Processing Cost Analysis of the African Biofuels Industry with Special Reference to Capital Cost Estimation Techniques

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But he said to me, “My grace is sufficient for you, for my power is made perfect in weakness.” Therefore I will boast all the more gladly of my weaknesses, so that the power of Christ may rest upon me.

2 Corinthians 12:9-10

Abstract

Access to energy, in the form of electricity and fuels, is a necessary condition for development. There are several reasons for biofuels to be considered important in many African countries. They include energy security, environmental concerns, foreign exchange savings and socio-economic opportunities for the rural population. Biofuels such as biogas, biodiesel and bioethanol may be easier to commercialise than other alternatives to crude-oil derived fuels, considering performance, infrastructure and other factors. Biofuels are in use in a number of developing countries (including some African ones for example, Mauritius, South Africa, Kenya), and have been commercialised in several OECD countries, as well as Brazil and China.

A good understanding of the production cost of biofuels, and the availability of robust and indigenous cost estimation models is essential to their eventual commercialization. However, available process engineering cost estimation relationships and factors are based on plant costs from developed countries, and thus have limited applicability and unknown accuracy when applied to African installations. The need to develop indigenous cost prediction relationships, which is central to economic feasibility studies, is driven not only by the limitations in terms of current data bases and methodologies for the generation of such. There is also a requirement for a more systematic presentation of cost data in equation forms, which will ensure easier and more rapid use of the data in numerical and economic models, and in preliminary design and plant optimisation in a time and cost effective manner, providing decision-makers with key information in the early design stages of a project.

It is these shortcomings and challenges that this dissertation attempts to address, through an analysis of the economic input factors, and the development of more robust, indigenous cost estimation relationships for both capital and operating costs for the biofuels process industry in Africa. The conceptual approach developed within this thesis addresses the current data gaps and deficiencies through analyses of establishment and operating costs of existing biofuels plants both on the continent and elsewhere. It aims to determine which factors most influence the production cost, and then proceed to modify known cost estimation tools for both capital and operating costs specifically for African biomass-to-biofuel conversion plants as a function of plant size, feedstock, location, exchange rates, and other site-specific variables. Shortcomings in the use of existing cost estimation models are addressed with the aid of a literature study, supported by the analysis of African biofuels plant establishment (biogas and bio-ethanol) and operating (bio-ethanol) costs[‡]. Plant establishment costs are analysed at two different levels of detail, corresponding to the concept development and pre-feasibility phases in the project planning cycle.

[‡] No Industrial biodiesel industry in Africa at the time of writing

The literature review contextualizes the development of an African biofuels industry, introduces the relevant theory of cost estimation, and reviews prior related academic work. Specifically, this section investigates the field of bioenergy and the contribution it can provide in the energy sector in Africa. The capital cost estimation methods considered include both variant and generative techniques. The variant-based model initially includes both the exponential method (size correction) and step-counting techniques, corrected with appropriate factors to allow for inflation and change of location, while the generative model is based on the factorial method. The scope of the research also covers the determination of operating or manufacturing cost including costs such as taxes, insurance, utility costs, labour requirements, local wage scales and maintenance.

Whilst the conventional financial wisdom in the process industry is that larger installations have advantages resulting from economies of scale, the regression analysis of the investigated 38 biogas installations from eleven African countries indicates that such economies of scale do not exist in the small to institutional scale biogas sector, as the cost capacity factor obtained exceeds unity, and is significantly different from the conventionally used “six-tenths” rule. The estimated value of scale exponent in community – large scale biogas systems was less than unity but t-tests could not reject the hypothesis of constant returns to scale at the 95 percent confidence level. The analysis further concludes that the cost of biogas technology is largely independent of geographical location of the plant. A Lang factor (f_L) value of 2.63 (20m^3 digester size), 2.91 (40m^3 digester size) and 3.04 (60m^3 digester size) has been obtained for small/medium scale biogas plants in two African locations. The increased f_L as plant capacity increases support the evidence of diseconomies of scale obtained for small/medium scale biogas plant; it appears that indirect costs may be an important cause of this lack of economies of scale. An f_L value of 1.79 was obtained for one large scale brownfields biogas plant.

The detailed analysis of the process economics of one African bioethanol facility suggests that conventional factorial capital cost estimation and factorial (multiplication factors) manufacturing cost estimation methods may be employed, but will lead to inaccurate cost predictions if applied in unmodified form to an annexed fuel ethanol plant in Africa. A Lang factor of 2.8 and 2.4 was obtained for the analysed annexed fuel ethanol for inside battery limits and outside battery limits plant respectively; the IBL factor been very close to reported values for annexed maize-based ethanol plants. The operating cost analysis of the same African distillery revealed that the factorial approach to estimation is principally a sound one, with no indication of untypical cost items. Some of the typical cost items do however display ratios to the base cost that are outside of previously reported limits, notably direct supervisory labour (much higher), maintenance (lower) and local taxes (lower). The greatest single operating cost item in the ethanol production studied is feedstock, which constitutes one third of the total cost of production. Steam and electricity costs constitute other major components of the operating expenses. Application of the Nguyen and Prince model to size optimisation and location-cost analysis of a bioethanol project in Nigeria confirm that it is more economical to build a number of intermediate scale distilleries rather than one large one. Optimal plant sizes lie in the range of 30-80 kl/day and are strongly dependent on agricultural yield intensity. The outcome also confirms that plant location close to the biomass supply is more appropriate as opposed to location close to the consumer.

For the case of biodiesel processing cost predictions in the African context, an analytical and demonstrative approach is presented. This approach is justified by the absence of commercial facilities and the very competitive and fragmented nature of the non-commercial biodiesel sector at the time of research and writing. Application of the published Nguyen and Prince plant size optimisation model in a South African context demonstrates that the optimal plant size varies widely in the range explored, being most sensitive to labour and transport costs whilst the resulting biodiesel cost is dominated by the feedstock cost. The analytical approach is supported by cost reviews of 16 German biodiesel installations, showing how industry-specific features have contributed to successful commercialisation. This analysis supports the findings that final biodiesel cost is relatively insensitive to economies of scale. An important implication of this finding is that small, decentralised (localised) biodiesel production (with standards satisfactory to engine manufacturers) could be a feasible option of encouraging biodiesel development in Africa; as such installations keep more resources and revenue within rural communities.

Based on the findings of the three fuel-specific chapters, it is observed that, variant approaches to cost prediction should be sufficient for biogas plant, especially at the small to medium scale. In bio-ethanol plants, generative approaches need to be mixed into variant-based approaches fairly early on, as site-specific variables (esp. in terms of feedstock and energy cost) determine, to a significant degree, the final cost of this fuel, while for biodiesel plants, variant based approaches to capital cost prediction should generally suffice a long way into any project, as by far the majority of the cost of this fuel is feedstock dependent. The corollary to this observation is that generative approaches need to be taken as early as possible to biodiesel feedstock cost predictions.

