis gaditana	CCMP 526/11	Eustigmatophyceae	ORP	F/2
Botryoccoccus braunii	UTEX 572	Green microalgae	ORP	Modified Bold 3N
Chlamydomonas nivalis	UTEX 2824	Green microalgae	ORP	Bold 1NV
Dunaliella salina	UTEX 1644	Green microalgae	PBR	2X Erdschreiber's Medium
Dunaliella tertiolecta	UTEX 999	Green microalgae	PBR	Erdschreiber's Medium
Arthrospira maxima	SAG 8479	Cyanobacteria	PBR	Spir
Arthrospira platensis	SAG 8579	Cyanobacteria	PBR	Enriched seawater
Haematococcus pluvialis	UTEX 2505	Green microalgae	PBR	MES-Volvox Medium

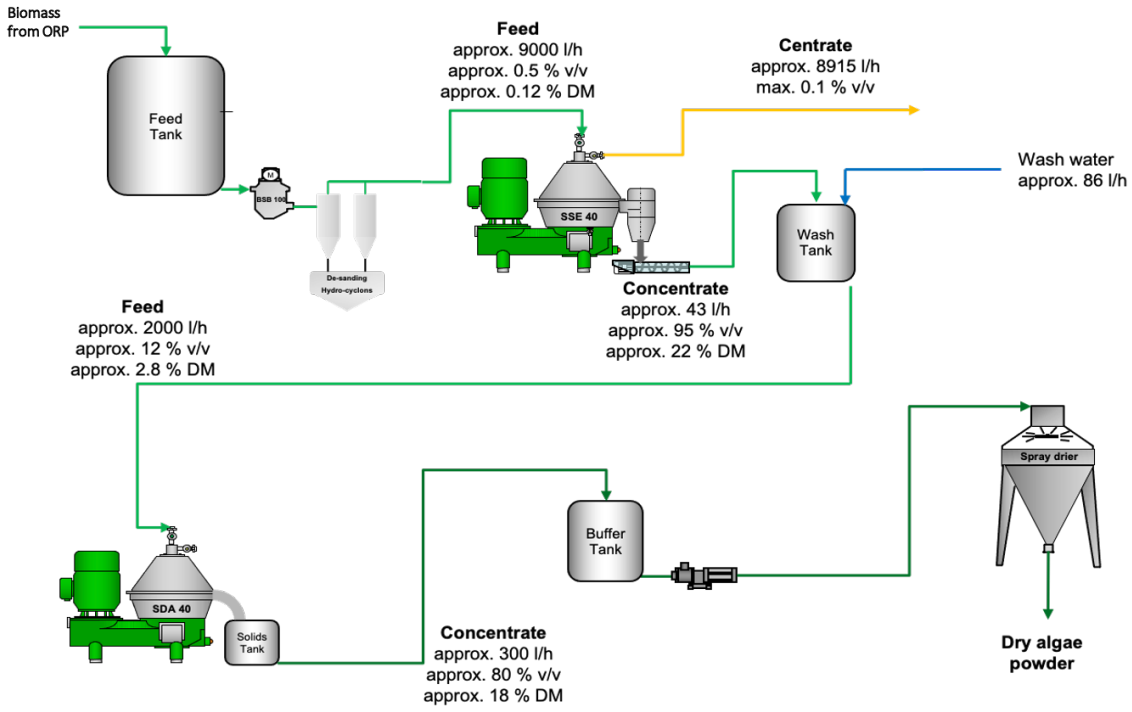


Figure 1.7. Algae processing in open raceway pond (ORP) system at IMBIYOTAB.

1.3.1.2.2. Photobioreactors. Photobioreactors, generally in the form of horizontal or vertical transparent tubulars or thin panels, are the most common types of closed reactors used for commercial-scale microalgae production. They are more complex in design and operationally costlier compared to ORPs; yet provide better process control, and less culture contamination risks. Most of their operating cost is due to the high energy requirements for pumping and circulation. PBRs are suitable for working with high biomass concentrations and yield higher microalgal biomass (5-15 g/L) inversely proportional to the diameters of tubulars (Fernandez et al., 2013). A schematic representation of algae processing in PBR is presented in Figure 1.8 below.

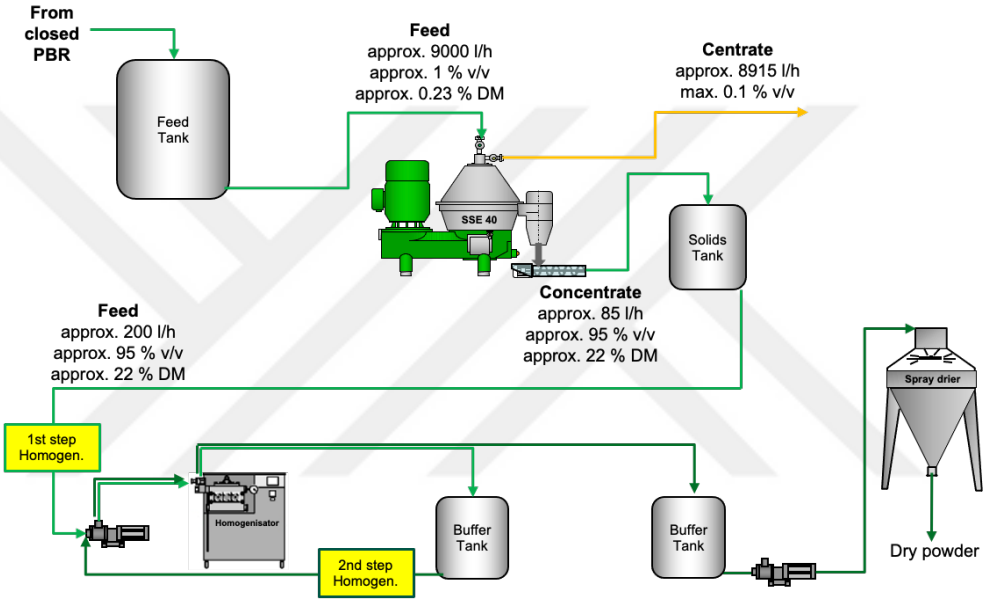


Figure 1.8. Algae processing closed photo-bio-reactor (PBR) at IMBIYOTAB.

The productivity of ORP reactors is found to be highly dependent on cultivated strain, climatic variations, air supply, dissolved oxygen, and possible contaminants. In addition, carbon dioxide, water and nutrient availability, such as nitrogen and phosphorus, are crucial for commercial-scale microalgae production; and will act as limiting factors if not supplied sufficiently. On the other hand, land requirements are to the minimum since algae do not require arable land, however, land selection directly affects water requirements (Batan et al., 2013; Davis et al., 2014). Thus, even though land availability does not pose direct limitations, the selected land should have available water resources and evaporation rates should be considered (Nogueira et al., 2018). When open reactors and closed reactors are compared, ORPs require huge amounts of water compared to PBRs due to the water lost to evaporation. Thus, water requirement could be a limiting factor for open reactors (Yang et al., 2011). In addition, temperatures between 20-30 °C are found to be optimal where high irradiance is important as long as photoinhibition is avoided (Fernandez et al., 2013).

1.3.2. Downstream Processes

1.3.2.1. Harvesting and Dewatering. Downstream processes start with the harvesting and dewatering of the algal biomass. When harvesting, the residual media in ORPs are preserved for possible reuse to reduce the water footprint. Each media is considered reusable at least 1-2 times after the nutrients are replenished. During dewatering, the watery and dilute body of algae generate a huge operating expense, making the production of algae-based fuels less economically viable (Uduman et al., 2010). Harvesting and dewatering of microalgae could be done by several methods. Dissolved air flotation (DAF) is one of the cheaper solid-liquid separation methods where algal biomass is floated to surface by generating micro-air bubbles with an air saturator and then skimmed/collected from the surface. Sedimentation/flocculation is another method where 75-95 % of the water could be removed (Chatsungnoen and Chisti, 2016). A coagulant is added to the algal biomass to flocculate small algae particles into big flocs and sink to the bottom of the tank, where then they are collected. Filtration is another method to remove algae from the media, but it is more efficient for large algae such as *Arthrospira* species. A more energy-intensive yet effective water removal method is centrifugation. 80-90 % of algal biomass could be recovered via centrifugation (Najjar and Abu-Shamleh, 2020). At IMBIYOTAB facility, harvesting and dewatering of the algal biomass is achieved by centrifugation.

1.3.2.2. Extraction and Conversion to Bioproducts. After harvesting and dewatering of algae, the obtained "algal cake" moves to the homogenization and extraction step. This stage varies according to the base ingredient of the main product to be produced. For an oil-based product, such as biofuel, the algal cake goes through lipid extraction, later to be used for the main product. The residual biomass, with protein and carbohydrate components, is then processed for the extraction again accordingly for the predetermined by-product/s. Figure 1.9 represents the general process flow of the algae extraction process.

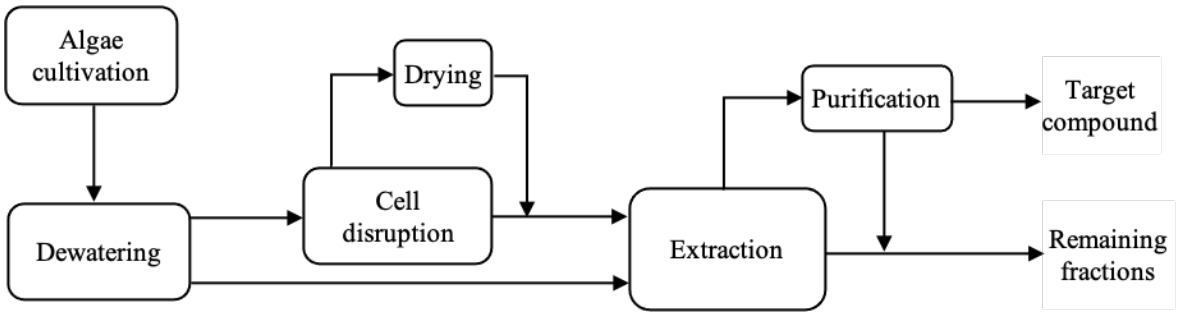


Figure 1.9. General process flow diagram of an algae extraction process (adopted from Bastiaens et al., 2017).

For conversion of algae to bio-jet fuels, only certain methods have been approved by ASTM-International. These methods are Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK), hydroprocessed esters and fatty acids synthetic paraffinic kerosene (HEFA-SPK) and hydroprocessed esters and fatty acids hydrotreated renewable jet (HEFA-HRJ) (Wang and Tao, 2016). Below in Figure 1.10 are further information about the conversion technologies. Biofuels obtained from these methods are blended with Jet A-1 in a ratio of up to 50 % and produced for use in the civil aviation industry. In this project, the HEFA-SFK method will be used and the bio-jet fuel obtained will be mixed at a specified rate, in accordance with the regulations of IATA, to be used in civil aviation flights. HEFA-jet fuel compared with conventional jet fuel, has similar characteristics with an advantage of higher cetane number, lower freezing point and lower GHG emissions (Pearlson, 2011). Further information about the properties of the comparison of commercial jet fuel and bio-jet fuel is presented in Chapter 5.

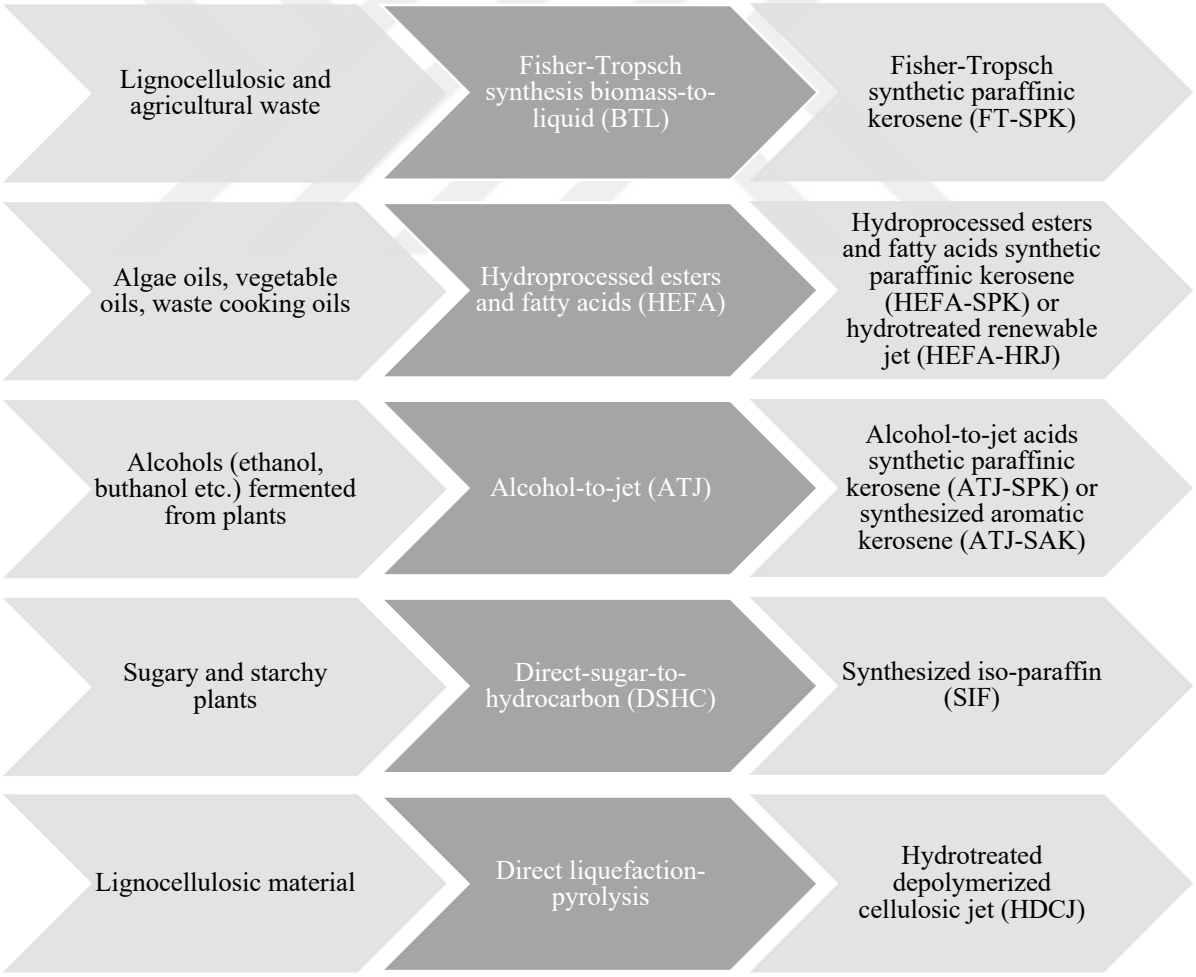


Figure 1.10. Conversion of biomasses to alternative biofuel by various technologies: Fisher-Tropsch biomass-to-liquid (BTL), hydrogeneration (HEFA), alcohol-to-jet (ATJ), direct liquefaction-pyrolysis.

2. LITERATURE REVIEW

2.1. Algal Extracts

The share of biomass in clean energy production has started to gain acceleration due to its positive effect on the carbon dioxide cycle and high conversion value to biofuels (Jose and Bhaskar, 2015). Although algal biomass is considered to be suitable for biofuel production, performance of the current production and prices are not enough that it can compete with traditional fossil fuel sources (Richardson et al., 2010; Acien et al., 2012). Nevertheless, microalgae-based biofuels stand out as an option to provide sustainable energy for the increasing demands of transportation sector. One of the most distinct obstacles restraining microalgae-based biofuels from being commercially produced is their cost, which is expected to decrease with the adoption of the integrated biorefinery approach and large-scale production (Das, 2015).

Valuable compounds are more difficult to extract from microalgae compared to other biomass resources. The complex polysaccharide layers provide structural rigidity and resistance to extraction. Therefore, pretreatment steps might be required to extract these compounds (Halim et al., 2012; Bastiaens et al., 2017). The main and minor compounds to be extracted are presented below in Table 2.1. In addition to the pathway to the extraction, additional unit operations such as freeze-drying could be required for a better yield in algal extracts.

Table 2.1. Overview of marketable algae compounds (adopted from Bastiaens et al., 2017; Cardozo et al., 2007; Khan and Rashmi, 2010; Michalak and Chojnacka, 2014).

Bulk/Main Components	
Proteins (6-71 % dw)	Functional peptides
Lipids (2-22 % dw)	Glycerides, Polar lipids, Essential lipids
Carbohydrate (8-69 % ds)	Polysaccharides, Starch
Minor Components	
Carotenoids	Astaxanthin, Beta-carotene, Lutein, Zeaxanthin, etc.
Other antioxidants	Polyphenols, etc.
Polyunsaturated fatty acids (PUFAs)	DHA, EPA
Vitamins	
Others	Minerals,Toxins

2.2. Valorization of Algae-Based Products

Algal biomass can be processed for the production of several valuable biocompounds. The biorefinery takes an approach to fraction these compounds to obtain multiple marketable products and to valorize the compounds optimally (Gouveia et al., 2014; Bastiaens et al., 2017). By-products produced from the residual biomass generate additional benefits and are a key aspect for the viability and commercialization of algae-based products. Hariskos and Posten (2014) categorize the production pathways based on the values of the products marketed. Pathway 1 includes low-value products, such as energy where oils are the main target compound, with value-added by-products from the residual compounds. Category 1 applications generally contain extraction of algal oils and conversion to biofuels which are respectively low-valued amongst the algal products such as aviation fuels, biohydrogen and bioethanol. After the extraction of algal oils, the remaining fraction of protein and carbohydrate components are processed for conversion to various value-added products such as animal feed and biofertilizer (Maurya et al., 2016). Market prices of the most common algal products are presented in Figure 2.1.

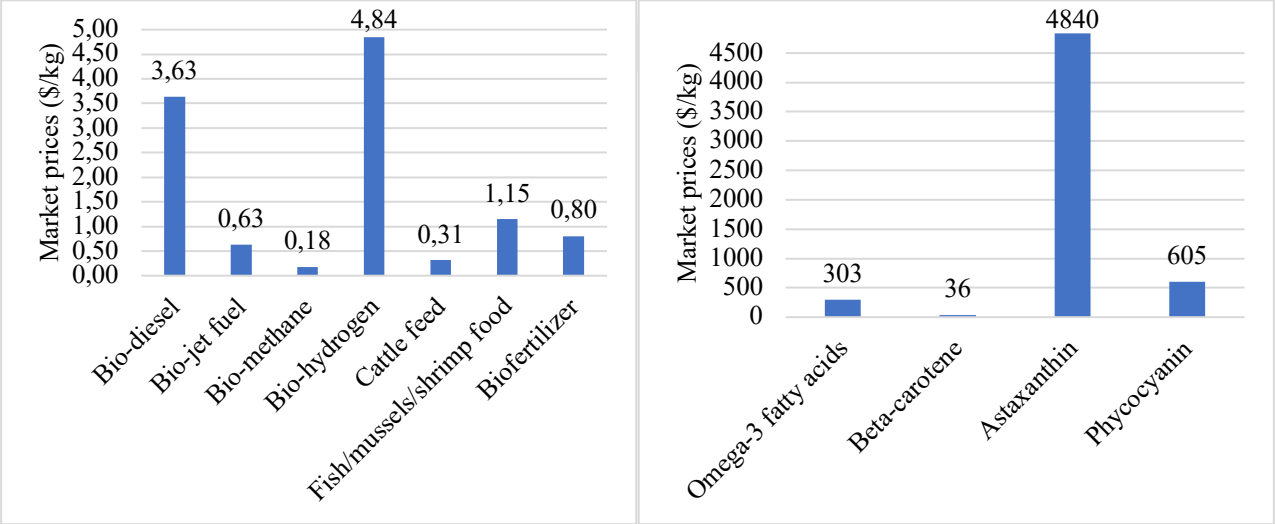


Figure 2.1. Market prices of algal products.

Pathway 2 involves bulk production of medium-value products (market volume more than 10.000 tons/year) combined with the value-added by-products from the residual compounds (Wijffels et al., 2010; Hariskos and Posten, 2014; Bastiaens et al., 2017). Polyunsaturated fatty acids (PUFAs), which could be used as food supplements, cosmetic industry and polymers are some of the examples of medium-value products in Pathway 2 (Spolaore et al., 2006; Cardozo et al., 2007). The remaining protein compound is suitable to serve as food additives for humans as well as additives to animal feed

while the remaining carbohydrates could be used for the production of cosmetics and pharmaceuticals (Bastiaens et al., 2017).

Pathway 3 includes the production of high-value products (mostly higher than 120$/kg) and valorization of the remaining fraction by production of by-products for viability purposes under an integrated biorefinery approach. The high-value products, such as beta-carotene, astaxanthin and omega-3 fatty acids EPA and DHA, are targeted through cosmetics, pharmaceuticals and nutraceuticals (Cuellar-Bermundez et al., 2015; Bastiaens et al., 2017). High-value products are mostly obtained from a small fraction of the compounds and leave great amounts of residual biomass to be valorized by converting into energy, fertilizer, or animal feed (Bastiaens et al., 2017).

Most of the studies in the literature focus on producing bioenergy products under the scope of Pathways 1 and 3 while there are no economic studies for Pathway 2 since the commercialization and bulk production of algal products are found to be non-viable. As in the integrated biorefinery discussed within this study, the production of high-value algal products with a combination of by-products and the worldwide adoption of the integrated biorefinery approach is expected to allow commercialization of algae-based products.

2.3. Techno-Economic Assessment

The optimal valorization being the key, the R&D step including proper selection of species and the production of algae for the targeted compound with a proper TEA carries crucial importance. The use of TEA to evaluate various production technologies, pathways and various product combinations is on the trendline since 2010 (Van Dael et al., 2013; Van Dael et al., 2014). Although TEA is a recognized term, the methodology for TEA is not constant. Almost every study in the literature uses different methods, different assumptions, different parameters for the same objective (Thomassen et al., 2017). Van Dael et al. (2014) uses TEA to optimized the production pathway of a biorefinery by evaluating various production technologies, maximizing the economic viability. Many studies (Thomassen et al., 2016; Giwa et al., 2018; Ortiz, 2020) use detailed economic evaluation to assess the investment and return of the investment with parameters such as net present value (NPV), internal rate of return (IRR) whilst some only consider lipid production costs (Acien et al., 2012; Taylor et al., 2013; Cheali et al., 2016; Bastiaens et al., 2017).

Thomassen et al. (2016) assessed the viability potential of four different production scenarios of a multi-product algal-based biorefinery producing 170 tons/year of dry algae following the methodology from Van Dael et al. (2014). The assessed multi-products were carotenoids as the main product and fertilizer from the residual biomass as the by-product. As presented in Table 2.2, Scenarios 1 and 2 were used for conventional and intermediate technology with recycling of media respectively with an open pond cultivation system. Scenario 3 used advanced technology, PBR, for cultivation. Scenarios 1, 2 and 3 used *Dunaliella salina* while scenario 4 used *Haematococcus pluvialis* combined with the same technologies as in scenario 3. Scenario 4 was already admitted to be economically viable for commercialization and was included as a comparison agent. The market study, process flow diagram and economic assessment steps were followed and the following results were obtained as shown in Table 2.2.

Table 2.2. Results of economic assessment for Scenarios (adopted from Thomassen et al., 2016).

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Investment costs (EUR)	11.223.432	10.748.522	43.139.268	46.146.384
Operational costs (EUR/year)	13.340.596	7.936.666	13.256.184	13.733.012
Revenues (EUR/year)	16.746.464	16.746.464	16.746.464	22.119.970
Net present value (EUR)	8.706.878	36.995.517	-13.771.402	8.347.261

The main components of the investment cost, operational cost and revenues are presented in Table 2.3. Due to the ORP cultivations in scenarios 1 and 2, the NPV were found to be positive, indicating viability. The media recycling carried in scenario 2 resulted in the lowest operational cost leading to the highest NPV of all scenarios, making the ORP cultivation with medium-recycling the most viable scenario of this study. PBRs used in scenarios 3 and 4 caused high investment costs and high operational costs due to energy requirements. As a result, the cultivation of *Dunaliella salina* in the ORP system with media recycling for beta-carotene and fertilizer was found to be suitable for large-scale production.

