

**An Investigation into the Production of Glycerol Biofuel
from Microalgae in South Africa**


by

Max I.D.B. Bloomfield

Submitted in fulfilment of the academic requirements for the degree of
Master of Science in the School of Agricultural, Earth and Environmental Sciences,
College of Agriculture, Engineering and Science,
University of KwaZulu-Natal,
Durban

December 2013

As the candidate's supervisor I have/have not approved this thesis/dissertation for
submission.

Signed:  Name: _____ Date: _____

Abstract

Energy provision in South Africa is going through great changes in this first half of the 21st century. Ensuring delivery of electricity to all households within the country, along with continued industrial growth, has left the national electricity provider and distributor, Eskom, with insufficient capacity. Understanding of environmental and health issues related to traditional energy generation methods, along with local and international political pressure has moved the South African Government to commit to long-term energy-efficiency and renewable energy targets. In recent years the door has begun to open to foreign and private investment on the energy-supply side. At the same time, the efficiency and price of alternative renewable energy sources has significantly improved, as global investments continue to rise. Confidence in the reliability of these technologies has risen, as developed countries demonstrate greater dependence on them, and prove that they can compete with traditional fossil fuels. This is further improved as a financial cost looms on the existing environmental and health costs associated with carbon dioxide and other greenhouse gas emissions. The use of microalgae to produce stable, transportable liquid fuels at greater efficiencies than traditional biofuels, in open ponds is investigated here. For the purpose of this study the microalgae *Dunaliella salina* producing glycerol as a biofuel is used, but the results could apply universally to the use of open raceway ponds. Geographic Information System analysis of the maximum and minimum temperature ranges, rainfall and solar irradiance shows that 11.3% of South Africa is well suited to this technology. Mapping of the 59 biggest emitters of carbon dioxide in South Africa reveal that 5 are located within this area, and within 500 m of a major river. Despite the great variation of external factors across South Africa, the results of this study show great promise for this type of renewable technology.

Keywords: Microalgae, Renewable, South Africa, Glycerol, Biofuel.

Preface

The work undertaken in this study was carried out at School of Agricultural, Earth and Environmental Sciences, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Durban. This research was completed under the supervision of the following academic staff:

Dr S.N. Njoya, of the School of Agricultural, Earth and Environmental Sciences, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Durban.

C. Reid, Senior Technician, School of Agricultural, Earth and Environmental Sciences, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Durban.

T. Wiggill, Technician, School of Agricultural, Earth and Environmental Sciences, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Durban.

Dr H. Watson, Senior Lecturer, School of Agricultural, Earth and Environmental Sciences, College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Durban (now retired).


The duration of this study was from January 2012 to December 2013.

The contents of this work have not been submitted in any form to another University and, except where the work of others is acknowledged in the text, the results are the author's own investigation.

Max I.D.B. Bloomfield

17 December 2013

We certify that the above statement is correct:



Dr S.N. Njoya

Caroline Reid

Declaration 1 – Plagiarism

I, Max I.D.B. Bloomfield, declare that:

1. The research reported in this dissertation, except where otherwise indicated, is my original research.
2. This dissertation has not been submitted for any degree or examination at any other university.
3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
 - a. Their words have been re-written but the general information attributed to them has been referenced.
 - b. Where their exact words have been used, then their writing has been placed in italics and inside quotation marks, and referenced.
5. This dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

Signed _____

Declaration 2 – Publications

- Bloomfield, M.I.D.B., Njoya, S.N., Reid, C. (2013). An Investigation into the Application of Sustainable Microalgae Biofuel in South Africa - A Literature Review, *Renewable and Sustainable Energy Reviews* (Submitted 20 November 2013, passed initial editorial review, 29 November forwarded to Editor-in-Chief Laurence L. Kazmerski Ph.D. for final review).
- Bloomfield, M.I.D.B., Njoya, S.N., Reid, C. and Wiggill, T.R. (2013). Suitability Analysis and Location Theory of Algal Glycerol Biofuel in South Africa using Geographical Information Systems (GIS), *International Journal of Geographic Information Science* (Submitted 10th December 2013).

Signed _____

Acknowledgements

It would be perfectly fair to say that the road to the submission of this thesis has been anything but smooth. Along the way there have been numerous hurdles to overcome, both large and small. Despite these setbacks, I am immensely pleased to be able to submit this completed research masters thesis, and happily acknowledge that this would have been quite impossible without the enormous support I've received from those around me.

I would like to thank Dr Helen Watson, who encouraged me to come to South Africa to study, and helped me to shape the earliest renditions of my project. When funding disappeared overnight, Dr Watson helped ensure that my efforts would not have been in vain, and through a remodelling of my project I was able to self-fund for the duration of my studies.

Without the unfailing support and encouragement and boundless energies of Caroline Reid, I am quite certain that I would not be in the position I am now. When my supervisor abruptly disappeared due to ill-health, it was thanks to Ms Reid's determination, during a time when all the staff was heavily overburdened, that a replacement supervisor was found, and my studies were able to continue. Throughout the project she has found the time to guide, coax and sometimes cajole the best out of me, and always kept a smile on her face.

To Dr Njoya, I am hugely indebted: at a time when you were already carrying a full workload, you gladly stepped in to help. Often having to stay late at night to do so, you always found time to review my work and have helped me reach this conclusion. I would also like to thank Timothy Wiggill for his calm, his excellent advice and suggestions, and for also finding the time to review and comment on my progress whenever I asked.

Lastly, I would like to thank my family and friends, for your support, patience and understanding, and for not disapproving too vocally. The millions of little things that you have done to help me over the last few years have ensured I got to this point. You know who you are and I thank you sincerely.

Table of Contents

Abstract	i
Preface	ii
Declaration 1 – Plagiarism	iii
Declaration 2 – Publications	iv
Acknowledgements	v
Table of Contents	vi
List of Figures	ix
List of Tables	xi
Abbreviations	xii
CHAPTER 1: Introduction and Background	1
1.1 Introduction	2
1.2 Background	2
1.3 Study Outline	3
1.3.1. Aims & Objectives	3
1.3.2. Outline of Thesis	4
CHAPTER 2: Study Area	5
2.1. Introduction	6
2.2. Geographic Location of South Africa	6
2.3. Terrain/Relief	8
2.4. Climate and Season	11
2.5. Rivers	12
2.6. Soils of South Africa	15
2.7. Agro-Ecological Zones and Biomes of South Africa	16
References	18
CHAPTER 3: The Application of Sustainable Microalgae Biofuel in South Africa – A Literature Review	19
Abstract	20
3.1. Introduction	21
3.2. Emissions and Climate Change in South Africa	22
3.2.1. Status Quo	24
3.2.2. Energy Supply and CO ₂ Emissions in South Africa	26

3.2.3. South African Coal-to-Liquid Technology	28
3.2.4. South Africa's Renewable Energy Commitments	29
3.2.5. Carbon Capture and Storage	30
3.2.6. Renewable Energy Status in South Africa	30
3.2.6.1. Hydro	30
3.2.6.2. Wind	32
3.2.6.3. Solar	32
3.2.6.4. Biomass and Biofuels	33
3.3. Biofuels	35
3.3.1. Criticism of Early Biofuels	35
3.3.2. Algae	36
3.3.3. Microalgae	37
3.3.4. <i>Dunaliella</i> and Glycerol	38
3.3.5. Commercial Development of Microalgae	41
3.3.6. Microalgae Optimal Growth Parameters	42
3.3.6.1. Light and Temperature	42
3.3.6.2. Salinity, pH and Turbidity	43
3.3.6.3. Carbon, Nitrogen and Phosphorous	43
3.3.6.4. Micronutrients	44
3.3.7. Infrastructure	44
3.3.8. Socio-Economic Benefits to South Africa	45
3.4. Limitations and Knowledge Gaps	46
3.5. Summary and Conclusions	49
References	50
CHAPTER 4: Suitability Analysis and Location Theory of Algal Glycerol	68
Biofuel in South Africa using Geographic Information Systems	
Abstract	69
4.1. Introduction	70
4.2. Consultation	71
4.3. Location Theory	74
4.4. Needs and Suitability Analysis	76
4.4.1. Climatic Factors	76
4.4.1.1. Temperature	76

4.4.1.2. Rainfall	78
4.4.1.3. Solar Irradiance	79
4.4.2. Other Environmental Factors	81
4.4.2.1. Altitude	81
4.4.2.2. Access to Water	81
4.4.2.3. Access to CO ₂ Supply	81
4.4.2.4. Geography and Geology	82
4.4.2.5. Access to Nutrient Supply	82
4.4.3. Socio-Economic Factors	83
4.4.3.1. Land Use and Surrounding Land Use	83
4.4.3.2. Access to Electrical Grid	83
4.4.3.3. Access to Transport Network	83
4.4.4. Summary	83
4.5. Results	84
4.5.1. Temperature	84
4.5.1.1. Minimum Temperature	85
4.5.1.2. Maximum Temperature	85
4.5.2. Rainfall	87
4.5.3. Solar Irradiance	90
4.5.4. Remaining Industries within Suitable Areas of South Africa	91
4.5.5. Access to Water	91
4.5.6. Land Use	93
4.6. Limitations	94
4.7. Discussion	96
4.8. Conclusions	97
References	98
CHAPTER 5: Limitations, Discussion and Conclusions	103
5.1. Limitations	104
5.2. Discussion and Conclusions	105
Appendix I – Consultee Responses to Consultation	108
Appendix II – Questionnaire Responses	112

List of Figures¹

Figure 2.1.	Location map	7
Figure 2.2.	Map of South Africa showing the 9 provinces and major cities	7
Figure 2.3.	The Great Escarpment	8
Figure 2.4.	Topographical map of South Africa	9
Figure 2.5.	Major rivers of South Africa	12
Figure 2.6.	Mean annual rainfall in South Africa	13
Figure 2.7.	Geology of South Africa	15
Figure 2.8.	Agricultural regions of South Africa	16
Figure 2.9.	Biomes of South Africa	17
Figure 3.1.	Chemical structure of glycerol	39
Figure 4.1.	Map showing the location of all consultee's sites throughout South Africa	75
Figure 4.2.a	Minimum temperatures	77
Figure 4.2.b	Maximum temperatures	77
Figure 4.3.	Distribution of average annual rainfall across South Africa	79
Figure 4.4.	Global horizontal irradiance for South Africa	80
Figure 4.5.a	Suitable and unsuitable temperatures for algal growth, where minimum temperature requirements are met	85
Figure 4.5.b	Suitable and unsuitable temperatures for algal growth, where maximum temperature requirements are met	86
Figure 4.6.	Suitability analysis for both minimum and maximum temperatures for algal growth	87

¹ All Figures with the source (*UKZN, SAEES*) are the product of the University of Kwa-Zulu Natal, School of Agriculture, Environment and Earth Sciences.

Figure 4.7.	Areas of suitable and unsuitable rainfall	88
Figure 4.8.	The most suitable areas for algal growth - temperature and rainfall	89
Figure 4.9.	The most suitable areas for algal growth showing also the global horizontal irradiance and study sites through South Africa	90
Figure 4.10.	Location and type of emitters that fall within suitable areas for algal growth	91
Figure 4.11.	Remaining sites after the suitability analysis within 500 m of a river	92
Figure 4.12.	World map showing global horizontal irradiation	96

List of Tables

Table 2.1.	Altitude, Temperature and Rainfall of major Cities and Towns in South Africa	14
Table 4.1.	Questionnaire to all potential algal pond pilot project sites	72
Table 4.2.	Responses and completed questionnaires received from consultees	73
Table 4.3.	A summary of the criteria that were included in the analysis and the reasoning behind including or excluding factors from the analysis	84
Table 4.4.	A list of sites in optimal locations in South Africa for temperature, rainfall, irradiance and proximity to a river	92

Abbreviations

Abbreviation	Definition
ATP	Adenosine Triphosphate
b/d	Barrels per day
BAU	Business-as-Usual
CCS	Carbon Capture and Storage
CDP	Carbon Disclosure Project
CHP	Combined Heat and Power
CI	Compression Ignition (diesel engine)
cm	centimetre
CO ₂	Carbon Dioxide
CTL	Coal-to-Liquid
DEA	Department of Environmental Affairs (South Africa)
DME	Department of Minerals and Energy (South Africa)
DRC	Democratic Republic of Congo
Ej	Exajoule (10 ¹⁸ joules)
EU	European Union
FAO	Food and Agriculture Organisation (US)
Fracking	Hydraulic Fracturing
GDP	Gross Domestic Product
GEF	Global Environmental Facility
GER	Green Economy Report
GHG	Greenhouse Gas
GIS	Geographic Information System
GW	Gigawatt (10 ⁹ watts)
Ha	Hectare
ICL	Indirect-Coal-to-Liquid
IEA	International Energy Agency (US)
IEP	Integrated Energy Plan
IHA	International Hydro Association
IRP	Integrated Resources Plan
Kg	Kilogram

KWh	Kilowatt-hour
KWh/m ²	Kilowatt-hours per square metre
LDC	Least Developed Country
LTMS	Long Term Mitigation Scenarios
mm	millimetre
Mt	Million tonnes
MW	Megawatt (10 ⁶ watts)
MWh	Megawatt Hour
N ₂ O	Nitrous Oxide
NGO	Non-Governmental Organisation
NO	Nitrogen Oxide
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Cooperation and Development
ppm	Parts Per Million
PV	Photo-voltaic
R&D	Research and Development
RE	Renewable Energy
REFIT	Renewable Energy Feed-In-Tariff (South Africa)
SO ₂	Sulphur Dioxide
TPE	Total Primary Energy
TWh	Terawatt-hours
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organisation
µm	Micrometre
US or U.S.	United States (of America)

CHAPTER 1

Introduction and Background

1.1. Introduction

South Africa is a country with a long history of dependence on cheap, domestic coal reserves to supply its own energy demands and much of southern Africa. South Africa has one of the largest accessible coal reserves in the world, and produces the majority of its electricity in a large, but aging number of coal-fired power stations across the country. Almost all of the oil required in the country is imported, at great expense. To slightly reduce this burden South Africa has for a long time relied on coal to provide a proportion of this demand, through coal-to-liquid technology.

A great change in energy supply throughout the world is now taking place, in the search for energy security, economy and independence. This is also true of South Africa, now on the verge of a possible transition to a mixed energy supply to include a variety of renewable energy technologies. However, South Africa is still a developing country, with many demands on its political machinery, pulling in different directions; a situation in which investing in new and relatively untested, financially risky technologies is made harder. As electricity generated from wind turbines, concentrated solar and solar photovoltaic technologies steadily increases, so South African investment in these technologies has commenced. However, renewable alternatives to liquid fuels have not been investigated to the same extent, and despite their steady growth internationally, South Africa has yet to seriously examine their potential².

1.2. Background

Global production of electricity from renewable sources is increasing rapidly, in an effort to curb the escalating levels of climate change causing gases in the earth's atmosphere. There will always be a need for sustainable, stable and transportable liquid fuels to replace fossil fuel oils. One of the most promising candidates is biofuel from the most efficient

² These details are examined at far greater length within Chapter 3, Literature Review, and therefore this chapter covers only the basics, to prevent unnecessary repetition. For the same reason full referencing has been omitted until Chapter 3.

photosynthesising group of plants known to science, microalgae. The rate of biofuel production has been shown to dwarf existing biofuel harvesting techniques, and has numerous direct and indirect advantages over existing fossil and bio-fuels.

South Africa has proposed non-binding targets for reducing its carbon dioxide (CO₂) emissions in the wake of binding targets for the developed nations. More recently the Government has committed to binding targets for a renewable energy mix, and has since witnessed the opening of its first commercial scale solar-photo-voltaic farm (in the Northern Cape). It is proposed that the warm, sunny climate that much of South Africa receives throughout the year will make it well adapted to outdoor open algal-farm ponds. To determine how accurate this is, it is essential to understand the optimal conditions for microalgae to grow under, in which to maximise the end-product biofuel.

For this study it was decided to investigate the use of *Dunaliella salina* microalgae, known for its high dry-weight glycerol content under certain conditions. This selection of biofuel is tied to the discovery that glycerol can be burned at extremely high efficiencies and low pollutant emissions in a diesel engine, with minor modifications. Since this was discovered in 2010, waste glycerol from European biodiesel production, has been used to produce electricity and heat in large combined heat and power (CHP) generators throughout Europe. In an effort to find a more sustainable supply of glycerol, for when demand outstrips current supply, *Dunaliella salina* (grown in saline algal ponds), has proven to be an extremely efficient source.

1.3. Study Outline

1.3.1. Aims and Objectives

The aim of this study is to determine if South Africa has the potential to produce biofuel glycerol in open algal ponds with the microalgae *Dunaliella salina*; and if so, to identify the most suitable locations in South Africa to implement this technology.

- The first objective is to carry out a literature review in order to understand all aspects and variables of this technology; to be best placed to recognise its viability under variable circumstances and locations.

- The second objective is to make contact and pursue consultation with the highest emitters of carbon dioxide in South Africa and to map their locations.
- The third objective is to use what has been learned in objective 1, along with Geographic Information Systems to determine areas in South Africa that are naturally predisposed to the successful generation of algal glycerol biofuel in open algal ponds; and to highlight the major emitting industries located within these areas, at which this technology might be used.

1.3.2. Outline of Thesis

This thesis is presented in the form of two papers which have been sent to peer-reviewed journals during completion. The first paper is written as a literature review of the science of algal glycerol biofuel. The objectives of this paper are to present all relevant information, pertinent to the science of algal glycerol biofuel, to develop a thorough understanding of all aspects of the field.

The second paper aims to identify and demarcate the optimal areas of South Africa for this emerging technology, and suggest prospective industrial sites at which pilot projects could be run. The objectives are to preclude areas of South Africa that are shown to be unsuitable to this technology and to source potential industries to be associated with this technology.

These two papers are presented in Chapters three and four respectively. Chapter one provides background and the context of the study; Chapter two is a review of the study area: South Africa, since a knowledge of the climate, weather and terrain of the study area will be critical to learning where open algal ponds can be sited to promote maximal end-product output; and Chapter five ties together and reviews Chapters three and four, along with discussion and conclusions.

CHAPTER 2

Study Area

2.1. Introduction

This study focuses on the growth of microalgae within open raceway-ponds, exposed to the physical elements of South Africa. The South African climate and weather conditions, including solar irradiation and daily and nightly temperatures, are all related to the geography of the country. An examination of the topography and climate of South Africa is pertinent to this study and is investigated in this chapter.

2.2. Geographical Location of South Africa

South Africa occupies the southern tip of the African continent (29°00'S 24°00'E). The coastline stretches in excess of 2 500 km from the northwest desert border with Namibia southwards around the tip of Africa and then north to the border with Mozambique (Figure 2.1.). The northern border of South Africa is approximately 772 km south of the Equator. The total land area of South Africa is 1 223 201 km²³, and it measures approximately 1 600 km from north to south and the same from east to west. Five countries border the north of South Africa - from the west: Namibia, Botswana, Zimbabwe, Mozambique and Swaziland. The Atlantic Ocean borders the west of South Africa and the Indian Ocean borders the east. These two oceans meet at Cape Agulhas.

South Africa is approximately the same size as Angola and Colombia; it is approximately one-eighth the size of the U.S.A. and twice the size of France (Anon., 2012). There are nine provinces in South Africa, varying considerably in size (Figure 2.2.). The smallest, Gauteng, is heavily populated, a highly urbanised region; the largest, the Northern Cape, is almost a third of South Africa's total land area, arid and sparsely populated.

³ Data compiled from ArcGIS mapping for South Africa in Chapter four.



Figure 2.1. Location map showing South Africa in relation to the African continent (Source: UKZN, SAEES).

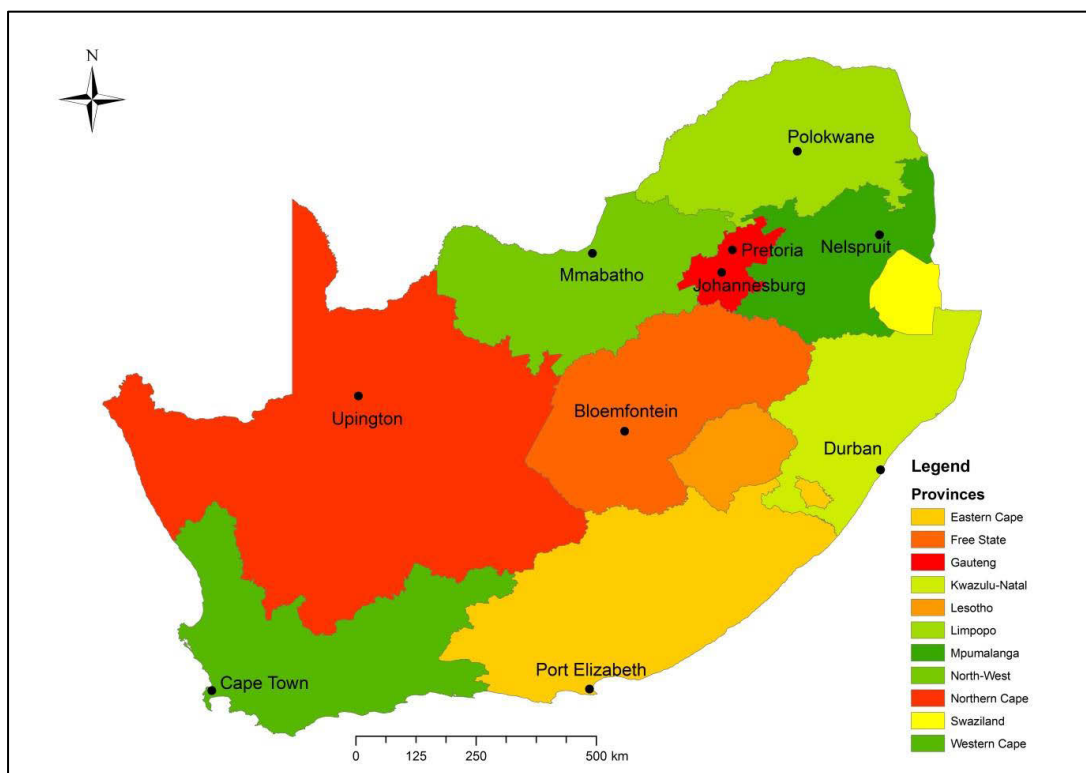


Figure 2.2. Map of South Africa showing the 9 provinces and major cities (Source: UKZN, SAEES).

2.3. Terrain/Relief

South Africa's landscape is dominated by a high central plateau, surrounded by a coastal lowland strip. Between sea level and the inland plateau forms a series of mountain ranges (the Great Escarpment (Figure 2.3.) that range between 2 000 and 3 300 m in elevation (Figure 2.4.). The inland plateau is made up of a series of rolling grasslands that arise from the Kalahari Desert (Anon, 2012). The largest sub-region in the plateau is the 1 200 – 1 800 m high central area (the Highveld). In the north the Highveld rises into a series of rock formations known as the Witwatersrand, a ridge of gold-bearing rock approximately 100 km long that serves as a watershed. The Witwatersrand is home to the world's largest proven gold deposits and South Africa's leading industrial city, Johannesburg (Whiteside, 2011; Henry & Greswell, 2011; Fox & Rowntree, 2000).

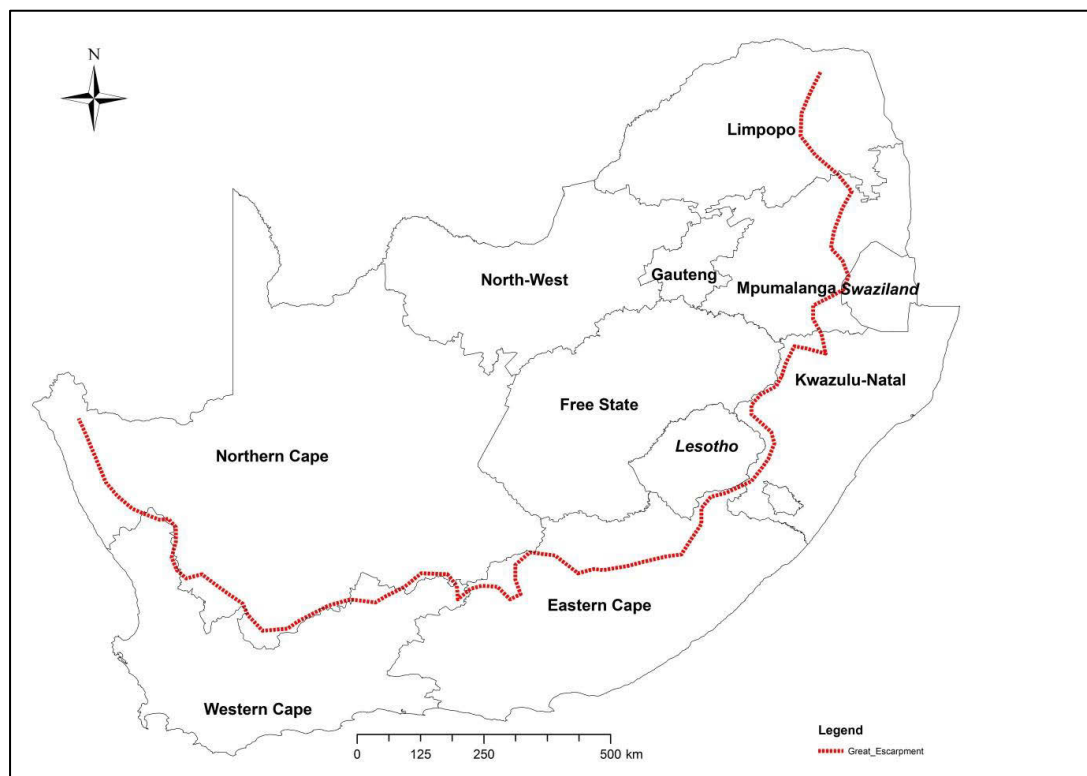


Figure 2.3. The Great Escarpment, southern Africa (representative) (Source: UKZN, SAEES).

The Bushveld is a dry savanna sub-region (approximately 350 km by 150 km) between 600 - 900 m above sea level, north of the Witwatersrand and characterized by open grasslands and scattered trees and bushes (Anon, 2012). The Bushveld, like the Witwatersrand, has great

mineral deposits. Deposits of platinum and chromium are found in the Bushveld, along with reserves of copper, gold, nickel, and iron (Henry & Greswell, 2011; Fox & Rowntree, 2000).

Immediately north of the Bushveld, a series of high plateaus and low mountain ranges form the southern edge of the Limpopo River Valley. The Waterberg and the Strydpoortberg mountain ranges are found here, and reach elevations of 1 700 m. The Kruger National Park abuts most of the north-south border with Mozambique (Henry & Greswell, 2011; Fox & Rowntree, 2000).

The southern basin of the Kalahari Desert (600 - 900 m altitude) borders Namibia and Botswana immediately west of the Bushveld. South from Namibia, along the Atlantic coastline, lies the Southern Namib Desert. The Cape Middleveld is situated between these two deserts, an arid area of undulating plains (reaching 900 m) (Henry & Greswell, 2011; Fox & Rowntree, 2000).

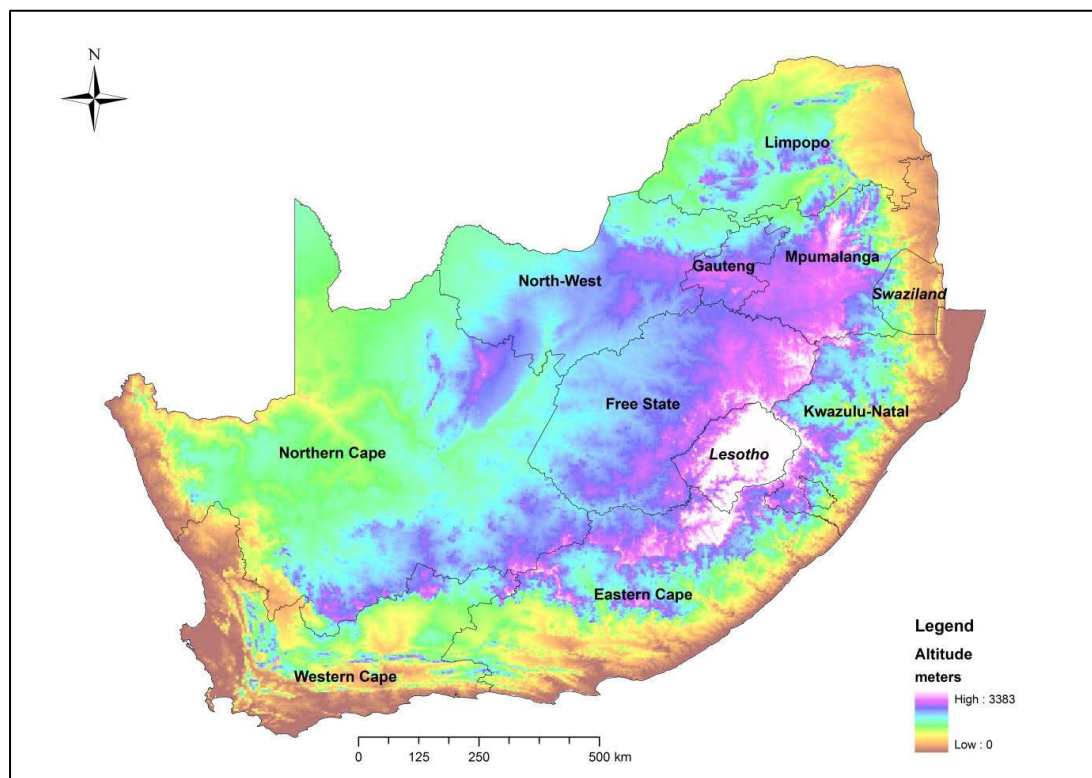


Figure 2.4. Topographical map of South Africa (Source: UKZN, SAEES).

South Africa's largest mountain range, the Drakensberg Mountains, form the southern and the eastern border of the Highveld. The highest peaks of the Drakensberg Mountains in KwaZulu-Natal exceed 3 300 m. The two highest peaks outside of the Drakensberg are in the Karoo, the Compassberg and Seweweekspoortpiek, with summit elevations of 2 504 m and 2 325 m respectively (Henry & Greswell, 2011; Dean & Milton, 1999).

In the south west of South Africa, the Cape Ranges are located where the north-south ranges meet a number of east-west ranges. Running parallel with the Atlantic coastline, the north-south Cape Ranges include the Cedarberg Mountains, the Witsenberg Mountains, and the Great Winterhoek Mountains. Running parallel with the southern coastline, the east-west Cape Ranges include the Swartberg and Langeberg Mountains (Fox & Rowntree, 2000).

The Great Karoo, a strip of semi-desert (450 - 750 m altitude), separates the Cape Ranges from the Highveld. South of the Great Karoo, between the Swartberg Mountains and the Langeberg Mountains, lies the Little Karoo: a strip of high plain arid savanna with a more temperate climate and more diverse flora and fauna than the Great Karoo (Dean & Milton, 1999).

