

The cultivation and harvesting of micro-algal biomass from the Hartbeespoort Dam for the production of biodiesel

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THESIS



SYNOPSIS

S U M M A R Y O F T H E S I S

SYNOPSIS

Renewable energy sources such as biomass are becoming more and more important as alternative to fossil fuels. One of the most exciting new sources of biomass is microalgae. The Hartbeespoort Dam, located 37 km west of South Africa's capital Pretoria, has one of the dense populations of microalgae in the world, and is one of the largest reservoirs of micro-algal biomass in South Africa. The dam has great potential for micro-algal biomass production and beneficiation due to its high nutrient loading, stable climatic conditions, size and close proximity to major urban and industrial centres.

There are five major steps in the production of biodiesel from micro-algal biomass-derived oil: the first two steps involve the cultivation and harvesting of micro-algal biomass; which is followed by the extraction of oils from the micro-algal biomass; then the conversion of these oils via the chemical reaction transesterification into biodiesel; and the last step is the separation and purification of the produced biodiesel. The first two steps are the most inefficient and costly steps in the whole biomass-to-liquids (BTL) value chain. Cultivation costs may contribute between 20–40% of the total cost of micro-algal BTL production (*Comprehensive Oilgae Report*, 2010), while harvesting costs may contribute between 20–30% of the total cost of BTL production (Verma *et al.*, 2010). Any process that could optimize these two steps would bring a biomass-to-liquids process closer to successful commercialization.

The aim of this work was to study the cultivation and harvesting of micro-algal biomass from the Hartbeespoort Dam for the production of biodiesel. In order to do this a literature study was done and screening experiments were performed to determine the technical and economical feasibility of cultivation and harvesting methods in the context of a new integrated biomass-to-liquids biodiesel process, whose feasibility was also studied.

The literature study revealed that the cyanobacterium *Microcystis aeruginosa* is the dominant micro-organism species in the Hartbeespoort Dam. The study also revealed factors that promote the growth of this species for possible incorporation into existing and new cultivation methods. These factors include stable climatic conditions, with high water temperatures around 25°C for optimal *Microcystis* growth; high nutrient loadings, with high phosphorus (e.g. PO_4^{3-}) and nitrogen concentrations (e.g. NO_3^-); stagnant hydrodynamic conditions, with low wind velocities and enclosed bays, which promote the proliferation of *Microcystis* populations; and substrates like sediment, rocks and debris which provide safe protective environments for *Microcystis* inoculums.

The seven screening studies consisted of three cultivation experiments, three harvesting experiments and one experiment to determine the combustion properties of micro-algal biomass. The three cultivation experiments were conducted in three consecutively scaled-up laboratory systems, which consisted of one, five and 135-litre bioreactors. The highest productivity achieved was over a period of six weeks in the 5-litre Erlenmeyer bioreactors with 0.0862 g/L/d at an average bioreactor day-time temperature of 26.0°C and an aeration rate of 1.5 L/min. The three cultivation experiments revealed that closed-cultivation systems would not be feasible as the highest biomass concentrations achieved under laboratory conditions were too low. Open-cultivation systems are only feasible if the infrastructure already exists, like in the case of the Hartbeespoort Dam. It is recommended that designers of new micro-algal BTL biodiesel processes first try to capitalize on existing cultivation infrastructure, like dams, by connecting their processes to them. This will reduce the capital and operating costs of a BTL process significantly.

Three harvesting experiments studied the technical feasibility and determined design parameters for three promising, unconventional harvesting methods. The first experiment studied the separation of Hartbeespoort Dam micro-algal biomass from its aqueous phase, due to its natural buoyancy. Results obtained suggest that an optimum residence time of 3.5 hours in separation vessels would be sufficient to concentrate micro-algal biomass from 1.5 to 3% TSS. The second experiment studied the aerial harvesting yield of drying micro-algal biomass (3% TSS) on a patch of building sand in the sun for 24 hours. An average aerial harvesting yield of 157.6 g/m²/d of dry weight micro-algal biomass from the Hartbeespoort Dam was achieved. The third experiment studied the gravity settling harvesting yield of cultivated Hartbeespoort Dam-sourced microalgae as it settles to the bottom of the bioreactor after air agitation is suspended. Over 90% of the micro-algal biomass settled to the bottom quarter of the bioreactor after one day.

Cultivated micro-algal biomass sourced from the Hartbeespoort Dam, can easily be harvested by allowing it to settle with gravity when aeration is stopped. Results showed that gravity settling equipment, with residence times of 24 hours, should be sufficient to accumulate over 90% of cultivated micro-algal biomass in the bottom quarter of a separation vessel. Using this method for primary separation could reduce the total cost of harvesting equipment dramatically, with minimal energy input.

All three harvesting methods, which utilize the natural buoyancy of Hartbeespoort Dam microalgae, gravity settling, and a combination of sand filtration and solar drying, to concentrate, dewater and dry the micro-algal biomass, were found to be feasible and were incorporated into new integrated BTL biodiesel process. The harvesting processes were incorporated and designed to deliver the most micro-algal biomass feedstock, with the least amount of equipment and energy use.

All the available renewable power sources from the Hartbeespoort Dam system, which included wind, hydro, solar and biomass power, were utilized and optimized to deliver minimum power loss, and increase power output. Wind power is utilized indirectly, as prevailing south-easterly winds concentrate micro-algal biomass feedstock against the dam wall of the Hartbeespoort Dam. The hydraulic head of 583 kPa of the 59.4 meter high dam wall is utilized to filter and transport biomass to the new integrated BTL facility, which is located down-stream of the dam. Solar power is used to dry the microalgae, which in turn is combusted in a furnace to release its 18,715 kW of biochemical power, which is used for heating in the power-intensive extraction unit of the processing facility. Most of the processes in literature that cover the production of biodiesel from micro-algal biomass are not thermodynamically viable, because they consume more power than what they produce. The new process sets a benchmark for other related ones with regards to its net power efficiency. The new process is thermodynamically efficient, exporting 20 times more power than it imports, with a net power output of 5,483 kilowatts.

The design of a new integrated BTL process consisted of screening the most suitable methods for harvesting micro-algal biomass from the Hartbeespoort Dam and combining the obtained design parameters from these harvesting experiments with current knowledge on extraction of oils from microalgae and production of biodiesel from these oils into an overall conceptual process. Three promising, unconventional harvesting methods from Brink and Marx (2011), a micro-algal oil extraction process from Barnard (2009), and a process from Miao and Wu (2005) to produce biodiesel through the acid-catalyzed transesterification of micro-algal oil, were combined into an

integrated BTL process. The new integrated biomass-to-liquids (BTL) process was developed to produce 2.6 million litres of biodiesel per year from harvested micro-algal biomass from the Hartbeespoort Dam. This is enough to supply 51,817 medium-sized automobiles per year or 142 automobiles per day of environmentally friendly fuel.

The new BTL facility consists of three sections: a cultivation section where microalgae grow in the 20 km² Hartbeespoort Dam to a concentration of 160 g/m² during the six warmest months of the year; a harvesting section where excess water is removed from the micro-algal biomass; a reaction section where fatty acid oils are extracted from the microalgae and converted to biodiesel, and dry biomass rests are combusted to supply heat for the extraction and biodiesel units of the reaction section. The cultivation section consist of the existing Hartbeespoort Dam, which make up the cultivation unit; the harvesting section is divided into a collection unit (dam wall part of the Hartbeespoort Dam), a concentration unit, a filtration unit, and a drying unit; the reaction section consists of an oil extraction unit, a combustion unit, and a biodiesel unit.

At a capital cost of R71.62 million (R1.11/L) ($\pm 30\%$), the new proposed BTL facility will turn 933,525 tons of raw biomass (1.5% TSS) into 2,590,856 litres of high quality biodiesel per year, at an annual operating cost of R11.09 million (R4.28/L at 0% producer inflation), to generate R25.91 million (R10.00/L) per year of revenue. At the current diesel price of R10.00/L, the new integrated BTL process is economically feasible with net present values (NPV) of R368 million (R5.68/L) and R29.30 million (R0.45/L) at discount rates of 0% and 10%, respectively. The break-even biodiesel prices are R5.34/L and R7.92/L, for a zero NPV at 0% and 10% discount rates, respectively.

The cultivation of micro-algal biomass from the Hartbeespoort Dam is only economical if the growth is allowed to occur naturally in the dam without any additional cultivation equipment. The cultivation of micro-algal biomass in either an open or a closed-cultivation system will not be feasible as the high cost of cultivation will negate the value of biodiesel derived from the cultivated biomass. The utilization of the three promising harvesting methods described in this work is one of the main drivers for making this process economically feasible. At a capital cost of R13.49 million (R37.77/ton of dry weight micro-algal biomass) and a operating cost of R2.00 million per year (R210.63/ton of dry weight micro-algal biomass) for harvesting micro-algal biomass from the Hartbeespoort Dam, harvesting costs account for only 19% and 18% of the overall capital and operating costs of the new process, respectively. This is less than harvesting

costs for other comparative processes world-wide, which contribute between 20 and 30% of the overall cost of biomass-to-liquids production.

At current fuel prices, the cultivation of micro-algal biomass from and next to the Hartbeespoort Dam is not economical, but the unconventional harvesting methods presented in this thesis are feasible, if incorporated into the new integrated biomass-to-liquids biodiesel process set out in this work.

Keywords: Hartbeespoort Dam; Microalgae; Biomass; Cultivation; Harvesting; Biodiesel; Biomass-to-Liquids

PROEFSKRIF



OPSOMMING

S I N O P S I S V A N T E S I S

OPSOMMING

Hernubare energiebronne soos biomassa as alternatiewe vir fossielbrandstowwe word al hoe belangriker. Een van die mees opwindende nuwe bronne van biomassa is mikro-alge. Die Hartbeespoortdam, geleë 37 km wes van Suid-Afrika se hoofstad Pretoria, het een van die digste bevolkings van mikro-alge in die wêreld en is een van die grootste reservoirs van mikro-algbiomassa in Suid-Afrika. Die dam het groot potensiaal vir mikro-algbiomassaproduksie en veredeling weens sy hoë nutriëntlading, stabiele klimaatstoestande, grootte en nabyheid aan hoof stedelike en industriële sentrums.

Daar is vyf hoofstappe in die produksie van biodiesel uit mikro-algbiomassa-afgeleide olie: die eerste twee stappe behels die kweking en oes van mikro-algbiomassa; gevolg deur die ekstraksie van olies uit die mikro-algbiomassa, dan die omsetting van hierdie olies via die chemiese reaksie trans-esterifikasie tot biodiesel en die laaste stap is die skeiding en suiwering van die geproduseerde biodiesel. Die eerste twee stappe is die oneffektiefste en duurste stappe in die hele biomassa-tot-vloeistof (BTV)-waardeketting. Verbouingskoste mag tussen 20–40% van die totale koste van mikro-alg-BTV-produksie bydra (*Comprehensive Oilgae Report*, 2010), terwyl oeskoste tussen 20–30% van die totale koste van BTV-produksie kan bydra (Verma *et al.*, 2010). Enige proses wat hierdie twee stappe kan optimiseer, sal 'n BTV-proses nader aan suksesvolle kommersialisering bring.

Die doel van hierdie werk was om die kweek en oes van mikro-algbiomassa uit die Hartbeespoortdam vir die produksie van biodiesel te bestudeer. Ten einde dit te doen, is 'n literatuurstudie onderneem en keuringseksperimente uitgevoer om die tegniese en ekonomiese lewensvatbaarheid van kweek-, verbouing- en oesmetodes binne die konteks van 'n nuwe geïntegreerde BTV-biodieselproses te bepaal en om ook die lewensvatbaarheid te bestudeer.

Die literatuurstudie het getoon dat die sianobakterium *Microcystis aeruginosa* die dominante mikro-organisme in die Hartbeespoortdam is. Die studie het ook faktore getoon wat die groei van hierdie spesie vir moontlike insluiting in bestaande en nuwe kweekmetodes bevorder. Hierdie faktore sluit in stabiele klimaatstoestande, hoë watertemperature rondom 25°C vir optimale *Microcystis*-groei, hoë nutriëntladings, hoë fosfor- en stikstofkonsentrasies, stagnante hidrodinamiese toestande, lae wind-snelhede en beskutte baaie, wat die proliferasie van *Microcystis*-bevolkings bevorder en substrate soos sediment, rotse en opdrifsels wat veilige beskermende omgewings vir *Microcystis*-inokulum voorsien.

Die sewe keuringstudies het bestaan uit drie kweek-eksperimente, drie oes-eksperimente en een eksperiment om die verbrandingseienskappe van mikro-algbiomassa te bepaal. Die drie kweek-eksperimente is uitgevoer in drie opeenvolgende opgeskaalde laboratoriumsisteme, wat bestaan uit 1-, 5- en 135-liter bioreaktore. Die hoogste produktiwiteit behaal onder optimum groeitoestande is bereik in die 5-liter Erlenmeyer-bioreaktore met 0.0862 g/L/d by 'n gemiddelde bioreaktor-dagtemperatuur van 26.0°C en 'n belugtingstempo van 1.5 L/min. Die drie kweek-eksperimente het getoon dat geslote kweekstelsels nie lewensvatbaar sou wees nie, want die hoogste biomassakonsentrasies behaal onder optimum laboratoriumtoestande was te laag. Oop kweekstelsels is net lewensvatbaar indien die infrastruktuur reeds bestaan, soos in die geval van die Hartbeespoortdam. Daar word aanbeveel dat ontwerpers van nuwe mikro-alg-BTV-biodieselprosesse eers probeer om te kapitaliseer op bestaande kweekinfrastruktuur, soos damme, deur hulle prosesse daaraan te verbind. Dit sal die kapitaal- en bedryfskoste van 'n BTV-proses beduidend verminder.

In drie oes-eksperimente is die tegniese lewensvatbaarheid bestudeer en ontwerpparameters vir drie belowende, onkonvensionele oesmetodes bepaal. In die eerste eksperiment is die skeiding van Hartbeespoortdam-mikro-algbiomassa van sy waterige fase, weens sy natuurlike dryfvermoë, bestudeer. Resultate verkry, suggereer dat 'n optimum residensietyd van 3.5 uur in skeidingshouers genoeg sou wees om die mikro-algbiomassa van 1.5 tot 3% TGS te konsentreer. In die tweede eksperiment is die oes-opbrengs van sondrogende mikro-algbiomassa (3% TGS) op 'n kol bousand vir 24 uur bestudeer. 'n Gemiddelde oesopbrengs van 157.6 g/m²/d droë gewig mikro-algbiomassa uit die Hartbeespoortdam is behaal. In die derde eksperiment is die oesopbrengs van gekweekte Hartbeespoortdam-verkreë mikro-alge, soos dit uitsak na die bodem van die bioreaktor na lugroering gestaak is, bestudeer. Meer as 90% van die mikro-algbiomassa het na een dag uitsak na die onderste kwart van die bioreaktor. Gekweekte mikro-algbiomassa verkry uit die Hartbeespoortdam kan maklik ge-oes word deur dit toe te laat om onder

swaartekrag uit te sak nadat belugting gestaak is. Bevindings het getoon dat swaartekrag-uitsaktoerusting, met residensietye van 24 uur, genoeg behoort te wees om meer as 90% van gekweekte mikro-algbiomassa in die onderste kwart van 'n skeidingshouer te akkumuleer. Deur gebruikmaking van hierdie metode vir primêre skeiding kon die totale koste van oestoerusting drasties verminder word, met minimale energie-inset.

Al drie oesmetodes wat die natuurlike dryfvermoë van Hartbeespoortdam mikro-alg en swaartekrag-uitsakking aanwend en 'n kombinasie van sandfiltrering en sondroging om die mikro-algbiomassa te konsentreer, ontwater en te droog, is lewensvatbaar bevind en is geïnkorporeer in 'n nuwe geïntegreerde BTV-biodieselproses. Die oesprosesse is ingesluit en ontwerp om die meeste mikro-algbiomassavoer te lewer met die kleinste hoeveelheid toerusting en energieverbruik.

Al die beskikbare hernubare kragbronne van die Hartbeespoortdam-sisteem, wat insluit wind, hidro-, son- en biomassa-krag, is aangewend en geoptimeer om minimum energieverlies en vermeerderde krag-uitset te lewer. Windkrag is indirek aangewend want heersende suid-ooste winde konsentreer mikro-algbiomassavoer teen die damwal van die Hartbeespoortdam. Die hidrouliese hoogte van 583 kPa van die 59.4 meter hoë damwal is aangewend vir die filtreer en vervoer van biomassa na die nuwe geïntegreerde BTV-fasiliteit wat stroom-af van die dam geleë is. Sonkrag is gebruik om die mikro-alg te droog, wat op sy beurt in 'n oond verbrand is om sy 18,715 kW biochemiese krag vry te stel, wat gebruik is vir verhitting in die krag-intensiewe ekstraksie-eenheid van die prosesseringfasiliteit. Die meeste van die prosesse beskryf in die literatuur wat die produksie van biodiesel vanaf mikro-algbiomassa dek, is nie termodinamies haalbaar nie, want almal verbruik meer krag as wat die totale proses produseer. Die nuwe proses stel 'n norm daar vir ander verwante prosesse met betrekking tot hul netto krag-doeltreffendheid. Die nuwe proses is termodinamies doeltreffend en voer 20 keer meer krag uit as wat dit invoer, met 'n netto kraguitset van 5,483 kilowatt.

Die ontwerp van 'n nuwe geïntegreerde BTV-proses bestaan uit keuring van die mees geskikte metodes vir die oes van mikro-algbiomassa uit die Hartbeespoortdam en kombinerings van die verkreeë ontwerpparameters van hierdie oes-eksperimente met huidige kennis van ekstraksie van olies vanaf mikro-alge en die produksie van biodiesel vanaf hierdie olies in 'n oorkoepelende konsepsionele proses. Drie belowende onkonvensionele oesmetodes van Brink and Marx (2011), 'n mikro-alg-olie-ekstraksieproses van Barnard (2009) en 'n proses van Miao and Wu (2005) om biodiesel te produseer deur die suur-gekataliseerde trans-esterifikasie van mikro-alg-olie is

gekombineer in 'n geïntegreerde BTV-proses. Die nuwe geïntegreerde BTV-proses is ontwikkel om 2.6 miljoen liter biodiesel per jaar te produseer uit ge-oeste mikro-algbiomassa van die Hartbeespoortdam. Dit is genoeg om 51,817 medium-grootte voertuie per jaar of 142 voertuie per dag te voorsien van omgewingsvriendelike brandstof.

Die nuwe BTV-fasiliteit bestaan uit drie afdelings: 'n kweekafdeling waar mikro-alge in die 20 km² Hartbeespoortdam groei tot 'n konsentrasie van 160 g/m² gedurende die ses warmste maande van die jaar, 'n oesafdeling waar oortollige water verwyder word uit die mikro-algbiomassa, 'n reaksie-afdeling waar vetsuurolies onttrek word vanuit die mikro-alge en omgesit word na biodiesel, en droë biomassa-reste verbrand word om hitte te verskaf vir die ekstraksie en biodiesel-eenhede van die reaksie-afdeling. Die kweek-afdeling bestaan uit die bestaande Hartbeespoortdam wat behels die kweekeenheid; die oesafdeling is verdeel in 'n versameleenheid (damwal-gedeelte van die Hartbeespoortdam), 'n konsentreereenheid, 'n filtreereenheid en 'n droogeenheid; die reaksie-afdeling bestaan uit 'n olie-ekstraksie-eenheid, 'n verbrandingseenheid en 'n biodieseleenheid.

Met 'n kapitaalkoste van R71.62 miljoen (R1.11/L) ($\pm 30\%$) sal die nuut voorgestelde BTV-fasiliteit 933,525 ton rou biomassa (1.5% TGS) omsit in 2,590,856 liter hoë kwaliteit biodiesel per jaar met 'n jaarlikse bedryfskoste van R11.09 miljoen (R4.28/L teen 0% produksie-inflasie), om R25.91 miljoen (R10.00/L) per jaar inkomste te lewer. Teen die huidige dieselprys van R10.00/L is die nuwe geïntegreerde BTV-proses ekonomies vatbaar met netto huidige waardes (NTW) van R368 miljoen (R5.68/L) en R29.30 miljoen (R0.45/L) teen verdiskonteerde koerse van 0% en 10%, onderskeidelik. Die gelykbreek-biodieselpryse is R5.34/L en R7.92/L vir 'n zero NTW by 0% en 10% verdiskonteerde koerse, onderskeidelik.

Die kweek van mikro-algbiomassa in die Hartbeespoortdam is slegs ekonomies indien die groei toegelaat word om natuurlik in die dam plaas te vind sonder enige bykomende kweektoerusting. Die kweek van mikro-algbiomassa in óf 'n oop óf 'n geslote kweekstelsel sal nie lewensvatbaar wees as die hoë koste van kweek die waarde van biodiesel verkry van die gekweekte biomassa sal kanselleer nie. Die benutting van die drie belowende oesmetodes beskryf in hierdie werk, is een van die hoofdrywers om hierdie proses ekonomies lewensvatbaar te maak. Teen 'n kapitaalkoste van R13.49 miljoen (R37.77/ton droëgewig mikro-algbiomassa) en bedryfskoste van R2.00 miljoen per jaar (R210.63/ton droëgewig mikro-algbiomassa) vir die oes van mikro-algbiomassa uit die Hartbeespoortdam beloop oeskoste slegs 19% en 18% van die oorkoepelende kapitaal en bedryfskoste van die nuwe proses, onderskeidelik. Dit is minder as oeskostes vir

ander vergelykbare prosesse wêreldwyd, wat tussen 20 en 30% van die oorkoepelende koste van BTV-produksie bydra.

Teen huidige brandstofpryse is die kweek van mikro-algbiomassa uit en langs die Hartbeespoortdam nie ekonomies nie, maar die onkonvensionele oesmetodes, aangebied in hierdie proefskrif, is lewensvatbaar indien dit geïnkorporeer word in die nuwe geïntegreerde BTV-biodieselproses wat in hierdie werk verduidelik word.

Kernwoorde: Hartbeespoortdam; Mikro-alg; Biomassa; Kweek; Oes; Biodiesel; Biomassa-tot-Vloeistof

THESIS



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& R E C O G N I T I O N S

*The fear of the LORD is the beginning of wisdom:
and the knowledge of the holy is understanding. Proverbs 9:10*

*The heavens declare the glory of God;
and the firmament sheweth his handywork. Psalms 19:1*

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THESIS



NOMENCLATURE

S Y M B O L O G Y

NOMENCLATURE

A	Drying area or surface area of growth plate (m ²)
a	Year(s)
A _p	Pipe cross-sectional area (m ²)
B	Bioreactor
C	Cost
C _e	Equivalent cost
C _i	Measured volume concentration of micro-algal biomass (%)
C _i [*]	Calculated volume concentration of micro-algal biomass (%)
C _{MB}	Volume concentration of micro-algal biomass (%)
C _r	Reference cost
C _u	Unit cost
d	day(s)
D	Diameter (m)
D/H	Diameter-to-height ratio
D _c	Column diameter (m)
df	Degrees of freedom
d _p	Optimum pipe diameter (m)
F	Ratio of two variance estimates
Fr	Froude number
g	Gravitational acceleration (9.81 kg.m/s ²)
I	Index
I _a	Index at time a
K	Constant
l _t	Plate spacing (m)
M	Micro-algal biomass cultivation (kg/s)
N	Agitator speed (s ⁻¹)

N_p	Power number
p	Observed significance level of hypothesis test
P	Shaft power
Q	Heat transfer per unit time (kW)
Q_p	Volumetric flow rate (m^3/s)
r	Specific growth rate (day^{-1})
R	Least-square residual
Re	Reynolds number
S	Plant site
t	Separation time (hours)
U	Overall heat transfer coefficient
u_w	Maximum allowable vapour velocity (m/s)
V	Liquid volume in bioreactor (L)
V_L	Liquid hold-up volume
V_{MB}	Volume of micro-algal biomass (L)
v_{opt}	Optimum fluid velocity (m/s)
V_{Tot}	Total volume of liquid and micro-algal biomass (L)
V_V	Vapour hold-up volume
V_w	Maximum vapour rate (kg/s)
W_d	Dry weight of micro-algal biomass (g)
W_i	Dry weight of biomass in section (i) of bioreactor (g)
W_o	Dry weight of microalgae at beginning of experiment (g)
W_t	Dry weight of microalgae at end of experiment (g)
W_{Tot}	Total dry weight of biomass in bioreactor (g)
W_w	Wet weight of micro-algal biomass (g)
y_H^*	Predicted harvesting yield (%)
y_A	Harvesting yield per drying area (g/m^2)
y_D	Harvesting yield per wet weight fraction of biomass (wt. %)
y_H	Harvesting yield (%)
y_V	Harvesting yield per volume of dam water (g/L)

Superscripts and subscripts:

a	Time a
b	Time b
H	High
i	Location i
L	Low

Greek letters:

α	Significance level used to compute the confidence level
δ_L	Liquid density (g/L)
δ_v	Vapour density (g/L)
ΔP	Delta pressure
ΔT_m	Delta mean temperature
ΔW	Dry weight accrual of micro-algal biomass
η	Productivity (g/L/day)
η_p	Pump efficiency (%)
μ	Viscosity (Pa.s)
ρ	Cell concentration (g/L)
ρ_A	Aerial growth concentration (g/m ²)
ρ_v	Volumetric growth concentration (g/L)
τ	Residence time (h)
ϕ	Microalgae growth phase

THESIS



ABBREVIATIONS

U S E D I N T H E S I S

ABBREVIATIONS

Aban.	Abandonment (Decommissioning)
BTL	Biomass-to-liquids
Capex	Capital cost
CM	<i>Cyclotella meneghiniana</i>
Com.	Commissioning
CV	Calorific value (MJ/kg)
Dam	Hartbeespoort Dam
Decomm.	Decommissioning
DFC	Direct field cost
Dia.	Diameter (m)
DP	Design pressure
DT	Design temperature
DWAF	Department of Water Affairs and Forestry (South Africa)
EPC	Engineering, procurement and construction
Feas.	Feasibility (Study)
FEED	Front-end engineering and design
HI-BTL	Hartbeespoort Dam Integrated Biomass-to-Liquids (process)
HMB	Hartbeespoort dam micro-algal biomass
HSM	Hartbeespoort dam-sourced microalgae
HSBM	Hartbeespoort dam-sourced biomass
HSMB	Hartbeespoort dam-sourced micro-algal biomass
Ht	Height (m)
IDC	Industrial Development Corporation
IFC	Indirect field cost
IRR	Internal rate of return
Liq.	Liquid

MEC	Main equipment cost
MS	Mean square
NPV	Net present value
OP	Operating pressure (kPa)
Opex	Operating cost
OT	Operating temperature (°C)
PBR	Photobioreactor
PPI	Producer price index
Pre-feas.	Pre-feasibility (study)
ROI	Return on investment
ROR	Rate of return
rpm	revolutions per minute
SEM	Scanning electron microscopy
SS	Sum of squares
TEC	Total erected cost
Tot.	Total
TSS	Total suspended solids
UK	United Kingdom
USA	United States of America
Vap.	Vapour
Vol.	Volume
wt.	Weight

CHAPTER ONE



INTRODUCTION

& THESIS OUTLINE

*We can't solve problems by using the same
kind of thinking we used when we created them.*

– Albert Einstein

1. INTRODUCTION

1.1 BACKGROUND

According to the *Energy Information Administration* (2010), global energy demand is projected to increase by 49 percent in the next 25 years. Global oil consumption is expected to grow from 86 million barrels per day in 2007 to 104 million barrels per day in 2030. The world's total proven oil reserves are estimated at 1.293 trillion barrels according to the *Oil & Gas Journal* (2005). Under these growth assumptions, less than half of the world's total proven oil reserves would be exhausted by 2030. As these oil reserves shrink, alternative liquid fuels, like biodiesel and bio-ethanol, are becoming more and more important as alternative energy sources to oil. The world produced over 33 billion litres of these biofuels in 2004. Biodiesel production is the fastest growing alternative liquid fuel, growing at a rate of more than 30% per annum, and production is projected to reach the 12 billion litre mark at the end of 2010 (Lim and Teong, 2010). Among the many oil sources for biodiesel production, such as soybean, rapeseed, sunflower and palm oil, microalgae promise the highest yield of oil per kilogram of biomass, and have much faster growth rates than terrestrial crops (Chisti, 2008).

One of the largest reservoirs of micro-algal biomass in South Africa is the Hartbeespoort Dam. With a surface area of approximately 20 km², it has great potential for micro-algal biomass production and biomass-to-liquids (BTL) beneficiation, due to its size and close proximity to major urban and industrial centres.

There are five major steps in the production of biodiesel from micro-algal biomass-derived oil: the first two steps involve the cultivation and harvesting of micro-algal biomass; which is followed by the extraction of the oils from the micro-algal biomass; then the conversion of these oils via the chemical reaction transesterification into biodiesel; and the last step is the separation and purification of the produced biodiesel. The first two steps are the most inefficient and costly steps in the whole BTL value chain. Cultivation costs may contribute between 20–40% of the total cost of BTL biodiesel production (*Comprehensive Oilgae Report*, 2010), while harvesting costs may add 20–30% to the total cost of oil production through algal biomass (Verma *et al.*, 2010).



Figure 1: Hartbeespoort Dam

1.2 MOTIVATION

In view of current and future global energy trends in the production of biodiesel, and the potential benefit this type of renewable energy source holds for the Republic of South Africa; in order to address the problem of micro-algal pollution in the Hartbeespoort Dam; and lastly, to enhance the feasibility of a BTL biodiesel process at the Dam, by improving its efficiency and reducing the costs of such a facility, this work aims to find improved and novel methods for the cultivation and harvesting of micro-algal biomass from the Hartbeespoort Dam, and to incorporate them into a new optimized and integrated biomass-to-liquids process to produce biodiesel from micro-algal biomass from the Hartbeespoort Dam.



Figure 2: Example of micro-algal pollution on the bank of the Hartbeespoort Dam.

1.3 PROBLEM STATEMENT

Although many studies have been conducted in the past on algae in the Hartbeespoort Dam, and specifically the pollution problem caused by these algal blooms, most of them focussed on the parameters influencing the growth and distribution of these algal blooms; few came up with practical solutions to manage and reduce them, and only a very few recommended ways to use and beneficiate them commercially. The key question to answer is whether micro-algal biomass from the Hartbeespoort Dam could be cultivated, harvested and turned into biodiesel feasibly; and if so, how could this be realised?

1.4 PURPOSE OF RESEARCH

The purpose of this work was to develop improved and novel methods for the cultivation and harvesting of micro-algal biomass from the Hartbeespoort Dam, and to incorporate them into a new integrated biomass-to-liquids biodiesel process. This research aimed to address many questions related to a micro-algal BTL process. Can microalgae from the Hartbeespoort Dam be cultivated economically? If not, what can be done to obtain micro-algal biomass viably? What are the most suitable methods for harvesting this micro-algal biomass? Can oils be extracted from this biomass? How efficiently can this oils be extracted? Can these oils be converted into biofuel, like biodiesel? Can microalgae from the Hartbeespoort Dam be turned into biodiesel thermodynamically and economically? How can all the constituents of a BTL process be combined, if at all, to make the overall process feasible?

1.5 SCOPE OF WORK

In order to develop improved and novel methods for the cultivation and harvesting of micro-algal biomass from the Hartbeespoort Dam, and to incorporate them into a new integrated biomass-to-liquids biodiesel process, this work was divided into the following main steps:

- A literature study was done to understand the aspects involved in the cultivation and harvesting of micro-algal biomass from the Hartbeespoort Dam; extract oils from the micro-algal biomass; production of biodiesel from algal-derived oils; process development; engineering design and sizing of equipment for a new process; cost estimation; economic evaluation; sensitivity analysis; and feasibility study;

- Conduct screening experiments to cultivate and harvest micro-algal biomass from the Hartbeespoort Dam;
- Develop a new integrated biomass-to-liquids biodiesel conceptual process;
- Perform rough sizing of equipment with screened design parameters;
- Estimate the rough order of magnitude cost of the new proposed BTL facility;
- Determine the economic feasibility of the new process with an economic evaluation;
- Perform a sensitivity analysis to determine the impact of different design and cost parameters on the overall design and project feasibility;
- Use all the above information to check the feasibility of cultivating and harvesting micro-algal biomass from the Hartbeespoort Dam, in the context of new integrated BTL process to produce biodiesel from the Hartbeespoort Dam.

1.6 OVERVIEW OF THESIS

Chapter One introduces the reader to the background, motivation, problem statement, purpose and scope of work of the research, as well as giving an overview of the thesis. Chapter Two includes theory relevant to the cultivation and harvesting of micro-algal biomass from the Hartbeespoort Dam; extraction of oils from the micro-algal biomass; production of biodiesel from algal-derived oils; process development; engineering design and sizing of equipment for a new process; cost estimation; economic evaluation; sensitivity analysis; and feasibility study. Chapter Three describes the screening experiments used to determine the most suitable cultivation and harvesting methods for the production of micro-algal biomass from the Hartbeespoort Dam; and the methods and materials used to develop, engineer, cost, evaluate, analyze and determine the feasibility of a new integrated biomass-to-liquids process. Chapter Four shows and discusses the results achieved. Chapter Five summarizes the conclusions reached and the recommendations made for each step in the work. The Appendices contain the raw data for the above-mentioned steps.

CHAPTER TWO



LITERATURE STUDY

WITH RELEVANT THEORY

It is knowledge that influences and equalizes the social condition of man; that gives to all, however different their political position, passions which are in common, and enjoyments which are universal.

– Benjamin Disraeli, 1844

2. LITERATURE STUDY

According to Wabeke (2011), all projects, whether large or small, go through the following six phases:

- Identification
- Assessment
- Selection
- Definition
- Execution
- Operation

During the project identification phase, the realization of potential benefits through a new project is identified. Existing data, information and knowledge are screened to identify potential projects and benefits. Project information that does not exist in the literature domain, needs to be obtained from experimentation. During project assessment, a project is assessed to see if it is feasible. During the project selection phase, strategic decisions are made which shape the concept of the project. During project definition the plan or design is specified and developed. In the execution phase the project plan is implemented and in the operation phase, the implemented plan is operated and maintained.

This work focussed on the first three steps: (1) potential opportunities and possible processes were identified through literature studies and new suitable processes and relevant design parameters were identified through screening experiments; (2) these processes were then assessed, in order to (3) select the most feasible option for the production of BTL biodiesel from Hartbeespoort Dam micro-algal biomass.

Section 2.1 consisted of a literature study on the identification of new opportunities, processes and design parameters. It includes all the aspects involved in cultivating and harvesting micro-algal biomass from the Hartbeespoort Dam, which covered the following areas: the background on global energy trends, and in particular biodiesel and one of its new sources, microalgae; the micro-algal reservoir Hartbeespoort Dam; the dominant micro-organism group cyanobacteria and the dominant species *Microcystis aeruginosa*; the management of micro-algal biomass in open ponds like the Hartbeespoort Dam; and the methods and costs associated with the cultivation and harvesting of micro-algal biomass.

Sections 2.2 to 2.7 contained relevant theory on the development of a new process; engineering design and sizing of equipment for a new process; estimating the costs of a process facility; economic evaluation; sensitivity analysis and feasibility study of a new process.

SECTION ONE



LITERATURE STUDY

FOR PROCESS IDENTIFICATION

2.1 LITERATURE STUDY FOR PROCESS IDENTIFICATION

2.1.1. Hartbeespoort Dam

The Hartbeespoort Dam covers a surface area of approximately 20 km², and has a maximum depth of 32.5 m and a mean depth of 9.6 m. Stable environmental factors such as low rainfall, windless weather and warm temperatures, which vary from a minimum of 9 to 13°C during winter periods and a maximum of 24 to 27°C during summer periods (Owuor *et al.*, 2007), create a suitable habitat for various micro-algal species. These equilibrium conditions coupled with the influx of nitrate and phosphate-rich run-off of fertilized agricultural land and effluent from sewage plants, stimulate the excessive growth of cyanobacteria in the Hartbeespoort Dam. Dense populations of the cyanobacterium *Microcystis aeruginosa* (hereafter *Microcystis*) dominate the dam throughout the year, comprising over 90% of the total micro-organism biomass (Hambright and Zohary, 2000).

2.1.2. Cyanobacteria

Cyanobacteria are one of the oldest photosynthetic life forms on earth. They are autotrophic organisms which *lack internal organelles, a discrete nucleus and the histone proteins associated with eukaryotic chromosomes*. Photosynthesis occurs *directly in the cytoplasm of the cell, rather than in specialized organelles*, with chlorophyll being used to absorb the solar radiation. Photosynthetic lamellae contain chlorophyll a and several pigments, such as phycoerythrin and phycocyanin, which give cyanobacteria their distinctive blue-green colour (Owuor *et al.*, 2007).

2.1.2.1. *Nutrients and cyanobacteria*

Nitrogen (in the form of nitrates like NaNO_3) and phosphorus (in the form of phosphates like K_2HPO_4) are the two most important nutrients for cyanobacterial growth. Unlike other algal and diatom species, cyanobacteria have the ability to fix nitrogen and store phosphorus for later use, which give them a competitive advantage in phosphorus-rich and nitrogen-limited water systems. In water systems like the Hartbeespoort Dam, cyanobacteria often becomes the dominant micro-organism, where surface water becomes enriched with nutrients, like phosphorus from run-off of fertilized agricultural land (Davis *et al.*, 2009).

2.1.2.2. *Cyanobacterial reproduction*

Reproduction in cyanobacteria occurs through a variety of methods, such as binary fission, budding or fragmentation. These various methods of reproduction cause cyanobacteria to appear in many different forms, such as patches, slimy masses, strings, filaments and branched filaments. Binary fission involves the duplication of DNA. Budding involves the formation of smaller cells from larger ones, while fragmentation involves breaking into fragments, each of which then regenerates into a complete micro-organism. The form of cyanobacteria that will grow is determined by the wavelength of photosynthetic light that is available. Nutrients such as phosphates and iron are also important in cyanobacterial growth and reproduction (Owuor *et al.*, 2007).

2.1.2.3. *Cyanobacterial organization*

Cyanobacteria have the ability to form many types of organizations, depending on environmental factors such as warm temperatures and the availability of phosphorous and nitrogen. Cyanobacteria can grow on rocks and stones (epilithic forms), on plants in the water (epiphytic forms), or on the bottom sediment of dams (epipellic forms), like the Hartbeespoort Dam. Cyanobacteria form the following different organizations (Owuor *et al.*, 2007):

- Single cells enclosed in a sheath of slime-like material or mucilage;
- Colonies of flattened sheets;
- Colonies of cubed or rounded balls;
- Colonies with elongated filaments.

Filamentous colonies of cyanobacteria occur in the following three cell types (Owuor *et al.*, 2007):

- Photosynthetic vegetative cells are formed under favourable growing conditions;
- Climate-resistant spores may form when environmental conditions become harsh;
- Thick-walled heterocyst cells.

2.1.2.4. *Cyanobacterial buoyancy*

Cyanobacteria contain gas vacuoles which enable them to regulate their buoyancy and form dense populations on the surface of lakes and ponds. The number of these intercellular gas vacuoles, determine the rate of surface accumulation (Owuor *et al.*, 2007). A number of mechanisms regulate the buoyancy of cyanobacteria, such as the form of stored carbohydrates, and the regulation of turgor pressure and gas vacuole synthesis (Oberholster *et al.*, 2004). According to Grobbelaar (2002), cyanobacteria lose their buoyancy in turbulent waters, due to the disturbance of the mechanism to regulate the gas vacuole synthesis.

2.1.2.5. *Temperature and cyanobacteria*

Cyanobacteria can survive in a wide range of temperatures, but really start to flourish when water temperatures exceed 20°C (Owuor *et al.*, 2007). Lower temperatures inhibit the growth of cyanobacteria, even in the presence of high concentrations of dissolved nitrogen (e.g. NO_3^-) and phosphorus compounds (e.g. PO_4^{3-}) in surface waters. Cyanobacteria frequently dominate eutrophic water systems during the warmest periods of the year (Davis *et al.*, 2009).

2.1.3. **Microcystis aeruginosa**

In the late seventies the hyacinth problem was eradicated, which caused phytoplankton to increase dramatically. One of the micro-organisms which became dominant was the cyanobacterium *Microcystis aeruginosa*, which comprised over 90% of the micro-organism biomass during the 6 to 10 warmest months of the year. During the colder autumn and winter months, *Microcystis* forms dense surface hyperscums up to 75 cm thick in wind-protected bays, often covering several hectares in surface area (Hambright and Zohary, 2000). The following factors have an influence on the growth and dominance of *Microcystis* in the Hartbeespoort

Dam: environment, temperature, nutrients, human intervention, buoyancy, wind, assemblages, and interaction with other species.

2.1.3.1. Environment and Microcystis

The fairly stable conditions around the Hartbeespoort Dam, which include constant temperatures, low wind intensities, and high supplies of nutrients from raw sewage and fertilizer run-off, create a fertile environment for the proliferation of *Microcystis*. Physical disturbances on the water column, like high wind velocities during the windy months, draining of the dam after the summer rainy season, and low temperatures during the winter period, result in short-term seasonal collapses of *Microcystis* populations, and short-term proliferation of other phytoplankton species (Owuor *et al.*, 2007).

2.1.3.2. Temperature and Microcystis

According to Davis *et al.* (2009), cyanobacteria dominate micro-organism populations in dams and lakes during the warmest periods of the year. This is more so in eutrophic systems, where cyanobacteria growth rates surpass the growth rates of green algae and diatoms. *Microcystis* growth is severely limited at temperatures below 15 °C and optimal at temperatures around 25°C according to Oberholster *et al.* (2004).

2.1.3.3. Nutrients and Microcystis

Davis *et al.* (2009) found that phosphates and nitrates significantly increased the growth rate of *Microcystis*. They also found that high concentrations of these two nutrients, in conjunction with high temperatures, yielded much greater growth rates than just increasing either of the two parameters.

2.1.3.4. Growth and Microcystis

Like most micro-organisms, *M. aeruginosa* follows an S-curve growth profile, with three distinct phases: an initial lag phase; a second rapid exponential phase; and a third stationary phase. Under laboratory conditions Oberholster *et al.* (2004) found that the initial lag phase of growth for *M. aeruginosa* took approximately 5 days and the second phase lasted 11 days, under light intensities between 3600 and 18,000 lux.

2.1.3.5. Buoyancy of *Microcystis*

Microcystis aeruginosa, like other cyanobacterial species, contains intercellular gas vacuoles which allow them to regulate their buoyancy and position in the water column. This mechanism gives *Microcystis* a competitive advantage over other aquatic micro-organisms, by enabling them to exploit spatial differences in nutrients, light and carbon dioxide. In water systems with high turbidity, like the Hartbeespoort Dam, *Microcystis* species generally dominate, because they have the ability to float to the surface and intercept most of the solar light. *Microcystis* reduce their chlorophyll content during periods of high light intensities, but increase chlorophyll synthesis during periods of low light intensities. The buoyancy regulation of *Microcystis* is severely impaired at low winter temperatures (Owuor *et al.*, 2007).

2.1.3.6. Wind and *Microcystis*

The size of *Microcystis* colonies are influenced by the frequency and intensity of the wind. During windy conditions large colonies of *Microcystis* are broken up into smaller formations in the middle of a dam, while concentrating them in thick patches against the side of the dam, depending on the wind direction. During calm conditions large formations of *Microcystis* occur at the surface at various sites (Owuor *et al.*, 2007). High wind velocities break up *Microcystis* blooms in the upper water column, by mixing them down into the lower water column (Hambright and Zohary, 2000).

2.1.3.7. Assemblages of *Microcystis*

Large buoyant colonies of *Microcystis* appear in two forms in the Hartbeespoort Dam: the net-shaped colonies of *M. aeruginosa forma aeruginosa* and the spherical or lens-shaped colonies of *M. aeruginosa forma flos aquae* (Owuor *et al.*, 2007). Throughout most of the year the Hartbeespoort Dam is dominated by net-shaped *Microcystis* colonies of 1-50 mm in length (Jarvis, 1986).

2.1.3.8. Substrates and *Microcystis*

Microcystis inoculum accumulate on any substrate present in the Hartbeespoort Dam, such as rocks, stones, debris, and sediment on the bottom of the dam. Most of the source of new *Microcystis* growth comes from dam sediment during spring (Owuor *et al.*, 2007).