Summarily, the dissertation makes two important contributions. It presents the first comprehensive treatise on a subject of process engineering economics in Africa, and thereby proposes some important modifications to cost estimation factors and methods in the domain studied. It also shows that engineering economic analysis concurs with environmental and social analysis concerning the subject of biofuels in Africa: biofuels should firstly be produced from waste materials, and secondly on a small to medium, distributed scale.

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There are so many people who have contributed to this PhD directly and indirectly. I would like to thank everyone personally but then that would be another thesis in itself.

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Abbreviations and Acronyms

FEMA	Forum of Energy Ministers of Africa
ECOWAS	Economic Community of West African States
EAC	East African Community
SADC	Southern African Development Community
CEMAC	Communauté Économique et Monétaire de l'Afrique Centrale (Economic and Monetary Community of Central African States)
MDGs	Millennium Development Goals
NEPAD	New Partnership for African Development
CDM	Clean Development Mechanism
CERs	Cost estimation relationships
ENR	Engineering and News Record Index
RETs	Renewable energy technologies
EU	European Union
GNP	Gross national product
GHG	Greenhouse gas
GEF	Global Environment Facility
WSSD	World Summit on Sustainable Development
ESDP	Energy Sector Development programme
REEEP	Renewable Energy and Energy Efficient Partnership
NNPC	Nigerian National Petroleum Corporation
GMOs	Genetically Modified Organisms
PEMs	Parametric Estimation Methods
WBS	Work Breakdown Structure
LSBF	Least Squares Best Fit
IEA	International Energy Agency
FOB	Freight on Board
CIF	Cost, Insurance and Freight (CIF)
FFAs	Free fatty acids
IBL	Inside battery limits
OBL	Outside battery limits

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Introduction and Problem Definition

1.1 Background and motivation

Most social and economic activities require the use of energy in various forms and quantities. Johansson and Goldemberg (2002) describe energy as one of the essential inputs for socio-economic development at regional, national and sub-national levels. Energy, in its many useful forms, plays a critical role in the development process, first as a domestic necessity but also as a factor of production whose cost directly affects the price of other goods and service (NEPAD, 2001). It affects all aspects of development - social, economic, industrial and environmental - including livelihoods, access to water, agricultural productivity, health, population levels, education and gender-related issues (Singh and Sooch, 2004; Modi *et al*, 2005).

Ensuring the provision of adequate, affordable, efficient and reliable high quality energy services with minimum adverse effect on the environment for a sustained period is not only pivotal for development, but crucial for African countries in which most are struggling to meet present energy demands. Further, the continent needs such energy services to be in the position to improve its overall net productivity and become a major player in global technological and economic progress. It aims to increase from 10% to 35% or more, access to reliable and affordable commercial energy supply to Africa’s population in 20 years (NEPAD, 2005). Solving these problems requires a new energy paradigm that considers the impacts of energy use at local and global scale, develops a wider portfolio of energy resources and cleaner technologies, widens access and increases efficiency, and addresses both our present needs and the welfare of future generations (Jefferson, 2000). As contained in the New Partnership for African Development (NEPAD) objectives on energy, African countries need to improve the reliability and lower the cost of energy supply to productive activities, in order to enable economic growth of 6% per annum, and to reverse environmental degradation and health impacts that are associated with the use of traditional fuels in rural areas. The Forum of Energy Ministers of Africa (FEMA) and several sub-regional economic communities, notably the Economic Community of West African States (ECOWAS), the East African Community (EAC) and the Economic Community of Central African States (CEMAC) have followed suite to develop energy strategies towards achieving the Millennium Development Goals (MDGs)[†] and realising the NEPAD objectives (FEMA, 2007). The strong link between energy and the MDGs and the existence of widespread poverty in Africa make it even more important to address the challenges and prospects for energy service provision on the continent (Modi *et al.*, 2005; Porcaro and Tadaka, 2005). An exemplary case that illustrates how energy development can be linked to the eradication of extreme poverty is the UNDP sponsored programme in Mali, which initiated the spread of biogas units in the peri-urban areas of the city of Bamako, including the development of a locally-adapted prototype (GEF, 2003). Wider use of such biogas units would help reduce the demand for firewood in peri-urban areas and would supply high-quality fertilizer for local farming efforts. This initiative will also help in achieving MDGs 4 -6 (Amigun *et al.*, 2008).

Africa is endowed with significant quantities of both fossil and renewable energy resources. However, the bulk of these are underutilised or used in their traditional form causing negative social and environmental consequences (Davidson, 2001). Any strategy to develop these energy resources must therefore be extremely mindful of both the environmental pollution problems (through carbon monoxide, ozone forming hydrocarbons, hazardous particulates, acid rain-causing sulphur dioxide etc.), and the threat of climate change associated with the use of fossil fuels. The latter is as a result of the accumulation of certain greenhouse gases (GHG's) in the atmosphere, mainly carbon dioxide, methane and nitrous oxide that trap heat in the lower atmosphere and lead to global warming. As adopted by the third conference of parties (COP3) in Kyoto, Japan, attempts have been made to agree to legally binding obligations on most developed countries to reduce their GHG emissions by an average of 5.2% below 1990 levels by 2008-2012 (Davidson, 2001). These attempts have resulted in the development of financing mechanisms such as the Clean Development

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[†] The Millennium Development Goals (MDGs) are the world's time-bound and quantified targets for addressing extreme poverty in its many dimensions-income poverty, hunger, disease, lack of adequate shelter, and exclusion - while promoting gender equality, education, and environmental sustainability. They are also basic human rights - the rights of each person on the planet to health, education, shelter, and security.

Mechanism (CDM) that may be able to leverage significant resources for the development of renewable energy resources on the African continent.

It is also noteworthy that there is an uneven distribution of the fossil energy resources on the African continent, which is reflected in energy production and consumption patterns. This uneven distribution of fossil fuel resources makes over 70% of countries on the continent dependent on imported energy resources, which again supports the development of abundant renewable energy resources. Africa has significant renewable sources that can, at a minimum, be harnessed for satisfying certain niches in the energy sector. It has been estimated by Marrison and Larson (1996), that planting 10% of the total land in Africa that is not forest, not wilderness and not cropland with biomass energy crops would deliver 18 EJ of bioenergy per year – equivalent to about 72% of the total primary energy supply (TPES) (25 EJ≈ 606 Mtoe) in 2005 in the African continent[‡] (EIA, 2007). Biomass can be converted into all main modern energy carrier types: heat, electricity and fuels for transportation and domestic use. The potentials for and impacts of electricity and heat production from biomass (especially via combustion) are widely known (Faaij, 1997) and such technologies are applied in various markets. Also, there are many other new or renewable technologies emerging for large scale electricity production with low or no carbon emission, such as (offshore) wind turbines and technologies for a cleaner use of fossil fuels (Hamelinck, 2004). On the other hand, the transportation sector, which is almost entirely based on fossil fuel (crude oil), has fewer substitutes. The development of renewable technologies and in particular bioenergy production will help reduce the dependence on this energy resource, as well as minimize the social impacts and environmental degradation problems associated with its use. Biomass, a widely dispersed and naturally occurring carbon resource, is now regarded by many as a logical choice as raw material for the production of a broad range of fossil fuel substitutes (Lynd *et al*, 1991; Lynd, 1996; Bridgwater, 2001; Lynd *et al*, 2005; CHOREN Industries, 2007; Maher and Bressler, 2007**).**