2.4. Climate and Seasonality

South Africa's border consists largely of the Atlantic and Indian oceans which meet at the southwestern corner. The cold Benguela current sweeps up from the Antarctic along the Atlantic coast, laden with plankton and providing rich fishing-grounds. The east coast has the Agulhas Current which provides warm waters from the north to the south. South Africa's climate is significantly affected by these two currents; the warm, evaporating eastern seas causing greater rainfall and the colder Benguela current creating desert conditions in the west as it retains its moisture (CIA, 2013; Whiteside, 2011).

Much of South Africa is classified as semi-arid, but has great variation in climate and topography. The UNCCD declares that 80% of South Africa is semi-arid to arid; 18% is dry sub-humid to humid (UN, 2005). The Great Karoo is very dry and gets more so in the north-west towards the Kalahari Desert. In the summer it can be extremely hot and in winter the temperature can be well below freezing (Cowling, 2004).

The eastern coastline, however, is often green with high rainfall, and rarely ever experiences freezing temperatures. The southern coast also receives plenty of rainfall, as does Cape Town, especially in winter. This south-western corner of the country has a Mediterranean climate, with wet winters and hot, dry summers. The wind around Cape Town blows intermittently for most of the year from either the southeast or the northwest (Fox & Rowntree, 2000; Henry & Greswell, 2011).

North of the Vaal River, the Highveld is better watered and its altitude (Johannesburg is at 1 740 m; its average annual rainfall is 760 mm) tempers the subtropical heat extremes. Winters are cold, though snow is rare. The deep interior provides the hottest temperatures. Letaba, in Limpopo Province, is the hottest place in South Africa (mean annual average temperature: 23.3°C; average annual maximum temperature: 35°C). Buffelsfontein, in the Western Cape, is the coldest place in South Africa (mean annual average temperature: 11.3°C; average annual minimum temperature: 2.8°C) (CIA, 2013).

South Africa has typical seasons of weather for the southern hemisphere. The coldest days of winter are between July and August whilst January - February brings the warmest. The Benguela Current modulates summer temperatures on the west coast; the Agulhas Current modulates winter temperatures on the east coast. On the central plateau, which includes Free State and Gauteng provinces, the altitude (approximately 1 700 m) helps maintain the average temperature below 30°C (Whiteside, 2011).

2.5. Rivers

South Africa has two major rivers: the Limpopo (a stretch of which is shared with Zimbabwe); and the Orange (with its major tributary, the Vaal) (Figure 2.5.). The Limpopo flows from west to east and exits South Africa through Mozambique and into the Indian Ocean. The Orange River flows across central South Africa from east to west, discharging into the Atlantic Ocean at the Namibian border (Henry & Greswell, 2011).

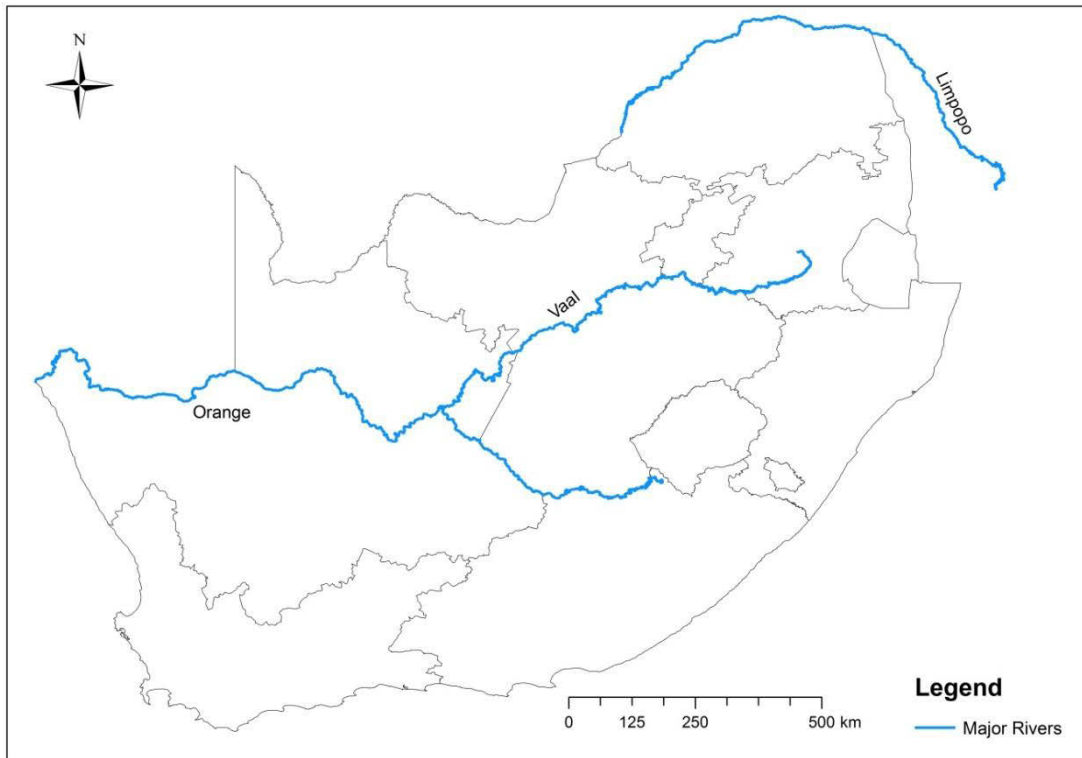


Figure 2.5. Major rivers of South Africa (Source: UKZN, SAEES).

Despite the great size of South Africa, none of the rivers that run into the sea along the coastline are navigable or have natural harbours. The South African coastline provides only one natural large harbour, at Saldanha Bay in the Western Cape. However, large industrial harbours now exist in Cape Town, Port Elizabeth, East London, Durban, and Richards Bay (Fox & Rowntree, 2000).

Figure 2.6. shows the mean annual rainfall in South Africa and Table 2.1. shows the altitude, temperature and rainfall of major cities and towns in South Africa. From Figure 2.6. it can be seen that far more rain falls on the eastern coastline and in the Cape, and very little rain falls on the west.

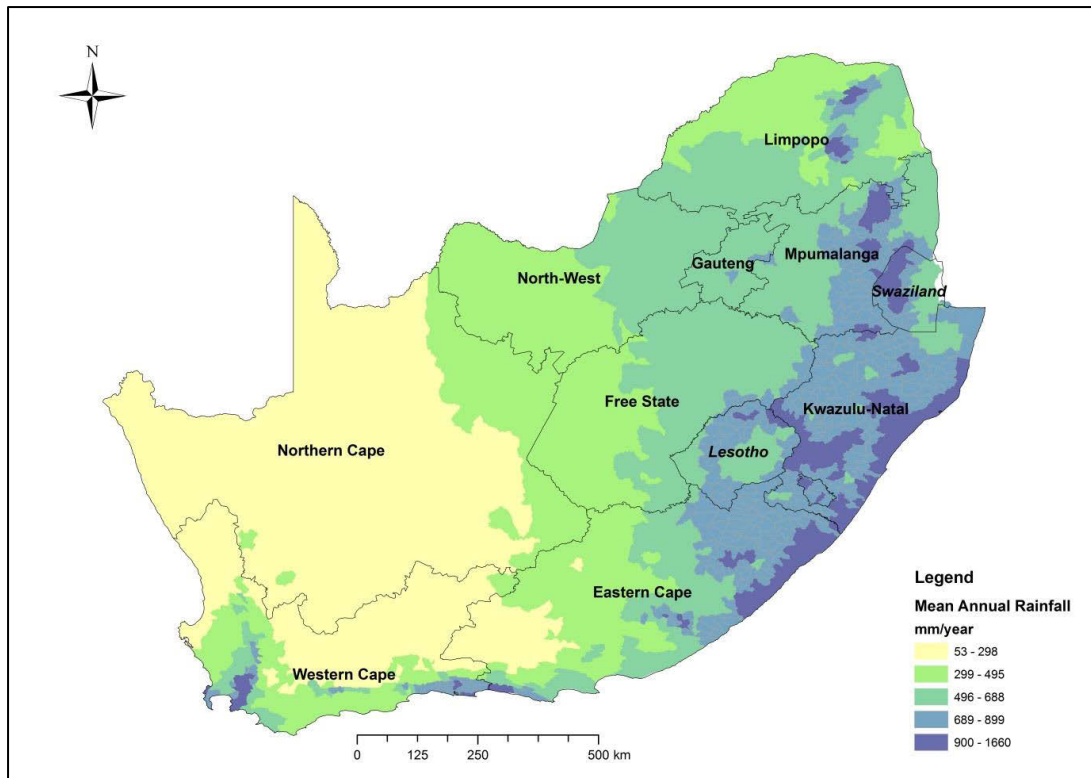


Figure 2.6. Mean annual rainfall in South Africa (Source: UKZN, SAEES).

Table 2.1. Altitude, temperature and rainfall of major cities and towns in South Africa. Source: South African Weather Service (sourced November 2013).

Town/City	Altitude (m)	Av. Max. (°C)	Av. Min. (°C)	Av. Monthly (mm)	Highest 24-hr (mm)
Bloemfontein (Free State)	1 351	24	8	559	142
Cape Town (Western Cape)	42	22	11	515	65
Durban (KZN)	8	25	17	1009	197
East London (Eastern Cape)	125	23	14	921	447
Johannesburg (Gauteng)	1 694	22	1	713	188
Kimberley (Northern Cape)	1 198	26	11	414	88
Nelspruit (Mpumalanga)	671	27	13	767	130
Pietermaritzburg (KZN)	613	26	11	844	225
Polokwane (Limpopo)	1 230	25	12	478	79
Port Elizabeth (Eastern Cape)	60	22	14	624	429
Pretoria (Gauteng)	1 330	25	12	674	160
Richards Bay (KZN)	47	26	17	1 228	317
Mthatha (Eastern Cape)	742	24	11	650	86

2.6. Soils of South Africa

Soil surveys have taken place since the arrival of European farming settlers within South Africa (throughout the 18th Century). Since the early 1970's surveys conducted by the land survey staff of the Agricultural Research Institute for Soil, Climate and Water (ARC-ISCW) have been the source of generalized soil maps. Figure 2.7. shows the geology of South Africa. In total there are 26 geological varieties, giving rise to a large and complex combination of soil patterns throughout South Africa.

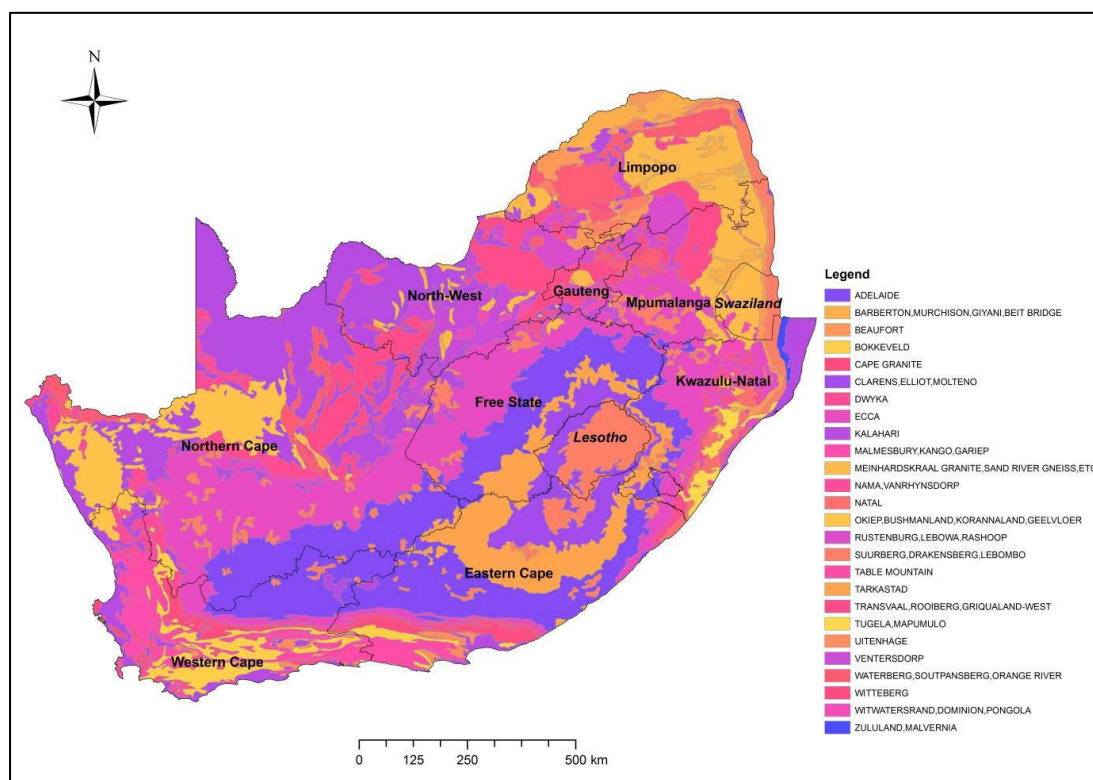


Figure 2.7. Geology of South Africa (Source: UKZN, SAEES).

Shallow soils with minimal development cover more than a third of South Africa (UN, 2005). The cultivated soils are generally very low in organic matter and are susceptible to wind erosion (UN, 2005). Acidification caused by cultivation and fertilization (nitrogen) is a serious issue and as such the use of lime is a common cultivation practice. This is especially common where soils are leached in higher rainfall areas (UN, 2005).

2.7. Agro-ecologic Zones and Biomes of South Africa

The Free State, North West and Mpumalanga Highveld are the highest yielding agricultural zones of South Africa (UN, 2005). Maize is the dominant field crop, followed by wheat (Free State), sunflowers, dry beans, grain sorghum and groundnuts (Free State and North West) (UN, 2005).

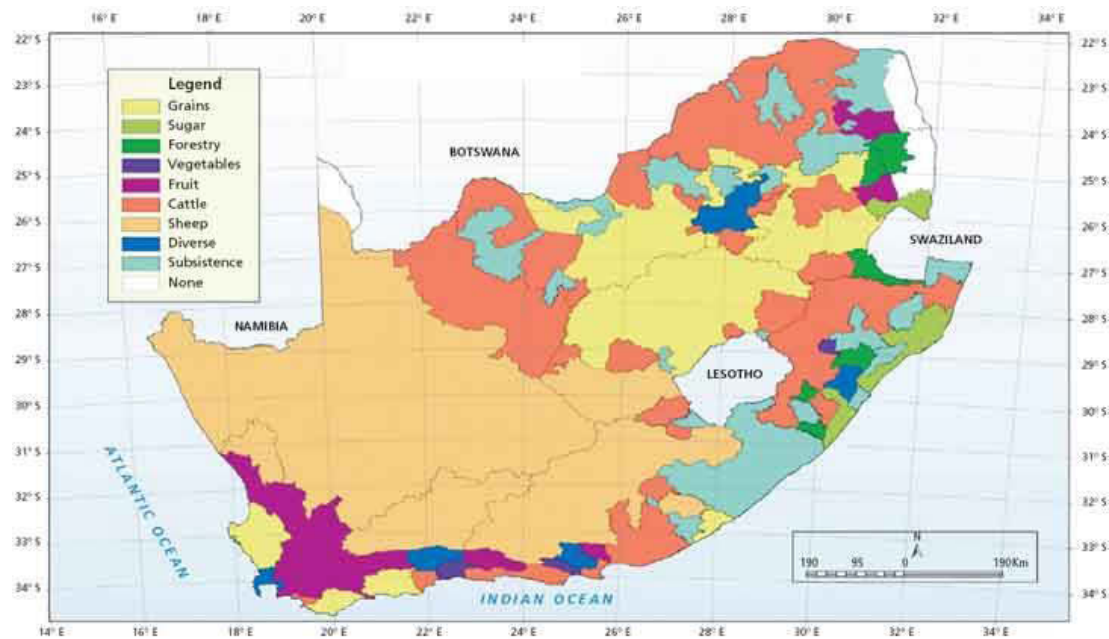


Figure 2.8. Agricultural regions of South Africa (Source: UN FAO <http://www.fao.org/docrep/008/y5998e/y5998e06.htm> [accessed November 2013]).

The dry climate in the Northern Cape requires irrigation farming, and this occurs mostly along the lower Orange River basin. The northeast of the Northern Cape produces low-yielding maize, sorghum and sunflowers as average rainfall is slightly higher and irrigation is unnecessary (UN, 2005). The Western Cape produces mostly cereals, particularly in the Rûens and Swartland sub regions, without the use of irrigation (UN, 2005). The Western Cape is famous for its vineyards and deciduous fruits. These are cultivated in sheltered valleys where agricultural variations allow (UN, 2005).

The higher rainfall of Kwazulu-Natal ensures that irrigation is unnecessary and sugar cane is the major crop, along with plantation forests for the paper industry (predominantly eucalyptus

with some pine). These are cultivated along the coast and through the Midlands. In the higher altitudes of northern Kwazulu-Natal (Winterton/Bergville) summer grain crops are the most common crop (UN, 2005). Mpumalanga province grows largely citrus, subtropical fruits and nuts, all under irrigation (UN, 2005).

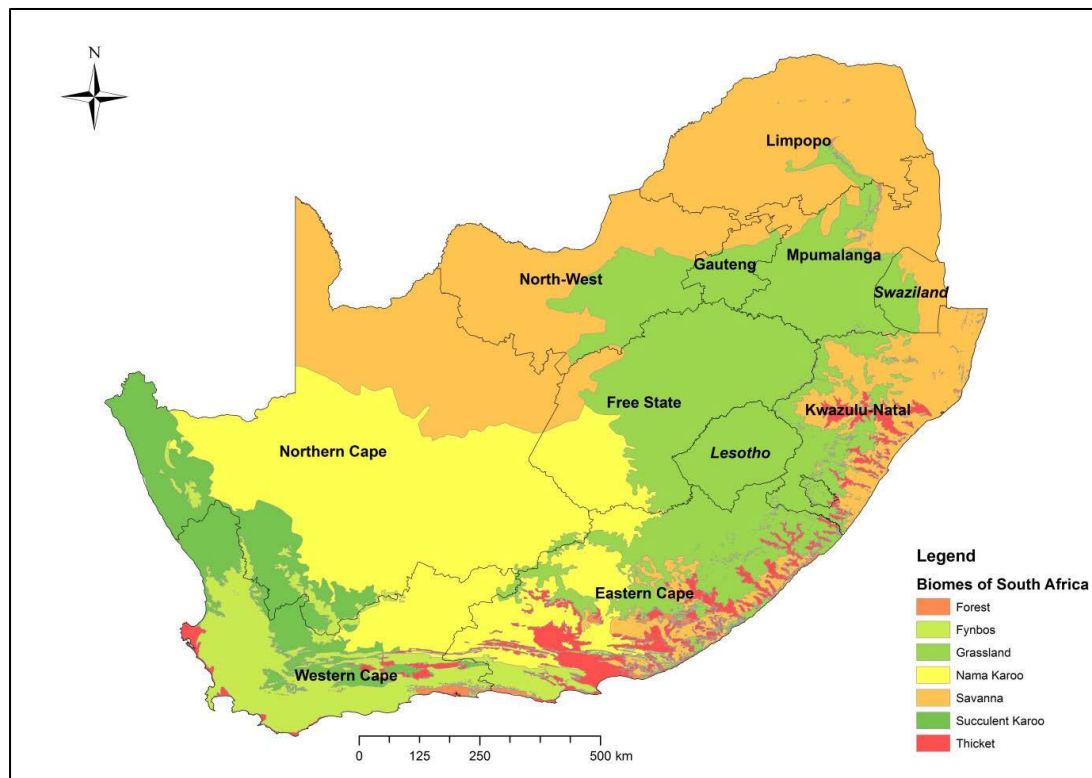


Figure 2.9. Biomes of South Africa (Source: UKZN, SAEES).

Figure 2.9. shows the major biomes across South Africa. These are closely related to the average rainfall and temperature (Figure 2.6. and Table 2.1.). The eastern coast with higher rainfall is dominated by forest, whilst the north and western inland areas that receive lower rainfall and have very high summer temperatures are dominated more by savannah and Nama Karoo (dominated by low shrub vegetation). The area between this is a wide expanse of grassland. Much of the Western Cape is covered by fynbos plants, likely due to the high levels of rainfall throughout winter and the warm summers.

References

- Anon. 2012. Geography and Climate: South Africa's Geography. South Africa Info. 28 06 2012.
<<http://www.southafrica.info/about/geography/geography.htm#.UphcgDZBtjo>>
(accessed November 2013).
- CIA. 2013. South Africa. In *The World Factbook*, by Central Intelligence Agency. Washington, D.C.: CIA.
- Cowling, R.M., Richardson, D.M. and Pierce, S.M. 2004. *Vegetation of Southern Africa*. Cambridge University Press.
- Dean, R.W.J. and Milton, S.J. 1999. *The Karoo: Ecological Patterns and Processes*. Cambridge University Press.
- Fox, R. and Rowntree, K. 2000. *The Geography of South Africa in a Changing World*. Oxford: University Press.
- Henry, W. and Greswell, P. 2011. *Geography of South Africa South of the Zambesi*. London: British Library, Historical Print Editions.
- Platt, R.B., Griffiths, J. 1969. *Environmental measurement and interpretation*. Worldwide: Van Nostrand Reinhold Company.
- UN, FAO. 2005. *Fertiliser Use by Crop in South Africa*. Rome: United Nations, Food and Agriculture Organisation. Publication number TC/D/Y5998E/1/5.05/300.
- Whiteside, J. 2011. *A New Geography of South Africa, 3rd Ed. Geography and Topography*. London: British Library, Historical Print Editions.

CHAPTER 3

The Application of Sustainable Microalgae

Biofuel in South Africa – A Literature Review

* This chapter is based on: **Bloomfield, M.I.D.B., Njoya, S.N., Reid, C. (2013). An Investigation into the Application of Sustainable Microalgae Biofuel in South Africa - A Literature Review, *Renewable and Sustainable Energy Reviews* (Submitted 20 November 2013, under editorial review).**

Abstract

This paper investigates current research into algal biofuels as a source of energy and how this renewable technology might be applicable, and applied, in South Africa. The early science and how climate change is affecting South Africa, the biggest emitters of greenhouse gases within South Africa and South Africa's obligations and commitments to climate change is reviewed. Greenhouse gas emissions and the biggest emitters of greenhouse gases are investigated along with early efforts in renewable energy technologies. Subsequently, biomass, biofuels and algal based biofuels are reviewed, followed by recent advances in glycerol biofuel and its production by microalgae. Microalgae commercial development, including the optimal environmental, biological and chemical requirements, is then reviewed. The socio-economic benefits of investing in local sources of renewable energy in South Africa is described including employment, energy security, health and the potential for national and international trade.

Limitations and knowledge gaps include the application of genetic manipulation and other efforts to close the financial gap with existing energy sources for South Africa. Biofuels are also competing against fossil fuels with global Government subsidies of US \$500 - 700 billion per year together with the largely ignored cost of pollution and human health impacts. The innovation system in South Africa is dominated by a state-owned electricity provider and distributor. This is compounded by a cheap and plentiful supply of coal and weak Government guidance and incentives which have greatly limited the earlier introduction of renewable technologies. Despite this, changes are happening. With the help of continued international pressure and investment, South Africa will take advantage of its potential in many forms of renewable technology, including microalgae.

Keywords: Algae, Microalgae, Biofuel, South Africa, Renewable, Sustainable, Glycerol

3.1. Introduction

Fourier in 1827 was the first person to recognise the *greenhouse* effect that atmospheric gases have, keeping our planet warmer than it otherwise would be (Fleming, 2000). Arrhenius proposed the connection carbon dioxide (CO₂) has with global warming and predicted that a doubling of atmospheric CO₂ levels would lead to a 5 - 6°C temperature rise (Berner, 1995). Callendar (1938) claimed that the 10% increase in atmospheric CO₂ from fossil fuel burning has been responsible for the warming trend since the 19th Century. Belief that the seas would absorb excess anthropogenic CO₂ was dispelled in 1957. It was revealed that an existing complex chemical buffering system prevents sea water from retaining as much atmospheric CO₂ as originally believed (Revelle, 1957).

In 1958 at the Mauna Loa observatory in Hawaii, long-term measurements of atmospheric CO₂ began (Keeling, 1978). These measurements revealed an annual increase of approximately 30% relative to pre-industrial levels, higher atmospheric CO₂ than at any time during the previous 700 000 years (Harding, 2007). Measurements from ice-core samples⁴ have been used to record the increase in atmospheric CO₂ from pre-industrial concentrations of 280 ppm (circa 1750) to current levels of 394 ppm (Harvey, 2007; Le Treut *et al.*, 2007; Meehl *et al.*, 2007). Other greenhouse gas (GHG) concentrations have also increased over this period, including methane at 700 ppb (circa 1750) to 1745 ppb at current levels⁵ (Harvey, 2007; Le Treut *et al.*, 2007; Meehl *et al.*, 2007; Houghton *et al.*, 1996). It has been estimated that fossil fuels are responsible for 29 Giga-tonnes of CO₂ and CO₂-⁶ emissions to the atmosphere, with carbon sequestration processes⁷ absorbing 12 Giga-tonnes of these emissions⁸ (Brennan & Owende, 2010).

⁴ Air bubbles trapped in the semi-permanent ice-caps of the Polar Regions are able to provide estimates of the atmospheric composition of a ten-year window, dating back hundreds of thousands of years.

⁵ Many gases in the atmosphere are involved in a complex interplay that creates the greenhouse effect and global warming. The GHG methane is approximately 21 times more potent than CO₂.

⁶ CO₂-^c refers to CO₂ equivalents: other greenhouse gases are more or less potent than CO₂ so their relative emissions are converted to the equal quantity of CO₂.

⁷ Carbon sequestration in this context refers to the capture of atmospheric CO₂ through the process of photosynthesis and its storage in organic reservoirs, either on land or in the oceans; it also includes CO₂ absorbed by dissolving in the oceans.

⁸ It is important to note that although the majority of scientific research indicates that anthropogenic pollution is the primary cause of climate change (including the Intergovernmental Panel on Climate Change (IPCC), the largest intergovernmental body responsible for collating and redistributing climate change-related research) there are some scientists who remain sceptical.

3.2. Emissions and Climate Change in South Africa

The South African Department of Environmental Affairs⁹ (DEA) acknowledges that South Africa contributes significantly to the emission of GHGs, and is simultaneously highly vulnerable to the impacts of climate variability and change (DEA, 2010). South Africa has one of the highest levels of GHG emissions per capita globally (DEAT, 2007). The total estimated South African GHG emissions are 500 million metric tonnes of CO₂-e (CDP, 2010). The World Resources Institute (WRI) identifies that in 2005 South Africa was responsible for approximately 1.1% of global and approximately 40% of sub-Saharan-African emissions (WRI, 2009).

At an average of 8.8 tonnes of CO₂-e per person in 2000, the per capita emission rate was above the global average of 6.7 tonnes and almost twice as high as the sub-Saharan-Africa average of 4.5 tonnes (WRI, 2009). At approximately 850 g CO₂/KWh, the South African average for energy efficiency is nearly twice as high as in industrialised countries. Thus, CO₂ accounts for the largest proportion of total GHG emissions in South Africa (approximately 80%), predominantly originating from electricity production (WRI, 2009).

South Africa is already facing climate change impacts in an increasingly carbon-constrained world, so a reduction in GHG emission intensity is urgently required (Pegels, 2009). The shortfall in electricity supply experienced since January 2008 (Von Hoffman, 2008), heavy dependence on imported oil and gas (BMI, 2011), increasing oil and gas prices, a desire for energy self-sufficiency, and global population growth put further pressure on South Africa to decrease carbon emissions.

The United Nations (UN) regards Africa as one of the continents most vulnerable to the impacts of climate change due to its agricultural dependence, existing water stress, and its weak adaptive capacity¹⁰ (IPCC, 2007). Warming in South Africa of 1.7°C by 2050 is predicted (Hulme, 1996), with the greatest warming mostly during the May to September dry season. Increases in rainfall during the wet season are more than offset by rainfall decreases

⁹ Department of Environmental Affairs and Tourism (DEAT) 1994-2009, Department of Environmental Affairs (DEA) 2009 onwards.

¹⁰ This is the capacity of a country or district to adapt to the anticipated changes in the climate, including *inter-alia* rising sea-levels, increased average temperatures, decreasing precipitation, the associated loss of agriculture and the spread of certain diseases.

in the remaining months of the year under these predictions. Increased evapotranspiration, associated with rising temperatures, put further strain on water resources and associated agriculture. Predictions for a range of climatic change scenarios for the entire African continent have been made, all of which predict warming, and significant decreases in rainfall over much of South Africa (Hulme *et al.*, 2001). South Africa may utilise most of its surface water resources within a few decades (DEAT, 2005a).

Water scarcity and demand for water are likely to increase due to climate change and lead to a deterioration of water quality. Much of South Africa is arid and subject to droughts and occasional flash floods, and these issues are likely to exacerbate desertification (DEAT, 2005b). Runoff into main rivers is likely to be reduced over much of South Africa, if global average temperatures increase over 2°C above pre-industrial temperatures (DEAT, 2005b). A 12% - 16% reported decrease in outflow at the mouth of the Orange River by 2050 is predicted (DEAT, 2005b). Economically, a loss of approximately 18% of fishery value may be precipitated by a national estuarine catch reduction of as much as 35%. Water security concerns have recently been further raised after the Government indicated an intention to permit fracking (hydraulic fracturing) by Shell SA within the Great Karoo. This is a semi-arid area of over 400 000 km², covering approximately 40% of South Africa (inland), and any pollution to the groundwater here could have drastic and long-lasting repercussions (Smith, 2013).

The majority of the poor in South Africa live in rural areas and rely on agricultural incomes, which are sensitive to changes in weather patterns likely to occur as a result of climate change (Mbuli, 2008). Also, malaria is expected to spread into malaria-free areas and may become more severe in areas where it already occurs (DEA, 2009). Aridification will lead to malaria carrying mosquitoes extending their range southwards and westwards into Namibia and northern South Africa (Hulme, 1996). The number of South Africans at *high risk* to malaria will quadruple by 2020, at a cost of 0.1% - 0.2% of GDP if no action is taken (DEA, 2009).

Unless corrective measures are taken, agricultural output (which needs to increase to meet the needs of a growing population) can be expected to decline. In addition, the adaptive capacity of large sections of the South African population is low: according to the UNDP, 45% of the population still live on less than US \$2 per day (UNDP, 2008). South Africa has been

experiencing a variety of unfavourable impacts from climate change and is foreseen to experience greater impacts in coming years (UNDP, 2008). South Africa is further constrained by its limited ability to adapt to these impending climactic changes and their effects (UNDP, 2008).