2.1.3.9. *Microcystis* interaction with other species

Microcystis has a competitive advantage over other micro-organism species by intercepting solar radiation and thereby controlling the light regime in the water column, due to its ability to regulate its buoyancy and form large colonies at the water's surface. The cyanobacterium *Pseudoanabaena* is one of only a very few species that can compete with *Microcystis* colonies (Hambright and Zohary, 2000). It is only with the mixing of surface water during increased spring winds that other species start to increase, due to increased access to solar light. Other competitive advantages of *Microcystis* include their ability to maintain large seed stocks in the sediment of dams, and their ability to fix nitrogen and store phosphorus (Owuor *et al.*, 2007).

2.1.3.10. Conditions conducive for *Microcystis* cultivation

From the above-mentioned literature study, the following parameters and conditions were identified for optimal cultivation of *Microcystis* biomass:

- A stable environment, with equilibrium conditions promotes the proliferation of *Microcystis* populations, and enclosed bays, with stagnant hydrodynamic conditions, provide protective environments for *Microcystis* seed stock.
- High water temperatures around 25°C are optimal for *Microcystis* growth. Lower temperatures negatively influence the ability of *Microcystis* to regulate its buoyancy.
- *Microcystis* flourish in nutrient-rich environments, with high concentrations of phosphorus and nitrogen compounds.
- Substrates like sediment, rocks and debris provide safe protective environments for *Microcystis* inoculums.
- The ability of *Microcystis* to regulate its buoyancy, ensures its dominance in the water column, regardless of the presence of other micro-algal species, as it intercepts solar radiation and hinders it from reaching micro-algal species further down in the water column. Windless conditions are a prerequisite for this mechanism. Any method that could influence the hydrodynamics of an open water system, like the Hartbeespoort Dam, would influence the dominance and abundance of *Microcystis* biomass.

2.1.4. Management of micro-algal biomass

The following methods were employed in the past to manage and reduce the population of microalgae in the Hartbeespoort Dam, with various degrees of success: physical removal; external nutrient loading reduction; flushings; bio-manipulation; aeration systems. Other remediation options being practiced internationally are biological nutrient removal and chemical control.

2.1.4.1. Physical removal

The most effective process used to manage cyanobacteria in the Hartbeespoort Dam is the physical removal of biomass, by pumping the biomass to dry areas and allowing them to decompose naturally. Although effective, this option remains labour-intensive, time-consuming and reactive (Owuor *et al.*, 2007).

2.1.4.2. External nutrient loading reduction

Restrictions on phosphorus concentrations of 1 mg/L, on all domestic and industrial effluents in the late eighties, reduced the phosphorus loading and subsequent concentration of phosphorus in the Hartbeespoort Dam significantly (Owuor *et al.*, 2007; Hambright and Zohary, 2000). This reduction in the external loading of nutrients into the dam was achieved by minimizing the use of fertilizers and pesticides in the catchment areas, improving and maintaining sewage plants and establishing natural vegetation around the dam to filter incoming water. This option is not practical in the Hartbeespoort Dam, as the dam traps and recycles nutrients through a process called internal loading, negating any remediation strategy (Owuor *et al.*, 2007).

2.1.4.3. Flushings

Microcystis populations can be reduced further by transporting the biomass with barges to the dam wall and then flushing the hyperscums over the dam wall. (Hambright and Zohary, 2000).

2.1.4.4. Bio-manipulation

Bio-manipulation, in conjunction with the re-establishment of aquatic plants, was another strategy that was initiated by DWAF to rid the Hartbeespoort Dam of its algal pollution. Bio-manipulation involves the removal of any natural factor that somehow contributes to the growth

of microalgae. One of these factors included the removal of bottom feeder fish, like carp, to stop them releasing phosphorus as they disturb the bottom sediment. Bio-manipulation is cost effective and has the potential to be a long-term solution according to Owuor *et al.* (2007).

2.1.4.5. Aeration systems

Another control mechanism tested in South Africa, involved aerated water systems which feed air through pipes along the dam floor. This mixes the water, increases the oxygen levels and interferes with mobilization of phosphorus, a limiting nutrient in algal growth. This option is extremely costly and involves large investment and operational expenditures (Owuor *et al.*, 2007).

2.1.4.6. Biological nutrient removal

Other forms of bio-remediation include a process called biological nutrient removal in which bacteria are introduced to a water body to remove limiting nutrients, like phosphorus, which are essential for algal growth. The bacteria ingest these limiting nutrients in the water and assimilate them in their biomass. When these bacteria die an insoluble phosphorus particulate is created in the presence of calcium carbonate and high pH, which reduces the amount of bio-available nutrients for algal growth (Owuor *et al.*, 2007).

2.1.4.7. Chemical control

Chemical additives, such as iron or aluminium sulphate, or copper can be used to prevent phosphorus from leaching out of sediments. Chlorine can be used as an algaecide, but can cause the release of toxins, such as microcystins. Copper or lime can also be used to kill algae, but without significant increase in microcystin concentration in the surrounding water (Oberholster *et al.*, 2004). Although chemical control of *Microcystis* blooms appears to be an effective solution, it is costly and could pose a problem for domestic water use (Owuor *et al.*, 2007).

2.1.4.8. Biological control

Biological control includes the use of host-specific viruses, myxobacteria and fungal parasites, to control cyanobacterial species and prevent them from growing, while allowing environmental friendly species to proliferate. The addition of barley straw and hay in a dam may also control

cyanobacteria, as the decomposition of straw and hay releases chemicals such as antibiotics which inhibits the growth of cyanobacteria like *Microcystis* (Oberholster *et al.*, 2004).

2.1.5. Cultivation of microalgae

There are five major steps in the production of biodiesel from micro-algal biomass-derived oil: the first two steps involve the cultivation and harvesting of micro-algal biomass; which is followed by the extraction of the oils from the micro-algal biomass; then the conversion of these oils via the chemical reaction transesterification into biodiesel; and the last step is the separation and purification of the produced biodiesel. The first two steps are the most inefficient and costly steps in the whole biomass-to-liquids (BTL) value chain. Cultivation costs may contribute between 20–40% of the total cost of BTL biodiesel production (*Comprehensive Oilgae Report*, 2010), while harvesting costs may add 20–30% to the total cost of oil production through algal biomass (Verma *et al.*, 2010). One of the major obstacles in the economic production of microalgae, are the development of cost effective methods for the cultivation of micro-algal biomass. One way of achieving this is by increasing the productivity of cultivation systems. Grobbelaar (1982) cited that the cost of producing one ton of dry algal matter can be decreased by 33% with a 59% increase in productivity.

2.1.5.1. Cultivation methods

There are two main categories of cultivation equipment for microalgae: open and closed-culture systems. Open-culture systems include open ponds and dams, while closed-culture systems include closed ponds and highly controlled photobioreactors (Mata *et al.*, 2010). Photobioreactors (PBRs) have much higher micro-algal biomass yields and productivities per cultivation area than open ponds, because the closed reactor reduces the risk of contamination from other algal species, and the controlled conditions provide the optimum environment for high growth rates. The downside of PBRs is that they are much more expensive than open ponds and require much higher capital and operating costs, which hinder their feasibility for the economic production of micro-algal biomass (*Oilgae*, 2010; Mata *et al.*, 2010; Verma *et al.*, 2010).

Table 1: Comparison between closed and open cultivation systems (Mata *et al.*, 2010)

Culture systems for microalgae	Closed-culture systems (PBRs)	Open-culture systems (Ponds)
Contamination control	Easy	Difficult
Contamination risk	Reduced	High
Sterility	Achievable	None
Process control	Easy	Difficult
Species control	Easy	Difficult
Mixing	Uniform	Very poor
Operation regime	Batch or semi-continuous	Batch or semi-continuous
Space required	Small	Large
Area/volume ratio	High (20-200 m ⁻¹)	Low (5-10 m ⁻¹)
Population density	High	Low
Light utilization	High	Poor
Temperature control	Uniform	Difficult
Productivity	3-5 time more productive	Low
Evaporation of growth medium	Low	High
Capital costs	High	3-10 times lower than PBRs
Operating costs	High	Low

2.1.5.2. Open-culture ponds

Open-cultivation pond systems are much cheaper to operate and maintain than closed-cultivation systems, like PBRs, because they utilize freely available sunlight and atmospheric carbon dioxide for micro-algal biomass growth, rather than artificially supplied illumination and carbon dioxide. Open-cultivation pond systems also require less capital cost per unit area to install than closed-cultivation systems, which makes them more suited for large-scale cultivation of microalgae (Oilgae, 2010; Mata *et al.*, 2010; Verma *et al.*, 2010). The most popular open-cultivation designs include raceway and circular ponds. Studies on open ponds have suggested that they should have standard dimensions of 10 m width, 100 m length and 30 cm depth for optimal micro-algal biomass growth. Open ponds should have paddle wheels for raceway systems and rotating arms for circular systems, to mix the algal biomass with the nutrients in the growth medium, and prevent material settling to the bottom of the ponds. *Maximum biomass productivity is attained under tropical or subtropical conditions*, and range between 10 to 50 g/m²/d, for both raceway and circular pond systems (Verma *et al.*, 2010). Disadvantages of open ponds include low growth rates compared to closed-cultivation systems; availability of cheap land and water; reliance on stable climatic conditions; high water loss due to evaporation; susceptible to contamination by other unwanted micro-organisms (Mata *et al.*, 2010; Verma *et al.*, 2010).

2.1.5.3. Closed-culture ponds

The disadvantages of open ponds can be mitigated by covering the ponds with a roof to control the temperature and reduce the risk of contamination by foreign algal species. Creating an enclosed environment extends the growing season slightly if unheated, but allows for year-round cultivation if heated. It is also possible to increase the productivity of these closed ponds by providing additional carbon dioxide (*Oilgae*, 2010). Closed pond systems cost more than the open ponds, but are considerably less than photobioreactors for similar areas of production (*Comprehensive Oilgae Report*, 2010).

2.1.5.4. Photobioreactors

PBRs have much higher productivities than open-cultivation ponds, because they offer better control over culture conditions and growth parameters like pH, temperature, mixing, carbon dioxide and oxygen. PBRs have the ability to increase the concentration of carbon dioxide by supplying additional air or carbon dioxide for the cultivation of microalgae. With their enclosed reactor walls, PBRs also offer a protected environment, preventing water and carbon dioxide losses and contamination by competing micro-organisms (Mata *et al.*, 2010).

Despite their advantages, PBRs are not as feasible as open ponds. Their main limitations include: overheating, bio-fouling, oxygen accumulation, difficulty in scaling up, the high cost of building and operating, cell damage by shear stress and deterioration of material used for the photo-stage. The cost of biomass production in PBRs is one order of magnitude higher than in ponds (Mata *et al.*, 2010). The most common PBRs include the widely used tubular, vertical-column, and flat-plate PBRs (*Oilgae*, 2010).

Table 2: Comparison between three types of photobioreactors (*Oilgae*, 2010)

Photobioreactor properties	Tubular	Vertical-column	Flat-plate
Illumination surface area	Large	Smallest	Highest
Fouling	Some degree of wall growth	Wall growth	Wall growth
Gradient of pH	High	Medium	Low
Gradient of dissolved O ₂	High	Medium	Low
Gradient of dissolved CO ₂	High	Medium	Low
Materials of construction	Cheaper	Cheap to expensive	Relatively cheap

2.1.5.5. Tubular photobioreactors

Tubular photobioreactors consist of straight, coiled or looped transparent tubing made from glass or plastics. These tubes are between 0.01 and 0.1 meters in diameter and fixed in a north-south direction. The floor beneath the tubes is painted white to increase reflection and maximize the capture of sunlight for micro-algal growth (Verma *et al.*, 2010). Tubular PBRs are very suitable for outdoor mass cultivation of microalgae since they have large illumination surface areas. Mixing in reactors is important to prevent sedimentation of cells and even distribution of gases, and is provided with circulation pumps or airlift systems. The disadvantages of tubular PBRs include poor mass transfer with scaled-up plants; oxygen build-up; photo-inhibition; fouling; and poor temperature and pH control (Oilgae, 2010).

2.1.5.6. Vertical-column photobioreactors

Vertical-column PBRs are compact, cheap, easy to operate, and have great potential for the large-scale cultivation of microalgae. Bubble column and air-lift PBRs (up to 0.19 meters in diameter) can attain a final biomass concentration and specific growth rate comparable to narrow tubular PBRs. Some bubble column PBRs are equipped either with draft tubes or constructed as split cylinders (Oilgae, 2010; Chiu, 2009).

2.1.5.7. Flat-plate photobioreactors

Flat-plate PBRs are made of transparent materials for maximum utilization of solar light energy and high photosynthetic efficiencies. They have large illumination surface areas and are very suitable for growing microalgae. Accumulation of dissolved oxygen concentrations in flat-plate PBRs are relatively low compared to horizontal tubular PBRs (Oilgae, 2010; Mata *et al.*, 2010).

2.1.5.8. Cultivation costs

The indicative capital cost of open ponds range between \$125,000 and \$150,000 per hectare, while closed pond systems cost approximately \$200,000 per hectare. The indicative operating cost of open ponds range between \$15,000 and \$35,000 per hectare, while the operating costs of closed pond systems range between \$20,000 and \$45,000 per hectare. PBRs are more expensive than other cultivation systems owing to their sophistication. In 2008, the capital cost of PBRs varied between \$60 and \$100 per square meter (Comprehensive Oilgae Report, 2010).

2.1.6. Harvesting methods for microalgae

One of the major obstacles in the economic production of microalgae is the development of cost effective methods for the harvesting of micro-algal biomass. The harvesting of micro-algal biomass is one of the most inefficient and costly steps in the whole biomass-to-liquids (BTL) value chain, mainly due to the dilute concentration of micro-algal cultures, and the substantial power input and operating costs required to separate them from their growth medium (Uduman *et al.*, 2010). Harvesting costs may add 20–30% to the total cost of oil production through algal biomass according to Verma *et al.* (2010). The cost of oils extraction from microalgae can be reduced significantly by concentrating the biomass as much as possible. Harvesting of micro-algal biomass normally involves the concentration of dilute suspensions of 0.02–0.06% total suspended solids (TSS) into a slurry or paste with concentrations of 5–25% TSS. Most harvesting processes consist of a two-step process, which involves a primary harvesting step to concentrate a dilute suspension into a slurry of 2–7% TSS, followed by a secondary dewatering step that produces an algal paste of 15–25% TSS. The concentration obtained in the harvesting steps is crucial to the overall process as it influences the subsequent drying process (Uduman *et al.*, 2010).

There are no single method which is the best for micro-algal harvesting, because microalgae are composed of several species with different shapes, sizes and motilities. The major methods of harvesting microalgae include centrifugation, electrophoresis, flocculation, flotation, screening, filtration and sedimentation (Uduman *et al.*, 2010). Centrifugation and electrophoresis remove microalgae reliably, but are very expensive; flocculation are less expensive, but require the use of chemical flocculants which contaminate the system; screening, filtration and sedimentation are less costly, but due to the small size of most microalgae (less than 20 μm in diameter), are difficult to harvest. However, in open reservoirs like dams, microalgae occur in large blooms as long filamentous colonies, which make them easy to microstrain, screen and filter. The least expensive method of harvesting microalgae is raking of partially submerged or floating microalgae with rotary microstrainers, but this is only applicable to filamentous algae. Costs associated with microstrainers are a tenth of chemical flocculation according to Benemann *et al.* (1977). Table 3 from Uduman *et al.* (2010) gives a comparison of the different harvesting methods.

Table 3: Comparison of different harvesting methods (Uduman *et al.*, 2010)

Harvesting Method	Highest possible Yield (% TSS)	Energy Usage (kWh/m ³)	Reliability	Limitations
Centrifugation	12.0	High (8)	Very good	High capital and operating costs of energy
Flocculation	22.0	Low	Very good	Chemicals are costly and cause contamination
Flotation	5.0	High	Good	High capital and operating costs
Screening	6.0	0.4	Good	High costs of replacing screens
Filtration	27.0	0.88	Very good	High costs of replacing filters
Sedimentation	1.5	0.1	Poor	Slow process and low yields
Electrophoresis	99.5	1.5	Very good	High costs to replace electrodes

Drying is the last harvesting step and requires moisture content in microalgae to be reduced to 12% or less. Mechanical methods like drum drying are the most efficient, but are costly and energy-intensive. Sun-drying on a lightly oiled surface is only effective when the initial slurry contains 10% solids (usually 0.25 cm in thickness). After a day of drying the micro-algal biomass on an area about 5% the growth area, the moisture content reduces to below 15% and the flaked solids are easily collected. Sand-bed drying can combine dewatering and drying of micro-algal biomass, beginning with 8-12 cm thick slurry. Most of the water drains away quickly, while the remainder of the drying process takes three to five days. After a few days the dried algal flakes can then be separated from most of the sand (Benemann *et al.*, 1977).

2.1.6.1. Screening

Screening is the process of passing a suspension of solids and liquids through a permeable medium or screen of specific pore size. The liquid passes the screens, while the solids are retained by the permeable medium, which has smaller pore sizes than the solids. Microstrainers and vibrating screen filters are the two main types of screens used for microalgae harvesting according to Uduman *et al.* (2010). Microstrainers can be described as rotating filters with fine mesh screens (5–20 µm) and a continual backwash (Garden, 2005). The cost of microstraining is determined by the flow-through rate of the screens, which is determined by the size of the screen openings, which again is dependent on the species of microalgae. Larger micro-algal species will require larger openings, resulting in faster flow rates and lower cost of screens. The concentration of microalgae is another factor that influences the efficiency of the process. A high micro-algal concentration can result in blocking of the screen, while a low micro-algal concentration can result in inefficient screening (Uduman *et al.*, 2010). The unit cost of

microstraining is between \$5 and \$15 per million litres of processed medium. Advantages of microstrainers include simple function and construction, easy operation, negligible attrition, low energy consumption, high filtration ratios, and low capital and operating costs. Limitations with microstrainers include incomplete solids removal, difficulty in handling solids fluctuations and build-up of algal slime on the microfabric (Shelef *et al.*, 1984).

2.1.6.2. Filtration

Filtration requires a pressure drop to be applied across the system in order to force the fluid through the filter. The extent of pressure required for the medium determines which type of driving force is used: gravity, vacuum, pressure, or centrifugal. Filtration of microalgae requires regular backwashing, because the microalgae tend to accumulate onto the filter and block the pore sizes, resulting in lower filtration rates (Uduman *et al.*, 2010). Drum filters, utilizing gravity flows with low head requirements and high flow rates, are regularly used to clean wastewater (Garden, 2005). Grima *et al.* (2003) found that microalgae with large cell sizes could easily be filtered using pressure or vacuum, while microalgae with sizes approaching bacterial dimensions are difficult to filter.

2.1.6.3. Sedimentation

Gravity sedimentation is the most economical separation method for micro-algal concentration, but is the slowest process with the lowest harvesting yield. Sedimentation tanks and lamella separators are the most widely used sedimentation equipment and utilize natural gravity to concentrate microalgae from their growth medium. Lamella separators offer better separation than conventional thickeners due to the orientation of their plates. The sedimentation rate and final micro-algal concentration can be improved by the addition of flocculants. Sedimentation tanks are not used widely in industry, but are a reliable method to concentrate micro-algal suspensions to 1.5% TSS. Micro-algal density is an important factor in gravity settling. Microalgae with high densities settle quickly, but low density microalgae settle poorly, resulting in insufficient separation (Uduman *et al.*, 2010).

2.1.6.4. Filtration costs

According to the *Comprehensive Oilgae Report* (2010), the major cost components for harvesting include: cost of drying the algae; harvesting infrastructure and equipments (capital

expense); maintenance of harvesting equipments; chemicals (if flocculation methods are used for harvesting); manpower costs; and electricity. Drum filtration is one of the most cost effective methods for harvesting large microalgae with sizes exceeding 20 μm in diameter (Uduman *et al.*, 2010). The average capital cost of drum filtration in the USA come to approximately \$0.2 per 1000 annual gallons of processed micro-algal growth medium. The average operating cost for drum filtration ranges between \$100 and \$120 per million gallons of processed micro-algal growth medium. In 2010, a 1 million L/h drum filtration system in the USA cost about \$0.4 million, and includes the drum filter, pumps and measuring equipment (*Comprehensive Oilgae Report*, 2010).

2.1.7. Extraction of oils from microalgae

There are many processes in literature to extract oils from microalgae. These processes include: thermochemical liquefaction, pyrolysis and gasification; and supercritical carbon dioxide extraction. Liquefaction is the preferred thermochemical process to produce biofuels from algae, because of its lower energy input requirements, compared to pyrolysis and gasification. Thermochemical liquefaction occurs between 200-300°C, while pyrolysis and gasification occur at 500°C and 2000°C, respectively. Aresta *et al.* (2005) compared the extraction of algal oils through thermochemical liquefaction and supercritical carbon dioxide extraction, and found that thermochemical liquefaction was more efficient from a quantitative point of view.

Barnard (2009) found that thermochemical liquefaction was a preferred option to extract oil from Hartbeespoort Dam microalgae. He found that the optimum process conditions in the liquefaction reactor of 300°C, 15000 kPa, and 3% dry weight microalgae from the Hartbeespoort Dam, with the remainder being water solvent, produced the highest oil yield of 15.60% in 30 minutes. After liquefaction, Barnard added 20% chloroform solvent and agitated the mixture at 750 rpm for ten minutes, to recover oils from the water phase. Barnard then used vacuum distillation at 70°C to isolate the micro-algal oils successfully from the chloroform solvent.

2.1.8. Biodiesel production from micro-algal oils

There are four primary ways to make biodiesel from microalgae: direct use and blending; micro-emulsions; thermal cracking (pyrolysis) and transesterification (Ma and Hanna, 1999). The most common way is transesterification, as the biodiesel from transesterification can be used directly or as blends with diesel (Peterson *et al.*, 1991; Zhang *et al.*, 2003).

Miao and Wu (2005) produced biodiesel in four hours of reaction time through the acidic transesterification of micro-algal oil. They found that the best process combination was 100% sulphuric acid catalyst quantity (based on oil weight) with 56:1 molar ratio of methanol to oil at a temperature of 30°C. They suggested that their process was feasible and effective. They found that alkali catalysts were not suitable for the transesterification of micro-algal oil, and suggested that it was probably due to the high acid value of the micro-algal oil.

SECTION TWO



LITERATURE STUDY

ON PROCESS DEVELOPMENT

2.2 LITERATURE STUDY ON PROCESS DEVELOPMENT

According to Peters and Timmerhaus (1991), process design refers to the design of equipment and facilities necessary to carry out a process.

There are five steps in process design (Fig. 3), according to Sinnott (1991):

- Design objective or intent;
- Data and information collection;
- Generation of possible solutions;
- Solution selection;
- Final design packaging.

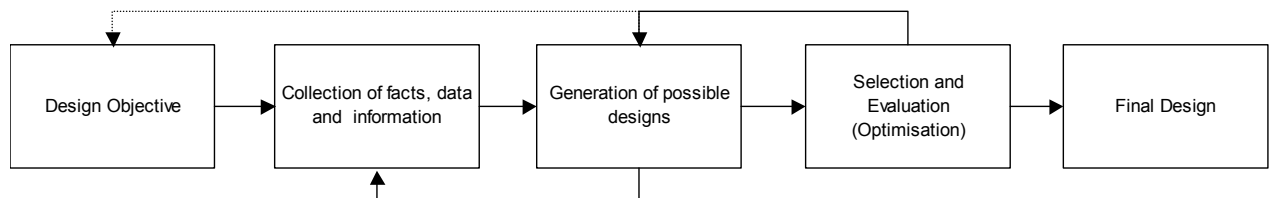


Figure 3: The design process (Sinnott, 1991).

The first step in process design consists of establishing the need or purpose of the client. The second step is the collection of data, information or knowledge relevant to the design. For process design this will include information on possible processes, equipment performance, and physical property data. The third part of the design process consists of generating many possible solutions to the problem or objective for analysis, evaluation and selection. The first activity in creating a new process design will be to sketch out a rough block diagram showing the main stages in the process. This is followed by expanding the block diagram into smaller blocks, describing the main processing stages, such as feedstock storage, reaction and product purification. The basic procedure in process design is to expand the design with more detail as

more and more data and information are obtained throughout the design process. The fourth step consists of analyzing, evaluating, comparing and selecting the most suitable option. The fifth and last step in process design consists of packaging the relevant information from the first four steps in a design document that forms the basis of all communication related to the design.

The following items should be considered when generating and comparing different process options (Peters and Timmerhaus, 1991):

- Technical factors (e.g. batch versus continuous operation);
- Raw materials (e.g. availability, processing required, storage and handling requirements);
- By-products (e.g. quantity, quality, value);
- Equipment (e.g. materials of construction, maintenance requirements, costs);
- Plant location (e.g. availability of land, labour and services);
- Costs (e.g. feedstock, power, labour, real estate).

The selection process for designs can go through the following stages (Sinnott, 1991):

- Possible designs (credible) – within the external constraints;
- Plausible designs (feasible) – within the internal constraints;
- Probable designs – likely candidates;
- Best design (optimum)

The design engineer will first start by identifying all the possible design options with a literature study. This is followed by rough cost estimations to narrow down the most plausible options. The most probable designs are then filtered out with more research and consultation. The last stage in the selection process is the identification of the most optimum design, through detailed design work, cost estimation and economic evaluation.

Figure 4 below, shows the generic stages of a typical chemical process. Each block represents a stage in the overall process of turning raw feedstock into high-value products. *Chemical engineering design is concerned with the selection and arrangement of the stages, and the selection, specification and design of the equipment required to perform the stage functions* (Sinnott, 1991):

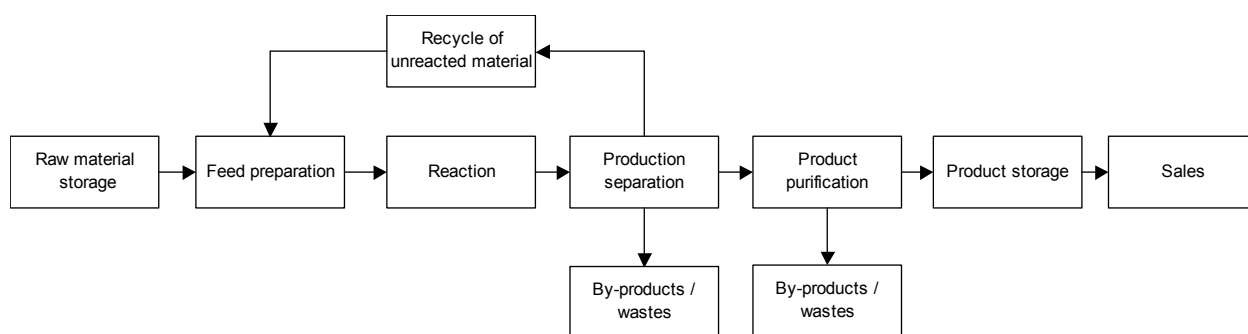


Figure 4: Anatomy of a chemical process (Sinnott, 1991).

Stage 1 is the raw material storage section where feedstock is delivered, handled and stored. Stage 2 is the feed preparation section where feedstock is prepared. Stage 3 is the reaction stage where feedstock is turned into high-value products. By-products and impurities are also produced in the reaction stage, and need to be separated from the products in stage 4, before being recycled or processed into saleable by-products. In stage 5 the main product will usually need purification to meet the product specification. Stage 6 consists of storage and handling facilities for final products. Gases will normally be transported in pipelines to customers, while liquids will normally be dispatched in bulk tankers or pipelines to customers. In addition to the main process stages shown in Fig. 4, provision is needed for the supply of utilities, such as process water, cooling water, steam, utility air and nitrogen. Facilities will also be needed for maintenance, administration, accommodation, laboratories, and emergency services (Sinnott, 1991).

SECTION THREE



LITERATURE STUDY

ON ENGINEERING DESIGN

2.3 LITERATURE STUDY ON ENGINEERING DESIGN

Peters and Timmerhaus (1991) consider all engineering aspects involved in the development of new, modified or expanded industrial plants as part of plant design. According to them, the preparation of engineering designs consists out of the following steps:

- Establishing the design basis;
- Drafting flow diagrams;
- Material and energy balances;
- Plant lay-out;
- Sizing of equipment with unit process principles;
- Summarizing equipment specifications in tables;
- Establishing utility requirements;
- Determining labour requirements;
- Estimating capital and operating costs;
- Economic evaluation;
- Capturing above information in design report;

The design basis consists of establishing the constraints and boundaries of the design. These constraints include flow rates and specifications of feedstock and products, and process conditions. The design basis is followed by the drafting of flow diagrams to aide the designing team throughout the rest of the engineering design process. Flow diagrams are visual tools to show the flow of materials and energy from one piece of equipment to another, and can be divided into three general types:

- Qualitative flow diagrams
- Quantitative flow diagram
- Combined detail flow diagrams

Qualitative flow diagrams indicate the flow of materials, unit operations, equipment and information on operating conditions. Quantitative flow diagrams show the quantities and flow rates of materials in the process. Combined detail flow diagrams are prepared by combining the information from the first two types of diagrams as the design develops. Combined detail flow diagrams show the location of major equipment, which is shown and designated by a defined identification number. For each equipment number, accompanying tables give essential information on operating conditions and design specifications. Material and energy balances are calculated next, and these balances are also shown on updated process flow diagrams. Updated process flow diagrams are followed by the lay-out of process equipment. The following items should be considered when arranging the best plant lay-out (Peters and Timmerhaus, 1991):

- New site development;
- Type and quantity of products to be produced;
- Type of process control;
- Operational convenience and accessibility;
- Economic distribution of utilities and services;
- Type of buildings;
- Health and safety considerations;
- Waste disposal requirements;
- Auxiliary equipment;
- Space available and space required;
- Roads and transportation infrastructure required and available;
- Possible future expansion.

Plant lay-out is followed by the sizing of equipment, which can be done through unit process principles, data from literature, or computer-aided programs. Pilot plant tests may then be necessary to verify the sizing and design of plant equipment. The design of reactors and filters normally require pilot plant data, while heat exchangers, distillation columns, pumps, vessels and storage tanks usually do not require pilot plant data. It is important to remember that the results of these pilot plant tests need to be scaled-up to the required plant capacity, to obtain a realistic design. *Maximum scale-up ratio for reactors should be in the order of 1:100, and the recommended safety or over-design factor should be 20%, compared to 10% for other types of equipment* (Peters and Timmerhaus, 1991).

In design work, the magnitude of safety factors is dictated by the following factors (Peters and Timmerhaus, 1991):

- Economic considerations;
- Accuracy of the design data and calculations;
- Potential changes in the operating performance;
- Background information available on the overall process;
- Amount of conservatism used in developing the individual components of the design.

Equipment specifications are generally summarized in the form of tables and included with the final design report. These tables usually include the following information:

- Distillation columns (number of plates, column diameter and height);
- Vessels (size, holdup time, materials of construction);
- Reactors (size, heat exchange facilities, materials of construction);
- Heat exchangers (duty, heat exchange area, materials of construction);
- Pumps (type, duty, power requirements, pressure differential);
- Agitators (duty, speed, size).

Equipment sizing is followed by establishing utility and labour requirements. This is followed by the estimation of capital and operating costs, which is then used in subsequent economic evaluations to identify the best designs and determine whether they should proceed. The last step in engineering design consists of capturing all the above information in a design report, which is then used to communicate the results of the design work.

SECTION FOUR



LITERATURE STUDY

ON COST ESTIMATION

2.4 LITERATURE STUDY ON COST ESTIMATION

2.4.1. Cost estimate types

In order to evaluate the economic feasibility of a project, a cost estimate first needs to be done to estimate the capital and operating costs of such a project. There are different types and classifications of estimates, depending on the amount of information available during the life of a project. The American Association of Cost Engineers published five definitions of estimate types as follows (Gerrard, 2007):

- Order of magnitude (variable accuracy over 30%);
- Study estimate (factored estimate, accuracy up to 30%);
- Preliminary estimate (generally for authorization, accuracy 20%);
- Definitive estimate (more detailed information, accuracy 10%);
- Detailed estimate (contractor's estimate, accuracy 5%).

Order of magnitude estimates can be done by applying overall ratios and appropriate escalation factors on costs for existing plants with similar functions. The error range of order of magnitude estimates lie between $\pm 30\%$ and $\pm 50\%$, with rough order of magnitude estimates even exceeding $\pm 50\%$. Many companies use order of magnitude estimates for quick screening only, and will normally require projects to proceed to the next phase of cost estimation. Study estimates have accuracies of up to $\pm 30\%$, and can be done on designs with preliminary flow diagrams, rough equipment sizing and geographical location for facilities. *Many authorities consider study estimates to be sufficient for the economic evaluation of a project* (Gerrard, 2007).

2.4.2. Cost estimate methods

Power law or exponential estimating can be done by deriving the cost of a new facility from historical cost data by using (Gerrard, 2007):

- The total cost of a similar (reference) plant;
- A comparatively simple breakdown of the costs of a similar plant;
- Costs for parts of related plants that can be assembled to represent the proposed plant.

The total cost of a proposed plant C can be estimated from the total cost of a similar reference plant C_r using:

$$\frac{C}{C_r} = \left(\frac{S}{S_r} \right)^n \quad (1)$$

where C is the plant cost and S the plant size. The scale exponent n can be derived from historical data for similar plants. For whole plants, n range between 0.4 and 0.8, but is typically 0.65.

Factorial estimating is a second costing method, which *can be used to produce study and preliminary estimates earlier and with far less information than definitive and detailed estimates* (Gerrard, 2007). Factorial estimating starts by first listing and sizing the main plant equipment, such as vessels, columns, reactors and pumps. The total erected cost of a facility is then estimated by multiplying the purchased cost of all major equipment with appropriate installation factors.

Computer cost estimating is a third costing method, which consists of two main activities. The first is the calculation of the plant cost, given a correlation, curve fit or rigorous model. The second use computer power to analyze a set of historical costs to trend and estimate costs (Gerrard, 2007).

2.4.3. Cost estimate factors

Cost estimates are dependent on and should be adjusted for differences in time, location and currency. The cost of equipment and materials increases with time, due to a variety of commercial, economic and social causes. In estimating the cost of equipment it is necessary to adjust the cost of an item at one time to the estimated cost at another time. This is generally achieved with the following cost indices relation (Gerrard, 2007):

$$\frac{C_a}{C_b} = \frac{I_a}{I_b} \quad (2)$$

where C_a is the cost at time a, and C_b is the cost at time b, I_a is the index at time a, and I_b is the index at time b.

Location is another factor influencing the cost of equipment. Thus, a specific item of equipment will cost different from one country to another. To compensate for the geographical factor, Eq. 2 could also be used, where C_a is the cost at location a, and C_b is the cost at location b, I_a is the index at location a, and I_b is the index at location b. Gerrard (2007) notes a location factor of 1.25 for equipment in South Africa versus the same equipment item in the United Kingdom and a factor of 1.15 for equipment in South Africa versus the same equipment in the United States.

The third important factor is currency differences. An item quoted in dollars or pounds sterling, needs to be converted into rands if the cost estimate is based in rands.

2.4.4. Cost estimate sources

Gerrard (2007) lists the following sources of cost estimate data:

- Detailed quotations from suppliers;
- Budget quotations from suppliers;
- Company records and databases;
- Trade literature;
- Unit pricing literature;
- Technical literature and textbooks;
- Computer data.

2.4.5. Capital costs

2.4.5.1. Capital cost items

Gerrard (2007) lists the following items making up a complete capital cost estimate:

- Purchased equipment costs;
- Equipment delivery costs;
- Equipment installation costs;
- Piping costs;
- Instrumentation and controls;
- Electrical costs;
- Building costs;
- Yard improvements;
- Service facilities;
- Land costs;
- Engineering and supervision;
- Construction expenses;
- Contractor's fees;
- Contingency;
- Working capital.

2.4.5.2. Purchased equipment costs

The cost of purchased equipment forms the basis of many cost estimate methods. The most accurate method for determining process equipment costs is to obtain recent quotations from suppliers and vendors. The second best method is to use costs from past purchases, and time adjusting them for present values (Peters and Timmerhaus, 1991).

2.4.5.3. Installation costs

Installation of equipment involves costs for labour, foundations, supports, platforms, construction expenses and other factors related to the erection of purchased equipment. Installation costs range between 20% and 60% of the purchased equipment costs for

compressors, pumps, tanks, heat exchangers and dryers, and up to 90% for evaporators and distillation columns (Peters and Timmerhaus, 1991).

2.4.5.4. Installed piping costs

Piping costs cover labour, valves, fittings, piping, supports, lagging and other items involved in the erection of piping used in the process. Piping costs can be as high as 80% of purchased equipment costs or 20% of the fixed capital investment (Peters and Timmerhaus, 1991). According to Perry (2008) this cost could range between 7 and 15% of the total installed plant cost.

2.4.5.5. Installed instrumentation and controls

For normal solid-fluid chemical processing plants, instrumentation and controls are 13% of the purchased equipment cost (Peters and Timmerhaus, 1991).

2.4.5.6. Installed electrical costs

Electrical installations are between 10% and 15% of the purchased equipment cost (Peters and Timmerhaus, 1991). According to Perry (2008) the cost of instrumentation and electrical range between 4 and 10%, with a median value of about 7.5% of the total installed plant cost.

2.4.5.7. Building costs

For normal solid-fluid chemical processing plants, cost of buildings and services are 12% of the fixed investment for a new plant at a new site, and 7% of a new unit at an existing site, and 4% of an expansion at an existing site (Peters and Timmerhaus, 1991).

2.4.5.8. Yard improvements

Yard improvements include fencing, grading, roads, sidewalks and landscaping, and range between 10 to 20% of the purchased equipment cost (Peters and Timmerhaus, 1991).

2.4.5.9. Installed service facilities

Utilities for supplying steam, water, power, utility and instrumentation air and fuel are part of the service facilities of a plant. Cost range between 30 and 80% of the purchased equipment cost with 55% representing an average for normal solid-fluid processing plants (Peters and Timmerhaus, 1991).

2.4.5.10. Land costs

As a rough average, land costs for industrial plants amount to 4 to 8% of the purchased equipment cost or 1 to 2% of the total capital investment (Peters and Timmerhaus, 1991).

2.4.5.11. Engineering and supervision costs

The costs for design, engineering, drafting, purchasing, accounting, construction and cost engineering, travel, reproductions, communications, and home office expenses constitute the capital investment for engineering and supervision. This is normally 8% of the total direct costs of the plant (Peters and Timmerhaus, 1991).

2.4.5.12. Construction expense costs

Construction expenses include the erection of a temporary construction and operation camp for the construction crew. It includes construction tools, accommodation, construction payroll, travel, taxes, insurance and construction overheads. This amounts to roughly 10% of the total direct field costs (Peters and Timmerhaus, 1991).

2.4.5.13. Contractor's fees

Contractor's fees vary for different situations, but average between 2 and 8% of the direct field costs (Peters and Timmerhaus, 1991).

2.4.5.14. *Contingency*

Every cost estimate has a margin of error. The variation between the estimated and the actual cost depends on a number of factors (Gerrard, 2007):

- Quality of the scope definition of the project;
- Quality and reliability of cost data available;
- Accuracy of the design;
- Validity of any quotations received;
- Unknown cost factors such as transport costs;
- Changes in inflation and cost escalation;
- Currency exchange rate fluctuations;
- Location and uncertainty of site problems;
- Local regulations;
- Local labour problems;
- Adverse weather during construction;
- Contractor delays.

In order to compensate for the above-mentioned uncertainties the cost estimator adds a contingency factor. According to Gerrard (2007), contingency factors range between 10% and 20% of direct and indirect plant costs. According to Peters and Timmerhaus (1991), contingency is about 10% of direct and indirect plant costs.

2.4.5.15. *Working capital*

Working capital can be defined as the funds, in addition to the fixed capital, land and start-up costs, which a company must provide in a project to get started. Working capital includes: wages, salaries, purchased services for a period of one to three months; raw materials and equipment spares in stock. According to Gerrard (2007) working capital accounts for 10% to 30% of the fixed investment, with Sinnott (1991) stating a figure of 15% of the fixed investment.

2.4.6. Start-up and commissioning costs

Start-up and commissioning costs consist of expenditure for modifications to the plant while and shortly after it has been commissioned. Start-up costs vary between 8 and 10% of the fixed capital investment according to Peters and Timmerhaus (1991). Commissioning costs may vary from 1% to 10% of the capital cost depending on the type and complexity of a plant according to Gerrard (2007). According to Perry (2008) start-up costs can be between 2 and 20% of the battery-limit fixed capital cost.

2.4.7. Decommissioning costs

Although not included in the initial capital investment, legal regulations require that companies set aside or plan for spending capital at the end of a plant's life to decommission, dismantle, rehabilitate and restore the site to its former green field's condition.

2.4.8. Operating costs

According to Peters and Timmerhaus (1991) production or operating costs are the yearly running costs needed to operate and maintain a plant. This cost can be divided into two main costs: manufacturing and general expenses. Manufacturing costs include the direct production costs, fixed charges and plant overhead costs. Direct production costs include cost of raw materials, solvents and catalysts; power, water and utilities; operating and maintenance labour and supplies; and royalties. Fixed charges include cost of depreciation, property taxes, insurance and rent. Plant overheads include cost of safety and protection equipment and supplies, medical, payroll overhead, packaging, restaurant, recreation and plant superintendence. General expenses include administrative expenses like executive salaries, clerical wages, engineering and legal costs, office maintenance and communications; and distribution and marketing expenses like sales office, shipping, advertising and technical sales service. Other general expenses include cost for research and development, and financing of interest.

2.4.8.1. Raw materials

Raw material costs are usually between 10 and 50% of the total operating cost (Peters and Timmerhaus, 1991).

2.4.8.2. Operating labour

Operating labour is the man-power needed to operate the plant. The costs should be calculated from an estimate of the number of shift and day personnel needed, based on experience with similar processes. Chemical plants do not normally employ many people, compared to the mining industry, and labour costs would not normally exceed 15% of the total operating cost (Sinnott, 1991). Haas (2005) included 40% on top of the total operating labour cost to account for labour fringe benefits, like yearly performance bonuses.

2.4.8.3. Utilities

Utility costs are usually between 10 and 20% of the total operating cost (Peters and Timmerhaus, 1991).

2.4.8.4. Maintenance and repairs

Maintenance and repair costs are usually 2% of the total fixed investment (Peters and Timmerhaus, 1991). According to Sinnott (1991) maintenance costs could be as high as 5 to 15% of the total capital cost for chemical plants.

2.4.8.5. Operating supplies

Operating supplies are about 15% of the total cost for maintenance and repairs (Peters and Timmerhaus, 1991).

2.4.8.6. Laboratory charges

Laboratory charges range between 10 and 20% of the operating labour (Peters and Timmerhaus, 1991), or 2 to 4% of the total operating cost according to Sinnott (1991).

2.4.8.7. Patents and royalties

Patent and royalty costs for patented processes are between 0 and 6% of the total operating cost (Peters and Timmerhaus, 1991). According to Sinnott (1991) this cost could add up to 1 to 5% to the sales price.

2.4.8.8. Depreciation

The annual depreciation rate for machinery and equipment is ordinarily about 10% of the total fixed investment (Peters and Timmerhaus, 1991).

2.4.8.9. Local taxes

Local property taxes are between 1 and 2% of the total fixed investment (Peters and Timmerhaus, 1991; Sinnott, 1991).

2.4.8.10. Insurance

Insurance is about 1% of the total fixed investment (Peters and Timmerhaus, 1991; Sinnott, 1991).

2.4.8.11. Utility costs

Utility costs are usually between 10 and 20% of the total operating cost (Peters and Timmerhaus, 1991).

2.4.8.12. Rent

Annual costs for rented land and buildings amount to about 8 to 12% of the value of the rented property (Peters and Timmerhaus, 1991).

2.4.8.13. General expenses

According to Haas (2005), general expenses can be estimated at 0.5% of the total capital cost, annually.

2.4.8.14. Administrative costs

Administrative costs are usually between 20 and 30% of the operating labour cost (Peters and Timmerhaus, 1991).

2.4.8.15. Distribution and marketing

Distribution and marketing costs are usually between 2 and 20% of the total operating cost (Peters and Timmerhaus, 1991).

2.4.8.16. Research and development costs

Research and development costs are usually between 2 and 5% of total sales cost (Peters and Timmerhaus, 1991).

2.4.8.17. Interest cost

Interest rate costs amount to 5 and 10% of the total value of the borrowed capital (Peters and Timmerhaus, 1991).

SECTION FIVE



LITERATURE STUDY

ON ECONOMIC EVALUATION

2.5 LITERATURE STUDY ON ECONOMIC EVALUATION

Economic evaluation is the process of estimating the economic criteria of a project, such as cash flow, net present value, rate of return, internal rate of return, and payback period, to determine its feasibility or compare it against other projects (Sinnott *et al.*, 1991).