Biofuels, as the name implies, are fuels (solid, liquid or gaseous) derived from biomass, a renewable resource that can potentially be harvested sustainably. Biomass energy production

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[‡] Total primary energy supply statistic in Africa is obtained from International Energy Agency (IEA), http://www.iea.org/textbase/nppdf/free/2007/key_stats_2007.pdf .

in most cases is still a local affair in most African countries. Whilst the topic of "bioenergy"[§] has received significant public and legislative attention in several developed countries such as OECD member countries (Canada, Germany, New Zealand, United Kingdom, United States) and developing countries like Brazil and India, relatively little effort has gone into promoting modern bioenergy in African countries, despite the estimated large resource base in many of them (Marrison and Larson, 1996). In a related example, out of the 21 countries (plus the European Commission) that participate in IEA Bioenergy - an international collaboration in bioenergy set up in 1978, only one country, South Africa comes from the African continent. The aim of IEA Bioenergy is to accelerate the use of environmentally sound and cost-competitive bioenergy on a sustainable basis, and thereby achieve a substantial contribution to future energy demands (IEA Bioenergy, 2007). Biomass-derived fuels share many of the same characteristics as their fossil fuel counterparts (Lynd, 1996; Klass, 1998; Fangrui, 1999). Once formed, they can be substituted in whole or in part for petroleum-derived products. With the petroleum age nearing its end, the biofuels relevance to the African economy that can at least partly close the prospective gap opening between globally rising energy demand and the uncertain expansion of energy supply are gasohol[**] , biogas[††] and biodiesel[‡‡].

Biofuels, which are a realistic contender as a major low-carbon fuel source for the future, present many opportunities. Multi-benefits analysis by the World Bank (1980) shows that a biofuel industry in Africa would have substantial environmental, economic, employment and wider social benefits on a national scale - especially for rural and regional sections of Africa . In a recent public symposium organised by United Nations Foundation (2006), it was noted that biofuels could also provide opportunities for poverty reduction and for satisfying the energy needs in rural and remote regions, help generate employment and local economic development opportunities, help curb global warming and contribute to the protection of human health from air pollution, whilst also enhancing energy security. Hence, it appears that biofuels are a sensible application of biomass as they can play a vital role in addressing many of the problems associated with conventional oil.

[§] Bioenergy is energy derived from biomass, which is organic material such as wood, plants, or animal wastes

[**] Gasohol is a blend of ethanol and gasoline (e.g. E80 - a blend of 80% fuel ethanol and 5% gasoline)

[††] Biogas is produced by means of anaerobic digestion of plant and animal waste to yield methane.

[‡‡] Biodiesel (a fatty-acid alkyl ester) is a cleaner burning diesel replacement fuel made from natural renewable sources such as new and used vegetable oil, by reaction of the triglyceride molecule with an alcohol.

This dissertation addresses some of the factors that could enhance biofuels (biogas, biodiesel and bioethanol) commercialisation in Africa. The economics of biofuel production and consumption in Africa will depend on a number of factors specific to the local situation. These factors include (a) the cost of biomass materials, which varies among countries, depending on land availability, agricultural productivity, labour costs, etc; (b) biofuel production costs, which depend on the factory location, size and technology, all of which might vary a great deal among countries; (c) the cost of corresponding fossil fuel (e.g. gasoline, diesel) in individual countries, which depends on fluctuating petroleum prices and domestic refining characteristics; and (d) the strategic benefit of substituting imported petroleum with domestic resources. The economics of biofuel production and use, therefore, will depend upon the specific country and project situation (Thomas and Kwong, 2001).

The cost of a plant in a developing country compared to one in a developed country will depends upon the complexity of the technology and the source of technical know-how (Montaner *et al*., 1995). Location does not only affect the cost of plant construction directly but also indirectly. Factors that are significant in analysing construction cost between similar plants in different locations or countries include: different laws (legislation), often a different language, the political and social environment, the industrial capability (which is a function of availability of bulk materials, construction labour and productivity), cultural and institutional factors, the financial resourcefulness, and the economic situation in the location. The effects of these several factors on cost will be very different in a developed country where the existing cost estimation models are concentrated, as compared with a developing African country. For biofuels projects to be developed in the various African countries, it is therefore important that an indigenous theory of cost prediction, central to economic feasibility studies, be developed. It appears that there is no such theory, and not even a good collection of relevant data. The existing methods have limited applicability and on many occasions disappointing accuracy because of the inappropriate nature of the estimating techniques.

1.2 Problem Statement

Large increases in sustainable energy demand, reflected in governmental strategy[§§] and regulation aimed at harnessing the potential of modern, clean biomass-derived fuels in African countries, is leading to the development of large-scale renewable energy supply which is strategically important for local, regional and global environmental sustainability.

A plethora of barriers, however, continue to slow the development of biofuels industries in Africa despite the availability of biomass resources. Amongst these is the lack of a good understanding of the capital and operating costs of biofuel production as a function of factors such as technology, feedstock, plant size and location. Such an understanding is a key to successful projects, as it impacts both the project profitability and influences the technical solutions. There exists no coherent body of knowledge on the costs and economics of process plant in Africa. All of the published plant cost indices and factors used in the process industries are developed from plants located in the developed nations, for example Britain, Canada, USA, Australia, Germany, and applying these factors to cost estimation in Africa will give wide variations due to the differences in the cultural and institutional settings, construction methods, labour productivity, political and social environment, industrial capability and economic diversification. Also, there are no published plant cost indices for the biofuel process industries in Africa, and the process industries in Africa altogether.

1.3 Research objectives

The ultimate aim of this dissertation is to generate in-depth understanding of production cost input factors, and to develop robust and indigenous capital cost estimating tools that can help:

- To generate baseline data for the technological and economic development of biofuels production and utilisation on the African continent. This will also expedite the environmental and economic benefits of renewable energy;
- To map out business opportunities for energy companies and entrepreneurs;

[§§] By way of example, the biofuel industrial strategy of the republic of South Africa outlines the government's approach to addressing policy, regulations and incentives. The strategy aims to achieve a 2% penetration level of biofuels in the national liquid fuel supply, or 400 million liters per annum by 2013.

- To assist governments to reform and harmonize biomass based energy regulations, strategy and legislation.

Solving this problem will thus require developing robust cost estimation tools (models) for both capital and operating costs, and reviewing their applications, for example in size optimization models.