3.2.1. Status Quo

The global energy sector is directly responsible for climate change, as stated by the Green Economy Report (GER) on Renewable Energy (UNEP, 2011). The GER asserts that in addition to being unsustainable, the current energy system is highly inequitable: 1.4 billion people are without access to electricity and 2.7 billion dependent on traditional biomass for cooking, heating and hot water. Associated with traditional biomass is indoor air pollution, responsible for over 1.5 million premature deaths each year in developing countries, half of them children under the age of five (UNEP, 2011). The cost in terms of adaptation is estimated to reach US \$50 - 170 billion per year by 2030, half of which will be borne by developing countries thereby affecting the poor disproportionately. “Ensuring access to electricity for all requires US \$756 billion, or US \$36 billion per year between 2010 and 2030, according to estimates by the IEA, UNDP and UNIDO” (UNEP, 2011, p.204).

Past emissions have stemmed from the energy sector of high-income countries (Stern, 2006). Less than 25% of cumulated emissions have been caused by developing countries. In recent years the developing countries share of global emissions has been rising, and in 2000 they accounted for approximately 55% of annual global GHG emissions (WRI, 2009). Global energy-related emissions are estimated to rise by 45% between 2006 and 2030, in a business-as-usual (BAU) scenario (IEA, 2008). Almost all of this increase (97%) is expected to occur in non-OECD¹¹ countries, mostly due to greater use of coal.

The majority of the world’s energy needs are supplied by petrochemical sources, coal and natural gases (Demirbas & Demirbas, 2007). With the exception of hydro and nuclear fission, these resources are all finite. Within the least developed countries (LDC) 70% of the population (50% of the world’s population), depend solely on biomass for cooking and for

¹¹ OECD – Organisation for Economic Co-operation and Development, an international organisation of 34 countries (currently) founded in 1961 to stimulate economic progress and global trade. Most OECD members are high-income economies and regarded as developed countries.

heating water and homes (Openshaw, 2010); in these countries it is the principal source of household energy (Openshaw, 2010; REN21, 2007). The UN estimates that global population will be 9.2 billion by 2050 and total energy demand (allowing for energy efficiencies and conservation measures) may be around 1000 EJ¹², or around twice what it is today (UNDP, 2008; IEA, 2009). Most of the world's power generating systems were built over the last 40 - 60 years, and this ageing infrastructure is inefficient and increasingly unreliable (EJS, 2012). Other industrial sectors have been dramatically transformed by technology and innovation, whilst the electricity sector has continued to operate for decades in the same way (EJS, 2012). Every year of delay in bringing the energy sector on the 450ppm¹³ trajectory would add US \$500 billion to the global costs for mitigating climate change (UNEP, 2011).

To meet the challenge of increased energy demand, the DME and Eskom jointly released a policy document entitled *National Response to South Africa's Electricity Shortage* (2008). This plan includes a 2.4 GW generation expansion involving two new coal-fired power stations, the return to service of three coal-fired power stations put into hibernation in the 1990's, and to a lesser extent the exploration of co-generation and renewable energy (RE) options (DME, 2008). On the demand side, the "Power Conservation Programme" is a Government initiative to reduce demand through power quota allocations combined with penalties and positive incentives. Eskom set aims to reduce demand by 3 GW by 2012 and 5 GW by 2025 through encouraging behavioural change in its customers. They aimed to achieve these savings through, *inter-alia*, the increased installation of solar water-heaters and the use of energy efficient light bulbs, although these programmes are making slow progress (Pegels, 2009). The obstacles to large-scale dissemination of RE in South Africa are numerous but not impossible to overcome; RE technologies can provide a solution to the electricity supply and emission intensity aspects of the South African energy challenge (Pegels, 2009). However, in spite of a high resource potential, there has so far been little progress in the deployment of renewable alternatives.

Most South African power stations were built in the 1970's - 1980's when exchange rates were favourable. Tied with the cheap price of coal, this is the major reason for the low price of electricity (Pegels, 2009). Currently this is an obstacle to RE investment: it may become a supportive factor in the future. Investment in a new utility should not be compared to the

¹² EJ, exajoule, equal to 10¹⁸ joules

¹³ Parts per million of CO₂ in the atmosphere, above which catastrophic climate change events are predicted.

current cost of electricity production, but to the rising cost of alternative investments. Eskom's applications for higher tariffs in 2008, 2009 and 2012 to finance investment in new power stations document this trend (Philip, 2012). However, the higher prices have attracted public opposition since they are perceived to threaten the goal of poverty reduction. Given these constraints, the political will to invest public money in comparatively risky RE technologies is greatly weakened (Pegels, 2009).

3.2.2. Energy supply and CO₂ emissions in South Africa

South Africa's economy is heavily dependent on coal. South African coal resources are approximately 34 billion tonnes, accounting for 95% of continental African reserves and 4% of world reserves (WEC, 1992). Coal provided a 72% share of South Africa's total primary energy supply in 2007 and accounts for 86% of electricity generation (DEA, 2010). Coal is also the feedstock for the country's synthetic fuel industry (Sasol). All South African coal is classified as bituminous¹⁴. Energy supply in South Africa is therefore heavily carbon-intensive.

South Africa's direct (Scope 1¹⁵) GHG emissions continue to be dominated by a few carbon-intensive companies (CDP, 2010). In terms of direct local emissions the CDP data highlights the predominant contribution of Sasol (coal to liquid technology - reported annual direct emissions of 60 million metric tonnes of CO₂-e), followed by Arcelor Mittal SA (mining company - 10.7 million metric tonnes), Pretoria Portland Cement (5.1 million metric tonnes) and Sappi (paper products - 4.8 million metric tonnes) (CDP, 2010).

The state-owned electricity generator and distributor, Eskom¹⁶, is the overall largest emitter of GHGs in South Africa. Eskom generates 60% of all electricity used on the African continent (total electricity capacity¹⁷ of approximately 68 GW); however, approximately 75% of Africans do not have access to electricity (Eskom, 2011). According to Eskom, their emissions of CO₂-e by the end of March 2010 were 224.7 million tonnes, approximately 45%

¹⁴ Coal is commonly classified between anthracite coal, the highest quality coal, lignite coal, the poorest quality coal, and bituminous coal between the two, containing the tar-like substance bitumen.

¹⁵ Scope 1 emissions are those directly emitted by an industry, such as from a furnace. Scope 2 emissions are indirectly emitted through consumption of electricity.

¹⁶ Eskom is the South African state-owned electricity producer, responsible for almost all electricity produced within South Africa.

¹⁷ Maximum theoretical power output from all power stations.

of the total estimated South African emissions (Eskom, 2012; Eskom, 2010). South Africa accounted for 38% of CO₂ emissions from fuel combustion on the African continent (2008) and it represented 1.1% of the global total (IEA, 2010a). Coal is the primary energy source used in electricity production (86%), followed by nuclear (5%) and other sources, including renewable sources (primarily hydro-electric) (Eskom, 2012; Eskom, 2010). The coal used is easily accessible, cheap and of poor quality, resulting in wide consumption and increased emissions.

The South African energy sector is dominated by Eskom, which produces 95% of all electricity in South Africa, and also owns and operates the national transmission system (Pegels, 2009). Over 100 million tonnes of low-grade coal is burnt annually in Eskom's power stations (Eskom, 2010). The quantities of oxides emitted by Eskom power stations, including nitrogen oxide (NO), sulphur dioxide (SO₂) and carbon dioxide (CO₂) are calculated annually (based on the coal characteristics and power station design parameters). CO₂, SO₂ and NO emissions are rising continually, primarily due to increased electricity demand and the requisite increase in burning coal (Eskom, 2011). At nearly 50 billion tonnes, South Africa has the world's 6th largest recoverable coal reserves (EIA, 2008)¹⁸.

In 1998 Eskom set itself a target to reduce overall particulate emissions to an average of 0.28 kg/MWh within five years (Eskom, 2011). This target was achieved in 2003 due to the retrofitting of bag filters at some of its power stations, and flue gas conditioning at others (Lethabo Power Station); the subsequent target was 0.24 kg/MWh (Eskom, 2011). Eskom maintains that due to South Africa's water scarcity, they are finding ways to improve their water usage practices and operate some of the largest dry-cooled power stations in the world. During 2009/2010 Eskom power stations used 1.35 litres of water/kWh of power - within their stated targets, which are set annually (Eskom, 2011).

Until the mid-1990's Eskom had excess supply capacity; in 1994 only 36% of households in South Africa had access to electricity (DOE, 2013). Mass electrification programmes led to 72% of households being electrified by 2004, and the Government aimed to achieve national access by 2012. Eskom is operating at nearly full capacity: peak demand is approximately 36

¹⁸ This estimate is 16 billion tonnes greater than the estimate on page 26 (WEC, 1992). This difference could be due to different techniques used in establishing the estimate, given the 16 year difference in the estimates. The earlier estimate also refers to coal resources, and this estimate refers to recoverable reserves, which might explain the difference.

GW, matched by an installed capacity of nearly 40 GW, leaving a narrow reserve margin of around 10% (DME, 2008). Economic growth and industrialisation have led to rising electricity consumption and this is expected to continue (demand increases by 4% per year), leading to a doubling of total demand and requiring an additional 40 GW by 2025 (Pegels, 2009). South Africa experienced serious power shortages in early 2008, the economic impact of which is estimated at US \$253-282 million (EIA, 2008).

3.2.3. South African Coal-to-Liquid Technology

The high cost of dependence on imported oil combined with very large coal reserves are the two main reasons for South Africa's use of coal to liquid (CTL) technologies. However, the efficiency of barrels of oil produced per tonne of coal input means that the carbon emissions are far greater than using traditional fossil oil. South Africa developed German CTL-technology in the 1950's and CTL now plays a vital part in South Africa's national economy, providing over 30% of their fuel demand (Höök & Aleklett, 2010). Sasol owns the only commercial-scale Indirect Coal to Liquid (ICL) plants in operation in South Africa¹⁹ (Sasol, 2009).

Sasol has produced over 1.5 billion barrels of synthetic oil, from its inception until 2005 (WCI, 2006). A number of different ICL-technologies have been developed by Sasol, the oldest ones date from the 1950's and were used to the late 1980's. Today, advanced technologies from the 1990's are utilized: the Sasol Advanced Synthol High Temperature FT-synthesis and the Sasol Slurry Phase Distillate Low Temperature FT-synthesis. Shell estimates the theoretical maximum thermal efficiency of ICL as 60%²⁰ (Tijmensen *et al.*, 2002). Detailed well-to-wheel²¹ analysis of energy flows for ICL diesel show typical overall efficiencies are around 50% (Van Vliet *et al.*, 2009).

¹⁹ Direct Coal to Liquid processes involve pyrolysis, carbonization or hydrogenation to produce liquefaction. Indirect CTL processes first involve gasification to produce syngas which is then processed and converted to petroleum and diesel.

²⁰ Thermal efficiency is a performance measure for devices that use thermal energy, such as engines and boilers, and measures the energy input compared with the energy output. Theoretical maximums are generally unachievable as they do not allow for any inefficiencies or loss of energy through the process.

²¹ Well-to-wheel refers to the total combined carbon emissions, including all processes from extraction and processing of the fuel, through to its final use, or combustion.

Sasol can be used to establish an empirical estimate of the coal consumption by CTL (Höök & Aleklett, 2010). The Secunda site consists of two CTL plants with a combined capacity of 150 000 barrels/day (b/d) and over 40 million tonnes (Mt) of coal per year is consumed (Sasol, 2009). In 2003 Sasol consumed 24% of all coal produced in South Africa (Höök & Aleklett, 2010), representing 57 million tonnes (40 - 57 Mt for Sasol coal consumption). One barrel of synthetic fuel consumes 0.73 - 1.04 tonnes of bituminous coal (1 - 1.4 barrels/tonne coal) (Höök & Aleklett, 2010). Approximately 2.86 tonnes of CO₂ are released for every tonne of coal combusted, so for every barrel of Sasol oil (159 litres) between 2.04 - 2.86 tonnes of CO₂ are emitted (12.8 - 17.9 kg/litre). A litre of standard petroleum releases 2.36 kg CO₂ when combusted, demonstrating the magnitude of increase in CO₂ emissions from CTL fuels as opposed to standard fossil fuels (Kageson, 2005).

3.2.4. South Africa's Renewable Energy Commitments

The Department of Energy's recently published legislative and policy framework is summarised in the Energy Journal Supplement (EJS, 2012): the Energy Act 34 of 2008; the Electricity Regulation Act, as amended; the White Paper on Renewable Energy Policy (under review); the Integrated Resources Plan (IRP) 2010 - 2030; work is progressing on the development of an Integrated Energy Plan (IEP), planned for 2014; and Draft Energy Efficiency Regulation (currently released for public comment).

In 2003 the South African Department of Minerals and Energy (DME) published a White Paper on renewable energy, setting a target of 10 000 GWh of RE contributions to final energy consumption by 2013. However, this target was cumulative, starting in 2003, and so equivalent to an average of 1 000 GWh per year (DME, 2009). South Africa produced two Long Term Mitigation Scenarios (LTMS) in 2007 (DEAT, 2007). They show possible emission pathways from 2003 to 2050: one business-as-usual (BAU) without any constraints on the growth of emissions; the other a mitigation scenario, aiming at reducing emissions by 30 - 40%. The LTMS energy model assumes a renewable electricity share of 15% in 2020 and 27% by 2030 (Hughes *et al.*, 2007). It is unclear how these targets will be achieved, as little has been done towards achieving this RE target (by 2009 only about 3% [269 GWh] had been installed) (DME, 2009).

Initial steps have been taken to enhance energy efficiency and promote RE, but they have failed to have any large scale effects (Pegels, 2009). There is a trend of businesses introducing the use of renewable energy to gain a competitive edge by reducing the need for conventional fossil fuels (Archbold, 2007; Demirbas, 2008); these businesses are also able to promote their *greenness* whilst saving costs. Biofuel policy must promote economic growth, particularly in rural areas, whilst promoting greater awareness and conservation for the environment (Puppán, 2002; Archbold, 2007; Demirbas, 2008). The use of biofuels in rural areas can provide employment as well as electrification, whilst promoting other environmental benefits such as soil conservation, run-off interception and carbon sequestration (Brennan & Owende, 2010).

3.2.5. Carbon Capture and Storage

In an effort to meet its targets to reduce CO₂ emissions, carbon capture and storage (CCS) has become an integral part of South Africa's proposed solution to the global emission problem. Mitigation strategies for large scale emitters of CO₂, such as coal-fired power stations, primarily involve a three-stage process of carbon-capture, (contained) release and storage. Separation technology involves the chemical absorption through the use of aqueous amines, followed by release through heating, an energy intensive process. The CO₂ is then processed, and compressed for transportation and storage. CCS has yet to be implemented within South Africa, and is still being trialled elsewhere in the world²².

However, research has commenced in this area and Sasol in particular are involved as CCS is part of their future business model (Sasol produces the world's largest point source of pure CO₂ from their coal to liquid plant in Secunda) (Goldenberg, 2010). A National Centre for CCS was established in South Africa in March 2009 and research has begun into potential storage sites. There is a growing belief, however, that it may be easier, less costly and safer to increase the CO₂ storage in biomass and soils, while at the same time increasing the supply of wood for biomass energy (Openshaw, 2010; Mendis *et al.*, 1997). CCS is currently a very expensive technology, still in very early stages of development. The use of microalgae to metabolise a proportion of these industrial CO₂ emissions and store them in a stable, transportable liquid state will have the same effect as CCS.

²² Essentially this is an untested theoretical solution to the problems of carbon emissions. The energy balances, technologies and financial expense are under research, particularly in Scotland.

3.2.6. Renewable Energy Status in South Africa

3.2.6.1. *Hydro*

Renewable energy can be divided into six main categories: Solar, Wind, Hydro, Ocean (tidal, wave and thermal), Geothermal and Bioenergy. Of the world's hydroelectric potential, just over one-third is currently developed (Eskom, 2010). Africa's hydro potential is not evenly distributed throughout the continent, varying from high hydro potential in high rainfall countries, such as the Democratic Republic of the Congo (DRC), to low hydro potential in water scarce countries such as South Africa. The management of water supplies in South Africa has been developed to ensure its full potential, resulting in strong ties between Eskom and the Department of Water. Eskom has three types of hydroelectric power stations: conventional reservoir (Gariep and Vanderkloof); run-of-river (Colley Wobbles, First and Second Falls and Ncora); and pumped storage schemes (Palmiet and Drakensberg).

South Africa has moderate hydroelectric potential, and the establishment of small hydroelectric projects could provide a sustainable energy supply (Anon., 2004). The US department of energy estimates that there are 6 000 to 8 000 potential sites in South Africa suitable for small hydro-projects below 100 MW, with KwaZulu-Natal and the Eastern Cape offering the best prospects. The largest hydroelectric power plant in South Africa is the 1 000 MW Drakensberg Pumped-Storage Facility, part of a larger scheme of water management that brings water from the Tugela River into the Vaal watershed. The country's second-largest plant is situated on the Palmiet River outside Cape Town, and won the 2003 International Hydropower Association's (IHA) Blue Planet Prize²³ (Eskom, 2011). This pumped storage scheme in the Western Cape transfers water from the Palmiet River catchment into the Steenbras Dam to supplement Cape Town's water supply, and can generate 400 MW during peak demand periods (Eskom, 2011). This hydro potential gives South Africa the opportunity to offset a portion of its existing coal-based electricity generation with a more sustainable long-term option.

²³ This prize is awarded by IHA every two years, with evaluation support by UNESCO's International Hydrological Programme, and an aim to increase awareness of hydropower's contribution to sustainable development. The prize recognises good practice and sound management in the development and operation of a hydropower scheme, on the basis of technical, economic, social and environmental criteria.

3.2.6.2. *Wind*

Wind energy accounts for only 0.05% of annual electricity production in South Africa, supplied mainly by the Darling wind farm and the Eskom Klipheuwel demonstration plant (Eskom, 2008). Two hybrid mini-grid wind turbines in the Eastern Cape add slightly to this amount, along with some other isolated off-grid turbines. The development of turbines in recent decades has allowed wind to become a feasible RE resource and contribute significantly to energy production (Jebaraj & Iniyar, 2006). Several studies have been carried out to assess the wind energy potential of South Africa and the estimates range from only 500 MW to a high estimate of 56 000 MW (Szewczuk & Prinsloo, 2010).

There have been relatively few wind-turbine projects in South Africa, mainly due to lack of funding and international NGO involvement (Van der Linde, 1996; Ackermann & Söder, 2000). Currently the Global Environmental Facility (GEF) and the Danish Government are funding a three-year project to develop an accurate wind resource map for the coastal regions of South Africa. Global wind power has a theoretical output of 20 000 to 50 000 terawatt hours (TWh) per year (WEA, 2000). Of the calculated global electricity consumption of 16 816.98 TWh, and South African consumption of 232.23 TWh (2008), this estimate may lead to wind providing a far greater portion of our energy supply (IEA, 2010b).

3.2.6.3. *Solar*

Photo-voltaic solar panels (PV) and Concentrated Solar Power (CSP) are the two best-developed techniques for converting energy from sunlight into electrical power. Photo-voltaic technologies convert direct sunlight into electricity through the generation of free electrons by semi-conductors within solar cells (WEA, 2000; Goswami *et al.*, 2004; Alboteanu *et al.*, 2006; Crabtree, 2007). This technology is advancing rapidly, and rates of conversion efficiency are constantly improving: mass produced solar panels currently have conversion efficiencies between 10 and 15% (WEA, 2000).

The current (levelized) cost of electricity production from CSP, currently the most competitive form of electrical solar-power, is approximately EUR \$0.13 per KWh (DLR, 2005). However, CSP is still at an early stage of commercialisation and the cost reduction potential is yet to be fully explored. The German Aerospace Centre (Deutsche Zentrum für Luft-und Raumfahrt) estimates a cost reduction down to EUR \$ 0.05 KWh at a global total

installed capacity of 40 GW between 2020 and 2025 (DLR, 2005) (Pegels, 2009). Renewable energy has yet to be exploited on a large scale in South Africa as the technology cannot compete with coal-fired power stations generating electricity at EUR \$ 0.03 KWh (Pegels, 2009). Recently, however, South Africa has opened its first grid-connected, large scale 75 MW solar farm, in the Northern Cape region (Meehan, 2013).

Solar water-heating (SWH) is a relatively old technology, used extensively throughout the world to produce hot water from the sun's energy. In spite of the short payback time for an investment into solar water-heating, it is still relatively new to South Africa and under-used (DOE, 2011). However, this is starting to change as Eskom and the Government set binding targets to utilise this technology, particularly in low-cost housing projects and formal/informal settlements throughout the country. In June 2009 a target of 1 million SWH's was announced by the minister for energy, to be installed on household and commercial buildings over the following five years. By the end of 2010 31 000 SWH's had been installed and the rate of installations was increasing exponentially (DOE, 2011).

3.2.6.4. Biomass and Biofuels

Bioenergy is energy made available from materials derived from biological sources. Traditionally bioenergy emphasis has been placed on crops that produce oils and lipids, first generation biofuels. These fuels are easily extracted and burned in their existing state, or else after fermentation or chemical alteration (such as trans-esterification) (Bringezu, 2009). Biomass is any organic material of biological origin that has stored sunlight in the form of chemical energy (Demirbas & Demirbas, 2007). Land biomass is composed mainly of cellulose, hemicellulose and lignin (Klass, 2004). The uses of biomass are commonly described by the four F's: Food, Feed, Fibre and Fuel (Johnson & Rosillo-Calle, 2007). As an energy source biomass can be used by either burning it directly or converting it into liquid, solid or gaseous fuels using conversion technologies (fermentation, bacterial digestion and gasification, respectively) (Hall & House, 1995). Globally biomass accounts for 11% of total primary energy (TPE) consumption and in developing countries it is the primary energy source; it accounts for over 61% of TPE in sub-Saharan-Africa (Johnson & Rosillo-Calle, 2007).

The primary energy source of over 80% of rural South African households is wood fuel (Damm & Triebel, 2008), used extensively throughout the country for heating, cooking and

lighting. Wood and charcoal is also used for cooking across all South African classes. According to the FAO, production of charcoal in South Africa has increased from 41 000 tonnes in 2002 to over 700 000 tonnes in 2011 (FAO-stat, 2012).

Two streams of biofuel technology are commonly categorised: First generation biofuels that are derived from conventional feedstock (agricultural crops); Second and Third generation biofuels that refer to newer and generally more efficient technologies (Luque *et al.*, 2008). Second Generation biofuels are derived from plants made from lignin, hemicellulose and cellulose and requires high temperature and enzymes to break down these complex carbohydrates to simple sugars (Oliver, 2009). Third generation biofuels is an emerging science primarily involving the use of algae, and to a lesser extent bacteria, to produce combustible fuel through photosynthesis.

The combustion of biomass, as a fuel, results in no net release of carbon emissions (Hall & House, 1995). When used instead of fossil fuels, carbon emissions from the displaced fossil fuels are avoided as well as associated pollutants such as sulphur (Hall & House, 1995). Biomass contributes significantly to energy supply in developing countries (20 - 33%), while to a lesser extent in developed countries (approximately 3%) (WEA, 2000). Approximately 85% of biomass energy is utilised as solid fuels in traditional methods for cooking, heating and lighting. This is a very inefficient use of biomass - utilising only 5 - 15% of the energy stored within the biomass (Hall & House, 1995; Johnson & Rosillo-Calle, 2007). The low conversion of solar energy captured to biomass energy produced means that there is a need for vast feedstock to provide appreciable amounts of fuel (Menegaki, 2008).

Biodiesel is defined as the esters derived from oils and fats from renewable biological sources (Clements, 1992). Typically, oils from microalgae, animal fats and oilseed crops are chemically very similar, if not identical (Brown, 2004). In the EU, biodiesel accounts for 80% of biofuels for transportation and 82% of total biofuels production (Bendz, 2005). Biodiesel is obtained by the transesterification of vegetable oils and animal fats for use in diesel engines (Bendz, 2005; Demirbas & Demirbas, 2007). It has similar combustion properties to that of fossil diesel and can be used directly in existing diesel engines or as a blend with fossil diesel (Bendz, 2005). Agricultural products grown as feedstock for biodiesel include rapeseed, sunflower, jatropha oil, cottonseed and corn-oils; currently soybean is the main feedstock (Bendz, 2005; Demirbas & Demirbas, 2007).

The main benefits offered by modern biofuels include sustainability, reduction in GHG emissions, regional development, improvements in social structure and agriculture as well as security of energy supply (Demirbas & Demirbas, 2007). Other major advantages are its stored energy capability, or *energy on demand*, which can be drawn on at any time (Karthi *et al.*, 2005; Johnson & Rosillo-Calle, 2007). Other renewable energy sources, such as daily or seasonally intermittent solar, wind and hydro sources are constrained by the high cost and complexity of energy storage. Biofuels exhibit a closed carbon system that unlike fossil fuels means that the carbon emissions from burning are offset by the carbon absorbed by the plant in the growing stages (Puppán, 2002). Biomass also has the capacity to produce all forms of energy carrier including electricity, gas, liquid fuels and heat (solar, wind, wave and hydro are limited to electricity and in some cases heat) (Johnson & Rosillo-Calle, 2007).

The Department of Minerals and Energy of South Africa released a Biofuels Industrial Strategy in December 2007, which is a proposal of the Government's approach to policy, regulations and incentives (DME, 2007). This envisioned a five year voluntary phase in of 2% biofuels into transport fuels, supported by various tax incentives. As these incentives have proved to be insufficient, the Government has recently agreed to an October 2015 mandate for a minimum of 5% biodiesel blends and 2% bioethanol blends (Voegelé, 2013).

3.3. Biofuels

3.3.1. Criticism of Early Biofuels

Biofuels from corn (maize) account for 90% of all biofuels used in the U.S.A (Groom *et al.*, 2008). Biofuels derived from corn are unsustainable as they have the highest inputs per unit area of any biofuel crop and one of the highest of any major U.S. crop (Groom *et al.*, 2008). Corn has low energy balances when compared with other feedstock's, is a low-yielding, temperate crop and requires twice as much land for cultivation to produce the same volume of ethanol that can be produced from, for example, sugarcane (Johnson & Matsika, 2006; Xavier, 2007). If ethanol is produced in large quantities from low-yielding crops it can have negative environmental impacts and may actually generate more GHG emissions than traditional fossil fuels (Xavier, 2007). In cases where a biofuel plant is fired from coal-based sources, the energy and carbon balance can be negative compared to fossil petroleum (Farrell *et al.*, 2006).

Current biofuel agricultural practices seldom consider the potential damage to soil or how to mitigate degradation of soil. There is a need to incorporate residues that reduce erosion and to incorporate tillage practices and crop rotations (Groom *et al.*, 2008). Fertilizers used in appreciable quantities can cause secondary impacts to aquatic systems: the excess nitrogen and phosphate has the potential to lead to damaging algal blooms and subsequent eutrophication of the water body (Puppán, 2002; Groom *et al.*, 2008). The cultivation of bioenergy crops may contribute to GHG emissions through nitrous oxide (N₂O) emissions from both fertilizer production and application (Fritsche *et al.*, 2006). The degradation of fertile soils through the overuse of irrigation, agrochemicals and heavy harvesting equipment can all be caused by an increase in annual bioenergy crops (Fritsche *et al.*, 2006).

Water use by bioenergy crops is an important environmental issue especially in water scarce regions like South Africa (Fritsche *et al.*, 2006). Global climate change models suggest a significant decrease in rainfall over southern Africa (WGCCD, 2005). Bioenergy crops could result in the loss of habitats and endangerment or extinction of rare species, obstruction of migration patterns, and the degradation of soils and water bodies (depending on its spatial distribution and cultivation practices) (Fritsche *et al.*, 2006).

A food versus fuel debate has arisen concerning land used for food production and bioenergy crop cultivation (Alexander, 1985; Cornland *et al.*, 2001; Kartha *et al.*, 2005; Fritsche *et al.*, 2006). Growing crops for fuel rather than food is a contentious issue, especially in the very poorest countries (Brennan & Owende, 2010). Conflicts between biodiversity and bioenergy crop cultivation have also arisen, as increasing demand for fuels results in damage to biodiversity rich habitats (International Birdlife, 2005; Fritsche *et al.*, 2006). The palm-oil industry, particularly in Malaysia and Indonesia, has faced heavy criticism, accused of clearing thousands of square miles of tropical rainforest for palm-oil plantations (Brown & Jacobson, 2005).

3.3.2. Algae

Algae are some of the oldest organisms on earth and are either simple multicellular macroalgae or unicellular microalgae (Grobbelaar, 1982; Converti *et al.*, 2009). Rapid reproduction enables colonisation of harsh environments through adaptation (Mata *et al.*, 2010). Algae classification is defined by their life-cycle, basic cellular structure and pigmentation (Brennan

& Owende, 2010). The three most common algal classes are green algae and red algae (belonging to the same class), diatoms and brown algae (Scott *et al.*, 2010). Algae are either autotrophic (with the ability to photosynthesise), heterotrophic (able to attain nutrients from external sources) or mixotrophic (able to grow in both ways) (Brennan & Owende, 2010; Mata *et al.*, 2010; Converti *et al.*, 2009). Mixotrophic algae are likely to become more commonly used due to their advantages during the diurnal cycle of varying their energy source (Mata *et al.*, 2010; Brennan & Owende, 2010).

The ability of algae to produce substantial amounts of fuel without taking up much space is a key attribute of algae, without high resource demands when compared with other forms of biofuel (Groom *et al.*, 2008; Chisti, 2007). Algal species that prefer saline or brackish water do not utilise potable fresh water resources (Puppán, 2002; Brennan & Owende, 2010; Mata *et al.*, 2010). Algae have the potential to produce over 100 000 litres of biofuel per hectare per year, far greater than any other feedstock (Groom *et al.*, 2008). Algae have the ability to significantly improve air quality by sequestering CO₂. They are also able to improve water quality by sequestering excess nitrogen and phosphate from contaminated waterways (Puppán, 2002; Mata *et al.*, 2010; Brennan & Owende, 2010).

The U.S. Aquatic Species Project's initial research from 1978 involved extensive work collecting algal species from natural habitats (Sheehan *et al.*, 1998). This was followed by extensive screening to determine which of these strains were able to tolerate mass culture conditions and produce large quantities of lipids (Barclay *et al.*, 1987). An extensive microalgae culture collection was established to provide the U.S. National Renewable Energy Laboratory (NREL) with a large gene pool for additional study and manipulation (Brown, 2004). In 1995 the US Department of Energy decided to stop further funding for this program, due to budget cuts, but a large collection of work from over 16 years remains a great source of knowledge in this area (Sheehan *et al.*, 1998).