2.5.1. Cash flow

Cash flow is the difference between all incomes generated by a business less all the expenses of that business. Projected cash flows are based on the best estimates of sales volumes and price, capital and operating costs, and tax rates. A cash flow diagram shows the forecast of cumulative net cash flow over the life of a project and gives a clear picture of the financial resources required and the timing of these resources for a project (Sinnott, 1991).

2.5.2. Net present value

Net present value represents the total sum of future earnings discounted at a chosen interest rate, which is often equivalent to the current interest rate that the money could have earned if invested (Sinnott, 1991).

2.5.3. Rate of return

Rate of return (ROR), which is the ratio of annual profit to capital cost, is a measure of the performance of capital invested. The simplest method is to base the ROR on the average income over the life of the project and the original capital investment (Sinnott, 1991).

2.5.4. Internal rate of return

Discounted cash flow analysis, which is used to calculate the present value of future earnings, is sensitive to the interest rate assumed. The interest rate that delivers a zero cumulative NPV at the end of a project, is called the internal rate of return. It is a measure of the maximum borrowing interest rate that a project could afford to still break even at the end of its life time (Sinnott, 1991).

2.5.5. Payback period

Payback period is the time required to pay back the initial capital investment with generated cash flow. Payback period is useful to evaluate projects that have a short life, or when the capital is only available for a short time (Sinnott, 1991; Perry, 2008).

2.5.6. Summary

A number of economic criteria need to be calculated when performing an economic evaluation on a project or comparing different projects. This will provide the evaluator with valuable information on the overall economics of a project. Capital investment indicates the initial investment needed to establish a business or plant, but does not show the performance of the project. NPV takes account of the time value of money, but is dependent on a specific discount rate used. ROR gives a measure of a project's performance, but takes no account of the timing of cash flows. Payback time shows how soon capital costs will be recovered, but gives no information on the latter part of a project (Sinnott, 1991).

SECTION SIX



LITERATURE STUDY

ON SENSITIVITY ANALYSIS

2.6 LITERATURE STUDY ON SENSITIVITY ANALYSIS

There are many factors that can influence the economics of a project, such as capital and operating costs, sales prices, product volumes, producer inflation, and tax rates. These factors are based upon estimates, which can influence the project economics, depending on their accuracy. The purpose of a sensitivity analysis is to determine the effect of these factors on the economic criteria of a project (Perry, 2008). The first step in a sensitivity analysis is to establish the base or reference case for analysis, which is based on the most probable values for various factors. This is followed by estimating the economic criteria of a number of alternate cases, by altering one factor at a time for each case, which is then compared against the reference case (Sinnott *et al.*, 1991). The estimates of each case are then tabulated or plotted to compare their relative effects on the economics of a project (Perry, 2008).

SECTION SEVEN



LITERATURE STUDY

ON FEASIBILITY STUDY

2.7 LITERATURE STUDY ON FEASIBILITY STUDY

In order to determine the overall feasibility of a project, many other factors have to be considered in conjunction with economic performance (Sinnott *et al.*, 1991). These factors include:

- Safety;
- Energy efficiency;
- Sustainability;
- Environmental friendliness and problems;
- Socio-political considerations;
- Location of plant, suppliers and customers;
- Availability of labour;
- Availability of supporting services;
- Company experience in the particular technology.

According to Peters and Timmerhaus (1991) the following list of items should be considered in making a feasibility study:

- Raw materials (availability, quantity, quality and cost);
- Thermodynamics and kinetics of chemical reactions (yields, rates, optimum conditions);
- Facilities and equipment available at present;
- Facilities and equipment which must be purchased;
- Estimation of production costs and total investment;
- Profits (probable and optimum, per litre of product and per year, return on investment);
- Materials of construction;
- Safety considerations;
- Markets (present and future supply and demand, present use, new uses, price range for products);

- Competition;
- Properties of products (chemical and physical properties, specifications);
- Sales and sales service (method of selling and distribution, advertising required);
- Plant location;
- Patent situation and legal restrictions.

CHAPTER THREE



EXPERIMENTAL

METHODS & MATERIALS

There are three principal means of acquiring knowledge. . . observation of nature, reflection, and experimentation. Observation collects facts; reflection combines them; experimentation verifies the result of that combination.

Denis Diderot (French philosopher, 1713-1784)

3. EXPERIMENTAL

Methods recommended by Habeke were used to perform experimental and design activities in Chapter Three. Scaled-up screening experiments were performed in Section 3.1 to identify process opportunities and determine design parameters, for the Process Design and Engineering Design in Sections 3.2 and 3.3. Equipment sizes obtained in Section 3.3 were used to cost the equipment and estimate the final cost for the overall facility in Section 3.4. An economic evaluation in Section 3.5 and a sensitivity analysis in Section 3.6 revealed the economic feasibility and sensitivity of the proposed process, which was summarized in Section 3.7.

SECTION ONE



METHODS & MATERIALS

FOR THE PROCESS IDENTIFICATION

3.1 METHODS & MATERIALS FOR THE PROCESS IDENTIFICATION

A literature study was done to see what knowledge is currently available on possible process steps and options. A series of screening experiments were conducted to fill the information gap on above processes. These experiments tested the technical feasibility of different processing options and determined design parameters for subsequent equipment selection and sizing.

3.1.1. Screening experiments for cultivation options

In Chapter Two of the Literature Study, parameters and conditions were identified for optimal growth of *Microcystis*. These parameters and process conditions were used to promote and improve the cultivation of Hartbeespoort Dam-sourced micro-algal biomass:

- A stable environment, with equilibrium conditions promotes the proliferation of *Microcystis* populations, and enclosed bays, with stagnant hydrodynamic conditions, provide protective environments for *Microcystis* seed stock.
- High water temperatures around 25°C are optimal for *Microcystis* growth. Lower temperatures negatively influence the ability of *Microcystis* to regulate its buoyancy.
- *Microcystis* flourish in nutrient-rich environments, with high concentrations of phosphorus and nitrogen compounds.
- Substrates like sediment, rocks and debris provide safe protective environments for *Microcystis* inoculums.

3.1.1.0. Culture organism and medium

Samples of micro-algal biomass were collected from the Hartbeespoort Dam (Fig. 5) during a sunny, cloudless day on 12 March 2009.



Figure 5: Micro-algal biomass on the banks of the Hartbeespoort Dam.

For the cultivation of Hartbeespoort Dam-sourced micro-algal biomass (HSMB), a growth medium was prepared according to the modified recipe set out by Krüger & Eloff (1977) in Tables 4 and 5 below:

Table 4: Modified BG-11 growth medium used for the cultivation of HSMB

Composition	g/L
NaNO ₃	1.500
K ₂ HPO ₄	0.040
MgSO ₄ ·7H ₂ O	0.075
Na ₂ CO ₃	0.020
CaCl ₂ ·2H ₂ O	0.036
Na ₂ SiO ₃ ·9H ₂ O	0.058
EDTA (disodium magnesium salt)	0.001
Citric acid	0.012
FeSO ₄	0.006
Trace-metal mix A5	1 mL

Table 5: Trace-metal mix A5 in BG-11 growth medium

Composition	g/L
H ₃ BO ₃	2.8600
MnCl ₂ ·4H ₂ O	1.8100
ZnSO ₄ ·7H ₂ O	0.0220
Na ₂ MoO ₄ ·2H ₂ O	0.3910
CuSO ₄ ·7H ₂ O	0.0790
Co(NO ₃) ₂ ·6H ₂ O	0.0494

An analysis of the actual species present in the Hartbeespoort Dam was done through an accredited water analysis laboratory (Eco Analytica) using a standard detection method. The results of the analysis are presented in Table 6.

Table 6: Comparison between culture medium used to cultivate the HSMB and analysis by Eco Analytica on actual water sample from Hartbeespoort Dam

Macro-elements	Hartbeespoort Dam Sample	Culture Medium
	mg/L	mg/L
SO ₄ ²⁻	70.62	29.26
Cl ⁻	58.36	18.01
NO ₃ ⁻	2.08	1094.29
PO ₄ ³⁻	0.86	21.81
NH ₄ ⁺	0.00	0.00

3.1.1.1. Methods & materials for cultivation in 1-litre bioreactor

Erlenmeyer flasks were used to cultivate Hartbeespoort Dam algae. The flasks were filled to 1000 mL with growth medium prepared according to the recipe given in Table 4 and 5. A pipette was used to inoculate each 1-litre growth medium with 10 mL of Hartbeespoort Dam-sourced micro-algal biomass of 0.97 g/L concentration (see Figures 6 and 7). Continuous aeration was provided with air pumps at different flow rates for each bioreactor. The cultures were kept indoors, but exposed to a 12 hour day/night cycle. The temperature of each bioreactor was measured with a thermometer ($\pm 1^{\circ}\text{C}$ experimental error), every hour on the hour from 09:00 to 18:00. After three weeks of cultivation, the contents of the flasks were filtered through 0.7 μm glass microfibre filter paper (Whatman cat. no. 1001090), which was weighed prior to filtration, and then placed in an oven to dry for an hour at 110°C . The dried filter paper was then weighed again in order to determine the dry weight accrual of biomass. The weight of microalgae was measured to the nearest 0.1 mg with a Sartorius 1602 MP8-1 balance (Zeiss West Germany, Optical Instruments (Pty) Ltd., Johannesburg, RSA).



Figure 6: HSMB inoculated into 1-L Erlenmeyer flasks on day one.



Figure 7: Hartbeespoort Dam microalgae growth in 1-litre Erlenmeyer bioreactors after three weeks of cultivation.

A two-factor factorial design with repetition, but no centre points, was used to assess the influence of temperature and aeration rate on the growth rate of Hartbeespoort Dam algae. The upper and lower limits of the design parameters are given in Table 7.

Table 7: Limits of varied parameters for the two-factor factorial design

Parameter	Lower limit	Upper limit
Temperature (°C)	22	24
Aeration rate (L/h)	3.6	72.0

The growth concentration, specific growth rate and the productivity of the cultivated algae were calculated according to Eq. 4, 5 and 6, respectively. The cell concentration of cultivated microalgae (g/L) at time i , was calculated with Eq. 3:

$$\rho_i = \left(\frac{W_i}{V} \right) \quad (3)$$

where W_i is the mean individual dry weight of microalgae at time i and V is the liquid volume in the bioreactor. The volumetric growth concentration of cultivated microalgae (g/L) was calculated with Equation 4:

$$\rho_v = \left(\frac{W_t - W_o}{V} \right) \quad (4)$$

where W_o and W_t are the mean individual dry weights at the beginning and end of each experiment. The specific growth rate (day^{-1}) of cultivated microalgae can be calculated with Equation 5 (Chiu *et al.*, 2009) and the productivity (g/L/d) can be calculated using Equation 6 (Kaewpintong *et al.*, 2007):

$$r = \frac{\ln(\rho_2 / \rho_1)}{t_2 - t_1} \quad (5)$$

where ρ_2 and ρ_1 are the cell densities calculated with Equation 3 at times t_2 and t_1 respectively.

$$\eta = \left(\frac{\rho_2 - \rho_1}{t_2 - t_1} \right) \quad (6)$$

3.1.1.2. Methods & materials for cultivation in 5-litre bioreactor

Erlenmeyer flasks were used to cultivate Hartbeespoort Dam algae. The flasks were filled to 4000 mL with growth medium prepared according to the recipe given in Table 4 and 5. A pipette was used to inoculate each 4-litre growth medium with 100 mL of Hartbeespoort Dam-sourced micro-algal biomass of 0.0114 g/L concentration (see Fig. 8). Continuous aeration was provided with air pumps at different flow rates for each bioreactor. The cultures were kept indoors, but exposed to a 12 hour day/night cycle. The temperature of each bioreactor was measured with a thermometer (± 1 °C experimental error), every hour on the hour from 08:00 to 18:00. After every two weeks of cultivation, the contents of the Erlenmeyer flasks were filtered through 0.7 μm glass microfibre filter paper (Whatman cat. no. 1001090), which was weighed prior to filtration, and then placed in an oven to dry for an hour at 110 °C. The dried filter paper was then weighed again in order to determine the dry weight accrual of biomass. After six weeks of cultivation, the entire content of each Erlenmeyer flask was also filtered through 0.7 μm glass microfibre filter paper and the whole drying and measuring procedure repeated as described above. The weight of microalgae was measured to the nearest 0.1 mg with a Sartorius 1602 MP8-1 balance. The growth of algal biomass is shown in Figures 8 to 10, initially and after three and six weeks of cultivation, respectively.



Figure 8: HSMB inoculated in 5-L Erlenmeyer bioreactor flasks on day one.



Figure 9: HSMB after three weeks of growth in 5-L Erlenmeyer bioreactors.



Figure 10: HSMB growth in 5-litre Erlenmeyer bioreactors after six weeks of cultivation.

The volumetric growth concentration, specific growth rate and the productivity of the cultivated algae were calculated according to Equations 4, 5 and 6, respectively.

3.1.1.3. Methods & materials for cultivation in 135-litre bioreactor

Hartbeespoort Dam-sourced micro-algal biomass was grown in a 180 litre (400 x 500 x 900 mm³) tank made from 5 mm thick glass panes. Six perspex plates of 3 mm thickness were inserted to act as growth substrates for support of micro-algal biomass growth. Samples of micro-algal biomass were collected from the Hartbeespoort Dam and used to inoculate a 135-litre glass tank bioreactor, filled with a growth medium prepared according to the modified recipe set out in Tables 4 and 5. One litre of Hartbeespoort Dam water, containing 0.0114 g/L of dry weight micro-algal biomass, was also poured into the tank, filling it to a height of 300 mm. Continuous aeration at a flow rate of 5.4 L/min was provided with six air pumps. The tank was kept indoors, but exposed to a 12 hour day/night cycle. The temperature of the bioreactor was measured with a thermometer, every hour on the hour from 08:00 to 18:00.



Figure 11: Cultivation of HSMB in 135-L glass tank bioreactor with growth plates.



Figure 12: Growth plates in 135-L glass tank bioreactor.

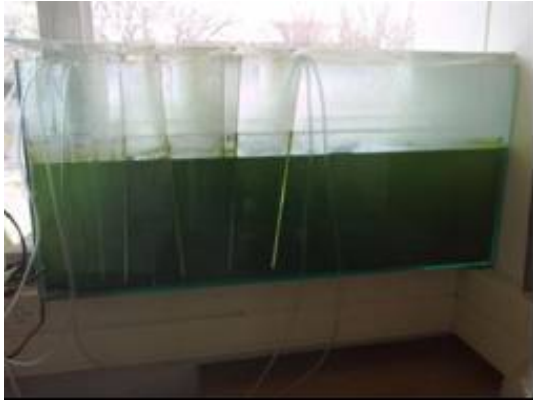


Figure 13: Hartbeespoort Dam microalgae growth in 135-litre glass tank bioreactor after six weeks of cultivation.

After every two weeks, one plate was removed from the tank and the micro-algal biomass scraped off manually with a scraper. The biomass was placed on glass microfibre filter paper (Whatman cat. no. 40) and placed in a desiccator with silica gel to dry for seven days. The dried biomass and filter paper was weighed and the combined weight subtracted from the original filter paper weight to determine the dry weight yield of the biomass. The weight of microalgae was measured to the nearest 0.1 mg with a Sartorius 1602 MP8-1 balance (Zeiss West Germany, Optical Instruments (Pty) Ltd., Johannesburg, RSA). The aerial growth concentration of the cultured microalgae was calculated according to Equation 8.

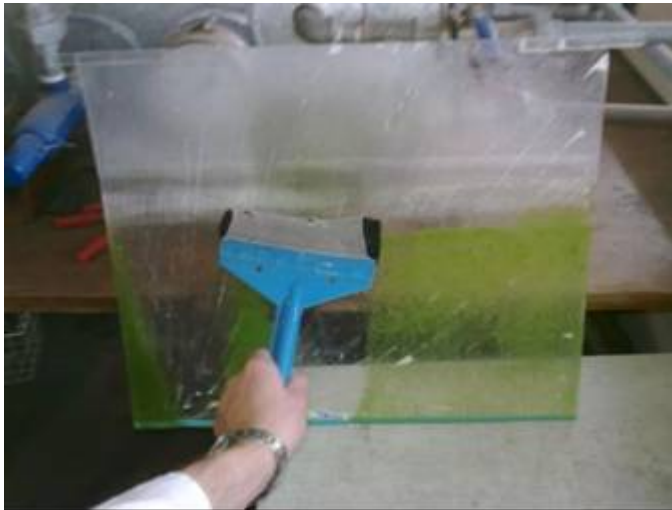


Figure 14: Cultivated Hartbeespoort Dam-sourced micro-algal biomass scraped off from growth plate.



Figure 15: Cultivated Hartbeespoort Dam-sourced micro-algal biomass collected on filter paper after scraping off.

The growth weight of cultured microalgae can be calculated as the dry weight accrual during the experiment according to the following equation:

$$\Delta W = W_t - W_o \quad (7)$$

where W_o and W_t are the individual dry weights at the beginning and end of each experiment in grams. In order to account for the growth substrate surface area (growth plates), the aerial growth concentration of the cultured microalgae can be calculated as the dry weight accrual per growth plate surface area during the experiment according to the modified equation based on Eq. (7):

$$\rho_A = \left(\frac{W_t - W_o}{A} \right) \quad (8)$$

where W_o and W_t are the individual dry weights at the beginning and end of each experiment, and A is the total surface area per growth plate in (m^2).

3.1.2. Screening experiments for harvesting options

The harvesting of micro-algal biomass is one of the most inefficient and costly steps in the whole biomass-to-liquids (BTL) value chain. Harvesting costs may contribute between 20–30% of the total cost of micro-algal biomass-to-liquids biodiesel production (Verma *et al.*, 2010). One of the major obstacles in the economic production of microalgae, are the development of cost effective harvesting methods for the separation of micro-algal biomass from its growth medium. Three promising, unconventional harvesting methods were investigated to harvest micro-algal biomass from the Hartbeespoort Dam, 37 km west of South Africa's capital city Pretoria. This dam has one of the world's dense populations of micro-algal biomass and has great potential for micro-algal biomass production and beneficiation due to its high nutrient loading, stable climatic conditions, size and close proximity to major urban and industrial centres.

Excessive growth of cyanobacteria is stimulated by the influx of large quantities of nitrates and phosphates into the Hartbeespoort Dam, from the run-off of fertilized agricultural land and effluent from sewage plants from the northern suburbs of Johannesburg. Dense populations of the cyanobacterium *Microcystis aeruginosa* dominate the dam throughout the year, comprising over 90% of the total algal biomass (Owuor *et al.*, 2007). Buoyancy in cyanobacteria, like *M. aeruginosa*, is regulated by a number of mechanisms, such as turgor pressure regulation, the form of stored carbohydrates, and most importantly, the regulation of gas vacuole synthesis. Cyanobacteria lose their buoyancy in turbulent waters, due to the disturbance of this last mechanism to regulate the gas vacuole synthesis (Grobelaar, 2002).

3.1.2.1. *Experimental for natural buoyancy separation*

Samples of concentrated biomass pulp were collected from the Hartbeespoort Dam (Fig. 5) and analyzed using scanning electron microscopy (SEM). Figures 16 and 17 show wet micro-algal biomass pulp on scales of 50 and 10 microns, respectively.

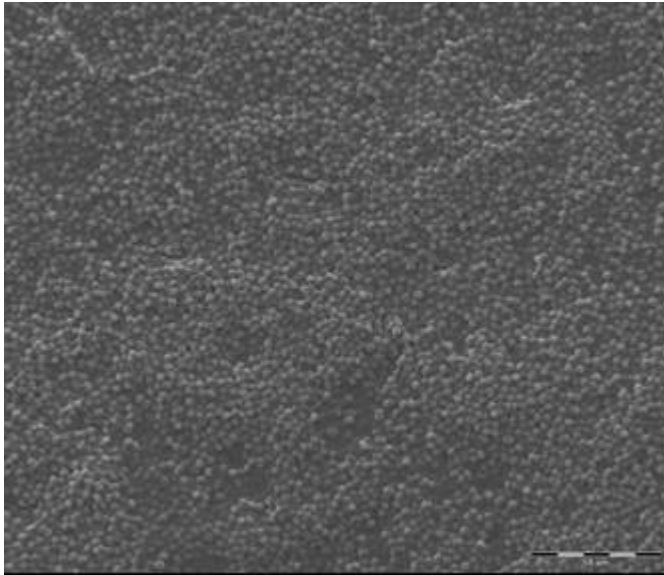


Figure 16: SEM image of Hartbeespoort Dam micro-algal biomass at scale of 50 microns.

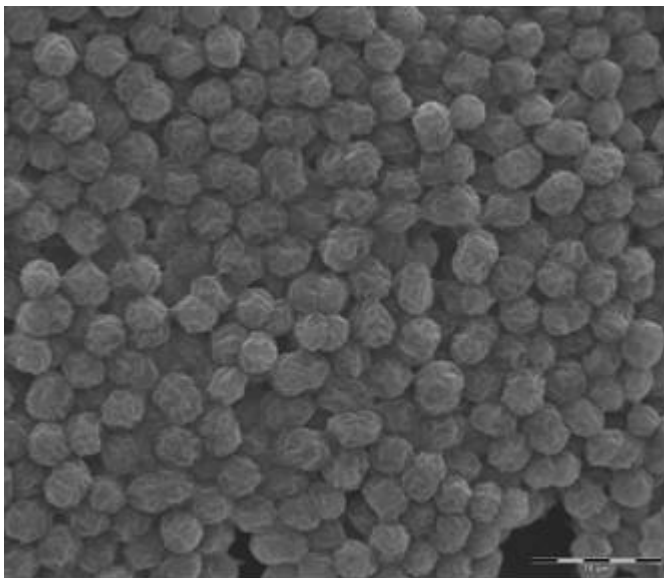


Figure 17: SEM image of Hartbeespoort Dam micro-algal biomass at scale of 10 microns.

A pulp sample was collected from the Hartbeespoort Dam and placed in a container and stirred for one minute to obtain a homogeneous mixture of algae and water. Three measuring cylinders of different diameters (65, 83 and 38 mm respectively) were each filled with 200 mL of the mixture. The time it took for the mixture to settle into two distinct layers (a bottom colourless aqueous layer, and a top green wet weight micro-algal biomass layer) was recorded. The volume of the top algae layer was recorded every 30 minutes over a period of 3.5 hours and also after 21.5 and 24 hours. Figures 18 to 21 show the separation of Hartbeespoort Dam micro-algal biomass from its aqueous phase due to its natural buoyancy.



Figure 18: Fresh Hartbeespoort Dam water and micro-algal biomass mixture poured into measure cylinder.



Figure 19: Fresh Hartbeespoort Dam water and micro-algal biomass mixture poured into three measure cylinders.



Figure 20: Hartbeespoort Dam micro-algal biomass concentrating at the top of measure cylinders after 1.5 hours.



Figure 21: Hartbeespoort Dam micro-algal biomass concentrating at the top of measure cylinders after 24 hours.

The volume concentration of wet micro-algal biomass in a container containing liquid can be calculated according to Eq. 9.

$$C_{MB} = \frac{V_{MB}}{V_{Tot}} \times 100\% \quad (9)$$

where C_{MB} is the volume concentration (v/v %) of wet micro-algal biomass in a liquid; V_{MB} is the volume of wet micro-algal biomass and V_{Tot} is the total liquid volume in a container in litres.

The predicted volume concentration of algal biomass in the reactor at any time t can be calculated using Equation 10:

$$C_i = a.\ln(t)+b \quad (10)$$

where C_i is the predicted volume concentration in (%) of wet micro-algal biomass, t is the separation time in (hours) and a and b are constants that can be obtained through fitting of the experimental data to the model using minimization of a least squares residual (Eq. 11).

$$\mathfrak{R} = \sum_{i=1}^n (C_i - C_i^*)^2 \quad (11)$$

R is the least-squares residual; C_i is the measured and C_i^* is the calculated values for the volume concentrations, respectively.

3.1.2.2. *Experimental for sand filtration and solar drying*

Three samples of wet biomass were taken from the Hartbeespoort Dam in 500 mL plastic bottles and allowed to settle for one day. The bottom water layer was drained with a tube and the remaining top layer of concentrated micro-algal biomass pulp was poured onto metal palettes with a layer of approximately 500 g of building sand with a voidage of 40%. The palettes were then placed on top of a laboratory roof and allowed to dry for 24 hours. A fourth palette contained only a layer of building sand to serve as the standard for the measurement of moisture loss after 24 hours of drying. The four metal palettes were weighed, filled with a layer of 0.484 m² (220 x 220 mm²) of building sand, and weighed again.



Figure 22: Micro-algal biomass from the Hartbeespoort Dam drying in the sun on top of a base of building sand.

After drying in the sun for 24 hours, the palettes, building sand and dried micro-algal biomass were weighed again. The dry weight of the dried micro-algal biomass was calculated by subtracting this weight from the weight of the sand-filled palettes. The moisture loss from the standard palette was obtained by subtracting the weight of the sand-filled palette before drying from its weight after drying. This value was divided by the original sand and palette weight to calculate the moisture loss fraction. This moisture loss factor was used to adjust the weights of the other free palettes, to calculate the true dry weight yield of micro-algal biomass, after moisture loss was included.

The volumetric harvesting yield of harvesting micro-algal biomass from the Hartbeespoort Dam is calculated as the dry weight of micro-algal biomass per litre of Hartbeespoort Dam water, according to Equation 12:

$$y_v = \frac{W_d}{V} \quad (12)$$

where y_v is the volumetric harvesting yield in (g/L); W_d is the dry weight of micro-algal biomass in (g); V is the volume of liquid from the Hartbeespoort Dam in (L).

The aerial harvesting yield of harvesting micro-algal biomass from the Hartbeespoort Dam can be expressed as the dry weight of micro-algal biomass harvested per square meter of drying area, and can be calculated according to Eq. (13):

$$y_A = \frac{W_d}{A} \quad (13)$$

where y_A is the aerial harvesting yield in (g/m²); W_d is the dry weight of micro-algal biomass in (g); A is the surface area available for sand and solar drying in (m²).

The wet weight harvesting yield of harvesting micro-algal biomass from the Hartbeespoort Dam can also be expressed as the dry weight of micro-algal biomass harvested per wet weight micro-algal biomass fraction in the Hartbeespoort Dam pulp, and can be calculated according to Eq. (14):

$$y_D = \frac{W_d}{W_w} \times 100\% \quad (14)$$

where y_D is the wet weight harvesting yield in weight percentage; W_d is the dry weight of micro-algal biomass in (g) and W_w is the wet weight fraction of micro-algal biomass in Hartbeespoort Dam pulp obtained through natural buoyancy separation in (g).

3.1.2.3. *Experimental for gravity settling harvesting*

Erlenmeyer flasks were used to cultivate Hartbeespoort Dam algae. The flasks were filled to 4000 mL with a modified growth medium prepared according to the recipe set out in Tables 4 and 5. A pipette was used to inoculate each 4-litre growth medium with 100 mL of Hartbeespoort Dam-sourced micro-algal biomass of 0.0114 g/L concentration. Continuous aeration was provided with air pumps at different flow rates for each bioreactor. The cultures were kept indoors, but exposed to a 12 hour day/night cycle. After six weeks of cultivation, the contents of the Erlenmeyer flasks were filtered through 0.7 μm glass microfibre filter paper (Whatman cat. no. 1001090), which was weighed prior to filtration, and then placed in an oven to dry for an hour at 110 °C. The dried filter paper was then weighed again in order to determine the dry weight accrual of biomass. The weight of microalgae was measured to the nearest 0.1 mg with a Sartorius 1602 MP8-1 balance. In order to measure the micro-algal biomass content at different depths in the bioreactor, the first 50% of the volume was decanted and filtered, then the next 25%, and then the remaining 25% of the volume.



Figure 23: Gravitation settling comparison between well-mixed bioreactor (left) and bioreactor that was allowed to settle for 24 hours.

The gravity settling harvesting yield of cultured microalgae can be calculated as the dry weight harvested from a section of a bioreactor over the total dry weight harvested during the experiment according to the following equation:

$$y_H = \frac{W_i}{W_{Tot}} \times 100\% \quad (15)$$

where W_i is the dry weight of micro-algal biomass harvested from a specific section (i) in the bioreactor and W_{Tot} is the total dry weight harvested from the bioreactor in grams.

SECTION TWO



METHODS & MATERIALS

FOR THE PROCESS DEVELOPMENT

3.2 METHODS & MATERIALS FOR THE PROCESS DEVELOPMENT

The process development was started of by sketching an overall block flow diagram (Fig. 24) of the overall process. A brain-storm was done to list all the major external constraints on the overall process.

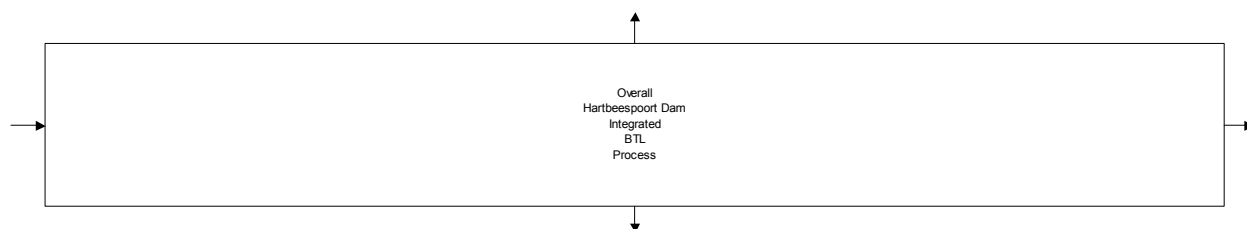


Figure 24: Overall block diagram of Hartbeespoort Dam integrated BTL process.

The overall block flow diagram was further divided into the main processing stages in Fig. 25. These stages include the Feed or Cultivation Section, which is followed by the Separation or Harvesting Section, and the Reaction Section.

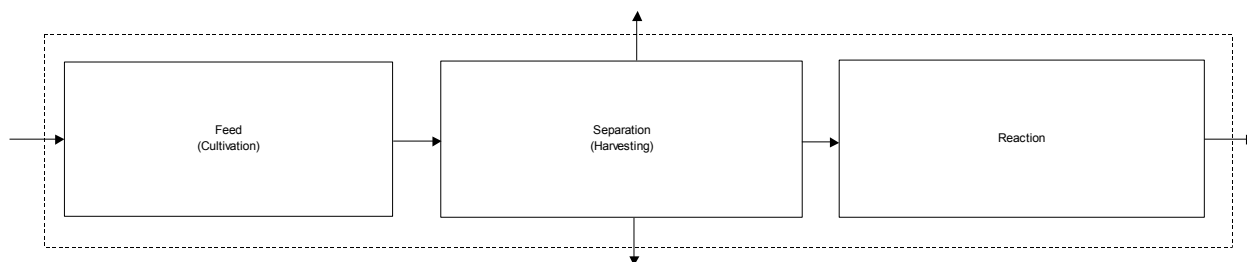


Figure 25: Block flow diagram of three main processes making up the Integrated Hartbeespoort Dam BTL process.

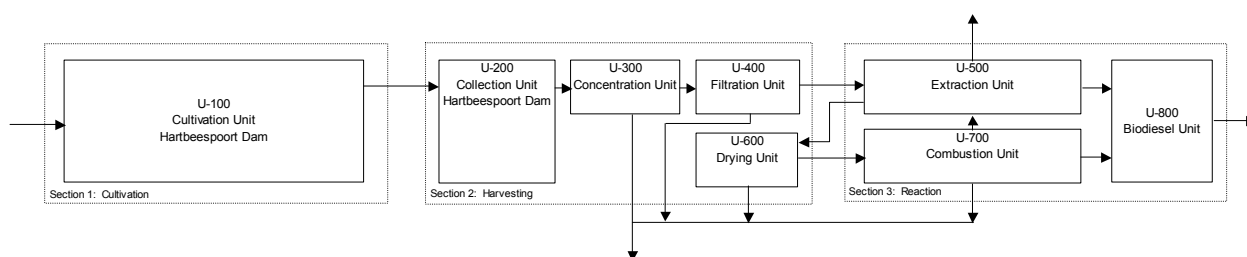


Figure 26: Block flow diagram of all eight units making up the Integrated Hartbeespoort Dam BTL process.

Fig. 25 was further dissected into smaller units that made up the Integrated Hartbeespoort Dam BTL process (Fig. 26). Section 1 consisted of the existing Hartbeespoort Dam. Section 2 consisted of a Collection Unit which is located at the dam wall of the Hartbeespoort Dam; a Concentration Unit to concentrate micro-algal biomass; a Filtration Unit to filter out excess water; the last unit in the Harvesting Section 2 is the Drying Unit where wet micro-algal biomass is dried before being sent and combusted in the Combustion Unit. The third and last Section 3 consist of three units: an Extraction Unit where oils are extracted from the micro-algal biomass; a Combustion Unit where dried micro-algal biomass rests are combusted to release valuable energy for heating purposes elsewhere in the process; the last unit is the Biodiesel Unit where micro-algal oils are converted into biodiesel through transesterification. Each unit block was then further divided into individual major equipment items to form the conceptual process.

SECTION FOUR



METHODS & MATERIALS

FOR THE ENGINEERING DESIGN

3.3 METHODS & MATERIALS FOR THE ENGINEERING DESIGN

3.3.1 Design methodology

The new process was designed according to the following engineering criteria:

- The concept design for the new BTL facility was based on a base or reference case with the most conservative design parameters. Alternate options were developed for the sensitivity analysis. Sensitivities of other alternate cases with varying parameters were set out and discussed in Section 3.6.
- Design parameters incorporated into the design, which could not be obtained from literature, were determined from screening and scaled-up experiments performed during the Identification Phase. These parameters are used in the subsequent design and set out in the next subsections 3.3.1 to 3.3.8.
- Modular design – process expansions could easily be done by adding additional modular units to the process
- No redundancy for major equipment – the whole process could be temporarily stopped, while maintenance is done on major equipment. Rotating equipment like pumps and agitators, will have two by 100% redundancy. Intermediate and final storage tanks would supply sufficient buffer time for planned and unplanned shutdowns, due to operational upsets, breakdowns or maintenance work.
- A general design factor of 1.1 were used to oversize all equipment throughout the process.

3.3.2 Design basis

The design basis was derived from data and information obtained from the literature study and screening experiments during the Process Identification phase.

3.3.3 Design of equipment

3.3.3.1. Unit 100 – Cultivation Unit

The highest productivity achieved from screening experiments in Sections 4.1.1.1, 4.1.1.2 and 4.1.1.3 were used to determine the total surface area required to cultivate microalgae from the Hartbeespoort Dam, in an open and in a closed-cultivation facility. It was assumed that optimum growth conditions could be maintained throughout the year for the closed-cultivation facility, except for two weeks per year, which is set out for planned and unplanned shutdowns. It was assumed that growth conditions for open-cultivation facilities were dependent on ambient conditions, which are only favourable during the warmer spring and summer months, and limiting during the colder autumn and winter months. The surface area required to cultivate micro-algal biomass were calculated with the following equation:

$$A = \frac{M}{p.d.t} \quad (16)$$

where A is the cultivation surface area, M is the total micro-algal biomass cultivated in a year, p is the productivity of the cultivation facilities, d is the optimum depth of cultivation bioreactors, and t is the operating days per year.

3.3.3.2. Unit 200 – Collection Unit

No concept engineering is necessary for the Collection Unit, as all infrastructure already exist.

3.3.3.3. Unit 300 – Concentration Unit

The separation rate of micro-algal biomass from its aqueous medium and the optimum residence time required to allow for efficient concentration of microalgae were obtained from the screening experiment results in Section 4.1.2.1.

3.3.4. Unit 400 – Filtration Unit

The filter was designed to dewater the micro-algal biomass from Hartbeespoort Dam to such a concentration, that the energy required to vapourize the water fraction and turn it into superheated steam and the energy required to boil off the chloroform solvent in the Solvent Distillation Column, is equal to the heating value of the dry biomass fraction, including the 25% energy loss through the Furnace (Q-701) and associated heat exchangers and piping.

3.3.5. Unit 500 – Extraction Unit

The Extraction Unit (U-500) was designed according to the process conditions used by Barnard (2009) in his thermochemical liquefaction experiments with Hartbeespoort Dam microalgae.

3.3.6. Unit 600 – Drying Unit

The surface area required to dry micro-algal biomass from the Hartbeespoort Dam was calculated by dividing the design rate of micro-algal biomass with the harvesting yield determined from screening experiments in Section 4.12.2.

3.3.7. Unit 700 – Combustion Unit

The Combustion Unit was sized according to the dry biomass production rate from the Drying Unit, including the heating value of the dried biomass.

3.3.8. Unit 800 – Biodiesel Unit

The focus of this work was on the cultivation and harvesting of micro-algal biomass from the Hartbeespoort Dam, in the context of a new biomass-to-liquids process to produce biodiesel. For the purpose of cost estimation and economic evaluation, it was assumed that the Biodiesel Production Unit would be installed as a proprietary vendor package as described by Haas *et al.* (2005), with the following modifications:

- Replace Haas's soybean oil feedstock with oils from Hartbeespoort Dam microalgae;
- Replace Haas's sodium methoxide catalyst with sulphuric acid, as recommended by Miao and Wu (2005);

- Increase catalyst concentration from 1.78% (wt.) to 100% (wt.);
- Reduce temperature of reactor from 60°C to 30°C, as recommended by Miao and Wu (2005);
- Increase the residence time in the transesterification reactor from 1 to 4 hours.
- Increase the methanol/feedstock concentration from 15.5% (wt.) to 56:1 molar ratio of methanol to oil;

3.3.9. Sizing of piping

All piping was sized using recommended optimum velocities by Sinnott (1991). For fluid densities between 800 and 1600 kg/m³, optimum velocities between 3.0 and 2.4 m/s were used. The piping cross-sectional area was calculated with Equation 17 by dividing the flow rate with the optimum fluid velocity, where Q_p is the flow rate and v_{opt} is the optimum fluid velocity:

$$A_p = \frac{Q_p}{v_{opt}} \quad (17)$$

The optimum pipe diameter was calculated with Equation (18):

$$d_p = \sqrt{\frac{4 \times A_p}{\pi}} \quad (18)$$

3.3.10. Pump sizing

The power requirements of all pumps were calculated with Equation 19 (Sinnott, 1991).

$$Power = \frac{\Delta P \cdot Q_p}{\eta_p} \times 100 \quad (19)$$

where ΔP is the pressure differential across the pump in N/m², Q_p is the flow rate in m³/s, and η_p is the pump efficiency in percentage.

3.3.10. Heat exchanger sizing

The general equation for heat transfer across a surface is (Sinnott, 1991):

$$Q = UA\Delta T_m \quad (20)$$

where Q is the heat transferred per unit time in watts, U is the overall heat transfer coefficient, $W/m^2/C$, A is the heat transfer area in m^2 and ΔT_m is the mean temperature difference, the temperature driving force in $^{\circ}C$. The heat transfer areas of all the heat exchangers were calculated with Equation 21, which was derived from Equation 20.

$$A = \frac{Q}{U \cdot \Delta T_m} \quad (21)$$

3.3.11. Reactor and tank sizing

The preliminary sizing of the liquefaction reactor and all the intermediate and final storage tanks were calculated as follows:

- Calculate the liquid hold-up volume V_L , by multiplying the liquid flow rate with the residence time τ (optimum extraction time determined from laboratory experiments);
- Add 25% vapour space;

$$V_L = Q_L \times \tau \quad (22)$$

$$V_T = V_L + V_V = V_L + \frac{V_L}{4} \quad (23)$$

3.3.12. Agitator sizing

The shaft power required to drive an agitator can be estimated using the following equations (Sinnott, 1991):

$$N_p = K \cdot Re^b \cdot Fr^C = K \cdot \frac{D^2 N \rho}{\mu} \cdot \frac{DN^2}{g} \quad (24)$$

$$N_p = \frac{P}{D^5 N^3 \rho} \quad (25)$$

where N_p is the power number, Re is the Reynolds number, Fr is the Froude number, P is the shaft power, K is a constant, dependent on the agitator type, size and agitator-tank geometry, ρ is the fluid density, μ is the fluid viscosity, N is the agitator speed, D is the agitator diameter and g is the gravitational acceleration.

3.3.13. Distillation column sizing

According to Sinnott (1991), the principal factor that determines the diameter of a distillation column is the vapour flow-rate. The vapour velocity must be below that which would cause excessive liquid entrainment or a high pressure drop. The equation below can be used to estimate the maximum allowable superficial vapour velocity:

$$u_v = (-0.171 \cdot l_t + 0.27 \cdot l_t - 0.047) \cdot \sqrt{\frac{\delta_L - \delta_v}{\delta_v}} \quad (26)$$

where u_v is the maximum allowable vapour velocity, based on the gross column cross-sectional area, in m/s and l_t is the plate spacing in m. The column diameter, D_c , can then be calculated:

$$D_c = \sqrt{\frac{4 \cdot V_w}{\pi \rho_v u_v}} \quad (27)$$

where V_w is the maximum vapour rate in kg/s.

SECTION FOUR



METHODS & MATERIALS

FOR THE COST ESTIMATION

3.4 METHODS & MATERIALS FOR THE COST ESTIMATION

The cost estimate was done for a reference case, as well as various alternate cases, which included and excluded artificial closed and open-cultivation systems. The reference case was based on an integrated BTL process with 183 operating days per year and a micro-algal biomass processing rate of 3.577 t/h. The alternate cases varied from the reference case with regards to their respective operating days; micro-algal biomass growth periods and growth phase durations; micro-algal concentrations in the Hartbeespoort Dam and oil content of its microalgae; capital, operating and decommissioning costs; discount and depreciation rates; rand-dollar exchange rates and producer price inflation.

The following three methods were used to perform cost estimates on the different units comprising the overall concept facility: computer cost estimating; power law estimating; factorial estimating. The cost estimation was based on a facility capacity designed for the highest productivity achieved with the above-mentioned cultivation experiments.

3.4.1. Unit 100 – Cultivation Unit

Factorial estimating was used to determine the capital and operating costs of a new open-cultivation and a new closed-cultivation facility, based on the general cost factors cited in the *Comprehensive Oilgae Report* (2010). According to the said Report the indicative capital cost of open ponds range between \$125,000 and \$150,000 per hectare, while closed pond systems cost approximately \$200,000 per hectare. The indicative operating cost of open ponds range between \$15,000 and \$35,000 per hectare, while the operating costs of closed pond systems range between \$20,000 and \$45,000 per hectare. The highest productivity of 0.0862 g/L/d achieved from screening experiments in Appendix C, where used to determine the total surface area required to cultivate microalgae from the Hartbeespoort Dam, in an open and in a closed-cultivation facility. It was assumed that optimum growth conditions could be maintained throughout the year, except for two weeks per year, which is set out for planned and unplanned

shutdowns. It was assumed that growth conditions for open-cultivation facilities were dependent on ambient conditions, which are favourable during the warmer spring and summer months, and limiting during the colder autumn and winter months. The surface area required to cultivate micro-algal biomass was calculated with Eq. 16. The capital and operating costs were estimated by multiplying the above-mentioned factors with the surface area from Eq. 28.

$$C = C_u \times A \quad (28)$$

where C is the total cost, C_u is the total unit cost and A is the total surface area required for cultivation.

3.4.2. Unit 200 – Collection Unit

No cost estimation was necessary for the Collection Unit, as all infrastructure already exist.

3.4.3. Unit 300 – Concentration Unit

The separation rate of micro-algal biomass from its aqueous medium and the optimum residence time required to allow for efficient concentration of microalgae were obtained from the screening experiments in Appendix E. Historical costs for excavation and lining of building foundations were used to estimate the cost of constructing a low cost dam, with a residence time of 3.5 hours, to concentrate micro-algal biomass from 1.5 to 3% TSS.

3.4.4. Unit 400 – Filtration Unit

A power factor capital cost estimate was based on a filtration cost of \$0.4 million for a one million L/h drum filtration system in the USA in 2010, which included the drum filter, pumps and measuring equipment *Comprehensive Oilgae Report* (2010).

3.4.5. Unit 500 – Extraction Unit

The major equipment costs were obtained from a historical equipment cost database of a major South African petrochemical company. A design and costing philosophy were followed that doubled rotating equipment and kept static equipment as singular items. Hence all the static

equipment were single items, and all the rotating equipment like pumps and agitators came with two by 100% redundancy.

3.4.6. Unit 600 – Drying Unit

The surface area required to dry micro-algal biomass from the Hartbeespoort Dam was calculated by dividing the design rate of micro-algal biomass with the harvesting yield determined from screening experiments in Appendix E. An average cost of R10,000 per hectare for agricultural land in the region, were multiplied with the surface area required to dry micro-algal biomass before being combusted in the Combustion Unit 700.