In particular, this dissertation seeks to achieve the following:

1. To analyse those factors that affect the production cost of biofuels. This is done by assessing three selected fuels: biogas, biodiesel and bioethanol. First, the key technologies will be studied, followed by the facility economic performance appraisal to determine which factors most influence the production. This aspect can help in the formulation of much awaited policies and regulations for biofuels in Africa.
2. To develop more robust tools for estimating capital and operating costs of biomass-to-biofuel conversion plants as a function of plant size, feedstock, location, exchange rates, and other site-specific variables.
3. To investigate the applicability of the techniques developed, specifically:
    - To demonstrate how biofuel plant size optimization will benefit from availability of better capital and operating cost estimating techniques.
    - To demonstrate how knowledge of African process economics on the one hand, and detailed knowledge of the dynamics of a specific biofuel as already produced elsewhere, can be combined to facilitate the introduction of such biofuel production into an African country.

1.4 Key questions

The main research questions of this dissertation are:

- Which factors most influence the production cost (economic input factors) of the selected biofuels?
- What is the importance of economies of scale in the biofuels process industry in Africa?
- What are the differences between cost estimation techniques developed for western countries as opposed to the ones to be developed for Africa?

- What is the impact of plant location on capital and operating cost variables in biofuel industry?

1.5 Scope

This dissertation focuses on the development of techniques for the estimation of capital and operating costs of bioethanol, biodiesel and biogas process plants located in different regions of Africa. Cost estimation is concerned with the prediction of the costs related to a set of activities before they have actually been executed. Within the existing cost estimating methods, two main approaches are utilised: variant-based and generative (reviewed in detail in section 2.10.2).

The capital cost estimation methods include both variant and generative methods. The variant-based models initially include both the exponential method (size correction) and step-counting techniques, corrected with appropriate factors to allow for inflation and change of location. These variant-based techniques are expected to find better application in the biogas industry as the method is most useful in small and medium batch manufacturing of relatively standard products (Weustink, 2000). The generative model is based on the factorial method.

The dissertation also analyses which factors most influence the production cost of bioethanol and biodiesel (biogas installations have minimal operating costs once established). This is expected to yield insights both on the possible barriers to implementation that need to be overcome, and on the technological improvement options that should be stimulated by research and development. The determination of production or manufacturing cost including costs such as taxes, insurance, utility costs, labour requirements, local wages scales and maintenance is based on a generative cost estimating approach. This is based on the fact that the costs of manufacturing a product depend on the required production operations.

Besides production costs, there are several important factors that strongly influence the feasibility of biofuels projects, such as the current debate on food security problems associated to the biofuels production, crude oil price, agricultural commodity prices, and even “carbon credits”. These issues, though important are not covered in the analysis presented in this dissertation.

1.6 Approach and methodology

1.6.1 Preliminary analysis

The methodology followed in developing this dissertation involved an initial step of country-level data gathering and development of a database to allow for consistent comparison of the biofuels plant costs from different countries on the African continent. The countries are differentiated according to the geographical location (landlocked or coastal), exchange rate history, and the presence of non-typical variables such as prevalence of corruption, political stability and other country-specific information. The data were used as basis for preparing a database using Microsoft Access. The database served as data pool during the analysis work, and was used for the purposes of development of cost estimation models.

1.6.2 Literature review

This section of the dissertation contextualizes the development of an African biofuels industry, introduces the relevant theory of cost estimation, and reviews prior related academic work. More detailed technology reviews of the three studied biofuels are presented in the appropriate chapters and sections of the dissertation.

1.6.3 Capital cost estimation methods

To analyse the prospect of each of the three studied biofuels, a technology review is first presented. These reviews are used for composing and selecting appropriate technology for the case studies, as this affects the overall economics. This is followed by the analysis of costs of existing African biofuels installations, obtained during site visits or via correspondence. The basic steps involved in the development of the cost estimation method (see Figure 1.1) are:

- Gathering of data from (a) biogas industries, (b) bioethanol industries located in different regions of Africa, and (c) biodiesel industries in the EU with special focus on production cost from Germany (to gain insights into the economics and other factors that have contributed to the success of Germany’s biodiesel industry since the development of biodiesel industry in Africa is still in its infancy). The collected data were adjusted for inflation using an appropriate time-based cost index (the Engineering and News Record Index (ENR) was used), for location, and for production rate. Absent cost items were accounted for while inapplicable cost items were removed through inspection of received data. Data normalisation aims at removing consistent sources of variation to make measurements mutually comparable.

- If necessary for the analysis of appropriateness of a particular cost estimation method, the previously adjusted cost data were then decomposed into several cost “modules”, as required for use in the investigated cost estimation methods.

- Cost estimation relationships (CERs) as proposed in the literature were then tested by inserting data and observing goodness of fit or accuracy of the predicted results. On this basis, adjustments were proposed to the form of the relationships, and/or key variables were calibrated.

- Lastly, where sufficient independent data could be obtained, the developed or adjusted CER’s were validated. CERs’ like any other parametric estimating technique are of value only if they can demonstrate with some level of confidence that they provide results within an acceptable number of trials, and they should be representative of the database domain for which they are applied. Inferential statistical methods were employed for model validation in this dissertation.

1.6.4 Operating cost estimation

The operating costs were determined by gathering data on those factors which can be definitely established e.g. taxes, insurance, utilities and making detailed estimates for the other factors based on local wages scale, manufacturers expected maintenance schedules e.t.c. Prior to obtaining the data, a particular format for collection of operating cost data was developed in order to assure uniformity of data categories across the different industries. The data were appropriately analysed, and correlated using the multiplication or factored approach for operating cost model development. Factored approaches are intended for quick, approximate estimates and for comparison of processing alternatives. These approaches have in common the factoring of process labour and fixed capital investment costs for addition to the costs of raw materials and utilities.