3.3.3. Microalgae

Microalgae are theoretically the most efficient photosynthesisers and hence producers of biofuel (Chisti, 2007; Gouveia & Oliveira, 2009; Mata *et al.*, 2010; Brennan & Owende, 2010). Microalgae can be cultivated on a wide scale throughout the year with continuous fuel production, requiring relatively little space (Grobbelaar, 1982; Chisti, 2007; Brennan &

Owende, 2010; Mata *et al.*, 2010). Microalgae can be grown in arid and semi-arid regions with poor soil quality where woody or herbaceous crops cannot be grown (Brown, 2004). Saline waters from aquifers or the ocean can be used for growing certain microalgae. Such water has few competing uses and cannot be used for agriculture, forestry or as potable water. The yield of biomass per acre from microalgae is 3 - 5 times greater than from typical crop plant acreage (Neenan *et al.*, 1986).

Studies show that economic fuel production will require microalgae to be intensively cultured in large outdoor ponds (Weissman & Tillett, 1992). Such a system consists of 0.15 m deep, raceway shaped ponds, with a paddlewheel for circulating the water. The use of raceways and other artificial environments allows for exploitation of non-arable land; the use of marine algae requires the use of brackish and saline water, hence placing minimal strain on freshwater resources (Campbell, 2008; Scott *et al.*, 2010; Wahal & Viamajala, 2010). Carbon dioxide and other nutrients can be injected into the culture to optimise algal growth and biofuel production. Increased biofuel accumulation within the cell is commonly triggered by environmental stress, such as depletion of a key nutrient (Brown, 2004).

Microalgae have a rapid growth rate, illustrating exponential growth under ideal conditions, allowing a doubling of their biomass in less than four hours in certain species (Chisti, 2007; Brennan & Owende, 2010). Another environmental benefit to the use of microalgae in the production of biofuel is the lack of need for harmful pesticides, herbicides and fertilizers (Puppán, 2002; Groom *et al.*, 2008; Brennan & Owende, 2010). The operation of microalgae biomass farms has emerged as a candidate for alternative approaches to capture and dispose of CO₂ (Chelf *et al.*, 1993). The microalgae essentially recycle the CO₂ from industrial flue gases into biofuel. Although this CO₂ is released when the biofuel is burned, the process effectively doubles the energy generated for a given quantity of CO₂ emissions.

3.3.4. *Dunaliella* and Glycerol

Aquafuel Research Limited, based in the United Kingdom, has developed a novel combustion cycle - the McNeil cycle - for standard production compression ignition engines (CI, diesel engines). Pure or crude glycerol can be combusted at very high efficiency without chemical alteration or the addition of combustion enhancers (Voegelé, 2008). Glycerol has traditionally been sourced as a low-value by-product of biodiesel manufacture from plant oil, as well as

other industrial by-products. Through transesterification of vegetable oils and ethanol, biodiesel and glycerol are produced: 1-unit glycerol for every 9-units of biodiesel (10%) (Pachauri, 2006; Dasari *et al.*, 2004). Catalytic salts remain in the glycerol and these are the only impurities that must be removed, usually through heat distillation, before the glycerol is fit for purpose (Ebiura, 2005). For pharmaceutical, cosmetic and dietary purposes crude glycerol requires further purifying to remove methanol and other contaminants (Thompson, 2006).

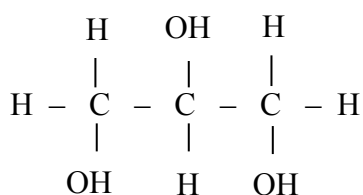


Figure 3.1. Chemical structure of glycerol (Source: UKZN, SAEES).

Glycerol combustion in combined heat and power (CHP) engines is more energy efficient than any known fossil, bio or synthetic fuel (34 – 37 % [10 – 30 kW] and 40 – 42% [up to 1 MW]), and no combustion particulate is produced ($1/10^{\text{th}}$ of the proposed 2013 California standards) (Harvey, 2010). Glycerol is water-soluble, bio-degradable, odourless, non-volatile, non-toxic, and non-flammable. Glycerol fuel stores can be safely used as thermal batteries, storing heat for CHP applications because glycerol has a high boiling point (290°C), relatively high density (1.26 g cm³), heat capacity (221.9 J/[mol K] at 25°C) and extremely low volatility (1mm Hg at 125.1°C). Glycerol could be used to power ships and even tankers carrying glycerol as a distributable fuel with minimal risk to the marine environment (Harvey, 2010).

Annual production of crude glycerol from biodiesel in the EU is approximately 1 million tonnes (2010). It is estimated that a 1 MW CHP engine will consume 4 800 tonnes of glycerol *per annum* to provide power and heat to supply over 1 000 homes and waste heat to distil 10 000 tonnes of crude glycerol per annum (conservative estimate approximately 1 MWh thermal per tonne of glycerol distilled). Alternatively, it could provide electricity for desalination to produce 5.3 million tonnes of potable water (1 tonne of potable water requires approximately 1.5 kWh of electricity) (Harvey, 2010). Aquafuel Research Ltd has carried out

long term experiments on the burning of biodiesel by-product glycerol in CHP diesel engines with very positive results (Voegelé, 2008).

The use of glycerol in power generation will reduce CO₂ emissions, but may also increase the demand for glycerol and the pressure on supplies of plant oil from which it is sourced. Glycerol synthesised *de novo* as an osmolyte in halotolerant microalgae is a potential source of glycerol, which does not require chemical processing of triglycerides (Ben-Amotz, 1981). In 1978 and 1980 patents were obtained for the production of glycerol from halophytic microalgae of the *Dunaliella* species (Ben-Amotz, 1978 and 1980). For the lifetime of these patents the use of this microalgae to produce glycerol commercially will require the legal consent of Ben-Amotz.

Dunaliella salina have no cellulose cell wall and produce glycerol in solution within the cell through photosynthesis. Up to 80% of their mass can be produced as glycerol in highly saline environments, dependant on biological (species and strain selection) and environmental constraints (Ben-Amotz, 1980). Industrial-scale production of these algae continued but the focus was moved to carotenoids, another valuable commodity, produced by the algae to protect from harmful ultra-violet.

Several hectares of *Dunaliella* halophytic algae are currently bred at industrial levels in Eilat, Israel, in shallow oval raceways (Seambiotic, 2010). In these production facilities geared to producing carotene from the *Dunaliella*, productivity levels of approximately 18 000 l ha⁻¹y⁻¹ have been achieved. However, little is known about the sustainability of glycerol production from microalgae and hence how this compares with glycerol production from biodiesel manufacture and other production pathways (Kishimoto *et al.*, 1994).

Experiments with *Dunaliella salina* of the late 1970's demonstrated that glycerol levels fluctuate dependent on the saline concentration, maximising production at 4-5mol (M) NaCl (Kaplan, 1980). Since this alga grows best on saline water, artificial ponds can be created in uncultivable arid areas, which have a supply of foul, brackish or saline water. Photosynthesis and starch breakdown both contribute to glycerol synthesis (Giordano *et al.*, 1994). The relative contribution of each pathway appears to be dependent on the magnitude of salinity stress, the light regime, external pH value and the starch content within the cells, and is directly related to CO₂ assimilation (Wegmann, 1971). Inorganic phosphate also plays a

major role in regulating the flux of carbon between the synthesis of starch and production of glycerol (Harvey, 2010). Adjustment of intracellular glycerol concentration through regulating the carbon flux between starch production in the chloroplast and accumulation of glycerol in the cytoplasm is a characteristic response of *Dunaliella salina* to salinity stress.

3.3.5. Commercial Development of Microalgae

Under natural conditions the concentration of *Dunaliella salina* microalgae is low and without commercial interest (Ben-Amotz, 1978). Cultivation under controlled conditions makes commercial exploitation of the specific properties of this alga possible. Photoautotrophic microalgae are mass cultured in either open systems such as natural rivers, lakes and dams, or artificial raceways; or in closed systems, which are photo-bioreactors consisting of glass or plastic tubes used to circulate the algae in carefully controlled solution (Puppán, 2002; Chisti, 2007; Campbell, 2008; Brennan & Owende, 2010; Mata *et al.*, 2010; Scott *et al.*, 2010; Wahal & Viamajala, 2010). Artificial raceways are more common (mainly due to their low initial setup costs) and are shallow (less than 0.5 m) to allow maximum light penetration to the algae. The water is circulated to facilitate exchanges between the air and water, reduce turbidity, and ensure algae do not sit shadowed on the pond floor (Campbell, 2008; Brennan & Owende, 2010).

Dissolved CO₂ is a limiting factor for algal productivity, therefore submerged pipes can be used to release bubbled CO₂ (Brennan & Owende, 2010). Significant improvements in glycerol yield have been demonstrated when diffusing flue gas directly from coal-fired power stations. Impurities in the flue gas act to catalyse the conversion rather than inhibit the process (Seambiotic, 2010). Fossil fuel derived GHGs can be directly incorporated into renewable biofuels, thus mitigating a portion of industrial CO₂ releases. By locating the algal glycerol ponds in close proximity to the source of CO₂, the expensive and energy intensive process of compression and transportation of gases is avoided (Seambiotic, 2010).

Open ponds are more susceptible to environmental changes, including temperature, evaporation, CO₂ deficiencies, seasonality and to the risk of contamination and disease (Moss, 1973a; Moss, 1973b; Trujillo & Thurman, 2005; Brennan & Owende, 2010; Wahal & Viamajala, 2010). Closed photo-bioreactors overcome many of these, but have significantly

greater construction costs; open raceways have lower construction costs, energy requirements and maintenance (Puppán, 2002; Chisti, 2007; Campbell, 2008; Brennan & Owende, 2010).

There are many potential by-products of a microalgae farm, which include carotenoids, omega-3 oils and biomass from the remaining cell structures. This biomass can be used either as animal/fish feed or organic fertiliser, or can be processed into biofuel and improve the energy balance. These potential resources will be necessary in maximising the financial return from a fully operating aquaculture farm, and ensuring that it can compete financially against traditional fossil fuels and alternative renewable sources (Harvey, 2010). The growth of algae is a complex process involving interactions between all growth parameters within the aquatic medium (Pillay, 2010). These parameters are intertwined, so it is necessary to evaluate all parameters simultaneously in order to ascertain the optimal growth conditions for *Dunaliella* (Converti *et al.*, 2009; Brennan & Owende, 2010; Mata *et al.*, 2010; Pillay, 2010).

3.3.6. Microalgae Optimal Growth Parameters

3.3.6.1. *Light and Temperature*

Light is shown to be the major factor affecting algal growth and productivity (Sorokin & Krauss, 1958; Foy *et al.*, 1976; Salisbury & Ross, 1992; Wahal & Viamajala, 2010; Scott *et al.*, 2010). Light attenuates through a water column according to depth, creating euphotic, disphotic and aphotic zones (Trujillo & Thurman, 2005). An increase in light intensity does not always cause an increase in algal growth. This can be due to other limiting environmental parameters (CO₂, temperature, salinity etc.) or to the alga being specialised to a particular water depth or shade and hence a range of light intensity (Sorokin & Krauss, 1958; Foy *et al.*, 1976).

The penetration of sunlight into an aquatic system is the main factor affecting its temperature (Trujillo & Thurman, 2005). A thermocline is formed as warmer water starts to lie over colder water. This thermocline is important in governing the exchange of nutrients between varying depths (Trujillo & Thurman, 2005). Microalgae are most productive at the water surface due to the abundance of light and the availability of nutrients through upwelling (Moss, 1973a; Moss, 1973b; Trujillo & Thurman, 2005; Converti *et al.*, 2009).

3.3.6.2. *Salinity, pH and Turbidity*

Salinity, pH and turbidity are important factors in the growth and productivity of microalgae (Abril *et al.*, 2004). For salinity this is closely related to the ability of CO₂ to dissolve in varying salt concentrations. As the salt concentration increases, CO₂ dissolves less readily, and lower salinities cause higher partial pressures of CO₂ (a linear relationship exists between salinity and partial pressures of CO₂) (García-Luque *et al.*, 2005). pH also affects the activity of enzymes within the cell walls of algae and the ability of the algae to uptake nutrients (Moss, 1973a). The availability of inorganic carbon ions is also altered by higher pH's (Moss, 1973a; Abril *et al.*, 2004). In order to prevent settling out of the microalgae and maximise their exposure to sunlight the turbidity of the water mix must be ensured. This is done by maintaining a constant flow of water around a raceway, for example through rotation of paddle-wheels.

3.3.6.3. *Carbon, Nitrogen and Phosphorous*

Dissolved inorganic carbon, through photosynthesis, is assimilated by photoautotrophic algae and converted to particulate organic carbon. Some species of microalgae are only able to assimilate carbon from either CO₂, bi-carbonate or carbonates, and the presence of other forms can be damaging (Moss, 1973a). Both nitrogen (N) and phosphorous (P) are integral nutrients to all primary producers within aquatic systems and can promote the production of organic matter (Salisbury & Ross, 1992; Gruber, 2008). Nitrogen, in the right form and bioavailable, is readily assimilated by algae to form amino acids and chlorophyll molecules – essential to growth and photosynthesis (Salisbury & Ross, 1992). In natural marine environments a circulatory system allows upwelling to constantly bring N and other nutrients to the euphotic zone - where the majority of primary production occurs (Trujillo & Thurman, 2005; Gruber, 2008).

Phosphorous forms structural and functional components in all biological organisms and is an integral part of adenosine triphosphate (ATP), the chemical energy carrier within cells (Salisbury & Ross, 1992). The availability of P is integral to photosynthesis and can therefore limit primary production (Paytan & McLaughlin, 2007). Within the photosynthetic reaction P must be available in the form of orthophosphate. Unlike N, which can be fixed into usable forms by a number of organisms, P cannot, and is often the limiting nutrient in primary production (Paytan & McLaughlin, 2007). Phosphorous enters the marine biological cycle

from the weathering of certain rocks, from volcanic activity and from upwelling, where P may be present in sediment (Slomp & Van Cappellen, 2007; Paytan & McLaughlin, 2007).

3.3.6.4. Micronutrients

Silica (Si) and iron (Fe) are the two most significant micronutrients required by algae. Iron is essential in plant metabolism for electron transfer during respiration, photosynthesis and in nitrate reduction, and yet is not readily bioavailable due to its insolubility (Sunda & Huntsman, 1997; Sunda & Huntsman, 1995; Salisbury & Ross, 1992). Certain algae have demonstrated accelerated growth with increased quantities of silica - some instances have shown promoted growth even when carbon is limited (Das & Chattopadhyay, 2000).

3.3.7. Infrastructure

Wiessman & Tillett (1992) describe the operation of an outdoor test facility in Roswell, New Mexico, as an engineering design assessment. Two 0.1 hectare raceway ponds were operated successfully, providing statistical data on microalgal growth rates in mass culture, CO₂ utilisation and pond design parameters. Concurrently, research was conducted into various means of lipid extraction and conversion to biodiesel (Nagle *et al.*, 1988; Nagle & Lemke, 1990). Biofuel harvesting from microalgae requires separation of the solids and liquids from the medium, this being a highly energy inefficient process (Mata *et al.*, 2010).

Harvesting methods, flocculation, filtration and centrifugal sedimentation, require large amounts of energy, and become more energy intensive with smaller algal cells with low cell density (Brennan & Owende, 2010). Species selection therefore becomes a factor when evaluating biofuel energy efficiencies. Flocculation reduces the negative charges between cells, which prevents them concentrating, causing aggregation. Flotation traps algal cells together on the water surface with air bubbles. Gravity sedimentation, based on Stokes' Law of settling attributes, is most suitable for use with larger algal cells (approximately 70 µm and larger) (Van Ommen, 2010). Filtration is usually performed after flocculation, flotation and gravity sedimentation techniques have been performed. For the smallest microalgae, ultrafiltration or microfiltration is employed over conventional techniques (Brennan & Owende, 2010).

Conventional algal biofuels, derived from algal oils, are converted into biofuels through thermochemical or biochemical technologies (Luque *et al.*, 2008; Brennan & Owende, 2010). Thermochemical (direct combustion, gasification, thermochemical liquefaction and pyrolysis) requires high energy input (temperatures - gasification requires 800-1000 °C thermochemical liquefaction requires 200-500 °C and pyrolysis requires 350-750 °C).

3.3.8. Socio-Economic Benefits to South Africa

Investment in RE reduces unemployment in the short-term, according to modelling for the GER, due to the higher labour intensity (UNEP, 2011). Direct employment from *greening* the energy sector could exceed Business-As-Usual (BAU) by approximately 15%, when an estimated 5 million jobs in goods and service businesses is considered (UNEP, 2011). In 2006 over 2.3 million people worldwide were estimated to be working either directly or indirectly in the RE sector. Further growth in employment will depend on factors such as further maturing of technologies, investment, overall progress in economic development, market size, national regulation and the quality and cost of the labour force. The Green Job Report estimates, with strong policy support, that up to 2.1 million people could be employed in wind energy and 6.3 million in solar PV by 2030, and approximately 12 million in biofuels-related agriculture and industry (UNEP, 2008; UNEP, 2011). The RE industry in Spain generates between 1.8 and 4 times more jobs per MW installed than conventional sources (Sastresa *et al.*, 2010).

Approximately 80% of sub-Saharan-African oil reserves are located in Angola and Nigeria (Davidson & Karekezi, 1992) and approximately 90% of the region's coal reserves are located in South Africa (WEC, 1992). Alternatively, RE sources are relatively well distributed throughout sub-Saharan-Africa, with potential to provide secure, environmentally sound energy future for the poorer populations within Africa (Davidson & Karekezi, 1992). Sub-Saharan-Africa has the largest bioenergy potential amongst all major world regions, after accounting for food production and resource constraints (Smeets *et al.*, 2004; Mathews, 2007). This is a result of large areas of available cropland and low productivity of existing agricultural production systems (Johnson & Matsika, 2006). Millions of sub-Saharan-Africans lack access to energy, or a reliable source of energy; an expansion of RE sources becomes critical in bringing reliable energy to the rural and urban poor. "South Africa, Swaziland and Namibia are not rich, nor do they have vast areas of arable land, so some

countries have far less ability to develop an intensive biofuel programme. The resulting rapid growth in consumption and of a decentralised renewable energy economy are seen as the primary options for Southern Africa to drive its economy in a direction that reflects the rich and the poor, the north and the south” (Sugrue, 2006, p.2). Providing decentralized, RE, particularly to more remote areas can significantly improve social, environmental and financial interests of communities.

The Food and Agriculture Organisation (FAO) of the UN Terrastat database identifies 1.1 billion hectares of potentially arable land in sub-Saharan-Africa (Mathews, 2007). However, only 158 million ha was under cultivation in 1994, and estimates measure that 197 million ha are under cultivation today. Mathews (2007) suggests that a biopact between the north and south could drive industrial development and drastically improve local economies. Even without this arrangement there are still many reasons to invest in renewable technologies. These include health improvement, reduced regional emissions, creation of rural livelihoods, and advantages of independence from imported sources of energy (Johnson & Matsika, 2006).

3.4. Limitations and Knowledge Gaps

In 1992 the UN Conference on Environment and Development (UNCED) held in Rio, Brazil, resulted in Agenda 21, which sought to instigate action on the concept of sustainable development. The conference was also the venue for the signing of the UNFCCC, and within both initiatives renewables were perceived as an important option for mitigating and abating GHG emissions (Socolow, 1992). The 2002 World Summit on Sustainable Development held in South Africa set a 2015 target of 15% RE for the Least Developed Countries (LDC), as part of the Millennium Development Goals (UNDP/WB, 2002). But the definition of RE was mainly confined to solar, wind and water, completely ignoring ‘traditional’ biomass fuels, which are considered to be ‘unsustainable’. Most LDCs would have already achieved the 15% RE target if biomass fuels had been included (Openshaw, 2010).

The World Bank Group Energy Strategy Approach Paper (WB, 2009) focuses on improved electricity access for developing countries and states that *traditional biomass* fuels are non-renewable and should be substituted. In many publications, such as the World Bank’s Annual

Development Report (WB, 2003), consumption of biomass is ignored. Only the commercial energy forms - petroleum, natural gas, coal, and hydro/ geothermal/ nuclear electricity - are recorded in energy statistics and the per-capita consumption of these forms are used as development indicators.

“Thus, an energy planner can talk about petroleum products accounting for 80% of energy consumption in Tanzania, with electricity accounting for the remaining 20% (Sharma, 1979), when in fact biomass accounts for 80% of energy consumption and that of petroleum products and electricity 16% and 4% respectively (FAO, 1970)” (Openshaw, 2010, p.8). Of the World Bank’s investment in the ten-year period ending 2003, energy development accounted for nearly 12%, US \$24.8 billion out of a total spending of US \$216.7 billion. Only 3.2% of that was for RE, the bulk of it non-biomass energy (WB, 2004).

Investments in RE projects carry particular risks, including those associated with new technologies, and the uncertain effective price of carbon that traditional energy sources will have to pay. “In addition there are issues of high upfront capital costs, access to finance, and the partial public-good nature of innovation. Together these hinder the competitiveness of renewable energy technologies, discouraging private investments in their development and deployment” (UNEP, 2011, p.205).

Land-clearing for arable agriculture has been highlighted as the cause of 95% of deforestation in sub-Saharan Africa (Openshaw, 2004). As a result more forest land is being cleared than is being replaced by newly planted or naturally regenerating trees. This has resulted in more CO₂ being released into the atmosphere from forest land clearance than is being sequestered. “Many publications assume that all carbon-based fuels increase atmospheric CO₂. The World Bank’s Environmental Department (WB, 1990) stated that until (non-polluting) new and renewable energy resources (water, wind, solar) are adopted on a large scale, the world will have to go on burning existing (polluting) fuels, but should do so as efficiently as possible. This statement was reiterated at the 2002 World Summit on Sustainable Development in South Africa (UNDP/WB, 2002). Such thinking completely ignores the fact that half the world’s population already uses biomass fuels, which are renewable and relatively non-polluting” (Openshaw, 2004) (p.6).

According to the UNEP, the maturity of technologies and the related *learning effects* have increasingly improved their economic competitiveness (UNEP, 2011). European hydro and off-shore wind resources are already competing with fossil fuels and nuclear technologies, and on-shore wind will soon be competitive with natural gas technologies (UNEP, 2011). Fossil fuel combustion has both pollution and human health impacts: if these externalities were factored into the energy production costs of fossil fuel, RE technologies would become highly competitive (UNEP, 2011). Government subsidies, for both fossil fuel production and consumption, total US \$500 - 700 billion per year globally according to IEA, OECD and World Bank estimates. Removing these subsidies would further help investment into renewable technologies. Increasing investment flows will result in accelerated cost-reducing innovation in all renewable technologies (UNEP, 2011).

Regulatory support for RE technologies has increased over the past 10 years. Between 2004 and 2009 the number of countries with supportive policies rose from 40 to over 100 (UNEP, 2011). Global new investment in sustainable energy (2011) hit a new record of US \$243 billion (Finance, 2011). This is over 30% greater than the US \$186 billion invested globally in 2009 and the US \$180 billion in 2008 (Finance, 2011). According to the UNEP SEFI Sustainable Energy Investment Trends Report (2010), approximately US \$188 billion in funding has been allocated to RE and energy efficiency globally (SEFI, 2010). Of that amount, however, only around 9% had been spent at the end of 2009. This delay reflects the time it takes for spending to be approved through administrative processes, and because some projects were only formally presented after the programmes were announced (UNEP, 2011).

The challenge of transforming entire economies is enormous, especially if a country is as fossil-fuel-based and emission intensive as South Africa (Pegels, 2009). The innovation system in South Africa is dominated by the state-owned Eskom (electricity) enterprise (Pegels, 2009). Along with Sasol, both companies have their core competencies in fossil fuel technologies. Capacity in RE is lacking at every stage of the technology cycle from research and development (R&D) to installation and maintenance (Pegels, 2009).

Eskom and Sasol are responsible for the bulk of investment in energy research and development, and they are the major employers of university graduates in the relevant fields. This has led to a bias in the innovative capacity towards fossil fuel innovation (Pegels, 2009). Through secondary and tertiary education there is a lack of capacity basis in RE technologies.

Both Eskom and Sasol have used their influence to protect the energy market's features suited to their core competencies (Pegels, 2009). Hence, fostering a favourable environment for RE providers has not been integral to their business model (Pegels, 2009).

DNA from microalgae with biofuel potential have been analysed chemically (Jarvis, 1991). Progress has also been made with respect to the development of new products for introducing foreign genes into microalgae (Dunahay, 1993). These efforts are made in order to improve the production of biofuels from algae and close the financial gap between these technologies and traditional fossil fuels, and much research continues in this area. In order to better understand the necessary growth conditions of specific algae species, the potential co-products and the maximum rate of photosynthesis, further species-specific investigation is needed (Brennan & Owende, 2010). The development of large-scale operations is also needed to determine actual maximum yields, since most algal yields are theoretical. The UNDP (2009), states that despite the potential, there is insufficient awareness and understanding of bio-carbon opportunities in eastern and southern Africa (UNDP, 2009).

3.5. Summary and Conclusions

Evidence from this chapter shows that South Africa is very susceptible to climate change and the rate at which GHGs are emitted must change drastically. This will be through a wide range of technologies, each of which contributes partly to the future total primary energy supply. A promising technology is the use of the microalgae *Dunaliella salina* to convert industrial CO₂ emissions into glycerol biofuel, whilst mitigating the release of geological carbon to the atmosphere. Algal ponds, or raceways, built to the optimal design, and located where temperature and climate is within the parameters of *Dunaliella salina*, will not utilise valuable agricultural land or land of ecological or residential value, and will use limited quantities of fresh water. Large scale field trials of this technology are being carried out around the world, and it has been demonstrated that much of South Africa has an excellent climate for this advanced type of biofuel. South Africa will require a significant change in its energy practices as well as significant financial investment into new technologies to achieve its energy commitment targets.

References

- Abril, G., Borges, A.V., Varfalvy, L., Roehm, C., and Garneau, M. (2004). Greenhouse gas emissions: Fluxes and processes, hydroelectric reservoirs and natural environments, carbon dioxide and methane emissions from estuaries. *Environmental Sciences Series*: 187-207.
- Ackermann, T., and Söder, L. (2000). Wind energy technology and current status: a review. *Renewable and Sustainable Energy Reviews*: (4) 315-374.
- Alboteanu, L., Manolea, G., and Ravigan, F. (2006). Positioning systems for solar panels placed in isolated areas. *Annals of the University of Craiova, Electrical Engineering Series*: (30) 163-168.
- Alexander, A. G. (1985). The energy cane alternative. In *Agricultural Experiment Station*, 509 P.P. Río Piedras, Puerto Rico: University of Puerto Rico.
- Anon. (2004). *SA's Hydro Power Potential*. South Africa Info. 07 23, 2004. <<http://www.southafrica.info/business/economy/infrastructure/hydroelectric.htm#UnyjkzZBtjo>> (accessed August 2013).
- Archbold, B. (2007). *Using algae to capture carbon dioxide and as a feedstock for biofuel*. Masters of Environmental Studies, thesis, Evergreen State College, U.S.A. : Unpubl. Lit.
- Barclay, W.R., Terry K.L., Nagle N.J., Weissman J.C., and Goebel R.P. (1987). Potential of new strains of marine and inland saline-adapted microalgae for aquaculture. *J. World Aquaculture Soc.*: (18) 218-228.
- Ben-Amotz, A. (1981). Glycerol and β -carotene metabolism in the halotolerant alga *Dunaliella*, a model system for biosolar energy conversion, glycerol production by *Dunaliella*. *Trends in Biochemical Sciences*: (6) 297-299.

- Ben-Amotz, A. (1980). The biotechnology of cultivating the halotolerant alga *Dunaliella* (patent). *Trends in Biotechnology* (Patent): (8) 121-126.
- Ben-Amotz, A. (1978). The role of glycerol in the osmotic regulation of the halophilic alga *Dunaliella parva*. Patent (1973) May. *Plant Physiology*: 51 (5), 875–878.
- Bendz, K. (2005). *EU-25 Oilseeds and products, biofuels situation in the European Union 2005*. Gain Report, EU.
- Berner, R.A. (1995). A.G. Hogbom and the development of the concept of the geochemical carbon cycle. *American Journal of Science*: (295) 491-495.
- BMI. (2011). *South Africa oil and gas report*. Q1, Business Monitor International.
- Brennan & Owende, L., and Owende, P. (2010). Biofuels from microalgae - A review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and Sustainable Energy Reviews*: (14) 557-577.
- Bringezu, S. (2009). Towards sustainable production and use of resources, assessing biofuels. *United Nations Environment Programme*. ISBN 978-92-807-3052-4.
- Brown, E., and Jacobson, M.F. (2005). *Cruel oil: how palm oil harms health, rainforest & wildlife*. Published Washington, DC.
- < <http://www.cspinet.org/palm/PalmOilReport.pdf> > (accessed November 2013).
- Brown, L.M. (2004). Biodiesel from microalgae: complementarity in a fuel development strategy. *National Renewable Energy Laboratory*: 902-908.
- < www.nrel.gov/docs/legosti/old/5715.pdf > (accessed November 2013).
- Callendar, G.S. (1938). The artificial production of carbon dioxide and its influence on temperature. *Quarterly Journal of the Royal Meteorological Society*: 64 (275) 223-240.
- Campbell, M.N. Biodiesel: algae as a renewable source for liquid fuel. *Guelph Engineering Journal*, 2008: (1) 2–7.

CDP. (2010). *South Africa JSE 100*. Carbon disclosure project 2010.

<<https://www.cdp.net/CDPResults/CDP-2010-South-Africa-JSE100.pdf>> (accessed November 2013).

Chelf, P., Brown, L.M., Wyman, C.E. (1993). Aquatic biomass resources and carbon dioxide trapping. *Biomass Bioenergy* 4: 175–183.

Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnology Advances*: (25) 294-306.

Clements, D. (1992). *Technology for expanding the biofuels industry*. Biodiesel working group, U. S. Department of Energy, US Department of Agriculture, Renewable Fuels Association, V-1-V-3.

Converti, A., Casazza, A.A., Ortiz, E.Y., Perego, P., and Del Borghi, M. (2009). Effect of temperature and nitrogen concentration on the growth and lipid content of *Nannochloropsis oculata* and *Chlorella vulgaris* for biodiesel production. *Chemical Engineering and Processing: Process Intensification* 48: 1146-1151.

Cornland, D., Johnson, F.X., Yamba, F., Chidumayo, E.N., Morales, M., Kalumiana, O., and Chidumayo, S.B.M. (2001). *Sugarcane resources for sustainable development: a case study in Luena, Zambia*. Stockholm Environment Institute. ISBN: 91 88714 71 3.

Crabtree, G.W. and Lewis, N.S. (2007). Solar energy conversion. *Physics Today*: 60, 37-42.

Damm, O., Triebel, R. (2008). *A Synthesis Report on Biomass Energy Consumption*. Johannesburg: ProBEC.

<http://www.ecoguinea.org/uploads/5/4/1/5/5415260/biomass_energy_consumption_availability_sa.pdf> (accessed November 2013).

Das, S. and Chattopadhyay, U. (2000). Role of silicon in modulating the internal morphology and growth of *Mycobacterium tuberculosis*. *Indian Journal of Tuberculosis*: 47, 87–91.