3.4.7. Unit 700 – Combustion Unit

The following equation from Sinnott (1991) was used to estimate the cost of the furnace in pounds sterling, based on its power capacity:

$$C_e = C \cdot S^n \quad (29)$$

In order to account for the specific location a South African location factor of 1.25 was used on top of the above figure. The exchange rate was used to derive the cost in pounds into rands.

3.4.8. Unit 800 – Biodiesel Unit

The power factor method was used to estimate the cost of a biodiesel unit, by scaling down all the major equipment costs from that estimated major equipment costs of a larger biodiesel unit estimated by Haas *et al.* (2005). A power factor of 0.65 was used to calculate the major equipment costs of a smaller biodiesel unit.

3.4.9. Total erected cost of BTL facility

Estimating factors, as indicated by Gerrard (2007), were used to calculate the total erected cost of the overall BTL biodiesel facility, from the total purchased cost of all delivered major equipment. Table 8 indicates the factors used to calculate the installation costs of all major equipment and associated infrastructure, and all indirect costs like engineering, supervision, contractor's fees and contingency costs.

Table 8: Breakdown of the capital cost of a facility

Item	% of MEC
Direct costs	
Purchased equipment delivered	100
Purchased equipment installation	39
Instrumentation and controls installed	13
Piping installed	31
Electrical installed	10
Buildings (including services)	29
Yard improvements	10
Service facilities (installed)	55
Land	6
Total direct facility cost (DFC)	293
Indirect costs	
Engineering and supervision	32
Construction expenses	34
Total direct and indirect plant costs	359
Contractor's fee (5% of DFC and IFC)	18
Contingency (10% of DFC and IFC)	36
Total erected cost (TEC)	413
Working capital (15% of TEC)	74
Total capital investment	487

SECTION FIVE



METHODS & MATERIALS

FOR THE ECONOMIC EVALUATION

3.5 METHODS & MATERIALS FOR THE ECONOMIC EVALUATION

An economic evaluation was performed on the reference case, as well as alternate cases. Five economic criteria were calculated to evaluate and compare the economics of the reference case, with that of the other 22 alternate cases. These criteria included cash flow, net present value, rate of return, internal rate of return, and payback-period. The following assumptions were used for the economic evaluation:

- 25 operating years;
- 3% annual producer price inflation;
- Capital depreciation rate of 10%;
- Corporate tax rate of 30%;
- Biodiesel price of R10 per litre.

SECTION SIX



METHODS & MATERIALS

FOR THE SENSITIVITY ANALYSIS

3.6 METHODS & MATERIALS FOR THE SENSITIVITY ANALYSIS

Parametrics were performed on all the major factors influencing the overall design, cost and resultant economics of the BTL process. All the parameters for each alternate case, except for one different parameter in each case, were kept constant and equal to that of the reference case. Parametrics were performed by changing one parameter at a time, to check the influence of a plus or minus 10% change in each parameter on the overall BTL facility's cost and economics. The percentage change was then compared to the reference case and the parameters sorted to show their relative weights. A sensitivity analysis was performed on the following parameters:

- Micro-algal biomass concentration in the Hartbeespoort Dam;
- Growth phase duration of Hartbeespoort Dam microalgae;
- Months of micro-algal biomass growth;
- Oil content of micro-algal biomass;
- Capital cost;
- Operating cost;
- Decommissioning cost;
- Discount rate;
- Depreciation;
- Production price inflation;
- Rand-dollar exchange rate.

SECTION SEVEN



METHODS & MATERIALS

FOR THE FEASIBILITY STUDY

3.7 METHODS & MATERIALS FOR THE FEASIBILITY STUDY

The following criteria were assessed to determine the feasibility of the new BTL process:

- Economic feasibility – the proposed BTL process should be economically feasible;
- Thermodynamic viability – any energy production process have to be energy net positive: produce more energy than it consumes.
- Technical feasibility – any new process have to technically feasible;
- Strategically positioned – to increase its competitiveness;
- Marketing – the new process and its products should be marketable;
- Environmental sustainability – the new process had to be environmentally friendly;
- Social responsibility – the new process had to contribute to social development, either through job creation or the delivery of essential products;
- Energy security – the process had to increase South Africa's energy security, by reducing its reliance on imported petroleum products, and utilizing existing renewable energy sources;
- Location – the location should be practical and strategic;
- Safety – the process should be safe;
- Risk – the process should mitigate risks.

CHAPTER FOUR



RESULTS & DISCUSSION

FINDINGS & REFLECTIONS

*It does not matter how fast you are moving –
if it is in the wrong direction you will never get where you want to go.*

Dr R.K. Pachauri, Director General TERI (India)

4. RESULTS & DISCUSSION

Chapter Four discusses the results achieved from the Process Identification, Process Development, Engineering Design, Cost Estimation, Economic Evaluation, Sensitivity Analysis and the Feasibility Study.

SECTION ONE



RESULTS & DISCUSSION

OF THE PROCESS IDENTIFICATION

4.1 RESULTS AND DISCUSSION OF THE PROCESS IDENTIFICATION

4.1.1. Results & discussion of cultivation screening experiments

4.1.1.1. *Results and discussion of cultivation in 1-litre bioreactors*

The objective of this experiment was to determine the highest growth rate that could be achieved in a 1-litre bioreactor with Hartbeespoort Dam-sourced micro-algal biomass (HSMB). A two-factor factorial design experiment with replication was also conducted in order to determine the effect of day-time temperature and aeration rate on the growth rate of HSMB. Micro-algal biomass was cultivated batchwise in 1-litre Erlenmeyer flask bioreactors, using a modified growth medium with high concentrations of nitrates (NO_3^-) and phosphates (PO_4^{3-}), which exceed that found in the Hartbeespoort Dam. It was found that both aeration rate and average day-time temperature have significant effects on the growth parameters of cultivated Hartbeespoort Dam-sourced micro-algal biomass, while there was no correlation between the combined interaction of aeration rate and average day-time temperature on these parameters. The highest average volumetric growth concentration of 0.909 g/L, specific growth rate of 0.217 day⁻¹ and productivity of 0.043 g/L/day, were obtained in the 1-litre Erlenmeyer bioreactors after the total cultivation period of three weeks, at an average day-time temperature of 24.1°C and an aeration rate of 72.0 L/h.

The results from the two-factor ANOVA statistical analysis, where the effects of day-time temperature and aeration rate were studied on the growth rate of cultivated micro-algal biomass from the Hartbeespoort Dam, are presented in Table 9. Sample growth data can be seen in Appendix B.

Table 9: ANOVA two-factor analysis on the effect of aeration rate and day-time temperature on the growth rate of HSMB in 1-litre bioreactors.

Source of Variation	SS	df	MS	F	p	F-critical
Aeration rate (L/h)	0.00153	1	0.00153	72.44211	0.00105	7.70865
Average day-time temperature (°C)	0.00023	1	0.00023	10.74384	0.03056	7.70865
Interaction	0.00012	1	0.00012	5.61044	0.07694	7.70865
Within	0.00008	4	0.00002			
Total	0.00196	7				

The calculated cultivation parameters (volumetric growth concentration, specific growth rate and productivity) for each experiment of the factorial design are presented in Table 10 and Figures 27, 28 and 29.

Table 10: Volumetric growth concentration, specific growth rate and productivity of HSMB in 1-L bioreactors

Bioreactor	Aeration (L/h)	Temperature (°C)	y_v (g/L)	r (day ⁻¹)	η (g/L/day)
1	3.6	22	0.132	0.128	0.006
2	3.6	22	0.075	0.103	0.004
3	3.6	24	0.224	0.150	0.010
4	3.6	24	0.116	0.122	0.006
5	72.0	22	0.638	0.200	0.030
6	72.0	22	0.408	0.179	0.019
7	72.0	24	0.996	0.219	0.045
8	72.0	24	0.860	0.214	0.041

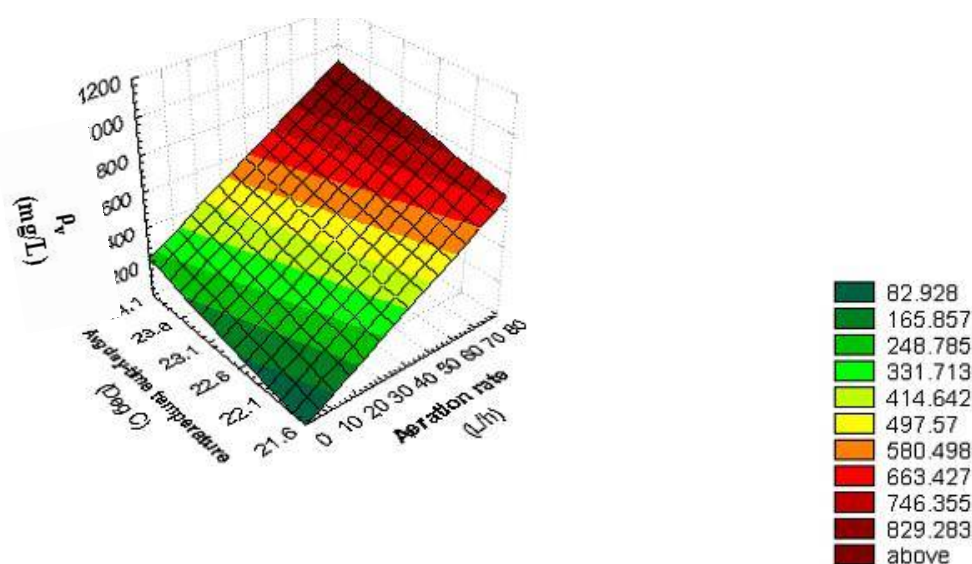


Figure 27: Influence of day-time temperature and aeration rate on micro-algal volumetric growth concentration in 1-L bioreactors.

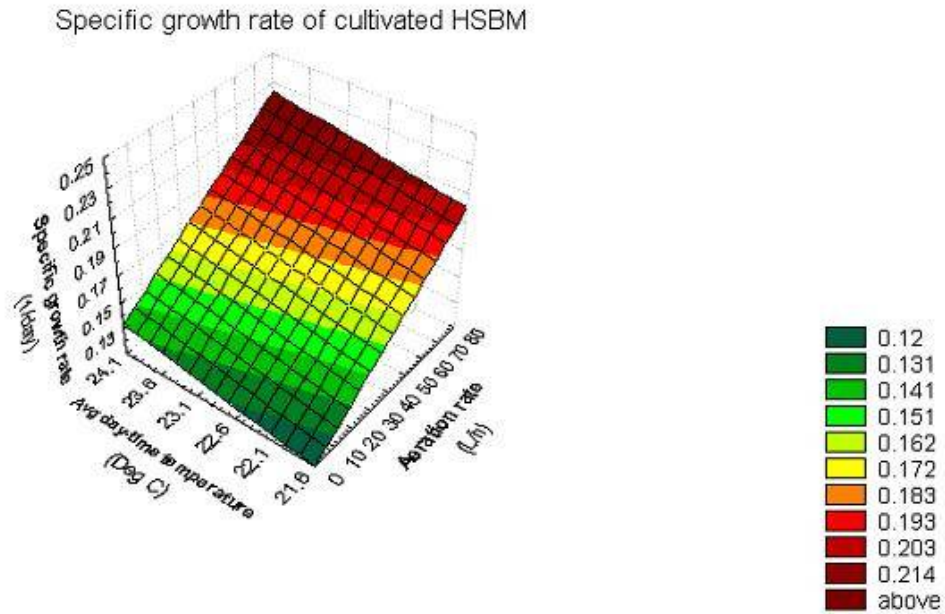


Figure 28: Influence of day-time temperature and aeration rate on microalgae specific growth rate in 1-L bioreactors.

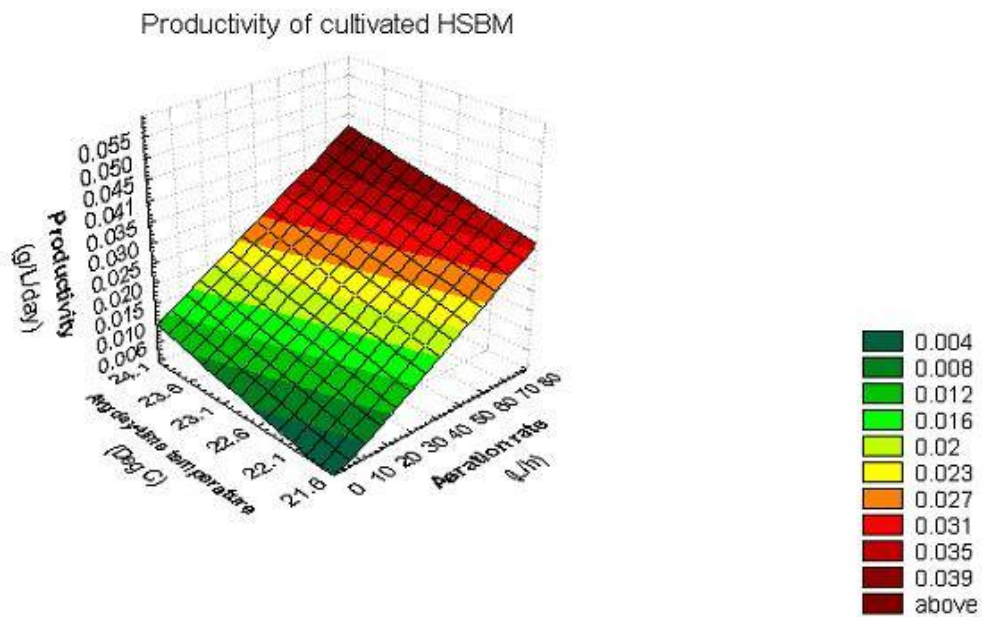


Figure 29: Influence of day-time temperature and aeration rate on microalgae productivity in 1-L bioreactors.

From Tables 9 and 10 it can be seen that the aeration rate had a significant effect on the cultivation of microalgae sourced from the Hartbeespoort Dam (p-value of 0.00105). In all instances, the productivity increased by more than 400% as the aeration rate increased from 3.6 to 72.0 L/h. This equates to an increase in the productivity of between 0.21 and 0.24% for every percentage increase in the aeration rate. Agitation caused by increased air flow through the culture would promote better contact between the cells and the carbon source that is necessary for growth. Agitation also promotes better circulation of the cells within the culture broth,

causing increased exposure to light and thus increase photosynthesis with a resultant increase in growth rate. From Tables 9 and 10 it can be seen that average day-time temperature has a significant effect on the cultivation of microalgae sourced from the Hartbeespoort Dam (p-value of 0.03056). At a constant aeration rate of 3.6 L/h, the productivity increased with 60%, as the average day-time temperature increased with 12% from 21.6 to 24.1°C. At a constant aeration rate of 72.0 L/h, the productivity increased with 74%, as the temperature increased with 12% from 21.6 to 24.1°C. This equates to an increase in the productivity of between 5.2 and 6.4% for every percentage increase in the average day-time temperature. There is no significant effect on the cultivation of microalgae sourced from the Hartbeespoort Dam, due to the interaction between aeration rate and the average day-time temperature, since the interaction p-value is greater than alpha ($0.07694 > \alpha = 0.05$).

4.1.1.2. Results and discussion of cultivation in 5-litre bioreactors

The objective of this experiment was to determine the highest growth rate that could be achieved in a 5-litre bioreactor with Hartbeespoort Dam-sourced micro-algal biomass (HSMB). In this experiment, micro-algal biomass, sourced from the Hartbeespoort Dam, was cultivated successfully in 5-litre Erlenmeyer flask bioreactors, using a modified batch growth medium with high concentrations of nitrates (NO_3^-) and phosphates (PO_4^{3-}). Growth followed an exponential S-curve, typical of micro-algal growth, reaching its stationary phase after four weeks. Only a small increase in growth occurred after six weeks. The highest volumetric growth concentration of 2.06 g/L and productivity of 0.0862 g/L/d of dry weight micro-algal biomass were achieved after the total cultivation period of six weeks, respectively, at an average day-time bioreactor temperature of 26.0°C and an aeration rate of 1.5 L/min. The lowest volumetric growth concentration of 0.28 g/L and productivity of 0.0067 g/L/d were achieved after six weeks of cultivation at an average day-time bioreactor temperature of 18.2 °C and aeration rate of 0.7 L/min.

Table 11: Volumetric growth concentration of cultivated HSMB after six weeks of cultivation in 5-L bioreactors

Bioreactor	Aeration rate (L/min)	Average day-time temperature (°C)	ρ_v (g/L)
B ₁	0.7	24.7	1.09
B ₂	1.5	26.0	2.06
B ₃	0.7	23.7	1.29
B ₄	0.7	27.6	0.72
B ₅	0.4	27.9	0.81
B ₆	1.0	28.5	1.61
B ₇	1.0	23.4	1.26
B ₈	0.7	18.2	0.28

The cumulative increase in algal biomass during the cultivation period at different aeration rates and temperatures is presented in Table 11 and 12.

Table 12: Accumulated biomass gain during cultivation period in 5-L bioreactors

Bioreactor	Aeration rate (L/min)	Average day-time temperature (°C)	Biomass weight (g)			
			Initially	Week 2	Week 4	Week 6
B1	0.7	24.7	0.0011	2.7333	4.0533	4.3458
B2	1.5	26.0	0.0011	4.8267	7.3867	8.2368
B3	0.7	23.7	0.0011	3.9200	4.3333	5.1417
B4	0.7	27.6	0.0011	2.3200	2.8667	2.8829
B5	0.4	27.9	0.0011	2.0933	2.6000	3.2580
B6	1.0	28.5	0.0011	2.3867	5.5067	6.4246
B7	1.0	23.4	0.0011	4.2533	4.3200	5.0212
B8	0.7	18.2	0.0011	0.7467	1.4000	1.1338

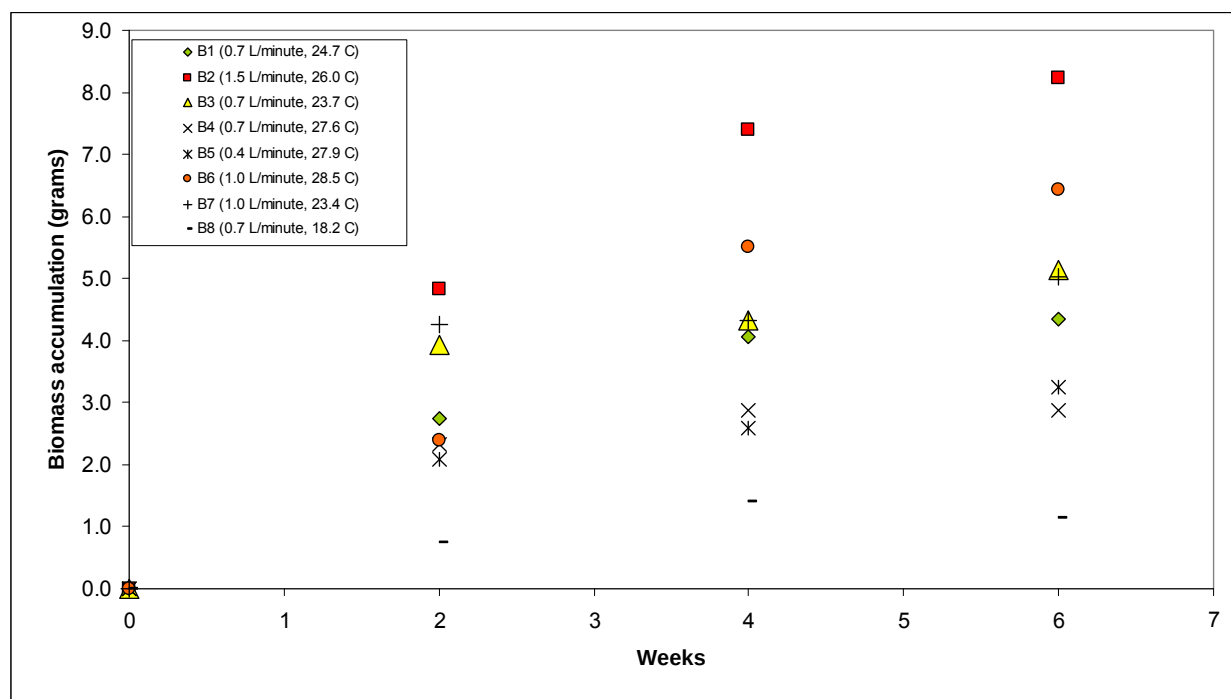


Figure 30: Dry weight accumulation of Hartbeespoort Dam-sourced micro-algal biomass over a period of six weeks of cultivation with different aeration rates and recorded average day-time temperatures.

Figure 30 shows algal growth in all instances, and as is expected for micro-algal growth, an S-shaped growth curve was obtained over time. The growth rates after six weeks of cultivation and productivity for the different cultivation conditions used in this study are summarized in Tables 11 and 12, respectively. The highest volumetric growth concentration of 2.06 g/L and productivity of 0.0862 g/L/d were achieved after the total cultivation period of six weeks at an average day-time bioreactor temperature of 26.0°C and an aeration rate of 1.5 L/min. The lowest volumetric growth concentration of 0.28 g/L and productivity of 0.0067 g/L/d were achieved after six weeks of cultivation, at an average day-time bioreactor temperature of 18.2°C and

aeration rate of 0.7 L/min. Aeration was varied between 0.4 and 1.5 L/min for the eight bioreactors. Aeration rate had a significant effect on the volumetric growth concentration and productivity, with the highest volumetric growth concentration of 2.06 g/L and productivity of 0.0862 g/L/d achieved at the highest aeration rate of 1.5 L/min, even though the specific bioreactor did not experience the highest average day-time temperature (at 26.0°C it was 2.5 degrees less than the highest). The average day-time temperatures of the eight bioreactors varied between 18.2 and 28.5°C.

Fig. 31 shows the relationship between the volumetric growth concentration of Hartbeespoort Dam-sourced micro-algal biomass cultivated in 4-litre Erlenmeyer flask bioreactors and the average day-time temperature of the bioreactors at a constant aeration rate of 0.7 L/min. The highest volumetric growth concentration of 1.29 g/L was achieved at an average day-time temperature of 23.7°C, while the volumetric growth concentration decreased quadratically as the average day-time bioreactor temperature varied from the optimum temperature.

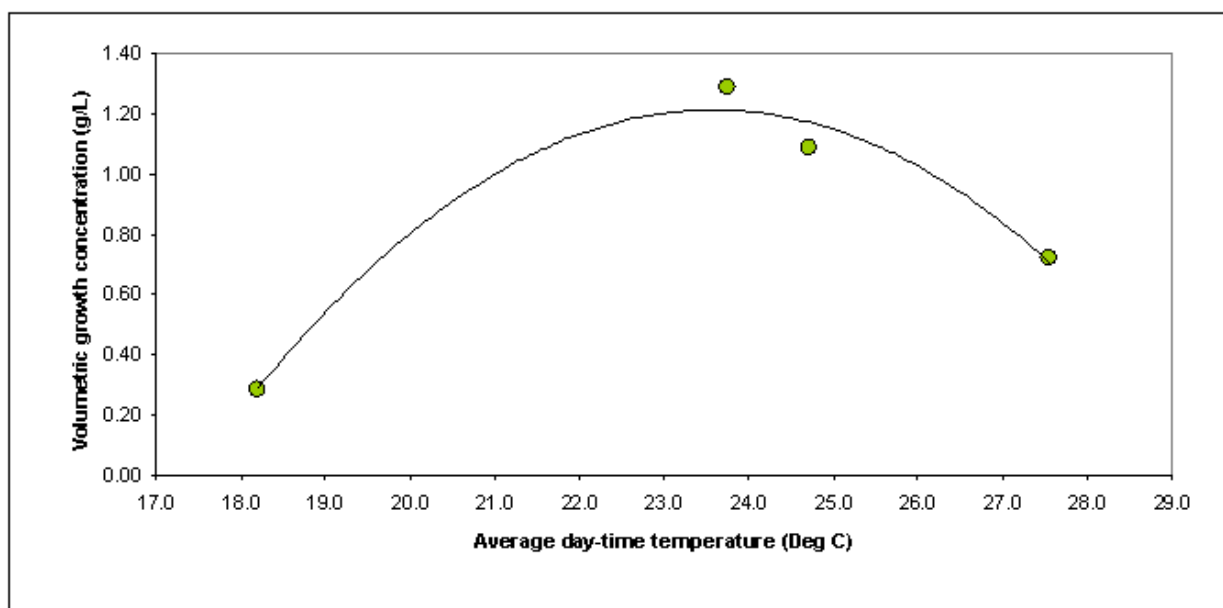


Figure 31: Volumetric growth concentration of Hartbeespoort Dam-sourced micro-algal biomass in 5-L bioreactors after 6 weeks of cultivation versus average day-time temperature at constant aeration rate of 0.7 L/min.

Fig. 32 shows the relationship between the growth yield of Hartbeespoort Dam-sourced micro-algal biomass cultivated in 5-litre Erlenmeyer flask bioreactors, aeration rate and average day-time bioreactor temperature in a three-dimensional graph.

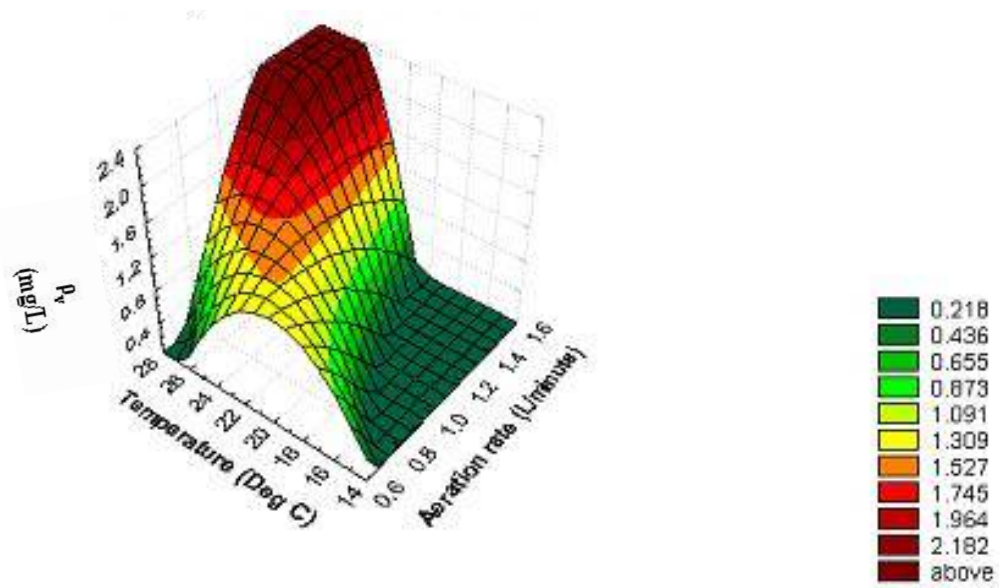


Figure 32: Volumetric growth concentration (g/L) of Hartbeespoort Dam-sourced micro-algal biomass after six weeks of cultivation in 5-L bioreactors at different aeration rates and average day-time bioreactor temperatures.

4.1.1.3. Results and discussion of cultivation in 135-litre bioreactor

The objective of this experiment was to determine the highest growth rate that could be achieved in a 135-litre bioreactor with Hartbeespoort Dam-sourced micro-algal biomass (HSMB). In this experiment, micro-algal biomass from the Hartbeespoort Dam was cultivated successfully in a 135-litre glass tank bioreactor, using a modified growth medium with high concentrations of nitrates (NO_3^-) and phosphates (PO_4^{3-}), natural solar lighting, and externally supplied aeration. Average temperatures between 24-26°C, and aeration rates which are sufficiently strong to keep the biomass in suspension, delivered the best production rates, after the optimum growth period of 4 weeks. The highest aerial growth concentration of 2.9557 g/m² of dry weight biomass per growth plate (0.3 m²) was achieved after 4 weeks of cultivation. Table 13 summarizes the biomass growth over six weeks.

Table 13: Micro-algal biomass production per bioreactor growth plate in 135-L glass tank bioreactor

Growth Time	Production	
Weeks	grams/plate	g/m ²
0	0.0000	0.0000
2	0.3314	1.1047
4	0.8867	2.9557
6	0.7999	2.6663

Cultivation of micro-algal biomass was improved through the addition of growth plates in the bioreactors. These growth plates mimic sheltered rock surfaces in the Hartbeespoort Dam, which create favourable conditions for algal blooming, by providing inoculums of cyanobacterial species. These growth plates also act as substrate on which the micro-algal biomass could grow and allow for easy manual harvesting. Fig. 34, 35 and 36 show the growth of biomass initially and after, two and six weeks of cultivation, respectively. Growth followed an exponential S-curve (Fig. 33), typical of micro-algal growth, reaching its stationary phase after 4 weeks.

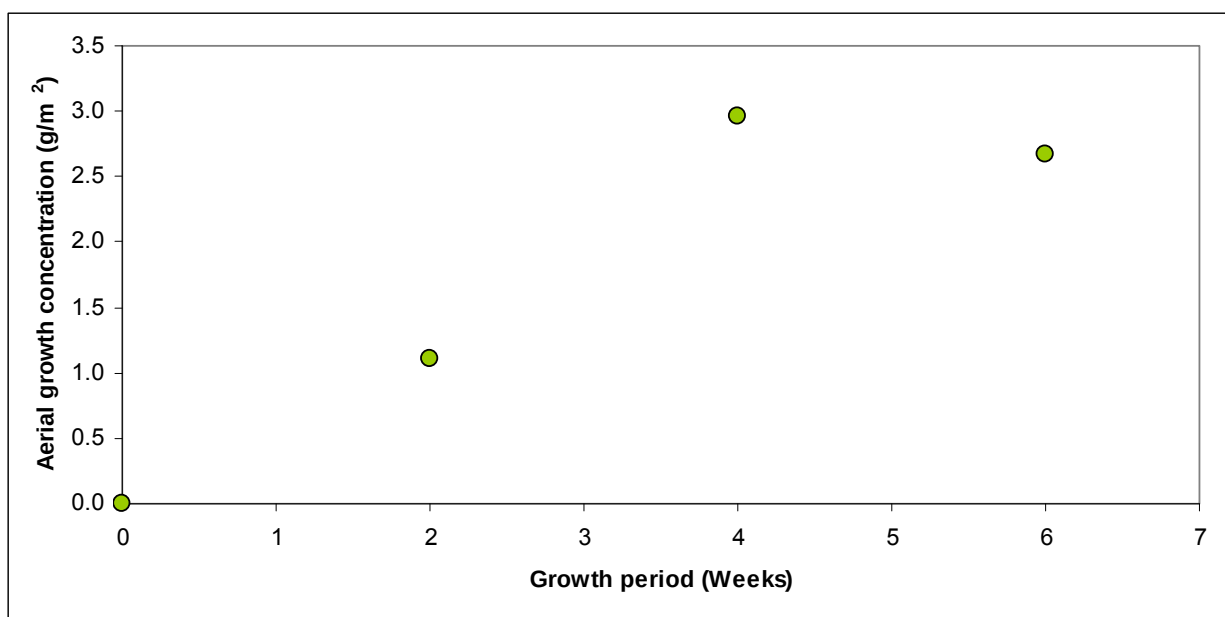


Figure 33: HSMB aerial growth concentration in 135-L glass tank bioreactor over period of six weeks.



Figure 34: HSMB inoculated in 135-L glass tank bioreactor.



Figure 35: HSMB growth in 135-L glass tank bioreactor after two weeks.

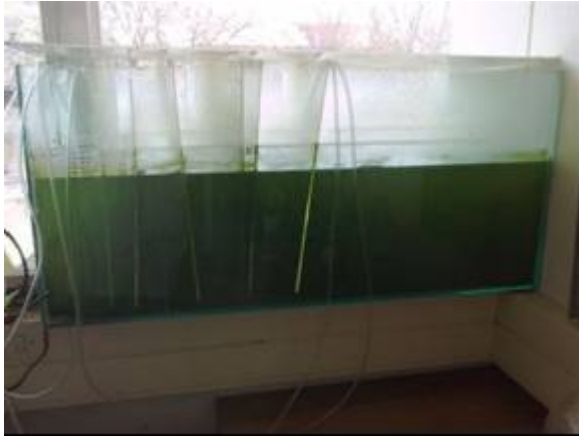


Figure 36: HSMB growth in 135-L glass tank bioreactor after six weeks.

4.1.2. Results & discussion of cultivation screening experiments

4.1.2.1. Results and discussion for natural buoyancy separation

The objective of this experiment was to develop models which could be used to predict the separation rate of Hartbeespoort Dam micro-algal biomass from its aqueous phase, which in turn could be used to determine optimum residence times for the sizing of separation equipment.

The separation rate of Hartbeespoort Dam micro-algal biomass from its aqueous phase, due to its natural buoyancy, followed a logarithmic trend, with a distinct biomass layer forming at the top of the measuring cylinder almost instantly, and stabilizing after 21.5 hours. Table 14 summarizes the measured volume concentration of wet micro-algal biomass as it separates from its aqueous phase due to its natural buoyancy over a period of 24 hours.

Table 14: Natural buoyancy separation rate of micro-algal biomass from the Hartbeespoort Dam in three measure cylinders over a period of 24 hours

Cylinder	83 mm	65 mm	38 mm
Separation Time	Micro-algal biomass concentration		
Hours	Volume %	Volume %	Volume %
0.0	100.0	100.0	100.0
0.5	75.0	71.4	83.0
1.0	67.5	67.1	70.0
1.5	62.5	62.9	66.0
2.5	60.0	60.0	61.0
3.5	57.5	58.6	58.5
21.5	55.0	52.9	49.0
24.0	55.0	52.9	49.0

Results show that micro-algal biomass concentration occurs rapidly over the first four hours of separation, reaching a steady plateau regime after four hours. The data were used to determine the constants in Equation 10, using least squares regression techniques. The accuracies of the three fits (R^2) were calculated to be between 80.42 and 94.18 %. The obtained constants with 95% confidence limits are given in Table 15.

Table 15: Fitted constants for Equation (2) with 95% confidence limits

Constant	83 mm cylinder	65 mm cylinder	38 mm cylinder
a	-4.437	-4.555	-7.794
b	66.937	66.104	71.406
R^2	0.8042	0.9418	0.9154

The regressed constants can now be used in Equations 4, 5 and 6 to predict the wet weight concentration of Hartbeespoort Dam algae separated due to natural buoyancy, in 83 mm, 65 mm and 38 mm cylinders, respectively.

$$C_{83mm} = -4.437 \cdot \ln(t) + 66.937 \quad (30)$$

$$C_{65mm} = -4.555 \cdot \ln(t) + 66.104 \quad (31)$$

$$C_{38mm} = -7.794 \cdot \ln(t) + 71.406 \quad (32)$$

Figure 37 compares the experimental separation rates of the micro-algal biomass against the predicted rates according to models 30, 31 and 32. From Figures 37 and 38 it can be seen that the diameter of the cylinder used has an influence on the volume concentration. Results obtained in this study revealed that the diameter of a separation vessel has an influence on the volume concentration. The larger the diameter, the slower the algae separates from the water phase. The hypothesis is that the smaller diameter cylinder requires a smaller volume to support the algae in the water phase for a certain natural buoyancy potential. Experimental results also revealed that a separation vessel used for the primary separation of Hartbeespoort Dam micro-algal biomass (wet weight fraction) from its aqueous phase should have a residence time of approximately 3.5 hours. Additional residence time would not provide any substantial benefit with regards to the volume concentration of the wet micro-algal biomass, but would increase vessel capacity and cost unnecessarily.

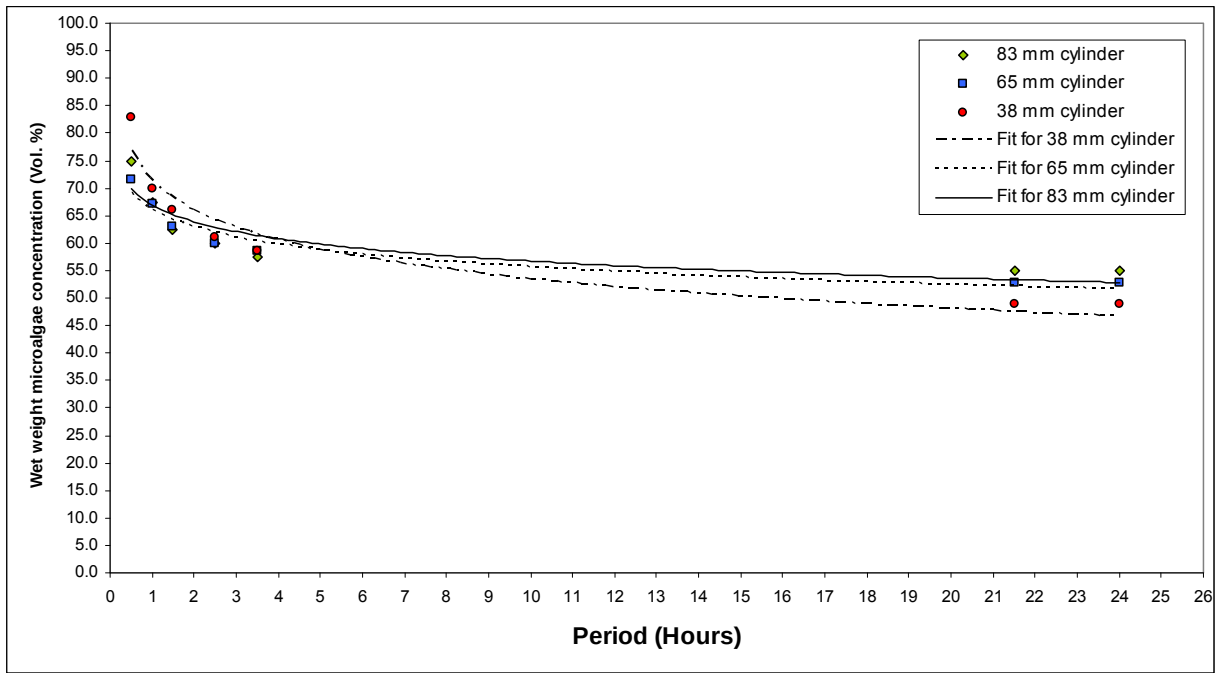


Figure 37: Experimental data with fitted models: (◇) 83 mm cylinder; (□) 65 mm cylinder; (○) 38 mm cylinder; (—) fitted 83 mm cylinder; (--) fitted 65 mm cylinder; (---) fitted 38 mm cylinder.

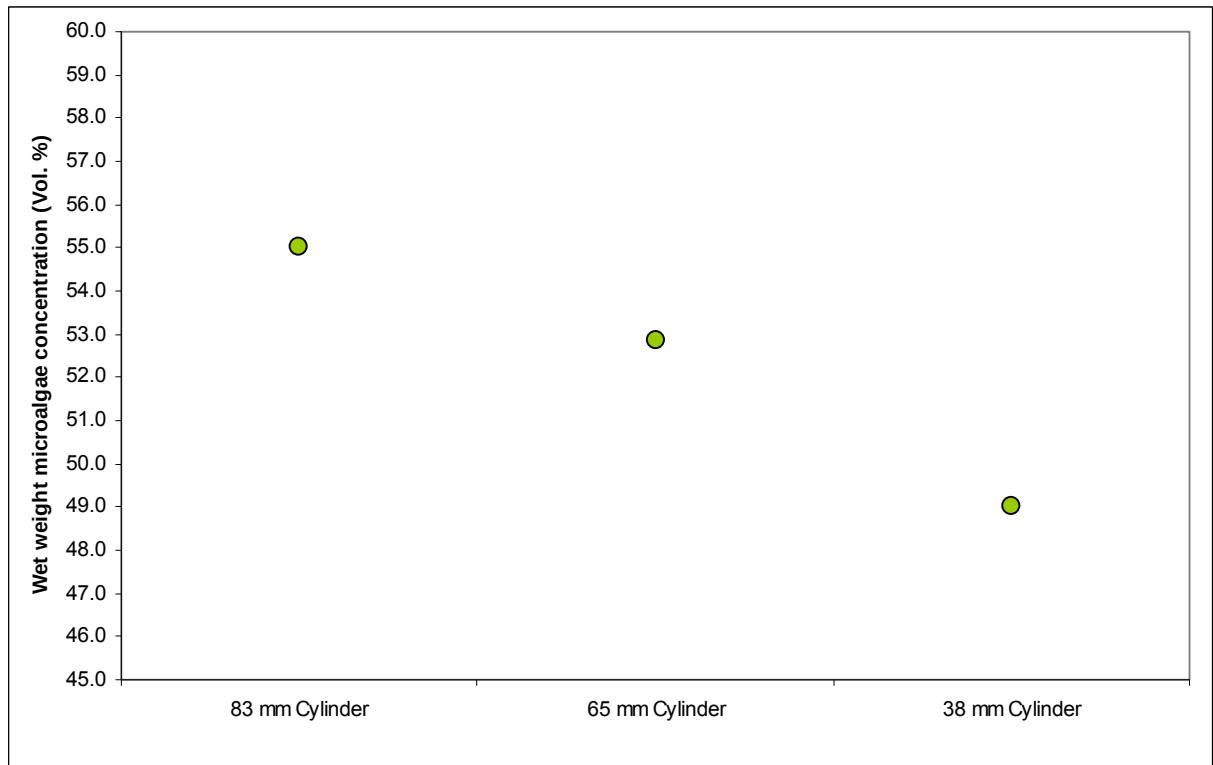


Figure 38: Volume concentration of wet micro-algal biomass after 24 hours of natural buoyancy separation in 83 mm, 65 mm and 38 mm cylinders.

4.1.2.2. Results and discussion for sand filtration and solar drying

The objective of this experiment was to quantify the utilization of sand and solar power to harvest and dry microalgae from the Hartbeespoort Dam. An average dry weight of 7.6 grams of dried micro-algal biomass from the Hartbeespoort Dam was harvested after one day of sun-drying on a patch of 0.0484 m² or 497.7 g of building sand. An average volumetric harvesting yield of 15.3 g/L or 1.5% (wt.) of dry weight micro-algal biomass were achieved per litre of pulp. Furthermore, an average aerial harvesting yield of 157.6 g/m² or 1.5% (wt.) of dry weight micro-algal biomass were achieved per square meter or weight of building sand, respectively. An average wet weight harvesting yield of 3.0% (wt.) of dry weight micro-algal biomass was achieved per wet weight micro-algal biomass fraction of Hartbeespoort Dam pulp. The average day-time temperature was 24.0°C.

The building sand substrate improves the separation of water from the wet micro-algal biomass. As water is absorbed into the sand, it increases the drying area and thus increases the drying rate of the micro-algal biomass. Solar radiation provides the energy to evaporate the moisture.

Samples of the concentrated wet weight micro-algal biomass pulp and dried micro-algal biomass flakes were analyzed with scanning electron microscopy (SEM). SEM images of wet micro-algal biomass pulp on scales of 50 and 10 microns are shown in Figures 40 and 41, respectively. SEM images of dry filtered micro-algal biomass from the Hartbeespoort Dam on scales of 20 and 2 microns are shown in Figures 42 and 43, respectively.



Figure 39: Sand-filtered, sun-dried Hartbeespoort Dam micro-algal biomass flakes.

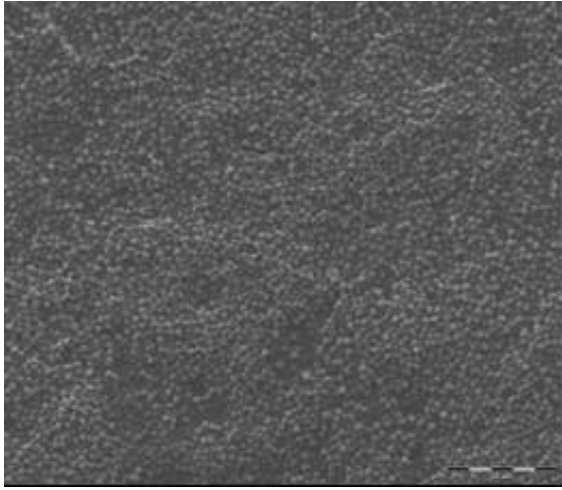


Figure 40: SEM image of wet Hartbeespoort Dam micro-algal biomass pulp at scale of 50 microns.

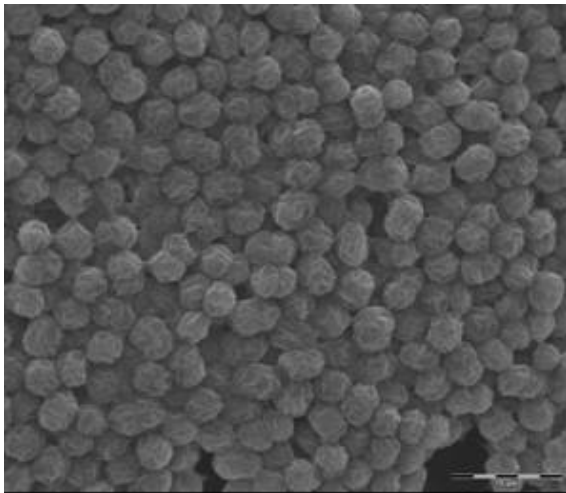


Figure 41: SEM image of wet Hartbeespoort Dam micro-algal biomass pulp at scale of 10 microns.