From a different perspective to the investment cost, Brown and Brown (2013) adopts the methods of Peters et al. (2002) and presents a simplified methodology for estimating the fixed capital investment through the total purchased equipment cost. The percentages to estimate the total capital investment through the equipment cost are presented below in Table 2.4.

Table 2.3. Main components of costs and revenues of TEA (adopted from Thomassen et al., 2016).

Investment costs	Equipment (liners, mixers, paddlewheels, centrifuge etc.) Landscaping Reactors (ORP, PBR), Inoculum production system, medium preparation unit, carbon dioxide supply unit Airconditioning, heat exchangers, air blowers) Installation (assumed 10 % of the total investment cost)
Operational costs	Salaries Salt, water, carbon dioxide, chemicals, nutrients
Revenues	Sales of main products (carotenoids: astaxanthin, beta-carotene) Sales of by-products (biofertilizer)

Table 2.4. Percentages for fixed capital investment estimation (adopted from Brown and Brown, 2013).

Parameter	**Factor**
Direct costs	
Purchased equipment, (PE)	100 %
Installation of purchased equipment	39 %
Instrumentation and controls	26 %
Piping	10 %
Electrical systems	31 %
Buildings (including services)	29 %
Landscaping, yard improvements	12 %
Service facilities	55 %
Total direct cost (TDC)	**302 %**
Indirect costs	
Engineering	32 %
Construction	34 %
Legal expenses and contractor fees	23 %
Contingencies	37 %
Total indirect cost (IC)	**126 %**
Fixed capital investment (FCI)	**428 %**

Although Brown and Brown (2013) conduct estimation with constants obtained from Peters et al. (2002), the factors of the parameters vary accordingly with the technology, species and other various conditions and, could not be used for critical evaluation.

Barlow and colleagues, who use a rotating algal biofilm reactor for cultivation and HTL technology for pilot and laboratory-scale biodiesel production, assessed the economic viability under

six different scenarios. Scenario 1 represents the baseline productivity (12 g afdw/m^2d) where scenarios 2, 3 and 4 represent mid-productivity (20 g afdw/m^2d) with small-scale production of approximately 1,000,000 liters of biodiesel. Scenarios 3 and 4 assess the effect of wastewater treatment, scenario 5 considers the 500 % scaling-up of the plant and scenario 6 represents the optimal productivity (30 g afdw/m^2d). The capital expenses (CAPEX) and operational expenses (OPEX) are assessed and the minimum selling prices of biodiesels from each scenario are evaluated and presented in Figure 2.2 below.

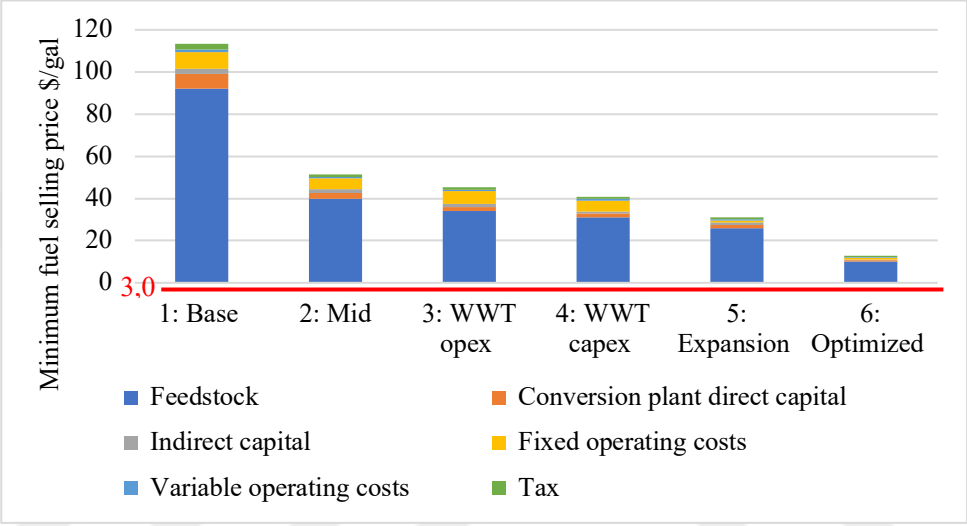


Figure 2.2. Minimum fuel selling prices (adopted from Barlow et al., 2016).

The overall results of the study indicated that the minimum selling price (MSP) of biodiesel exceeded the selling price of petroleum-based fuel in every scenario. Prices belonging to each aspect are presented below in Table 2.5.

Table 2.5. Price components of scenarios (adopted from Barlow et al., 2016).

$/Liter	**1: Base**	**2: Mid**	**3: WWT OPEX**	**4: WWT CAPEX**	**5: Expansion**	**6: Optimized**
Feedstock	24,34	10,58	8,99	8,20	6,88	2,65
Conversion plant direct capital	1,85	0,66	0,53	0,50	0,40	0,21
Indirect capital	0,66	0,53	0,40	0,26	0,26	0,08
Fixed operating costs	2,12	1,32	1,59	1,32	0,26	0,21
Variable operating costs	0,26	0,21	0,16	0,24	0,21	0,11
Tax	0,79	0,32	0,29	0,26	0,24	0,11
Total Cost	30,03	13,62	11,96	10,79	8,25	3,36

Prices presented above are calculated accordingly with the factors below in Table 2.6. As stated before, factors are not constant throughout literature and vary from study to study.

Table 2.6. Baseline economic inputs for analysis of algal cultivation and separation facility (values in millions of dollars) (adopted from Barlow et al., 2016).

Installed costs	Cultivation plant	61,6
	Separation plant	6,2
	Total installed cost (TIC)	**67,8**
Direct costs	Buildings (1 % TIC)	0,7
	Site development (9 % TIC)	6,1
Indirect costs	Prorated expenses (10 % TDC)	7,5
	Home office and construction fees (20 % TDC)	14,9
	Field expenses (10 % TDC)	7,5
	Project contingency (10 % TDC)	7,5
	Startup and permits (5 %) TDC	3,7
	Fixed capital investment (FCI)	**115,6**
	Working capital	5,8
	Land	1,4
	Total capital investment	**122,8**
Operating costs	Labor	0,3
	Overhead and maintenance	0,3
	Maintenance capital	2,0
	Insurance and taxes	0,8
	Field operating costs	3,4
	Electricity	1,1
	Total OPEX	**4,5**

Scenario 1, with the highest MSP, yields 104,31 $/gal (27.5 $/L) while scenario 2 yields 47,38 $/gal (12,5 $/L). In scenario 3, the displacement of wastewater treatment causes a decrease in the MSP with 45,70 $/gal (12 $/L) and 40,60 $/gal (10,7 $/L) in scenario 4. Scaling-up of the plant by 500 % in Scenario 5 results in 28,63 $/gal (7,5 $/L). In scenario 6 the optimal productivity yields an MSP of 11,90 $/gal (3 $/L). Although scenario 6 is optimized and reduced the MSP to 3 $/L, it is still far away from competing with the gasoline price of 0,8 $/L, requiring approximately a 300 % price reduction of scenario 6 (Barlow et al., 2016).

On the other hand, Taylor et al. (2013) assesses different conversion techniques applied to a carbon-neutral and self-supplying biorefinery by solar panels. The production processes were accepted to be carbon-negative due to the consumption of carbon dioxide during the growth of biomass and the use of concentrated solar power (CSP). Route 1 is based on gasification and Fisher-Tropsch where routes 2, 3 and 4 use transesterification technology for biodiesel production. Routes 3 and 4 differ from route 2 in the lipid's conversion phase.

Acien et al. (2012), Taylor et al. (2013) and Brownbridge et al. (2014) use the same Equation 2.1 below, to assess scaling-up opportunities:

$$C = C_{unit}\left(\frac{Q_{demand}}{Q_{unit}}\right)^{\phi} \quad (2.1)$$

where; C: cost, Q: capacity, ϕ: Economics of Scale Component (varies between 0.7-0.9 according to the type of plant)

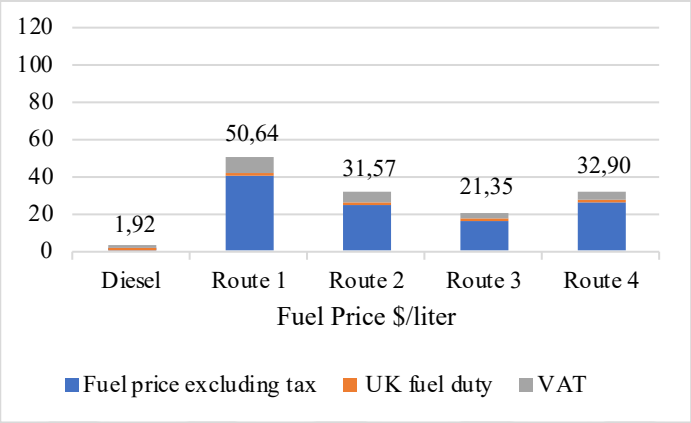


Figure 2.3. Fuel prices with respect to routes of scenarios (adopted from Taylor et al., 2013).

For consistency, the converted prices from £ to $ are presented in the Figure 2.3. Taylor et al. (2013) state that even though route 3 seems to have the lowest MSP, it is still more than 10 times bigger than the price of petroleum-based diesel in UK. Taylor and colleagues indicate that the greatest cost is caused by CSP by 34 % and the technology should be advanced in order to lower the MSP.

When the Economics of Scale Component is set to 0,7, the MSP decreases below the diesel selling price while when it is set to 0,9 it is 4,5 times the diesel selling price. This concludes that the viability of biofuels depends strongly on the scale of the production.

Setting the Economics of Scale Component to 0,8, Brownbridge et al. (2014) assesses the techno-economics of a plant using carbon dioxide from a power plant. CAPEX and OPEX of production of 1 kg biodiesel (2,6 kg dry wt algae with 30 wt% oil content) with a capacity of 10.000 ton/year are presented in Table 2.7 below.

Table 2.7. CAPEX and OPEX of production processes (adopted from Brownbridge et al., 2014).

Process	Feedstock	Products	Amount	CAPEX	OPEX
CSP		Electricity	30,3 MJ	0,28 $	0,11 $
PBR	CO_2		5,33 kg	1,4 $	1,15 $
	NH_3		0,26 kg		
	Electricity		28,8 MJ		
		Algae	2,61 kg		
Separation	Algae		2,61 kg	0,74 $	0,5 $
	Electricity		1,4 MJ		
		Algae oil	0,78 kg		
		Residue	1,83 kg		
Esterification	Algae oil		0,78 kg	0,00171 $	0,00331 $
	Methanol		0,08 kg		
	Electricity		2,8 MJ		
		Biodiesel	0,79 kg		
		Glycerol	0,07 kg		
Gasification and FT	Residue		1,83 kg	0,0471 $	0,09 $
		Synth. diesel	0,21 kg		
		Naphtha	0,09 kg		
		Electricity	2,7 MJ		
TOTAL				**2,47 $**	**1,9 $**

When the scale of the biorefinery plant is similar to an industrial plant, production rates incline and the cost of production declines. Acien et al. (2012) examine the distribution of costs occurring in an industrial-scale plant cultivating *Scenedesmus almeriensis* in PBRs; labor costs accounting for more than 50 % of the costs while depreciation account for 40-45 %, raw materials and utilities together below 10 %. Acien and colleagues suggest automation in order to decrease labor cost. The study indicates that scaling-up of the production from 3.8 ton/year to 200 ton/year leads to a decrease in the production cost from 83$/kg to 15$/kg. Moreover, using flue gases from industrial sources instead of carbon dioxide decreases the production cost to 3$/kg and, the addition of recycling to the production route decreases the cost to 2$/kg. It is also indicated that changing the type of tubular PBRs used to panel PBRs will further reduce the production cost.

Once again emphasizing the importance of the scale of the plant Giwa et al. (2018) assesses a large-scale plant with an integrated biorefinery approach combining *Dunaliella tertiolecta* and Jatropha plant. Scenarios 1 and 2 implicates the production of bioethanol, biofertilizer and biogas while scenario 3 implicates the production of biodiesel, glycerol, animal feed and biohydrogen. Process flow diagrams of the scenarios are presented below in the Figures 2.4, 2.5 and 2.6.

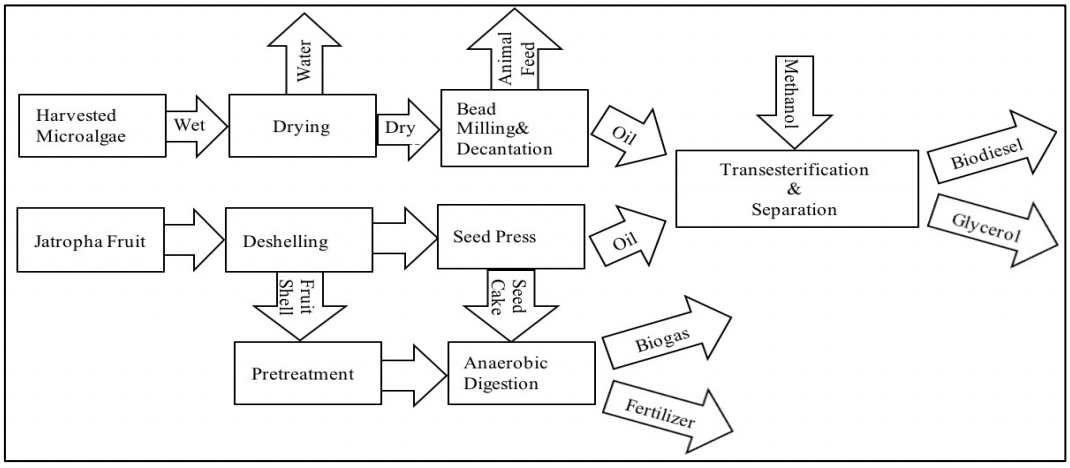


Figure 2.4. Flow diagram of Scenario 1 (adopted from Giwa et al., 2018).

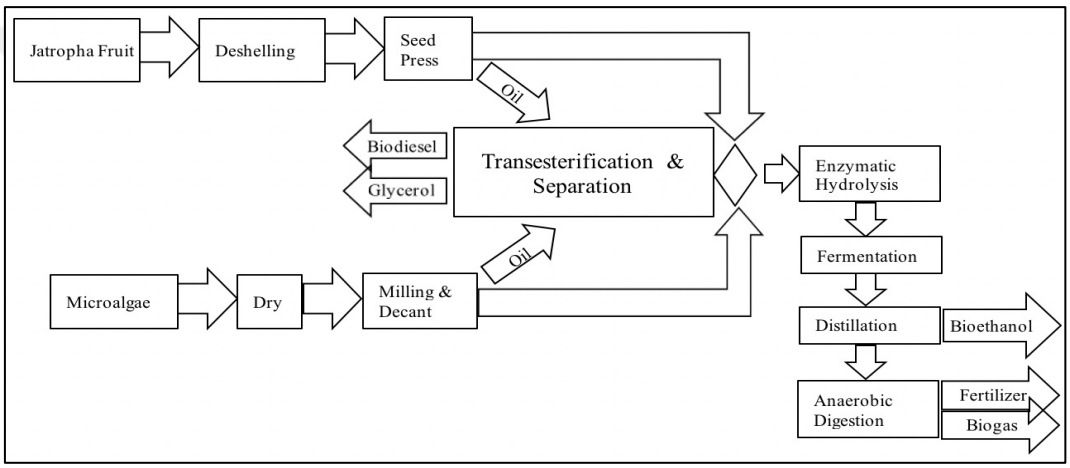


Figure 2.5. Flow diagram of Scenario 2 (adopted from Giwa et al., 2018).

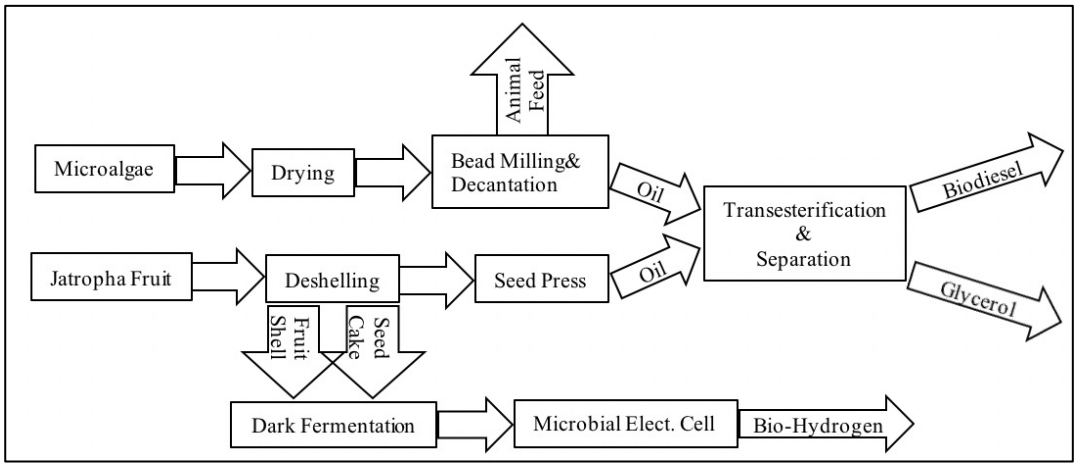


Figure 2.6. Flow diagram of Scenario 3 (adopted from Giwa et al., 2018).

Although high-value products produced in scenarios 2 and 3 are expected to compensate for the high costs, high investment costs counterwork profitability. The sales prices of each product produced are presented in Table 2.8 and the results of the TEA are presented in Table 2.9 below.

Table 2.8. Unit prices of products (adopted from Giwa et al., 2018).

Product	Price
Biodiesel	0,70 $/kg
Glycerol	0,33 $/kg
Methanol recycle	0,49 $/kg
Animal feed	0,31 $/kg
Ethanol	0,63 $/L
Methane	0,72 $/$m^3$
Biofertilizer	41 $/ton
Algae feed	0,31 $/kg
Jatropha feed	0,43 $/kg

Table 2.9. TEA indicators for all scenarios (adopted from Giwa et al., 2018).

Parameter	Scenario 1	Scenario 2	Scenario 3
Total investment ($)	13.866.000	14.730.000	23.421.000
Total revenue ($/year)	17.052.000	17.463.000	17.907.000
Operating cost ($/year)	12.395.000	16.278.000	18.007.000
Gross margin (%)	30,0	4,0	2,3
Return on investment (%)	31,0	11,0	10,3
Payback time (year)	3,3	9,2	9,7
NPV ($)	8.020.000	-19.299.000	-13.519.000

In the assessment, labor is the highest contributing cost followed by raw material costs and facility costs, where utility costs are the lowest contributing to the total. Only scenario 1 is profitable due to its low investment requirements in addition to its high production rate and low operational cost (12.4 million $/year) compared to scenarios 2 (16.3 million $/year) and 3 (18 million $/year). While having the lowest request for investment, scenario 1 also has the highest gross margin of 30 % in 3,3 years payback time while other scenarios offer almost 10 years for payback.

2.4. Gaps and Challenges of the Literature

The main gap in the literature is the lack of knowledge and studies on integrated biorefineries. There are few studies about the biorefinery concept, yet none of them use a full-scale integrated biorefinery. Most of the studies consider data from either lab or pilot-scale biorefineries. Thus, this study aims to lead the literature with real data from a full-scale integrated biorefinery.

The gaps in the TEA are caused by uncertainty of the parameters, widely variable costs used throughout the literature, varying market prices causing inaccuracy when calculating benefits and returns, usage of assumptions causing vague results. Thomassen et al. (2017) group these gaps under four titles as the main operational challenges of TEA; unclarity of the framework, technical maturity, assumptions and integration. In literature, most of the studies do not have a distinct framework and the studies do not use similar guidelines which cause both not accurate and non-comparable results. This wide variety in the parameters of different studies and the lack of knowledge focusing on commercial production prevents the acceleration of the commercial-scale production of algae.

Throughout the literature same challenges are indicated repeatedly; commercialization problem of the algal biofuel is the most to appear. Technological and economical challenges prevent the commercialization of algae-based biofuel despite the high algal productivity and low land requirements. Algae species are sensitive to the environmental factors and the productivity is highly dependent on the geospatial conditions. The lack of knowledge and expertise in the area limits the development of new technologies and result in high capital costs due to the equipment. Vast majority of the high operational costs are due to the cultivation process of the algal biomass. High capital cost and operational cost combined limits the minimum fuel selling price to a higher price than petroleum-based fuel.

Furthermore, microalgae require intense energy during harvesting, as their density ratio is close to water. In addition to high expenses for cultivation, energy-intensive processes, such as centrifugation and extraction, add even more to the minimum fuel selling price.

Production costs remain higher than petroleum-based fuels caused by general difficulties in removing oil by breaking down the cell walls. These high capital costs combined with production costs and high energy requirements are the main obstacles of commercialization of algae-based products. Due to the recent price changes in the oil market and relatively cheap crude oil prices,

microalgae-based biofuels cannot compete with conventional fossil fuels and there are difficulties in transitioning to large-scale commercial production all over the world. In addition to these challenges, drops in the oil prices have direct effects on the viability of biofuels since the petroleum-based fuel prices will drop as well.

2.5. Significance of the Project

Today, energy security is one of the most critical issues and access to sustainable energy sources is a must to overcome these issues caused by the supply-demand imbalance of non-renewable energy resources. Environmentally and financially sustainable alternative biofuel sources are promising solutions as renewable energy sources. Substituting and/or blending algae-based bio-jet fuel with Jet A-1 for the civil aviation sector, which constitutes a large portion of transportation fuels, will have a great impact on the global energy demand.

Despite the urgent need, algae-based fuels are not yet to be commercialized due to their high costs compared with standard petroleum-based fuels. Algae-based fuel costs remain higher than petroleum-based fuels as energy-intensive processes, high capital and operational costs are required for production. These challenges could be resolved via adopting the integrated biorefinery concept where the production of bio compounds is enabled under industrial zero-waste principles. By this approach, the feedstocks are utilized to their maximum, supporting sustainability and compensating the high operational costs.

With recent advancements in technology and the widespread adoption of the zero-waste concept, integrated biorefineries are ascending in the trend line as well as the techno-economic assessment which is the cornerstone for any viable production (Song et al., 2015). Despite this trend, current research still focuses on conventional biorefineries.

Although there are up-to-date studies on obtaining value-added additional products by processing microalgal biomass, most of these studies are at the modeling/simulation level and are on a laboratory scale. There only exists a few studies with real data from an integrated biorefinery and no applications of any full-scale integrated biorefineries as well as carbon-negative production are studied. Considering the conjuncture, one of the most important aspects of this study is being the first TEA study on a full-scale real integrated algal biorefinery that is operating carbon negative.

This study conducts a TEA of bio-jet fuel obtained from microalgal biomass grown under carbon-negative integrated biorefinery settings, aiming to reduce the use of fossil-based fuels in civil aviation and paving the way for the commercialization of biomass-based fuels. With the production of other high value-added products, such as astaxanthin, beta-carotene and spirulina powder, side-by-side with bio-jet fuel within the integrated biorefinery plays a major role in cost reduction. Results of the TEA for production of algae-based bio-jet fuel, meeting international aviation-fuel standards, beta-carotene, astaxanthin and Spirulina powder is presented in the further chapters of this study.

Considering that the electricity demand is provided by wind renewable energy from the wind turbine in the facility and the carbon dioxide retention rates of microalgae, this thesis study is one of the first examples in the literature to produce carbon-negative algal products and to conduct a techno-economic assessment of the process.

This project also holds the importance of being the first pilot-scale bio-jet fuel production within the integrated biorefinery concept in Turkey and its techno-economic assessment. For the first time in Turkey, the national flag carrier Turkish Airlines will use the bio-jet fuel demonstrated on a domestic flight.