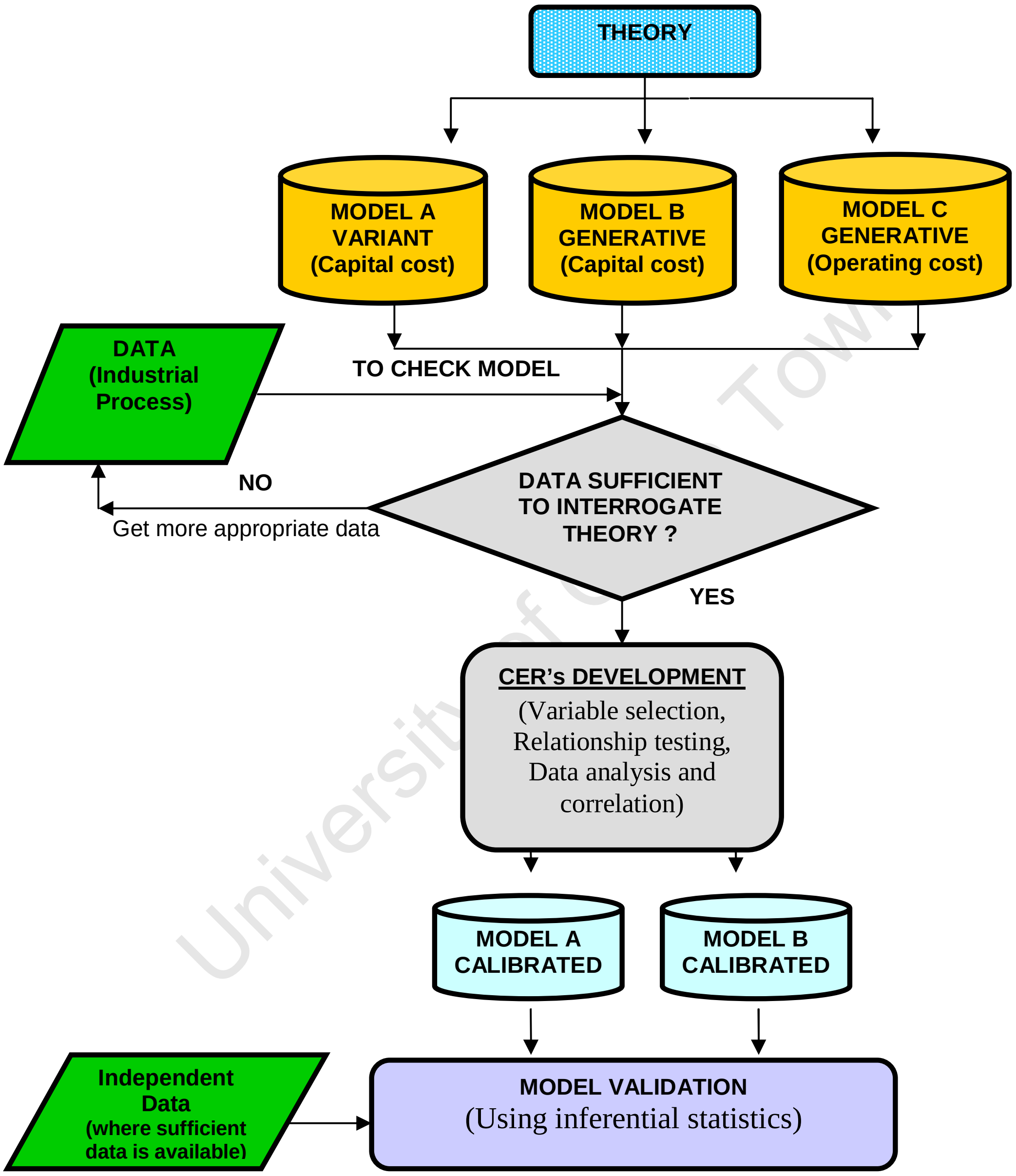

Figure 1.1: Diagrammatic representation of model development

1.7 Thesis outlook

Renewable energy technologies (RETs) and specifically biofuels offer developing countries some prospect of self-sufficiency in energy supply at national and local levels, with potential economic, ecological, social, and energy security benefits. Biofuels are a component of the diversification for future energy demand. This dissertation aims to make a contribution towards the widespread utilisation of biofuels in Africa, through proper analysis leading to understanding of their processing cost structure and the development of cost estimation models.

A unique attempt is presented aimed at developing robust and indigenous capital and operating cost models for the biogas, biodiesel and bioethanol process industry in Africa. The outcome of this dissertation is expected to help enable meaningful market penetration of the biofuels process industry in Africa. The greater the uncertainties of projected costs such as capital cost, the more cautious investors are likely to be. Hence the more accurate the estimates are, the greater the likelihood of the more marginal projects proceeding, to the benefit of all concerned. The approach to fulfilling the aims and scope of this study, as outlined above, is closely reflected in the thesis layout represented diagrammatically in Figure 1.2.

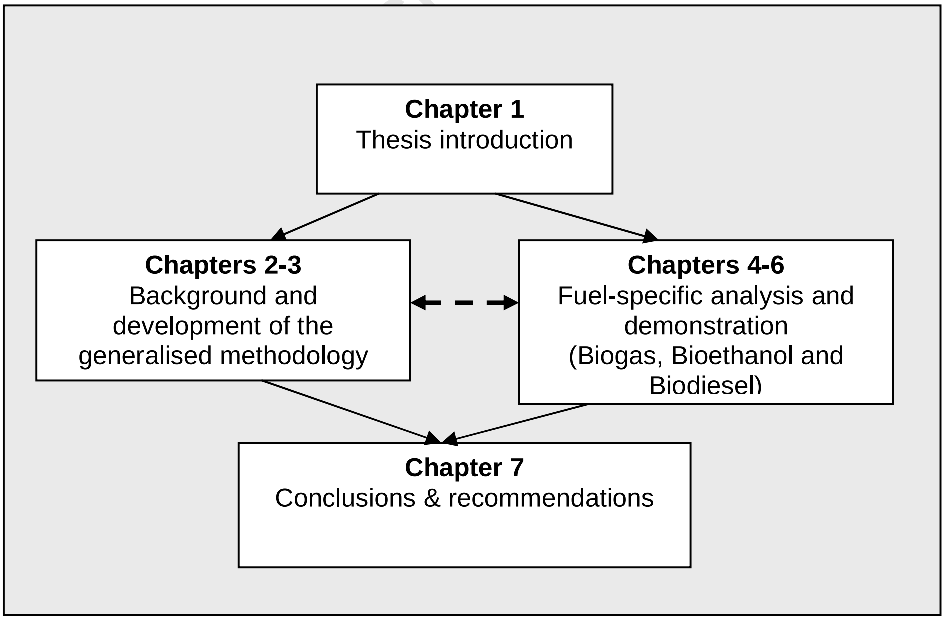

Figure 1.2: Diagrammatic representation of thesis outlook

Chapters 2 and 3 are aimed at developing the qualitative understanding, protocols and methodological guidelines which support the proposed predictive approach. In particular, Chapter 2 elaborates the background and introduces the theory necessary for understanding and undertaking the further research tasks carried out in the dissertation; while Chapter 3 explains the adopted research methodology in terms of the technical tasks associated with the model development. It also discusses constraints encountered during data gathering around the continent and presents the techniques employed to overcome them. Chapters 4 to 6 embody the application of the approach developed in Chapter 3, each, dealing with one of the three selected biofuels. Capital costs are analysed at different levels of detail yielding a different quality of results and insight. Chapter 4 (on biogas) investigates capital cost estimation techniques at both the order of magnitude and the study estimate level, as well as the effect of location on the economics of biogas technology in Africa. Chapter 5 (on bioethanol) investigates the determination of optimal plant size and the effect of location of bioethanol plant in two industrialised states in Nigeria. This is followed by the development of capital and operating cost model using both variant and generative approaches for one distillery, operating in a poorly accessible rural area, in a landlocked East African country. Chapter 6 (on biodiesel) commences with a preliminary study of biodiesel plant size optimisation in South Africa, followed by an analysis of investment and operating costs of biodiesel production in the European Union (Germany). Finally, Chapter 7 discusses the significant findings and conclusions of applying the developed indigenous capital and operating models on one hand and detailed understanding of dynamics of specific biofuel as produced elsewhere to commercialisation of biofuel process industry in an Africa country and forward relevant recommendations.