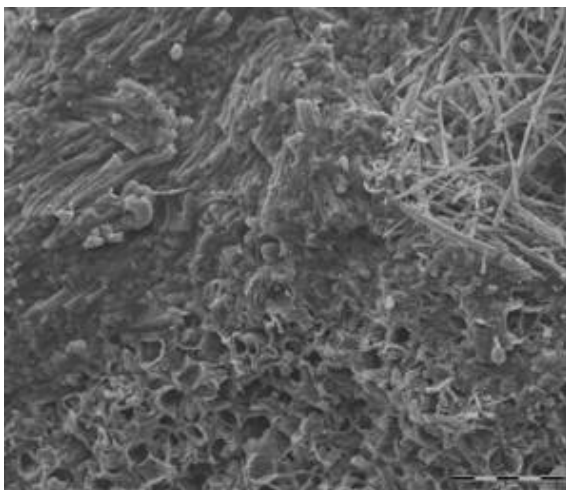


Figure 42: SEM image of dry filtered Hartbeespoort Dam micro-algal biomass at scale of 20 microns.

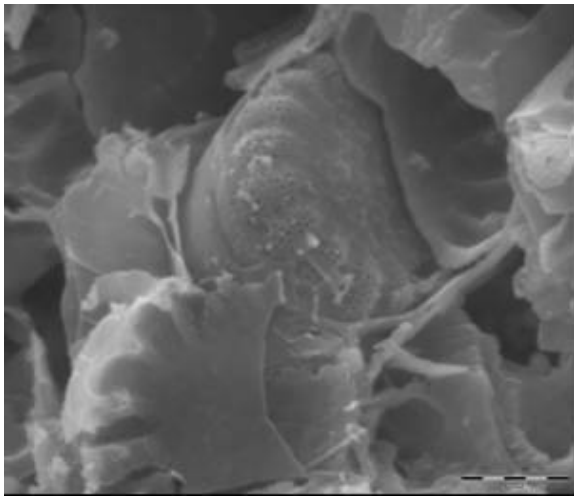


Figure 43: SEM image of dry filtered Hartbeespoort Dam micro-algal biomass at scale of 2 microns.

4.1.2.3. Results and discussion for gravity settling harvesting

The objective of this experiment was to quantify the harvesting of cultivated Hartbeespoort Dam-sourced micro-algal biomass in 5-L Erlenmeyer bioreactors through the process of gravity settling. Micro-algal biomass, sourced from the Hartbeespoort Dam, was cultivated in three 5-litre Erlenmeyer flask bioreactors for six weeks. Aeration was stopped and the bioreactors were shaken for five minutes to ensure an equal distribution of micro-algal biomass throughout the bioreactor. Three bioreactors were allowed to stand for one, five and 14 days respectively, in order to measure the accumulation of micro-algal biomass in different sections (top 50%, middle 25%, bottom 25%) of each bioreactor. After one day, 90.1% (wt.) of the micro-algal biomass accumulated in the bottom quarter of the first bioreactor. After five days 94.6% and after 14 days 98.5% of dry weight micro-algal biomass accumulated in the bottoms of the second and third bioreactors, respectively. Cultivated micro-algal biomass sourced from the Hartbeespoort Dam, can easily be harvested by allowing it to settle with gravity when aeration is stopped. Results showed that gravity settling equipment, with residence times of 24 hours, should be sufficient to accumulate over 90% of cultivated micro-algal biomass. Using this method for primary separation could reduce the total cost of harvesting equipment dramatically, by separating more than 90% of the total cultivated micro-algal biomass from over 75% of the total water or growth medium with minimal energy input. The progressive results of gravity settling can be seen visually through Figures 44 to 47. Over 90% of the cultivated micro-algal biomass settled to the bottom quarter of the bioreactor after one day of gravity settling. After five and 14 days the total weight of microalgae that settled in the bottom quarter of the bioreactor increased to 95% and 99%, respectively.



Figure 44: Well-mixed 5-L bioreactor after zero hours of gravity settling.



Figure 45: 5-L bioreactor after 24 hours of gravity settling.



Figure 46: 5-L bioreactor after five days of gravity settling.

In Fig. 47 one can clearly see how the micro-algal biomass accumulated at the bottom of the Erlenmeyer flask bioreactor.



Figure 47: Micro-algal biomass accumulation at the bottom of the 5-L Erlenmeyer flask bioreactor.

In Fig. 48 one can see the comparison between micro-algal biomass accumulation in a well-mixed bioreactor (left) and a bioreactor which was allowed to stand for 24 hours (right). More than 90% (wt.) of the micro-algal biomass accumulated in the bottom quarter of the bioreactor on the right after 24 hours of gravity settling.



Figure 48: Gravitation settling comparison between well-mixed bioreactor (left) and bioreactor that was allowed to settle for 24 hours.

Table 16 below shows the results from the harvesting of micro-algal biomass from the 4-L Erlenmeyer flask bioreactors through gravity settling. The results show that over 90% (wt.) of the micro-algal biomass accumulated in the bottom quarter of the flask bioreactor after one day. After five days of settling, the micro-algal biomass accumulation in the bottom quarter of the bioreactor increased to nearly 95% (wt.), and after two weeks increased to almost 99% (wt.) of the total biomass content.

Table 16: Results of micro-algal biomass harvesting from 5-L bioreactors through gravity settling

Bioreactor	Settling time	Harvesting yield (%) of micro-algal biomass in various sections of bioreactor		
		Top 50%	Middle 25%	Bottom 25%
B ₁	1	3.5573	6.3237	90.1191
B ₂	5	2.1737	3.2054	94.6210
B ₃	14	0.4784	0.9789	98.5426

Figure 49 shows that the concentration of cultivated micro-algal biomass, sourced from the Hartbeespoort Dam, increases logarithmically with increased depth in the flask bioreactors through gravity settling.

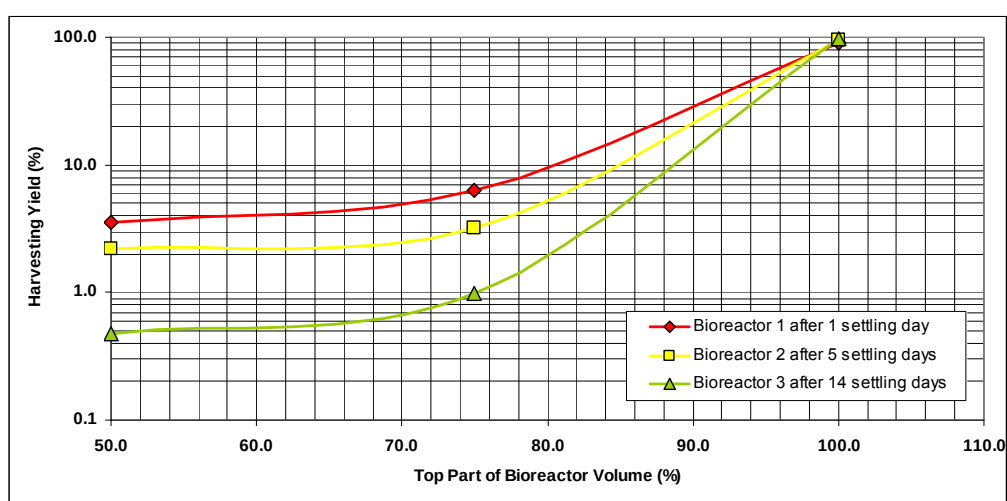


Figure 49: Logarithmic graph of gravity settling harvesting yield of cultivated micro-algal biomass, sourced from the Hartbeespoort Dam, in the top 50%, middle 25%, and bottom 25% of three Erlenmeyer bioreactors: (◇) bioreactor 1; (□) bioreactor 2; (Δ) bioreactor 3. The solid lines do not constitute a fit, but just a visual guide.

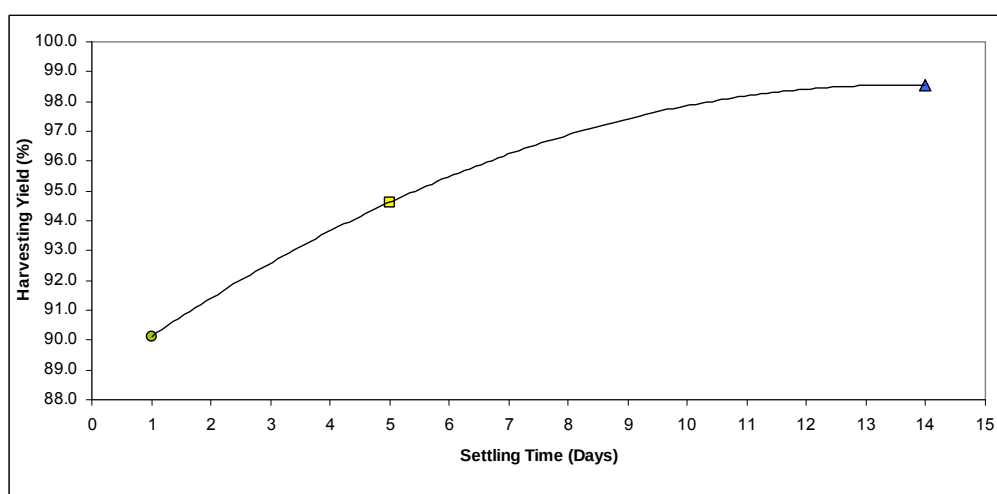


Figure 50: Harvesting yield of cultivated micro-algal biomass sourced from the Hartbeespoort Dam versus gravity settling time in the bottom 25% of three Erlenmeyer bioreactors: (○) bioreactor 1; (□) bioreactor 2; (Δ) bioreactor 3; The solid line does not constitute a fit, but just a visual guide.

SECTION TWO



RESULTS & DISCUSSION

OF THE PROCESS DEVELOPMENT

4.2 RESULTS AND DISCUSSION OF THE PROCESS DEVELOPMENT

The design of a biomass-to-liquids (BTL) conceptual process consisted of the following steps: (1) conducting a series of screening experiments to determine the most suitable methods for harvesting micro-algal biomass from the Hartbeespoort Dam; (2) combining current knowledge on extracting oils from microalgae and production of biodiesel from these oils into a holistic conceptual process. The screening studies identified three methods with great potential to harvest micro-algal biomass from the Hartbeespoort Dam sustainably and environmentally friendly. One method utilized the natural buoyancy of Hartbeespoort Dam microalgae to concentrate it from 1.5 to 3% TSS; the second method utilized gravity settling to concentrate micro-algal biomass from its aqueous medium; the third method used a combination of sand filtration and renewable solar energy to dry and harvest the concentrated micro-algal biomass. Barnard (2009) extracted oils from microalgae harvested from the Hartbeespoort Dam successfully with a small laboratory-scale pilot plant. Miao and Qu (2006) produced biodiesel successfully through the acid-catalyzed transesterification of micro-algal oil. The harvesting methods identified in the screening studies were incorporated with the extraction and reaction methods and design parameters recommended by Barnard (2009) and Miao and Wu (2006), respectively, into an integrated biomass-to-liquids process to produce biodiesel from micro-algal biomass from the Hartbeespoort Dam.

4.2.1 Design basis

The design basis was based on data from the literature study and the screening experiments in the Process Identification phase.

- The design of the reference case was based on micro-algal biomass concentration of 160 g/m² in the 20 km² Hartbeespoort Dam for a conservative growth period of six months of the year (Hambright and Zohary, 2000). Alternate cases were developed for 7, 8, 9 and 10 months, to compare their sensitivity to that of the reference case.

- Since micro-algal growth occurs during the warmer 6 months of the year, and micro-algal populations collapse and biomass start to decompose during the colder autumn and winter months, the operating period for the new integrated BTL facility was set at 183 days per year for the reference case. As mentioned, alternate cases were developed for 7, 8, 9 and 10 months, to compare their sensitivity to that of the reference case.
- The growth phase of the microalgae was taken as 41 days (Piorreck, 1984), since over 90% of the micro-algal biomass consist of *Microcystis aeruginosa* (Hambricht and Zohary, 2000).
- Barnard (2009) harvested fresh microalgae from the Hartbeespoort Dam and succeeded in extracting 15.60% micro-algal oils from the biomass on a dry basis.
- Although only 17.7% of dry weight of *Microcystis aeruginosa* consisted of lipids (hereafter referred to as micro-algal oils), and only 3.2% of dry weight of *M. aeruginosa* consisted of fatty acids at nitrogen concentrations comparable to that found in the Hartbeespoort Dam (Piorreck *et al.*, 1984), it was assumed that 100% of the total lipids could be converted into biodiesel, as was founded by Miao and Wu (2006).
- The raw micro-algal biomass from the Hartbeespoort Dam was taken as 1.53% TSS (Sections 4.1.2.1 and 4.1.2.2).
- Raw micro-algal biomass from the Hartbeespoort Dam could be concentrated from 1.53 to 2.66% TSS in 3.5 hours time. The biomass could be concentrated further to 2.78% TSS in 21.5 hours time, but the 5% extra concentration did not justify the additional 18 hours in residence time, which would increase the capital cost with over 614% (Sections 4.1.2.1 and 4.1.2.2).
- The filter design was based on dewatering the micro-algal biomass from 2.66 to 16.26% TSS. The 16% TSS is based on the energy required to turn the water fraction in the wet biomass into superheated steam at 300°C and 15,000 kPa and boil off the chloroform solvent with the Solvent Distillation Reboiler (H-504), from the energy available in the dry biomass fraction, including the 25% energy loss by the Furnace (Q-701) and associated heat exchange equipment and piping.
- The Extraction Reactor (R-501), Solvent Mixing Tank (T-501), and Solvent Distillation Column (C-501) were designed according to process conditions used by Barnard (2009) during his thermochemical liquefaction experiments on Hartbeespoort Dam microalgae.
- The Settling Dam (D-501) was sized according to harvesting yield results obtained from Section 4.1.2.3. A residence time of 24 hours were used for the design.
- The Drying Field was sized according to harvesting results achieved from the sand filtration and solar drying experiments in Section 4.1.2.2.

4.2.2 Design rates

The following design rates (Table 17) were derived using the above-mentioned design basis. The second column lists the total suspended solids concentration (TSS) of micro-algal biomass on a dry weight basis. The third column shows the total calendar-year flow rates of the feeds entering Units 300 to 800. The last three columns show the flow rates of the water, biomass and oil fractions of these feed streams, respectively.

Table 17: Mass balance across the BTL process

Unit	TSS	Total Flow	Water Flow	Biomass Flow	Oil Flow
#	wt. %	t/a	t/a	t/a	t/a
U-100	<1.5	-	-	-	-
U-200	1.5	-	-	-	-
U-300 feed	1.5	933,525	919,242	14,283	2,228
U-400 feed	3	536,952	522,669	14,283	2,228
U-500 feed	16	87,841	73,558	14,283	2,228
U-600 feed	44	32,672	18,389	12,055	0
U-700 feed	100.0	12,055	0	12,055	0
U-800 feed	0.0	2,228	0	0	2,228

4.2.3 Process description

The new integrated BTL process (Fig. 51) consists of three sections: (1) a cultivation section where microalgae grow abundantly in the 20 km² Hartbeespoort Dam to a concentration of 160 g/m² during the six warmest months of the year (Hambright and Zohary, 2000), due to stable climatic conditions and the influx of large quantities of nitrates and phosphates from the run-off of fertilized agricultural land and effluent from sewage plants from the northern suburbs of Johannesburg (Owuor *et al.*, 2007); (2) a harvesting section where excess water is separated and removed from the micro-algal biomass; (3) a reaction section where fatty acid oils are extracted from the microalgae and converted to biodiesel, and dry biomass rests are combusted to supply heat for the reaction section.

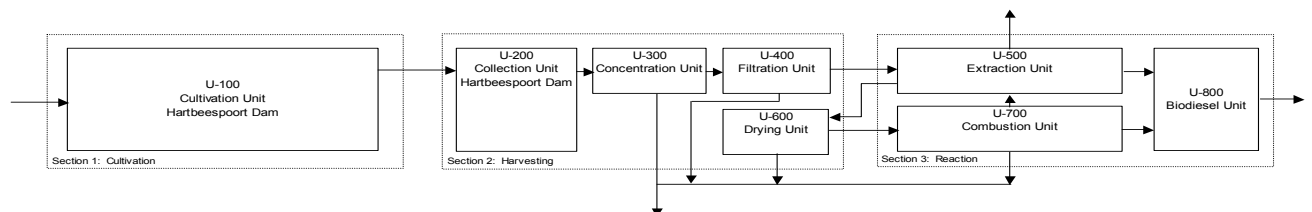


Figure 51: Block flow diagram of the new BTL process

Micro-algal biomass in the Hartbeespoort Dam (U-100) is concentrated against the dam wall (U-200) at 1.5% TSS through prevailing south-easterly winds. Micro-algal biomass is drained from the topside of the dam wall at a calendar-year flow rate of 930 megalitres per annum into the

concentration dam (D-301) of Unit 300 where the biomass is concentrated to 3% TSS due to the natural buoyancy of the Dam's microalgae in 3.5 hours time. Read the rest of the process description in conjunction with the process flow diagram of the whole process in Fig. 62 for a more clear understanding.



Figure 52: Hartbeespoort Dam microalgae separating to the top of the measuring cylinders after 3.5 hours at a concentration of 3% TSS.

Biomass then flows via gravity to the Filtration Unit (U-400) where it is dewatered to 16% TSS through a drum filter (F-401). The filtration pressure of 451 kPa is supplied by the hydraulic head of 46 meters between the elevation of the concentration dam (D-301) and the filter (F-401). Excess water is recovered from Unit 300 and Unit 400 by draining it back into the river, downstream of the dam wall. The filtered biomass is then pumped into the liquefaction reactor (R-501) at 15,000 kPa, where the contents are agitated at 420 rpm, and liquefaction occurs at 300°C with a residence time of 30 minutes, to release fatty acid oils in the microalgae to a maximum content of 15.60% (wt.) (Barnard, 2009). The reactor contents are heated through hot flue gas from the dried micro-algal biomass combusted in the furnace (Q-701) of the Combustion Unit (U-700).



Figure 53: Experimental set-up used by Barnard (2009) to extract oils from Hartbeespoort Dam microalgae, showing the liquefaction autoclave and associated monitoring and regulating equipment.

The oil-water-biomass mixture flows to a mixing tank (T-501) where 20% (wt.) chloroform solvent is added to the water-biomass mixture and agitated at 420 rpm for 10 minutes to extract the oils. The contents are then send to a separation tank (T-502) were the hydrocarbon chloroform-oil phase settles to the bottom, and the aqueous biomass phase accumulates at the top of the tank, as shown by Fig. 54 below.



Figure 54: Water-oil-solvent mixture separating into two distinct layers: a top layer of water and micro-algal biomass rests, and a bottom layer consisting of oil and chloroform solvent.

The hydrocarbon layer is send to a distillation column (D-501) where chloroform exits the top of the column into a solvent storage tank (T-503) and purified oils leaves the bottom of the column into an intermediate feedstock storage tank (T-504) with 24 hours storage capacity. The solvent chloroform is recycled from the intermediate storage tank back into the mixing tank (T-501) with

a solvent recycle pump (P-502). A column pre-heater (H-502) uses the hot reactor outlet stream to heat the solvent-oil phase to 60 °C, just below the solvent's flash point. Excess heat from the reactor outlet stream is used to heat the distillation column reboiler (H-504), while excess water drained back into the river is used to cool the solvent condenser located at the overheads of the distillation column (D-501).

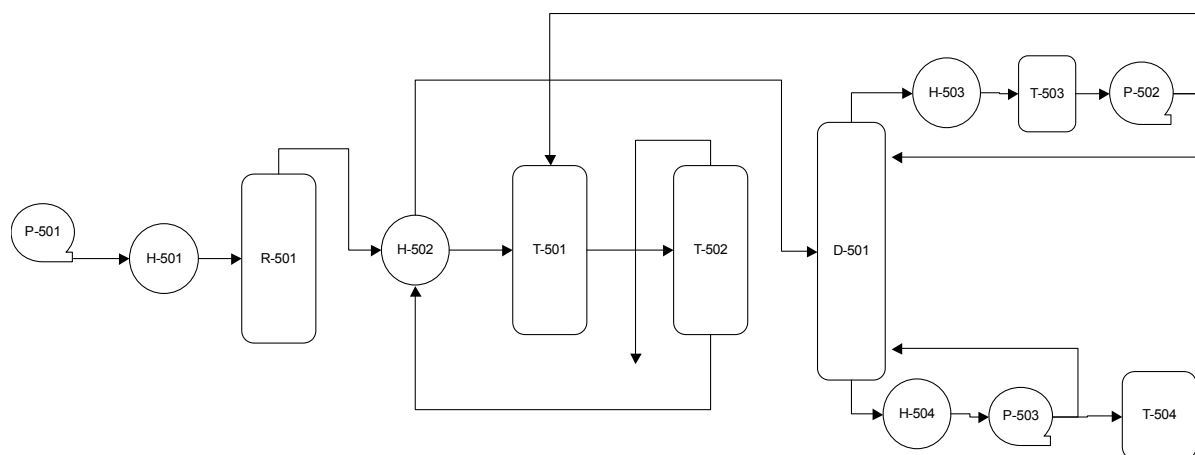


Figure 55: Process flow diagram of the Extraction Unit (U-500).



Figure 56: Vacuum distillation set-up used by Barnard (2009) to separate micro-algal oils from the chloroform solvent.

The oils are then sent to the Biodiesel Unit (U-800) where fatty acids are converted into fatty acid esters through acidic-catalyzed transesterification (Miao and Wu, 2005). The process of Haas *et al.* (2005) could be used to produce biodiesel from micro-algal oils, if the sodium methoxide catalyst is replaced with sulphuric acid, as recommended by Miao and Wu (2005). The transesterification reaction should be performed with a 100% sulphuric acid catalyst quantity

(based on oil weight), with a 56:1 molar ratio of methanol to oil, at a reaction temperature of 30°C, in 4 hours time.



Figure 57: Comparison of two 5-litre Erlenmeyer flasks with cultivated microalgae from the Hartbeespoort Dam, showing a well-mixed flask on the left, and the concentrated microalgae that settled to the bottom of the right flask after 24 hours.

The top aqueous biomass layer in the separation tank (T-502) is then sent to a settling dam (D-601) where the micro-algal biomass is allowed to settle with gravity in 24 hours time (Fig. 64). The top water layer is then drained into the river, and the bottom concentrated biomass layer is irrigated onto a field of cleared soil (E-601) via a set of irrigation pumps (P-601 A/B) and an irrigation pivot-point, where the biomass is allowed to dry for 24 hours, yielding 157.6 grams of dried micro-algal biomass per square meter (Section 4.2.1.2). The dried biomass is then harvested with solar-powered riding lawn mowers which are fitted with rake-ends to gather the dried biomass flakes.



Figure 58: A 4 m² patch of cleared soil containing a layer of harvested wet Hartbeespoort Dam micro-algal biomass.



Figure 59: Sun-dried patch of micro-algal biomass from the Hartbeespoort Dam.



Figure 60: Manually harvested sand-filtered, sun-dried Hartbeespoort Dam micro-algal biomass flakes.

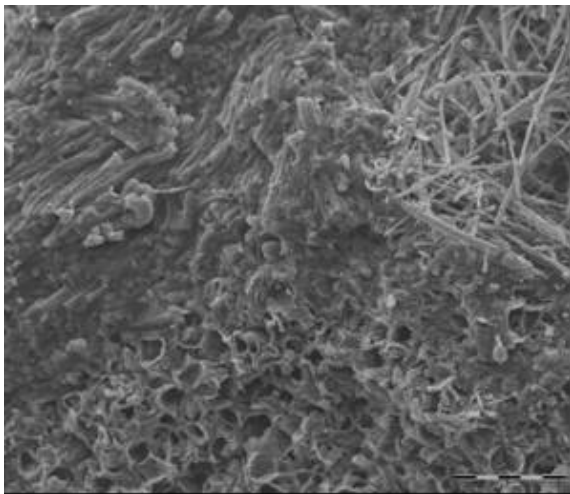
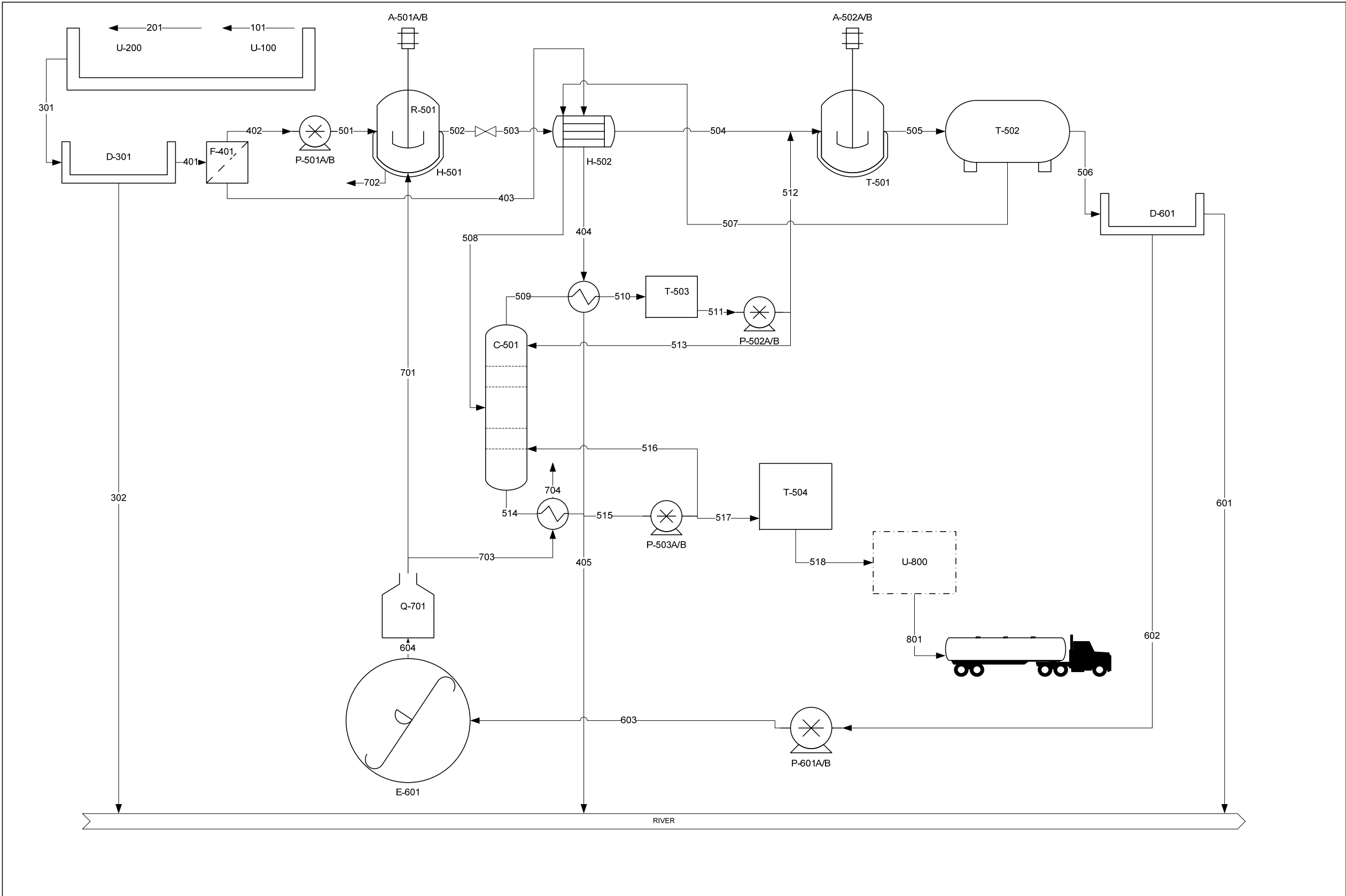


Figure 61: Microphotograph of sun-dried Hartbeespoort Dam micro-algal biomass at 20 microns (SEM Laboratory, 2009).

The biomass is then fed into a furnace and combusted to release its 19.27 MJ/kg of combustion bio-energy (Brink and Marx, 2010). The hot combustion gas is used for heating in the Extraction and Biodiesel Units (U-500 and U-800). Ash produced during the combustion process is sold or ploughed back into the gardens and land around the facilities as phosphate-rich fertilizer.



Stream Number	101	201	301	302	401	402	403	404	405	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	601	602	603	604	701	702	703	704	801
Pressure (kPa)	85	85	85	85	451	300	300	200	100	15000	15000	800	700	600	500	500	400	300	200	100	700	300	450	350	450	450	350	100	100	900	85	150	100	150	100	400
Temperature (°C)	20	20	20	20	20	20	20	30	40	20	300	300	50	50	50	50	60	70	50	50	50	50	70	80	80	80	20	20	20	20	20	550	400	550	400	20
Design Flow (t/h)	233.8	233.8	233.8	99.4	134.4	17.9	116.6	116.6	116.6	17.9	17.9	17.9	17.9	21.5	20.9	6.4	6.4	5.8	5.8	5.8	5.8	5.8	0.6	0.6	0.6	0.6	0.6	10.7	6.6	6.6	3.0	3.0	3.0	3.0	3.0	0.6

Figure 62: Process flow diagram of Hartbeespoort Dam integrated biomass-to-liquids process.

SECTION THREE



RESULTS & DISCUSSION

OF THE ENGINEERING DESIGN

4.3 RESULTS AND DISCUSSION OF THE ENGINEERING DESIGN

Equipment sizing was based on the design basis in Section 4.2. Results of the equipment sizing are summarized in Table 18. Details of all calculations for the reference case, as well as all the alternate cases can be seen in Appendix H.

The reference case was based on a calendar-year production rate of 14,283 tons of dry weight micro-algal biomass per 183 operating days per year. The reference case did not include an artificial cultivation system, but utilized the cultivation capacity of the existing Hartbeespoort Dam.

Alternate cases were performed to test the sensitivity of additional open and closed-cultivation facilities in the integrated BTL process. A design basis of 183 operating days per year and a maximum productivity of 0.0862 g/L/d for an open-cultivation system will require a pond capacity of 473,415 m³. Using an optimum pond depth of 30 cm (Tanner, 2009; Benemann *et al.*, 1977), requires a surface area of 158 hectares. A closed-cultivation system has the advantage over an open-cultivation system, in that it could cultivate microalgae for more days per year. Assuming the maximum productivity of 0.0862 g/L/d could be maintained for 350 days per year, a closed-cultivation system will require 907,298 m³ to produce 27,373 tons of dry micro-algal biomass. A total surface area of 302 hectares is required at a pond depth of 30 cm.

Table 18: Summary of equipment sizing

Equipment		OP	DP	OT	DT	Elevation	Flow	Vol	Area	Ht	Dia	Power
Name	No.	kPa	kPa	C	C	m	m ³ /h	m ³	m ²	m	m	kW
Concentration Dam	U-300	85	113	20	27	56	233	1018	678	1.5	26	
Dewatering Filter	F-401	451	601	20	27	10	133					
Reactor Feed Pumps	P-501	15000	20000	20	27	9	21					96
Reactor Heater	H-501	15000	20000	300	400	9	21		171			13545
Liquefaction Reactor	R-501	15000	20000	300	400	9	21	13		5	1.8	
Reactor Agitators	A-501	15000	20000	300	400	9	21				0.6	16
Mixing Tank	T-501	800	1067	50	67	9	26	16		3	2	
Mixing Tank Agitators	A-502	800	1067	50	67	9	26				0.8	92
Separation Tank	T-502	700	933	50	67	9	26	16		3	2	
Column Pre-heater	H-502	600	800	60	80	9	15		552			13545
Distillation Column	D-501	400	533	70	93	9	5			6	1	
Solvent Condenser	H-503	300	400	70	93	9	5		22			491
Solvent Recycle Pumps	P-502	700	933	50	67	9	5					22
Solvent Storage Tank	T-503	200	267	50	67	9	5	3		3	1	
Column Reboiler	H-504	450	600	70	93	9	5		5			491
Oil Storage Tank	T-503	350	467	20	27	9	0.5	14		3	2	
Settling Dam	D-601	500	667	20	27	8	20	613	409	1.5	20	
Irrigation Pump	P-601	900	1200	20	27	7	7					2
Drying Field	E-601	85	113	20	27	5	7				479	
Biomass Furnace	Q-701	150	200	550	733	5	2					16161

4.3.9. Plot plan

Figure 63 indicates the plot plan arrangement of the different processing units. Unit 300 is located 75 meters away from the dam wall, around 3.4 meters below the dam wall top, on the slopes of the mountain range. The rest of the facilities is located another 100 meters away from the dam wall 46 meters below the dam wall top. The hydraulic head difference between the concentration dam (D-301) and the next Unit 400 is used to supply the energy and the pressure of 451 kPa to the filter (F-401). The Extraction and Biodiesel Units (U-500 and U-800) is located next to the Filtration Unit, with the Biodiesel Storage Tank (T-801) located next to the existing road that intersects with the public road (R104) that crosses the dam wall. The units with the lowest elevation, the Drying and Combustion Units (U-600 and U-700), are located on the flat space next to the river, 59 meters below the dam wall top. The Utility Unit 900 is located between Units 400 and 800.

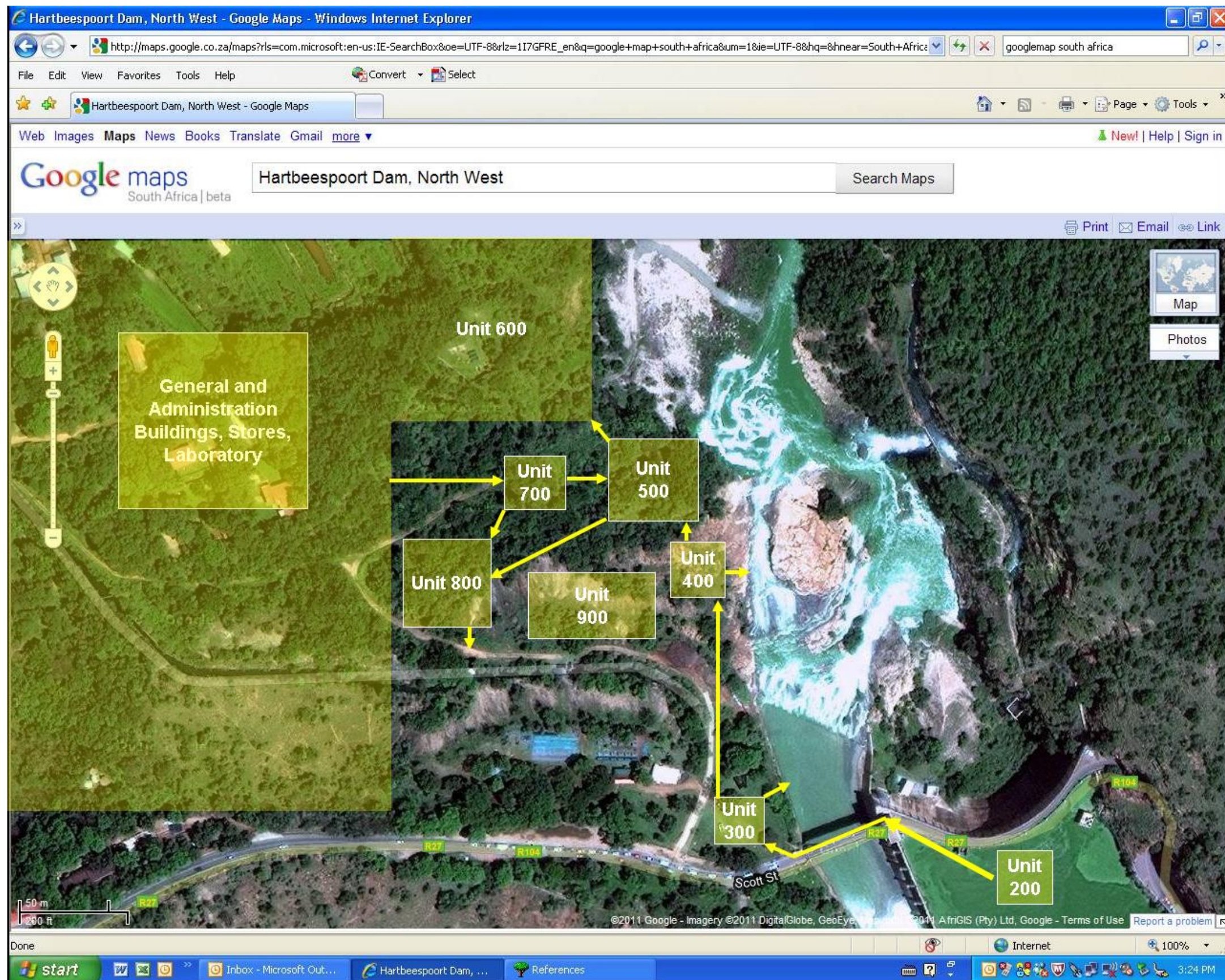
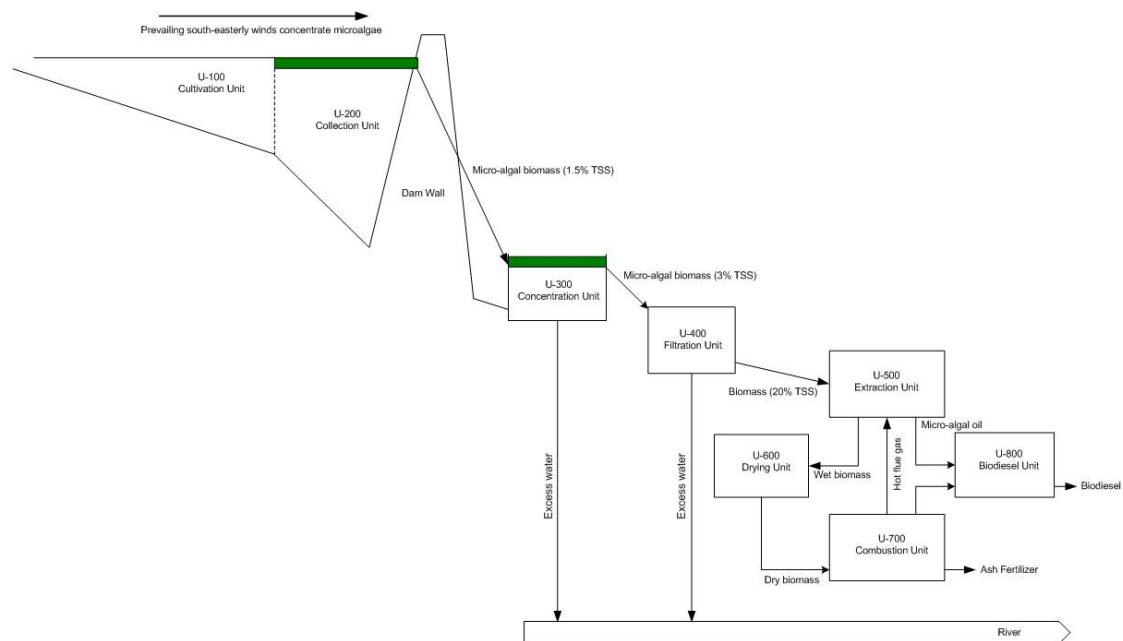


Figure 63: Site lay-out and location of units making up the new integrated BTL process at the Hartbeespoort Dam.



SECTION FOUR



RESULTS & DISCUSSION

OF THE COST ESTIMATION

4.4 RESULTS AND DISCUSSION OF THE COST ESTIMATION

The total capital cost of the new integrated BTL facility was calculated by multiplying the total purchased cost of all delivered major equipment with estimating factors obtained from Table 8. The purchased cost of all delivered major equipment was estimated with cost estimation methods specific to each major equipment item in Sections 3.4.1 to 3.4.8. Refer to the Economics Model in Appendix H for details of all costing calculations. The total capital cost of the new BTL process was estimated at R71.62 million (R1.11/L) ($\pm 30\%$) for the reference case at zero producer inflation. The most expensive part of the new BTL facility is the Extraction Section, which contributed 44% of the total capital cost. The Biodiesel Section was the second most expensive part with 37% of the cost. Harvesting costs contributed only 19% of the total BTL capital cost, which is much less than harvesting costs for other comparative processes worldwide, which contribute between 20 and 30% of the overall cost of biomass-to-liquids production (Verma *et al.*, 2010).

The operating costs associated with the new BTL process were estimated with factors obtained from Section 2.4.8. The total annual operating cost of the new BTL facility was estimated at R11.09 million per year or R4.28/L in the first year of operation. The largest contributor to the operating cost is the Extraction Section, with 42% of the total operating cost. Second is the Biodiesel Section, with 40% of the operating cost. Harvesting costs contribute the remaining 18% of the total operating cost of the BTL process. The break-down of the capital and operating cost estimates can be seen in Tables 19 and 20 below.

A calendar-year production rate of 14,283 tons of dry weight micro-algal biomass per year, with the most conservative case of 183 operating days per year for an open-cultivation system, with a productivity of 0.0862 g/L/d requires a pond capacity of 473,415 m³. Using an optimum pond depth of 30 cm, requires a surface area of 158 hectares. At an average capital cost of \$150,000 and an operating cost of \$35,000 per hectare (*Comprehensive Oilgae Report*, 2010), respectively,

the capital cost of an artificial open-cultivation system near the Hartbeespoort Dam is estimated at R196 million, and the operating cost would be estimated at R39 million per year. A closed-cultivation system operating at 350 days per year, and a productivity of 0.0862 g/L/d requires a pond size of 907,379 m³. Using an optimum pond depth of 30 cm, requires a surface area of 302 hectares. At an average capital cost of \$200,000 and an operating cost of \$45,000 per hectare (*Comprehensive Oilgae Report*, 2010), respectively, the capital cost of a closed-cultivation system near the Hartbeespoort Dam would be estimated at R502 million, and the operating cost would be estimated at R95 million per year.

Table 19: Capital cost breakdown for reference case

Item	Rands
Direct costs	
Concentration Feed Pipe (L-301)	30,203
Concentration Drain Pipe (L-302)	6,474
Concentration Dam (D-300)	508,843
Filter Feed Pipe (L-401)	32,368
Filter Drain Pipe (L-402)	6,474
Dewatering Filter (F-401)	989,660
Extraction Feed Pipe (L-501)	3,237
Extraction Drain Pipe (L-501)	8,054
Reactor Feed Pumps (P-501A/B)	517,445
Reactor Heater (H-501)	289,889
Liquefaction Reactor (R-501)	770,255
Reactor Agitators (A-501A/B)	218,416
Mixing Tank (T-501)	162,670
Mixing Tank Agitators (A-502A/B)	518,231
Separation Tank (T-502)	162,670
Column Pre-heater (H-502)	654,621
Distillation Column (D-501)	234,484
Solvent Condenser (H-503)	79,226
Solvent Storage Tank (T-503)	72,532
Solvent Recycle Pumps (P-502)	156,822
Column Reboiler (H-504)	48,235
Oil Storage Tank (T-503)	146,654
Settling Dam (D-601)	306,528
Water Drain Pipe (L-601)	3,721
Biomass Drain Pipe (L-602)	89,209
Irrigation Pump (P-601)	174,843
Irrigation Pivot-Point (S-601)	298,854
Drying Field (E-601)	322,417
Biomass Furnace (Q-701)	2,443,486
Biodiesel Unit (U-800)	5,450,289
<i>Purchased equipment delivered</i>	<i>14,706,809</i>
Installation	5,735,655
Instrumentation and controls	1,911,885
Piping (installed)	4,559,111
Electrical (installed)	1,470,681
Buildings (including services)	4,264,975
Yard improvements	1,470,681
Service facilities (installed)	8,088,745
Land	882,409
<i>Total direct facility cost</i>	<i>43,090,949</i>
Indirect costs	9,706,494
Engineering and supervision	4,706,179
Construction expenses	5,000,315
<i>Total direct and indirect facility costs</i>	<i>52,797,443</i>
Contractor's fee	2,647,226
Contingency	5,294,451
<i>Total erected cost</i>	<i>60,739,120</i>
Working capital	10,883,038
Total capital cost	71,622,158

The Extraction Section, comprising of Units 500 and 700, is the most expensive part of the BTL process, contributing R0.49 of the capital investment for every litre of biodiesel produced. The Biodiesel Section (Unit 800) is second, contributing R0.41/L, while the Harvesting Section, comprising of Units 300, 400 and 600, makes up the remainder of the capital investment, with R0.21/L of biodiesel produced.