Dasari, M.A., Kiatsimkul, P., Sutterlin, W.R., and Suppes, G.J. (2004). Low-pressure hydrogenolysis of glycerol to propylene glycol. *Applied Catalysis A*: 281, 225-231.

- Davidson, O.R. and Karekezi, S. (1992). *A new, environmentally-sound energy strategy for the development of sub-Saharan Africa*. African Energy Policy Research Network.
- DEA. (2010). National climate change response green paper. South Africa department of environmental affairs, 25 November 2010, Staatskoerant, 4-38.
- DEA. (2009). *South Africa's clean technology fund investment portfolio, final presentation*. South Africa department of environmental affairs, Clean Technology Fund, 27th October 2009.
- < <https://www.climateinvestmentfunds.org/cifnet/?q=country/south-africa>> (accessed March 2013).
- DEAT. (2005a). *Integrated Environmental Management Information, Environmental Reporting*. Series 17, South Africa Department of Environmental Affairs and Tourism.
- <https://www.environment.gov.za/documents/strategicdocuments?q=content/integrated_environmentalmanagement_informationseries> (accessed March 2013).
- DEAT. (2005b). *Global climate change and ozone layer protection, vulnerability and adaptation: the situation in South Africa*. South Africa department of environmental affairs and tourism.
- < <https://www.environment.gov.za/documents/reports>> (accessed November 2012).
- DEAT. (2007). South Africa department of environmental affairs and tourism, Long term mitigation scenarios. South Africa Department of Environmental Affairs and Tourism, Energy Research Centre.
- < <https://www.environment.gov.za/documents/reports>> (accessed November 2012).
- Demirbas, A. (2008). Biofuels sources, biofuel policy, biofuel economy and global biofuel projections. *Energy Conversion and Management*. 49, 2106-2116.

- Demirbas, A.H. and Demirbas, I. (2007). Importance of rural bioenergy for developing countries. *Energy Conversion and Management*: 48, 2386–2398.
- DLR. (2005). *European concentrated solar thermal road-mapping*. Stuttgart: Deutsches Zentrum für Luft-und Raumfahrt, Ecostar Project Road Map Document.
<www.promes.cnrs.fr/uploads/pdfs/ecostar/ECOSTAR.Roadmap.pdf> (accessed March 2013).
- DME. (2007). *Biofuels Industrial Strategy*. Department of Minerals and Energy.
<[http://www.energy.gov.za/files/esources/petroleum/biofuels_indus_strat.pdf\(2\).pdf](http://www.energy.gov.za/files/esources/petroleum/biofuels_indus_strat.pdf(2).pdf)> (accessed January 2013).
- DME. (2013). *Biofuels Industrial Strategy of the Republic of South Africa*. Department of Minerals and Energy.
<<http://www.innovationeasterncape.co.za/download/presentation18.pdf>> (accessed January 2013).
- DME. (2008). National response to South Africa's electricity shortage. South Africa department of minerals and energy.
- DME. (2009). Renewable energy directorate implementation progress for the first five years of the renewable energy white paper. South Africa department of minerals and energy.
< <https://www.environment.gov.za/documents/reports>> (accessed November 2012).
- DOE. (2013). Keynote Address by the Minister of Energy, Ms Dipuo Peters, MP.
<<http://www.energy.gov.za/files/media/speeches/2013/KeynoteAddressBy%20MinisterOfEnergy-5.6-millionthSwitch-On-Magareng-06June2013.pdf>> (accessed March 2013).
- DOE. (2011). Department of Energy Solar Water Heating Programme Outline.
<http://www.energy.gov.za/files/swh_frame.html> (accessed October 2013).

- Dunahay, T.G. (1993). Transformation of *Chlamydomonas reinhardtii* with silicon carbide whiskers. *Biotechniques*: 15, (3), 452-8.
- Ebiura, T. (2005). Selective transesterification of triolein with methanol to methyl oleate and glycerol using alumina loaded with alkali metal salt as a solid-base catalyst. *Applied Catalysis A*: 283, (1–2), 111–116.
- EIA. (2008). *Energy information administration (US)*.
 <[http://www.eia.doe.gov/cabs/ South_Africa/Electricity.html](http://www.eia.doe.gov/cabs/South_Africa/Electricity.html)> (accessed November 2013).
- EJS. (2012). *Energy Journal Supplement*. Unpubl. Lit.
- Eskom. (2012). Annual Report.
 <http://www.eskom.co.za/OurCompany/Investors/IntegratedReports/Pages/Annual_Statements.aspx> (accessed November 2013).
- Eskom. (2011). *Cop 17 factsheet pack., December 2011*. Distributed at the Durban COP 17: Unpubl. Lit.
- Eskom. (2010). Hydro electricity in South Africa, Factsheet.
 <http://www.eskom.co.za/OurCompany/SustainableDevelopment/ClimateChangeCOP17/Documents/Renewable_energy_Hydroelectric_power_stations.pdf> (accessed January 2012).
- Eskom. (2008). *Renewable energy factsheet, looking at renewable energies*. Nov. 2008.
 <http://www.eskom.co.za/AboutElectricity/RenewableEnergy/Pages/Renewable_Energy.aspx> (accessed January 2012).
- FAO. (1970). *Tanzania: a wood consumption survey and timber trend study*. UN Food and Agriculture Organization.
 < <http://www.fao.org/docrep/l2015e/l2015e01.htm>> (accessed January 2012).

- Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M., and Kammen, D.M. (2006). Ethanol can contribute to energy and environmental goals. *Science*: 311 (5760), 506-508.
- Finance, Bloomberg New Energy. (2011). Global renewable energy market outlook. <<http://about.newenergyfinance.com/about/white-papers/bloomberg-new-energy-finance-global-renewable-energy-market-outlook/>> (accessed May 2013).
- Fleming, J.R. (2000). The 'greenhouse effect', and the quest for a universal theory of terrestrial temperatures. *Endeavour*, 23 (2), 72-75.
- Foy, R., Gibson, C., and Smith, R. (1976). The influence of day length, light intensity and temperature on the growth rates of planktonic blue-green algae. *European Journal of Phycology*: 11, 151-163.
- Fritsche, U.R., Katja, H., Hermann, A., Schulze, F. and Wiegmann, K. (2006). *Sustainability standards for bioenergy*. 1-80, Frankfurt am Main: WWF Germany.
- García-Luque, E., Forja, J.M., and Gómez-Parra, A. (2005). Characterization of atmosphere–water exchange processes of CO₂ in estuaries using dynamic simulation. *Journal of Marine Systems*: 58, 98-106.
- Giordano, M., Davis, J.S., and Bowes, G. (1994). Organic carbon release by *Dunaliella salina* (chlorophyta) under different growth conditions of carbon dioxide, nitrogen, and salinity. *Journal of Phycology*: 30, (2), 249–257.
- Goldenberg, S. (2010). Obama administration will 'hold South Africa to account for Eskom plant CO₂'. *Guardian Newspaper*. <guardian.co.uk> (accessed March 2011).
- Goswami, D.Y., Vijayaraghavan, S., Lu, S., and Tamm, G. (2004). New and emerging developments in solar energy. *Solar Energy*: 76, 33-43.
- Gouveia, L. and Oliveira, A.C. (2009). Microalgae as a raw material for biofuels production. *Journal of Industrial Microbiology and Biotechnology*: 36, 269-274.

- Grobbelaar, J.U. (1982). Potential of algal production. *Water SA*: 8, 79-85.
- Groom, M.J., Gray, E.M., and Townsend, P.A. (2008). Biofuels and biodiversity: principles for creating better policies for biofuel production. *Conservation Biology*: 22, 602-609.
- Gruber, N. (2008). The marine nitrogen cycle: overview and challenges. *Elsevier Inc., Amsterdam, Netherlands*: 1–50.
- Hall, D.O. and House, J.I. (1995). Biomass: a modern and environmentally acceptable fuel. *Solar Energy Materials and Solar Cells*: 38, 521-542.
- Harding, S. (2007). The long road to enlightenment. *Guardian newspaper*.
 <<http://www.theguardian.com/environment/2007/jan/08/climatechange.climatechangeenvironment>> (accessed November 2013).
- Harvey, D.L.D. (2007). Allowable CO₂ concentrations under the United Nations Framework Convention on Climate Change as a function of the climate sensitivity probability distribution function. *Environmental Research Letters*: 2 (014001), 10 P.P.
- Harvey, P.J. (2010). Glycerol power from microalgae, EU funding proposal. Unpubl. Lit. University of Greenwich, United Kingdom.
- Höök, M. and Aleklett, K. (2010). A review on coal to liquid fuels and its coal consumption. *International Journal of Energy Research*: 34 (10), 848-864.
- Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N. (1996). *Climate change 1995: the science of climate change, contribution of working group I to the second assessment report of the intergovernmental panel on climate change*. Vols. ISBN 0-521-56433-6 (1996) (eds). Cambridge University Press.
- Hughes, A., Haw, M., Winkler, H., Marquard, A. and Merven, B. (2007). *Energy emissions: a modelling input into the long term mitigation scenarios process*. Vol. LTMS Input Report 1. Cape Town, Western Cape: University of Cape Town (Energy Research Centre).

- Hulme, M. (1996). *Climate change and Southern Africa: an exploration of some potential impacts and implications in the SADC region*. Norwich: CRU/WWF.
- Hulme, M., Doherty, R., Ngara, T., New, M., and Lister, D. (2001). African climate change: 1900-2100. *Climate Research*: 17, 145-168.
- IEA. (2010a). *CO2 emissions 1971-2008 (2010 Edition)*. Carbon dioxide emissions from fuel combustion, highlights, International Energy Agency.
- IEA. (2010b). *Key world energy statistics 2010*. Paris: International Energy Agency. ISBN: 9789264095243.
- IEA. (2009). *Key world energy statistics 2007*. Paris: International Energy Agency.
<http://www.coprocem.com/documents/key_stats_2007.pdf/at_download/file>
(accessed November 2013).
- IEA. (2008). *World energy outlook 2008 (executive summary)*. International Energy Agency.
<http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCsQFjAA&url=http%3A%2F%2Fwww.worldenergyoutlook.org%2Fmedia%2Fweoweb%2F20081994%2Fweo2008.pdf&ei=llAhU5meJcPMhAeoj_oCABA&usg=AFQjCNFQq9B2iLzqciRav5mtXLEEL24GjQ> (accessed November 2013).
- International, Birdlife. (2005). EU must ensure bioenergy is really 'green'. Report.
- IPCC. (2007). *Intergovernmental panel on climate change, climate change 2007: impacts, adaptation and vulnerability, contribution of working group II to the 4th Report of the IPCC*. Cambridge: Cambridge University Press.
- Jarvis, E.E. and Brown L.M. (1991). Transient expression of firefly luciferase in protoplasts of the green alga *Chlorella ellipsoidea*. *Current Genetics*: 19, 317-321.
- Jebaraj, S. and Iniyan, S. (2006). A review of energy models. *Renewable and Sustainable Energy Reviews*: 10, 281-311.

- Johnson, F. and Matsika, E. (2006). Bio-energy trade and regional development: the case of bio-ethanol in Southern Africa. *Energy for Sustainable Development*: X (1), 42-53.
- Johnson, F. and Rosillo-Calle, F. (2007). *Biomass, livelihoods and international trade-challenges and opportunities for the European Union and Southern Africa*, *Climate Energy Report*. Stockholm: Stockholm Environmental Institute, 1-80.
- Kageson, P. (2005). *Reducing CO₂ emissions from new cars: a progress report on the car industry's voluntary agreement and an assessment of potential policy instruments*. European Federation for Transport and Environment.
- Kaplan, A. (1980). Salt-induced metabolic changes in *Dunaliella salina*. *Plant Physiology*: 65 (5), 810-813.
- Kartha, S., Leach, G., and Rajan, C. (2005). *Advancing bioenergy for sustainable development: roles for policymakers and entrepreneurs, report for the World Bank energy management assistance programme (ESMAP)*. Stockholm: Stockholm environment institute (SEI).
- Keeling, C.D. (1978). Atmospheric carbon dioxide in the 19th century. *Science*: 202 (4372), 1109-1102.
- Kishimoto, M., Okakura, T., Nagashima, H., Minowa, T., Yokoyama, S., and Yamaberi, K. (1994). Carbon dioxide fixation and oil production using micro-algae. *Journal of Fermentation and Bioengineering*: 78 (6), 479-482.
- Klass, D. (2004). *Biomass for renewable energy and fuels*. Oxford: Encyclopedia of Energy.
- Le Treut, H., Somerville, R., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson T., and Prather, M. (2007). *Historical overview of climate change, climate change 2007: the physical science basis, contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge, United Kingdom: Cambridge University Press.

- Luque, R., Herrero-Davila, L., Campelo, J.M., Clark, J.H., Hidalgo, J.M., Luna, D., Marinas, J.M., and Romero, A.A. (2008). Biofuels: a technological perspective. *Energy and Environmental Science*: 1, 542-564.
- Mata, T.M., Martins, A.A., and Caetano, N. (2010). Microalgae for biodiesel production and other applications: a review. *Renewable and Sustainable Energy Reviews*: 14, 217-232.
- Mathews, J.A. (2007). Biofuels: what a biopact between North and South could achieve. *energy policy* 35: 3550–3570.
- Mbuli, B.N. (2008). *Poverty reduction strategies in South Africa*. Unpub. Master thesis, Pretoria: University of South Africa.
- Meehan, C. (2013). *South Africa's First Large-Scale PV Plant Now Online*. September 18, 2013.
<<http://www.cleanenergyauthority.com/solar-energy-news/south-africa-large-scale-pv-online-091713>> (accessed September 2013).
- Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., and Zhao, Z.C. (2007). *Global Climate Projections: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.
- Mendis, M., Gowen, M., Hargrave, T., Openshaw, K., Dang, M., and Brackett, N. (1997). *Greenhouse gas assessment handbook, a practical guidance document for assessment of project-level GHG emissions*. World Bank global environmental division.
- Menegaki, A. (2008). Valuation for renewable energy: a comparative review. *Renewable and Sustainable Energy Reviews*: 12, 2422-2437.

- Moss, B. (1973a). The influence of environmental factors on the distribution of freshwater algae: An experimental study: II. The role of pH and the carbon dioxide-bicarbonate System. *Journal of Ecology*: 61, 157-177.
- Moss, B. (1973b). The influence of environmental factors on the distribution of freshwater algae: An experimental study: III. Effects of temperature, vitamin requirements and inorganic nitrogen compounds on growth. *Journal of Ecology*: 61, 179-192.
- Nagle N., Chelf P., Lemke P., and Barclay W. (1988). Conversion of lipids through biological pretreatment, Institute of Gas Technology. *Proceedings of Energy from Biomass and Waste XII*: 15-19.
- Nagle, N. and Lemke P. (1990). Production of methyl ester fuel from microalgae. *Appl. Biochem. Biotechnol*: 24/25, 355-361.
- Neenan, B., Feinberg, D., Hill, A., McIntosh, R., and Terry, K. (1986). Fuels from microalgae:technology status, potential, and research requirements. *Solar Energy Research Institute*: SERI/SP-231-2550:149 P.P.
- Oliver, R.I. (2009). Quo vadis biofuels. *Energy & Environmental Science*: 2, 343 P.P.
- Openshaw, K. (2004). *Natural resources: population growth & sustainable development in Africa, Low Pak Sum (ed.), Climate Change and Africa*. Cambridge: Cambridge University Press.
- Openshaw, K. (2010). *Can biomass power development*. International institute for environment and development (IIED): biofuels. ISSN: 1357-9258.
<<http://pubs.iied.org/pdfs/14598IIED.pdf>> (accessed November 2013).
- Pachauri, N. (2006). *Value-added utilization of crude glycerol from biodiesel production, American society of agricultural and biological engineers*. paper number: 066223, Idaho: University of Idaho.

- Paytan, A. and McLaughlin, K. (2007). The oceanic phosphorus cycle. *Chemical Reviews*: 107, 563-576.
- Pegels, A. (2009). Prospects for renewable energy in South Africa – mobilising the private sector. *Energy Policy*: 38, 4945–4954.
- Philip, D. (2012). Eskom applies for another tariff increase. *Enerati*: 17th July 2012.
- Pillay, K. (2010). Physico-chemical interactions within KwaZulu-Natal Estuaries. Unpubl. lit.
- Puppán, D. (2002). Environmental evaluation of biofuels. *Periodica Polytechnica, Ser. Soc. Man. Sci*: 10, 95-116.
- REN 21 (2007). *Renewables global status report*. Paris: REN 21 secretariat. <<http://www.worldwatch.org/files/pdf/renewables2007.pdf>> (accessed November 2013).
- Revelle, R., Suess, H., E. (1957). *Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO₂ during the past decades*. received September 4th 1956, Scripps Institute of Oceanography, University of California: 9, (1), 18-27.
- Salisbury, F.B. and Ross, C.W. (1992). *Plant physiology, fourth edition*. 682 P.P.: Wadsworth inc.
- Sasol. (2009). *Unlocking the potential wealth of coal, information brochure*. <http://www.sasol.com/sasol_internet/downloads/CTL_Brochure_1125921891488.pdf> (accessed November 2013).
- Sastresa, E.L., Uson, A.A., Bribian, I.Z., and Scarpellini, S. (2010). Local impact of renewables on employment: assessment methodology and case study. *Renewable and Sustainable Energy Reviews*: 14, 679–690.

- Scott, S.A., Davey, M.P., Dennis, J.S., Horst, I., Howe, C.J., Lea-Smith, D.J., and Smith, A.G. (2010). Biodiesel from algae: challenges and prospects. *Current Opinion in Biotechnology*: 21, 277-286.
- Seambiotic. (2010). Algae Pilot Plant Description Worksheet. August 2010.
<<http://www.seambiotic.com/uploads/Seambiotic%20Ltd.%20-%20Algae%20Pilot%20Plant%20white%20paper.pdf>> (accessed July 2013).
- SEFI, UNEP. (2010). *Global trends in sustainable energy investment 2010 Report*. Sustainable Energy Finance Initiative, United Nations Environment Programme.
- Sharma, S. (1979). Energy consumption in Tanzania. *12 Symposium on Energy Resources in East Africa, EAA*. Nairobi: proceedings of the East African Academy (EAA).
- Sheehan, J., Dunahay, T., Benemann, J., Roessler, P. (1998). A look back at the U.S. department of energy's aquatic species program-biodiesel from algae. *National Renewable Energy Laboratory* (U.S. Department of Energy): Unpubl. Lit.
- Slopp, C. and Van Cappellen, P. (2007). The global marine phosphorus cycle: sensitivity to oceanic circulation. *Biogeosciences*: 4, 155-171.
- Smeets, E., Faaij, A., and Lewandowski, I. (2004). *A quickscan of global bio-energy potentials to 2050, an analysis of the regional availability of biomass resources for export in relation to the underlying factors*. ISBN 90-393-3909-0.
- Smith, D. (2013). *Guardian.co.uk*. August 23, 2013.
<<http://www.theguardian.com/world/2013/aug/23/south-africa-fracking-karoo>> (accessed September 2013).
- Socolow, R.H. (1992). Environment-Respectful Global Development of the Energy System. Centre for Energy and Environmental Studies. Princeton University.
- Sorokin, C. and Krauss, R.W. (1958). The effects of light intensity on the growth rates of green algae. *Plant Physiology*: 33, 109 P.P.

- Stat, FAO. (2012). *South Africa: Wood charcoal, production weight*. Factfish. <<http://www.factfish.com/statistic-country/south%20africa/wood%20charcoal%2C%20production%20weight>> (accessed May 2013).
- Stern, N. (2006). *Stern review on the economics of climate change*. Cambridge University press. *World Economics*: 7 (2), 1-10.
- Sugrue, A. (2006). *Towards a southern NGO position on biofuels*. Citizens united for renewable energy and sustainability (CURES) South Africa.
- Sunda, W.G. and Huntsman, S.A. (1997). Interrelated influence of iron, light and cell size on marine phytoplankton growth. *Nature*: 390, 389-392.
- Sunda, W.G. and Huntsman, S.A. (1995). Iron uptake and growth limitation in oceanic and coastal phytoplankton. *Marine Chemistry*: 50, 189-206.
- Szewczuk, S. and Prinsloo, E. (2010). *Wind atlas for South Africa (WASA): project overview and current status*. <www.conference.csir.co.za> (accessed November 2013).
- Thompson, J. C. (2006). Characterization of crude glycerol from biodiesel production from multiple feedstocks. *Applied Engineering in Agriculture*: 22 (2), 261-265.
- Tijmensen, M.J.A., Faaij, A.P.C, Hamelinck, C.N., and van Hardeveld, M.R.M. (2002). Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification. *Biomass and Bioenergy*: 23, 129 - 152.
- Trujillo, A.P. and Thurman, H.V. (2005). *Essentials of oceanography*. Prentice Hall, eighth edition: 532 P.P. ISBN: 0131447734.
- UNDP. (2009). *Bio-carbon opportunities in Eastern & Southern Africa, harnessing carbon finance to promote sustainable forestry, agro-forestry and bio-energy*. 1-6, United Nations Development Programme.

- UNDP. (2008). *Human development indices: a statistical update 2008*. United Nations Development Programme.
- UNDP/WB. (2002). *World summit on sustainable development, proceedings, Cape Town, South Africa*. Cape Town: United Nations Development Program, World Bank.
- UNEP. (2011). *Green Economy Report (GER) – renewable energy*. United Nations Environment Programme.
- UNEP. (2008). *Green jobs report*. UNEP, ILO, IOE, ITUC, United Nations Environment Programme.
- Van der Linde, H. (1996). Wind energy in South Africa. *Renewable energy*: 9, 880-883.
- Van Ommen, R. (2010). Sedimentation: particle technology. *Department of Chemical Engineering, Delft University of Technology*: Unpubl. Lit.
- Van Vliet, O.P.R., Faaij, A.P.C., and Turkenberg, W.C. (2009). Fischer-Tropsch diesel production in a well-to-wheel perspective: a carbon, energy flow and cost analysis. *Energy Conversion and Management*: 50 (4), 855-876.
- Voegele, E. (2013). *South Africa to mandate biofuel blending starting in 2015*. October 8, 2013.
 <<http://www.ethanolproducer.com/articles/10329/south-africa-to-mandate-biofuel-blending-starting-in-2015>> (accessed October 2013).
- Voegele, E. (2008). Technology allows glycerin to power diesel generator. *Biodiesel Magazine*: Unpubl. Lit.
- Von Hoffman, N. (2008). South Africa energy crisis, energy lessons from South Africa. Unpubl. Lit.
- Wahal, S. and Viamajala, S. (2010). Maximizing algal growth in batch reactors using sequential change in light intensity. *Applied Biochemistry and Biotechnology*: 161, 511-522.

- WB. (2003). *Annual development report*. Washington DC: World Bank.
- WB. (1990). *Annual environmental report, environmental department*. Washington DC: World Bank.
- WB. (2004). *Renewing our energy business, WB Group Energy Program Implementation Progress Report 2001-03*. World Bank.
- WB. (2009). *World development report 2010 - development and climate change*. World Bank.
- WCI. (2006). *Coal: liquid fuels*. World Coal Institute.
- <[http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCsQFjAA&url=http%3A%2F%2Fwww.worldcoal.org%2Fbin%2Fpdf%2Foriginal_pdf_file%2Fcoal_liquid_fuels_report\(03_06_2009\).pdf&ei=g14hU_iRDrLb7AbnjoDwAg&usg=AFQjCNHJgqjuMs5ch1G0RGlyFHjwUE5nKw](http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCsQFjAA&url=http%3A%2F%2Fwww.worldcoal.org%2Fbin%2Fpdf%2Foriginal_pdf_file%2Fcoal_liquid_fuels_report(03_06_2009).pdf&ei=g14hU_iRDrLb7AbnjoDwAg&usg=AFQjCNHJgqjuMs5ch1G0RGlyFHjwUE5nKw)> (accessed November 2013).
- WEA. (2000). *Energy and the challenge of sustainability*. Bureau for development policy, World Energy Assessment / United Nations Development Programme, 508 P.P.
- WEC. (1992). *Energy for tomorrow's world - the realities, the real options and the agenda for achievement: draft summary of global report*. World Energy Council,.
- Wegmann, K. (1971). Osmotic regulation of photosynthetic glycerol production in *Dunaliella*. *Biochimica et Biophysica Acta (BBA) - Bioenergetics*: 234, (3), 317–323.
- Weissman. J.C. and Tillett, D.M. (1992). *Design and operation of an outdoor microalgae test facility: large-scale system results*. NREL MP-232-4174, In Brown, L. M. and S. Sprague, aquatic species project report: National Renewable Energy Laboratory, 32-56.
- WGCCD. (2005). *Africa - up in smoke 2, the second report on Africa and global warming*. Working Group on Climate Change & Development.
- WRI. (2009). *Climate analysis indicators tool (CAIT), Version 6.0*. World Resources Institute.

Xavier. (2007). *The Brazilian sugarcane ethanol experience, issue analysis*. Competitive Enterprise Institute.

CHAPTER 4

Suitability Analysis and Location Theory of Algal Glycerol Biofuel in South Africa using Geographical Information Systems

* This chapter is based on: **Bloomfield, M.I.D.B., Njoya, S.N., Reid, C. and Wiggill, T.R. (2013). Suitability Analysis and Location Theory of Algal Glycerol Biofuel in South Africa using Geographic Information Systems (G.I.S.), *International Journal of Geographic Information Science* (submitted 10 December 2013).**

Abstract

South Africa is aiming to reduce its carbon dioxide emissions and produce more of its energy through renewable sources. Recently, the door has been opened to private investment in alternative technologies. To develop the concept of open algal ponds in South Africa producing glycerol biofuel from the microalgae *Dunaliella salina* as economically as possible, an industrial source of carbon dioxide must be available and adjacent to the scheme. The aim was to use Geographic Information Systems and an understanding of the optimal conditions for algal glycerol production to highlight the areas of South Africa best suited to this technology. Informal consultation with the largest emitters of greenhouse gases in South Africa presented a picture of the existing levels of understanding, interest and investment into modern renewable energy technologies. Using these site locations as a model, Geographic Information System analysis of a variety of environmental, climatic and socio-economic factors across South Africa revealed the areas and locations most suited for this type of technology. Further investigation of the remaining sites highlighted five remaining sites, representing different types of industry, situated in ideal locations for this renewable technology. After this analysis it is apparent that South Africa has very great potential for biofuel produced from microalgae in open algal ponds.

Keywords: Algae, GIS, Biofuel, South Africa, Sustainable, Glycerol.

4.1. Introduction

Global energy production since the industrial revolution is directly responsible for climate change (Harvey, 2007; Le Treut *et al.*, 2007; Meehl *et al.*, 2007; UNEP, 2011). Renewable and sustainable energy sources are being developed in an effort to prevent the continued rise of atmospheric carbon dioxide (CO₂) concentration. Algae that produce lipids and sugars that can be chemically altered into biodiesel and petroleum is one alternative that is being further developed (Grobbelaar, 1982; Mata *et al.*, 2010; Scott *et al.*, 2010; Chisti, 2007; Gouveia & Oliveira, 2009). The recent technique for burning glycerol cleanly and efficiently in a diesel engine has led to the use of this waste product from the bio-diesel production chain as a biofuel (Voegelé, 2008). A more sustainable supply of glycerol can come from the microalgae *Dunaliella salina*, which under the right conditions can produce 80% dry weight glycerol (Ben-Amotz, 1981; Ben-Amotz, 1980).

Algae are able to produce substantial amounts of fuel whilst utilising limited space or resource demands, when compared with alternative biofuels (Groom *et al.*, 2008; Chisti, 2007). Certain algal species do not utilise potable fresh water resources as they prefer saline or brackish environments (Puppán, 2002; Brennan & Owende, 2010; Mata *et al.*, 2010). Estimates have been made that algae can produce over 100 000 litres of biofuel per hectare per year, greater than any alternatives (Groom *et al.*, 2008). Algae also have the potential to improve the water quality of contaminated waterways by removing excess nitrogen and phosphate (Puppán, 2002; Mata *et al.*, 2010; Brennan & Owende, 2010).

Research has shown that microalgae have the highest theoretical rate of photosynthesis and therefore ability to produce biofuel (Chisti, 2007; Gouveia & Oliveira, 2009; Mata *et al.*, 2010; Brennan & Owende, 2010). Given the correct climate, microalgae can be grown throughout the year, on an industrial scale, continuously producing biofuel (Grobbelaar, 1982; Chisti, 2007; Brennan & Owende, 2010; Mata *et al.*, 2010). Arid and semi-arid regions with poor soil quality, where agricultural plants can't be grown, are perfectly acceptable sites for algal raceway ponds (Brown, 2004). Certain microalgae can be grown using saline waters from aquifers, estuaries or the ocean: water that cannot be used for agriculture, forestry or as potable water. Neenan *et al.* (1986) state that microalgae yield 3 - 5 times greater biomass per acre than from typical crop plant acreage.

Certain species of microalgae illustrate exponential growth under ideal conditions and allow a doubling of their biomass in less than four hours (Chisti, 2007; Brennan & Owende, 2010). The lack of need for harmful pesticides, herbicides and fertilizers is another environmental benefit for using microalgae in the production of biofuel (Puppán, 2002; Groom *et al.*, 2008; Brennan & Owende, 2010). An alternative approach to the capture and dispose of CO₂ that has emerged in recent years, is the operation of microalgae biomass farms (Chelf *et al.*, 1993). CO₂ from industrial flue gases is recycled into biofuel by microalgae. The CO₂ is released into the atmosphere when the biofuel is burned, but the process approximately doubles the energy output for the same quantity of CO₂.

Algal farms are being run at pilot-project and industrial scales in, but not limited to, the U.S.A, China, Israel, Japan, Taiwan, Australia and India. In some of these projects they are sited next to an industrial source of CO₂, which is pumped into the saline water of the algal culture. Since a linear relationship exists between salinity and partial pressures of CO₂ (García-Luque *et al.*, 2005); this method helps to supplement the effect in which CO₂ dissolves less readily in waters of higher saline concentration.

4.2. Consultation

In order to gauge both the level of interest in biofuels within South African industries and the existing investment into renewable technologies, consultation was carried out with the biggest emitters of greenhouse gas (GHG). Eskom is the state-owned national producer and distributor of electrical power in South Africa. A meeting and presentation was held with an environmental manager at Eskom, Durban, early in 2012, from which a list of 36 Eskom environmental consultees at all Eskom sites across South Africa was provided. A further 23 of the biggest South African GHG emitters were sourced from published data, representing the major industry types (CDP, 2009). Figure 4.1. shows their locations across South Africa.