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2

Background and Theory

Concurrent histories of biofuels are necessary to understand the foundation for today's perception of biofuels, in general. The history of biofuel is more political and economical than technological. It was the influences of the industrial magnates during the 1920's and 1930's on both the politics and economics of those times that created the foundation for our perceptions today …………………………………. Momentum Biofuels, Inc., 2006.

2.1 Introduction

This chapter contextualizes the development of an African biofuels industry, introduces the relevant theory of cost estimation, and reviews prior related academic work. More detailed reviews of biofuels technology specific topics are presented in the appropriate chapters and sections of this thesis. In this chapter, the reader will be pointed to these sections when appropriate.

2.2 Energy overview in Africa

Africa is the second largest continent after Asia making up only 10% of the world's population, equivalent to about 80% of India's population. It has a total surface area of 30.3 million km^2, including several islands, and an estimated total population of 888 million (as of 2005) (EIA, 2002). Its population density in some regions is rather low. This is due in part to the Sahara Desert, which occupies one-fourth of Africa's landmass and is not suitable for habitation. In 1999, the population of sub-Saharan Africa was estimated to be 642 million, over 80% of the African continent. Poverty in Africa is mainly rural. Africa is not only the poorest region in the world; it was the only major developing region with negative growth in income per capita during 1980-2000 (World Bank, 2003). According to the World Development Indicators of 2006, the growth rate of Sub-Saharan Africa (4.8%) improved significantly in 2004 to exceed the global growth rate (4.1%) of that year. However, this improvement does not detract from the fact that Africa remains the poorest continent in the world with one-third of the population starving (World Bank, 2006). The continent remains fragile with perpetual poverty due to several factors. Among the factors identified are the deterioration of ecosystems (with 25% of dry lands in Africa carrying degraded soils; 10% of soils in the humid parts of Africa being susceptible to deterioration) and the fast growing human population. Other factors are poor political and economic management that increases poverty and have resulted in precarious political and economic environments. There is a direct correlation between the poor and the use of traditional biomass where a large proportion of people who live on less than \$2 a day use traditional biomass as energy source (Figure 2.1).

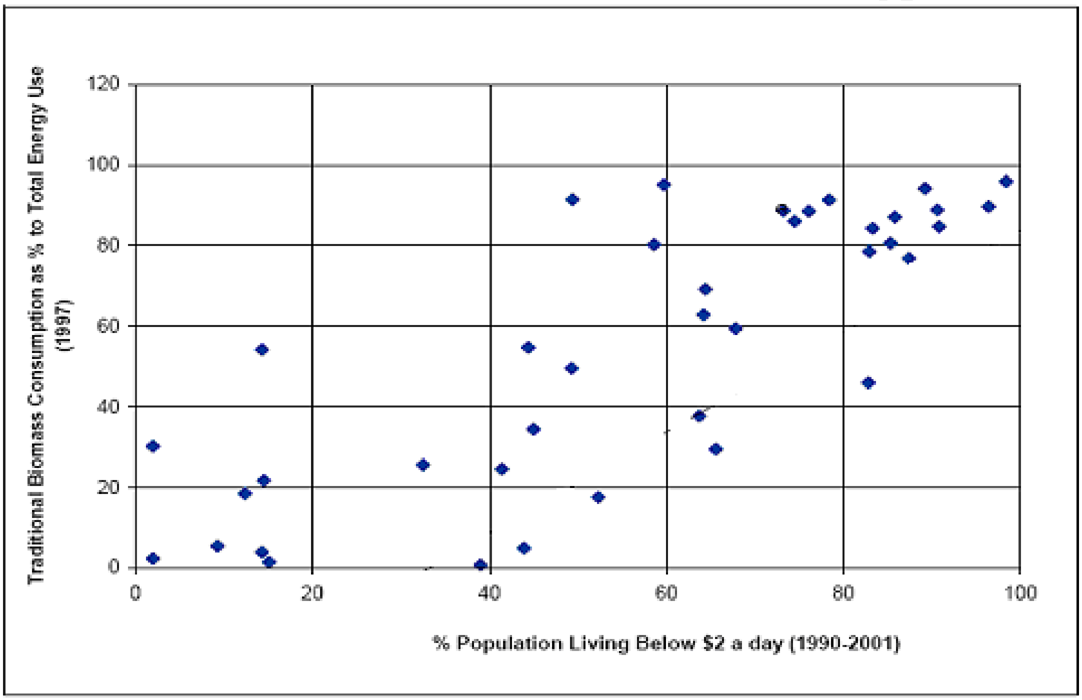

Figure 2.1: The Link between Poverty and Traditional Energy Use (Karekezi *et al.*, 2004).

The relationship of gross national product (GNP) per capita to energy consumption per capita for most countries of the world correlate very well with the status of economic and technological development. The World Bank (1989) defines developing countries such as African countries as low- and middle-income countries for which the annual GNP is US\$5,999 or less per capita. By this definition, it includes all countries in Africa. As illustrated in Fig 2.2, there appears to be a correlation between [*]GNI[***] (also known as GNP) per capita and total energy consumption per capita.

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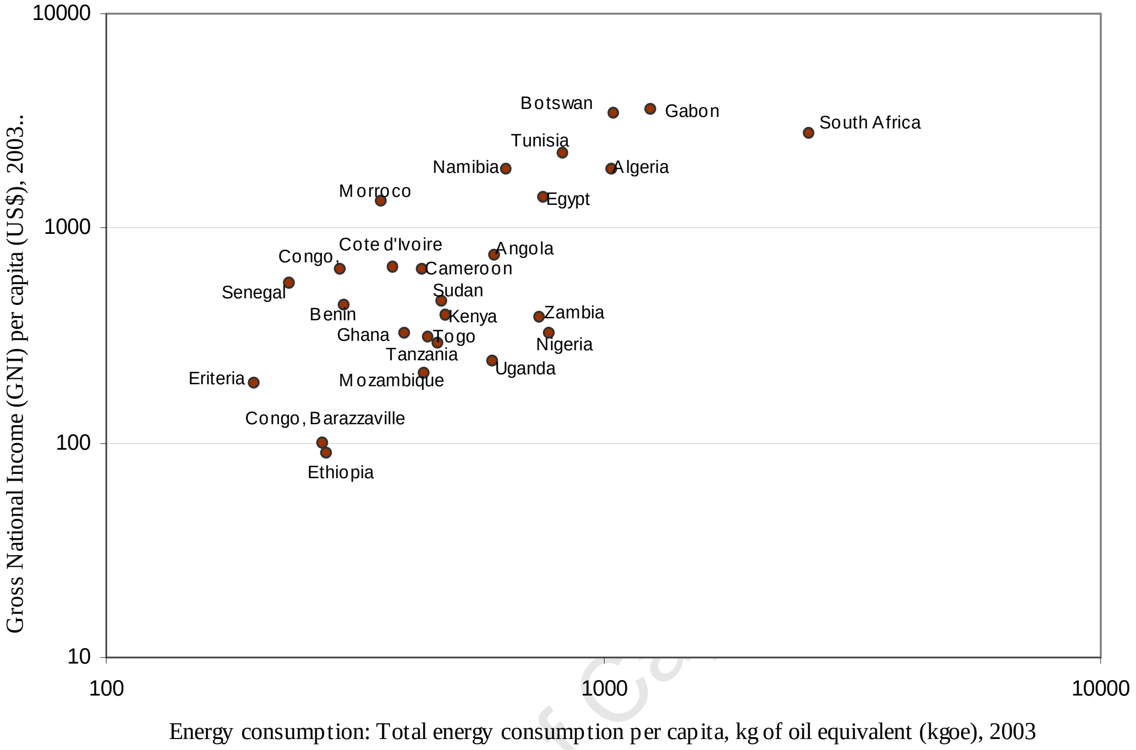