Table 20: Operating cost breakdown for reference case

Item	Rands / year
Raw materials	535,027
Operating labour	624,600
Maintenance labour	607,391
Supervision	91,608
Power	546,329
Water	38,466
Maintenance supplies	607,391
Operating supplies	114,926
Laboratory charges	62,460
Royalties	244,917
Catalysts	133,932
Solvents	10,735
Depreciation	6,073,912
Taxes (property)	436,797
Insurance	607,391
<i>Manufacturing costs</i>	<i>10,735,882</i>
General and administrative expenses	358,111
Total operating costs	11,093,993

The Extraction Section contributes R1.79 of operating costs per litre of biodiesel produced. The Biodiesel Section contributes R1.72/L, while the Harvesting Section makes up the remainder of the operating cost with R0.77/L.

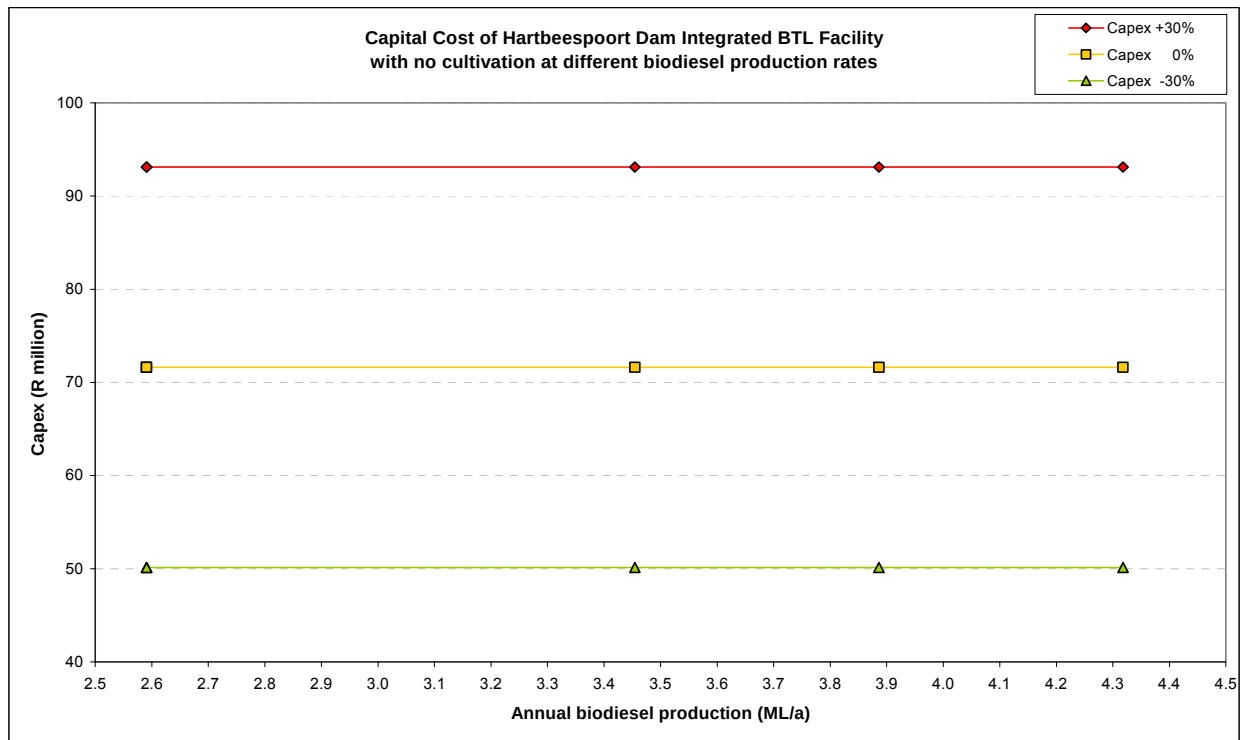


Figure 65: Capital cost of Hartbeespoort Dam integrated BTL facility with no cultivation at different biodiesel production rates.

Fig. 65 shows the capital cost estimates for the BTL facility with no cultivation at different biodiesel production rates. The biodiesel production rate is dependent on the micro-algal growth period, which varies from six to ten months of the year, according to Hambright and Zohary (2000). Although the biodiesel production rate varies, the capital cost remains constant as the stream-day design rate remains constant as the operating days increase with an increased growth period.

Figures 66 and 67 show the capital and operating cost estimates of BTL facilities next to the Hartbeespoort Dam at different micro-algal and resultant biodiesel production rates, comparing facilities with no cultivation systems to that of additional open and closed-cultivation facilities. BTL facilities with additional closed-cultivation infrastructure are 25% more expensive than those with additional open-cultivation facilities; and 365% more expensive than a BTL facility with no cultivation facility, except the existing Hartbeespoort Dam.

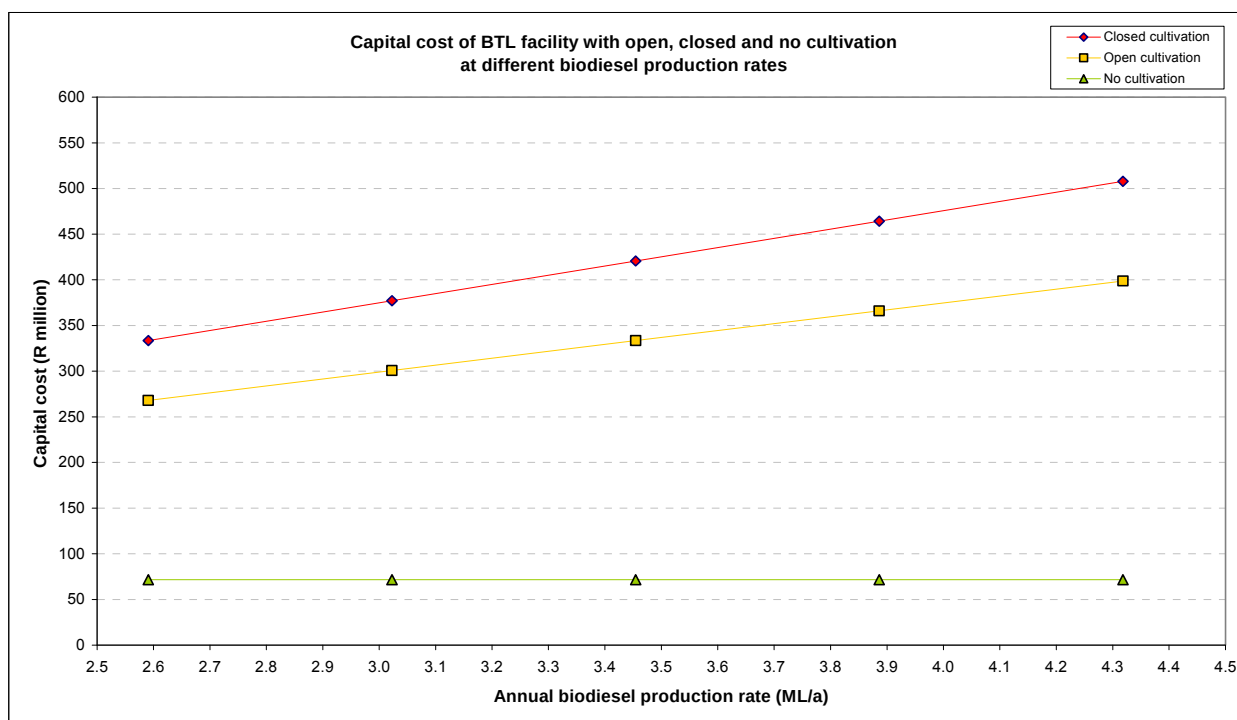


Figure 66: Capital cost of BTL facility with open, closed and no cultivation at different biodiesel production rates.

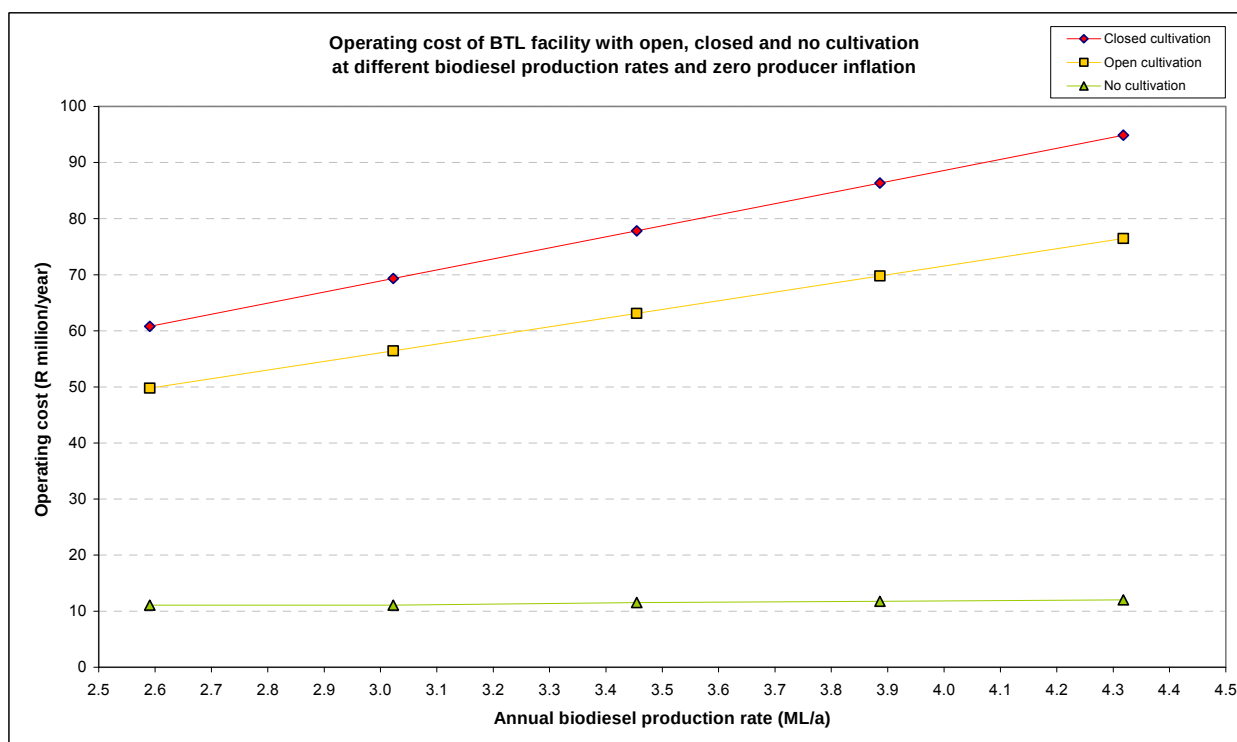


Figure 67: Operating cost of BTL facility with open, closed and no cultivation at different biodiesel production rates and zero producer inflation.

Figure 68 gives a cost breakdown of the capital and operating costs of the four sections making up the BTL facility with no cultivation to produce 2.6 megalitres a year of biodiesel at 0% producer inflation. The Extraction Section is the most expensive part, contributing 44% of the capital cost and 42% of the operating cost. The Biodiesel Section is the second most expensive part, adding 37% and 40% of the capital and operating costs, respectively. The Harvesting Section is the least expensive, contributing only 19% and 18% of the capital and operating costs, respectively.

Figure 69 gives a cost breakdown of the capital and operating costs of the eight processing units making up the BTL facility with no cultivation to produce 2.6 megalitres a year of biodiesel at 0% producer inflation. The most expensive part of the Extraction Section is the Extraction Unit 500, contributing 62% and 65% of the capital and operating costs, respectively. The remainder of the Extraction Section is made up by the Combustion Unit 700. The most expensive part of the Harvesting Section is the Drying Unit 600, making up 43% and 50% of the capital and operating costs, respectively. The second most expensive part of the Harvesting Section is the Filter Unit 400, which contributed 37% and 32% of the capital and operating costs, respectively. The remainder of the Filter Unit costs is made up by 20% and 18% of the capital and operating costs, respectively.

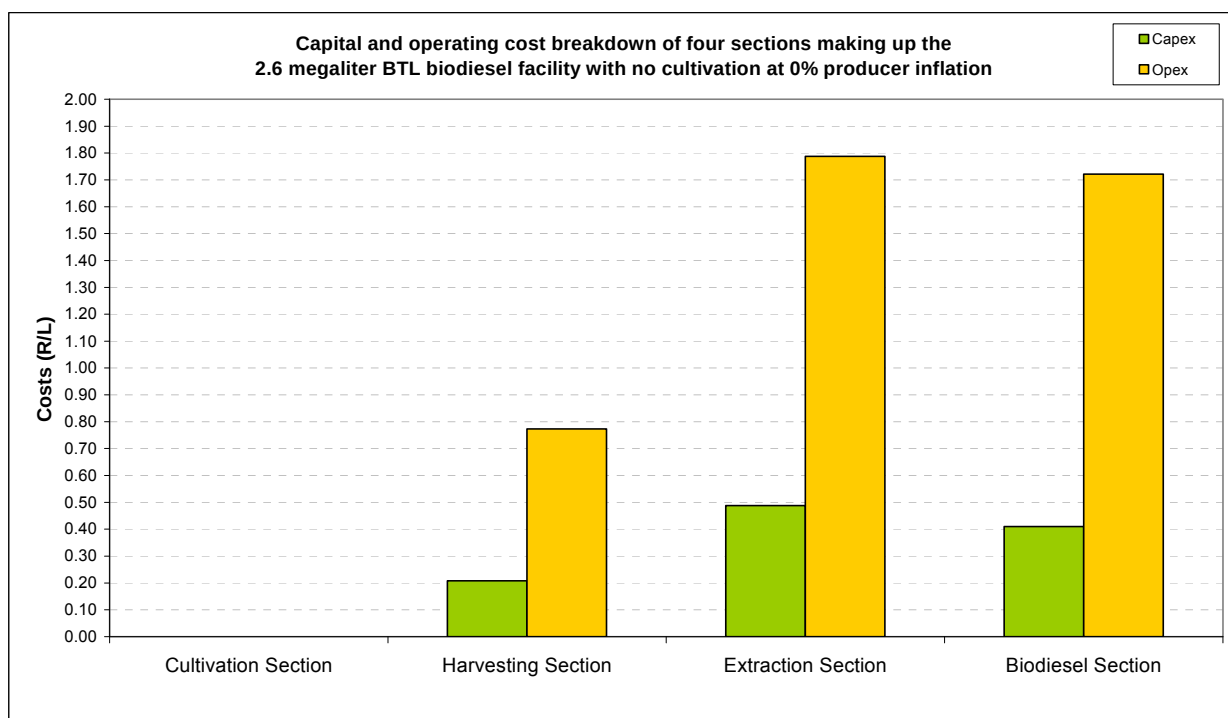


Figure 68: Capital and operating cost breakdown of four sections making up the 2.6 megalitre BTL biodiesel facility with no cultivation at 0% producer inflation.

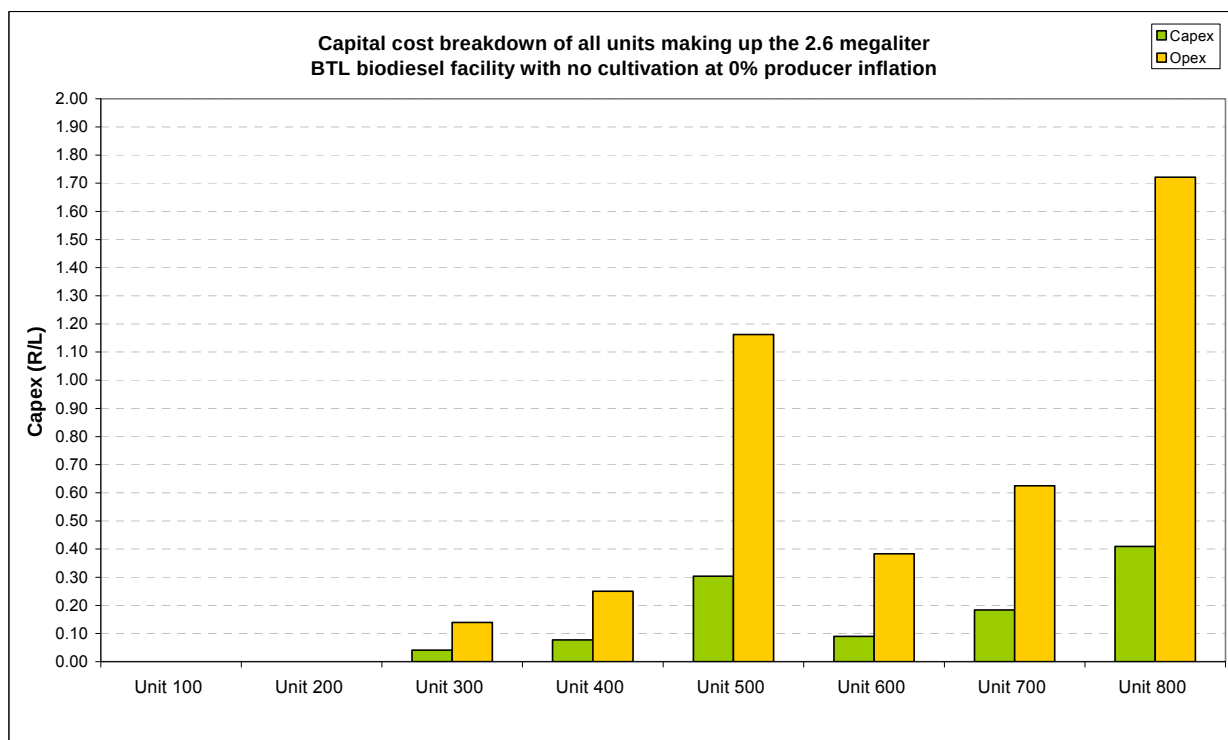


Figure 69: Capital and operating cost breakdown of all the units making up the 2.6 megalitre BTL biodiesel facility with no cultivation at 0% producer inflation.

SECTION FIVE



RESULTS & DISCUSSION

OF THE ECONOMIC EVALUATION

4.5 RESULTS AND DISCUSSION OF THE ECONOMIC EVALUATION

The economic evaluation of the reference case for an annual production of 2.6 megalitres of biodiesel per year, revealed that a minimum biodiesel price of R5.34/L will be required to ensure a zero net present value after 25 operating years at a discount rate of 0%, and a minimum biodiesel price of R7.92/L for a discount rate of 10%. The internal rate of return is 15.06% for the current biodiesel price of R10.00/L. A summary of the major economic criteria can be seen in Tables 21 and 22.

Table 21: Summary of economic criteria for reference case at 0% producer inflation and R10/L biodiesel price

Economic criteria:	R million	R/L
Capital cost	71.622	1.11
Revenue	25.91	10.00
Opex	11.094	4.28
Tax (30%)	4.444	1.72
Net profit	10.370	4.00
NPV at 0%	367.89	5.68
NPV at 10%	29.30	0.45

Table 22: Capital cost breakdown for reference case at 0% producer inflation

Capital costs:	R million	R/L	% of Capex
Pre-feasibility cost	0.072	0.001	0.1
Feasibility cost	0.143	0.002	0.2
FEED	0.573	0.009	0.8
EPC	60.091	0.928	83.9
Commissioning	10.743	0.166	15.0
Decommissioning	1.432	0.022	2.0

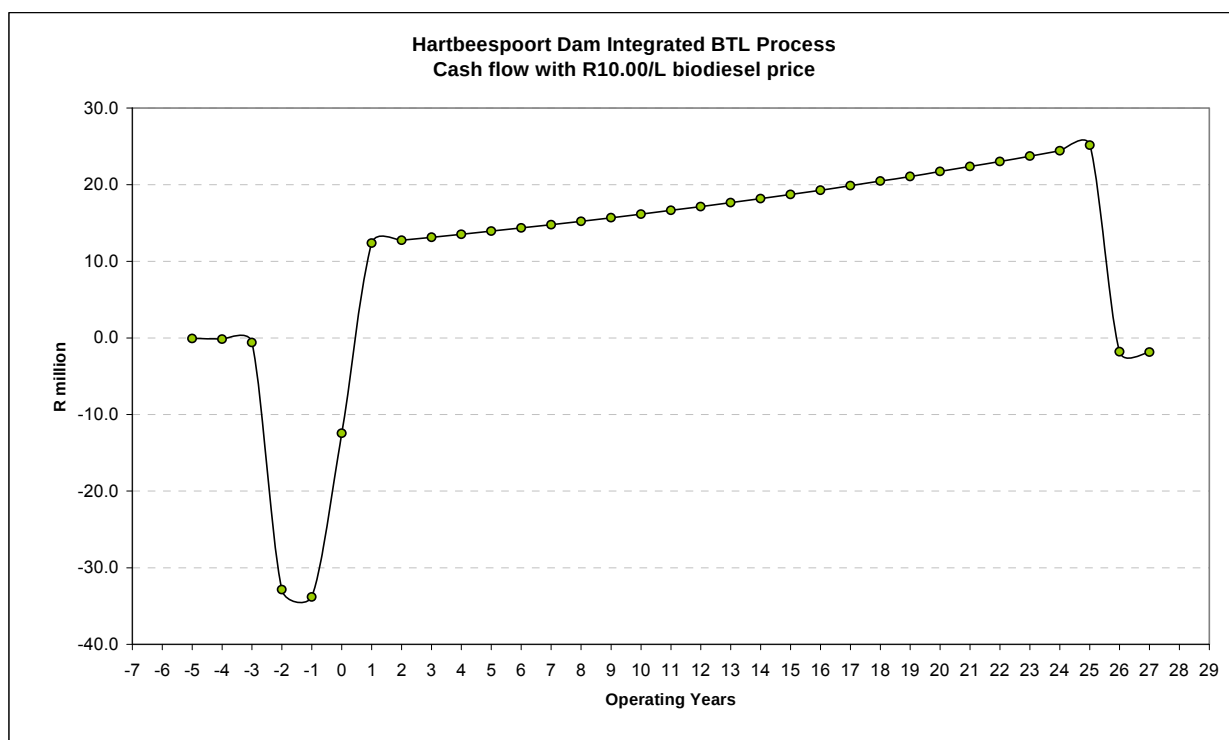


Figure 70: Cash flow of Hartbeespoort Dam BTL process at R10.00/L biodiesel price.

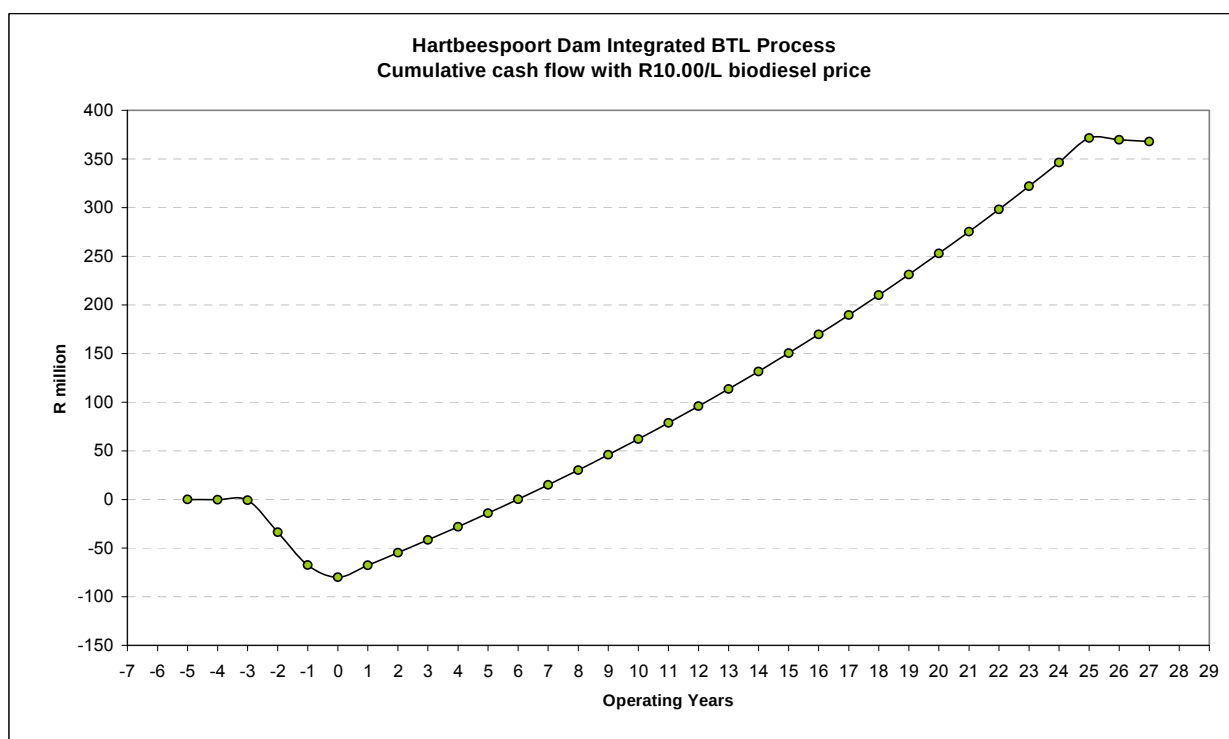


Figure 71: Cumulative cash flow of Hartbeespoort Dam BTL process at R10.00/L biodiesel price.

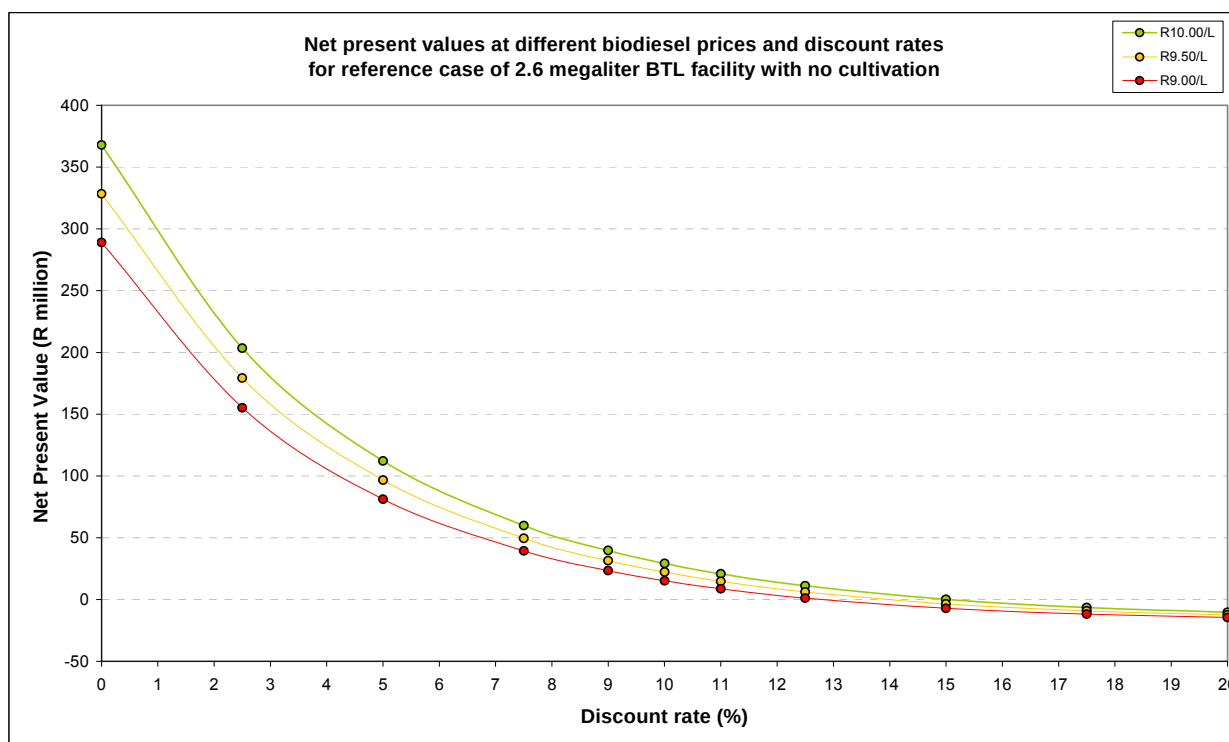


Figure 72: Net present value of Hartbeespoort Dam BTL process at different discount rates for the reference case of 2.6 megalitre BTL facility with no cultivation.

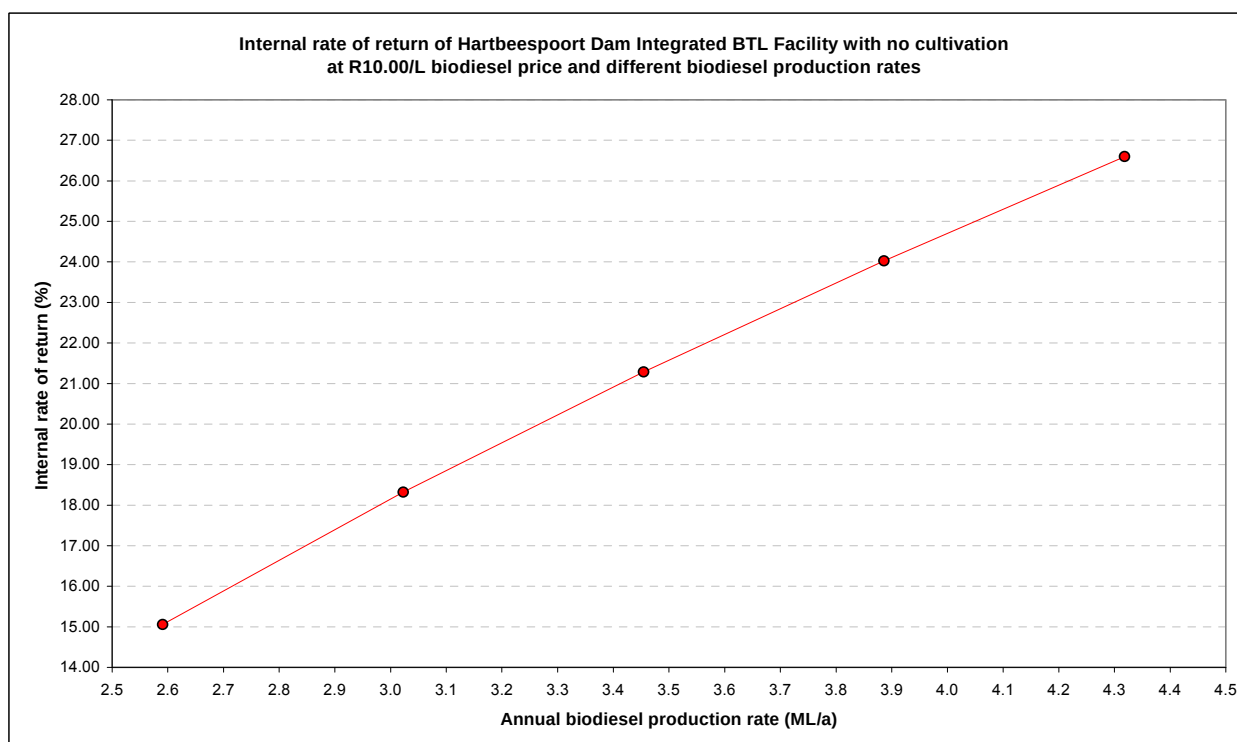


Figure 73: Internal rate of return of Hartbeespoort Dam integrated BTL facility with no cultivation at R10/L biodiesel price and different biodiesel production rates.

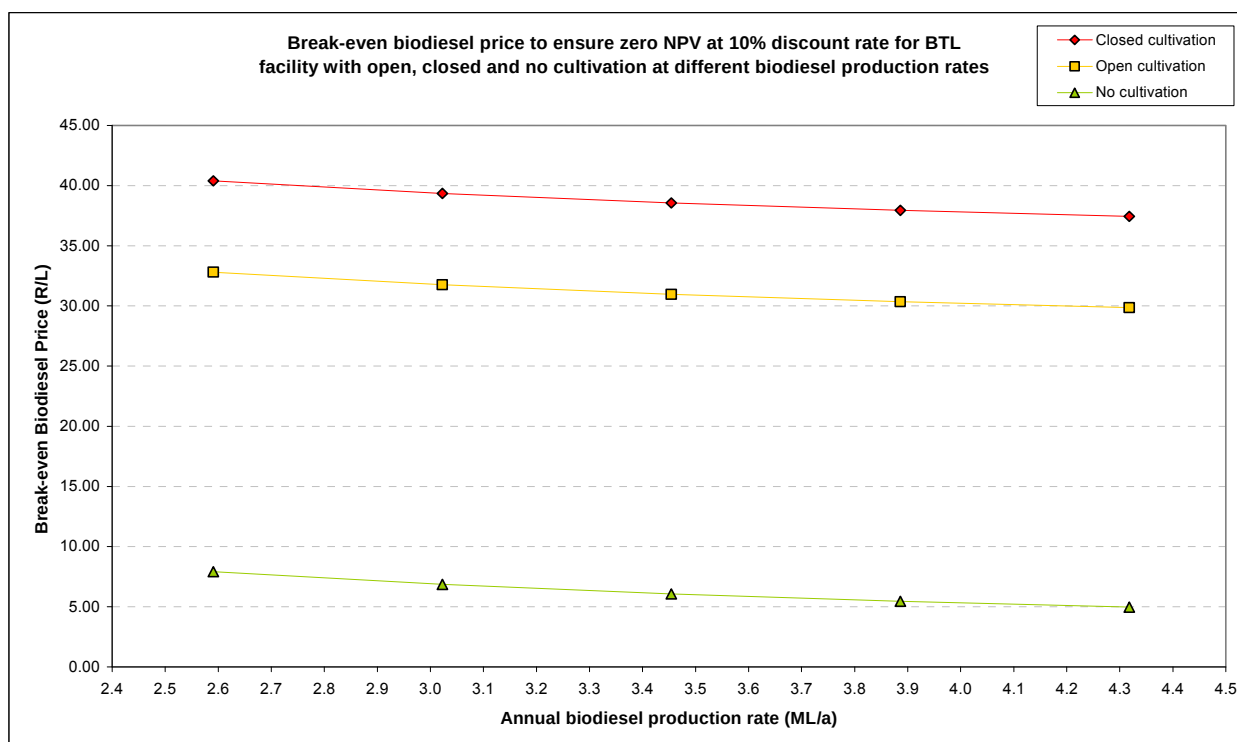


Figure 74: Break-even biodiesel price to ensure a zero NPV at 10% discount rate for BTL facility with open, closed and no cultivation at different production rates.

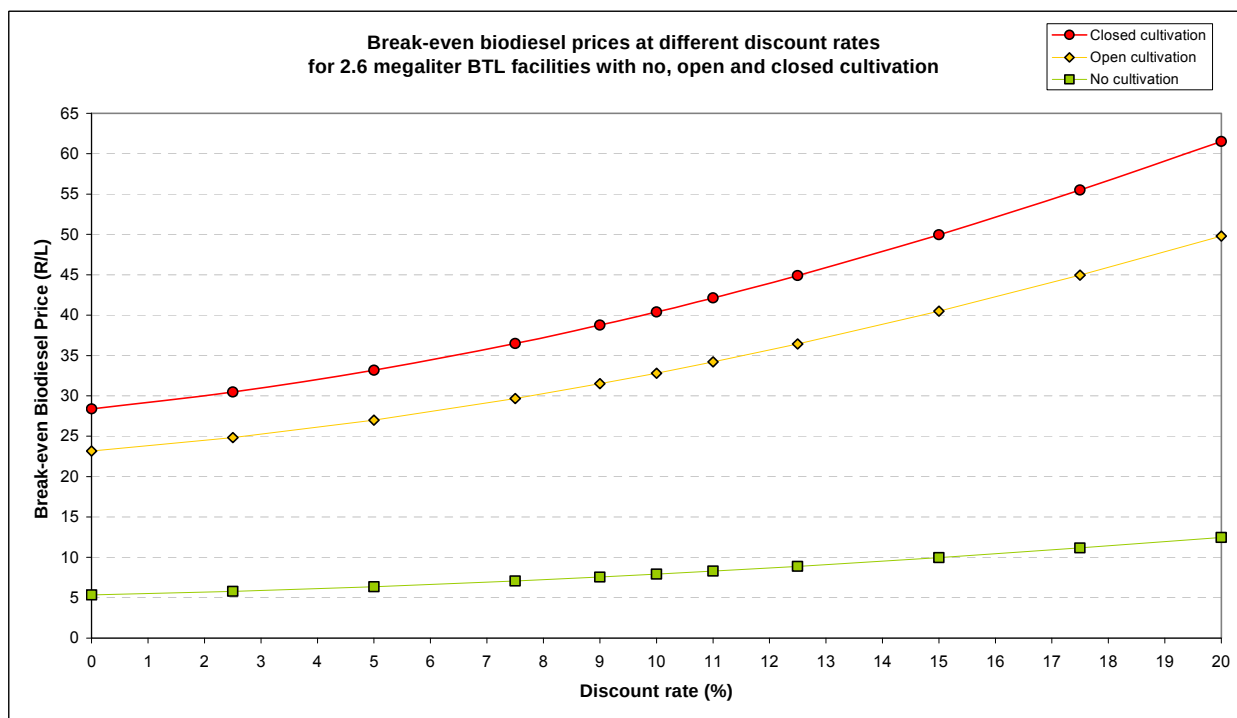


Figure 75: Break-even biodiesel prices at different discount rates for 2.6 megalitre BTL facilities with no, open and closed cultivation.

Hartbeespoort Dam BTL Process - Economic Evaluation of Reference Case																																			
Economic Evaluation	Yr	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	
Project Phase		Pre-Feas.	Feasibility	FEED	EPC	EPC	Commission	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Operation	Decomm.	Decomm.		
Production capacity	%	-	-	-	-	-	-	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	-	-
PPI	%	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	
PPI Escalation Factor	#	1.00	1.03	1.06	1.09	1.13	1.16	1.19	1.23	1.27	1.30	1.34	1.38	1.43	1.47	1.51	1.56	1.60	1.65	1.70	1.75	1.81	1.86	1.92	1.97	2.03	2.09	2.16	2.22	2.29	2.36	2.43	2.50	2.58	
Biodiesel Price	R/L	10.00	10.30	10.61	10.93	11.26	11.59	11.94	12.30	12.67	13.05	13.44	13.84	14.26	14.69	15.13	15.58	16.05	16.53	17.02	17.54	18.06	18.60	19.16	19.74	20.33	20.94	21.57	22.21	22.88	23.57	24.27	25.00	25.75	
Biodiesel Production	ML/y	-	-	-	-	-	-	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	2.59	-	-
Biodiesel Revenue	R'M	-	-	-	-	-	-	30.94	31.86	32.82	33.80	34.82	35.86	36.94	38.05	39.19	40.36	41.58	42.82	44.11	45.43	46.79	48.20	49.64	51.13	52.67	54.25	55.87	57.55	59.28	61.06	62.89	-	-	
Capex	R'M	0.07	0.15	0.61	32.83	33.82	12.45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Opex	R'M	-	-	-	-	-	-	13.25	13.64	14.05	14.48	14.91	15.36	15.82	16.29	16.78	17.28	17.80	18.34	18.89	19.45	20.04	20.64	21.26	21.89	22.55	23.23	23.93	24.64	25.38	26.14	26.93	-	-	
Decommissioning	R'M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.79	1.84		
Gross Profit	R'M	-	-	-	-	-	-	17.69	18.22	18.77	19.33	19.91	20.51	21.12	21.76	22.41	23.08	23.77	24.49	25.22	25.98	26.76	27.56	28.39	29.24	30.11	31.02	31.95	32.91	33.89	34.91	35.96	-	-	
Pre-Tax Cash Flow	R'M	(0.07)	(0.15)	(0.61)	(32.83)	(33.82)	(12.45)	17.69	18.22	18.77	19.33	19.91	20.51	21.12	21.76	22.41	23.08	23.77	24.49	25.22	25.98	26.76	27.56	28.39	29.24	30.11	31.02	31.95	32.91	33.89	34.91	35.96	(1.79)	(1.84)	
Tax (30%)	R'M	-	-	-	-	-	-	5.31	5.47	5.63	5.80	5.97	6.15	6.34	6.53	6.72	6.92	7.13	7.35	7.57	7.79	8.03	8.27	8.52	8.77	9.03	9.31	9.58	9.87	10.17	10.47	10.79	-	-	
Net Cash Flow (after tax)	R'M	(0.07)	(0.15)	(0.61)	(32.83)	(33.82)	(12.45)	12.38	12.75	13.14	13.53	13.94	14.35	14.79	15.23	15.69	16.16	16.64	17.14	17.65	18.18	18.73	19.29	19.87	20.47	21.08	21.71	22.36	23.04	23.73	24.44	25.17	(1.79)	(1.84)	
Cumulative Cash Flow	R'M	(0.07)	(0.22)	(0.83)	(33.66)	(67.48)	(79.93)	(67.55)	(54.79)	(41.66)	(28.13)	(14.19)	0.17	14.95	30.18	45.87	62.02	78.66	95.80	113.46	131.64	150.37	169.66	189.53	210.00	231.08	252.79	275.16	298.19	321.92	346.36	371.53	369.74	367.89	
Economic Criteria																																			
Capex	R'M	71.62																																	
Decommissioning	R'M	1.43																																	
Opex	R'M	11.09																																	
ROI	%	17.29																																	
IRR	%	15.06																																	
NPV @ 0.0%	R'M	367.89																																	
NPV @ 10.0%	R'M	29.30																																	
Payback Period	y	5.99																																	

Figure 76: Cash flow table with calculated economic criteria for reference case.

SECTION SIX



RESULTS & DISCUSSION

OF THE SENSITIVITY ANALYSIS

4.6 RESULTS AND DISCUSSION OF THE SENSITIVITY ANALYSIS

Results of the sensitivity analysis are summarized in Table 23. The most significant parameter, with the biggest impact on the overall economics of the new BTL facility is the growth period of the micro-algal biomass in the Hartbeespoort Dam. Since it is dependent on unpredictable climatic conditions, it can vary from six to ten months of the year. The reference case, however, is based on the most conservative case of six months of growth per year, which would make the project even more economic if growth conditions should increase. This parameter could change the economics of the new BTL facility with 18.93% (Fig. 77), should it vary with $\pm 10\%$. The revenues from the new BTL facility could increase by 67%, and the net present value (at 10% discount rate) could increase by 303% if the growth period of micro-algal biomass should increase by 67% from six to ten months of the year.

Table 23: Sensitivity analysis summary

Sensitivity Analysis		Break-even biodiesel price (R/L)		Difference (%)		Range
Parameter	Units	-10%	+10%	-10%	+10%	%
Months of micro-algal biomass growth	months	8.75	7.25	10.42	-8.51	18.93
Oil content of micro-algal biomass	%	8.64	7.33	9.08	-7.49	16.57
Operating cost	R/y	7.49	8.35	-5.41	5.41	10.81
Capital cost	R	7.56	8.28	-4.59	4.59	9.19
Discount rate	%	7.57	8.29	-4.45	4.71	9.16
Micro-algal biomass concentration in Dam	g/m ²	8.23	7.66	3.86	-3.25	7.12
Growth phase duration	d/φ	7.64	8.20	-3.58	3.48	7.06
Depreciation	%	7.68	8.16	-3.03	3.03	6.05
Rand-dollar exchange rate	R/\$	7.69	8.15	-2.91	2.91	5.81
Production price inflation (PPI)	%	7.88	7.96	-0.49	0.51	0.99
Decommissioning cost	R	7.92	7.92	-0.01	0.01	0.03

The oil content in the microalgae harvested from the Hartbeespoort Dam has the second biggest impact on the economics of the BTL facility. According to Piorreck *et al.* (1984), the lipid or oil content of the dominant micro-algal species in the Hartbeespoort Dam, *Microcystis aeruginosa*, can vary from 13.7 to 17.7%, depending on the growth conditions and nutrient concentrations present in the dam. Larger equipment sizes, with more capital and operating costs, will be

required to process additional raw biomass to extract the same amount of oils if the oil content is reduced, from the reference case's 15.6% oil content. The break-even biodiesel price will change by 16.57% for a $\pm 10\%$ change in the oil content in the microalgae.

Owing to the time-value of money, capital cost has the largest impact on the economics (NPV) of a project, and operating costs a much lower impact, because the costs are spread over time. However, owing to the relatively large operating costs associated with the various processing steps of the new integrated BTL process, operating cost has a bigger impact on the overall economics than the capital cost.

The fifth most significant parameter is the discount rate at which the net present value is based on. Should borrowing costs increase by 10%, this would result in the break-even biodiesel price increasing with 9%.

The microalgae concentration in the Hartbeespoort Dam varies widely, depending on climatic conditions, wind velocities and direction, and location in the Dam. As this concentration determines the feedstock abundance and availability, this factor has a huge impact on the new process. High concentrations reduce the size of equipment, while low concentrations increase the size and cost of harvesting equipment substantially.