3. MATERIALS AND METHODS

3.1. Techno-Economic Assessment

Techno-economic assessment is an important tool to evaluate the technological and economic efficiency of any process, product or service. TEA is also be defined as the overall evaluation of the economic consequences of a technology by the Advanced Research Projects Agency. The assessment provides a guide for the viability, investment decisions and further improvements of the process, product or service by considering capital expenditures (CAPEX) (also referred to as capital cost) and operational expenditures (OPEX) (also referred to as operational cost).

TEA accounts equipment, energy, labor, raw materials, product yields, product values, by-products, market costs, transportation and many other aspects within the framework of upstream and downstream costs to provide an integrated economic and technological representation of any production process. In addition, TEA could be utilized for identifying the most efficient and beneficial route for the target of production. When this scope is adopted to the integrated algal biorefineries, it has an accurate usage as a device to assess the most efficient production route for the algal species to the designated end product and by-products. Scenarios with combinations of different production routes, different algal species and products could be evaluated via TEA, and both benefits and costs could be compared. TEA helps the path towards commercialization of biorefineries by identifying different production pathways, and factors affecting the economic viability (Thomassen et al., 2016).

Besides, conducting TEA in the R&D stage enables to determine the potential economic viability of the production route beforehand. Evaluating the production costs of a given production route based on certain production levels and targets serves to compare various routes during the decision phase and allows the assessment of the economic feasibility of process configurations. Results of the TEA indicates which route and technology have the highest potential for success.

In this study, conceptual process designs, detailed process models and production routes are examined. The focus point of the production is to commercialize the main product, bio-jet fuel. Other main products, astaxanthin and beta-carotene and Spirulina powder are high-value products and are important contributors to the economics of the production by their profits, compensating the high

production costs. By-products such as animal feed and fertilizer are chosen in accordance to maximize the usage of the residual biomass.

Major variable and fixed operating costs are assessed under depreciation, raw material, utility and labor categories and, are directly taken from the biorefinery as well as direct and indirect capital costs. Revenues are estimated by the current market prices. There are several TEA tools that are used in this study; static cost-benefit method, annuity method and return on investment (ROI). The static cost-benefit method is used to compare the benefits and costs of the production routes for an average year, without regard to interest rates and inflation rates, providing an idea for the decision stage of production routes and the preliminary checks. The annuity method, which operates with the same principle as the cost-benefit method, is used to calculate the payback of the investment. The capital payback and interest rates are taken into account, while the inflation rate is excluded. The initial investment cost is divided throughout the project lifetime using an assumed interest rate and, is deducted from the net benefit for each year of project operation. This method provides realistic results as long as there are no unexpected fluctuations in inflation or interest rate. The disadvantage of this method is that it will not be possible to distinguish variations in the cost and benefits of different years, the same net benefit is be used for each year. Also, the delay between the investment and the start of production is not possible to consider. Regarding these disadvantages, a sensitivity analysis could be done by changing the parameters of the assessment to see the influence of a specific parameter variation on the results. It is frequently found in studies that fuel price, product selling prices and market availability are significant parameters for sensitivity variations. ROI is the average return rate of the capital investment. It is used to measure the performance and profitability of the investment. It is expected to be 15 % or higher for a desirable investment and a short period of time for payback. The ROI could be interpreted as a measure of the efficiency of the investment and economic quality of the project.

3.2. Parameters of Techno-Economic Assessment

TEA allows highlighting the parameters that have a strong influence on the total cost. These highlights provide a comprehensive projection of the impact of technology on economic viability and production process. TEA ensures the full understanding of viability limiting parameters. Identification of these parameters enables the solutions of bottlenecks that occur throughout the production process. Key elements of TEA for a biorefinery are presented below in Figure 3.1.

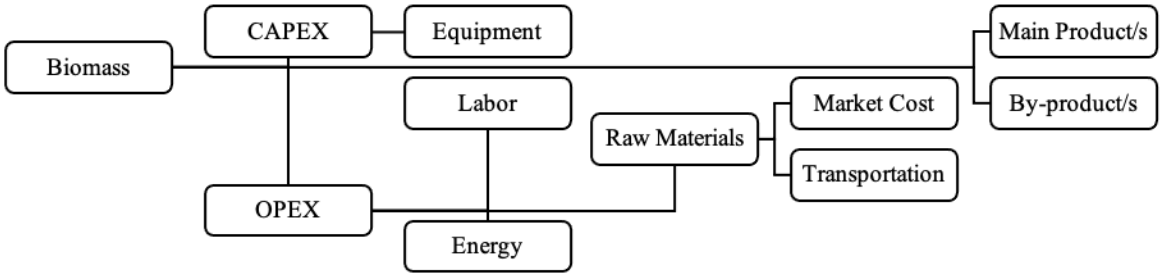


Figure 3.1. Key elements of TEA.

3.2.1. Cost Assessment

3.2.1.1. Capital expenses (CAPEX). Capital expenses are the initial investment required to start up a production plant. Investment costs are a contribution to the cost of return as they represent the cost for products that will generate benefits over time.

Initial cost (I): Initial investment costs are costs that occur at the first stage of setting up the plant related to project design, development/planning and construction including purchasing of the plant area, infrastructure establishment, construction of the plant and initial setup costs including operational tests and permits. Any cost relevant to the initial setup of the plant is included under the initial cost category.

Fixed cost (I_f): Fixed costs are annual costs that occur in a plant. Fixed costs are also referred to as administration or overhead costs and include costs related to taxes, rents, insurance of the plant, licensing and any other cost that a plant acquires annually as it operates. Usually, insurances are estimated to be 1-2 % of the investment costs for large-scale plants (Lauer, 2008).

3.2.1.2. Operational expenses (OPEX). Operational expenses, also referred to as cost of goods, are expenses that are required for the production of the designated products such as; fuel, labor, maintenance and other costs.

Utility cost: Utility cost is the total expenses resulted mainly by electricity, gas and water use during the production processes. Electricity expenses which are included separately due to its notable significance. Utility cost is generally accounted annually for commensurability purposes. When calculating the utilities consumption, capacity factors should be regarded since plants are not able to

work with 100 % efficiency. Thus, over optimistic assessments of production capacity have become a common error in TEAs (Lauer, 2008).

Labor cost: Labor cost is the total cost of labor required for the operation of the plant, calculated on an annual basis for commensurability and to be able to regard holidays. Information on specific labor costs can be easily obtained from national industrial associations (Lauer, 2008).

Maintenance cost: Maintenance cost includes all expenses for the upkeep of the plant including cleaning and repairing of the machinery. Maintenance cost is interrelated with the intensity of the production, period of production and in addition, the size of the investment on individual categories of investment such as buildings, mechanical equipment, infrastructure, etc. relative to the complexity of the equipment. The maintenance cost of plants is not consistent and will change each year accordingly with the age of the plant and various equipment will require replacement throughout the lifetime of the plant.

Other costs: Costs differing from utility, labor and maintenance costs are accounted for under other costs category. Consumables are one of the most common factors of other costs. Consumables include plasticware, glassware, chemicals, etc. Contingencies are also accounted under other costs.

3.2.2. Benefit Assessment

Benefits in plants are due to the profits from the sales of the main products and by-products produced. The amount of products produced is directly proportional with the capacity of the plant, working efficiency and full capacity operation time. In order to benefit from a product, the production price should be kept lower than the market prices. For algae-based biofuel, the price of petroleum-based fuel should be taken as the competitive market price as the algae-based biofuel aims to serve as an alternative. For extra safety, prices could be overestimated to compensate for any contingencies.

3.2.2.1. Annual Average Static Costs and Benefit Assessment. Annual average static costs and benefits are calculated without interest rates and inflation. Neglecting these rates causes this calculation to generally be very optimistic. This calculation method should only be used during the fast evaluation of a new plan to understand whether to carry on or out. Equation 3.1 below Lauer (2008) represents the calculations for a static cost-benefit assessment. Annual result of cost-benefit assessment (r) is obtained by calculating the total difference between total benefits and total costs.

Total costs accounts for the total of both capital and operational costs where benefits account for the total earnings.

$r = B_{tot} - C_{tot}$ where;

$C_{tot} = C_{inv} + C_{op}$ where; (3.1)

$C_{inv} = A + i_a + i_i$ with $A = I/n$ where;

$Cop = O_u + O_l + O_m + O_o$

3.2.2.2. Net Cash Flow. The net cash flow (NCF) represents the total inflow from the sales and the outflow, indicating the net loss or profit on an indicated time period. Mostly it is processed on a yearly basis, however, the time period could vary according to the expected lifetime of the plant. All incoming and outgoing cash are processed into the tablet to calculate the net cash at the end of the period, providing an understanding of the years required to obtain a positive cash flow (profit). If the cash data are not up to date or not correct, the net cash flow will project a wrong answer which can jeopardize the state of the plant. The net cash flow does not represent the viability of the project and the results of the net cash flow should not be interpreted to viability; but gives a summary of the timeline of the cash actions of the plant.

3.2.3. Target Price for Biofuel

3.2.3.1. Return on Investment. Return on investment (ROI) represents the return rate of the investment, indicating the probability of gaining returns from the investment. ROI is simply calculated by the ratio between the net income and investment, given by Equation 3.2. As the ROI increases, the payback period (given in Equation 3.3) for the investment decreases and the probability of success for the investment increases. As the ROI increases, the minimum selling price (given in Equation 3.4) decreases and increases the chance of competition of the produced product with conventional products. Further information on ROI and selling price and calculations for the subjected products are presented in Chapters 4.2, 4.4, 4.6 and 4.8.

$$ROI = \frac{Net\ Annual\ Cash\ Flow \times 100\%}{Total\ Investment} \quad (3.2)$$

$$Payback\ Priod(years) = \frac{Total\ Investment}{Net\ Annual\ Cash\ Flow} \quad (3.3)$$

$$\text{Target price of biofuel} = \frac{\left(\frac{\text{CAPEX}}{\text{ROI}}\right)+\text{OPEX}}{(\text{Max biofuel productivity})} \quad (3.4)$$

The minimum selling prices are designated by the CAPEX, OPEX, productivity and desired ROI of the product. Below 15 % ROI is not desirable for an investment thus, when the minimum selling prices are being decided on, the ROI is set to 15 %. With Equation 3.3, adopted from Batan et al. (2016), minimum selling prices are calculated for each product produced and the results are presented in Chapter 4.

4. RESULTS AND DISCUSSION

4.1. Production of Bio-Jet Fuel from Microalgae

With 3,8 billion passengers traveling by plane each year, the aviation sector carries 35 % of the global trade volume (ATAG, 2017). This high volume creates a serious carbon footprint causing 2 % of the global greenhouse gas emissions. The number of passengers increasing by 5 % each year, the Intergovernmental Panel on Climate Change (IPCC) estimates the current greenhouse gas emissions to increase to 3 % by 2050. In this context, the International Air Transport Association (IATA) has committed to reducing the net carbon emissions of the civil aviation sector by 50 % by 2050. Achieving this challenging goal could only be possible by using alternative biological fuel instead of petroleum-based jet fuel with high carbon dioxide emissions.

The civil aviation sector focuses on second and third-generation biomass resources that do not only interfere with food production and use water and soil resources efficiently for alternative fuel production and has adopted camelina, jatropha, cellulose-containing wastes and algae as candidate biomass resources in the production of alternative jet fuel (IATA 2018). Among these alternatives, microalgae, considered as next generation bioenergy sources, are advantageous compared to other sources in terms of efficiency in light and carbon dioxide absorption compared to other energy crops, and they reach oil levels enough to produce bio-jet fuel 6-8 times faster than a typical plant. In addition, species that can grow in saltwater also provide an advantage in terms of protecting freshwater resources. Furthermore, current studies show that bio-jet fuel derived from algae can reduce the aviation industry's greenhouse gas emissions by 76-80 % (Stratton, 2010; Fortier et al., 2014; Kousoulidou and Lonza, 2016).

In order for Jet A-1 type kerosene to be compatible with civil aviation, its physical properties must comply with the D1655 standards of the American Society for Testing and Materials (ASTM) (Wilson et al., 2013). As for that, synthetically produced kerosene and similar alternative jet fuels are required to fulfill D7566 specifications and after blending with Jet A-1 50-50 %, the blended fuel must comply with D1655 standards (Bann et al., 2017). The target blending rate for the bio-jet fuel obtained in this project is 1-5 % and, is analyzed to meet D7566 before and D1655 after blending. Table 4.1 below presents a comparison of the properties of Jet A-1 and bio-jet fuel.

Table 4.1. Comparison of the basic properties of pure bio-jet fuel and blend obtained in preliminary studies with Jet A-1.

Properties	**100 % Standard Jet A-1 (ASTM D1655)**	**50 % Jet A-1, 50 % Bio-Jet fuel blend**	**100 % Bio-Jet fuel**
Flash point (°C)	Min 38	46	45
Freezing point (°C)	Max -47	-57	-57
Energy Density (MJ/kg)	Min 42,8	43,6	43,9
Density (kg/m^3 @ 15°C)	Min 775, Max 840	778	761
Thermal stability	Standard	Perfect	Perfect
Aromatics	Min 8, Max 25	8,5	0

Unfortunately, microalgae require intense energy during harvesting, as their density ratio is close to water. In addition, production costs remain higher than petroleum-based fuels due to the general difficulties in removing oil by breaking down the cell walls. Due to the recent price changes in the oil market and relatively cheap crude oil prices, microalgae-based biofuels cannot compete with conventional fossil fuels and there are difficulties in transitioning to large-scale commercial production all over the world.

In addition, the productivity of biomass plays a crucial role in determining the selling price of the obtained fuel. The productivity is highly dependent on geospatial conditions and very is very sensitive. Each strain acts differently under the same conditions. Hence, species selection is very important for a successful production. For this purpose, different types of microalgae are grown in closed photobioreactors and open pool systems, then subjected to hydroconversion processes with the help of catalysts optimized for microalgae biomass and oils, and converted into bio-jet fuel and by-products in accordance with ASTM standards.

4.1.1. Cultivation of Microalgae for Biofuel Production

Microalgae grown to produce biofuels do not need a sterile environment. The main reasons for this are that they are grown to be a non-food consumable and biofuel production requires huge amounts of algal biomass. In closed systems such as PBRs, growing large amounts of microalgae is very time intensive and expensive since these closed systems have lower capacity. Thus, microalgae for biofuel are cultivated in open pond systems (ORP). With a total of 80 tons ORP capacity, the IMBIYOTAB facility has 2400 tons of wet algae processing capacity. Schematic representation of algae processing by ORP could be revisited at Figure 1.3.

A total of 4 species were selected to be converted into biofuel, two with HEFA technology and two with HTL technology, presented in Table 4.2. Among these species, *Chlamydomonas nivalis,* otherwise known as "snow algae", stands out with its resistance to strong winter conditions and is especially transformed with HTL technology in order to benefit from all biomass due to its low oil content.

Table 4.2. Production technologies and assumed wet biomass yields of species selected for bio-jet fuel.

Species	Production pathway	Assumed capacity
Ettlia oleoabundans	HEFA	2400 tons/year
Nannochloropsis gaditana	HEFA	2400 tons/year
Botryoccoccus braunii	HTL	2400 tons/year
Chlamydomonas nivalis	HTL	2400 tons/year

The total capacity was assumed to be used for each species and each product separately for optimization purposes. For optimization purposes and to determine the break-even point, the lipid percentages were selected as a range rather than single data to enable a real projection of each scenario. Scenarios with corresponding lipid percentages and bio-jet fuel conversion yield rates are presented below in Table 4.3 and 4.4.

Table 4.3. Scenarios for conversion of bio-oil by HTL technology.

Chlamydomonas nivalis	**L 3***	**L 5***	**L 10***
HTL 68**	L3H68	L5H68	L10H68
HTL 81,3**	L3H81,3	L5H81,3	L10H81,3
HTL 96,6**	L3H96,6	L5H96,6	L10H96,6

Botryoccoccus braunii	**L 40***	**L 50***	**L 60***
HTL 68**	L40H68	L50H68	L60H68
HTL 81,3**	L40H81,3	L50H8,3	L60H81,3
HTL 96,6**	L40H96,6	L50H96,6	L60H96,6

* Lipid content wt%
** HTL conversion efficiency wt% yield.

Table 4.4. Scenarios for conversion by HEFA technology.

Ettlia oleoabundans	**L 20***	**L 25***	**L 30***
HEFA 50**	L20H50	L25H50	L30H50
HEFA 60**	L20H60	L25H60	L30H60
HEFA 70**	L20H70	L25H70	L30H70

Nannochlorapsis gaditana	**L 35***	**L 40***	**L 45***
HEFA 50**	L35H50	L40H50	L45H50
HEFA 60**	L35H60	L40H60	L45H60
HEFA 70**	L35H70	L40H70	L45H70

* Lipid content wt%
** HEFA conversion efficiency wt% yield.

4.1.2. Conversion of Microalgae to Biofuel by Hydrothermal Liquefaction

Hydrothermal liquefaction is the breakdown of large molecules in solid biomass into smaller intermediates that recompose oil compounds (Djandja et al., 2020). HTL is a very suitable thermochemical conversion method for wet algal biomass since it does not require expensive dewatering and drying treatments and incorporates every part of the biomass (lipids, proteins, carbohydrates) into the process, utilizing the whole biomass (Djandja et al., 2020). HTL produces bio-oil, also referred to as bio-crude, with differing yield rates according to the algae composition.

4.1.2.1. Process Flow. After the cultivation and harvesting, the algae continue into the dewatering process to be concentrated and reach the required loading rate to be fed into the HTL. Both *C. nivalis and B. braunii* are dewatered by centrifugation, forming an algal paste. The algal paste proceeds to HTL after dewatering by centrifugation, without drying or processing any components (lipids, carbohydrates, proteins etc.), to be converted into bio-oil. A schematic representation of HTL process is given in Figure 4.1.

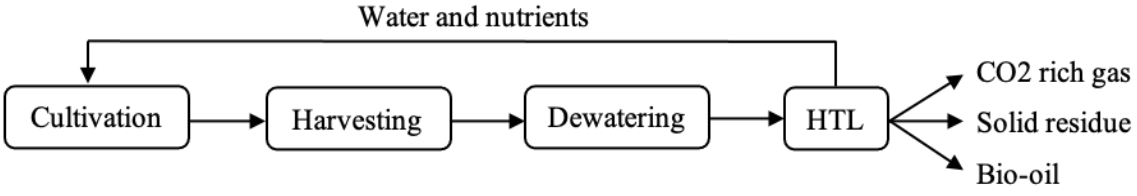


Figure 4.1. Conceptual scheme of HTL in an algae biorefinery.

During HTL, besides bio-oil, aqueous (water-soluble), gaseous and solid residues are also produced. Lipids, usually in the form of triacylglycerols (TAGs), are converted mainly to glycerol and fatty acids together with other products by hydrolysis. Later on, glycerol is converted to ethanol, methanol, gas products (mainly carbon monoxide, carbon dioxide and hydrogen), and other products. Fatty acids are converted to long-chain hydrocarbons (Djandja et al., 2020). Proteins, the main contributor to nitrogen in bio-oil, hydrolyze into amino acids then undergo decarboxylation and deamination, resulting in organic acids, carbonic acid, ammonia and amines (Djandja et al., 2020). Afterwards, these acquired products go under repolymerization and form aromatic ring structures and long-chain hydrocarbons (Djandja et al., 2020). The carbohydrates decompose into organics that are water-soluble such as organic acids (such as formic, lactic, acetic etc.), benzenes, alcohols and aldehydes where benzenes and aldehydes form larger hydrocarbons contributing to the bio-oil yield (Chen et al., 2015; Wu et al., 2020). Consequently, the bio-oil yield is highly influenced by lipids, followed by proteins and then, carbohydrates (Sheehan and Savage, 2017; Huang et al., 2018).

The aqueous residue contains water-soluble organics, mostly high amounts of nutrients. 25 to 40 % of the carbon as dissolved carbon dioxide and 50-60 % of the nitrogen as nitrogen-containing compounds are discarded with the aqueous residue (Zhu et al., 2019). The rich-in-nutrient aqueous residue is recycled to the cultivation process, lowering the operational cost.

Other products, especially bio-oil has to be upgraded to optimize their utilization potential. Solid residue mostly contains ash and some hydrogen, sulfur and nitrogen. It mostly yields lower than 10 % (Minowa et al., 1995; Yang et al., 2004; Ross et al., 2010) and the nutrients could be used as soil amendment while the remaining ash could be used for algae cultivation (Barreiro et al., 2013). Carbon dioxide rich gas mostly yields 20 % and contains hydrogen gas besides carbon dioxide (Brown et al., 2010; Jena and Das, 2011; Alba et al., 2012).

4.1.2.2. Process Parameters. Process time, temperature and pressure are crucial parameters for HTL. Reaction temperature, the most important parameter, has the most influence on the characteristics of the product. Hydrolysis, promoted by high lipid content in the biomass takes place around 220 °C and depolymerization is intensified between 260-300°C. The depolymerization negatively affects the bio-oil yield. When the temperature is increased from 200 to 300°C the decomposition of proteins and the polymerization of the reaction intermediates which are mostly organic acids are promoted, leading to an increase in hydrocarbons. The bio-oil yield increases as the temperature increase and reaches an optimal point between 280-350°C. Process time up to 30 minutes is favorable, after 30

minutes biochar formation occurs (Djandja et al., 2020). Also, pressure range of 5-10 MPa is favorable as high pressures cause an increase in the gaseous fraction of the products. Slowly rising pressure is found to be the most favorable for high bio-oil yield by (Djandja et al., 2020).

Amongst temperature, pressure and time, algae composition is highly influential on the bio-oil yield as low-lipid algae ha higher productivity than high-lipid algae. Lipids and carbohydrates are the major contributors to the bio-oil yield, lipids being the major contributor. Carbohydrates could be easily decomposed and converted into gas, causing low yields of bio-oil. In addition, as the amount of volatile matter and fixed carbon increases and the amount of ash decreases, the bio-oil yield increases (Djandja et al., 2020).

By HTL, *Botryoccoccus braunii* and *Chlamydomonas nivalis* biomasses were first transformed into bio-oil and then upgraded to biofuel by catalytic hydroconversion under 300-400°C and 50-200 bar pressure (5-20 MPa) (Bwapwa et al., 2017).

4.1.2.3. Bio-Oil Yield. Bio-oil yield is the main determinant in biofuel production. Although HTL was initially assessed for high lipid containing species, low lipid containing species with higher growth rates were also found to be suitable feedstocks for HTL technology since high-lipid species usually have lower growth rates, leaving a supply gap of feedstock for production (Chisti, 2007; Alba et al., 2012).

Bio-oil yields vary over a wide range and differ from strain to strain as well as differing within the strain even under identical conditions (Barreiro et al., 2013). Bio-oil yields of 52 % for high lipid containing algae and 89 % for low lipid containing algae were presented by Li et al. (2014) and bio-oil yields between 50-60 % were reported by Barreiro et al. (2013). Also, high lipid containing algae were noted to have a higher bio-oil yield where low lipid containing algae indicated higher proportions of hydrocarbons in the bio-oil, also presented by Li et al. (2014).

Among the four main microalgae species to be used for biofuel production, *Botryoccoccus braunii* and *Chlamydomonas nivalis* are converted to bio-oil with HTL technology without being subjected to cell wall disruption and oil extraction after harvesting and subsequently to bio-jet fuel with the help of high-performance catalysts.