Consultation began with a brief introductory email, followed after two days with the full consultation email. This consisted of a signed letter of endorsement from the University of Kwa-Zulu Natal (Dr. H. Watson), a 3-page document with further reading on the project, and a simple seven question questionnaire (Table 4.1.). If no reply was received after four weeks

a follow up consultation email was delivered as a reminder. No statistical analysis of the results of this consultation was carried out; the results were for information only. The questions within the questionnaire were designed to encourage the highest possible response rate. Of the 59 consultees, 29% (17) returned the completed questionnaire and of these only 8% (5) confirmed that they wished to be further updated as the project developed²⁴. From the completed questionnaires it was possible to form a picture of their understanding of renewable alternatives, the prevalence of these technologies, and the further interest each consultee had in this project.

Table 4.1. Questionnaire to all potential algal pilot project sites.

No.	Question
1	Do you currently use any forms of renewable technologies on site?
2	If yes, please describe them.
3	If no, do you have any plans in the future to use any forms of renewable technology on site?
4	Do you have any company policies or drives to encourage energy and water conservation and to reduce GHG emissions?
5	What quantity of CO ₂ is released into the atmosphere on a daily, monthly and annual basis at your site?
6	Do you have any plans to use carbon capture and storage (CCS) technologies at your site?
7	Would you be interested in your site being further involved in this theoretical study to determine ideal pilot study sites for this technology?

Table 4.2. shows a summary of the responses from the Eskom and non-Eskom consultees. Some of these responses were to indicate no interest in participation with this study. The green shading indicates a response, or that questionnaires were completed. Only the consultees who did respond in some form or another are shown. Those consultees excluded did not respond at all to any of the attempts to open dialogue.

²⁴ These results have been rounded to the nearest whole number as we are dealing with a small number of human consultees.

Table 4.2. Responses and completed questionnaires received from consultees.

Eskom consultees				non-Eskom consultees			
Contact #	Response to 1st contact	Response to 2nd contact	Completed Questionnaire	Contact #	Response to 1st contact	Response to 2nd Contact	Completed Questionnaire
				37			
2				40			
4				43			
5				44			
11				45			
12				46			
14				51			
17				53			
18				54			
22				55			
24				57			
25				58			
29				59			
32							
34							
36							
Total	7/36	6/36	11/36	Total	10/23	3/23	6/23
%	13/36 (36%)		31%	%	13/23 (57%)		26%

The results show an initial response rate of 19% (Eskom) and 43% (non-Eskom) and a final response rate of 36% (Eskom) and 57% (non-Eskom). Only 31% of Eskom consultees and 26% of non-Eskom consultees completed and returned the questionnaire. A summary of the completed questionnaires:

- 29% of the 17 consultees that returned the questionnaire are utilising some form of renewable energy at their site.
- 36% of Eskom and 50% of non-Eskom consultees do not currently use renewable technologies, but are aware of plans to include them in the future energy mix.
- 91% of Eskom consultees and 100% of non-Eskom consultees are aware of company policies to encourage energy and water conservation and reduce GHG emissions.
- 55% of Eskom consultees and 100% of non-Eskom consultees were able to report their site CO₂ emissions.
- 45% of Eskom consultees and 33% of non-Eskom consultees know that their companies are, or will be considering CCS technology.

4.3. Location Theory

Location theory is the science of where and why industries are geographically located where they are (Beckmann, 1968). Because of the relationship between the algal culture ponds and the sources of CO₂ they will be sited adjacent to, location theory is relevant to this study. There are many environmental and biological impacts that can directly affect the productivity of open algal ponds. To ensure the best return on investment in this technology it is important to locate the algal ponds in areas that will provide the closest to ideal conditions for biofuel production.

There are many CO₂ emitting industries located throughout South Africa. The consultee's industries (Figure 4.1.) are in locations that are either more or less favourable to the requirements for algal biofuel production. Through location theory it is possible to identify which industries are located in the more favourable places. It may also be possible to observe if particular industry types tend to be located in more favourable places than other industry types.

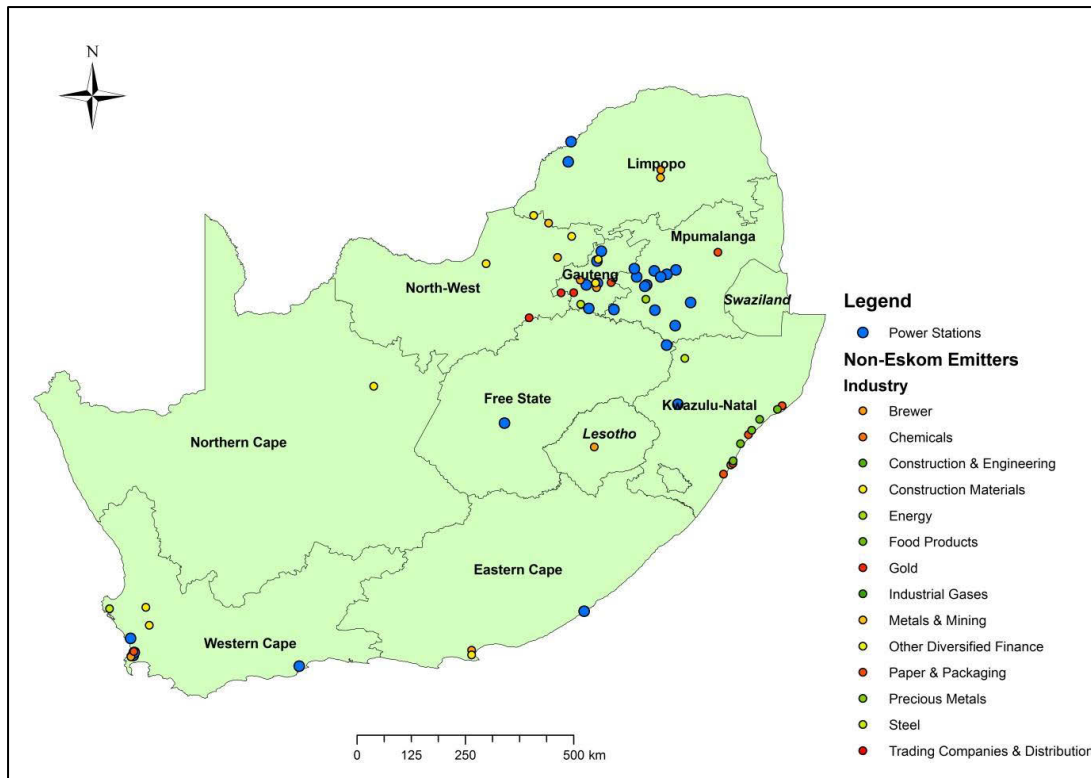


Figure 4.1. Map showing the location of the consultee's sites throughout South Africa²⁵ (Source: UKZN, SAEES).

The majority of sites shown on Figure 4.1. are located in and around the major cities of Johannesburg and Pretoria, Gauteng province. Others cluster around Cape Town and along the northeast coastline between the ports of Durban and Richards Bay, and a few are near the Eastern Cape capital, Port Elizabeth. Very few sites are situated outside of these centres.

Further examination shows that a large number of the power stations are located in and around Gauteng and Mpumalanga. This can be explained through the large population, number of power consuming industries and electrical draw of Johannesburg and Pretoria; and also due to the concentration of coal mines in these areas. To minimise transport costs, coal-fired power stations are often located in proximity to the mines that supply them. Transportation of electricity is cheaper than transportation of the vast quantities of coal required to produce it.

²⁵ Some of the consultees were not included at this stage as they either did not emit CO₂ directly from their site, or they owned too many sites that would have obscured the map. In total 51 sites are displayed here.

Other mining, metals and precious metals, chemicals and construction materials are for the most part located in similar areas. This again takes advantage of the proximity of the base resources with the large population, transport and infrastructure of these two large cities (Johannesburg and Pretoria). A more ubiquitous producer, the brewer, has sites distributed throughout the country, close to each major capital: Cape Town, Johannesburg, Port Elizabeth and Durban. The paper-industry and food manufacturers are largely concentrated along the north east coast of Kwa-Zulu Natal, where the wetter climate has enabled farming of sugar-cane and eucalyptus-tree plantations.

4.4. Needs and Suitability Analysis

The ability of microalgae to maximise photosynthesis and biofuel production is dependent on various environmental and logistical factors. Understanding these influences is critical to ensuring that ideal pilot project locations are selected, and improving the quantities of biofuel produced and the project economics.

4.4.1. Climatic Factors

4.4.1.1. Temperature

To maximise the biofuel production of the algal ponds the temperature range should be between 20 and 40 °C for as much of the time as possible, generally never exceeding 45 °C and never close to freezing (Wegmann, 1971). The temperature of the algal solution can be controlled, but this will consume energy and have a negative influence on the energy balance of the biofuel produced (Gnansounou *et al.*, 2007; Van Gerpen, 2005). The pilot site should be able to produce biofuel throughout the year; a site that has suitable weather throughout the summer but very cold winter temperatures will make the site redundant for half of the year (Seambiotic, 2008).

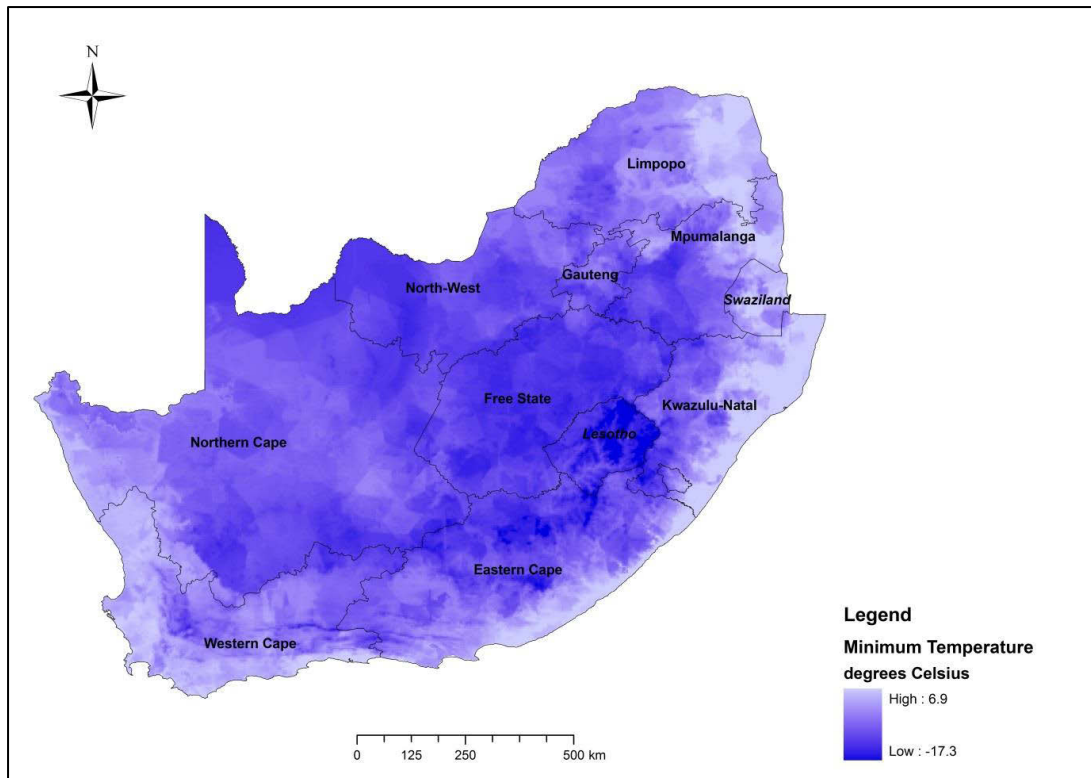


Figure 4.2.a Minimum temperatures experienced throughout South Africa (Source: UKZN, SAEES).

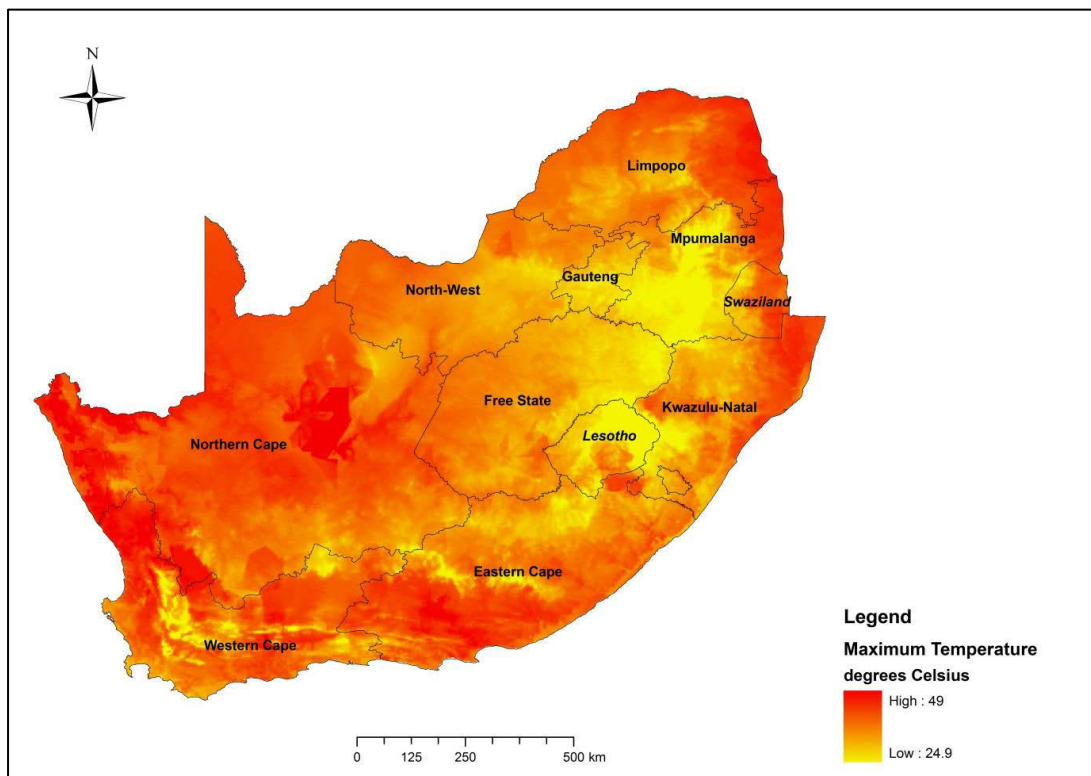


Figure 4.2.b Maximum temperatures experienced throughout South Africa (Source: UKZN SAEES).

Average temperatures throughout South Africa need to be examined, and areas below the minimum temperature thresholds or above the maximum, excluded. Areas that often experience sub-zero temperatures in winter include the northern extremes of the Great Inland Karoo, the Drakensberg Mountains and Sutherland in the western Roggeveld Mountains (Anon., 2012). At the opposite extreme, Dunbrody, in the Eastern Cape, recorded 50.0 °C on 3 November 1918 (SAWS, 2013). These extremes have the potential to kill off an open pond of microalgae and must be considered.

Figures 4.2.a and 4.2.b display the minimum and maximum temperatures experienced in South Africa, throughout the year. The coldest temperatures are shown in the mountainous areas in and around Lesotho and throughout the northern areas of the Great Karoo up to the border of Namibia and Botswana. Coastal areas rarely experience the extreme minimum temperatures as experienced in the interior. The lowest coastal temperatures appear along the escarpment and in the more mountainous areas in the Western Cape.

4.4.1.2. Rainfall

Rainfall is unlikely to have a significant direct impact on the productivity of open algal ponds. Excess rain and cloud cover reduces the levels of irradiance and photosynthetic-hours. This can be examined more directly when looking at solar irradiance. The levels of the ponds can easily be controlled in times of heavy rain in order to prevent flooding. If saline ponds are being used there is a possibility that heavy rain might impact on the salinity, thereby affecting the optimal conditions for the microalgae, and this will need to be adjusted accordingly. It is anticipated that this problem will resolve itself naturally in the most part, as the evaporative effect of warm sunny weather will offset any dilution during normal rainy cycles. However, during periods of extreme rainfall, this will need to be monitored.

Low rainfall must be considered: in the interests of social responsibility it is important to ensure that a project will not negatively impact on the local water reserves. Although this technology is not heavily dependent on fresh water, there will be times when some is required. For this reason it would be irresponsible and negligent to build such a plant in an area already suffering water-shortage strain. Anywhere in South Africa that is designated as desert (below 250 mm rainfall per year [(Miller, 2005)], or arid (ranging between 100 and 200 mm rainfall per year [FAO, 1989]) is to be ruled out of contention.

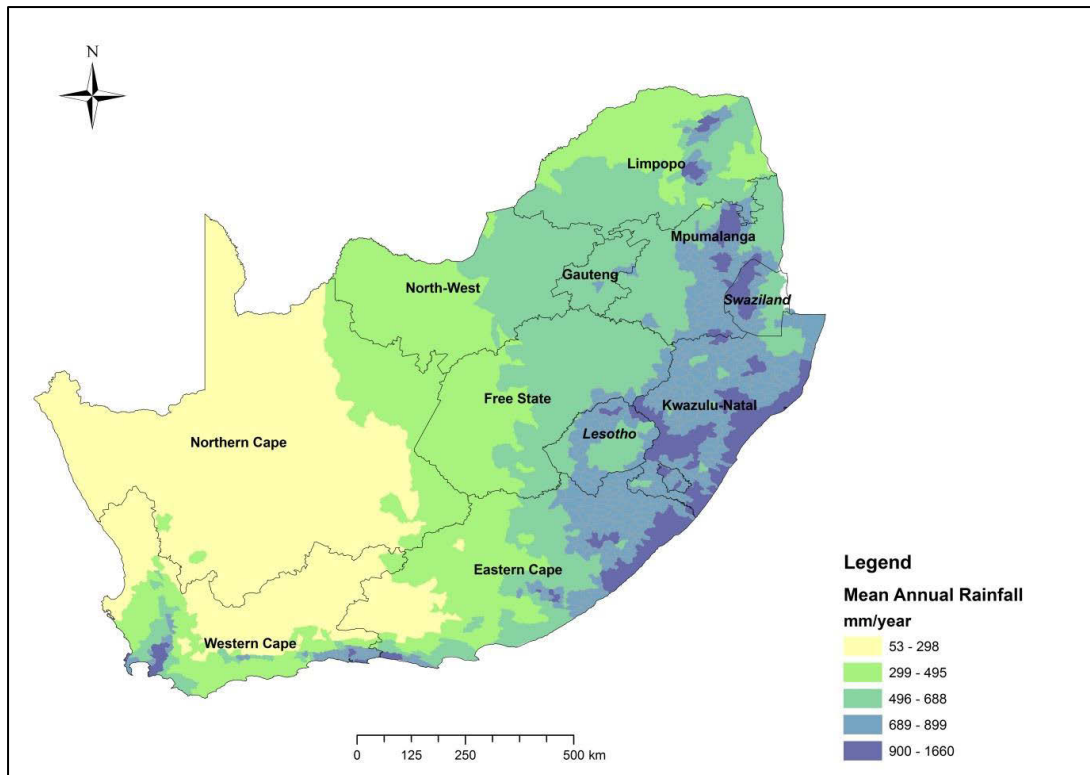


Figure 4.3. Distribution of average annual rainfall across South Africa (Source: UKZN,SAEES).

Figure 4.3. shows the mean annual rainfall throughout South Africa. The majority of South Africa's rain arrives with the easterly winds from the Indian Ocean and fall on Kwa-Zulu Natal, Mpumalanga and the northern Eastern Cape (CIA, 1996; Rautenbach, 1998). Cape Town, and coastal areas of the Western Cape, receives much of their rainfall throughout winter. Away from the coastal areas, much of northern Western Cape has much less rainfall, and is classified as arid.

4.4.1.3. Solar Irradiance

Solar irradiance has a direct impact on the photosynthetic productivity of microalgae (Loeblich, 1982). Below a certain annual threshold of light intensity the volume of glycerol produced will be low enough to make it uncompetitive with alternative fossil and bio fuels. Solar irradiance throughout South Africa is high and the minimum levels are not considered to be a limiting factor (DOE, Online, no date).

Excessive exposure to high levels of solar irradiance is damaging to microalgae, and causes the wasteful energetic production of additional protective pigments, and a marked reduction

in rates of photosynthesis (Lesser & Farrell, 2004). In South Africa the limiting factor will be excessive solar irradiance rather than moderate irradiance.

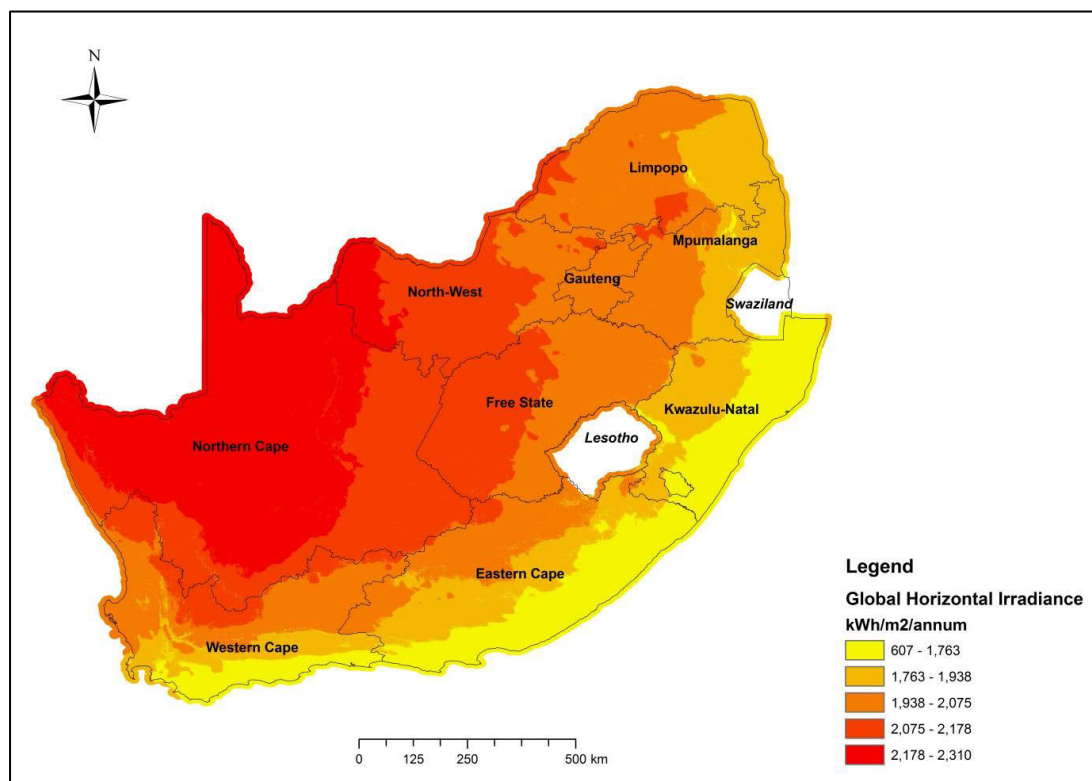


Figure 4.4. Global Horizontal Irradiance for South Africa showing the total amount of shortwave radiation received from above by a surface horizontal to the ground (Source: UKZN, SAEES).

Figure 4.4. displays the solar irradiance throughout the country. The pattern of irradiance does not mimic that of the maximum temperatures, as might be suspected, but more closely resembles that of the rainfall in Figure 4.3. Levels of irradiance are lowest along the lowland coastal band sweeping up from Cape Town to the border of northern Kwa-Zulu Natal and Mozambique. The irradiance graduates upwards in the same shape towards the highest irradiance in the northwest of the Northern Cape and along the borders with Namibia and Botswana.

4.4.2. Other Environmental Factors

4.4.2.1. *Altitude*

In order for the thinning of air to become a significant impact to the productivity of the photosynthesising microalgae, the altitude will have to be far in excess of where industrial plants in South Africa are located. Algae are recorded in nature at altitudes well above

4 000 m. The indirect impact that altitude will have on the productivity of microalgae is in relation to temperature (Wegmann, 1980). This factor is of greater significance, and covered above.

4.4.2.2. *Access to Water*

Open algal ponds for this project require water for the microalgae, although this water can be non-potable and brackish or saline and even heavily polluted. This can add to the positive life cycle analysis of the site, since little potable water is required. In some examples of this technology, the biofuel producing microalgae have also helped remove pollution from industrial and residential waste streams (Wegmann, 1971). Any location close to a coast or an estuary can supply saline water and proximity to a residential area or certain types of industry will be able to provide other forms of waste water.

However, some access to clean potable water will be required, both for use by staff on-site, and in smaller quantities, for use in the extraction of glycerol from the algae. Any industrial complex that can provide CO₂ will also have access to potable water. It will be advantageous if the site is located within 500 m proximity to a river in order to abstract fresh water, under permit, when the situation arises, and without immediate impacts to potable plumbed water. If the site is to be used to help remove pollutants from a nearby river, the cleaned waste water from the algal ponds can be discharged downstream.

4.4.2.3. *Access to CO₂ Supply*

Carbon is the essential building block on which all organic life is constructed. In almost all photosynthesising organisms, the mechanism for this is through a complex conversion of solar energy into chemical energy, and the conversion of CO₂ from the air, into carbon-based polymers. Every site included in this study has been selected due to the large quantities of

CO₂ emitted. For this reason the availability of a CO₂ supply does not need to be considered a limiting factor.

4.4.2.4. Geography and Geology

The major soil geography risk is that loose sand and dust will contaminate the open ponds and prevent their success. Any adjacent sites that consist of loose sand or dust, in windy conditions, will lead to the regular pollution of the open ponds, reduced transparency of the photosynthesising medium, and contamination of the algae within the ponds. With any open ponds there is an unavoidable degree of this, no matter where the ponds are located, and some down-time is expected, periodically, to remove this sediment. If it happens too regularly, however, it will impact more significantly on the productivity of the site, and affect its ability to compete financially with alternative bio and fossil fuels.

The contours, steepness of slopes and material being worked upon can be overcome by modern construction techniques. A flat, even surface will assist in keeping construction costs to a minimum and improving the return on investment of a pilot site. Slopes, however, could be used to allow gravitational transfer of solutions and algae into and out of ponds through progressive steps.

4.4.2.5. Access to Nutrient Supply

Certain nutrients are required in small quantities for the health and metabolism of the cultured microalgae. These include, but not limited to, potassium, phosphate and nitrogen (Harvey 2010; Giordano *et al.*, 1994). Nutrients of this kind can be purchased and delivered to site or else can be sourced more sustainably and cheaply from human and agricultural waste streams. The algal ponds can be utilized additionally to process polluted waste streams into cleaner water, as mentioned in 3.3.2., which can be discharged into streams and rivers. Every prospective site will be in proximity to such a waste stream from the adjacent industry, or else will have transport networks available for delivery of any necessary nutrients. Some polluted rivers have high concentrations of these nutrients, from, amongst other things, fertiliser run off from agricultural areas. Again, algal ponds can be utilised to help reduce the concentration of these chemicals from polluted rivers.

4.4.3. Socio-Economic Factors

4.4.3.1. *Land Use/Surrounding Land Use*

To ensure a positive life cycle analysis the existing land-use of the proposed site must not be residential, agricultural, forested, wetland or have any biodiversity value (Gnansounou *et al.*, 2009). Ideally the site should be of low ecological value, such as an old brownfield site.

Open pond raceways are susceptible to contamination and pollution so consideration should be given to surrounding land use. In windy conditions contaminants from neighbouring lands may pollute the ponds with extraneous biological matter, bacteria and fungi. Activities such as open cast mining will be likely to produce large amounts of dust and will preclude open algal ponds within close proximity.

4.4.3.2. *Access to Electric Grid*

Paddle wheels to circulate the water around the open pond raceways, water-pumps, centrifuges, filters and lighting will all consume electrical power at a pilot project site. All proposed sites in this study are located in close proximity to a large industrial complex, ensuring that this access will not restrict any of the prospective sites.

4.4.3.3. *Access to Transport Network*

Transport will be necessary both during the construction period of the project, for bringing in materials, machinery and construction staff, and during the running of the project. The biofuel produced will also require distribution; staff will require transport links and other nutrients may need to be delivered. All proposed sites are located adjacent to a large industrial complex, ensuring good existing transport networks.

4.4.4. Summary

Many of the proposed limiting factors would not actually be significant or limiting for South Africa (Table 4.3). Land Use data would have been an important aspect to consider but unfortunately there is no data for the whole of South Africa to cover this as a GIS analysis. Once the potential sites were located, land-use could be considered further only through carrying out a visual inspection (Google Earth[®]) to determine the current land use of the area: and if those specific locations could be considered appropriate based on this.

Table 4.3: A summary of the criteria that were included in the analysis and the reasoning behind including or excluding factors from the analysis.

Criteria	Included/ excluded	Reasoning
Temperature	Included	Most significant factor
Rainfall	Included	Significant social factor
Solar Irradiance	Included	Significant
Altitude	Excluded	Not significant
Land Use	Excluded	No data coverage for SA
Access to water	Excluded	Not significant
Geography and Geology	Excluded	Not significant
Access to Nutrient Supply	Excluded	Not significant
Access to CO ₂ Supply	Excluded	Not significant
Access to Electric Grid	Excluded	Not significant
Access to Transport Network	Excluded	Not significant

4.5. Results

ArcGIS 9.3.1 was used to create maps for rainfall, solar irradiance and temperature, and the coordinates for every consultee involved in this study. Where a consultee had multiple sites that emit large quantities of CO₂, every site was included. However, certain consultees included earlier in the study had to be excluded from this part of the study. For some, their total GHG emissions, although very high, are divided into such a large number of small emitters, that it would obstruct the visual effect of the maps. For others, such as financial service industries, their GHG emissions are in fact third party. In total, sites under investigation in the results consist of 29 Eskom power stations and 22 non-Eskom sites.

4.5.1. Temperature

The temperature maps were reclassified into 2 categories to allow for easier analysis. The 2 categories used were:

1 = Suitable

0 = Not Suitable

The criteria for selection were:

4.5.1.1. Minimum temperature

The salinity of the open ponds will inhibit freezing of the water, even under conditions where temperatures drop as low as -5°C , as long as the duration of such cold spells is short (e.g. overnight) (Ebbing & Gammon, 1990). Therefore minimum temperatures below -5°C for any duration were classified as 0 and all temperatures above this were classified as 1 (Figure 4.5.a).

4.5.1.2. Maximum temperature

Optimal temperatures are between 20 and 40°C , whilst temperatures over 45°C for any prolonged period will reduce algal metabolic efficiency, reducing the production of biofuel. It may also begin to cause damage to the algal cells. Therefore maximum temperatures above 40°C were all classified as 0 whilst temperatures below this were classified as 1 (Figure 4.5.b).