Although the growth phase of the micro-algal biomass is the seventh most influential parameter, this should not vary significantly from literature studies. The depreciation rate has a medium impact on the economics of the BTL facility, as it increases the operating cost of the facility. Exchange rate has a low impact on the project's economics, since only few equipment items are imported, and linked to the exchange rate. The producer inflation rate has a small impact on the economics of the BTL facility. Decommissioning and rehabilitation costs at the end of the facility's life will have the least impact on its economics, as the costs are only spend at the end of the facility's life time.

Figure 77 compares the relative sensitivities of the major parameters influencing the economics of the new BTL facility. The logarithmic plot shows the percentage range of the break-even biodiesel prices, for a $\pm 10\%$ change in the individual parameters.

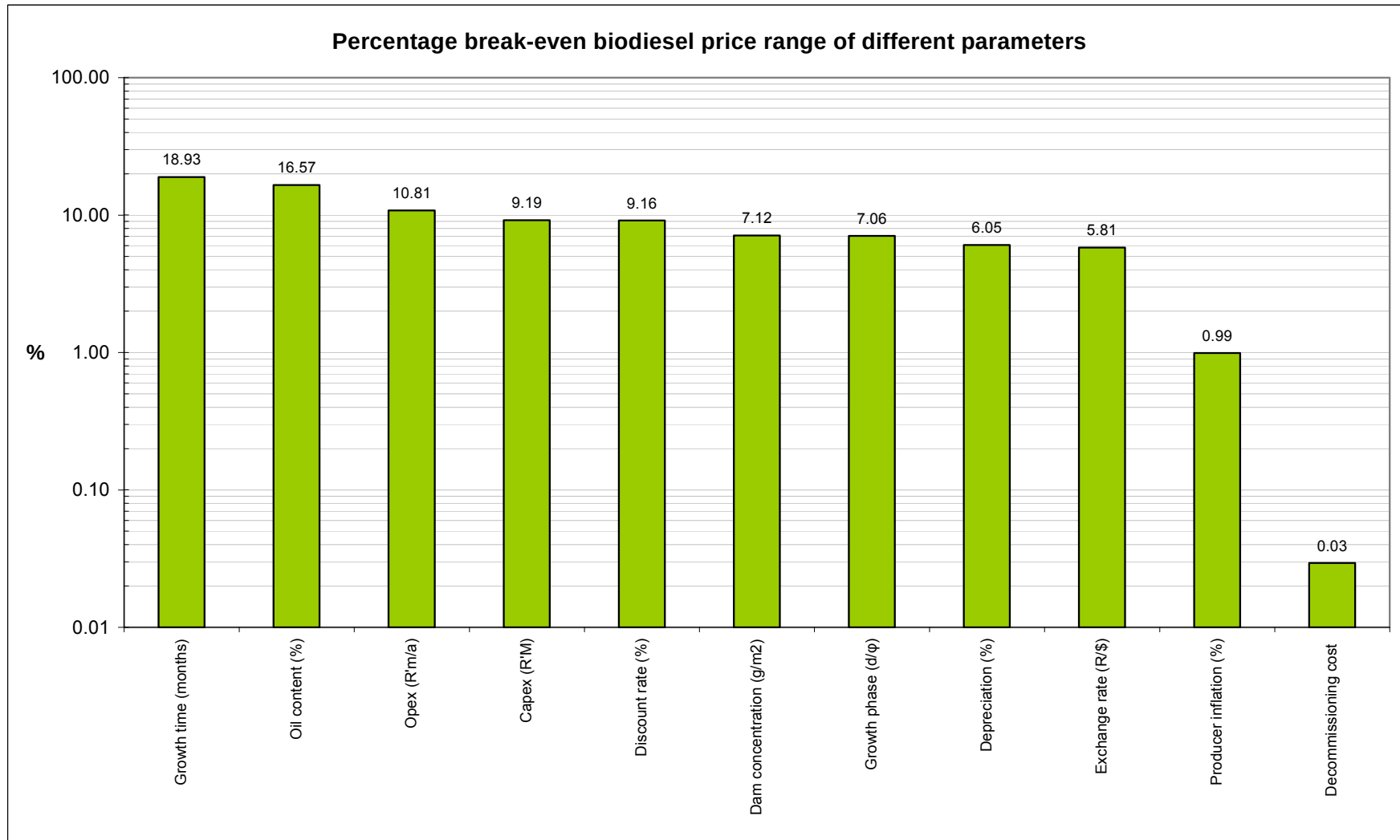


Figure 77: Sensitivity analysis summary of different percentage break-even biodiesel price ranges for different parameters.

SECTION SEVEN



RESULTS & DISCUSSION

OF THE FEASIBILITY STUDY

4.7 RESULTS AND DISCUSSION OF THE FEASIBILITY STUDY

Section Seven contains the results and discussion for the feasibility study criteria.

4.7.1. Economic feasibility

With annual revenues of R25.91 million at a diesel price of R10.00/L, and a capital cost of R71.62 million (R1.11/L) ($\pm 30\%$), the reference case of the new integrated BTL process is economically feasible with net present values (NPV) of R368 million (R5.68/L) and R29 million (R0.45/L) at discount rates of 0% and 10%, respectively. The cultivation of micro-algal biomass from the Hartbeespoort Dam is only economical if the growth is allowed to occur naturally in the Dam without any additional cultivation equipment. The cultivation of micro-algal biomass in either an open or a closed-cultivation system will not be feasible as the high cost of cultivation will negate the value of biodiesel derived from the cultivated biomass. The utilization of three unconventional harvesting methods described in this work is one of the main drivers for making this process economically feasible. At a capital cost of R13.49 million (R0.21/L) and a operating cost of R2.00 million per year (R1.16/L) for harvesting micro-algal biomass from the Hartbeespoort Dam, harvesting costs account for only 19% and 18% of the overall capital and operating costs of the new process, respectively. This is much less than harvesting costs for other comparative processes world-wide, which contribute between 20 and 30% of the overall cost of biomass-to-liquids production (Verma *et al.*, 2010).

4.7.2. Thermodynamic efficiency

The new process is thermodynamically viable, exporting 20 times more power than it imports, with a net power output of 5,483 kilowatts. The extraction and drying units (U-500 and U-600) are the most power-intensive units of the new process, each consuming 14,752 kW and 18,715 kW, respectively. The extraction unit requires 14,036 kW of heating, 491 kW of cooling, and

225 kW of electricity. Heating is supplied by hot flue gas from the dry micro-algal biomass combusted in the Furnace Unit (U-700). Cooling is supplied by excess water from the process, and electricity is supplied by external suppliers. The drying unit utilizes renewable solar power to dry the micro-algal biomass, while the extraction unit needs to import its power requirements from external electricity suppliers. Except for the electricity requirements needed for pumping and agitation in the Extraction Unit, and the irrigation pumps of the drying unit, all power required by the process to produce biodiesel from harvested micro-algal biomass from the Hartbeespoort Dam were supplied by renewable power sources.

The new integrated BTL process combines four renewable power sources to produce 2.6 ML of biodiesel per year. Wind power is utilized indirectly, as prevailing south-easterly winds concentrate micro-algal biomass against the dam wall of the Hartbeespoort Dam. The hydraulic head of 583 kPa of the 59.4 meter high dam is utilized for transportation of the biomass to the facility, which is located down-stream of the dam, and to supply the pressure for the biomass filter. Solar power is used to dry the microalgae, which in turn is combusted in a furnace to release its 18,715 kW of biochemical power, which is used for heating in the power-intensive extraction unit of the processing facility. Three unconventional harvesting methods, which utilize the natural buoyancy of Hartbeespoort Dam microalgae; gravity settling; and a combination of sand filtration and solar drying; to concentrate, dewater and dry the micro-algal biomass, were incorporated into the design to minimize the power required to harvest the micro-algal biomass sustainably and environmentally friendly.

4.7.3. Technical feasibility

Literature data and screening experiments have verified the laboratory-scale technical feasibility of all the processes making up the overall BTL process.

4.7.4. Strategic advantages

Currently there is no company in South Africa with the technology to harvest micro-algal biomass, extract oil and convert it into automotive-grade biodiesel economically and thermodynamically efficiently. The proposed process has the potential to be developed into a viable technology.

4.7.5. Marketing analysis

The harvesting and production facilities will be located next to the Hartbeespoort Dam, which lies in the Madibeng Municipality, with a population of over 420,000 people. Most of the agriculture practiced in this municipal district consists of intensive vegetable farming, which is done on approximately 180,000 hectares of irrigated land, using over 6 million litres of diesel annually. The proposed facilities will produce over 2.6 million litres of biodiesel per year, which is 43% of the existing diesel usage by farmers in the Madibeng Municipal district.

4.7.6. Socio-economic viability

The new process is socially responsible, as it will create 38 new permanent jobs, with a total of R1.33 million in annual salaries. The lowest paid non-skilled workers will receive twice the minimum wage in South Africa. The process will contribute R0.44 million a year in property taxes into the coffers of local government and R4.44 million per year in corporate taxes to the central government.

4.7.7. Energy security

The new process will increase the energy security of South Africa, by reducing its reliance on imported petroleum products, as it will produce 2.6 million litres of biodiesel annually, which is sufficient to supply 52,000 medium-size cars a year or 142 cars a day of fuel.

4.7.8. Environmental sustainability

The new process is environmentally friendly, as it removes micro-algal biomass pollution from the Dam, with resultant increases in biodiversity, and reduces the net amount of phosphates in the Dam, and recovers the said phosphates as fertilizer. Notwithstanding the socio-economic benefits, the new process would reduce the production of greenhouse gases by 21,996 tons of carbon dioxide per year, by substituting 2.6 ML/a of fossil fuel-based diesel, with carbon net-zero biodiesel.

4.7.9. Location

The new BTL process is ideally located next to its feedstock and utilities source, and strategically central to its major urban markets, and labour and support services.

4.7.10. Safety

The new process utilizes dangerous chemicals such as chloroform and sulfuric acid as solvent and catalyst, respectively. The extraction reactor and its associated equipment are operated at very high pressures, which increase the risk of leakages, fires and explosions.

4.7.11. Risks

4.7.11.1. Strengths

Strengths include the availability of free, untapped feedstock, renewable energy and abundant water. Further strengths include strategic location, which is close to available market, labour and support services.

4.7.11.2. Weaknesses

The harvesting and production facilities require approximately 23 hectares of land, which could be difficult and expensive to obtain, due to the intensive utilization of land around the Hartbeespoort Dam for residential development. Reliance on stable climatic conditions and constant supply of renewable solar energy, make this process vulnerable to meteorological instability. Growth of microalgae is dependent on warm climatic conditions, which occurs between 6 and 10 months of the year. Colder winter months cause a collapse in micro-algal populations, which results in minimal to no feedstock for the process for two to six months of the year, which increases the design rate and investment costs of the proposed processing facility.

4.7.11.3. Opportunities

The volatile oil market, which is projected to increase in future, makes the utilization of local energy sources more viable. Governments and non-profit organizations are becoming more vocal on carbon and greenhouse gas reductions, minimization of fossil fuels, and the promotion of renewable energy sources, like: wind, solar, hydro and biomass.

4.7.11.4. Threats

The biggest threats to this project are the successful commercialization of new unproven technologies, like the liquefaction extraction of oils from micro-algal biomass and the acid-catalyzed transesterification of these oils into biodiesel.

4.7.11.5. Critical success factors

Critical success factors include the acquisition of inexpensive land, and obtaining low-cost financing from development agencies like the Industrial Development Corporation (IDC) or the World Bank, who both support the development of renewable energy industries in developing countries. Another critical success factor is corporate tax rebates for renewable energy businesses, which would make them much more attractive for investors.

CHAPTER FIVE



CONCLUSIONS

& RECOMMENDATIONS

Advances are made by answering questions.

Discoveries are made by questioning answers.

Bernhard Haisch

5. CONCLUSIONS & RECOMMENDATIONS

Chapter Five contains the conclusions reached and the recommendations made from the study of cultivating and harvesting micro-algal biomass from the Hartbeespoort Dam for the production of biodiesel, in the context of an integrated biomass-to-liquids process.

SECTION ONE



CONCLUSIONS & RECOMMENDATIONS

FROM THE PROCESS IDENTIFICATION

5.1 CONCLUSIONS AND RECOMMENDATIONS FROM THE PROCESS IDENTIFICATION

5.1.1. Conclusions and recommendations from cultivation experiments

Three cultivation experiments revealed that the construction of a closed-cultivation system as part of an integrated biomass-to-liquids facility would not be feasible as the highest cultivation productivity (0.0862 g/L/d of dry weight micro-algal biomass) achieved under laboratory conditions was too low, requiring a cultivation surface area of 158 hectares, to produce the same amount of micro-algal biomass that the Hartbeespoort Dam is currently producing. The productivity need to be 495% higher at 0.4265 g/L/d, not to exceed the maximum cultivation surface area of 32 hectares, which will ensure a break-even net present value over 25 years of operation at a discount rate of 0%. The productivity will need to be 1562% higher at 1.3464 g/L/d, not to exceed the maximum cultivation area of 10 hectares, to ensure a zero NPV at a discount rate of 10%.

For a open-cultivation system, the productivity need to be 382% higher at 0.3297 g/L/d, not to exceed the maximum cultivation surface area of 41 hectares, which will ensure a break-even net present value over 25 years of operation at a discount rate of 0%. The productivity will need to be 1197% higher at 1.0319 g/L/d, not to exceed the maximum cultivation area of 13 hectares, to ensure a zero NPV at a discount rate of 10%.

For current productivities achieved under laboratory conditions, an open-cultivation system is only feasible if the infrastructure is already there, like the Hartbeespoort Dam. The Hartbeespoort Dam currently acts as a natural open-cultivation system, producing 160 g/m² of micro-algal biomass for six to ten months of the year (Hambricht and Zohary, 2000). This is sufficient to produce between 14 and 24 kilotons of dry micro-algal biomass, and 2.6 and 4.3 megalitres of biodiesel per year, without spending additional capital and operating costs to cultivate the micro-algal biomass feedstock. It is recommended that designers of new micro-algal

BTL biodiesel processes first try to capitalize on existing cultivation infrastructure, like dams, by connecting their processes to them. This will reduce the cost of a BTL process significantly.

The Hartbeespoort Dam, as an unlined open pond, has the potential to produce over 7 tons of dry micro-algal biomass per hectare per year, which is a little less than the 10-30 tons/ha/year yields cited by Rösch *et al.* (2009) for commercially operated open ponds, but much less than 60-100 tons/ha/year for closed-cultivation systems. Although the Hartbeespoort Dam has lower yields than artificial open and closed-cultivation systems, it still produces sufficient amounts of micro-algal biomass feedstock to ensure an economical BTL process.

5.1.2. Conclusions and recommendations from harvesting experiments

5.1.2.1. Conclusions from natural buoyancy separation experiments

Screening experiments to harvest micro-algal biomass from the Hartbeespoort Dam, by utilizing the tendency of colonial *M. aeruginosa* to float, revealed that it could be done practically and energy-efficiently. Results obtained suggest that primary separation equipment, like separation ponds or tanks, with a residence time of 3.5 hours would be sufficient to concentrate micro-algal biomass from 1.5% to 3% TSS. Additional residence time would not provide any substantial benefit with regards to TSS concentration, but would increase vessel capacity and cost unnecessarily.

5.1.2.2. Conclusions for sand filtration and solar drying experiments

Micro-algal biomass from the Hartbeespoort Dam was successfully harvested by sun-drying on beds of sand. This method holds great potential to reduce the energy consumption of drying biomass as it utilizes renewable solar energy and sand filtration to dry the algae. Larger scale studies could be performed to quantify the technical and energy efficiency of irrigating micro-algal biomass pulp, at different TSS concentrations, on sand surfaces, and allowing it to dry in the sun. A series of vapourization ponds could be employed in the same manner as salt production pans for such studies. The dried micro-algal biomass can then be harvested manually or mechanically. Figures 78 and 79 show examples of how such studies could be performed.



Figure 78: A patch of 4 m² of cleared soil containing a layer of Hartbeespoort Dam micro-algal biomass.

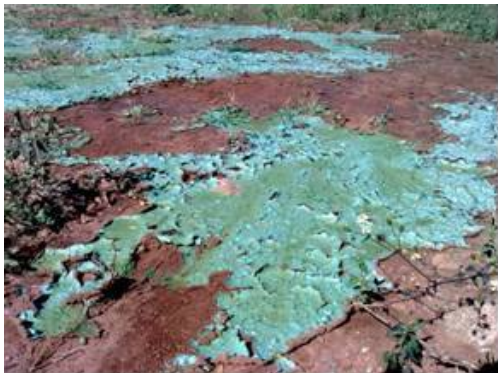


Figure 79: Sun-dried patch of micro-algal biomass from the Hartbeespoort Dam.

5.1.2.3. Conclusions for gravity settling harvesting

Cultivated micro-algal biomass sourced from the Hartbeespoort Dam can easily be harvested by allowing it to settle with gravity when aeration is stopped. Results showed that gravity settling equipment, with residence times of 24 hours, should be sufficient to accumulate over 90% of cultivated micro-algal biomass. Using this method for primary separation could reduce the total cost of harvesting equipment dramatically, by separating more than 90% of the cultivated micro-algal biomass from over 75% of the water medium with minimal energy input.

5.1.2.4. Conclusions from the harvesting experiments

The economic and energy-efficient harvesting of micro-algal biomass poses one of the greatest challenges for researchers in this field. This work describes and combines three promising methods to harvest micro-algal biomass from the Hartbeespoort Dam into an integrated biomass-to-liquids process. These methods increase harvesting efficiency through environmentally friendly, renewable energy sources, and increase the feasibility of a BTL process.

SECTION TWO



CONCLUSIONS & RECOMMENDATIONS

FROM THE PROCESS DEVELOPMENT

5.2 CONCLUSIONS AND RECOMMENDATIONS FROM THE PROCESS DEVELOPMENT

A new integrated biomass-to-liquids (BTL) conceptual process was developed to produce biodiesel from harvested micro-algal biomass from the Hartbeespoort Dam. A holistic approach was followed to incorporate and synergize all the resources available in and around the Hartbeespoort Dam. The new integrated BTL process combined four renewable power sources to produce 2.6 million litres of biodiesel per year. Wind power is utilized indirectly, as prevailing south-easterly winds concentrate micro-algal biomass against the dam wall of the Hartbeespoort Dam. The hydraulic head of 583 kPa of the 59.4 meter high dam wall is utilized to filter and transport micro-algal biomass to the rest of the BTL facility, down-stream of the dam. Solar power is used to dry the microalgae, which in turn is combusted in a furnace to release its 18,715 kW of biochemical power, which in turn is used for heating in the power-intensive extraction unit of the processing facility. Three promising harvesting methods, which utilize the natural buoyancy of Hartbeespoort Dam microalgae; a combination of sand filtration and solar drying; and gravity settling; to concentrate, dewater and dry the micro-algal biomass, were incorporated into the design to minimize the power required to harvest micro-algal biomass sustainably and environmentally friendly.

Most of the processes in literature that cover the production of biodiesel from micro-algal biomass, are not thermodynamically viable, as they all consume more power than what the overall process produce. The new process sets a benchmark for other related ones with regards to its net power efficiency. The new process is thermodynamically viable, exporting 20 times more power than it imports, with a net power output of 5,483 kilowatts. The extraction and drying units (U-500 and U-600) are the most power-intensive units of the new process, each consuming 14,752 kW and 18,715 kW, respectively. The extraction unit requires 14,036 kW of heating, 491 kW of cooling, and 225 kW of electricity. Heating is supplied by hot flue gas from the dry micro-algal biomass combusted in the Furnace Unit (U-700). Cooling is supplied by excess water from the process, and electricity is supplied by external suppliers. The Drying Unit utilizes renewable solar power to dry the micro-algal biomass, while the extraction unit needs to import

its power requirements from external electricity suppliers. The new process could be modified to generate its own electricity with solar panels, but with a substantial capital cost increase. Except for the electricity requirements needed for pumping and agitation in the Extraction Unit, and the irrigation pumps of the Drying Unit, all power required by the process to produce biodiesel from harvested micro-algal biomass from the Hartbeespoort Dam are supplied by renewable power sources.

SECTION THREE



CONCLUSIONS & RECOMMENDATIONS

FROM THE ENGINEERING DESIGN

5.3 CONCLUSIONS AND RECOMMENDATIONS FROM THE ENGINEERING DESIGN

Literature data and screening experiments have verified the small-scale, technical feasibility of all the processes making up the proposed BTL process. It is recommended that these batch, laboratory-scale experiments be scaled up and pilot plants be designed and build to test the technical feasibility of running these pilot plants at higher flow rates, continuously, and on an integrated basis. Optimization exercises should be performed on these pilot plants, and design parameters obtained and models developed, which could be used to scale up and develop larger semi-commercial pilot plants, on those pilot-plants showing promising results.

Each of the processes making up the BTL process, should be studied further to gather more detail and information which could change the feasibility of these processes. Since the liquefaction process is the most expensive part of the overall process, it should be studied further to find optimum process conditions which would reduce the capital and operating costs associated with it. An alternative is to find improved processes that could replace the extraction of micro-algal oils through liquefaction, completely.

SECTION FOUR



CONCLUSIONS & RECOMMENDATIONS

FROM THE COST ESTIMATION

5.4 CONCLUSIONS AND RECOMMENDATIONS FROM THE COST ESTIMATION

The results from the cost estimation exercise can be assumed to be fairly reliable, as approximately 75% of the purchased equipment cost was derived from actual equipment costs over a period of ten years in the cost estimation database of a major petrochemical company in South Africa. The remainder of the purchased equipment costs were estimated from equipment costs in literature. In order to increase the accuracy and resultant reliability of the cost estimation, vendors should be requested to provide budget quotes, or if possible, actual quotes, for equipment items. Engineering and construction companies could also be requested to supply budget quotes for complete engineering, procurement and construction of individual unit packages or quotes for the complete construction of the total BTL facilities. This will provide a more reliable picture of the costs involved in building a new BTL facility at the foot of the Hartbeespoort Dam.

The cost estimate for a closed-cultivation facility next to the Hartbeespoort Dam was 12% more than the cost estimate for a similar-sized photobioreactor complex in the USA (Lawson, 2010). The geographical factor could explain the higher cost estimate for a cultivation system in South Africa compared to one in the USA. Although labour costs are cheaper in South Africa compared to the USA, equipment costs are more expensive, due to South Africa's remote location, and high importation costs like custom levies.

At a capital cost of R13.49 million (R37.77/ton of dry weight micro-algal biomass) and a operating cost of R2 million per year (R210.63/ton) for harvesting micro-algal biomass from the Hartbeespoort Dam, harvesting costs account for only 19% and 18% of the overall capital and operating costs of the new process, respectively. This is less than harvesting costs for other comparative processes world-wide, which contribute between 20 and 30% of the overall cost of biomass-to-liquids production (Verma *et al.*, 2010). The combined lifecycle cost of producing micro-algal biomass is R249/ton (\$36/ton), which is significantly less than other comparable micro-algal biomass production processes world-wide, which produce micro-algal biomass at

around R21,000/ton (\$3000/ton). According to Chisti (2008), for any process to produce micro-algal biomass economically, it needs to be able to be competitive against petroleum-sourced fuels. Micro-algal biomass with an oil content of around 15% should be produced at a cost less than R1167/ton (\$167/ton), to be competitive against the current crude oil prices of \$100/bbl. The proposed micro-algal production process is significantly cheaper than the minimum cost required to be competitive against petroleum-sourced fuels. This is achieved by utilizing existing cultivation infrastructure, i.e. the Hartbeespoort Dam, which reduced the total cost of biomass production significantly.

Notwithstanding the relatively high operating cost of R5.78/L for the new BTL process, it is still less than the production cost of R19.60/L (\$2.80/L) to produce micro-algal oil from photobioreactors cited by Wen and Johnson (2009), and a little more than the minimum cost of R4.79/L (\$2.59/gal) of algal oil to be competitive against petroleum diesel at a crude oil price of \$100/bbl.

The cost estimate for the biodiesel unit compares well to similar-sized plants. According to Gonzales (2006) a 10,370 L/d biodiesel plant cost \$1.90 million in 2002. This equates to a capital cost of R24.43 million in South Africa in 2011. The cost estimated in this work for a biodiesel plant was R2 million or 9% more expensive compared to Gonzales' estimate. As mentioned previously, South Africa's remote location, adds a premium to imported equipment, due to high transportation costs and long delivery schedules.

SECTION FIVE



CONCLUSIONS & RECOMMENDATIONS

FROM THE ECONOMIC EVALUATION

5.5 CONCLUSIONS AND RECOMMENDATIONS FROM THE ECONOMIC EVALUATION

At a capital cost of R71.62 million (R1.11/L of biodiesel) ($\pm 30\%$) the newly proposed BTL facility will turn 933,525 tons of raw biomass (1.5% TSS) into 2.6 million litres of high quality biodiesel per year at an annual operating cost of R11.09 million (R4.28/L), to generate R25.91 million (R10.00/L) of revenue. At the current diesel price of R10.00/L the new integrated BTL process is economically feasible with net present values (NPV) of R368 million (R5.68/L) and R29 million (R0.45/L) at discount rates of 0% and 10%, respectively. The break-even biodiesel prices are R5.34/L and R7.92/L for a zero NPV at 0% and 10% discount rates, respectively. With ever-increasing oil prices, this process becomes more and more attractive.

The cultivation of micro-algal biomass from the Hartbeespoort Dam is only economical if the growth is allowed to occur naturally in the Dam without any additional cultivation equipment. The cultivation of micro-algal biomass in either an open or a closed-cultivation system will not be feasible as the high cost of cultivation will negate the value of biodiesel derived from the cultivated biomass. The utilization of the three promising harvesting methods described in this work is one of the main drivers for making this process economically feasible. At a capital cost of R13.49 million (R0.21/L) and a operating cost of R2.00 million per year (R1.16/L) for harvesting micro-algal biomass from the Hartbeespoort Dam, harvesting costs account for only 19% and 18% of the overall capital and operating costs of the new process, respectively. This is much less than harvesting costs for other comparative processes world-wide, which contribute between 20 and 30% of the overall cost of biomass-to-liquids production (Verma *et al.*, 2010).

This project has a great economical potential, even under severe economic conditions. At current economic conditions, such as 3% producer inflation, low lending rates, and a high diesel price of R10.00/L, the BTL process is economically very robust. The process has a very high net profit margin of 40%, which provides the project with a steady stream of cash flow, which is the life blood of any business. With an internal rate of return of over 15%, this project delivers 50% more returns, than the average borrowing rate in South Africa of 10%. This project also has a

relatively quick payback period of 6 years, making it a very attractive business for potential investors.

SECTION SIX



CONCLUSIONS & RECOMMENDATIONS

FROM THE SENSITIVITY ANALYSIS

5.6 CONCLUSIONS AND RECOMMENDATIONS FROM THE SENSITIVITY ANALYSIS

A sensitivity analysis revealed that the proposed BTL facility is economically very robust, and will remain economically viable, even with severe, negative changes in the parameters impacting the overall process. The parameter with the greatest impact on the sensitivity of the overall process economics is the growth period of the micro-algal biomass in the Hartbeespoort Dam. Although the growth period can vary from six to ten months of the year, the reference case was based on the most conservative case of six growth months, and the reference case remained economical, even at discount rates up to 10%. This BTL facility will remain economical even if the growth period dropped to 3 and 4.7 months at a discount rate of 0% and 10%, respectively.

The parameter with the second biggest impact on the economics of the BTL facility is the oil content in the microalgae harvested from the Hartbeespoort Dam. But even if the oil content in the microalgae from the Hartbeespoort Dam drops to a low of 7.4% or 11.8% at a discount rate of 0% and 10%, respectively, the BTL facility will remain economical.

Due to the wide processing range, which include solids and liquids handling, and the intensive nature of the oil extraction process, operating costs, which are 43% of the revenue, are relatively high for the overall process. Owing to this, any change in the operating costs has a big influence on the economics of the process, because of the relatively high operating costs associated with the new process. Notwithstanding the relatively high operating costs, the new BTL process will remain economical, even with a 109% or a 49% increase in the operating cost at a discount rate of 0% and 10%, respectively. The new BTL process will remain economical, even with a 440% or a 58% increase in the capital cost at a discount rate of 0% and 10%, respectively.

In South Africa the current borrowing rate remains below 10%. According to recent remarks by the governor of the South African Reserve Bank, the prime lending rate will remain stable for the foreseeable future, with a slight increase in the latter part of 2011. The strong performance of the rand over the past few years, has placed a damper on any inflation-related prime lending rate

increases. This process will remain economical, even if borrowing rates should increase by 50% to 15% and remain there for the duration of the BTL facility's life.

The microalgae concentration in the Hartbeespoort Dam varies widely, depending on climatic conditions, wind velocities and direction, and location in the Dam. As this concentration determines the feedstock abundance and availability, this factor has a huge impact on the new process. High concentrations reduce the size of equipment, while low concentrations increase the size and cost of harvesting equipment substantially. That said, this process will remain economical, even if the microalgae concentration in the Hartbeespoort Dam drops by 38.4% and 87.7% at a discount rate of 0% and 10%, respectively.

Although the growth phase of the micro-algal biomass is the seventh most influential parameter, this should not vary significantly from literature studies. However, even if it increases to 75 or 171 days per growth phase, compared to the 41 days in literature, this process will remain economical at a discount rate of 0% and 10%, respectively.

The process will remain economical even if the exchange rate weakens to R30.83/\$ or R13.32/\$, at a discount rate of 0% and 10%, respectively, or if the depreciation rate increased to 29.4% or 18.7%, at a discount rate of 0% and 10%, respectively. Decommissioning costs has a small impact on the economics of the BTL facility. Even if it increases to 204% of the capital cost, the project will remain economical.

SECTION SEVEN



CONCLUSIONS & RECOMMENDATIONS

FROM THE FEASIBILITY STUDY

5.7 CONCLUSIONS AND RECOMMENDATIONS FROM THE FEASIBILITY STUDY

Section Seven summarizes the conclusions and recommendations of the main criteria of the feasibility study.

5.7.1. Economic feasibility

At a capital cost of R71.62 million (R1.11/L) ($\pm 30\%$) the newly proposed BTL facility will turn 933,525 tons of raw biomass (1.5% TSS) into 2.6 million litres of high quality biodiesel per year at an annual operating cost of R11.09 million (R4.28/L), to generate R25.91 million (R10.00/L) of revenue. At the current diesel price of R10.00/L the new integrated BTL process is economically feasible with net present values (NPV) of R368 million (R5.68/L) and R29 million (R0.45/L) at discount rates of 0% and 10%, respectively. The break-even biodiesel prices are R5.34/L and R7.92/L for a zero NPV at 0% and 10% discount rates, respectively. With ever-increasing oil prices, this process becomes more and more attractive.

The cultivation of micro-algal biomass from the Hartbeespoort Dam is only economical if the growth is allowed to occur naturally in the Dam without any additional cultivation equipment. The cultivation of micro-algal biomass in either an open or a closed-cultivation system will not be feasible as the high cost of cultivation will negate the value of biodiesel derived from the cultivated biomass. The utilization of three promising harvesting methods described in this work is one of the main drivers for making this process economically feasible. At a capital cost of R13.49 million (R0.21/L) and a operating cost of R2.00 million per year (R1.16/L) for harvesting micro-algal biomass from the Hartbeespoort Dam, harvesting costs account for only 19% and 18% of the overall capital and operating costs of the new process, respectively. This is much less than harvesting costs for other comparative processes world-wide, which contribute between 20 and 30% of the overall cost of biomass-to-liquids production (Verma *et al.*, 2010).

5.7.2. Thermodynamic efficiency

Most of the processes in literature that cover the production of biodiesel from micro-algal biomass are not thermodynamically viable, because they consume more power than what they produce. The new process sets a benchmark for other related ones with regards to its net power efficiency. The new process is thermodynamically viable, exporting 20 times more power than it imports, with a net power output of 5,483 kilowatts. The extraction and drying units (U-500 and U-600) are the most power-intensive units of the new process, each consuming 14,752 kW and 18,715 kW, respectively. The extraction unit requires 14,036 kW of heating, 491 kW of cooling, and 225 kW of electricity. Heating is supplied by hot flue gas from the dry micro-algal biomass combusted in the Furnace Unit (U-700). Cooling is supplied by excess water from the process, and electricity is supplied by external suppliers. The Drying Unit utilizes renewable solar power to dry the micro-algal biomass, while the extraction unit needs to import its power requirements from external electricity suppliers. The new process could be modified to generate its own electricity with solar panels, but with a substantial capital cost increase. Except for the electricity requirements needed for pumping and agitation in the Extraction Unit, and the irrigation pumps of the Drying Unit, all power required by the process to produce biodiesel from harvested micro-algal biomass from the Hartbeespoort Dam were supplied by renewable power sources.

The new integrated BTL process combined four renewable power sources to produce 2.6 ML of biodiesel per year. Wind power is utilized indirectly, as prevailing south-easterly winds concentrate micro-algal biomass against the dam wall of the Hartbeespoort Dam. The hydraulic head of 583 kPa of the 59.4 meter high dam is utilized for transportation of the biomass to the facility, which is located down-stream of the dam, and to supply the pressure for the biomass filter. Solar power is used to dry the microalgae, which in turn is combusted in a furnace to release its 18,715 kW of biochemical power, which is used for heating in the power-intensive extraction unit of the processing facility. Three promising harvesting methods, which utilize the natural buoyancy of Hartbeespoort Dam microalgae; gravity settling; and a combination of sand filtration and solar drying; to concentrate, dewater and dry the micro-algal biomass, were incorporated into the design to minimize the power required to harvest the micro-algal biomass sustainably and environmentally friendly.

5.7.3. Technical feasibility

Literature data and screening experiments have verified the laboratory-scale technical feasibility of all the processes making up the overall BTL process. It is recommended that the laboratory experiments be scaled up to pilot plants to test the technical feasibility at higher flow rates, on a sustained basis. All batch processes described in the thesis should be turned into continuous processes to test their sustainability. Each of the stages discussed in this work should be studied further to gather more detail and information which could change the feasibility of this process. Since the liquefaction process is the most expensive part of the overall process, it should be studied further to find optimum process conditions which would reduce the capital and operating costs associated with it. An alternative is to find improved processes, like single-step extraction-transesterification of wet micro-algal biomass, which could replace liquefaction oil extraction completely.

5.7.4. Strategic advantages

Currently there is no company in South Africa with the technology to harvest micro-algal biomass, extract oil and convert it into automotive-grade biodiesel economically and thermodynamically efficiently. The proposed process has the potential to be developed into a viable technology, which could be aligned with the economic and environmental goals of the South African government. These goals include the utilization of renewable energy sources and the creation of jobs in the energy sector. The process is attractive enough to be commercialized with the help of government and non-governmental organizations like the Industrial Development Corporation (IDC), the commercialization and development arm of the South African Department of Trade & Industry, or the World Bank, with the support of the Department of Water Affairs and Forestry and the Department of Environmental Affairs and Tourism.

5.7.5. Marketing analysis and strategy

5.7.5.1. Market Analysis

The harvesting and production facilities will be located next to the Hartbeespoort Dam, which lies in the Madibeng Municipality, with a population of over 420,000 people. Most of the agriculture practiced in this municipal district consists of intensive vegetable farming, which is done on approximately 180,000 hectares of irrigated land, using over 6 million litres of diesel annually. The proposed facilities will produce over 2.6 million litres of biodiesel per year, which is 43% of the existing diesel usage by farmers in the Madibeng Municipal district.

5.7.5.2. Marketing Strategy

In order to enter the market and gain initial market share, by selling the biodiesel at an initial discount of R9.50 per litre in the first year at the pump through existing retailers, which is 5% less than market price, the supply area will be kept to a minimum to reduce transportation costs which can off-set the said discount. Biodiesel will be supplied wholesale at R9.00 per litre (R4.72 more than the break-even price) for the first year to service stations and agricultural cooperations in and around the Hartbeespoort Dam area, in a 60 km radius around the production plant situated on the banks of the Dam. Important supply centres include Hartbeespoort, Mooiooi, Magaliesburg, Krugersdorp, Roodepoort, Brits and Pretoria. The retail and wholesale prices will be linked to the international price of Brent crude, allowing for a 5% retail discount, and a 5% or 50 cent per litre profit margin for wholesalers.

The supply area consists of numerous crop farms, and due to their intensive farming techniques, require large volumes of liquid fuel to run their agricultural vehicles. In order to simplify the supply chain, biodiesel can be supplied to a handful of fueling stations and agricultural cooperations. By focusing on only a few agricultural service centres, target marketing could be done, which would reduce the overall cost of marketing from 5% to 2% of the total operating cost. This equates to an annual marketing cost of around R222,000 per year.

5.7.6. Socio-economic viability

The new process is socially responsible, as it will create 38 new permanent jobs, with a total of R1.33 million in annual salaries. The lowest paid non-skilled workers will receive twice the minimum wage in South Africa. The process will contribute R0.44 million a year in property taxes into the coffers of local government and R4.44 million per year in corporate taxes to the central government.

5.7.7. Energy security

The new process will increase the energy security of South Africa, by reducing its reliance on imported petroleum products, as it will produce 2.6 million litres of biodiesel annually, which is sufficient to supply 52,000 medium-size cars a year or 142 cars a day of fuel.

5.7.8. Environmental sustainability

The new process is environmentally friendly, as it removes micro-algal biomass pollution from the Dam, with resultant increases in biodiversity, and reduces the net amount of phosphates in the Dam, and recovers the said phosphates as fertilizer. Notwithstanding the socio-economic benefits, the new process would reduce the production of greenhouse gases by 21,996 tons of carbon dioxide per year, by substituting 2.6 ML/a of fossil-fuel-based diesel, with carbon net-zero biodiesel.

5.7.9. Location

The new BTL process is ideally located next to its feedstock and utilities source, and strategically central to its major urban markets, and labour and support services.

5.7.10. Safety

The new process utilizes dangerous chemicals such as chloroform and sulphuric acid as solvent and catalyst, respectively. It is recommended that further research be done to minimize or eliminate these chemicals from the process. Except for the extraction reactor and associated equipment, which is operated at high pressures, the rest of the plant is operated at low or near atmospheric conditions, which reduces the risk of leakages, fires and explosions. It is

recommended that further research be conducted to reduce the operating pressure of the extraction unit, or to eliminate the liquefaction process completely.

5.7.11. Risks

5.7.11.1. Strengths

Strengths include the availability of free, untapped feedstock, renewable energy and abundant water. Further strengths include strategic location, which is close to available market, labour and support services.

5.7.11.2. Weaknesses

The harvesting and production facilities require approximately 23 hectares of land, which could be difficult and expensive to obtain, due to the intensive utilization of land around the Hartbeespoort Dam for residential development. Reliance on stable climatic conditions and constant supply of renewable solar energy, make this process vulnerable to meteorological instability. Growth of microalgae is dependent on warm climatic conditions, which occurs between 6 and 10 months of the year. Colder winter months cause a collapse in micro-algal populations, which results in minimal to no feedstock for the process for two to six months of the year, which increases the design rate and investment costs of the proposed processing facility. In the absence of south-easterly winds to blow and concentrate micro-algal biomass against the dam wall of the Hartbeespoort Dam, barges could be used to collect floating micro-algal biomass and transport it to the dam wall zone. An alternative solution is to open the sluices of the dam wall, to drain the Hartbeespoort Dam, and force micro-algal blooms to migrate to the dam wall zone.

5.7.11.3. Opportunities

The volatile oil market, which is projected to increase in future, makes the utilization of local energy sources more viable. Governments and non-profit organizations are becoming more vocal on carbon and greenhouse gas reductions, minimization of fossil fuels, and the promotion of renewable energy sources, like: wind, solar, hydro and biomass.

5.7.11.4. Threats

The biggest threat to this project is the successful commercialization of new unproven technologies, like the liquefaction extraction of oils from micro-algal biomass and the acid-catalyzed transesterification of these oils into biodiesel.

5.7.11.5. Critical success factors

Critical success factors include the acquisition of inexpensive land, and obtaining low-cost financing from development agencies like the Industrial Development Corporation (IDC) or the World Bank, who both support the development of renewable energy industries in developing countries. Another critical success factor is corporate tax rebates for renewable energy businesses, which would make them much more attractive for investors.

5.7.12. Overall feasibility

Overall the new process, especially the unconventional harvesting methods described in this work, promises many advantages over existing processes: its simplicity of design and operation which enables the usage of low skilled-labour; utilization of renewable energy and feedstock sources, which reduces the environmental footprint and improves the sustainability of the process. The new process has great potential and looks attractive enough for further studies. It is recommended that a thorough investigation be done on patent and legal restriction which may hamper or restrict the development and implementation of the new process. The construction of facilities, to harvest and produce biodiesel from micro-algal biomass in the Hartbeespoort Dam, could be done practically with significant environmental and socio-economic benefits.

5.7.13. Alternative scenarios

Instead of selling the biodiesel wholesale to fuel stations and agricultural cooperations, a dedicated fuel station could be build on site which could sell biodiesel in bulk at retail (especially to farmers), which would add another 50 cents per litre or R1.30 million to the annual turnover. However, this scenario would result in an additional R5 million in capital expenditure to erect a new retail fueling station.

SECTION EIGHT



CONCLUSIONS & RECOMMENDATIONS

FROM THE OVERALL STUDY

5.8 CONCLUSIONS AND RECOMMENDATIONS FROM THE OVERALL WORK

5.8.1. Final conclusions

This work identified improved and novel methods for the cultivation and harvesting of micro-algal biomass from the Hartbeespoort Dam and incorporated them into a new integrated conceptual biomass-to-liquids process. This research found that microalgae from the Hartbeespoort Dam could not be cultivated economically in artificial cultivation systems, but found that micro-algal biomass could be harvested viably from the existing Hartbeespoort Dam on a small scale. It was concluded that utilizing renewable energy sources in and around the Hartbeespoort Dam, such as wind, hydro, solar and biomass, have the potential to improve the feasibility of harvesting microalgae from the Dam, if combined into an integrated process. It was found that natural buoyancy separation, drum filtration, gravity settling, sand and solar filtration were the most suitable methods for the harvesting of micro-algal biomass from the Hartbeespoort Dam. All four of these methods utilized the physical properties of colonial micro-algal biomass from the Hartbeespoort Dam, such as size, concentration and buoyancy, to optimize the harvesting process. Barnard (2009) found that oils could be extracted efficiently from Hartbeespoort Dam microalgae and Miao and Wu (2005) found that automotive-grade biodiesel could be produced from micro-algal oil. In conclusion, it is the serendipitous combination of freely available feedstock, renewable energy sources, central location of the Hartbeespoort Dam, and the optimal integration of novel harvesting methods and the application of the latest research into micro-algal oil extraction and conversion into biodiesel, which makes the new proposed BTL process feasible and attractive.

5.8.2. Final recommendations

Although it was concluded that the new integrated BTL process was conceptually feasible, and that all its constituent sub-processes were practical on a small scale, these sub-processes need to be scaled-up to determine the constraints of scaling up. Future research should also study the

practicality and assess the economic feasibility of combining the individual sub-processes into an integrated pilot plant.

THESIS



APPENDICES

& ATTACHMENTS

It is a capital mistake to theorize before one has data.

Arthur Conan Doyle (1859-1930)

APPENDICES & ATTACHMENTS

The Appendices contains the article that was presented at the Pittsburgh Coal Conference in 2010, as well as all the data for the six screening experiments.

APPENDIX A



ARTICLE 1

REDUCING GHG EMISSIONS FROM COAL COMBUSTION BY ADDING MICRO-ALGAL BIOMASS

2010 International Pittsburgh Coal Conference
Istanbul, Turkey
October 11–14, 2010

PROGRAM TOPIC:
ENERGY SUSTAINABILITY – EFFICIENCY AND CONVERSION TO REDUCE GHG

REDUCING GREENHOUSE GAS EMISSIONS FROM COAL COMBUSTION BY ADDING MICRO-ALGAL BIOMASS

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Abstract

Each year millions of tons of greenhouse gases are released during combustion of coal in coal-fired power plants. Supplementing the coal feedstock to these power plants with micro-algal biomass, could maintain energy production, while decreasing the net contribution of greenhouse gases to the atmosphere, with resultant improvements to the environment. The research project compared the calorific value and the elemental composition of low-grade Highveld coal, one of the major coal types mined in South Africa and one of the main types used for power generation in South Africa, against two sources of micro-algal biomass. One of the sources of micro-algal biomass was the dominant species in the Hartbeespoort Dam (37 km west of Pretoria, South Africa), *Microcystis aeruginosa*, which was harvested directly from dam. The second source of micro-algal biomass, *Cyclotella meneghiniana*, was cultivated in 5-litre Erlenmeyer bioreactors, using a modified growth medium. The low-grade Highveld coal had a calorific value of 21.65 MJ/kg, and a carbon, hydrogen, nitrogen and sulfur content of 56.06, 2.33, 1.51 and 0.78 mass %, respectively. In comparison, micro-algal biomass from the Hartbeespoort Dam had almost a similar calorific value of 21.02 MJ/kg compared to the low-grade coal's; and a carbon, hydrogen, nitrogen and sulfur content of 42.00, 6.75, 8.87 and 0.72 mass %, respectively. The cultivated micro-algal biomass, *Cyclotella meneghiniana*, had a lower calorific value of 17.30 MJ/kg; and a

carbon, hydrogen, nitrogen and sulfur content of 38.80, 6.49, 6.41, 0.33 mass %, respectively. Supplementing coal feedstock to coal-fired power plants with micro-algal biomass holds great potential for minimizing the net production of greenhouse gases.