Scenarios of different levels of lipid content were assessed for each biofuel feedstock species. Coefficients of yield for lipids, proteins and carbohydrates (kL, kP and kC) were obtained from Li et al. (2014). Below is the bio-oil yield calculation Equation 4.1, adopted from Biller and Ross (2011) and Li et al. (2017). The equation estimates the bio-oil yield as a relation to the component conversion efficiencies and mass fraction (dw%) of each component of the feedstock without considering the catalysts nor ash.

$$Y_{bio} = kL \times L + kP \times P + kC \times C$$

$$Y_i = \Sigma Y_{ij} = \Sigma k_{ij} \times j = kiL \times L + kiP \times P + kiC \times C \quad (4.1)$$

Chlamydomonas nivalis enables the biorefinery to cultivate algal biomass not only in warm but harsh cold weather as the strain is very resistant to low temperature conditions. *C. nivalis* has a very low lipid content of 3-10 %, dominated by 40-55 % protein and 20-30 % carbohydrate, making it favorable for HTL biofuel production. Bio-oil yields for *C. nivalis* and *B. braunii* with different lipid levels are presented in Tables 4.5 and 4.6 respectively.

Table 4.5. Bio-oil yield of *C. nivalis*.

	Lipid (%)	TL* (ton/year)	kL	Protein (%)	TP** (ton/year)	kP	Carbohydrate (%)	TC*** (ton/year)	kC	Y_{bio} (ton/year)	Y_{bio} (%)
C. nivalis	3 %	72	0,85	40 %	960	0,45	20 %	480	0,22	598,8	25 %
	5 %	120	0,85	45 %	1080	0,45	25 %	600	0,22	720	30 %
	10 %	240	0,85	55 %	1320	0,45	30 %	720	0,22	956,4	40 %

* total lipid,
** total protein
*** total carbohydrate

Table 4.6. Bio-oil yield of *B. braunii*..

	Lipid (%)	TL* (ton/year)	kL	Protein (%)	TP** (ton/year)	kP	Carbohydrate (%)	TC*** (ton/year)	kC	Y_{bio} (ton/year)	Y_{bio} (%)
B. braunii	40 %	960	0,85	30 %	720	0,45	30 %	720	0,22	1.298,4	54 %
	50 %	1.200	0,85	25 %	600	0,45	25 %	600	0,22	1.422	59 %
	60 %	1.440	0,85	18 %	432	0,45	19 %	456	0,22	1.518,72	63 %

* total lipid,
** total protein
*** total carbohydrate

4.1.2.4. Catalytic Upgrading (Hydrotreating) and Bio-Jet Fuel Yield. Bio-oil obtained by HTL is typically rich in nitrogen, 5-8 wt% (Eboibi et al., 2015). Due to its high oxygen and nitrogen content and high viscosity, HTL bio-oil is not suitable to use as a transportation fuel as is (Djandja et al., 2020). The high oxygen content decreases the calorific value of the bio-oil while the high content of nitrogen makes it unsuitable for combustion in addition to poor chemical stability (Zhou et al., 2020).

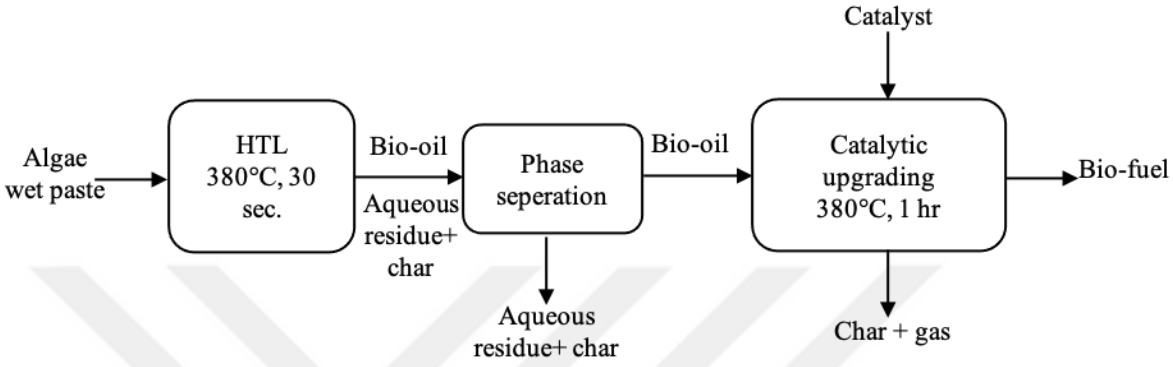


Figure 4.2. HTL process flow diagram.

Removal of oxygen, nitrogen and sulphur heteroatoms is mandatory for high-quality biofuel. The biofuel is freed from its oxygen and nitrogen content and converted into biofuel with a catalytic upgrading process (Patel et al., 2017). A schematic representation of the upgrading process is presented in Figure 4.2.

In catalytical upgrading, the catalyst is used to modify the product yields, reshaping the chemical and physical properties, such as viscosity and heteroatom content, of the bio-oil (Babich et al., 2011). In addition, catalyst use helps reducing char formation and improves the process efficiency (Djandja et al., 2020).

In catalytic upgrading, catalysts such as carbon, Pd, Pt, Ru, NiMo and zeolite, Al_2O_3, etc. are used to reduce nitrogen and oxygen, enhance the quality and obtain biofuel suitable for transportation (Patel et al., 2017). Heterogenous catalysts, usually zeolite, were found to be preferable for their high potential in deoxygenation and denitrogenation to upgrade algal bio-oil to high-quality biofuel by Zhou and Hu (2020). Zeolites degrade macromolecules into smaller particles to be deoxygenated and form hydrocarbons (Zhou and Hu, 2020). In addition, the upgrading process also requires hydrogen to remove heteroatoms. The end product, biofuel, has low viscosity, lower oxygen content, improved stability, higher aromatic hydrocarbons and higher specific energy (energy density) (Zhou and Hu, 2020).

Catalytic upgrading yield rate assumptions for bio-jet fuel yield were adopted as 96,6 % and 81,3 % from Patel et al. (2017). Catalytic upgrading by $NiMo/Al_2O_3$ (3 wt% Ni and 14 wt% Mo loading), at 380 °C for 60 minutes was also noted to yield 96,6 wt% biofuel by Patel et al. (2017) and the average yield was also noted as 81,3 wt% by Elliott et al. (2013) and Elliott et al. (2014) in addition to 95-98 % decrease in oil acidity and decrease in nitrogen content by 42,7 % (Patel et al., 2017). Upgraded bio-jet fuel yields are presented in Table 4.7.

Table 4.7. Upgraded bio-jet fuel yields of *C. nivalis* and *B. braunii* with 96,6 % and 81,3 % conversion rates.

	Lipid (%)	Protein (%)	Carbohydrate (%)	Bio-oil yield (ton/year)	Bio-jet fuel yield (ton/year) (96,6 %)	Bio-jet fuel yield (ton/year) (81,3 %)
C. nivalis	3 %	40 %	20 %	598,8	578,4	486,82
	5 %	45 %	25 %	720,0	695,5	585,36
	10 %	55 %	30 %	956,4	923,9	777,5
	15 %	60 %	35 %	1.138,8	1.100,1	925,84
B. braunii	40 %	30 %	30 %	1.298,4	1.254,3	1.055,6
	50 %	25 %	25 %	1.422,0	1.373,7	1.156,1
	60 %	18 %	19 %	1.518,7	1.467,1	1.123,7

4.1.3. Conversion of Microalgae to Bio-jet fuel by Hydrogenated Esters and Fatty Acids

4.1.3.1. Process Flow. HEFA (hydrogenated esters and fatty acids) is used for hydrotreating fatty acids and triglycerides in the algal oil to produce bio-jet fuel. The HEFA process mainly consists of two steps. The unsaturated fat content of each biomass is different and a hydrogenation process is required to saturate the double carbon bonds (Kalnes et al., 2010).

Therefore, the first step includes the conversion of unsaturated fatty acids and glycerides into saturated triglycerides (TAG) using catalytic hydrogenation. Afterwards, the glycerol part of the TAG structure is converted into propane using propane cleavage with the addition of hydrogen. Then, the oxygen in the free fatty acids (FFA), which are released by the separation of glycerol, are subjected to hydrodeoxygenation and the oxygen is decomposed as water (Wang and Tao, 2016).

In the second part of the conversion, since the jet fuel require certain cold flow and flash point properties, hydrocarbons with long chains has to be processed in order to be brought to C9-C15 range

(Kalnes et al., 2010). Thus, the straight hydrocarbons undergo hydrocracking and isomerization, resulting in branched structures and mixed fuels. While isomerization converts straight-chain hydrocarbons to branched structured hydrocarbons to reduce the freezing point, hydrocracking process cracks and saturates paraffins, creating lighter liquids and gas products (Gary et al., 2007). The mixed fuels are then subjected to fractionation to be separated into jet fuel, diesel, naphtha and light gasses (Wang and Tao, 2016). Catalysts used for the process used to be noble metals in addition to zeolites and oxides yet in recent years, the use of catalysts such as Ni, Mo, Co has gained acceleration due to catalyst deactivations and operational expenses (Wei et al., 2019).

The general process flow chart for HEFA-jet fuel technology is presented below in Figure 4.3. Bio-jet fuels obtained from HEFA-jet fuel carry the characteristics of petroleum-based fuel. In addition, HEFA- jet fuel has higher cetane number, lower sulfur and aromatics content, lower freezing point and lower GHG emissions, making the HEFA-jet fuel the first approved biomass, by ASTM D7655 standards, to bio-jet conversion technology (Pearlson, 2011).

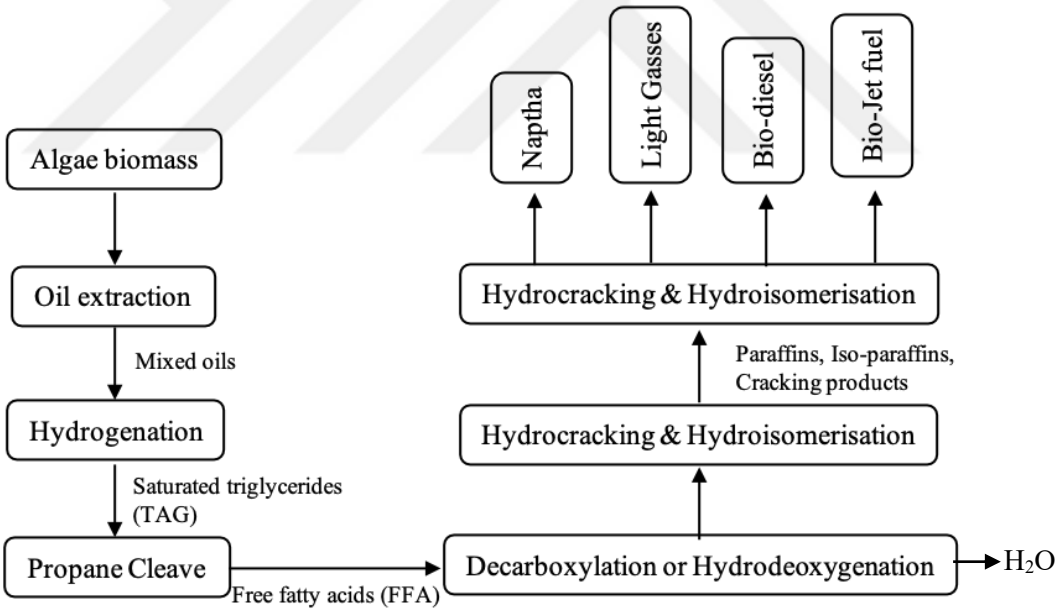


Figure 4.3. Process flow diagram of HEFA technology (adopted from Wang and Tao, 2016).

4.1.3.2. Bio-Jet Fuel Yield. HEFA conversion technology directly utilizes the lipid content of the biomass. HEFA jet fuel yields per amount of algal oil are adopted as 50 % and 70 % (Carter, 2012), 60 % (Chen et al., 2016). Results of 50 %, 60 % and 70 % conversion efficiencies of lipid content to HEFA-jet fuel are presented below in Table 4.8.

Table 4.8. Bio-jet fuel yields of *E. oleoabundans* and *N. gaditana* with 50 %, 60 % and 70 % conversion rates.

			HEFA-jet fuel yield (ton/year)		
	Lipid Composition (wt%)	Total Lipid (ton/year)	50 wt%	60 wt%	70 wt%
Ettlia oleoabundans	20 %	480	240	288	336
	25 %	600	300	360	420
	30 %	720	360	432	504
Nannochloropsis gaditana	35 %	840	420	504	588
	40 %	960	480	576	672
	45 %	1080	540	648	756

HEFA jet fuel yield is highly dependent on isomerization. The isomerization step allows the production of high-quality biofuel with good cold flow properties but at the same time, this step decreases the HEFA jet fuel on a scale impossible to ignore (Starck et al., 2016). In addition, over-hydrocracking will cause low yields of long-chain hydrocarbons and high yields of short-chain hydrocarbons that are not suitable for high-quality bio-jet fuel ad lower the economic value (Wang and Tao, 2016).

Among the microalgae species that undergo conversion to bio-jet fuel by HEFA technology, *N. gaditana* has higher biofuel yields compared with *E. oleoabundans* primarily due to its higher lipid contents. The worst scenario lipid content 35 % of *N. gaditana* exceeds the HEFA jet fuel yields from the best scenario lipid content 30 % of *E. oleoabundans* by 420 ton/year, 504 ton/year, 588 ton/year and 360 ton/year, 432 ton/year, 504 ton/year respectively.

4.2. Results of Techno Economic Assessment of Bio-Jet Fuel

The techno-economic assessment (TEA) of microalgae cultivation accounts for the full process flow including the growth phase to the wet paste extraction. The TEA of the cultivation plays a crucial role in determining the economics of the final main and by-products. The price of the final product, compatibility to the market and commercialization of the product highly depend on the outcomes of the TEA.

4.2.1. CAPEX

The capital expenditure (CAPEX) for microalgae covers the purchase and installation of upstream and downstream equipment in addition to the construction, infrastructure and land expenses.

In this study, CAPEX is calculated with exact expenses of the equipment, construction, land and infrastructure; but the CAPEX could also be estimated by assuming a linear depreciation and dividing the equipment cost by an estimated lifespan.

In the present study, a total of 80 m^3 of open raceway ponds (ORP) and a total of 30 m^3 tubular photobioreactors (PBR) capacity were used for per-batch microalgae cultivation. The cost for turnkey installation including the training for the ORP reactors are presented below in Table 4.9. As mentioned in previous sections, although ORPs have low capital and operating costs, they are not suitable for cultivation of every species considering their disadvantages such as low volumetric productivity and water contamination due to the environmental factors. Relative to ORPs, PBRs are more complex and have higher productivity leading to higher capital and operating costs. In addition to the higher efficiency, PBRs are less susceptive to environmental factors and have a very low chance of contamination thus, a lower chance of culture crushing. The cost for turnkey installation including the training for the PBR is presented below in Table 4.9.

Table 4.9. Capital cost of upstream equipment.

ORP	**Cost ($)**
Raceway (0.1 m^3) (x6)	2.621,01
Raceway (1 m^3) (x6)	30.866,64
Raceway (10 m^3) (x3)	71.558,22
Raceway (15m^3) (x3)	80.976,72
Control systems	12.012,96
Electronic enclosures	7.401,76
Shipping charges	8.133,00
ORP turn key installation	**213.570,31**
PBR	
PBR reactor (30m^3)	220.220,00
Inoculation	49.222,80
Lighting systems	101.640,00
Installation costs, training	106.649,40
PBR turn key installation	**477.732,20**
Reactors Total Cost	**691.302,51**

Factors majorly affecting the capital cost of cultivation are reactors with 46 % contribution for PBRs followed by installation and training by 23 % and lighting systems by 21 %. For ORPs, the major contributors are the ponds with a total of 86 %. Below in Figure 4.4 is a representation of distributions of the contributors.

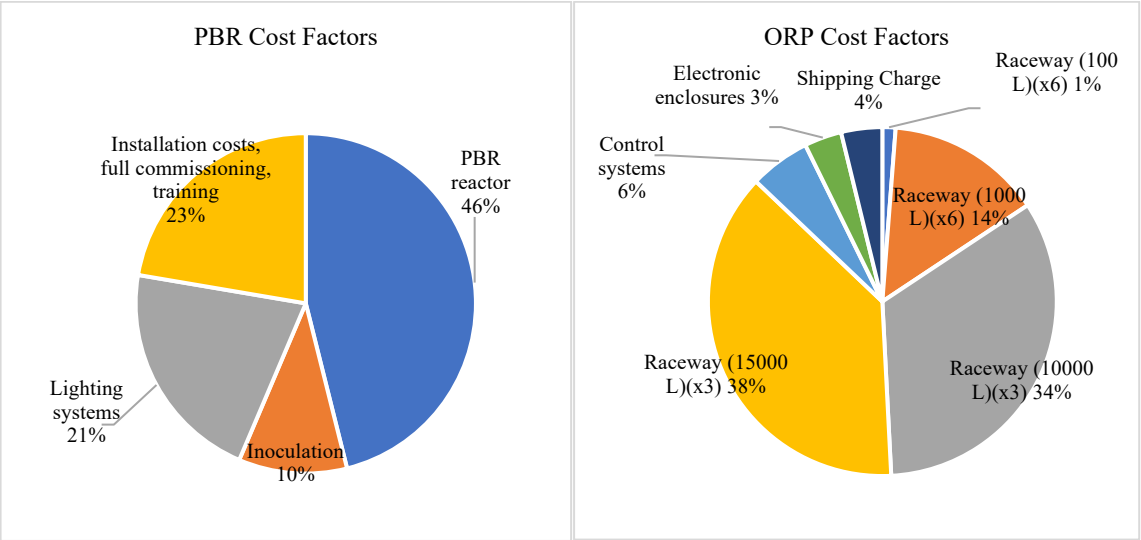


Figure 4.4. Cost factors of PBR and ORP.

Downstream equipment costs account for the equipment used after cultivation of microalgae such as centrifuges, spray dryers and homogenization units. Below in Table 4.10 is a detailed cost table for downstream equipment.

Table 4.10. Capital cost of downstream equipment.

Downstream equipment costs	**Cost ($)**
PBR processing system with harvesting and homogenization units	Lump sum
ORP processing system with harvesting and straining units	
Spray Dryer	
Equipment total (PBR, ORP, spray dryer)	**1.862.190,00**
CIP (cleaning in place)	114.950,00
Total downstream process capital cost ($)	**1.977.140,00**

Construction costs are directly taken from the financial construction contract for IMBIYOTAB. The construction costs include the construction of the whole biorefinery facility and totals 1 M$. Dissociated construction costs are presented below in Table 4.11.

Table 4.11. Capital cost for construction of IMBIYOTAB.

Construction costs	Cost ($)
Construction zoning	658.637,27
Mechanical installation	30.620,15
Electrical installation	60.221,62
Retaining walls	17.668,49
Mounting system	3.530,02
Air conditioning	229.322,45
Total ($)	**1.000.000,00**

When the major contributors to the cost of construction are examined, construction zoning appears as the primary contributor with 66 % followed by air conditioning with 23 %. Below, in Figure 4.5, is a detailed presentation of the contributors to the construction cost.

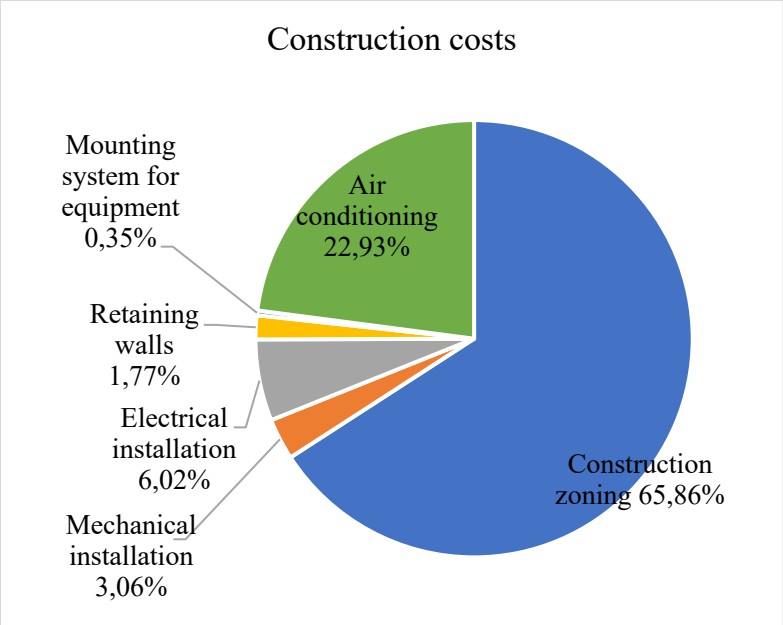


Figure 4.5. Contributors to capital cost of construction.

4.2.2. OPEX

Labor, utilities [electricity, water, heating, consumables (carbon dioxide, glassware, plasticware, chemical, biological)], culture media were accounted as direct operational costs and maintenance was accounted as indirect cost. The maintenance cost was assumed to be 3 % of the total installed

equipment cost and was approximated to be 80.053,27 $/year (Rogers et al., 2014). The annual productivity of the facility was determined to be 2400 tons of wet algae processing and, the year-based operating costs were determined according to the productivities.

ORP cultivation was started in small ponds and scaled up step by step for controlled growth. In 10 m^3 and 15 m^3 ponds, media was recycled after harvesting the microalgae. While harvested microalgae proceeded to dewatering, the remaining water with non-sufficient nutrients was replenished with nutrients and was used for the cultivation of another batch of microalgae. The used culture media was recycled only for three cycles for productivity purposes.

Costs for 1L of media used for various species are presented below in Table 4.12. For and only for 10 and 15 m^3 ponds, water was recycled but nutrients were added as usual. 80 m^3 of media was used in the ORPs while 30 m^3 of media was used in PBRs leading to a total of 110 m^3, with 2400 tons of algae processing capacity per year. For easy calculation purposes, the average cost of media was calculated to be 0,264 $/L, leading to a 633.120,00 $/year as the cost of media.

Relative to ORPs, PBRs are more complex reactors. The media cycles within the tubulars and the carbon dioxide are supplied externally by pumps. The lighting for optimal algae growth is provided by artificial lighting sources. Thus, the operational expenses of PBRs are higher compared to ORPs.

During the growth phase, microalgae release oxygen by utilizing the carbon dioxide and nutrients in the media. Although the carbon dioxide in the environment may be sufficient, the addition of carbon dioxide greatly increases productivity and supports the amount of biomass required for biofuel production. Therefore, the carbon dioxide levels in the ORPs are supported by aerators and rotating paddlewheels to ensure mixing and aeration. The mixing action enables optimizing the growth by enabling microalgae to benefit from light. Although the electricity needed for mixing and aeration motors is supplied by the wind turbine in the property, the carbon dioxide is accounted as a consumable.

Labor cost was calculated to be 40.000,00 per year for 10 people. Electricity required for the plant and for heating was supplied by the wind turbine installed at the property, decreasing the operational cost.

Table 4.12. Operational costs of medias used for cultivation.