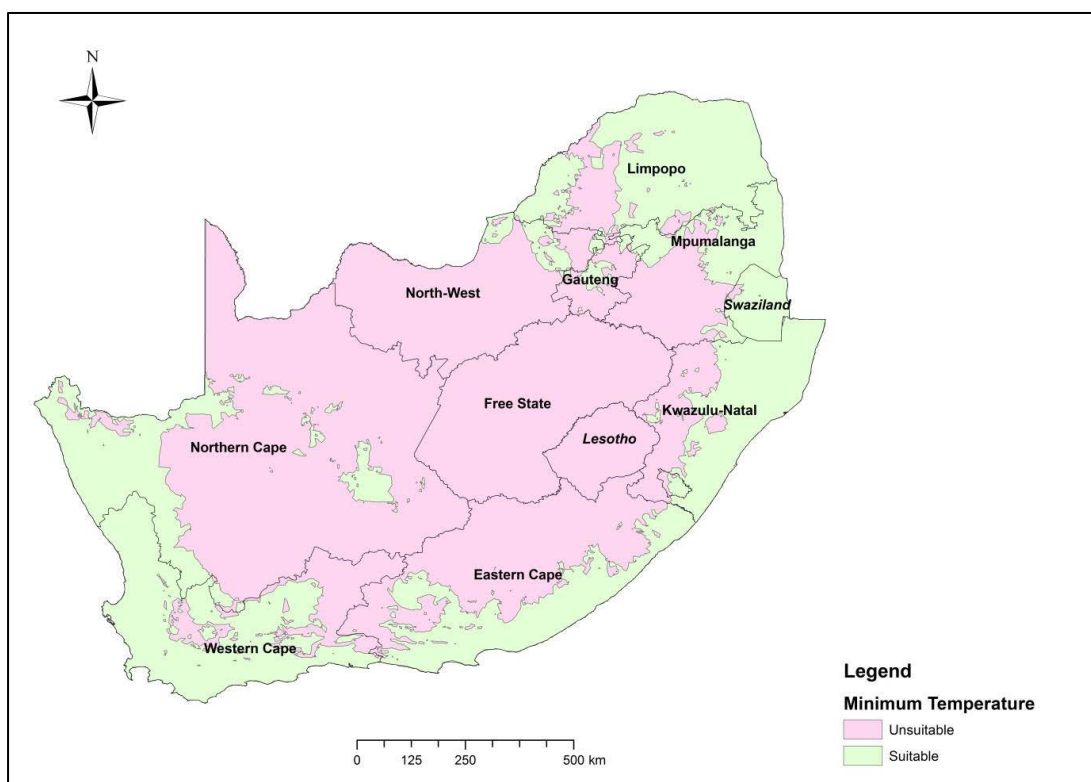


Figure 4.5.a Suitable and unsuitable temperatures for algal growth, where the minimum temperature requirements are met. Areas in green are where algae will be able to grow (Source: UKZN, SAEES).

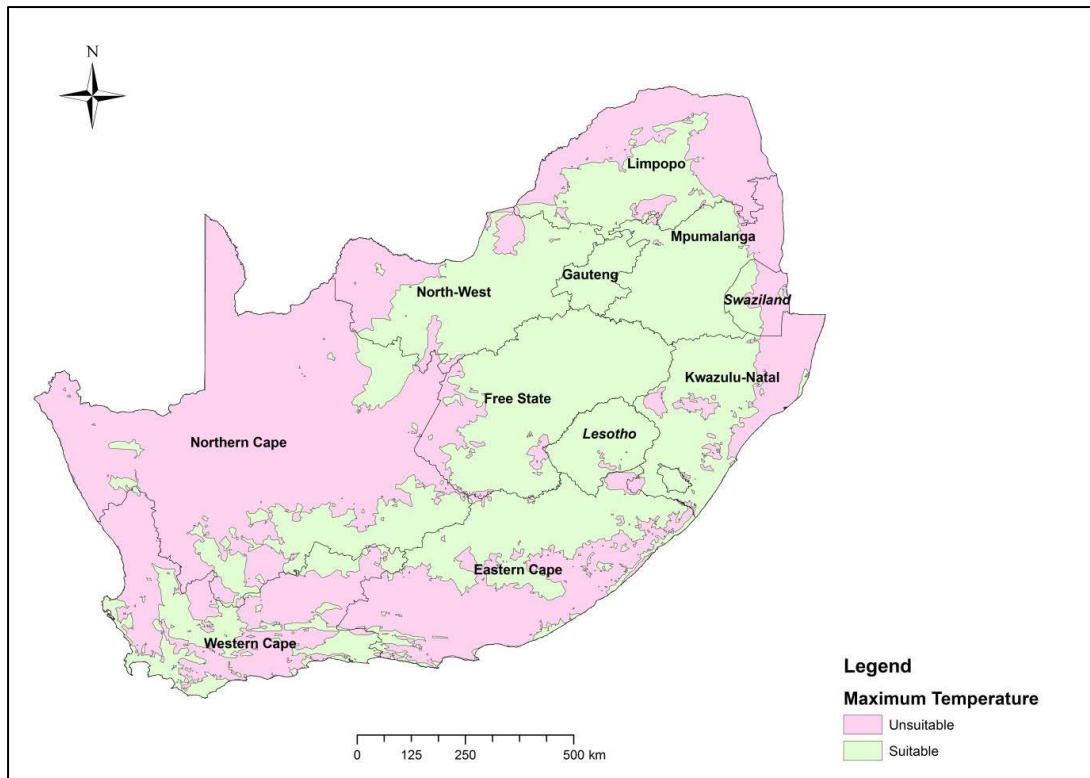


Figure 4.5.b Suitable and unsuitable temperatures for algal growth, where the maximum temperature requirements are met. Areas in green are where algae will be able to grow (Source: UKZN, SAEES).

Raster calculator was then used to combine these 2 maps. All areas of ideal temperature are shown in green (classified as 1) and all areas of unsuitable temperature are shown in pink (classified as 0) (Figure 4.6.).

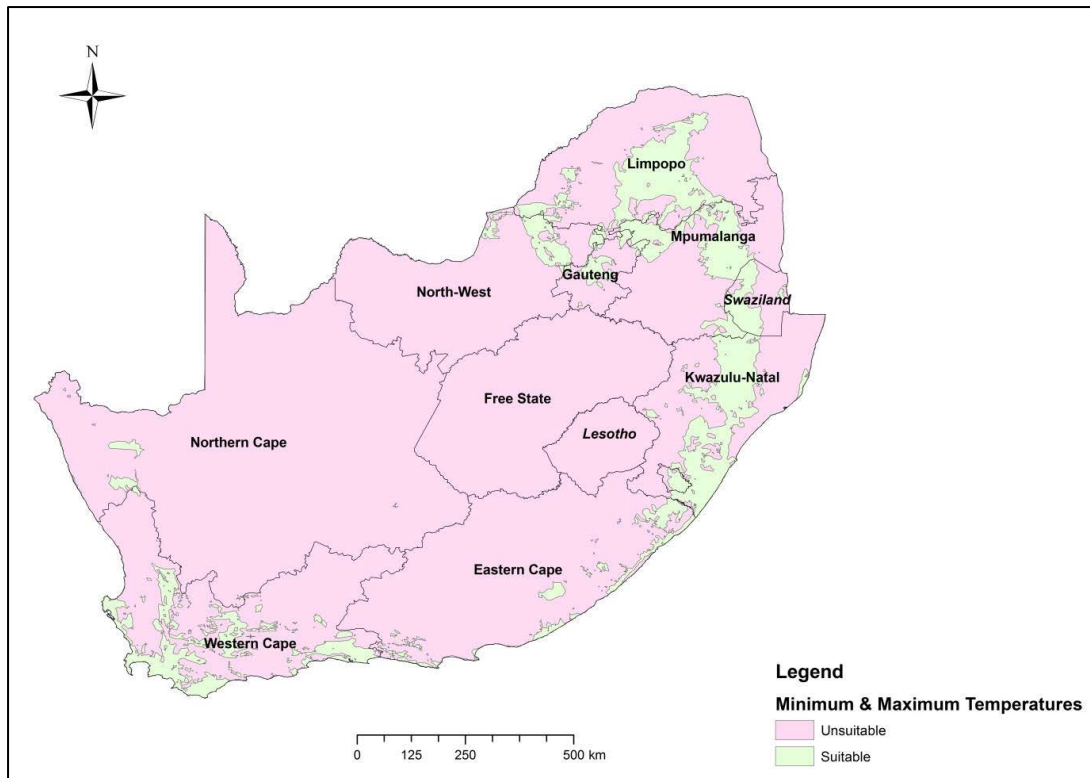


Figure 4.6. Suitability analysis for both minimum and maximum temperatures for algal growth²⁶ (Source: UKZN, SAEES).

4.5.2. Rainfall

The rainfall map was reclassified into 2 categories to allow for easier analysis. The 2 categories used were:

1 = Suitable 0 = Not Suitable

Areas are considered arid when they have rainfall of 100 – 200 mm per year. For this reason all areas with a rainfall below 200 mm per year were assigned a category of 0 whilst areas with higher rainfall were classified as 1. The driest areas of the country are the Northern Cape and the north of the Western Cape.

²⁶ Areas in green are where algae will be able to grow throughout the year. These areas are considered the best for the pilot algal site.

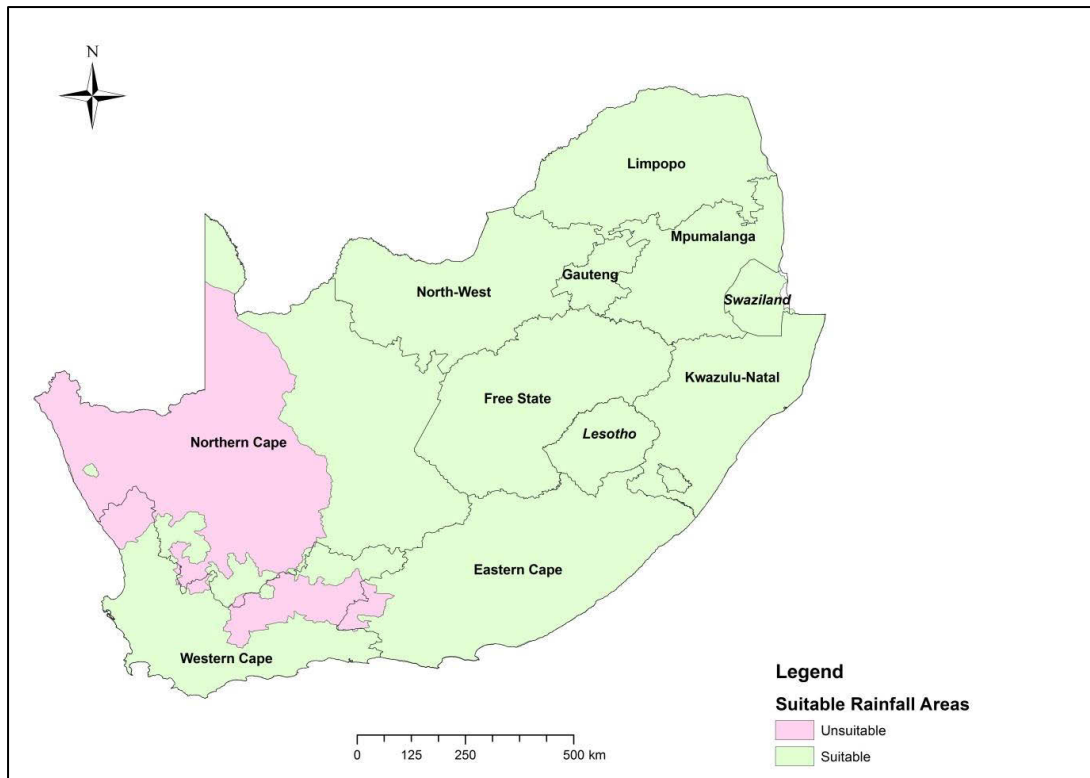


Figure 4.7. Areas of suitable and unsuitable rainfall. The more arid areas with average annual rainfall of less than 200 mm per year were classified as unsuitable whilst those of more than 200 mm per year were considered suitable (Source: UKZN, SAEES).

The temperature and rainfall maps were then combined using raster calculator again and all the areas of suitable temperature but not suitable rainfall were removed from the analysis (Figure 4.8.).

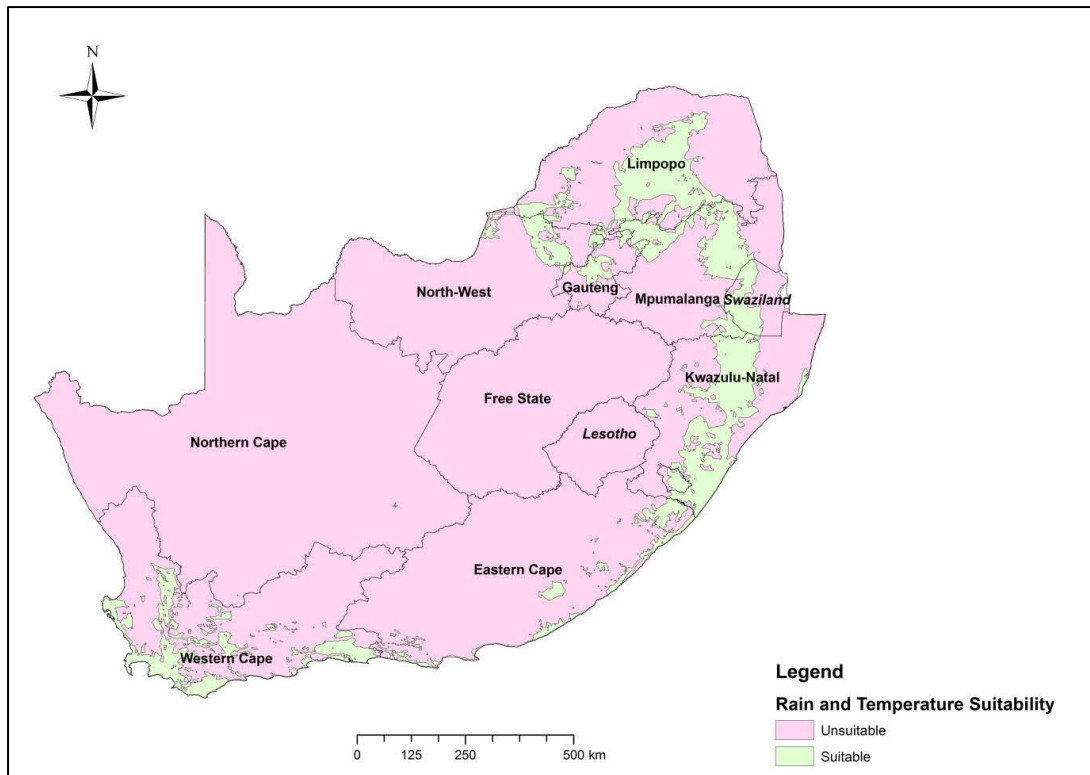


Figure 4.8. The most suitable areas for algal growth in terms of temperature and rainfall. Some areas in the Northern Cape have been removed from the analysis as there is too little rainfall in that area (Source: UKZN, SAEES).

The remaining areas of suitable environmental conditions sweep in an arch from Cape Town in the Western Cape, along the coast of the Eastern Cape and Kwa-Zulu Natal, before coming inland slightly through northern Kwa-Zulu Natal and Mpumalanga and Limpopo provinces. The largest suitable areas are through these later, more northern provinces. Almost all of the Northern Cape, the Free State and the North West Province are excluded at this point on these environmental constraints. Only a narrow strip of land along the coastline through the Eastern Cape is passed at this stage, essentially the entirety of inland Eastern Cape is excluded.

The total size of environmentally favourable habitat (most suitable areas in terms of temperature and rainfall), provided by the GIS software, is 13 815 051 hectares (ha). The GIS mapping records that a total of 108 505 049 ha have been classified as unsuitable (total size of RSA given as 122 320 100 ha). This is equal to 11.29% of South Africa that is most favourable and 88.71% less favourable.

4.5.3. Solar Irradiance

Figure 4.9. shows the suitable areas overlaid on the irradiance map for South Africa. The location of the consultee study sites are also overlaid on this map. From this map it can be seen that the area of highest irradiance is least suitable because of limiting rainfall. This level of irradiance may in fact be so high as to be harmful to the microalgae, and lead to reduced biofuel productivity. A large number of the consultee study sites are in the areas of suitable environmental conditions for algal growth. These are in Limpopo, Mpumalanga and Gauteng, where the irradiance is higher than at the coast.

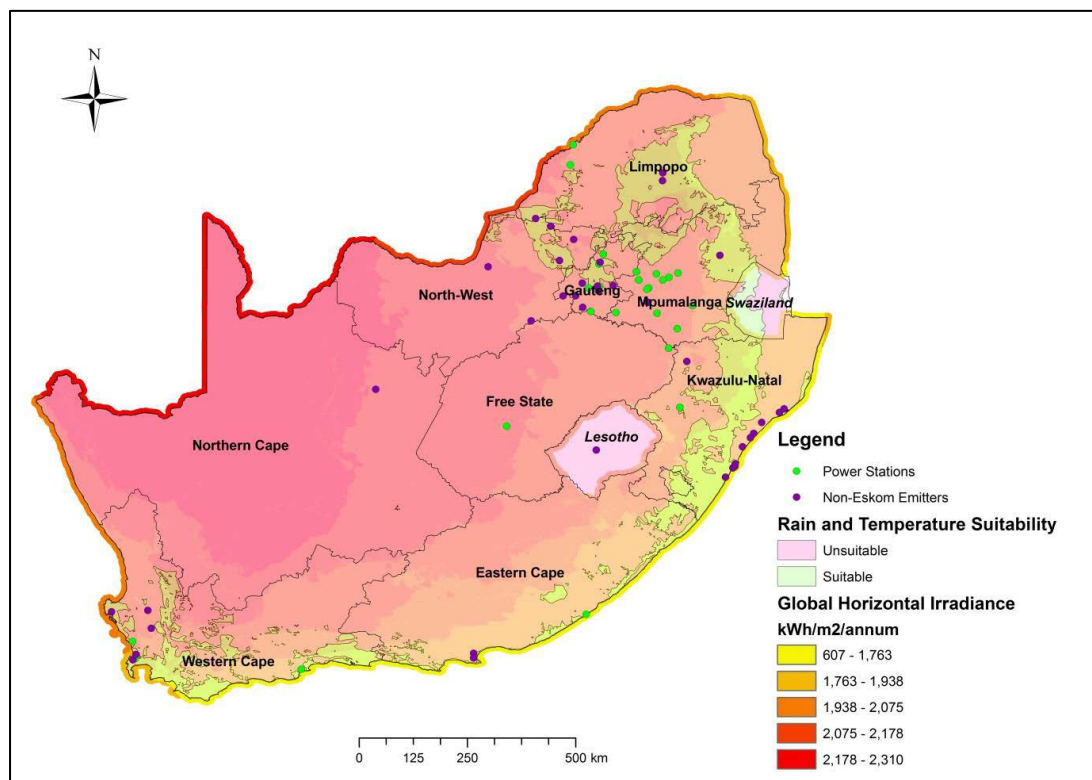


Figure 4.9. The most suitable areas for algal growth, also showing the global horizontal irradiance and study sites throughout South Africa. All study sites are shown to present which fall inside and which outside of the optimal areas (Source: UKZN, SAEES).

4.5.4. Remaining Industries Within Suitable areas of South Africa

There are 11 non-Eskom sites and 4 Eskom sites that fall within the suitable areas (Figure 4.10.). These sites are closely grouped in Cape Town and in Gauteng, around Johannesburg, made up of a variety of industry types. Outside of these heavily populated areas the remaining sites are widely dispersed, through the Western Cape, Kwa-Zulu Natal, Mpumalanga, Limpopo, and the North West Province. Metals and mining industries are selected a short distance outside of Gauteng. Two power stations are selected in Cape Town and another two around Johannesburg. A brewer is selected in Cape Town and in the Limpopo capital, Polokwane. The north coast of Kwa-Zulu Natal has a paper manufacturer. The north coast of Kwa-Zulu Natal has a paper manufacturer.

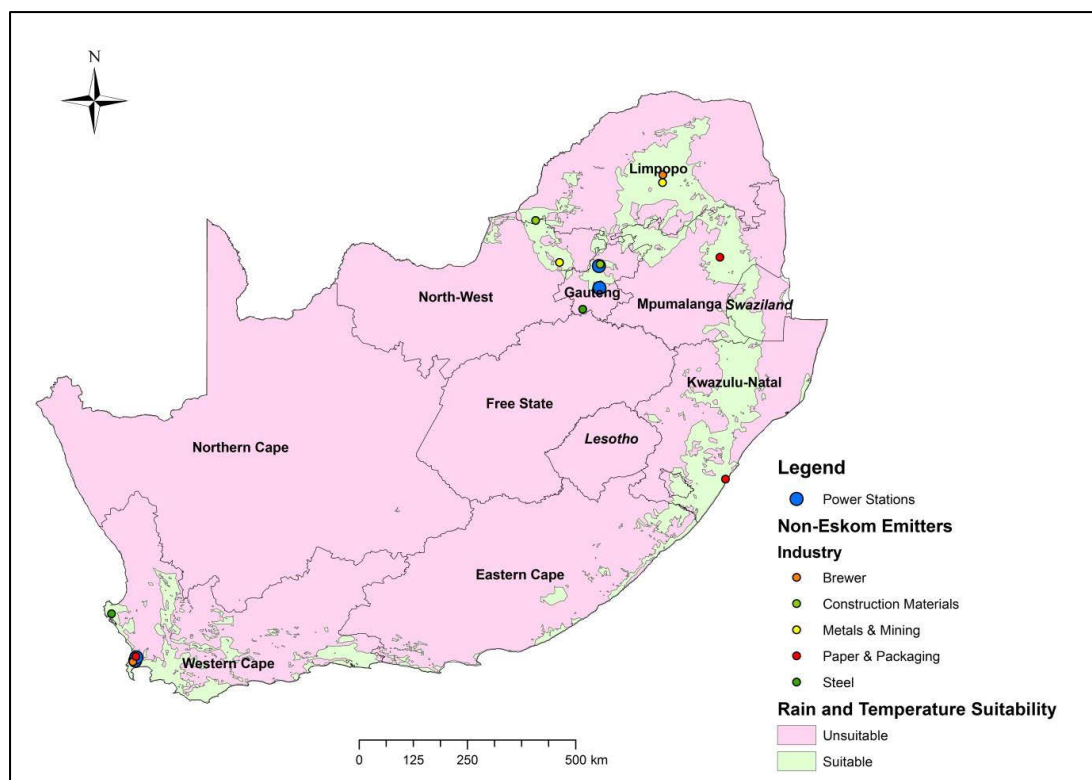


Figure 4.10. Location and type of emitters that fall within suitable areas for algal growth (Source: UKZN, SAEES).

4.5.5. Access to water.

ArcGIS 9.3.1 was used to exclude any of the study sites that are further than 500 m from a plotted river. This resulted in 4 non-Eskom sites and one Eskom power station remaining. These are shown in Table 4.4. and their locations in Figure 4.11.

Table 4.4. A list of the sites in optimal locations in South Africa for temperature, rainfall, irradiance and proximity to a river.

Consultee Study Site	Name of nearby river
Non-Eskom a	Umkomaas
Non-Eskom b	Ngodwana
Non-Eskom c	Liesbeek
Non-Eskom d	Apies
Eskom a	Vyakraal

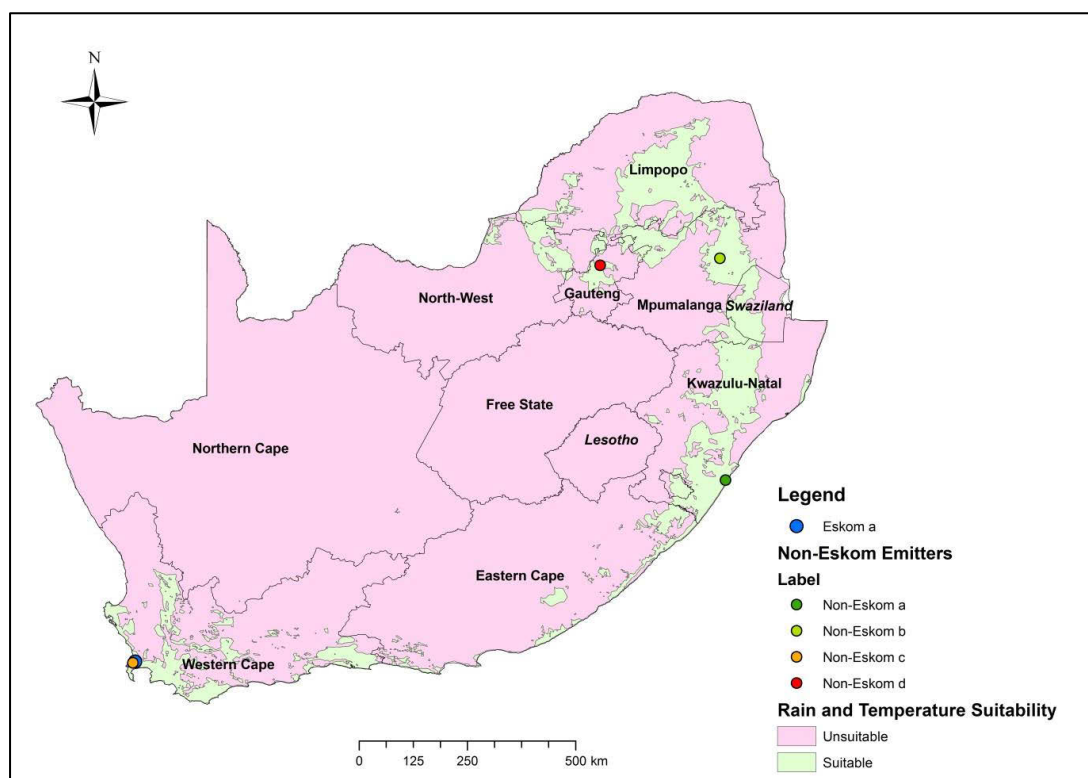


Figure 4.11. Remaining sites after the suitability analysis within 500 m of a river (Source: UKZN, SAEES).

Two of these sites are located in Cape Town, an Eskom power station and a paper manufacturer. Two of the remaining three sites are also paper manufacturers, in Kwa-Zulu Natal and Mpumalanga. The remaining site produces construction materials (concrete) and is located near Johannesburg.

4.5.6. Land Use

A final visual inspection was carried out of the five remaining study sites in order to gauge suitability of existing and neighbouring land use, and whether land for such a development would be available. Satellite imagery was used for this inspection, and the results are as follows:

- Non-Eskom a: This site is located within a bend of the Umkomaas river, on a large industrial footprint. Surrounding the compound are what appear to be relatively undisturbed areas of natural vegetation. A large number of residential properties lie scattered on the opposite bank of the river. On a cursory inspection it appears that a considerable amount of unused land within the industrial compound could easily accommodate a number of open algal ponds for a pilot project. Further space would likely be available for expansion as the project develops, and hence this site is thought to hold good potential for such a scheme.
- Non-Eskom b: This site consists of a vast industrial complex, surrounded by large expanses of agriculture and undeveloped land, with a small town to the east. The buildings are well spaced out across the complex, and there are no obvious competing land uses immediately adjacent. It is considered likely that space could be found either within the existing industrial complex, or immediately adjacent, on land to be developed. On initial inspection this site looks to hold good potential for further investigation.
- Non-Eskom c: This site is located in a heavily urbanised area of Cape Town, with other industries completely surrounding the site, railway lines and busy roads not far away. Only a narrow strip of undeveloped land exists close by, buffering an adjacent railway line. Due to the likely planning issues that will arise, in addition to lack of available land, and high price of land in this area, this site is not considered favourable for this type of development.
- Non-Eskom d: This site is a large industrial compound, surrounded on all sides by busy highways and mainline railway lines. This would preclude any expansion outside of the compound. A cursory visual inspection suggests that there would be little room for development within what is already a well-developed site. There may

be room for a small number of pilot algal ponds, but it would not be possible to develop further from this stage.

- Eskom a: This power station, although located within central Cape Town, and surrounded by residential areas and highways, exists on its own large plot of relatively undisturbed land. Nearby is a large sewage treatment works. Any algal ponds would visually be in keeping with the surrounding development. It is thought, given the very large expanses of undeveloped land within the power station compound, this site would easily accommodate a pilot project scheme.

The visual inspection has suggested that the Eskom Power station, plus two of the four non-Eskom sites all have suitable available land either within the existing site complex, or on immediately adjacent land. Hence, three of the last five remaining sites under investigation would warrant further on-site inspection; they are ideally located for temperature, rainfall, access to water and land-use.

4.6. Limitations

The scope of this project has been much greater than initially conceived such that time and resources have not been sufficient to investigate this project as thoroughly or as far as originally envisaged. For this reason the number of consultees and the number of sites throughout South Africa was limited to under 60. This project looks at the production of one specific type of biofuel, glycerol, produced in high concentration by only a limited number of microalgae species. Ideally, as a source of information to Government and private investors, further research should look at the logistics and scalable economics of many algal species and biofuel products.

A number of assumptions have been made. As it is not known at this time exactly what molar concentration of salt will be present in the algal solutions, an estimate was made that -5°C would be an acceptable lower limit for minimum temperatures. This was allowing consideration that this is likely to be a brief and extreme night-time temperature.

To allow for some error in the data collection a 1 km buffer was included around the areas of acceptable temperature limits. This did not increase the number of sites included in the

acceptable areas. With a further buffer of 2 km an additional 2 non-Eskom sites are included. With a 2.5 km buffer an additional 3 non-Eskom sites and 1 Eskom site are included. With an additional 3 km buffer an additional 4 non-Eskom sites and 2 Eskom sites are included. However, it was decided to keep to the 1km buffer in the analysis as a buffer greater than this would introduce sites outside of the desired parameters.

For this investigation it was decided to include some of the Eskom power stations that have been decommissioned in recent years. This is due to the recent trend of re-commissioning of a number of these sites as Eskom has struggled to match their capacity to the national demand. Given the possibility that these remaining decommissioned sites might also be re-commissioned in time, it was decided to include them in the study.

There are no studies in peer reviewed literature that examine the optimal levels of horizontal solar irradiance. As such it was not possible to use this layer of GIS data to help select ideal locations in South Africa. The map of solar irradiance is presented for information only, and it is explained that excessive amounts of irradiance are known to be harmful to microalgae and can actually reduce their ability to photosynthesise. When more data is available with regard to this, further selection processes can be used to help select ideal locations.

Other limitations existed in the amount of GIS data available. This type of study is limited by what data exists for the whole of South Africa. For example, land use data for the whole of South Africa was not available, hence this layer could not be used. An aerial visual inspection could be carried out, using satellite imagery, but would also bring in elements of human error and subjectivity. Also, when using Google Earth® the images might be out-dated and currently it is not possible to accurately date the image one is analysing. In the future it is envisaged that a greater wealth of GIS data will be available for such analysis; as a result for a study of this type, more accuracy can be achieved in finding ideal site locations.

For the purposes of this study the GIS analysis included the small neighbouring country of Swaziland. It was decided to include this area as much of the country was found to be suitable for this renewable technology and it is hoped that this information will lead to further investigation specifically for Swaziland.