Keywords: Highveld coal; Hartbeespoort Dam; Micro-algal biomass; Calorific value; Greenhouse gases

1. Introduction

According to the Energy Information Administration's *International Energy Outlook 2010 (IEO2010)*, global energy demand is projected to increase by 49 percent in the next 25 years. Total world energy use is projected to rise from 495 quadrillion British thermal units (Btu) in 2007 to 590 quadrillion Btu in 2020 and 739 quadrillion Btu in 2035. In the absence of national policies and binding international agreements that would limit or reduce greenhouse gas emissions, world coal consumption is projected to increase by 56 percent from 132 quadrillion Btu in 2007 to 206 quadrillion Btu in 2035, at an average annual rate of 1.6 percent. Coal's share of world energy consumption is expected to grow from 27 percent in 2007 to 28 percent in 2035. World energy-related carbon dioxide emissions are expected to grow from 29.7 billion metric tons in 2007 to 33.8 billion metric tons in 2020 and 42.4 billion metric tons in 2035. Coal's share of world carbon dioxide emissions, which grew from 39 percent in 1990 to 42 percent in 2007, is projected to increase to almost 46 percent by 2035. Coal is the most carbon-intensive of the fossil fuels, and it is the fastest growing carbon-emitting energy source (EIA, 2010).

Growing concern over the impact of global warming on the environment, and the increased usage of fossil fuels worldwide, which is regarded as one of its prime contributors, are forcing governments and corporations to look into alternatives for fossil fuels, like coal. Of these alternatives, biomass is one of the fastest growing renewable energy sources. Among the many sources of biomass, like wood and terrestrial crops, microalgae promise the highest yield per kilogram of biomass and also have much faster growth-rates than terrestrial crops (Chisti, 2008), making them one of the most promising supplements for fossil fuels like coal. One of the largest reservoirs of micro-algal biomass in South Africa is the Hartbeespoort Dam, located 37 km west of Pretoria, and covering a surface area of approximately 20 km². The Hartbeespoort Dam has great potential for micro-algal biomass production and beneficiation due to its size and close proximity to urban and industrial centres.



Figure 80: Hartbeespoort Dam

2. Objective of study

The research project compared the calorific value and elemental compositions of low-grade Highveld coal against two sources of micro-algal biomass, in order to evaluate their potential for supplementing coal feedstock to coal-fired power plants.

3. Theory

Coal currently provides 73% of South Africa's primary energy and 95% of the country's electricity is derived from coal-fired thermal generation. Coal in South Africa is found in 19 coalfields, located mainly in KwaZulu-Natal, Mpumalanga, Limpopo, and the Free State provinces. The Minerals Bureau estimates the total coal reserves in South Africa at 33.8 billion tons, and projects it to last until around 2050. The Highveld Coalfield is the second most productive coalfield in South Africa with ten operating collieries. In 2001, it accounted for about 73.65 million tons (24.92 %) of the total run-of-mine production. Low-grade Highveld coal consists of bituminous coal with an ash content of 20–35% and a calorific value of 18–25 MJ/kg (Jeffrey, 2005).

Microalgae, like all other biomass sources, are renewable energy sources, and do not contribute to the net emission of greenhouse gases, as they absorb the constituents of their biomass directly from the environment. The dominant micro-organism species in the Hartbeespoort Dam is the cyanobacterium *Microcystis aeruginosa*, which comprises over 90% of the total micro-organism biomass in the dam. Excessive growth of these micro-organisms are stimulated by the influx of large quantities of nitrates and phosphates into the dam, from the run-off of fertilized agricultural land and effluent from sewage plants from the northern suburbs of Johannesburg (Owuor *et al.*, 2007).

4. Experimental

4.1. Hartbeespoort Dam

4.1.1. Culture organisms

Samples of *Microcystis aeruginosa* biomass were collected from the Hartbeespoort Dam in 500 mL litre plastic bottles (see Fig. 81).



Figure 81: Micro-algal biomass on the banks of the Hartbeespoort Dam.

4.1.2. Harvesting procedure

The contents of the 500 mL plastic bottles were allowed to settle for one day (see Fig. 82). The bottom water layer was drained with a tube and the remaining top layer of concentrated micro-algal biomass pulp (wet weight micro-algal biomass) was poured onto metal palettes with a layer of approximately 500 g of building sand with a voidage of 40%. The palettes were then placed on top of the laboratory roof of the North-West University's School of Chemical and Minerals Engineering, and allowed to dry for 24 hours.



Figure 82: Concentrated micro-algal biomass pulp separating to the top after 24 hours.



Figure 83: Micro-algal biomass from the Hartbeespoort Dam drying in the sun on top of a base of building sand, located on top of the roof of the laboratory at the North-West University at Potchefstroom.



Figure 84: Sun-dried palette of micro-algal biomass from the Hartbeespoort Dam on top of a base of building sand, located on top of the roof of the laboratory at the North-West University at Potchefstroom.



Figure 85: Sand-filtered, sun-dried Hartbeespoort Dam micro-algal biomass flakes.

Small samples of dried micro-algal biomass flakes were sent to the SEM Laboratory at the School of Chemical and Minerals Engineering, for electron microscopy. Figures 86 and 87 show sun-dried micro-algal biomass from the Hartbeespoort Dam on scales of 20 and 2 microns, respectively.

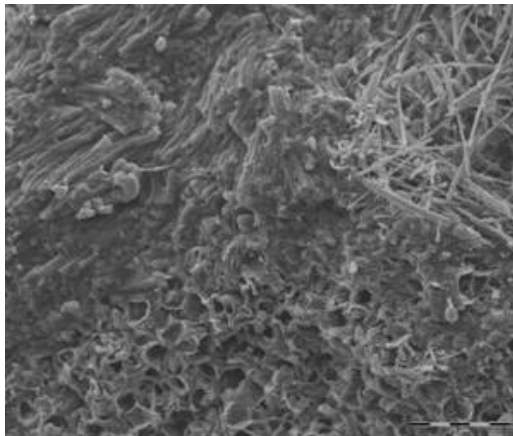


Figure 86: Shows a microphotograph of sun-dried Hartbeespoort Dam micro-algal biomass at 20 microns (SEM Laboratory, 2009).

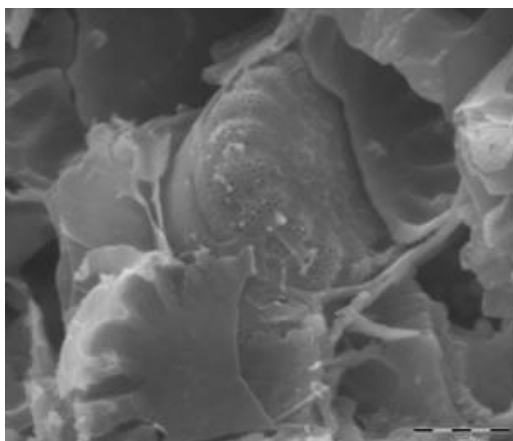


Figure 87: Shows a microphotograph of sun-dried Hartbeespoort Dam micro-algal biomass at 2 microns (SEM Laboratory, 2009).

4.2. *Cyclotella meneghiniana*

4.2.1. Culture organisms

Cultures of *Cyclotella meneghiniana* were obtained from the Botany Department of the North-West University.

4.2.2. Culture medium

For the cultivation of *C. meneghiniana*, a growth medium was prepared according to the modified recipe set out by Krüger & Eloff (1977).

4.2.3. Culturing procedure

Erlenmeyer flasks were used to cultivate *C. meneghiniana* algae. The flasks were filled to 4000 mL with growth medium prepared according to the above-mentioned recipe. A pipette was used to inoculate each 4-litre growth medium with 10 mL of *C. meneghiniana*. Continuous aeration was provided with air pumps. The cultures were kept indoors, but exposed to a 12 hour light and 12 hour night cycle.



Figure 88: Cultivation of *Cyclotella meneghiniana* in 5-L Erlenmeyer flasks.

4.2.4. Harvesting procedure

After six weeks of cultivation, the entire content of each Erlenmeyer flask were filtered through 0.7 μm glass microfibre filter paper and the biomass placed in an oven to dry for an hour at 110°C.

4.3. Harvesting micro-algal biomass from the Hartbeespoort Dam

The practicality of harvesting micro-algal biomass from the Hartbeespoort Dam was demonstrated with a small scale experiment (Fig. 89 and 90). Forty litres of micro-algal biomass were collected from the dam and poured onto a patch of 4 m² of cleared soil and allowed to dry for seven days. The dried micro-algal flakes were then collected manually.



Figure 89: A 4 m² patch of cleared soil containing a layer of wet Hartbeespoort Dam micro-algal biomass.



Figure 90: Sun-dried patch of micro-algal biomass from the Hartbeespoort Dam, on its bank at Kosmos.

4.4. Calorific value measurement

The calorific value of the coal and the two micro-algal biomass samples were measured with a CAL2k bomb calorimeter.

4.5. Elementary analysis

The elementary analysis of the coal and the two micro-algal biomass samples were performed with a Leco 2000 CHN analyzer for the carbon, hydrogen and nitrogen analysis and a Leco SC-432 analyzer for the sulfur.

5. Results and discussion

Harvesting of micro-algal biomass from the Hartbeespoort Dam could be performed relatively easily, utilizing renewable solar energy for drying. A combination of sand filtration and solar drying yielded 15.3 g/L of dry weight micro-algal biomass per litre of dam water or 157.6 g/m² of sun-drying area, respectively. The small-scale experiment demonstrated the potential of harvesting micro-algal biomass from the Hartbeespoort Dam energy-efficiently. Table 24 compares the analysis of low-grade Highveld coal to cultivated *Cyclotella meneghiniana* and harvested micro-algal biomass from the Hartbeespoort Dam.

Table 24: Elementary and calorific analysis of coal and two micro-algal biomass samples

Content	Units	Coal	CM	HMB
C	% (wt.)	56.06	38.80	42.00
H	% (wt.)	2.33	6.49	6.75
N	% (wt.)	1.51	6.41	8.87
S	% (wt.)	0.78	0.33	0.72
CV	MJ/kg	21.65	17.30	21.02

The carbon content of the two biomass samples are more than 25% lower than the coal sample's, while the hydrogen and nitrogen contents of the biomass samples, are thrice and four to six times that of the coal sample's, respectively. The sulfur content of the cultivated *C. meneghiniana* is half the coal sample's, while the biomass harvested from the Hartbeespoort Dam had almost similar sulfur content than the coal sample. The calorific value of the cultivated *C. meneghiniana* was 20% lower than the coal sample's, while the calorific value of the Hartbeespoort Dam micro-algal biomass was almost the same as the coal sample's, making the latter a suitable supplement for low-grade coal feedstock for coal-fired power generation.

6. Conclusions

Analysis of two micro-algal biomass samples revealed that harvested micro-algal biomass from the Hartbeespoort Dam had a relatively similar calorific value than low-grade Highveld coal. Supplementing this low-grade coal feedstock in coal-fired power plants with harvested micro-algal biomass from the Hartbeespoort Dam could maintain energy production, while reducing the net emission of greenhouse gases.

Nomenclature

CM	<i>Cyclotella meneghiniana</i>
CV	Calorific value
HMB	Hartbeespoort Dam micro-algal biomass

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APPENDIX B



DATA

FOR CULTIVATING HARTBEESPOORT DAM MICROALGAE IN 1-LITRE BIOREACTORS

APPENDIX B – DATA FOR CULTIVATING MICROALGAE IN 1-L BIOREACTORS

Table 25: Data for cultivating Hartbeespoort Dam microalgae in 1-litre bioreactors after 3 weeks of cultivation

Time	Temp	FLTL	FLTL*	FLTH	FLTH*	FHTL	FHTL*	FHTH	FHTH*
9:00	°C	20.0	20.0	21.0	21.0	20.0	20.0	21.0	21.0
10:00	°C	20.5	20.5	22.0	22.0	20.5	20.5	22.0	22.0
11:00	°C	21.0	21.0	24.0	24.0	21.0	21.0	24.0	24.0
12:00	°C	22.0	22.0	24.5	24.5	22.0	22.0	24.5	24.5
13:00	°C	22.0	22.0	25.0	25.0	22.0	22.0	25.0	25.0
14:00	°C	22.0	22.0	25.0	25.0	22.0	22.0	25.0	25.0
15:00	°C	22.0	22.0	25.0	25.0	22.0	22.0	25.0	25.0
16:00	°C	22.0	22.0	25.0	25.0	22.0	22.0	25.0	25.0
17:00	°C	22.0	22.0	25.0	25.0	22.0	22.0	25.0	25.0
18:00	°C	22.0	22.0	24.0	24.0	22.0	22.0	24.0	24.0
Average bioreactor	°C	21.6	21.6	24.1	24.1	21.6	21.6	24.1	24.1
Air flow rate	L/h	3.6	3.6	3.6	3.6	72.0	72.0	72.0	72.0
Filter paper weight	g	0.7286	0.8873	0.7226	0.8835	0.7250	0.8810	0.7204	0.7228
Filter paper & dry biomass wt.	g	0.8707	0.9719	0.9480	1.0089	1.3730	1.2987	1.6844	1.5958

APPENDIX C



DATA

FOR CULTIVATING HARTBEESPOORT DAM MICROALGAE IN 5-LITRE BIOREACTORS

APPENDIX C – DATA FOR CULTIVATING MICROALGAE IN 5-L BIOREACTORS

Table 26: Data for cultivating Hartbeespoort Dam microalgae in 5-litre bioreactors after two weeks of cultivation

Time	Temp	B1	B2	B3	B4	B5	B6	B7	B8
8:00	°C	13.0	12.0	15.0	14.0	13.5	14.0	14.0	14.0
9:00	°C	15.0	13.5	16.0	16.0	15.0	16.0	14.0	14.0
10:00	°C	18.0	16.0	19.0	21.0	20.0	21.0	17.0	14.0
11:00	°C	19.0	19.0	21.0	24.0	23.0	24.0	19.0	15.0
12:00	°C	22.0	23.0	23.0	27.0	26.0	27.0	22.0	15.0
13:00	°C	26.0	27.0	23.5	31.0	31.0	31.0	24.0	15.0
14:00	°C	33.0	30.0	25.0	31.0	32.0	33.0	25.0	16.0
15:00	°C	30.0	32.0	25.0	31.0	33.0	34.0	26.0	16.0
16:00	°C	30.0	33.0	25.0	30.0	33.0	34.0	25.0	16.0
17:00	°C	29.0	32.0	25.0	29.0	31.0	32.0	25.0	17.0
18:00	°C	26.0	28.0	24.0	27.0	29.0	30.0	23.0	17.0
Average bioreactor temperature	°C	23.7	24.1	22.0	25.5	26.0	26.9	21.3	16.0
Air flow rate	L/min	0.7	1.5	0.7	0.7	0.4	1.0	1.0	0.7
Filter paper weight	g	0.5516	0.5748	0.5386	0.5300	0.5591	0.5445	0.5433	0.5460
Filter paper weight	g	0.5800	0.6164	0.5720	0.5335	0.5673	0.5500	0.5230	0.5410
Filter paper weight	g	0.5870	0.6253	0.5590	0.5440	0.5713	0.5569	0.5580	0.5480
Filter paper & dry biomass wt.	g	0.5571	0.5901	0.5460	0.5310	0.5674	0.5553	0.5542	0.5466
Filter paper & dry biomass wt.	g	0.5870	0.6266	0.5810	0.5419	0.5713	0.5520	0.5330	0.5440
Filter paper & dry biomass wt.	g	0.5950	0.6360	0.5720	0.5520	0.5747	0.5620	0.5690	0.5500

Table 27: Data for cultivating Hartbeespoort Dam microalgae in 5-litre bioreactors after four weeks of cultivation

Time	Temp	B1	B2	B3	B4	B5	B6	B7	B8
8:00	°C	19.5	19.0	20.5	20.0	20.0	20.0	21.0	18.5
9:00	°C	21.0	20.0	22.0	22.0	22.0	21.5	21.0	19.0
10:00	°C	23.0	23.0	24.0	27.0	26.0	26.0	23.0	19.5
11:00	°C	24.0	25.0	25.0	29.0	28.0	29.0	23.0	20.0
12:00	°C	25.0	28.0	25.0	31.0	31.0	32.0	25.0	21.0
13:00	°C	25.0	31.0	26.0	34.0	33.0	33.0	25.0	21.0
14:00	°C	26.0	32.0	26.0	34.0	34.0	34.0	25.0	22.0
15:00	°C	27.0	32.0	26.0	33.0	33.0	35.0	26.0	22.0
16:00	°C	27.0	32.0	26.0	32.0	32.0	34.0	26.0	22.0
17:00	°C	26.0	28.0	26.0	31.0	31.0	32.0	28.0	22.0
18:00	°C	24.4	27.0	24.7	29.3	29.0	29.7	24.3	20.7
Average bioreactor temperature	°C	19.5	19.0	20.5	20.0	20.0	20.0	21.0	18.5
Air flow rate	L/min	0.7	1.5	0.7	0.7	0.4	1.0	1.0	0.7
Filter paper weight	g	0.5915	0.5524	0.5355	0.5817	0.5780	0.5285	0.5437	0.5337
Filter paper weight	g	0.6066	0.6341	0.5887	0.6133	0.5574	0.5624	0.5868	0.5491
Filter paper weight	g	0.6783	0.7309	0.6302	0.5372	0.5405	0.5732	0.5600	0.5525
Filter paper & dry biomass wt.	g	0.6017	0.5663	0.5467	0.5924	0.5836	0.5380	0.5546	0.5391
Filter paper & dry biomass wt.	g	0.6152	0.6582	0.6012	0.6195	0.5666	0.5797	0.5984	0.5508
Filter paper & dry biomass wt.	g	0.6899	0.7483	0.6390	0.5418	0.5452	0.5877	0.5699	0.5559

Table 28: Data for cultivating Hartbeespoort Dam microalgae in 5-litre bioreactors after six weeks of cultivation

Time	Temp	B1	B2	B3	B4	B5	B6	B7	B8
8:00	°C	16.0	15.0	18.0	17.0	16.0	17.0	17.0	16.0
9:00	°C	17.0	16.0	18.0	18.0	18.0	18.0	17.0	16.0
10:00	°C	20.0	18.0	21.0	22.0	22.0	22.0	20.0	18.0
11:00	°C	21.0	21.0	24.0	26.0	25.0	20.0	22.0	18.0
12:00	°C	25.0	25.0	25.0	29.0	30.0	30.0	25.0	18.0
13:00	°C	28.0	29.0	26.0	32.0	32.0	32.0	27.0	18.0
14:00	°C	32.0	32.0	28.0	34.0	35.0	36.0	30.0	18.0
15:00	°C	34.0	35.0	29.0	33.0	36.0	37.0	30.0	18.0
16:00	°C	33.0	36.0	28.0	33.0	35.0	37.0	29.0	19.0
17:00	°C	32.0	35.0	28.0	32.0	34.0	36.0	28.0	19.0
18:00	°C	29.0	32.0	26.0	30.0	31.0	33.0	27.0	19.0
Average bioreactor temperature	°C	26.1	26.7	24.6	27.8	28.5	28.9	24.7	17.9
Air flow rate	L/min	0.7	1.5	0.7	0.7	0.4	1.0	1.0	0.7
First two litres of bioreactor									
Filter paper weight	g	1.1141	0.7265	0.7291	0.7296	0.7279	0.7273	0.7251	1.0533
Filter paper & dry biomass wt.	g	5.0469	0.9010	0.7537	3.6124	0.8804	0.8350	3.3681	1.0609
Filter paper weight	g	0.7255	0.7211			0.7274	1.0677	0.7261	0.7153
Filter paper & dry biomass wt.	g	1.1386	0.9538			0.8544	1.0997	3.1043	0.7480
Filter paper weight	g		0.7215			1.0856			
Filter paper & dry biomass wt.	g		0.8650			2.8886			
Filter paper weight	g					0.7283			
Filter paper & dry biomass wt.	g					1.9038			
Third litre of bioreactor									
Filter paper weight	g		0.7245	1.0947			0.7314		0.7215
Filter paper & dry biomass wt.	g		0.9483	1.1057			0.9373		0.7932
Filter paper weight	g			0.7281					
Filter paper & dry biomass wt.	g			0.7674					
Last litre of bioreactor									
Filter paper weight	g		0.7118	1.0726			0.7258		0.7254
Filter paper & dry biomass wt.	g		2.0833	6.0353			4.2086		1.7472
Filter paper weight	g		0.7158	0.7251			0.7278		
Filter paper & dry biomass wt.	g		1.1163	0.8292			1.5945		
Filter paper weight	g		0.7227				0.7270		
Filter paper & dry biomass wt.	g		6.5565				1.2993		
Filter paper weight	g						0.7262		
Filter paper & dry biomass wt.	g						1.8835		

APPENDIX D



DATA

FOR CULTIVATING HARTBESPOORT DAM MICROALGAE IN 135-LITRE BIOREACTOR

APPENDIX D – DATA FOR CULTIVATING MICROALGAE IN 135-L BIOREACTOR

Table 29: Data for cultivating Hartbeespoort Dam microalgae in 135-litre bioreactor

	Units	Week 0	Week 2	Week 4	Week 6
Filter paper weight	g	0.0000	4.3410	4.6764	5.4680
Filter paper & dry biomass wt.	g	0.0000	4.6724	5.5631	6.2679

APPENDIX E



DATA

FOR HARVESTING MICROALGAE THROUGH NATURAL BUOYANCY SEPARATION

APPENDIX E – DATA FOR HARVESTING MICROALGAE THROUGH NATURAL BUOYANCY SEPARATION

Table 30: Data for harvesting microalgae through natural buoyancy separation

Time	Column A		Column B		Column C	
in	Green Layer	Water Layer	Green Layer	Water Layer	Green Layer	Water Layer
Hours	mL	mL	mL	mL	mL	mL
0.0	200.0	0.0	200.0	0.0	200.0	0.0
0.5	142.9	57.1	150.0	50.0	166.0	34.0
1.0	134.3	65.7	135.0	65.0	140.0	60.0
1.5	125.7	74.3	125.0	75.0	132.0	68.0
2.5	120.0	80.0	120.0	80.0	122.0	78.0
3.5	117.1	82.9	115.0	85.0	117.0	83.0
21.5	105.7	94.3	110.0	90.0	98.0	102.0
24.0	105.7	94.3	110.0	90.0	98.0	102.0

APPENDIX F



DATA

FOR HARVESTING MICROALGAE THROUGH SAND FILTRATION AND SOLAR DRYING

APPENDIX F – DATA FOR HARVESTING MICROALGAE THROUGH SAND FILTRATION AND SOLAR DRYING

Table 31: Data for harvesting microalgae through sand filtration and solar drying

Parameters	Units	Std Palette	Palette 1	Palette 2	Palette 3
Metal palette surface area	m ²	0.0484	0.0484	0.0484	0.0484
Metal palette weight	g	1435.0	1437.3	1431.9	1454.0
Metal palette and sand weight	g	2078.0	1963.6	1890.0	1962.8
Metal palette, sand and wet biomass weight	g		2203.8	2148.0	2220.1
Metal palette, sand and dry biomass weight	g		1968.2	1895.4	1967.0
Metal palette and sand after one day of drying	g	2074.9			

APPENDIX G



DATA

FOR HARVESTING CULTIVATED MICROALGAE THROUGH GRAVITY SETTLING

APPENDIX G – DATA FOR HARVESTING CULTIVATED MICROALGAE THROUGH GRAVITY SETTLING

Table 32: Data for harvesting cultivated microalgae through gravity settling

Time	Temp	B3	B6	B8
8:00	°C	18.0	17.0	16.0
9:00	°C	18.0	18.0	16.0
10:00	°C	21.0	22.0	18.0
11:00	°C	24.0	20.0	18.0
12:00	°C	25.0	30.0	18.0
13:00	°C	26.0	32.0	18.0
14:00	°C	28.0	36.0	18.0
15:00	°C	29.0	37.0	18.0
16:00	°C	28.0	37.0	19.0
17:00	°C	28.0	36.0	19.0
18:00	°C	26.0	33.0	19.0
Average bioreactor temperature	°C	24.6	28.9	17.9
Air flow rate	L/min	0.7	1.0	0.7
First two litres of bioreactor				
Filter paper weight	g	0.7291	0.7273	1.0533
Filter paper & dry biomass wt.	g	0.7537	0.8350	1.0609
Filter paper weight	g		1.0677	0.7153
Filter paper & dry biomass wt.	g		1.0997	0.7480
Filter paper weight	g			
Filter paper & dry biomass wt.	g			
Filter paper weight	g			
Filter paper & dry biomass wt.	g			
Third litre of bioreactor				
Filter paper weight	g	1.0947	0.7314	0.7215
Filter paper & dry biomass wt.	g	1.1057	0.9373	0.7932
Filter paper weight	g	0.7281		
Filter paper & dry biomass wt.	g	0.7674		
Last litre of bioreactor				
Filter paper weight	g	1.0726	0.7258	0.7254
Filter paper & dry biomass wt.	g	6.0353	4.2086	1.7472
Filter paper weight	g	0.7251	0.7278	
Filter paper & dry biomass wt.	g	0.8292	1.5945	

Filter paper weight	g		0.7270	
Filter paper & dry biomass wt.	g		1.2993	
Filter paper weight	g		0.7262	
Filter paper & dry biomass wt.	g		1.8835	

APPENDIX H



ECONOMICS MODEL

FOR HARTBEESPOORT DAM BIOMASS-TO-LIQUIDS PROCESS

APPENDIX H – ECONOMICS MODEL FOR HARTBEESPOORT DAM BIOMASS-TO-LIQUIDS PROCESS

The Economics Model was created in Microsoft Excel. Column E contains information related to the reference case. Columns F to Y contain information related to the 22 alternate cases, which provide information on the sensitivities of these cases relative to the reference case. Columns Z to AD contain information on the BTL process with additional open-cultivation facilities included. Columns AE to AN contain information on the BTL process with additional closed-cultivation facilities included.

Table 33: Economics model for Hartbeespoort Dam integrated biomass-to-liquids process

Economics Model for Hartbeespoort Dam Integrated Biomass-to-Liquids (HI-BTL) Process

Description		Case 1.0	Case 1.1	Case 1.2	Case 1.3	Case 1.4	Case 1.5	Case 1.6	Case 1.7	Case 1.8	Case 1.9	Case 1.10	Case 1.11	Case 1.12	Case 1.13	Case 1.14	Case 1.15	Case 1.17	Case 1.18	Case 1.19	Case 1.20	Case 1.21	Case 1.22	Case 2.1	Case 2.2	Case 2.3	Case 2.4	Case 2.5	Case 3.1	Case 3.2	Case 3.3	Case 3.4	Case 3.5	Case 4.1	Case 4.2	Case 4.3	Case 4.4	Case 4.5	Case 4.6	Case 4.7	Case 4.8	Case 4.9	Case 4.10	Case 4.11	Case 4.12	Case 4.13	Case 4.14	Case 4.15	Case 4.16	Case 4.17	Case 4.18	Case 4.19	Case 4.20	Case 4.21	Case 4.22	Case 4.23	Case 4.24	Case 4.25	Case 4.26	Case 4.27	Case 4.28	Case 4.29	Case 4.30	Case 4.31	Case 4.32	Case 4.33	Case 4.34	Case 4.35	Case 4.36	Case 4.37	Case 4.38	Case 4.39	Case 4.40	Case 4.41	Case 4.42	Case 4.43	Case 4.44	Case 4.45	Case 4.46	Case 4.47	Case 4.48	Case 4.49	Case 4.50	Case 4.51	Case 4.52	Case 4.53	Case 4.54	Case 4.55	Case 4.56	Case 4.57	Case 4.58	Case 4.59	Case 4.60	Case 4.61	Case 4.62	Case 4.63	Case 4.64	Case 4.65	Case 4.66	Case 4.67	Case 4.68	Case 4.69	Case 4.70	Case 4.71	Case 4.72	Case 4.73	Case 4.74	Case 4.75	Case 4.76	Case 4.77	Case 4.78	Case 4.79	Case 4.80	Case 4.81	Case 4.82	Case 4.83	Case 4.84	Case 4.85	Case 4.86	Case 4.87	Case 4.88	Case 4.89	Case 4.90	Case 4.91	Case 4.92	Case 4.93	Case 4.94	Case 4.95	Case 4.96	Case 4.97	Case 4.98	Case 4.99	Case 4.100	Case 4.101	Case 4.102	Case 4.103	Case 4.104	Case 4.105	Case 4.106	Case 4.107	Case 4.108	Case 4.109	Case 4.110	Case 4.111	Case 4.112	Case 4.113	Case 4.114	Case 4.115	Case 4.116	Case 4.117	Case 4.118	Case 4.119	Case 4.120	Case 4.121	Case 4.122	Case 4.123	Case 4.124	Case 4.125	Case 4.126	Case 4.127	Case 4.128	Case 4.129	Case 4.130	Case 4.131	Case 4.132	Case 4.133	Case 4.134	Case 4.135	Case 4.136	Case 4.137	Case 4.138	Case 4.139	Case 4.140	Case 4.141	Case 4.142	Case 4.143	Case 4.144	Case 4.145	Case 4.146	Case 4.147	Case 4.148	Case 4.149	Case 4.150	Case 4.151	Case 4.152	Case 4.153	Case 4.154	Case 4.155	Case 4.156	Case 4.157	Case 4.158	Case 4.159	Case 4.160	Case 4.161	Case 4.162	Case 4.163	Case 4.164	Case 4.165	Case 4.166	Case 4.167	Case 4.168	Case 4.169	Case 4.170	Case 4.171	Case 4.172	Case 4.173	Case 4.174	Case 4.175	Case 4.176	Case 4.177	Case 4.178	Case 4.179	Case 4.180	Case 4.181	Case 4.182	Case 4.183	Case 4.184	Case 4.185	Case 4.186	Case 4.187	Case 4.188	Case 4.189	Case 4.190	Case 4.191	Case 4.192	Case 4.193	Case 4.194	Case 4.195	Case 4.196	Case 4.197	Case 4.198	Case 4.199	Case 4.200	Case 4.201	Case 4.202	Case 4.203	Case 4.204	Case 4.205	Case 4.206	Case 4.207	Case 4.208	Case 4.209	Case 4.210	Case 4.211	Case 4.212	Case 4.213	Case 4.214	Case 4.215	Case 4.216	Case 4.217	Case 4.218	Case 4.219	Case 4.220	Case 4.221	Case 4.222	Case 4.223	Case 4.224	Case 4.225	Case 4.226	Case 4.227	Case 4.228	Case 4.229	Case 4.230	Case 4.231	Case 4.232	Case 4.233	Case 4.234	Case 4.235	Case 4.236	Case 4.237	Case 4.238	Case 4.239	Case 4.240	Case 4.241	Case 4.242	Case 4.243	Case 4.244	Case 4.245	Case 4.246	Case 4.247	Case 4.248	Case 4.249	Case 4.250	Case 4.251	Case 4.252	Case 4.253	Case 4.254	Case 4.255	Case 4.256	Case 4.257	Case 4.258	Case 4.259	Case 4.260	Case 4.261	Case 4.262	Case 4.263	Case 4.264	Case 4.265	Case 4.266	Case 4.267	Case 4.268	Case 4.269	Case 4.270	Case 4.271	Case 4.272	Case 4.273	Case 4.274	Case 4.275	Case 4.276	Case 4.277	Case 4.278	Case 4.279	Case 4.280	Case 4.281	Case 4.282	Case 4.283	Case 4.284	Case 4.285	Case 4.286	Case 4.287	Case 4.288	Case 4.289	Case 4.290	Case 4.291	Case 4.292	Case 4.293	Case 4.294	Case 4.295	Case 4.296	Case 4.297	Case 4.298	Case 4.299	Case 4.300	Case 4.301	Case 4.302	Case 4.303	Case 4.304	Case 4.305	Case 4.306	Case 4.307	Case 4.308	Case 4.309	Case 4.310	Case 4.311	Case 4.312	Case 4.313	Case 4.314	Case 4.315	Case 4.316	Case 4.317	Case 4.318	Case 4.319	Case 4.320	Case 4.321	Case 4.322	Case 4.323	Case 4.324	Case 4.325	Case 4.326	Case 4.327	Case 4.328	Case 4.329	Case 4.330	Case 4.331	Case 4.332	Case 4.333	Case 4.334	Case 4.335	Case 4.336	Case 4.337	Case 4.338	Case 4.339	Case 4.340	Case 4.341	Case 4.342	Case 4.343	Case 4.344	Case 4.345	Case 4.346	Case 4.347	Case 4.348	Case 4.349	Case 4.350	Case 4.351	Case 4.352	Case 4.353	Case 4.354	Case 4.355	Case 4.356	Case 4.357	Case 4.358	Case 4.359	Case 4.360	Case 4.361	Case 4.362	Case 4.363	Case 4.364	Case 4.365	Case 4.366	Case 4.367	Case 4.368	Case 4.369	Case 4.370	Case 4.371	Case 4.372	Case 4.373	Case 4.374	Case 4.375	Case 4.376	Case 4.377	Case 4.378	Case 4.379	Case 4.380	Case 4.381	Case 4.382	Case 4.383	Case 4.384	Case 4.385	Case 4.386	Case 4.387	Case 4.388	Case 4.389	Case 4.390	Case 4.391	Case 4.392	Case 4.393	Case 4.394	Case 4.395	Case 4.396	Case 4.397	Case 4.398	Case 4.399	Case 4.400	Case 4.401	Case 4.402	Case 4.403	Case 4.404	Case 4.405	Case 4.406	Case 4.407	Case 4.408	Case 4.409	Case 4.410	Case 4.411	Case 4.412	Case 4.413	Case 4.414	Case 4.415	Case 4.416	Case 4.417	Case 4.418	Case 4.419	Case 4.420	Case 4.421	Case 4.422	Case 4.423	Case 4.424	Case 4.425	Case 4.426	Case 4.427	Case 4.428	Case 4.429	Case 4.430	Case 4.431	Case 4.432	Case 4.433	Case 4.434	Case 4.435	Case 4.436	Case 4.437	Case 4.438	Case 4.439	Case 4.440	Case 4.441	Case 4.442	Case 4.443	Case 4.444	Case 4.445	Case 4.446	Case 4.447	Case 4.448	Case 4.449	Case 4.450	Case 4.451	Case 4.452	Case 4.453	Case 4.454	Case 4.455	Case 4.456	Case 4.457	Case 4.458	Case 4.459	Case 4.460	Case 4.461	Case 4.462	Case 4.463	Case 4.464	Case 4.465	Case 4.466	Case 4.467	Case 4.468	Case 4.469	Case 4.470	Case 4.471	Case 4.472	Case 4.473	Case 4.474	Case 4.475	Case 4.476	Case 4.477	Case 4.478	Case 4.479	Case 4.480	Case 4.481	Case 4.482	Case 4.483	Case 4.484	Case 4.485	Case 4.486	Case 4.487	Case 4.488	Case 4.489	Case 4.490	Case 4.491	Case 4.492	Case 4.493	Case 4.494	Case 4.495	Case 4.496	Case 4.497	Case 4.498	Case 4.499	Case 4.500	Case 4.501	Case 4.502	Case 4.503	Case 4.504	Case 4.505	Case 4.506	Case 4.507	Case 4.508	Case 4.509	Case 4.510	Case 4.511	Case 4.512	Case 4.513	Case 4.514	Case 4.515	Case 4.516	Case 4.517	Case 4.518	Case 4.519	Case 4.520	Case 4.521	Case 4.522	Case 4.523	Case 4.524	Case 4.525	Case 4.526	Case 4.527	Case 4.528	Case 4.529	Case 4.530	Case 4.531	Case 4.532	Case 4.533	Case 4.534	Case 4.535	Case 4.536	Case 4.537	Case 4.538	Case 4.539	Case 4.540	Case 4.541	Case 4.542	Case 4.543	Case 4.544	Case 4.545	Case 4.546	Case 4.547	Case 4.548	Case 4.549	Case 4.550	Case 4.551	Case 4.552	Case 4.553	Case 4.554	Case 4.555	Case 4.556	Case 4.557	Case 4.558	Case 4.559	Case 4.560	Case 4.561	Case 4.562	Case 4.563	Case 4.564	Case 4.565	Case 4.566	Case 4.567	Case 4.568	Case 4.569	Case 4.570	Case 4.571	Case 4.572	Case 4.573	Case 4.574	Case 4.575	Case 4.576	Case 4.577	Case 4.578	Case 4.579	Case 4.580	Case 4.581	Case 4.582	Case 4.583	Case 4.584	Case 4.585	Case 4.586	Case 4.587	Case 4.588	Case 4.589	Case 4.590	Case 4.591	Case 4.592	Case 4.593	Case 4.594	Case 4.595	Case 4.596	Case 4.597	Case 4.598	Case 4.599	Case 4.600	Case 4.601	Case 4.602	Case 4.603	Case 4.604	Case 4.605	Case 4.606	Case 4.607	Case 4.608	Case 4.609	Case 4.610	Case 4.611	Case 4.612	Case 4.613	Case 4.614	Case 4.615	Case 4.616	Case 4.617	Case 4.618	Case 4.619	Case 4.620	Case 4.621	Case 4.622	Case 4.623	Case 4.624	Case 4.625	Case 4.626	Case 4.627	Case 4.628	Case 4.629	Case 4.630	Case 4.631	Case 4.632	Case 4.633	Case 4.634	Case 4.635	Case 4.636	Case 4.637	Case 4.638	Case 4.639	Case 4.640	Case 4.641	Case 4.642	Case 4.643	Case 4.644	Case 4.645	Case 4.646	Case 4.647	Case 4.648	Case 4.649	Case 4.650	Case 4.651	Case 4.652	Case 4.653	Case 4.654	Case 4.655	Case 4.656	Case 4.657	Case 4.658	Case 4.659	Case 4.660	Case 4.661	Case 4.662	Case 4.663	Case 4.664	Case 4.665	Case 4.666	Case 4.667	Case 4.668	Case 4.669	Case 4.670	Case 4.671	Case 4.672	Case 4.673	Case 4.674	Case 4.675	Case 4.676	Case 4.677	Case 4.678	Case 4.679	Case 4.680	Case 4.681	Case 4.682	Case 4.683	Case 4.684	Case 4.685	Case 4.686	Case 4.687	Case 4.688	Case 4.689	Case 4.690	Case 4.691	Case 4.692	Case 4.693	Case 4.694	Case 4.695	Case 4.696	Case 4.697	Case 4.698	Case 4.699	Case 4.700	Case 4.701	Case 4.702	Case 4.703	Case 4.704	Case 4.705	Case 4.706	Case 4.707	Case 4.708	Case 4.709	Case 4.710	Case 4.711	Case 4.712	Case 4.713	Case 4.714	Case 4.715	Case 4.716	Case 4.717	Case 4.718	Case 4.719	Case 4.720	Case 4.721	Case 4.722	Case 4.723	Case 4.724	Case 4.725	Case 4.726	Case 4.727	Case 4.728	Case 4.729	Case 4.730	Case 4.731	Case 4.732	Case 4.733	Case 4.734	Case 4.735	Case 4.736	Case 4.737	Case 4.738	Case 4.739	Case 4.740	Case 4.741	Case 4.742	Case 4.743	Case 4.744	Case 4.745	Case 4.746	Case 4.747	Case 4.748	Case 4.749	Case 4.750	Case 4.751	Case 4.752	Case 4.753	Case 4.754	Case 4.755	Case 4.756	Case 4.757	Case 4.758	Case 4.759	Case 4.760	Case 4.761	Case 4.762	Case 4.763	Case 4.764	Case 4.765	Case 4.766	Case 4.767	Case 4.768	Case 4.769	Case 4.770	Case 4.771	Case 4.772	Case 4.773	Case 4.774	Case 4.775	Case 4.776	Case 4.777	Case 4.778	Case 4.779	Case 4.780	Case 4.781	Case 4.782	Case 4.783	Case 4.784	Case 4.785	Case 4.786	Case 4.787	Case 4.788	Case 4.789	Case 4.790	Case 4.791	Case 4.792	Case 4.793	Case 4.794	Case 4.795	Case 4.796	Case 4.797	Case 4.798	Case 4.799	Case 4.800	Case 4.801	Case 4.802	Case 4.803	Case 4.804	Case 4.805	Case 4.806	Case 4.807	Case 4.808	Case 4.809	Case 4.810	Case 4.811	Case 4.812	Case 4.813	Case 4.814	Case 4.815	Case 4.816	Case 4.817	Case 4.818	Case 4.819	Case 4.820	Case 4.821	Case 4.822	Case 4.823	Case 4.824	Case 4.825	Case 4.826	Case 4.827	Case 4.828	Case 4.829	Case 4.830	Case 4.831	Case 4.832	Case 4.833	Case 4.834	Case 4.835	Case 4.836	Case 4.837	Case 4.838	Case 4.839	Case 4.840	Case 4.841	Case 4.842	Case 4.843	Case 4.844	Case 4.845	Case 4.846	Case 4.847	Case 4.848	Case 4.849	Case 4.850	Case 4.851	Case 4.852	Case 4.853	Case 4.854	Case 4.855	Case 4.856	Case 4.857	Case 4.858	Case 4.859	Case 4.860	Case 4.861	Case 4.862	Case 4.863	Case 4.864	Case 4.865	Case 4.866	Case 4.867	Case 4.868	Case 4.869	Case 4.870	Case 4.871	Case 4.872	Case 4.873	Case 4.874	Case 4.875	Case 4.876	Case 4.877	Case 4.878	Case 4.879	Case 4.880	Case 4.881	Case 4.882	Case 4.883	Case 4.884	Case 4.885	Case 4.886	Case 4.887	Case 4.888	Case 4.889	Case 4.890	Case 4.891	Case 4.892	Case 4.893	Case 4.894	Case 4.895	Case 4.896	Case 4.897	Case 4.898	Case 4.899	Case 4.900	Case 4.901	Case 4.902	Case 4.903	Case 4.904	Case 4.905	Case 4.906	Case 4.907	Case 4.908	Case 4.909	Case 4.910	Case 4.911	Case 4.912	Case 4.913	Case 4.914	Case 4.915	Case 4.916	Case 4.917	Case 4.918	Case 4.919	Case 4.920	Case 4.921	Case 4.922	Case 4.923	Case 4.924	Case 4.925	Case 4.926	Case 4.927	Case 4.928	Case 4.929	Case 4.930	Case 4.931	Case 4.932	Case 4.933	Case 4.934	Case 4.935	Case 4.936	Case 4.937	Case 4.938	Case 4.939	Case 4.940	Case 4.941	Case 4.942	Case 4.943	Case 4.944	Case 4.945	Case 4.946	Case 4.947	Case 4.948	Case 4.949	Case 4.950	Case 4.951	Case 4.952	Case 4.953	Case 4.954	Case 4.955	Case 4.956	Case 4.957	Case 4.958	Case 4.959	Case 4.960	Case 4.961	Case 4.962	Case 4.963	Case 4.964	Case 4.965	Case 4.966	Case 4.967	Case 4.968	Case 4.969	Case 4.970	Case 4.971	Case 4.972	Case 4.973	Case 4.974	Case 4.975	Case 4.976	Case 4.977	Case 4.978	Case 4.979	Case 4.980	Case 4.981	Case 4.982	Case 4.983	Case 4.984	Case 4.985	Case 4.986	Case 4.987	Case 4.988	Case 4.989	Case 4.990	Case 4.991	Case 4.992	Case 4.993	Case 4.994	Case 4.995	Case 4.996	Case 4.997	Case 4.998	Case 4.999	Case 5.000	Case 5.001	Case 5.002	Case 5.003	Case 5.004	Case 5.005	Case 5.006	Case 5.007	Case 5.008	Case 5.009	Case 5.010
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