Figure 2.2: Gross national income versus energy consumption of some African countries

The low levels that are found in most Sub-Saharan African countries imply a very low level of energy consumption. African countries such as South Africa, Botswana, Gabon, and Algeria with relatively high GNI per capita tend to consume more energy. Although not conclusive, the graph does suggest that high income can contribute to improved energy services. Annual global energy consumption statistics by region illustrated in Table 2.1, show that although fossil fuels supply the vast majority of energy demand, the developing areas of the world consume more biomass energy than the developed or more industrialised countries (Klass, 1998). Africa is an unexploited resource for biofuels development. Although the majority of African countries rely on biomass as a main energy resource, it is inefficiently used and to the detriment of a households' well-being. This fact is also

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[***] Gross Domestic Product/Income: The sum total of all incomes produced in a particular country in the form of wages, profits, rents, interest (for activities carried out in that country).

highlighted in Figure 2.3, the share of renewables in the total primary energy supply (Africa renewables share is 50.1% in 2003). Tropical Sub-Saharan African population is expected to serve as a prerequisite that will underpin the growth of the continent's economy in rural areas. The high poverty level in Africa is revealed in the consumption model of modern energy. Per capita consumption of modern energy in African continent is very low when compared to other continent. Out of the total primary energy supply of 514 Mtoe on the continent in 2001, 48.7% which is largely in traditional form is combined renewable and waste (UNEP, 2004).

Table 2.1: Global Energy Consumption by region and Energy Source in 1990

	Fossil fuel[†††] (EJ)					
Region[‡‡‡]	Solids	Liquids	Gases	Electricity[§§§] (EJ)	Biomass[****] (EJ)	Total (EJ)
Africa	2.96	3.36	1.55	0.18	4.68	12.73
America, N.	21.55	38.48	22.13	4.69	3.75	90.60
America, S.	0.68	4.66	2.09	1.29	2.71	11.43
Asia	35.52	27.58	8.38	2.57	8.89	82.94
Europe	35.18	40.90	37.16	6.25	1.29	120.85
Oceania	1.64	1.70	0.85	0.14	0.19	4.53
World	97.52	116.68	72.18	15.13	21.51	323.02

Source: (United Nations, 1992)

The low levels of modern (commercial) energy consumption prevalent in Africa apart from the heavy usage of traditional (non-commercial) fuels - primarily biomass as indicated in Figure 2.4, is also due to massively underdeveloped energy resources, poorly developed commercial energy infrastructure, widespread and severe poverty which makes it impossible for people to pay for conventional energy resources. The use of biomass fuels endangers biodiversity and risks further damaged or destruction to the landscape. 86% of Africa's biomass energy is used in the sub-Saharan region, excluding South Africa (EIA, 1999). Even

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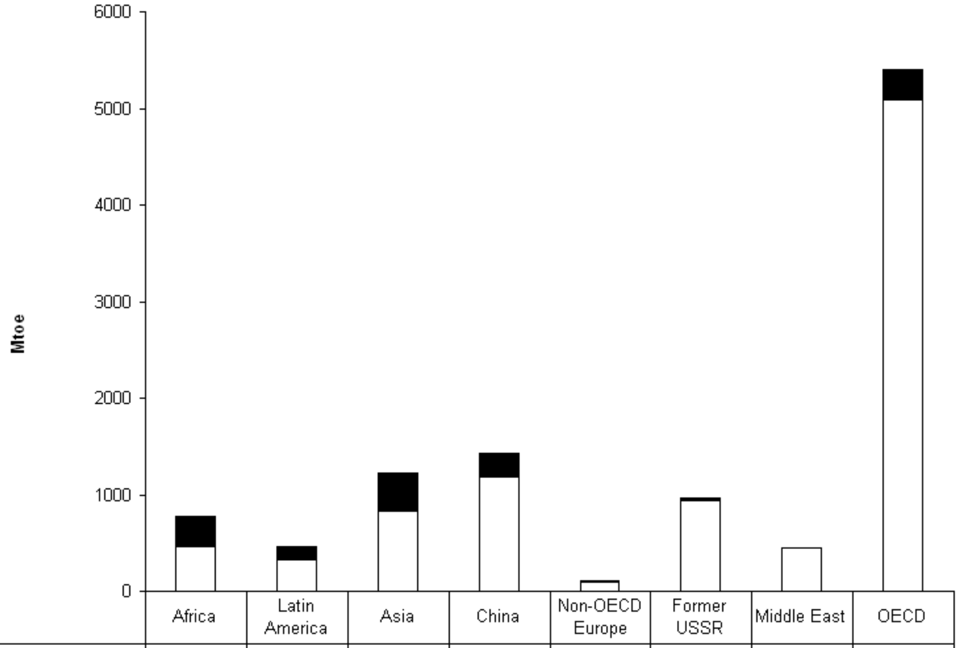
[†††] Solids are hard coal, lignite, peat, and oil shale. Liquids are crude petroleum and natural gas liquids. Gases are natural gas.

[‡‡‡] Europe includes former USSR

[§§§] Electricity includes hydro, nuclear, and geothermal sources, but not fossil fuel based electricity which is included in fossil fuel.

[****] Biomass includes fuel wood, charcoal, bagasse, and animal, crop, pulp, paper, and municipal solid wastes, but not include derived fuel

where other forms of energy are available, it is not harnessed and utilized efficiently, underscoring the need to promote energy efficiency where energy access is available. Another important factor is the landlocked status of some African countries (there are 15 landlocked countries in Africa) which makes the cost of importing commercial energy more expensive (EIA, 2006).