Modified Bolds 3N Media	**g/L**	**$/kg**	**$/L**
$NaNO_3$	0,75	1,6	0,0012
$CaCl_2.2H_2O$	0,025	0,29	0,00001
$MgSO_4.7H_2O$	0,074	0,33	0,00002
KH_2PO_4	0,175	6,7	0,0012
K_2HPO_4	0,075	21,5	0,0016
NaCl	0,025	1,76	0,0001
PIV	6	0,038	0,0002
Soilwater: GR+Medium	40	0,02	0,0008
Vitamin B12	1	232,4	0,2324
Biotin vitamin soln.	1	17,7	0,018
Thiamine vitamin soln.	1	18,5	0,019
Total Price ($/ 1L)			**0,274**

Spir 1 Media	**g/0,5 L**	**$/kg**	**$/L**
$NaHCO_3$	13,61	0,32	0,0044
Na_2CO_3	4,03	0,35	0,0014
K_2HPO_4	0,5	21,5	0,011
Spir 2 Media	**g/0,5L**	**$/kg**	**$/L**
$NaNO_3$	2,5	1,6	0,004
K_2SO_4	1	0,88	0,0009
NaCl	1	1,76	0,0018
$MgSO_4$ $7H_2O$	0,2	0,33	0,00007
$CaCl_2$ $2H_2O$	0,04	0,29	0,00001
PIV metal soln.	6	0,038	0,00023
Chu micronutrient soln.	1	0,014	0,00001
Vitamin B_{12}	1	232,4	0,2324
Total Price ($/ 1L)			**0,256**

F/2 Media	**g/L**	**$/kg**	**$/L**
$NaNO_3$	0,075	1,6	0,00012
$Na_2HPO_4.$ H_2O	0,005	2,8	0,000014
$Na_2SiO_3.$ $9H_2O$	0,03	475	0,0143
Trace metals soln.	1	0,01	0,00001
Vitamin B12	1	232,4	0,2324
Biotin vitamin soln.	1	17,7	0,018
Thiamine vitamin soln.	1	18,5	0,019
Total Price ($/ 1L)			**0,283**

Bolds 1NV Media	**g/L**	**$/kg**	**$/L**
$NaNO_3$	0,25	1,6	0,0004
CaCl . $2H_2O$	0,025	0,29	0,00001
$MgSO_4.$ $7H_2O$	0,075	0,33	0,00003
K_2HPO_4	0,075	21,5	0,00161
KH_2PO_4	0,175	6,7	0,00117
NaCl	0,025	1,76	0,00004
PIV	6	0,04	0,00023
Vitamin B12	1	232	0,2324
Biotin vitamin soln.	1	17,7	0,018
Thiamine vitamin soln.	1	18,5	0,019
Total Price ($/ 1L)			0,272

MES-Volvox Media	**g/L**	**$/kg**	**$/L**
$Ca(NO_3)_2.4H_2O$	0,118	103,8	0,0123
$MgSO_4.7H_2O$	0,04	0,33	0,000013
$C_3H_7Na_2O_6P.5H_2O$	0,05	428,34	0,02142
KCl	0,05	8,07	0,000404
MES	1,95	1754,5	3,4213
PIV	6	0,038	0,00023
NH_4Cl	0,0267	67,15	0,0018
Vitamin B12	1	232,4	0,2324
Biotin vitamin soln.	1	17,7	0,018
Total Price ($/ 1L)			3,708

Erdshreiber's Media	**g/L**	**$/kg**	**$/L**
Pasteurized seawater	1000	0	0
PIV	12	0,038	0,0005
$NaNO_3$	0,2	1,6	0,0003
$Na_2HPO_4.$ $7H_2O$	0,018	5,28	0,0001
Soilwater: GR+Medium	50	0,02	0,001
Vitamin B12	1	232,4	0,2324
Total Price ($/ 1L)			**0,234**

4.2.3. Total CAPEX and OPEX

Total CAPEX and OPEX indicate the total liabilities of the IMBIYOTAB facility during a year-long production period with 2400 tons of wet algae processing capacity for each product separately. Below, in Table 4.13, is the comprehensive presentation of total CAPEX and OPEX, with expenses directly from the facility. The direct operating cost (DOC) accounts for labor, utilities, consumables and media

Table 4.13. Total capital and operating costs (all numbers in $).

Installed costs	Upstream equipment	691.302,51
	Downstream equipment	1.977.140,00
	Total installed cost (TIC)	**2.668.442,51**
Direct costs	Buildings (1 % TIC)	26.684,43
	Site development (9 % TIC)	240.160,00
	Additional piping (4,5 % TIC)	120.079,91
	Total direct cost (TDC) (accounted in FCI)	**386.924,34**
Indirect costs	Prorated expenses (10 % TDC)	38.692,43
	Home office and construction fees (20 % TDC)	77.384,87
	Field expenses (10 % TDC)	38.692,43
	Project contingency (10 % TDC)	38.692,43
	Startup and permits (5 %) TDC	19.346,22
	Total indirect cost	**212.808,39**
Fixed costs	**Capital investment (FCI)**	**1.000.000,00**
	Total CAPEX	**3.881.250,90**
Operating costs	Labor (10 people)	40.000,00
	Utilities (electricity, heating) (wind turbine)	0
	Utilities (water)	29.186,4
	Consumables (plasticware, glassware, chemical) (0,2 % TIC)	5.337,00
	Culture media (2400 ton/year)	633.120,00
	Maintenance (3 % TIC)	80.053,27
	Contingencies (5 % TDC+TIC)	29.986,64
	Total OPEX (per year)	**817.683,31**
	OPEX CAPEX Total	**4.698.934,20**

Major contributors of CAPEX and OPEX are examined, revealing downstream equipment as the primary contributor to CAPEX with 49 %, followed by construction with 25 %. As for operational expenses, media cost, due to the 2400-ton capacity, is the major contributor with 77 %, followed by maintenance by 9,8 %. Below is a detailed analysis of the distribution in Figure 4.6.

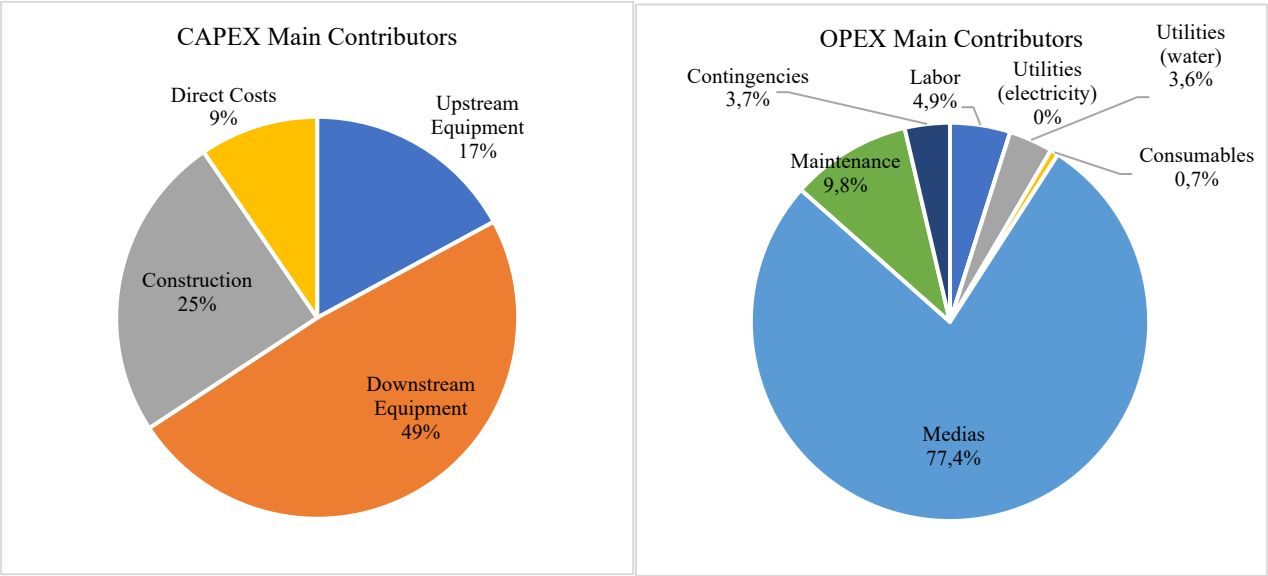


Figure 4.6. CAPEX and OPEX contributors.

4.2.4. Biofuel Yield Rates

Since every algae species has different lipid content which varies under different growth conditions, several lipid accumulation percentages were considered. The lipid content ranges for species *C. nivalis, B. braunii, E. oleoabundans and N. gaditana* were taken as 3-5 %, 40-50 %, 20-30 % and 35-45 % respectively. In addition, since the yields from each technology varies throughout the literature, 68 %, 81,3 % and 96,6 % conversion rates were adopted from Elliott et al. (2013), Patel et al. (2017) and Ren et al. (2018) for HTL technology and 50 %, 60 %, 70 % were adopted from Carter (2012) for HEFA conversion technology.

Bio-jet fuel production rates, in accordance with the scenarios presented in Tables 4.3 and 4.4, for each species were calculated with respect to the conversion technology yields and lipid contents. Detailed bio-jet fuel production rates of each species regarding HTL technology for defined scenarios are presented below in Table 4.14.

Table 4.14. Bio-jet fuel production rates of *C. nivalis* and *B. braunii* with respect to lipid contents and conversion rates.

C. nivalis **Max bio-jet fuel production (ton/year)**	**L3***	**L5***	**L10***
HTL68**	407,18	489,60	650,35
HTL81,3**	486,82	585,36	777,55
HTL96,6**	578,44	695,52	923,88

B. braunii **Max bio-jet fuel production (ton/year)**	**L40***	**L50***	**L60***
HTL68**	882,91	966,96	1.032,73
HTL81,3**	1.055,60	1.156,09	1.234,72
HTL96,6**	1.254,25	1.373,65	1.467,08

* Lipid content wt%
** HTL conversion efficiency wt% yield.

For HTL technology, while the bio-jet fuel yield ranges between 407-924 ton/year for *C. nivalis*, it ranges between 883-1467 ton/year for *B. braunii.* The differences in bio-jet fuel yields are primarily caused by the gap between the lipid contents of the two species. Although HTL technology utilizes whole algal biomass instead of using only the lipid part, lipid contents are the primary determinant of the yield. Below are comparisons of each scenario with different lipid contents for *C. nivalis* and *B. braunii* in Figures 4.7 and 4.8.

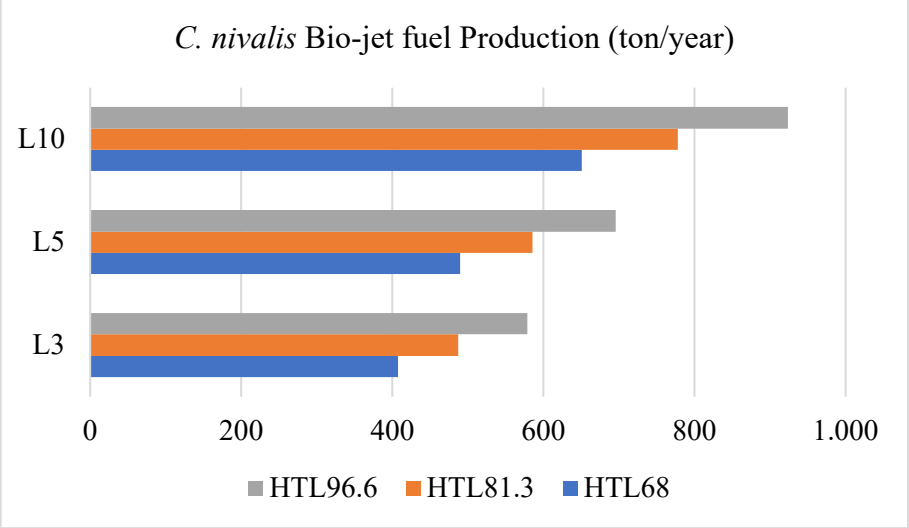


Figure 4.7. Bio-jet fuel production of *C. nivalis* with HTL technology with respect to different lipid and conversion rates.

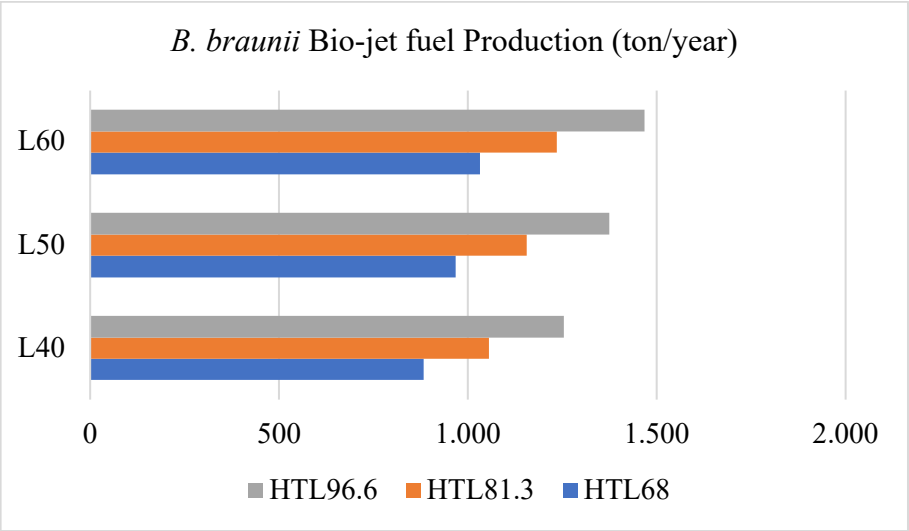


Figure 4.8. Bio-jet fuel production of *B. braunii* with HTL technology with respect to different lipid and conversion rates.

For conversion with HEFA technology, *E. oleoabundans* yields 240-504 ton/year of bio-jet fuel while *N. gaditana* yields 420-756 tons/year bio-jet fuel. The production yields are in coordination with the lipid contents and conversion rates. As the lipid contents and conversion rates get higher, biofuel yield increases. With a 70 % conversion rate and 25 wt% lipid content, *E. oleoabundans* equalizes *N. gaditana* with a 50 % conversion rate and 35 wt% lipid content. More detailed production rates of each species for defined scenarios with respect to the conversion technology yields and lipid contents are presented below in Table 4.15.

Table 4.15. Bio-jet fuel production rates of *E. oleoabundans* and *N. gaditana* with respect to lipid contents and conversion rates.

E. oleoabundans **Max bio-jet fuel prod (ton/year)**	**L20***	**L25***	**L30***
HEFA50**	240,00	300,00	360,00
HEFA60**	288,00	360,00	432,00
HEFA70**	336,00	420,00	504,00

N. gaditana **Max bio-jet fuel prod (ton/year)**	**L35***	**L40***	**L45***
HEFA50**	420,00	480,00	540,00
HEFA60**	504,00	576,00	648,00
HEFA70**	588,00	672,00	756,00

* Lipid content wt%
** HEFA conversion efficiency wt% yield.

Further comparison of bio-jet fuel yield for each species with different lipid content are presented below in Figures 4.9 and 4.10 for *E. oleoabundans* and *N. gaditana* respectively.

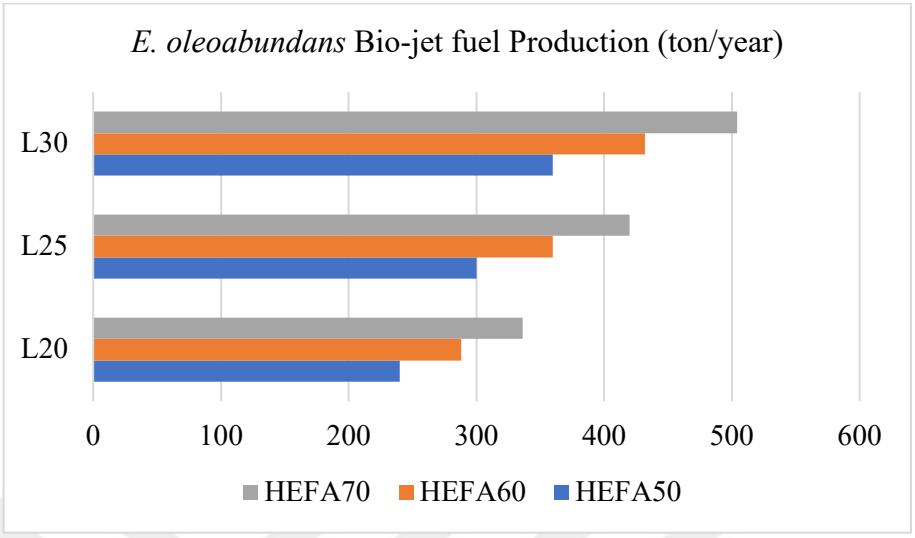


Figure 4.9. Bio-jet fuel production of *E. oleoabundans* with HTL technology with respect to different lipid and conversion rates.

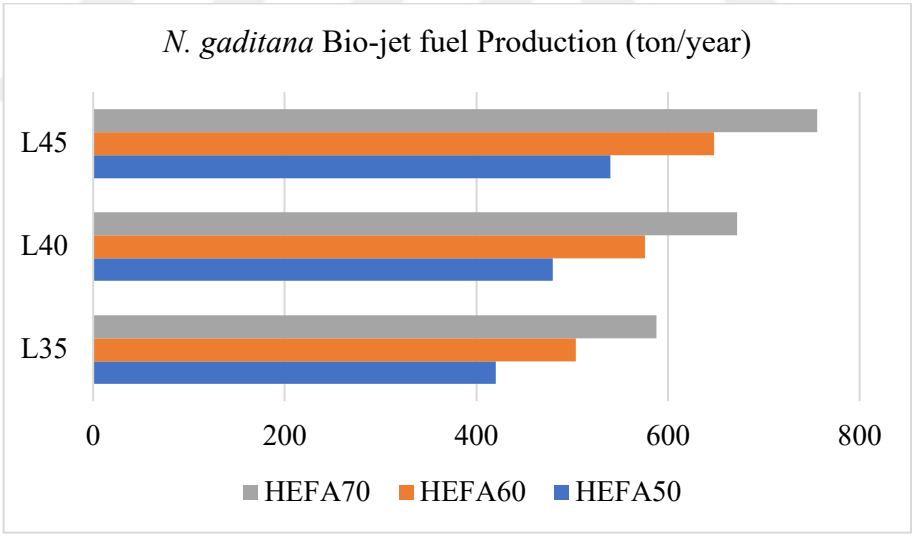


Figure 4.10. Bio-jet fuel production of *N. gaditana* with HTL technology with respect to different lipid and conversion rates.

4.2.5. Year-Based Cost Scenarios

In order to get more realistic capital expenditure (CAPEX) results, 20-10-5 years were defined as terms of investment. For a 20-year scenario, the total investment is expected to be paid in 20 installments with a return on investment (ROI) of 15 %. With the same principle, 10-years and 5-

years scenarios consider payments in 10 installments and 5 installments, both with a ROI of 15 %. Below in Tables 4.16, 4.17, 4.18 and 4.19 are the total capital investments per year for each scenario with respect to species and lipid contents.

Table 4.16. Capital expenses for *C. nivalis* with respect to 20-10-5-year installments and lipid contents.

C. nivalis **CAPEX $/year**		**L3***	**L5***	**L10***
20 years	**HTL68****	635.152,27	645.085,59	664.460,49
	HTL81,3**	644.751,06	656.627,22	679.791,61
	HTL96,6**	655.793,27	669.904,43	697.428,18
10 years	**HTL68****	792.152,20	804.540,89	828.704,96
	HTL81,3**	804.123,66	818.935,43	847.825,71
	HTL96,6**	817.895,34	835.494,56	869.821,75
5 years	**HTL68****	1.185.991,8	1.204.539,9	1.240.717,8
	HTL81,3**	1.203.915,2	1.226.091,1	1.269.344,9
	HTL96,6**	1.224.533,9	1.250.883,0	1.302.276,9

* Lipid content wt%
** HTL conversion efficiency wt% yield.

Table 4.17. Capital expenses for *B. braunii* with respect to 20-10-5-year installments and lipid contents**.**

B. braunii **CAPEX $/year**		**L40***	**L50***	**L60***
20 years	**HTL68****	692.490,15	702.620,17	710.547,16
	HTL81,3**	713.303,55	725.414,89	734.892,30
	HTL96,6**	737.246,79	751.637,38	762.898,36
10 years	**HTL68****	863.663,13	876.297,13	886.183,55
	HTL81,3**	889.621,28	904.726,35	916.546,44
	HTL96,6**	919.482,92	937.430,64	951.475,17
5 years	**HTL68****	1.293.056,34	1.311.971,68	1.326.773,39
	HTL81,3**	1.331.920,29	1.354.535,25	1.372.232,00
	HTL96,6**	1.376.628,44	1.403.499,35	1.424.526,49

* Lipid content wt%
** HTL conversion efficiency wt% yield.

Table 4.18. Capital expenses for *E. oleoabundans* with respect to 20-10-5-year installments and lipid contents.

E. oleoabundans **CAPEX $/year**		**L20***	**L25***	**L30***
20 years	**HEFA50****	609.433,22	615.272,58	621.111,95
	HEFA60**	614.104,71	621.111,95	628.119,18
	HEFA70**	618.776,20	626.951,31	635.126,42
10 years	**HEFA50****	760.075,79	767.358,56	774.641,32
	HEFA60**	765.902,00	774.641,32	783.380,64
	HEFA70**	771.728,21	781.924,08	792.119,95
5 years	**HEFA50****	1.137.967,79	1.148.871,38	1.159.774,96
	HEFA60**	1.146.690,66	1.159.774,96	1.172.859,26
	HEFA70**	1.155.413,53	1.170.678,55	1.185.943,57

* Lipid content wt%
** HEFA conversion efficiency wt% yield.

Table 4.19. Capital expenses for *N. gaditana* with respect to 20-10-5-year installments and lipid contents.

N. gaditana **CAPEX $/year**		**L35***	**L40***	**L45***
20 years	**HEFA50****	626.951,31	632.790,67	638.630,03
	HEFA60**	635.126,42	642.133,65	649.140,89
	HEFA70**	643.301,52	651.476,63	659.651,74
10 years	**HEFA50****	781.924,08	789.206,85	796.489,61
	HEFA60**	792.119,95	800.859,27	809.598,59
	HEFA70**	802.315,82	812.511,69	822.707,56
5 years	**HEFA50****	1.170.678,55	1.181.582,13	1.192.485,72
	HEFA60**	1.185.943,57	1.199.027,87	1.212.112,17
	HEFA70**	1.201.208,58	1.216.473,60	1.231.738,62

* Lipid content wt%
** HEFA conversion efficiency wt% yield.

When capital expenditures of *C. nivalis, B. braunii, E. oleoabundas and N.* gaditana are compared, in case of maximum yield from the conversion technologies, *C. nivalis* and *B. braunii* stand out with their higher capital expenditures. As the lipid content and efficiency of the conversion increase, the CAPEX increases. As an exception biofuel production from *C. nivalis* by HTL is not affected by the lipid content as much as other species; expenditures have lower variation amongst lipid content scenarios. In general, the installment plan is the most effective factor for capital expenditure where lipid content plays a mild determinant role. Conversion efficiency is also a determinant for some species. The capital expenditure of the conversion of *C. nivalis* by 96,6 % and 68 % have a wider gap whereas *B. braunii, E. oleoabundans* and *N. gaditana* are slightly variant over

conversion efficiencies. Below is Figure 4.11, comparing capital expenditures of each species with respect to lipid content, conversion efficiencies and installment plans.