Due to reasons of privacy it was decided not to publish the details of the consultees, only the type of industry they belonged to. This was in part because permission was not requested from the consultees to publish their responses and their details. It is quite possible that they may be perfectly happy to be included, and in a future study this permission would be requested.

4.7. Discussion

The GIS maps presented in Section 4.5. reveal a great deal of information regarding climatic and environmental variations across South Africa. Figure 4.12. shows the global horizontal irradiance for the world, and visually demonstrates the high levels of irradiance experienced by South Africa, when compared with much of the developed world and the northern hemisphere, particularly Europe. When used in conjunction with Figure 4.9., it becomes apparent that even the areas of South Africa with lower solar irradiance, when compared with much of Europe, still maintain very good potential for high photosynthetic rates.

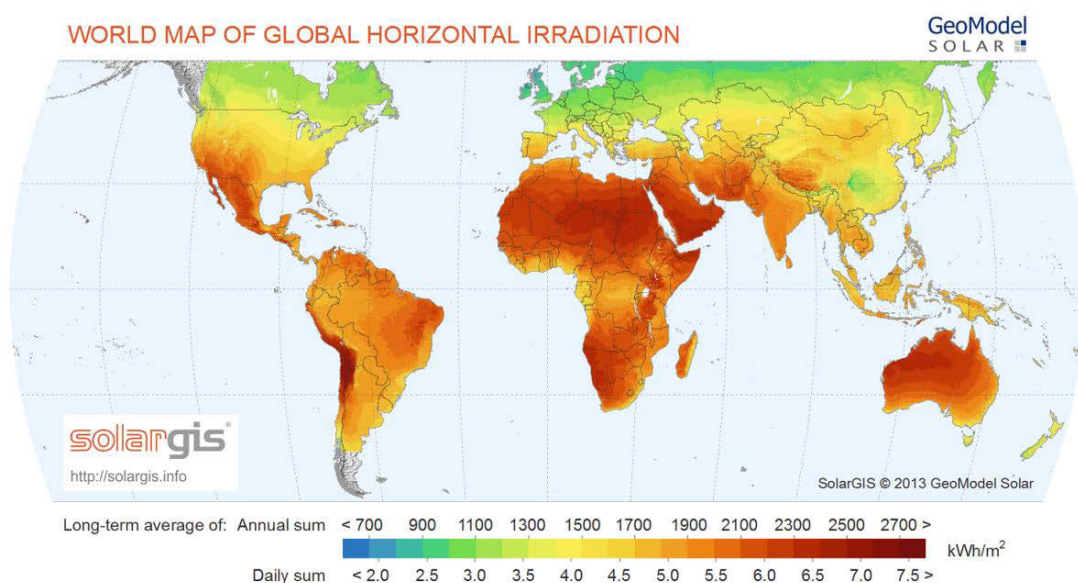


Figure 4.12. World map showing global horizontal irradiation. Units are in KWh/m² (Map is kindly provided with the permission of Solargis).

Within the limits for successful creation of biofuel glycerol from microalgae in open ponds, a relatively large area of South Africa remains (13.8 million hectares or 11.29% of South Africa). This study was intent on highlighting the areas in South Africa that were optimal for

culturing algal biofuel in open ponds. It is worth noting that this does not preclude areas outside of these limits from this technology. Conditions outside of these areas might still be able to provide economically competitive biofuel: this study merely highlighted the areas that are most likely to provide this, with minimal input (infrastructure) or disturbance (such as only viable for part of the year).

Of the final five sites that were not excluded due to the environmental constraints, three of these were from the paper industry. The environmental conditions that would encourage the growth of the trees used in the paper industry are likely to be within similar parameters as those required for algal ponds. From a location theory perspective, as both of these industries rely on the high rate of photosynthesis of an organic plant species they will both select locations for good solar irradiance, not excessively hot, and with good levels of rainfall. It is highly likely that they will be located in similar areas.

Of the four non-Eskom sites and one Eskom site that remained at the end of the study (Figure 4.11.), it was found that three of the non-Eskom sites were connected to a consultee that had responded to the early consultation, and had returned the completed questionnaire. Unfortunately they did not wish to be involved any further in the progress of the project.

4.8. Conclusion

Until a pilot plant is actually constructed and run for some time it will be impossible to know with absolute certainty how cost-competitive this renewable technology can be. Until this is done, there is little chance for this biofuel technology to create its own niche in South Africa.

From this study it can be seen that GIS is an essential tool in helping to select for preferred site locations to enable maximum productivity from such a bio-energy production site.

It is the author's opinion that South Africa has an enormous potential for biofuel from open algal ponds. Using the strictest environmental constraints, there remains an enormous area (13.8 M ha) with great potential for algal ponds. For this study only the biggest emitters have been used, but almost any industry with a chimney that emits CO₂ could be utilised.

References

- Anon. 2012. *Geography and Climate: South Africa's Geography*. South Africa Info. 28 06 2012.
<<http://www.southafrica.info/about/geography/geography.htm#.UphecgDZBtjo>>
(accessed November 2013).
- Beckmann, M.J. 1968. *Location theory*. 101-269-287 : Random House (New York).
- Ben-Amotz, A. 1981. Glycerol and β -carotene metabolism in the halotolerant alga *Dunaliella*, a model system for biosolar energy conversion, glycerol production by *Dunaliella*. *Trends in Biochemical Sciences*: (6) 297-299.
- Ben-Amotz, A. 1980. The biotechnology of cultivating the halotolerant alga *Dunaliella* (patent). *Trends in Biotechnology* (Patent): (8) 121-126.
- Brennan, L., and Owende, P. 2010. Biofuels from microalgae - A review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and Sustainable Energy Reviews*: (14) 557-577.
- Brown, L.M. 2004. Biodiesel from microalgae: complementarity in a fuel development strategy. *National Renewable Energy Laboratory*: 902-908.
- CDP. 2009. *South Africa JSE 100, Carbon Disclosure Project 2009*. CDP.
<http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCsQFjAA&url=http%3A%2F%2Fwww.saice.org.za%2Fdownload%2Fother%2Fcdp_%25202009_SA_JSE_100Report.pdf&ei=4GEhU87EM-nY7Aapm4CQDQ&usg=AFQjCNECZX9PT-if33p4QXV3rsIJcFaqyA> (accessed November 2013).
- Chelf, P., Brown, L.M., and Wyman, C.E. 1993. Aquatic biomass resources and carbon dioxide trapping. *Biomass Bioenergy* 4: 175–183.
- Chisti, Y. 2007. Biodiesel from microalgae. *Biotechnology Advances*: (25) 294-306.

- CIA, 1996. World Factbook. *South Africa Weather and Rainfall*. Photius.
<http://www.photius.com/countries/south_africa/climate/south_africa_climate_climate_and_rainfall.html> (accessed November 2013).
- DOE. *Renewable Energy: Solar Power*. South African Department of Energy. Not stated.
<http://www.energy.gov.za/files/esources/renewables/r_solar.html> (accessed November 2013).
- Ebbing, D.D., and Gammon, S.D. 1990. *General Chemistry*. 3rd Edition, Houghton Mifflin. 481 P.P.
- FAO. 1989. *Arid zone forestry: a guide for field technicians*. Rome, Italy.: Food and agricultural organisation (United Nations). ISBN 92-5-102809-5.
- García-Luque, E., Forja, J.M., and Gómez-Parra, A. 2005. Characterization of atmosphere–water exchange processes of CO₂ in estuaries using dynamic simulation. *Journal of Marine Systems*: 58, 98-106.
- Giordano, M., Davis, J.S., and Bowes, G. 1994. Organic carbon release by *Dunaliella salina* (chlorophyta) under different growth conditions of carbon dioxide, nitrogen, and salinity. *Journal of Phycology*: 30, (2), 249–257.
- Gnansounou, E, L Panichelli, and J.D. Villegas. 2007. *Sustainable liquid biofuels for transport: the context of Southern African Development Community. Working paper ref. 430.100*. Lausanne, Switzerland.: Ecole Polytechnique Federal De Lausanne, 1-21.
- Gnansounou, E., Dauriat, A., Villegas, J., Panichelli, L. 2009. Life cycle assessment of biofuels: energy and greenhouse gas balances. *Bioresources Technology* 100, no. (21): 4919-30.
- Gnansounou, E., Panichelli, L. and Villegas, J.D. 2007. Sustainable liquid biofuels for transport: the context of Southern African Development Community. Working paper

- ref. 430.100. Lausanne, Switzerland.: Ecole Polytechnique Federal De Lausanne. 1-21.
- Gouveia, L. and Oliveira, A.C. 2009. Microalgae as a raw material for biofuels production. *Journal of Industrial Microbiology and Biotechnology*: 36, 269-274.
- Grobbelaar, J.U. 1982. Potential of algal production. *Water SA*: 8, 79-85.
- Groom, M.J., Gray, E.M., and Townsend, P.A. 2008. Biofuels and biodiversity: principles for creating better policies for biofuel production. *Conservation Biology*: 22, 602-609.
- Harvey, D.L.D. 2007. Allowable CO₂ concentrations under the United Nations Framework Convention on Climate Change as a function of the climate sensitivity probability distribution function. *Environmental Research Letters*: 2 (014001), 10 P.P.
- Harvey, P.J. 2010. Glycerol power from microalgae, EU funding proposal. *Unpubl. Lit.* University of Greenwich, United Kingdom.
- Le Treut, H., Somerville, R., Cubasch, U., Ding, Y., Mauritzen, C., Mokssit, A., Peterson T., and Prather, M. 2007. *Historical overview of climate change, climate change 2007: the physical science basis, contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge, United Kingdom: Cambridge University Press.
- Lesser, M.P., and Farrell, J.H. 2004. Exposure to solar radiation increases damage to both host tissues. *Coral Reefs* 23: 367–377.
- Loeblich, L.A. 1982. Photosynthesis and pigments influenced by light intensity and salinity in the halophile *Dunaliella salina* (chlorophyta). *Journal of the marine biological association of the United Kingdom* 62: 493-508.
- Mata, T.M., Martins, A.A., and Caetano, N. 2010. Microalgae for biodiesel production and other applications: a review. *Renewable and Sustainable Energy Reviews*: 14, 217-232.

- Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Noda, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., and Zhao, Z.C. 2007. *Global Climate Projections: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.
- Miller, G.T. 2005. Living in the environment, principles, connections and solutions. *Cengage Learning* 10th edition: Brooks/Cole. ISBN 0495556718.
- Neenan, B., Feinberg, D., Hill, A., McIntosh, R., and Terry K. 1986. Fuels from microalgae: technology status, potential, and research requirements. *Solar Energy Research Institute*: SERI/SP-231-2550:149 P.P.
- Puppán, D. 2002. Environmental evaluation of biofuels. *Periodica Polytechnica, Ser. Soc. Man. Sci*: 10, 95-116.
- Rautenbach, C.J. de W. 1998. The unusual rainfall and sea surface temperature. *Water SA* 24: 165-172.
- Scott, S.A., Davey, M.P., Dennis, J.S., Horst, I., Howe, C.J., Lea-Smith, D.J., and Smith, A.G. 2010. Biodiesel from algae: challenges and prospects. *Current Opinion in Biotechnology*: 21, 277-286.
- Seambiotic. 2010. Algae Pilot Plant Description Worksheet.
<<http://www.seambiotic.com/uploads/Seambiotic%20Ltd.%20-%20Algae%20Pilot%20Plant%20white%20paper.pdf>> (accessed November 2013).
- Seambiotic. 2008. Method for growing photosynthetic organisms. International application number PCT/IL2008/000302 Patent pub. no. US 2008/0220486.
- SAWS. 2013. South African Weather Service. *What are the temperature, wind and rainfall extremes in SA?* South African Weather Service.

- <<http://www.weathersa.co.za/web/index.php/corporate?id=167>> (accessed November 2013).
- UNEP. 2011. *Green Economy Report (GER) – renewable energy*. United Nations Environment Programme. ISBN: 978-92-807-3143-9.
- Van Gerpen, J. 2005. Biodiesel processing and production. *Fuel Processing Technology* 86, no. (10): 1097-1107.
- Voegelé, E. 2008. Technology allows glycerin to power diesel generator. *Biodiesel Magazine*.
 <<http://www.google.co.uk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CCsQFjAA&url=http%3A%2F%2Fwww.biodieselmagazine.com%2Farticles%2F3076%2Ftechnology-allows-glycerin-to-power-diesel-generator&ei=AaolU6fvD4ORhQfZpoDgDw&usg=AFQjCNEE7GLIfE3lMI8T3NGR4J5sCme8yw&bvm=bv.62922401,d.Yms>> (accessed November 2013).
- Wegmann, K. 1971. Osmotic regulation of photosynthetic glycerol production in *Dunaliella*. *Biochimica et Biophysica Acta (BBA) - Bioenergetics*: 234, (3), 317–323.
- Wegmann, K., Ben-Amotz, A., and Mordhay, A. 1980. Effect of Temperature on Glycerol Retention in the Halotolerant Algae *Dunaliella* and *Asteromonas*. *Plant Physiology* 66, no. (6): 1196-1197.
- Wegmann, K. 1971. Osmotic regulation of photosynthetic glycerol production in *Dunaliella*. *Biochimica et Biophysica Acta (BBA) - Bioenergetics*: 234, (3), 317–323.

CHAPTER 5

Limitations, Discussion and Conclusions

5.1. Limitations

When looking at the benefits of algal biofuels in South Africa one aspect that warrants investigation are the socio-economic benefits; these might include employment growth, energy security, reduced local pollution and related health benefits, improved local infrastructure, transport links and schooling. Although Chapter 3 describes in general terms the recognised benefits of decentralised and rurally based micro-generation schemes, there was not enough time or scope in this scheme to look into these benefits in more detail. For the Government of South Africa, and for foreign investors, to consider venturing into a renewable technology of this nature, the benefits must go beyond merely supplying a novel form of fuel. Benefits, such as social and economic benefits to those living in the local vicinity of the project sites, must be well researched.

Modern biofuels all undergo a full life cycle analysis: a thorough investigation of the carbon footprint of producing and burning the fuel, including all infrastructure, over the lifetime of the industry. Thus the carbon footprint of modern biofuels can be compared with other biofuels and traditional fossil fuels, and valued in terms of their benefit to reducing GHG emissions. Any further investigation of this (glycerol from *Dunaliella*), or any other type of algal biofuel should include at least an estimate of life-cycle analysis.

This study only briefly looked into location theory, and noted a very simple association between algal pond locations and paper-industry plantations. With more time it was hoped that deeper insights might be made with more in-depth investigation. Closer associations with other industry types might be made, and in so doing help find prime locations for pilot project sites.

A weighted analysis of the criteria affecting growth rates of microalgae would have helped create results maps which more accurately weight the criteria according to importance. However, nothing similar has been noted in published research on which to base such a weighting. This meant that such a weighting would have to be decided upon based upon the findings of the research within this thesis. Any further investigation of this subject would hopefully pursue this.

The use of GIS is heavily dependent on the data sets that are available for the area being studied. In this study we were fortunate to have data for rainfall, maximum and minimum temperature, major rivers and solar irradiance. Altitude was also available (but valued as unnecessary against temperature). A data set for land use would provide a more accurate assessment of the practicalities of exactly where a pilot site could be sited, in close proximity to a source of CO₂ (such as a chimney stack). The visual inspection using satellite imagery presented in Chapter 4 proved to be useful for this study, but is subject to the potential errors that arise when a subjective analysis is incorporated.

5.2. Discussion and Conclusions

The use of microalgae to grow biofuels is recognised by industry experts to be the most efficient method of producing renewable liquid fuels. There are limited countries around the world that have a climate which is so well suited to this technology. The more suited the climate, the more biofuel can be produced and the more competitive this technology will be against existing forms of energy.

This study relates to the changing energy situation and the future energy goals, the pollution problems and the effects of climate change that are already being faced, the broad environmental, physiological, climatic and socio-economic variations experienced across South Africa. Chapter 2 describes the differences in weather, climate, altitude and geography in South Africa. Investigating the introduction of open algal ponds to South Africa brings a very specific biological process, easily affected by external factors, to a land of great variation.

The literature review of Chapter 3 brings together a comprehensive understanding of these specific biological processes of open algal ponds. Within the context of the historical and current conditions, Chapter 4 introduces the largest emitters of CO₂ in South Africa and the consultation carried out with these industries. It goes on to explore in greater detail the most significant external factors to influence the productivity of open algal ponds. The knowledge gathered from Chapter 3 has been used in Chapter 4 to select the most important factors affecting the choice of location for open algal ponds. This analysis has shown that large areas of South Africa, totalling nearly 14 million ha (11.3%), fit within the selected parameters. A

similarity is also recognised between the suitable locations for microalgae producing biofuels, and tree plantations for the paper industry.

The GIS analysis has highlighted approximately 11.3% of the landmass of southern Africa (South Africa and Swaziland) as ideally suited to build pilot project sites for open algal raceway ponds. This landmass is distributed across southern and eastern South Africa and includes the Western Cape, the Eastern Cape, Kwa-Zulu Natal, Mpumalanga, Limpopo, the North-West Province and Gauteng (7 of the 9 provinces). The idea of decentralised biofuel production and distribution sites raised in Chapter 3, and the associated socio-economic benefits, tie in very well with this distribution of suitable land. Apart from the Northern Cape and the Free State, locally produced algal glycerol biofuel could be produced and distributed locally for much of South Africa; this would also reduce the environmental and financial costs associated with transport over long distances.

South Africa has the ability to take advantage of its suitability for developing algal biofuels. Not only has it been shown that all criteria for maximal biofuel production are met by nearly 14 million ha of land within South Africa, but the timing for such investment fits perfectly into the Government's aims and targets. In Chapter 3 we learn that binding targets have been set for renewable energy sources to be added to the forms of energy provision, and how opportunities are now arising to foreign energy investment in energy in South Africa. The consultation in Chapter 4 suggests that there is an understanding of renewable alternatives and an interest in using them, and this is sure to grow as the Government's targets become more widely understood.

As the environmental and health costs associated with the use of South Africa's cheap coal reserves continue to rise, and as national and international pressure to use renewable alternatives increase, and the cost-competitiveness of these technologies continues to improve, South Africa must consider taking full advantage of this opportunity. Few countries in the world are so well located and suited and timed for the development of liquid biofuels produced by microalgae, and this technology should play an important role in the future of sustainable energy provision in South Africa.

Appendices

Appendix I. Consultee Responses to Consultation

Eskom Consultees	Reply to 1 st Contact	Reply to 2 nd Contact	Reply to 3 rd Contact	Response	Completed Questionnaire	Further Interest?
1	Yes	Yes		Out of office		
2		Yes	Yes		Yes	Yes
3		Yes	Yes			
4	Yes	Yes	Yes			
5		Yes	Yes		Yes	
6		Yes	Yes			
7		Yes	Yes			
8			Yes			
9		Yes	Yes			
10		Yes	Yes			
11	Yes				Yes	No answer – ask person X.
12					Yes	Yes
13		Yes	Yes			
14		Yes	Yes	Busy with audits this week	Yes	
15		Yes	Yes			
16		Yes	Yes			
17	Yes	Yes		Yes	Yes	No answer
18	Yes	Yes	Yes			
19		Yes	Yes			
20		Yes	Yes			
21		Yes	Yes			
22				Please forward to [...]		
23		Yes	Yes			

Eskom Consultees	Reply to 1st Contact	Reply to 2nd Contact	Reply to 3rd Contact	Response	Completed Questionnaire	Further Interest?
24		Yes	Yes	Please afford me time to get permission on whether or Not we are allowed to disclose any information other than public reports	Yes	No
25					Yes	Yes
26		Yes	Yes	Out of office		
27		Yes	Yes			
28		Yes	Yes			
29		Yes	Yes		Yes	
30		Yes	Yes			
31		Yes	Yes			
32		Yes	Yes		Yes	
33		Yes	Yes			
34	Yes	Yes	Yes			
35		Yes	Yes			
36	Yes		Yes		Yes	No

Non Eskom Consultee & Sector		Reply to 1st Contact	Reply to 2nd Contact	Reply to 3rd Contact	Completed Questionnaire	Further interest?
1	Energy	Yes	Yes	Yes		
2	Metals & Mining					
3	Steel					
4	Metals & Mining	Yes		Yes		
5	Industrial Gases					
6	Construction Materials					
7	Paper & Packaging	Yes			Yes	No
8	Paper & Packaging	Yes	Yes	Yes	Yes	No
9	Gold	Yes				
10	Gold	Yes	Yes	Yes		
11	Brewer		Yes	Yes		
12	Construction & Engineering					
13	Food Products					
14	Trading Companies & Distribution					
15	Precious Metals				Yes	no
16	Metals & Mining					
17	Metals & Mining	Yes			Yes	Yes
18	Construction & Engineering	Yes	Yes	Contact X.	Yes	Yes
19	Food Products	Yes				
20	Precious Metals					
21	Other Diversified Finance	Yes			Full response below	
22	Chemicals					
23	Metals & Mining	Yes				

Response from non-Eskom Consultee 21: “We appreciate the confidence in which you have written to us. However, we regret that it will not be possible to comply with your request. Requests to participate in surveys or to confirm the accuracy of data used in surveys or to provide additional information used in research engagements arrive at our offices almost daily. To respond to all these requests would be extremely time-consuming. On the other hand, to make exceptions would be unfair. For these reasons it is our company’s practice not to participate in research, questionnaires, surveys and other similar projects. As regards the specific area of research for your Master degree [consultee 21] is an investment holding company and as such only seeks investment opportunities in, inter alia, renewable energy which has already advanced to “mature and commercial” phases. As such we do not have an environmental officer to refer your enquiry too. We trust that you will understand our position and wish you success with your current project.”

Appendix II – Questionnaire Responses

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
Eskom	Do you currently use any forms of renewable technologies on site?	If yes, please describe them	If no, do you have any plans in the future to use any forms of renewable technology on site?	Do you have any company or site specific policies or drives to encourage energy and water conservation and to reduce GHG emissions?	What quantity of CO₂ is released into the atmosphere on a daily, monthly and annual basis at your site?	Do you have any plans to use carbon capture and storage (CCS) technologies at your site?	Would you be interested in your site being further involved in this theoretical study to determine ideal pilot study sites for this technology?
2	Yes.	Solar energy geysers in some buildings	Not in the near future – but we do have energy efficiency projects to save electricity and natural resources.	Yes, we drive energy efficiency through our SHE Programme and every group must include environmental conservation as part of their SHE system – but we don't have Yes, we drive energy efficiency through our SHE Programme and every group must include environmental conservation as part of their SHE system – but we don't have emissions. This SHE requirement forms part of our audit system. Emissions. This SHE requirement forms part of our audit system.	N/A	N/A	No.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
5	We currently do not co-fire our boilers with any form of biofuels.	Yes, we are currently running a pilot scale solar plant at [...] and [...] Power Stations were the energy generated is used to power part of the administration building. The intent of this energy efficiency initiative is to reduce the internal auxiliary power consumption within the power station using a renewable energy source. We are also busy with pre-feasibility concept studies on the use of biomass (wood-chips) to be co-fired with coal in some of the existing power plants.	N/A	Yes, our Demand Side Management (FY2012: 1 422 gwh) and Internally Energy Efficiency Programs (FY2012: 45 gwh).	231.9 Mt of CO ₂ emitted in the financial year ending 31 March 2012 (224 785 gwh of energy sold).	Eskom is currently evaluating this technology and its development in association with international and local partners. No decision can be made until a large scale viable solution is found.	Yes, via our Research and Testing Department and Eskom EPPEI Program (Suggest that a one-page proposal be submitted for consideration).
11	No we are currently just re-using our water (ash, storm, cooling and demin)	N/A	Looking in PV solar and one gas turbine.	Yes various procedures and see attached environmental statement.	Refer to the attached emission reporting document [...] to assist,	[...] to submit.	[...] to submit.

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
12	Yes – applicable to power generation technology	With regards to the Hydro and Pumped Storage, both use technologies and processes that are renewable. At Hydro stations once the water has run through the turbines it is discharged below the power station to run back into the river and continue its course. At Pumped storage stations instead of the water being discharged, it is retained in the system and re-used. Klipheuwel Wind farm:	Future consideration: Eskom has considered Solar photovoltaic (PV) as one renewable option, on some of the Peaking Stations..	Yes; 49M is an Eskom initiative, endorsed by government and business partners, spurring an urgent need for 49 million South Africans to embrace energy savings as a national culture, and joining the global journey towards a sustainable future. - Eskom's Energy Efficiency Directive (32-522); - Water Management Policy; Unique Identifier: 32-1163; This policy is therefore developed to further demonstrate the commitment of Eskom on water sustainability issues. It provides Eskom's key objectives on water issues throughout its business value chain, including our suppliers. - Air Quality Policy & compliance; - Renewable energy research Eskom continues to invest considerable effort into research and development of renewable energy sources.	Statistics provided for Example: Gourikwa Power Station	Coal is expected to remain part of South Africa's energy mix in the foreseeable future. Our challenge is to develop and deploy advanced clean coal technologies that allow us to continue to use this abundant, indigenous resource. Improved thermal efficiencies as well as the deployment of Carbon Capture and Storage (CCS) would allow us to reduce the carbon intensity of South Africa's electricity supply while ensuring that fossil fuels remain part of our diverse portfolio of generation. Eskom is therefore involved in several initiatives to assess and progress deployment of CCS technology in South Africa:	N/A This question should be directed at the Renewable Energy Division – Corporate. Scenarios produced by the Climate Change and Sustainability Department have indicated a potential role for CCS in the electricity generation mix, expected to become commercially available from around 2025 – 2030.
14	No		No	Yes, we do have ZLED policy (zero effluent discharge), water and emission licences.	MONTHLY CO2 EMISSION TONS (COAL FIRED) ; April 2012- 538856; May 2012 -719918; June 2012- 680107; July 2012 – 634255	No	Yes

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
17	No		Not yet plan	We do have procedures in place that we use that drives Conservation of Resources (235-552 RESOURCE CONSERVATION PROCEDURE due Jan 2015 Rev 2) The procedure include: Best practise for energy: Best practice for water conservation-Closing of taps when water is not in use, repairs all the leaking taps, Maintain plant to prevent unnecessary leaks. Comply with Eskom policy for zero effluent discharge: Best practice for air quality-To switch off electrical appliance when not in use	Not yet started with the monitoring of CO2. The reporting still to be correlated and it was suppose to start this months	Not yet plan	N/A
24	None currently	For future purpose, an Authorisation was received for: The proposed construction of a biomass co- firing demonstration facility at the Arnot Power Station, Mpumalanga.	Eskom is proposing the substitution of a limited amount (between 10% and 15%) of coal with biomass (wood pellets) as a co-firing fuel source at the existing Arnot Power Station. This project is considered a pilot exercise which forms part of Eskom's	Yes, Eskom has numerous policies and initiatives to reduce emissions	For the 2011/12 financial year: Annual emissions = 14.57 million tons; Monthly Average = 1.21 million tons.	Research is currently underway.	Not really – this would more appropriately be done with Eskom's Research, Testing and Development Department.

			initiatives towards the reduction of their carbon footprint.				
25	No		Yes, PV installation is in the pipeline	N/A	On average 20489 tons per month	Not as a short-term plan maybe in the long run...	Yes, most definitely
29	No		Not aware of any	Yes, there's a drive on Energy and water conservation	N/A	Not aware of any	N/A
32	We have Solar energy currently that generate power for the buildings onsite and it caused a lot of money just to produce 1megawatt. Decisions are to be made for any further continuation.			We have weekly and monthly meeting to address water conservation, head office is compiling report on GHG and we have measures in place for reduction of those GHG.	C02:+/-24 000 000 tons/annum, S02:190 000 tons/annum, Nox:100 000tons/annum (both coal fired and fuel oil)	CCS technologies has been introduced to us but we have not yet made final decision of using the technology as yet.	N/A
36	No		(No cause am working for coal fired stations)	Yes	(I think the best person to answer the question is the people who are based at the power stations) Ask [...] from megawattpark her email address [...]	No	(No,I am working for the coal unit which is the head office for five power station)

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
Non-Eskom	Do you currently use any forms of renewable technologies on site?	If yes, please describe them	If no, do you have any plans in the future to use any forms of renewable technology on site?	Do you have any company or site specific policies or drives to encourage energy and water conservation and to reduce GHG emissions?	What quantity of CO₂ is released into the atmosphere on a daily, monthly and annual basis at your site?	Do you have any plans to use carbon capture and storage (CCS) technologies at your site?	Would you be interested in your site being further involved in this theoretical study to determine ideal pilot study sites for this technology?
7	In terms of a technology as you are referring to in your msc, no. However, we do burn renewable fuels – biomass and black liquor, to generate steam/electricity	Biomass boiler at our [...] Mill	Besides what is mentioned above, nothing is envisaged in the short term.	See the [...] website, for details.... We have targets to reduce the specific energy and water usage in our global operations	See the [...] website, for details.... See Carbon Disclosure Project...	We capture carbon dioxide in [...]. +- 13 million tonnes per year.	From a Biorefinery Specialist point of view a pilot plant study would add value. However, [...] currently would not be interested in such, as the technology is not commercialised.
8	Yes we use renewable energy sources in our processes [...] and we use combined heat and power for electricity generation	See Above	N/A	We have targets in place for energy and water conservation as well as maximizing the use of renewable resources which drives reductions in GHG emissions	Annual CO ₂ emissions from fossil fuel for [8] is reported in the CDP – link to where this report is available...	No	No
15	No	N/A	Yes	Yes	Direct CO ₂ emissions - Group FY2012 (t '000): 418; Indirect CO ₂ emissions - Group FY2012 (t '000): 3 289	No	No

	Q1	Q2	Q3	Q4	Q5	Q6	Q7
17	Not now, in future through our Energy leg Cennergi.	Wind, solar	N/A	Yes, currently have energy and water management programs in place	2.4 mt/annum	When we venture into electricity generation, yes we will be compelled to look into it	Yes
<u>18</u>	No, specific renewable technologies – only recycled asphalt	N/A	Nothing at present, although there has been some interest in bio-fuels as a substitution for some of our diesel use and bio-binders as a part substitution for our [...].	Yes, we do have a specific environmental policy covering energy and water conservation and we have set targets for GHG emission reduction.	We release on average 28 – 32 kg CO2/ton of asphalt produced. We operate 16 static sites across the country producing anything from 50 tons/day to 2000 tons per day per site and generally manufacturing between 4500 – 12000 tons per day for the group.	None at present	Yes we would
22	No	N/A	Yes – we are investigating the use of PV Panels to replace or supplement purchased electricity.	Yes – we have launched a process called “Green Gauge” – more details on this can be found on our website at...	For annual Scope 1 and 2 emissions for 2011 please refer to our annual report...	No	No

Sensitive information has been removed and replaced with parentheses’ or periods. Otherwise these responses have been left largely unedited.