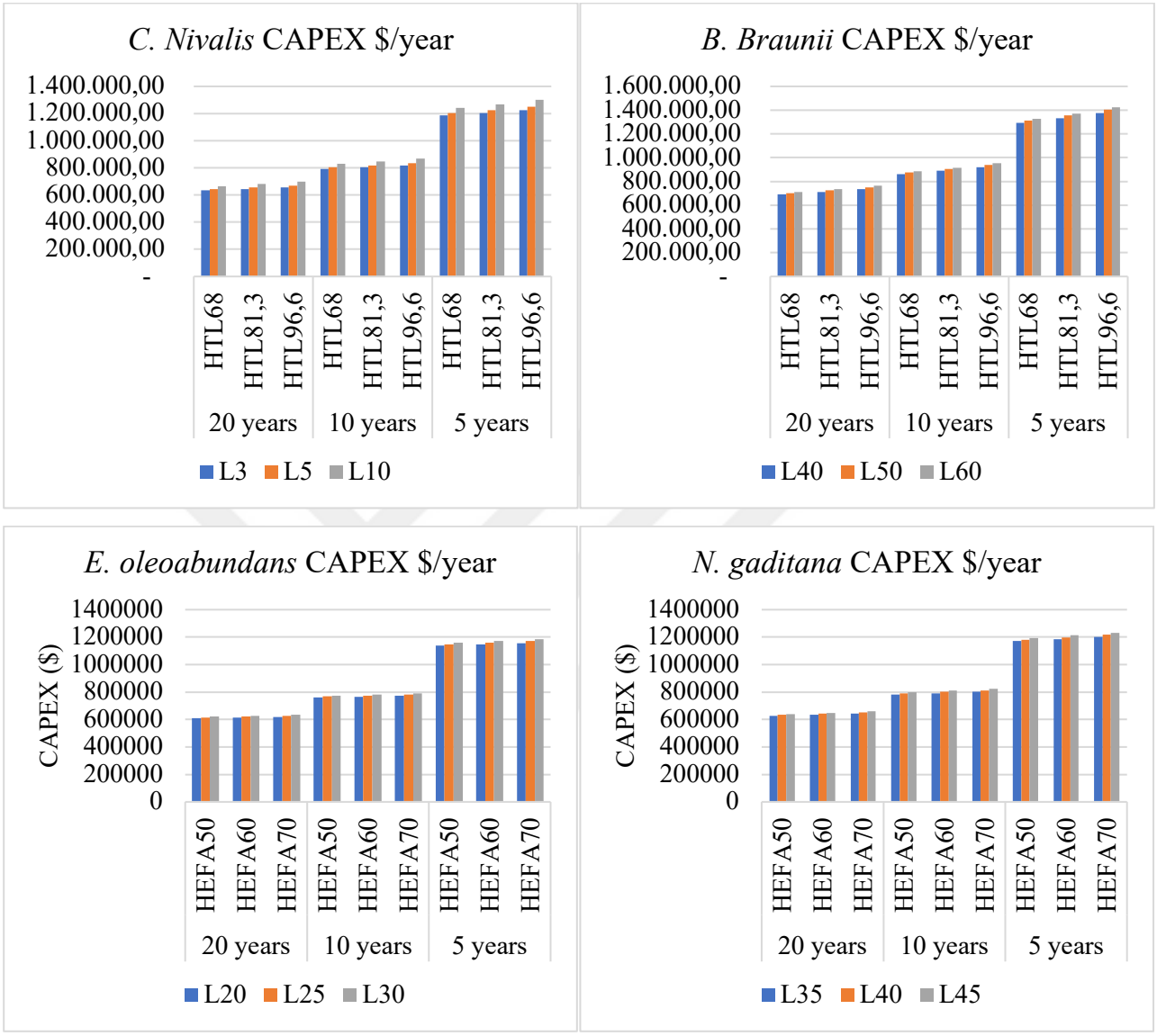


Figure 4.11. Capital expenditures of *C. nivalis*, *B. braunii*, *E. oleoabundans* and *N. gaditana* with respect to lipid content, conversion rate and installment plan.

Operational requirements, hence the expenses, vary from species to species. For *C. nivalis* and *B. braunii*, 0,024 $/gal was adopted from Jones et al. (2014) as the operational expenditure for producing one gallon of upgraded HTL biofuel. The operational expense was calculated to be 6,84 $/ton and was applied to biofuel yields current production capacity of IMBIYOTAB, presented in Chapter 4.1.2.4 for HTL. Operational expense for producing upgraded HTL bio-jet fuel regarding annual biofuel production capacity of the biorefinery is presented below in Figure 4.12. More detailed OPEX calculations for *C. nivalis* and *B. braunii* are presented in Table 4.20.

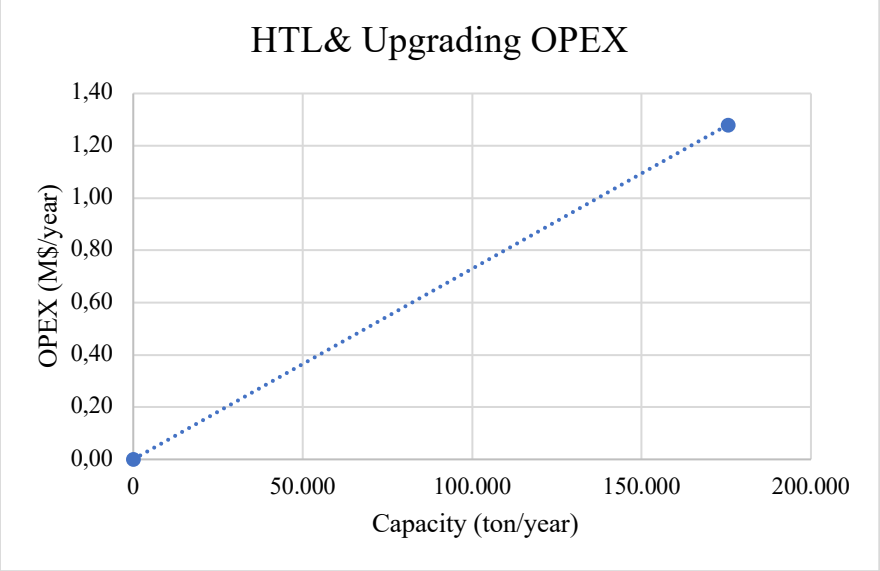


Figure 4.12. Operational HTL expenses regarding annual production capacity.

Table 4.20. Annual operational expense of producing upgraded HTL biofuel from *C. nivalis* and *B. braunii*.

C. nivalis **OPEX ($/year)**	**L3***	**L5***	**L10***
HTL68*	2.784,16	3.347,69	4.446,85
HTL81,3*	3.328,71	4.002,46	5.316,60
HTL96,6*	3.955,15	4.755,69	6.317,14

B. braunii **OPEX ($/year)**	**L40***	**L50***	**L60***
HTL68**	6.037,01	6.611,69	7.061,40
HTL81,3**	7.217,77	7.904,86	8.442,53
HTL96,6**	8.576,10	9.392,49	10.031,34

* Lipid content wt%
** HTL conversion efficiency wt% yield.

For *E. oleoabundans* and *N. gaditana*, 939 $/ton was adopted from Pearlson (2011) as the operational expenditure for producing 1ton of HEFA-jet fuel. The operational expenses are calculated with regards to biofuel yields from the current production capacity of IMBIYOTAB, presented in Chapter 4.1.3.2. Operational expenses regarding annual production capacity are presented below in Figure 4.13. More detailed OPEX calculations for *C. nivalis* and *B. braunii* are presented in Table 4.21.

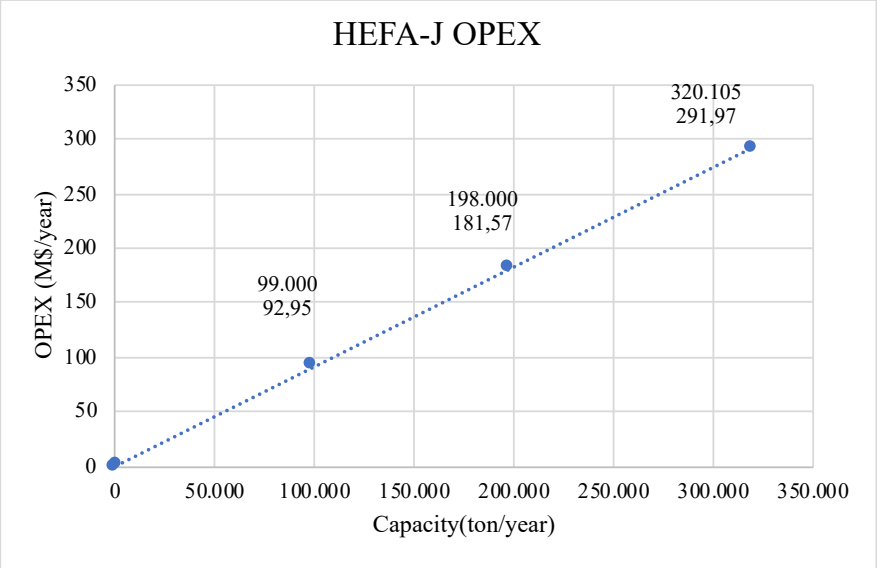


Figure 4.13. Operational HEFA expenses regarding annual production capacity.

Table 4.21. Annual operational expense of producing upgraded HEFA-jet fuel from *E. oleoabundans* and *N. gaditana.*

E. oleoabundans **OPEX ($/year)**	**L20***	**L25***	**L30***
HEFA50**	225.333,33	281.666,67	338.000,00
HEFA60**	270.400,00	338.000,00	405.600,00
HEFA70**	315.466,67	394.333,33	473.200,00

N. gaditana **OPEX($/year)**	**L35***	**L40***	**L45***
HEFA50**	394.333,33	450.666,67	507.000,00
HEFA60**	473.200,00	540.800,00	608.400,00
HEFA70**	552.066,67	630.933,33	709.800,00

* Lipid content wt%
** HEFA conversion efficiency wt% yield.

Total annual costs of CAPEX and OPEX, which could also be referred to as annual production cost, for scenarios of *C. nivalis, B. braunii, E. oleoabundas and N. gaditana* in accordance with each year of investment are presented below in Tables 4.22, 4.23, 4.24 and 4.25 respectively. As expected, total CAPEX and OPEX are at the lowest when the investment period is the longest. The annual total expenses increase as the time period shortens, lipid content increases and conversion efficiency increases.

Table 4.22. Total annual expense of producing biofuel from *C. nivalis* via HTL regarding installment scenarios.

C. nivalis **CAPEX + OPEX $/year**		**L3***	**L5***	**L10***
20 years	**HTL68****	637.936,44	648.433,29	668.907,34
	HTL81,3**	648.079,77	660.629,68	685.108,22
	HTL96,6**	659.748,42	674.660,12	703.745,32
10 years	**HTL68****	794.936,37	807.888,58	833.151,81
	HTL81,3**	807.452,38	822.937,89	853.142,31
	HTL96,6**	821.850,49	840.250,25	876.138,90
5 years	**HTL68****	1.188.776.0	1.207.887,6	1.245.164,6
	HTL81,3**	1.207.244,0	1.230.093,5	1.274.661,5
	HTL96,6**	1.228.489,0	1.255.638,7	1.308.594,0

* Lipid content wt%
** HTL conversion efficiency wt% yield.

Total production cost, including annual CAPEX and OPEX, for a year in a 20-years scenario, varies between 638 K$/year to 704 K$/year according to the lipid content and conversion efficiency while it ranges between 795K-876K $/year for 10-year scenario and 1,2 M-1,3M $/year for the 5-year scenario. Although the total production costs change slightly when conversion efficiency or lipid content changes, the prices increase drastically as the period of investment shortens.

Table 4.23. Total annual expense of producing biofuel from *B. braunii* via HTL regarding installment scenarios.

B. braunii **CAPEX + OPEX $/year**		**L40***	**L50***	**L60***
20 years	**HTL68****	698.527,16	709.231,87	717.608,56
	HTL81,3**	720.521,33	733.319,75	743.334,82
	HTL96,6**	745.822,89	761.029,87	772.929,70
10 years	**HTL68****	869.700,13	882.908,83	893.244,95
	HTL81,3**	896.839,06	912.631,21	924.988,96
	HTL96,6**	928.059,02	946.823,13	961.506,51
5 years	**HTL68****	1.299.093,35	1.318.583,37	1.333.834,79
	HTL81,3**	1.339.138,06	1.362.440,11	1.380.674,53
	HTL96,6**	1.385.204,54	1.412.891,84	1.434.557,83

* Lipid content wt%
** HTL conversion efficiency wt% yield.

Even though *B. braunii* has higher lipid contents than *C. nivalis,* the total cost of production is higher for *B. braunii.* This is primarily caused by the productivities of the species. Although *B. braunii* has higher productivity thus, yields in higher amounts of biomass whereas *C. nivalis* has lower lipid content and yields lower amounts of biomass. Thus HTL, utilizing the whole algae

biomass, yields higher when the biomass amount fed is higher. Following that, as the processing time is longer, utilities used are much more and the workforce required is greater, the production prices for *B. braunii* are higher.

Table 4.24. Total annual expense of producing bio-jet fuel from *E. oleoabundans* via HEFA regarding installment scenarios.

E. oleoabundans **CAPEX+OPEX $/year**		**L20***	**L25***	**L30***
20 years	**HEFA50****	834.766,55	896.939,25	959.111,95
	HEFA60**	884.504,71	959.111,95	1.033.719,18
	HEFA70**	934.242,87	1.021.284,64	1.108.326,42
10 years	**HEFA50****	985.409,13	1.049.025,22	1.112.641,32
	HEFA60**	1.036.302,00	1.112.641,32	1.188.980,64
	HEFA70**	1.087.194,88	1.176.257,42	1.265.319,95
5 years	**HEFA50****	1.363.301,13	1.430.538,04	1.497.774,96
	HEFA60**	1.417.090,66	1.497.774,96	1.578.459,26
	HEFA70**	1.470.880,19	1.565.011,88	1.659.143,57

* Lipid content wt%
** HEFA conversion efficiency wt% yield.

When *E. oleoabundans* and *N. gaditana* are compared, there is a distinct difference between the annual production prices. The difference is primarily caused by the lipid contents of the species as the HEFA technology utilizes the lipid contents of the biomass. The highest lipid content and highest conversion efficiency with 5-year installment achieve to catch up with lowest lipid content and mid conversion efficiency with 5-year installment at 1,66 M$/ year.

Table 4.25. Total annual expense of producing bio-jet fuel from *N. gaditana* via HEFA regarding installment scenarios.

N. gaditana **CAPEX+OPEX $/year**		**L35**	**L40**	**L45**
20 years	**HEFA50**	1.021.284,64	1.083.457,34	1.145.630,03
	HEFA60	1.108.326,42	1.182.933,65	1.257.540,89
	HEFA70	1.195.368,19	1.282.409,97	1.369.451,74
10 years	**HEFA50**	1.176.257,42	1.239.873,51	1.303.489,61
	HEFA60	1.265.319,95	1.341.659,27	1.417.998,59
	HEFA70	1.354.382,49	1.443.445,03	1.532.507,56
5 years	**HEFA50**	1.565.011,88	1.632.248,80	1.699.485,72
	HEFA60	1.659.143,57	1.739.827,87	1.820.512,17
	HEFA70	1.753.275,25	1.847.406,94	1.941.538,62

* Lipid content wt%
** HEFA conversion efficiency wt% yield.

Below is Figure 4.14, comparing total annual capital and operational expenses, annual production costs, of each species with respect to lipid content, conversion efficiencies and installment plans.

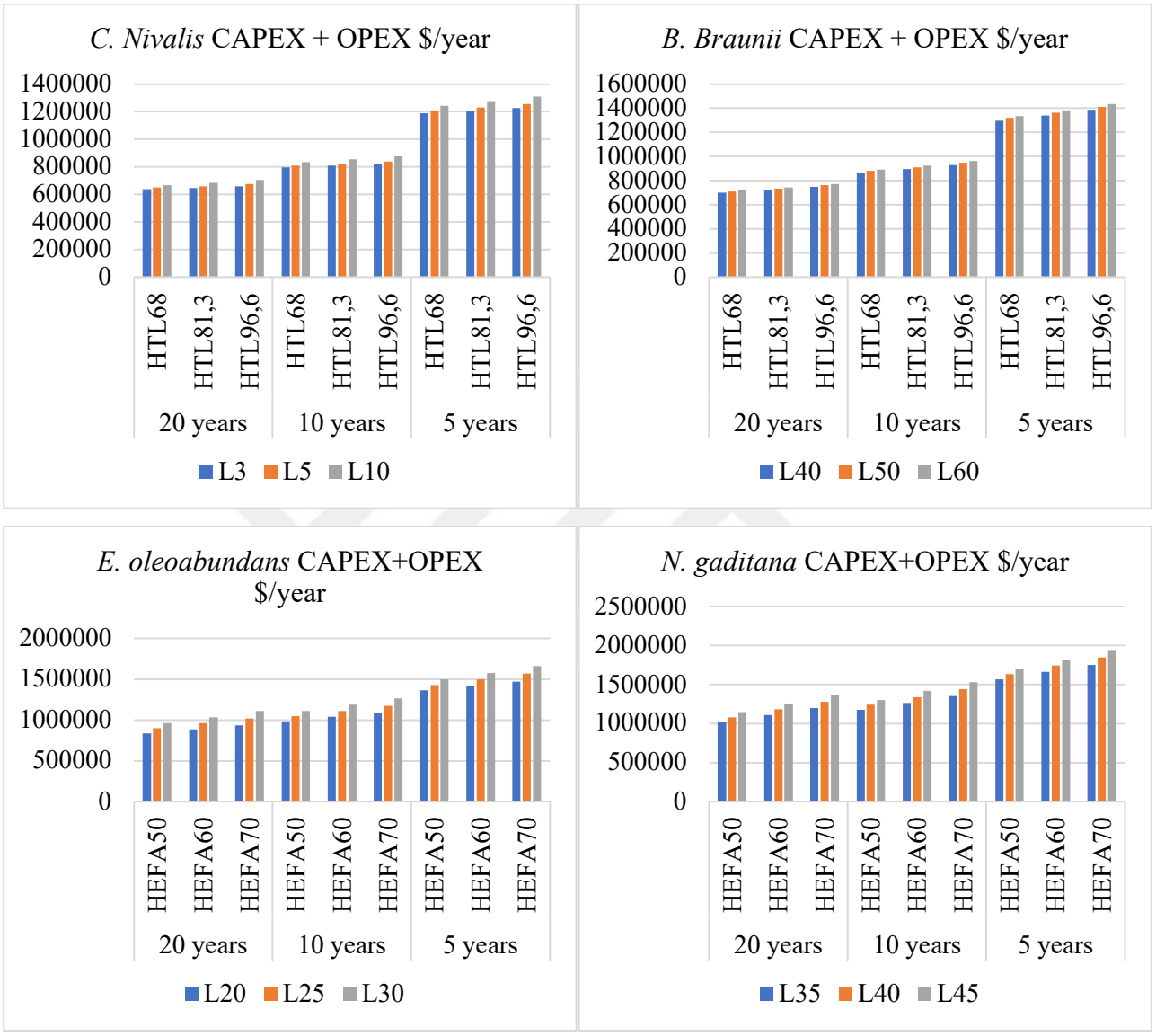


Figure 4.14. Annual production costs of each species with respect to lipid content, conversion efficiencies and installment plans.

While the annual production costs of *C. nivalis* and *B. braunii* remain below 1,5 M$/year, the annual production costs of *E. oleoabundans* and *N. gaditana* exceed 1,5 M$/year, *N. gaditana* getting closer to 2 M$/year. The operational cost difference of the conversion technologies HTL and HEFA is the foremost cause of production cost differences followed by lipid contents and specie productivities.

4.2.6. Minimum Fuel Selling Prices

The minimum fuel selling prices (MFSP) of the bio-jet fuels obtained via different technologies are primarily determined by the capital expenses and operational expenses. In addition, the return on investment, showing how feasible and desirable an investment is, is expected to be set higher than 15 %. Thus, the MFSP is adjusted that the ROI is higher than 15 % and the investment is feasible.

While the MFSP has to cover the capital cost, operational cost and have a ROI above 15 %, it also has to be competitive with the conventional products in order to be viable as a substitute. Below, in Table 4.26, 4.27, 4.28 and 4.29 are the MFSP per ton bio-jet fuel for each species.

Table 4.26. Minimum fuel selling price for *C. nivalis* bio-jet fuel obtained via HTL technology, with respect to lipid content, conversion efficiency and installment plan.

C. nivalis **MFSP $/ton**		**L3***	**L5***	**L10***
20 years	**HTL68****	10.405,94	8.790,68	6.818,13
	HTL81,3**	8.836,18	7.485,17	5.835,31
	HTL96,6**	7.565,01	6.427,98	5.039,43
10 years	**HTL68****	12.976,44	10.961,92	8.501,78
	HTL81,3**	11.018,66	9.333,70	7.276,01
	HTL96,6**	9.433,27	8.015,18	6.283,41
5 years	**HTL68****	19.424,62	16.408,52	12.725,26
	HTL81,3**	16.493,48	13.970,79	10.890,08
	HTL96,6**	14.119,88	11.996,74	9.403,97

* Lipid content wt%
** HTL conversion efficiency wt% yield.

Table 4.27. Minimum fuel selling price for *B. braunii* bio-jet fuel obtained via HTL technology, with respect to lipid content, conversion efficiency and installment plan.

B. braunii **MFSP $/ton**		**L40***	**L50***	**L60***
20 years	**HTL68****	5.235,67	4.851,02	4.593,69
	HTL81,3**	4.511,73	4.190,00	3.974,77
	HTL96,6**	3.925,48	3.654,72	3.473,57
10 years	**HTL68****	6.528,16	6.048,43	5.727,49
	HTL81,3**	5.625,27	5.224,02	4.955,58
	HTL96,6**	4.894,11	4.556,42	4.330,50
5 years	**HTL68****	9.770,41	9.052,17	8.571,67
	HTL81,3**	8.418,62	7.817,88	7.415,98
	HTL96,6	7.323,95	6.818,36	6.480,12

* Lipid content wt%
** HTL conversion efficiency wt% yield.

Table 4.28. Minimum fuel selling price for *E. oleoabundan*s bio-jet fuel obtained via HEFA technology, with respect to lipid content, conversion efficiency and installment plan.

E. oleoabundans **MFSP $/ton**		**L20***	**L25***	**L30***
20 years	**HEFA50****	17.867,59	14.611,61	12.440,96
	HEFA60**	15.154,28	12.440,96	10.632,09
	HEFA70**	13.216,19	10.890,50	93.40,03
10 years	**HEFA50****	22.052,11	17.991,30	15.284,10
	HEFA60**	18.668,10	15.284,10	13.028,10
	HEFA70**	16.250,96	13.350,38	11.416,67
5 years	**HEFA50****	32.549,11	26.469,36	22.416,20
	HEFA60**	27.482,65	22.416,20	19.038,57
	HEFA70**	23.863,76	19.521,09	16.625,97

* Lipid content wt%
** HEFA conversion efficiency wt% yield.

Table 4.29. Minimum fuel selling price for *N. gaditana* bio-jet fuel obtained via HEFA technology, with respect to lipid content, conversion efficiency and installment plan.

N. gaditana **MFSP $/ton**		**L35***	**L40***	**L45***
20 years	**HEFA50****	10.890,50	9.727,65	8.823,21
	HEFA60**	93.40,03	8.370,99	7.617,29
	HEFA70**	82.32,56	7.401,95	6.755,92
10 years	**HEFA50****	13.350,38	11.900,10	10.772,09
	HEFA60**	11.416,67	10.208,09	92.68,09
	HEFA70**	10.035,44	8.999,52	8.193,81
5 years	**HEFA50****	19.521,09	17.349,75	15.660,93
	HEFA60**	16.625,97	14.816,53	13.409,18
	HEFA70**	14.558,03	13.007,08	11.800,78

* Lipid content wt%
** HEFA conversion efficiency wt% yield.

Comparisons of minimum fuel selling prices of *C. nivalis, B. braunii, E. oleoabundas and N. gaditana* are presented below in Figure 4.15. The MFSP differs from species to species, technology to technology accordingly with lipid content and conversion efficiency. MFSP for *C. nivalis* ranges between 5,2-6,5 K$/ton. While the MFSP is lowest at the combination of highest conversion efficiency, highest lipid content and longest installation period, it is highest at the combination of lowest lipid content, lowest conversion efficiency and shortest installment period. This principle applies to each species. The prices are at the highest when the biofuel yield is at the lowest and the installment plan is at the shortest. The prices are at the lowest when the biofuel yield is at highest and the installment plan is at the longest.

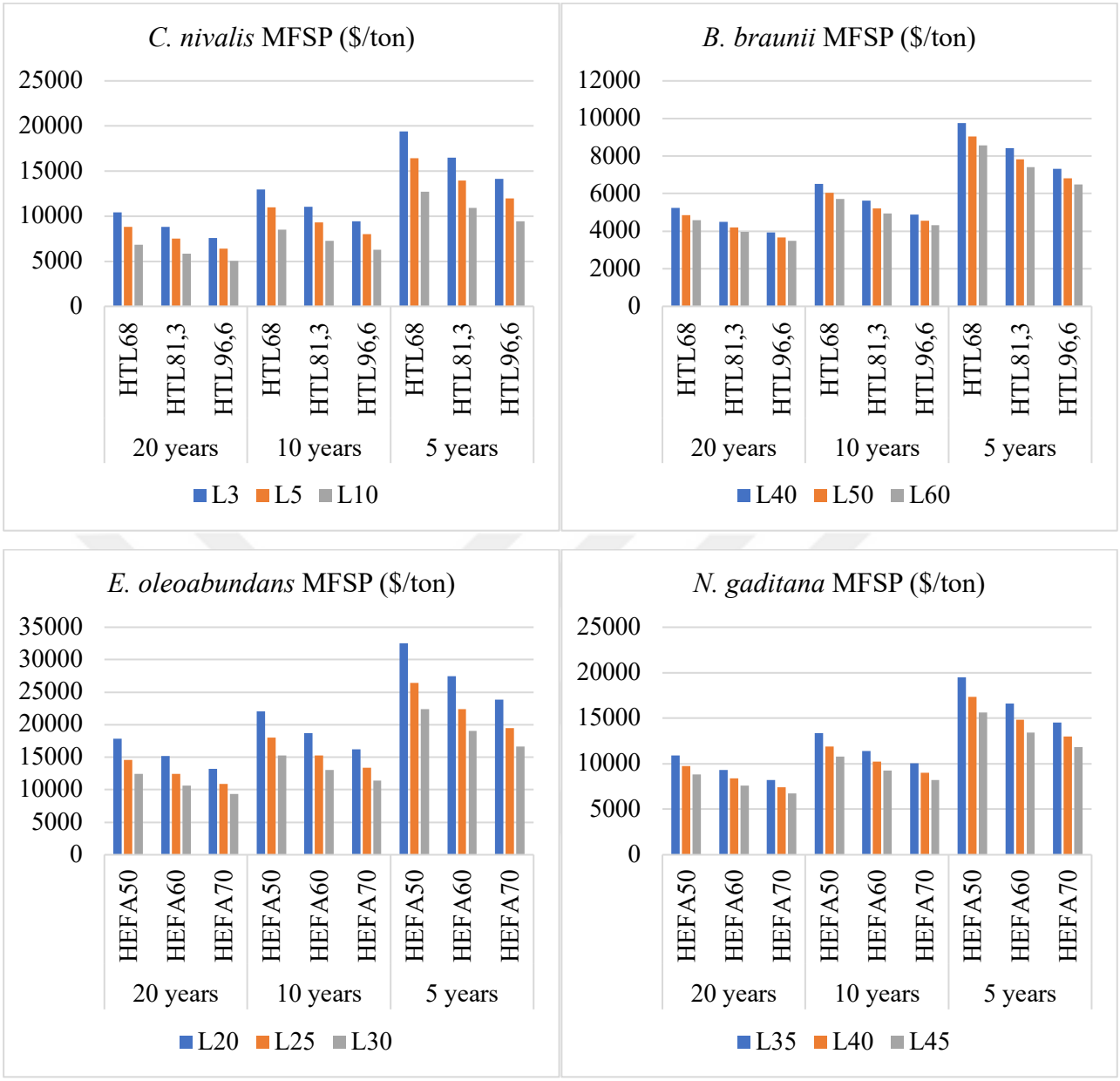


Figure 4.15. Minimum fuel selling prices of each species with respect to lipid content, conversion efficiencies and installment plans.

Table 4.30. Average MFSP for of *C. nivalis, B. braunii, E. oleoabundas* and *N. gaditana.*

Average MFSP	**$/ton**
C. nivalis	10.238,43
B. braunii	5.850,73
E. oleoabundans	17.418,63
N. gaditana	11.409,39

Average MFSP for each species without regarding lipid content, conversion efficiency and installment plan are presented above in Table 4.30. These results give a broad understanding of an average scenario and the most likely MFSP to be obtained. *B. braunii is followed* by *C. nivalis, N.*

gaditana and E. oleoabundans from lowest MFSP to highest. Production of bio-jet fuel from *B. braunii* via HTL technology is the most likely option to compete with commercial biofuels. Although *C. nivalis* has the lowest lipid content, it has the second-lowest MFSP, once more indicating that HTL technology has lower production costs compared with HEFA and is more likely to compete against commercial technologies used for petroleum-based fuels.

When bio-jet fuel is blended with Jet A-1 by the ratio 50-50 %, approved by ASTM D7655, the MFSPs exceed the market price of Jet A-1 and fail the chance to be commercialized as a substitute to Jet A-1, as presented in Table 4.31 below.

Table 4.31. MFSP for 50 % bio-jet fuel blend with Jet A-1.

	Bio-jet MFSP ($/ton)	**Jet A-1 ($/ton)**	**50 % Bio-jet blend MFSP ($/ton)**
C. nivalis	10.238,40	603,2	5.420,80
B. braunii	5.850,70	603,2	3.226,95
E. oleoabundans	17.418,60	603,2	9.010,90
N. gaditana	11.409,40	603,2	6.006,30

2021 price of Jet A-1 is noted as 603,2 $/ton by IATA. Hence, commercialization of bio-jet fuel for 50-50 % blending rate is not feasible with the current MFSP. Decreasing the blending ratio of bio-jet fuel will increase the chances of competition with commercial jet fuel. MFSPs for 5 % bio-jet fuel blended with 95 % Jet A-1 are presented below in Table 4.32.

Table 4.32. MFSP for 5 % bio-jet fuel blend with Jet A-1.

	Bio-jet MFSP ($/ton)	**Jet A-1 ($/ton)**	**5 % Bio-jet blend MFSP ($/ton)**
C. nivalis	10.238,40	603,2	1.084,96
B. braunii	5.850,70	603,2	865,58
E. oleoabundans	17.418,60	603,2	1.443,97
N. gaditana	11.409,40	603,2	1.143,51

Blending the obtained bio-jet fuel by 5 % with 95 % Jet A-1 deduces prices of 1085 $/ton, 865,6 $/ton, 1444 $/ton and 1143,5 $/ton for *C. nivalis, B. braunii, E. oleoabundans* and *N. gaditana* respectively. The obtained prices for the blends are higher than conventional Jet A-1 thus, it is non-viable to commercially use 5 % blends if produced under the assumptions within this study.

Table 4.33. MFSP for 1 % bio-jet fuel blend with Jet A-1.

	Bio-jet MFSP ($/ton)	Jet A-1 ($/ton)	1 % Bio-jet blend MFSP ($/ton)
C. nivalis	10.238,40	603,2	699,55
B. braunii	5.850,70	603,2	655,68
E. oleoabundans	17.418,60	603,2	771,35
N. gaditana	11.409,40	603,2	711,26

Although biofuels are approved to be used as 50 % blends for the aviation sector, blending high concentrations of bio-jet fuel with Jet A-1 is not viable. On the other hand, decreasing the blend ratio of biofuel will decrease the MFSP but, it will also negatively affect the sustainability goals. Above in Table 4.33, are the MFSPs for 1 % bio-jet fuel blend. The 1 % blend with 99 % Jet A-1 deduces prices of 699,5 $/ton, 655,7 $/ton, 771,4 $/ton and 711,3 $/ton for *C. nivalis, B. braunii, E. oleoabundans* and *N. gaditana* respectively. The MFSP results indicate that 1 % blends of biofuel have the potential to compete with commercial aviation fuel as the differences between selling price of petroleum-based fuel and 1 % blends are lower than 5 % blends. Further decrease in the MFSP could be obtained by utilizing the by-products, carbon capturing, developing the conversion technologies or increasing the production capacities. These adjustments are foreseen to increase the operational expenses but also to increase the net income in the long run.

4.2.7. Carbon Capturing

Algae are known to utilize atmospheric carbon dioxide and utilize it as algae oil. Using the advantage of algae, IMBIYOTAB integrates carbon capturing for producing carbon-negative bio-jet fuel. Sayre (2010) states that algae are capable of capturing 1,6 g carbon dioxide for 1 g of algal biomass produced. On the other hand, conversion of biomass to bio-jet fuel with HTL technology emits 20,5 g CO_2eq/MJ, indicated by Nie and Bi (2018). In addition, carbon emissions from HEFA technology for bio-jet fuel is reported as 37,5 g CO_2eq/MJ by Zemanek et al. (2020).

As of June 2021, the market price of carbon is 60 $/ton to be sold for carbon offsetting where carbon-emitting sources compensate their emissions by funding the carbon savings of a sink. The captured carbon dioxide could be sold and will reduce the MFSP of the obtained bio-jet fuel. Lozano et al. (2020) reports that even in the best scenario the MFSP could be decreased by 15 % by carbon capturing for HTL fuels, including the CAPEX and OPEX of collection and storage of carbon dioxide. Average year-round carbon capturing for species used in bio-jet fuel production are presented in Table 4.34 below.

Table 4.34. Average carbon capture of bio-jet fuel production from microalgae.

	Average bio-jet fuel production (ton/year)	Average bio-jet fuel production (MJ/year)	Total Carbon Emission (ton CO_2/ MJ biofuel/year)	Total Carbon Capture (ton CO_2/year)	Net Carbon Capture (ton CO_2/year)	Cost reduction by carbon capturing ($/ton)
C. nivalis	621,64	26.108.678,40	535,23	1.536,00	1.000,77	96,6
B. braunii	1.158,22	48.645.315,04	997,23	1.536,00	538,77	28,0
E. oleoabundans	360,00	15.120.000,00	309,96	1.536,00	1.226,04	204,3
N. gaditana	576,00	24.192.000,00	495,94	1.536,00	1.040,06	108,3

The total carbon emissions are calculated accordingly with the HTL and HEFA technologies and the bio-jet fuel production yields. Total carbon captures are calculated by including dry biomass yields and carbon capturing capacity of algae. Net carbon captures account for the net carbon captured throughout the life-cycle of bio-jet fuel. Cost reductions are calculated in accordance with the market price of carbon dioxide and the amount captured.

Since each species have a different biofuel yield and processed with different technologies, total carbon emissions and total carbon captures differ, resulting in various reduction rates in the MFSP. A detailed presentation of the revised MFSPs considering carbon capture reductions is presented below in Table 4.35.

Table 4.35. Revised MFSP with carbon capture for 1 %, 5 % and 50 % blends of bio-jet fuel with Jet A-1.

	50 % Blend Revised MFSP ($/ton)	5 % Blend Revised MFSP ($/ton)	1 % Blend Revised MFSP ($/ton)	100 % Jet A-1 Fuel Price ($/ton)
C. nivalis	5.324,21	988,37	602,96	603,2
B. braunii	3.199,04	837,66	627,76	603,2
E. oleoabundans	8.806,56	1.239,63	567,01	603,2
N. gaditana	5.897,96	1.035,17	602,92	603,2

When compared with MFSPs without carbon capturing, the revised MFSP with carbon capturing are more likely solutions for replacing non-renewable petroleum-based jet fuels. MFSP for 50 % blends and 5 % are still not economically viable but, 1 % blend MFSPs are competitive and show promise to be commercialized as a replacement for petroleum-based jet fuels. MFSP for *C. nivalis, E. oleoabundans* and *N. gaditana* are obtained to be lower than the conventional fuel price of 603,2 $/ton while the price of *B. braunii* is still higher.

4.3. Production of Astaxanthin from Microalgae

Besides being prominent with the amount of oil accumulation and their contribution to biofuel production, microalgae are important sources of carotene. Although microalgae are attractive sources for biofuel production, their economic viability is still under investigation. High-value products, other than fuel, produced from algae contribute to the economic suitability of algae since their selling prices are much higher than fuel.

Among carotenoids, astaxanthin is the most valuable carotenoid produced by microalgae, and *Haematococcus pluvalis* has the highest astaxanthin content among all microalgae (Del Rio et al., 2008; Benarjee and Ramaswamy, 2017). It is heavily used in cosmetics and pharmaceuticals as an anti-aging and anti-inflammatory agent (Borowitzka, 2013). Synthetic (fossil-fuel-based) astaxanthin ranges from 2.000$/kg to 7.000$/kg in the market and it holds risk to health in addition to its risks to sustainability (Benarjee and Ramaswamy, 2017). Against all these risks, algae-based astaxanthin promises a sustainable and harmless to health substitute.

4.3.1. Cultivation and Dewatering

For most effective astaxanthin accumulation, the cultivation of *Haematococcus pluvalis* has two stages. The first stage of cultivation starts in the PBRs, for stimulating algae growth, and the second stage continues in the ORPs for stimulating astaxanthin accumulation and limiting cell division and growth by nutrient starvation (Fabregas et al., 2001). Dewatering *Haematococcus pluvalis* also has two stages. The first stage includes the addition of organic flocculants and the second stage is centrifugation (Li et al., 2011; Li et al., 2013).

The dewatering process is very energy-intensive, depending on the market value of the final product, the centrifuge process is often found infeasible. In this case, astaxanthin is a very high-value product and can compensate the costs of energy-intensive processes accordingly with the production capacity.

4.3.2. Extraction

The extraction process of the astaxanthin from the microalgae is the most crucial and quality determinate state in astaxanthin production. The commercialization potential, feasibility, market selling price and the quality of the astaxanthin are heavily dependent on the extraction phase.

Haematococcus pluvalis, because of its hard exterior, requires a three-phase extraction; cell disruption followed by cell dehydration and recovery of the astaxanthin compound (Benarjee and Ramaswamy, 2017). Cell disruption is obtained by bead milling and followed by spray drying for dehydration, yielding 95 wt % of the dry biomass (Mendes-Pinto et al., 2001). The bead milling and spray drying thins the walls of the cell and enables retrieving of the astaxanthin content. The process flow diagram for astaxanthin production is presented below in Figure 4.16.

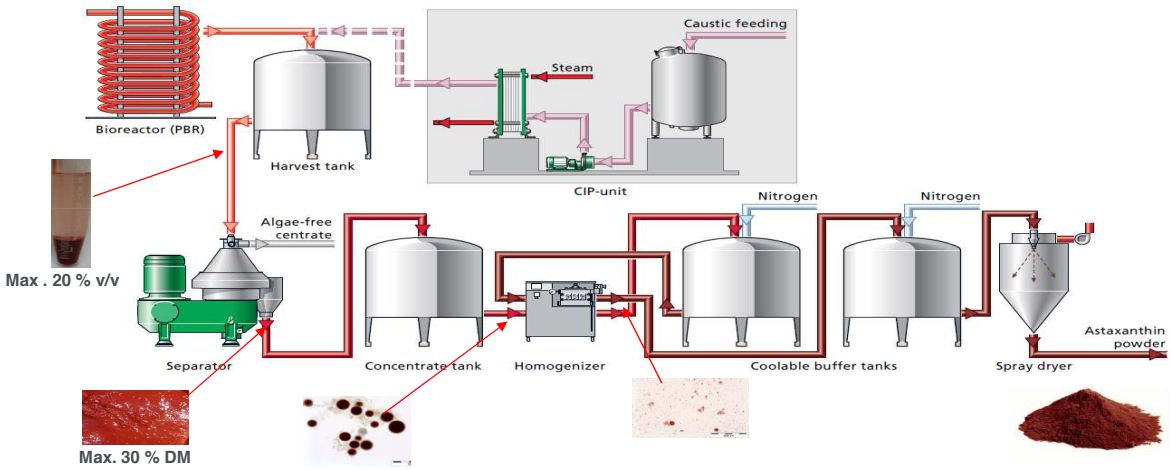


Figure 4.16. Process flow for Astaxanthin powder from PBR at IMBIYOTAB.

4.4. Results of Techno-Economic Assessment for Astaxanthin Production

The productivity of astaxanthin varies accordingly with the geospatial conditions. 0,35 kg/ton, 0,42 kg/ton and 0,38 kg/ton astaxanthin production rates were noted by Benarjee and Ramaswamy (2017) for Albuquerque, Phoenix and San Diego, US respectively.

In this study, astaxanthin production of 0,38 kg/ton is assumed and a TEA is conducted to assess the feasibility of 0,38 kg/ ton production in IMBIYOTAB with 2400 ton yearly wet algae processing capacity. Productivity and cost estimates were adopted from Li et al. (2011), Shah et al. (2016) and Benarjee and Ramaswamy (2017).

4.4.1. CAPEX and OPEX

Construction, installation and equipment of biorefinery were assumed to be the exact cost of IMBIYOTAB facility. CAPEX includes construction, upstream equipment such as the cultivation reactors and downstream equipment such as spray dryers. OPEX mainly includes the labor costs, utilities, consumables and contingencies. Land prices and electricity expenses were neglected since the property is owned by Bogazici University and operates with wind power supplied by the wind turbine in the property.

The production rate of 0,38 kg/ton was adjusted accordingly to 2400-ton capacity to a 913 ton/year production of astaxanthin if the whole capacity of the facility is devoted to *Haematococcus pluvalis* and astaxanthin only. Detailed results of CAPEX and OPEX are presented below in Tables 4.36 and 4.37.

Table 4.36. Total capital expenditure for production of astaxanthin.

Installed costs	Upstream equipment	691.302,51
	Downstream equipment	1.977.140,00
	Total installed cost (TIC)	**2.668.442,51**
Direct costs	Buildings (1 % TIC)	26.684,43
	Site development (9 % TIC)	240.160,00
	Additional piping (4.5 % TIC)	120.079.91
	Total direct cost (TDC) (accounted in FCI)	**386.924,34**
Indirect costs)	Prorated expenses (10 % TDC)	38.692,43
	Home office and construction fees (20 % TDC)	77.384,87
	Field expenses (10 % TDC)	38.692,43
	Project contingency (10 % TDC)	38.692,43
	Startup and permits (5 %) TDC	19.346,22
	Total indirect cost	**212.808,39**
Fixed costs	**Capital investment (FCI)**	1.000.000,00
	Total CAPEX	**3.881.250,90**

Table 4.37. Total operational expenditure for astaxanthin production.

Operating Expenses	OPEX($/year)	OPEX ($/kg)
Raw materials	20.225,60	0,022
CO_2 distribution	4.400,00	0,005
Water (with recycling)	11.334,40	0,012
Labor (10 people)	40.000,00	0,044
Maintenance (3 % TIC)	80.053,27	0,088
Operating supply	432,80	0,000
Contingencies & Overhead (5 % TDC+TIDC)	5.000,00	0,005
Overhead	30.000,00	0,033
TOTAL OPEX ($/year)	**191.446,07**	**0,210**

Major contributors to the selling price of astaxanthin appear as maintenance by 50 %, labor with 25 % and overhead costs by 19 %, followed by raw material costs by 13 %. The distribution of the major contributors of OPEX/year and OPEX/kg astaxanthin are presented below in Figure 4.17.

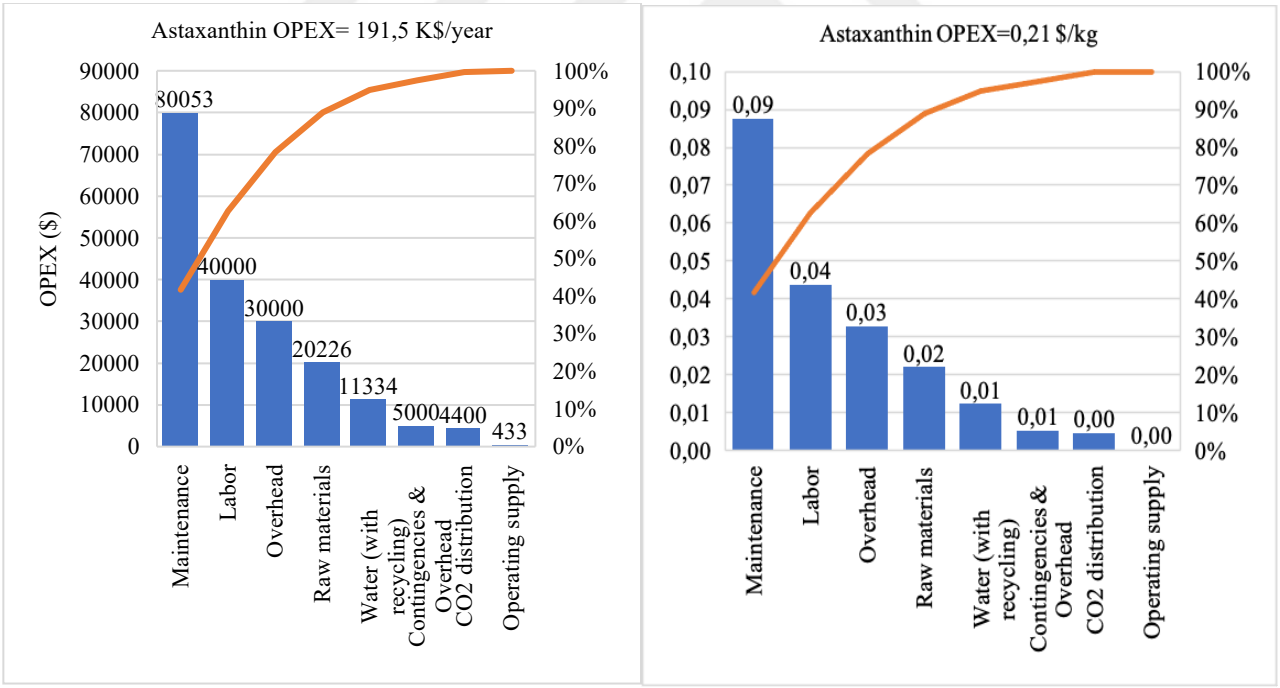


Figure 4.17. Major contributors to annual operational expenses and operational cost per kg astaxanthin.

4.4.2. Return on Investment and Payback Period

In order to be feasible for commercialization, the economic viability of the production of Astaxanthin is assessed with economic measures. ROI, return on investment, is a widely used tool for deciding the strength and viability of an investment. ROI should be equal to or greater than 15 % in order to indicate that the investment is desirable. ROI and the payback period of the investment are calculated with Equation 4.2 and 4.3, revisited from Chapter 3.

$$ROI = \frac{Net\ Annual\ Cash\ Flow \times 100\%}{Total\ Investment} \quad (4.2)$$

$$Payback\ Priod(years) = \frac{Total\ Investment}{Net\ Annual\ Cash\ Flow} \quad (4.3)$$

Table 4.38. Total net revenues, ROI and payback period from astaxanthin with various selling prices.

Astaxanthin ($/kg)	Net Revenue ($/year)	ROI %	Payback (years)
850,0	584.603,93	15,06	6,64
900,0	630.253,93	16,24	6,16
1.000,0	721.553,93	18,59	5,38
2.000,0	1.634.553,93	42,11	2,37
3.000,0	2.547.553,93	65,64	1,52
4.000,0	3.460.553,93	89,16	1,12
5.000,0	4.373.553,93	112,68	0,89
6.000,0	5.286.553,93	136,21	0,73
7.000,0	6.199.553,93	159,73	0,63

Market prices ranging from 850 $/kg to 7000 $/kg were used to calculate ROI. The calculations are presented in Table 4.38. The MFSP, with a ROI of 15 %, was reached by 850 $/kg with a 6,6 years payback period and, the prices lower than 850 $/kg were found to be infeasible for effective investment. Selling prices above 850 $/kg were found to have desirable returns on investment. Prices of 900 $/kg and 1.000 $/kg had 16,2 % and 18,6 % returns of investment with 6 and 5,3 years of payback time while 2.000 $/kg and 3.000 $/kg prices had 42 % and 65,6 % ROIs with 2,3 and 1,5 years of payback. Prices higher than 4.000 $/kg had ROIs greater than 89 % and return times of 1 or fewer years.

4.5. Production of Beta-Carotene from Microalgae

Beta-carotene is an orange-colored pigment, generally used as a food coloring agent, antioxidant and vitamin A supply. It is known to reduce the oxidative stress on the body and protect against heart diseases, cancer and cognitive disorders such as Alzheimer's disease. It is mostly found in fungi, plants fruits and some algae. Exploration of the presence of beta-carotene in *Dunaliella Salina* goes back to the 1960s when Aasen et al. (1969) took notice of its high carotene capability. With this discovery, in the 1960s, research to use algae as a source for commercial beta-carotene production started and beta-carotene has been commercially marketed since 1985 (Borowitzka and Borowitzka, 1990).

4.5.1. Cultivation, Harvesting, Dewatering and Drying

The production of beta-carotene is very similar to the astaxanthin production processes. Dunaliella salina species are cultivated in PBPs, with 2400 ton/year wet algae processing capacity. Harvested algae are then centrifuged and undergo a spray drying process. The dry algae powder that comes out at the end of this spray drying process is rich in beta-carotene and is ready for consumption as a beta-carotene supplement. For further extraction aimed to produce pigments, cell disruption could be obtained by high-pressure homogenizers. Process flow diagram for beta-carotene production from microalgae can be found in Figure 4.18.

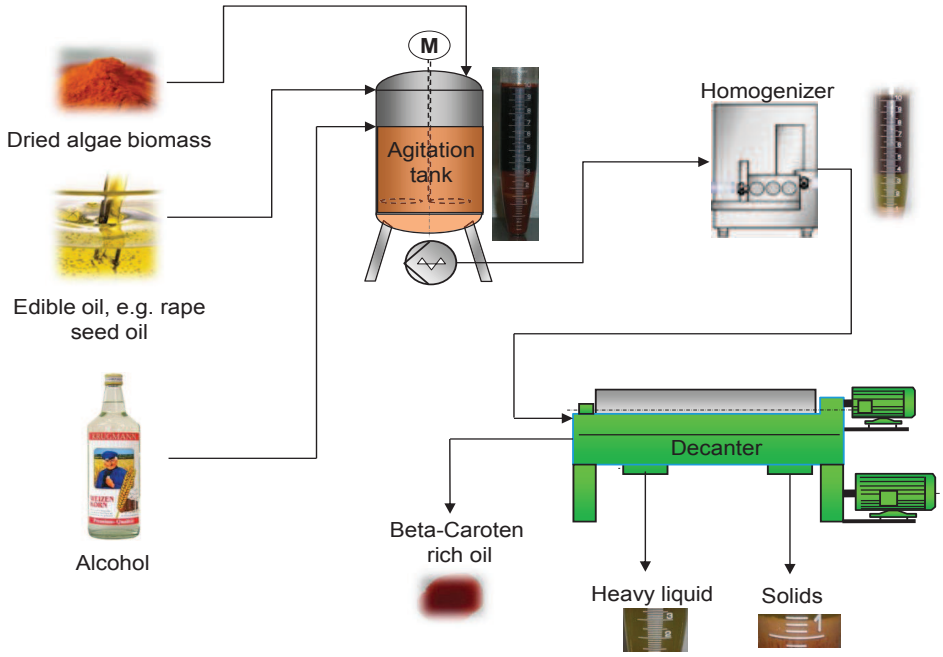


Figure 4.18. Process flow for beta-Carotene extraction at IMBIYOTAB.

4.6. Results of Techno-Economic Assessment for Beta-Carotene Production

Productivities ranging between 0,75 g/m2 and 3,0 g/m2 AFDW and total carotenoid content of 60-90 g/kg AFDW were noted by CORDIS-EU (2013). Also, Zhang et al. (2014) reported obtaining 138,3 mg/g of beta-carotene in *D. salina.* Assumptions for *D. salina* productivity and beta-carotene production in this study are adopted from Kleinergis et al. (2011) as 13,5 mg beta-carotene/ L reactor volume and 6-14 wt% beta-carotene. When the productivity from Kleinergis et al. (2011) is adapted to 2400 ton/year capacity, it yields 32,4 ton/year beta-carotene production.

4.6.1. CAPEX and OPEX

The CAPEX and OPEX are taken as the exact costs of IMBIYOTAB since no extra equipment is needed to be purchased for cultivation, harvesting or dewatering and, no further extraction is applied to the beta-carotene other than spray drying. The CAPEX includes construction, upstream equipment such as the cultivation reactors and downstream equipment such as spray dryers. OPEX mainly includes the labor costs, utilities, consumables and contingencies. Land prices and electricity expenses are neglected since the property is owned by Bogazici University and operates with wind power supplied by the wind turbine in the property A more detailed review of CAPEX and OPEX are presented below in Table 4.39 and 4.40.

Table 4.39. Total capital expenditure for beta-carotene production.

Installed costs	Upstream equipment	691.302,51
	Downstream equipment	1.977.140,00
	Total installed cost (TIC)	**2.668.442,51**
Direct costs	Buildings (1 % TIC)	26.684,43
	Site development (9 % TIC)	240.160,00
	Additional piping (4,5 % TIC)	120.079,91
	Total direct cost (TDC) (accounted in FCI)	**386.924,34**
Indirect costs	Prorated expenses (10 % TDC)	38.692,43
	Home office and construction fees (20 % TDC)	77.384,87
	Field expenses (10 % TDC)	38.692,43
	Project contingency (10 % TDC)	38.692,43
	Startup and permits (5 %) TDC	19.346,22
	Total indirect cost	**212.808,39**
Fixed costs	**Capital investment (FCI)**	**1.000.000,00**
	Total CAPEX	**3.881.250,90**

Table 4.40. Total operational expenditures for beta-carotene production.

Operating costs	Labor (10 people)	40.000,00
	Utilities (electricity, heating) (wind turbine)	0
	Utilities (water)	29.186,4
	Consumables (plasticware, glassware, chemical) (0.2 % TIC)	5.337,00
	Medias (2400 ton/year)	633.120,00
	Maintenance (3 % TIC)	80.053,27
	Contingencies (5 % TDC+TIC)	29.986,64
	Total OPEX ($/year)	**817.683,31**

4.6.2. Return on Investment and Payback Period

The selling price for beta-carotene ranges between is 30$/kg-180$/kg throughout the market. ROI for selling prices in this range and the payback periods are presented in Table 4.41.

Table 4.41. Total net revenues, ROI and payback period from beta-carotene with various selling prices.

Beta-carotene ($/kg)	Net Revenue ($/year)	ROI %	Payback (years)
30,00	154.316,69	4,0	25,15
40,00	478.316,69	12,3	8,11
43,50	591.716,69	15,2	6,56
50,00	802.316,69	20,7	4,84
60,00	1.126.316,69	29,0	3,45
70,00	1.450.316,69	37,4	2,68
80,00	1.774.316,69	45,7	2,19
10,00	2.422.316,69	62,4	1,60
12,00	3.070.316,69	79,1	1,26
14,00	3.718.316,69	95,8	1,04
160,00	4.366.316,69	112,5	0,89
180,00	5.014.316,69	129,2	0,77

Market prices ranging from 30 $/kg to 180 $/kg were used to calculate ROI. Return on investments of 30 $/kg and 40 $/kg were calculated to be less than 15 % with payback periods of 25,15 and 8,11 years thus, were indicated as undesirable and infeasible. MFSP was calculated as 43,5 $/ton via 15 % ROI. Selling prices of 50 $/kg and above were found to be feasible with less than 5 years to return on the investment. 70 $/kg and 80$/kg prices lead to 37,4 % and 45,7 % ROIs with 2,7 and 2,2 years to return respectively. Prices between 100-120 $/kg offered 62,4 % and 79 % ROIs and the investment to pay back in 1,6 to 1,3 years while prices of 140 $/kg and higher were found to achieve full payback in approximately 1 year time.

4.7. Production of Spirulina Powder

Arthrospira platensis and *Arthrospira maxima* otherwise known as Spirulina, is a blue-green, spiral shaped microalgae specie that is known to grow in warm lakes and feed flamingos. Spirulina, one of the earliest lifeforms 3,6 billion years old, stands out with its resistance to harsh conditions and its ability to survive even in conditions where other algae species cannot survive (Indian Ocean Comission, 2012).

In addition to its survival ability, Spirulina is one of the two most used microalgae species for food and is considered to be a Super Food containing 60 % protein, high amounts of beta-carotene and vitamin B-12. Spirulina is widely used to overcome malnourishment, especially in countries suffering from food shortages, and is a perfect supplement containing more nutritional value than any known food (Indian Ocean Comission, 2012).

4.7.1. Cultivation, Harvesting, Dewatering and Drying

Arthrospira platensis and *Arthrospira maxima* are cultivated using PBRs with 2400 ton/year wet algae processing capacity. and are very similar to beta-carotene and astaxanthin cultivation processes. The full-grown biomass is harvested and dewatered with centrifugation. After, the biomass is fully dried by the spray drier, it is taken under a mechanical process to be shredded into powder form. IMBIYOTAB stops the processes after achieving the powder but, further processes such as packaging or capsulation could be added to the process flow according to the target product.

4.8. Results of Techno-Economic Assessment for Spirulina Powder Production

A research about the marketable spirulina indicates 1,9 kg/ton of marketable yield of spirulina powder (Uddin et al., 2020). When this product yield is applied to IMBIYOTAB with 2400 ton/year wet algae processing capacity, a production rate of 4560 kg/year marketable spirulina powder is achieved.

4.8.1. CAPEX and OPEX

CAPEX and OPEX are considered to be the same as IMBIYOTABs; construction, installation and equipment costs are taken as the exact cost of the IMBIYOTAB facility since no further purchase

of equipment or operation is required other than already existing. The CAPEX includes construction, upstream equipment such as the cultivation reactors and downstream equipment such as spray dryers. OPEX mainly includes the labor costs, utilities, consumables and contingencies. A more detailed review of CAPEX and OPEX are presented below in Table 4.42 and 4.43.

Table 4.42. Total capital expenditure for production of Spirulina powder.

Installed costs	Upstream equipment	691.302,51
	Downstream equipment	1.977.140,00
	Total installed cost (TIC)	**2.668.442,51**
Direct costs	Buildings (1 % TIC)	26.684,43
	Site development (9 % TIC)	240.160,00
	Additional piping (4.5 % TIC)	120.079,91
	Total direct cost (TDC) (accounted in FCI)	**386.924,34**
Indirect costs	Prorated expenses (10 % TDC)	38.692,43
	Home office and construction fees (20 % TDC)	77.384,87
	Field expenses (10 % TDC)	38.692,43
	Project contingency (10 % TDC)	38.692,43
	Startup and permits (5 %) TDC	19.346,22
	Total indirect cost	**212.808,39**
Fixed costs	**Capital investment (FCI)**	**1.000.000,00**
	Total CAPEX	**3.881.250,90**

Table 4.43. Total operational expenditure for production of Spirulina powder.

Operating costs	Labor (10 people)	40.000,00
	Utilities (electricity, heating) (wind turbine)	0
	Utilities (water)	29.186,40
	Consumables (plasticware, glassware, chemical) (0.2 % TIC)	5.337,00
	Medias (2400 ton/year)	633.120,00
	Maintenance (3 % TIC)	80.053,27
	Contingencies (5 % TDC+TIC)	29.986,64
	Total OPEX ($/year)	**817.683,31**
	OPEX CAPEX Total	**4.698.934,20**

4.8.2. Return on Investment and Payback Period

Prices of Spirulina powder are very inconsistent throughout the market. Selling prices are ranging from 60$/kg to 350$/kg and the same range was used to calculate ROIs and the payback times of the investments. The rates of return on investment and payback times are presented below in Table 4.44 in detail.

Table 4.44. Total net revenues, ROI and payback period from Spirulina powder with various selling prices.

Spirulina powder ($/kg)	Net Revenue ($/year)	ROI %	Payback (years)
60,5	(541.803,31)	-13,96	-
75,0	(475.683,31)	-12,26	-
90,0	(407.283,31)	-10,49	-
100,0	(361.683,31)	-9,32	-
150,0	(133.683,31)	-3,44	-
200,0	94.316,69	2,43	41,15
250,0	322.316,69	8,30	12,04
300,0	550.316,69	14,18	7,05
307,0	582.236,69	15,0	6,67
325,0	664.316,69	17,12	5,84
350,0	778.316,69	20,05	4,99

The price range of 60,5 $/kg - 150$/kg was found to be infeasible by negative ROIs, indicating not only that the investment is undesirable but impossible to return in a lifetime. Prices above 200$/kg and below 300 $/kg were found to have positive ROIs but they are also not desirable since the ROIs are lower than 15 % and the payback times are respectively long. MFSP was calculated to be 307 $/kg with a ROI of 15 % and the prices higher than 307 $/kg were found to be desirable since the ROIs are greater than 15 %. The MFSP with a ROI of 15 % generally pays back in 6 to 7 years. On the other hand, as the selling prices increase the payback period decreases. As for 325$/kg, the ROI and payback time are 17 % and 5,8 years respectively while the ROI for 350$/kg is 20 % and the investment is expected to return on investment in 5 years.

4.9. Discussion

The techno-economic assessment (TEA) of a biorefinery accounts for the full process flow including the growth phase to the final product. The TEA plays a crucial role in determining the economics of the final main and by-products. As well as the investment decision, the price of the final product, compatibility to the market and commercialization of the product highly depend on the outcomes of the TEA.

The economic sustainability of a biorefinery depends on obtaining maximum benefit from each product produced within. When the maximum level of benefit is obtained and it is greater than the capital investment, the investment is expected to pay back itself in a small period of time accordingly with its ROI. A ROI of 15 % or higher is preferred when investing for a desirable payback. As the ROI decreases the payback period increases and the investment loses its attractiveness.

Biofuel obtained from microalgae is known to have very high expenses and it has been a struggle to commercialize algae-biofuel because of the economic unfeasibility. Algae are respectively cheap to cultivate but the following processes for biofuel production are energy-intensive and elevate the production cost as well as the selling price.

ORPs are cheaper to cultivate algae in when compared to PBRs but have the disadvantage of being susceptible to external factors. Contamination by the surroundings makes ORP cultivation unsuitable for the production of high-grade delicate products. Thus, in IMBIYOTAB, only biofuel feedstocks were suitable for ORP cultivation.

The success of the biorefinery also relies on the production capacity and yield of biomass. For a more precise analysis for biofuel production, ranges for lipid yield percentages of the species and ranges for yields from conversion technologies were taken to consideration. A yield range for each species indicated the range of possible biofuel yield in addition to the range of minimum fuel selling prices.

A range of 3-10 % of lipid content were taken for *C. nivalis,* 40-60 % for *B. braunii,* 20-30 % for *E. oleoabundas* and 35-45 % for *N. gaditana.* Ranges for conversion for HTL were taken as 68-81,3 and 96,9 % for HTL and, 50-60-70 % for HEFA.

The yield analysis revealed that *C. nivalis* production ranged between 407,2-923,8 ton/year while *B. braunii* production ranged between 882,9-1467 ton/year, *E. oleoabundas* 240-504 ton/year and *N. gaditana* 420-756 ton/year.

It was seen that as the lipid contents increased and as the time interval lengthened the total CAPEX and OPEX decrease as well as the minimum fuel selling price, increasing the viability of algal biofuel for commercialization.

The result of the minimum selling prices without carbon capturing showed that even though *C. nivalis* has very low lipid content, it had almost equal MFSP with *N. gatditana* which had 3-5 times more lipid content. This is mainly caused by the conversion technology.

In HTL technology, algae are directly fed to the system after centrifugation, without any extraction. By this, the whole contents of the algae are utilized. On the other hand, in HEFA, only the lipid content is utilized. Thus, although the production rates and the lipids contents are different, by using the most optimal technology, *C. nivalis* succeeded to compete with MFSP of *N. gaditana* despite the expensive high pressure and temperature requirements of the HTL technology.

B. braunii, the specie with the highest production rate also accounted for the lowest MFSP for all of the scenarios 5-10 and 20 years, proving the importance of contents of the specie and the importance of the conversion technology. Amongst all species, *E. oleoabundas* had the highest MFSP. All of the MFSP were in accordance with the lipid contents and the conversion yields. As the lipid content increased, the production cost decreased and as the conversion yield increased the production increased which led to lower MFSPs.

For each species average MFSP, without implementation of carbon capturing, were calculated as 10.238,4 $/ton for *C. nivalis,* 5.850,7 $/ton for *B. braunii*, 17.418,63 $/ton for *E. oleoabundas. and* 11.409,4 $/ton for *N. gaditana.* Compared with petroleum-based jet fuel with a 603,2 $/ton selling price, algae-based biofuel production with 2400 wet algae/year is not viable. These very high prices are only possible when other components, such as carbon capturing, are integrated to the process.

Algae are capable of capturing atmospheric carbon dioxide and utilize it as algae oil. A ton of algae could capture 1.6 times of itself in weight during the cultivation phase. For each species, the carbon capturing was calculated to be 1536 tons of carbon dioxide per year. On the other hand, both conversion technologies HTL and HEFA emits 20,5 g CO_2/MJ and 37,5 g CO_2 /MJ respectively during the conversion processes. Total net carbon captures were calculated in accordance with the emissions from relevant technologies. For each species average carbon captures for a year period were calculated to be 1001 ton CO_2/year for *C. nivalis,* 539 ton CO_2/year for *B. braunii,* 1226 ton CO_2/year for *E. oleoabundas* and 1040 ton CO_2/year for *N. gaditana.* As of 2021, the market selling price of carbon is 60 $/ton. When the captured is utilized, the MFSP for each species decreases to 602,9 $/ton for *C. nivalis*, 627,7 $/ton *for B. braunii,* 567 $/ton *for E. oleoabundas.* and 602,9 $/ton for *N. gaditana,* revealing the potential for 1 % blends of bio-jet fuel to be available for

commercialization. The revised prices demonstrate that the bio-jet fuel is present for competition with petroleum-based jet fuel.

In this study, since biofuel had a very delicate price limit to compete with conventional fuel, a bottom-up approach was used for biofuel TEA. Since the price ranges for astaxanthin, beta-carotene and spirulina are very variable, a top-down approach is used for the TEA of these products.

All CAPEX includes the real prices from the establishment of the IMBIYOTAB facility and includes all the required upstream, downstream and processing equipment for the production of astaxanthin, beta-carotene and spirulina. Thus, the CAPEX was taken the same for each production process, and the OPEXs were also the same except astaxanthin which required additional raw materials.

Astaxanthin, beta-carotene and spirulina productions in IMBIYOTAB were assessed under CAPEX, OPEX and ROI frameworks with respect to current market prices. In accordance with the astaxanthin market, 850 $/kg to 7000 $/kg price range was examined. For 850 $/kg with 913 kg/year production, a return on investment in 6.6 years is expected. With the same amount of production, as the selling price increases, the time interval of the payback decreases. For 3,000 $/kg, payback in 1.5 years is expected while for 5000 $/kg and above it decreases to less than a year. All ROIs for the assessed price range were above 15 % which indicates that the production of 913 kg/year astaxanthin is economically viable for the selling prices 850$/kg and above.

For beta-carotene, the price range of 30 $/kg to 180 $/kg was assessed. IMBIYOTAB is capable of producing 32.400 kg/year of beta-carotene. Even when the production is at full capacity, the prices between 30-40 $/kg reveals a ROI below 15 % indicating an unfeasible investment. For prices above 140 $/kg, immediate return on investment in less than a year is expected while for the prices between 60-100 $/kg return periods of 3,5-2 years are calculated respectively.

Spirulina prices are also very variant. The prices can go as low as 60,5 $/kg to as high as 35 $/kg with a very wide range. IMBIYOTAB has the potential to produce 4560 kg/year of spirulina powder. For this production rate, prices between 60,5-200 $/kg result in negative revenues since the expenses exceed the revenues. For prices between 250-300, the returns on investment are not desirable, below 15 %, but the revenues are positive and the payback is expected in 7-12 years. When the selling price increases to 325 $/kg the ROI is 17 % and the payback is expected to be in approximately 6 years.

For 350 $/kg and above, the investment is feasible and the paybacks are expected in 5 or fewer years according to the selling price.

5. CONCLUSIONS

Algae have been considered as an important source for many commercial products such as astaxanthin and beta-carotene. In recent years, algae have become prominent as a sustainable third generation energy feedstock that does not compete for nutrients and land conflicting with food security and, can grow under harsh conditions such as non-arable lands, using salt or brackish water. In this context, algae have the potential to meet a portion of the worldwide energy demand yielding 30 times more energy than other energy crops as reported by U.S. Energy Information Administration (2013) and Ullah et al. (2014). Besides supplying energy, algae capture 2 % of the atmospheric carbon dioxide by fixing 30-50 billion tons of carbon dioxide each year and utilizing it as algae oil then to be converted into biofuel (Biotechnology Innovation Organization, 2021). In addition, the use of algae-based bio-jet fuel releases 60 % less GHG compared to conventional jet fuel biofuel (Biotechnology Innovation Organization, 2021). However, algae have never been economically viable. High equipment costs and energy-intensive processes required to cultivate, dewater and refine algae have been hindering the economic viability and commercialization of algae-based biofuels.

Techno-economic assessment is a crucial tool for determining the potential economic viability of any process. The appliance of the assessment provides a guide for the viability, investment decisions and further improvements of the process, product or service by considering capital expenditures and operational expenditures. TEA accounts for equipment, energy, labor, raw materials, product yields, product values, by-products, market costs, transportation and many other aspects within the framework of upstream and downstream costs to provide an integrated economic and technological representation of any production process. Besides, TEA could be utilized for identifying the most efficient and beneficial route for the target of production. Evaluating the production costs of a given production route based on certain production levels and targets allows the assessment of the economic feasibility of process configurations

When this scope is adapted to the integrated algal biorefineries, it has an accurate usage as a device to assess the most efficient production route and selling prices of the designated end products. Scenarios with combinations of different production routes, different algal species and products are evaluated via TEA and, benefits, costs and minimum selling prices for successful returns on investments are compared. This analysis shines a light through the path of commercialization of

biorefineries by identifying different production pathways, and factors affecting the economic viability (Thomassen et al., 2016).

Techno-economic assessments indicated that, by carbon-negative bio-jet fuel production, IMBIYOTAB has achieved to obtain competitive prices for 1 % bio-jet fuel blend (approved by ASTM standards), paving the way for commercialization of algae-based biofuels. Compensating for the carbon emissions by HTL and HEFA conversion to bio-jet fuel processes, with approximately 500-1.000 tons of net carbon capture, the minimum fuel selling price was obtained to be between 567-627 $/ton. More detailed carbon capture data and minimum fuel selling data for each blend ratio and species could be found in Chapter 4.2.7.

Besides producing bio-jet fuel from microalgae, IMBIYOTAB also practices astaxanthin, beta-carotene and spirulina powder production from microalgae. Astaxanthin production from microalgae in the facility yields promising results with desirable returns of investment above 850 $/kg selling price which is the lowest of the price range suggested by the worldwide high-grade astaxanthin market, proving the commerciality of astaxanthin production from microalgae.

Besides being prominent with the amount of oil accumulation and their contribution to biofuel production, microalgae are important sources of beta-carotene. The commercial production of beta-carotene dates back to the 1980s and has continued since. Beta-carotene production from microalgae in IMBIYOTAB reveals promising results as expected. With 2400 ton/year wet algae processing capacity, the minimum selling price is calculated to be 43,5 $/ton for beta-carotene. With the commercial market prices ranging from 30 to 180 $/ton for beta-carotene, the achieved price from IMBIYOTAB is very competitive and favorable.

Spirulina powder from *Arthrospira platensis* and *Arthrospira maxima,* one of the earliest lifeforms to be known dating back 3,6 billion years, is a Super Food containing 60 % protein, high amounts of beta-carotene and vitamin B-12. It is widely used to overcome malnourishment, especially in countries suffering from food shortages, and is a perfect supplement containing more nutritional value than any known food (Indian Ocean Comission 2012). Production of Spirulina powder in IMBIYOTAB facility with 2400 ton/year wet algae processing capacity reveals a minimum selling price of 307 $/kg with the commercial market prices ranging from 60,5 to 350 $/kg. The obtained minimum selling price reveals the potential of the product whilst it also reveals the room for advancement of the production.

For each of the individual products produced, scaling up the production capacity will result in an increase in the operational expenses and capital expenses in the first step. As the production levels increase, the benefits from the products sold will increase thus, lowering the minimum selling prices, making the products more competitive and favorable.

Another approach for lowering the selling prices is to advance the production technologies which will also increase the operational expenses and capital expenses in the first step, however, will also increase the production capacity and product yield, again lowering the minimum selling prices.

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