	Africa	Latin America	Asia	China	Non-OECD Europe	Former USSR	Middle East	OECD
■ share of renewables in total energy supply	279	135	400	243	10	27	3	305
□ Total primary energy supply	559	464	1224	1426	103	962	446	5395

Figure 2.3: Renewables share of total energy supply (data sourced from EIA, 2002)

Good and reliable energy infrastructure is a prerequisite for export diversification and sustained growth. It is vital for resource-based manufacturing and commodity processing, as well as trade in services. Reliable energy is also needed to increase efficiency in the agricultural sector and to develop non-traditional exports (UNECA, 2004). The inability of many African countries to provide good and adequate energy services has been a major constraint to their export diversification. This problem further underlines the need for energy diversification, in which biofuel can play a vital role. Renewable energy technologies (RETs) in general and biofuel specifically, offer developing countries some prospect of self-reliant energy supplies at national and local levels, with potential economic, ecological, social, and security benefits (Biswas *et al.*, 2001). Amongst the biofuels, bioethanol, biogas and biodiesel, jointly account for more than 90 percent of global biofuel usage (Dufey, 2006).

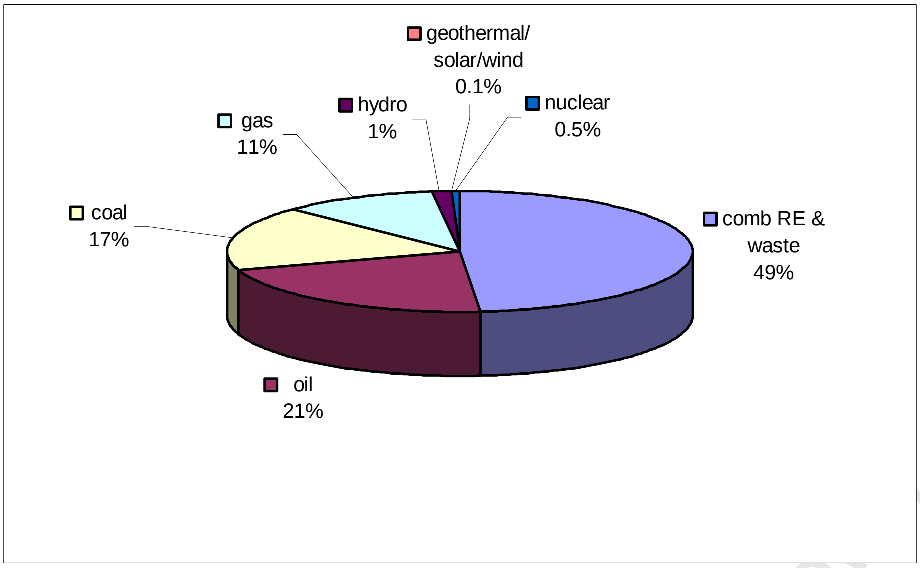


Figure 2.4: Share of total primary energy supply in Africa in 2001(World Bank, 2003).

2.3 Regional diversity: Commercial energy distribution

Although the African continent is often divided into five distinct regions namely West, Central, East, North, and South, its energy sector is best understood as three distinct regions illustrating the uneven distribution of commercial energy production. The energy resources distribution in Africa shows that every sub-region of Africa except East Africa is a net exporter of energy, at the same time importing petroleum products at the cost that is crippling the economy (see Table 2.2). North Africa is by far the largest, with significant oil and gas exports going to Europe and other markets. West Africa's exports are almost exclusively oil, and from one country - Nigeria. Southern Africa's net energy exports are oil (from Angola) and coal mainly from South Africa (99% of Africa's coal output). Natural gas production, on the other hand, is overwhelmingly concentrated in North Africa (mainly Algeria and Egypt). Crude oil production is more widespread, with North Africa (Algeria, Egypt, and Libya), West Africa (Nigeria), Central Africa (Gabon), and southern Africa (Angola), all having significant reserves. East Africa produces almost no oil, gas, or coal, while the rest of the sub-Saharan Africa is largely reliant on biomass (EIA, 1999). Oil rich sub-Saharan countries such as Nigeria continue to rely on traditional biomass energy to meet the bulk of their household energy: It is estimated that about 91% of the household energy needs are met by biomass (Karekezi, 1999). In 1997, South Africa and the North African region jointly accounted for over 50% of the total modern energy generated on the continent. In terms of electricity generation, South Africa is estimated to account for about half the continent’s total installed capacity (Karekezi, 2002). Most of Africa’s biomass energy use is in sub-Saharan Africa, biomass accounts for 5% of North African, 15% of Southern African, and 86% of sub-Saharan (excluding South Africa) consumption. Traditional biomass use has substantial environmental drawbacks. The indoor air pollution from the use of unvented biofuel cooking stoves (fuel wood for cooking) is probably a major cause of respiratory illness in many highland areas of sub-Saharan Africa: smoke is a carcinogen and causes respiratory problems. About 75% of wood harvested in sub-Saharan Africa is used for household cooking. Reliance on biomass (especially in the form of charcoal) also intensifies environmental (land) degradation. The abundant biomass energy resources in Africa need to be developed and delivered sustainably and reliably to all categories of energy consumers for overall development benefit.

Table 2.2: African countries which import and export energy (EIA Book, 2006).

Major Energy Exporter*	Net Energy Exporter	Importers**
Nigeria	Angola	Benin
Algeria	Cameroon	Eritrea
Libya	Congo	Ethiopia
South Africa	Democratic Republic of Congo	Ghana
Egypt	Cote d' Ivoire	Kenya
Gabon	Gabon	Morocco
Congo	Sudan	Mozambique
		Namibia
		Senegal
		Tanzania
		Togo
		Zambia
		Zimbabwe

* Major energy exports are in excess of 0.5 quads
** Most of the African countries imports are very small (less than 0.3 quads)

2.4 A Biofuels process industry in Africa

The inexhaustible nature of biofuel as energy source is an important asset for their future potential from the security standpoint. Biofuels, as the name implies, and for the purpose of this dissertation are fuels (liquid and gas) derived from biomass, a renewable resource that can potentially be harvested sustainably (Amigun and Julius, 2006). Another definition of biofuel is: “any fuel with an 80% minimum content by volume of materials derived from living organisms harvested within the ten years preceding its manufacture” (Klass, 1988). They can substitute for conventional fuels either totally or partially in a blend and they are made from biomass through biochemical or thermochemical processes (Demibras and Balat, 2006). Biofuels have the potential to cut CO_2 production because the plants they are made from absorb CO_2 as they grow. This is released again when the biofuel is burnt. Since energy is required to cultivate and harvest the plants, convert the biomass harvested into biofuel and distribute the fuel, additional CO_2 is produced. This means that the CO_2 benefits of biofuels must be assessed by life cycle analyses or well-to-wheels studies. In well-to-wheels studies, the net CO_2 emitted is calculated from the growing of the plant right through to the vehicle exhaust emissions.

Not all biofuels are the same. Liquid biofuels are often classified under two categories: ‘first generation’ and ‘second generation’. There are significant differences between first and second-generation biofuels and between biofuels of the same generation. First-generation biofuels are made from food crop feedstocks while second-generation biofuels are made from agriculture and forestry waste, such as woodchips and straw (Figure 2.5). The manufacture and use of biofuels also varies in cost, performance and CO_2 production. The overview of various conversion routes to biofuel is illustrated in Figure 2.6.

First-generation biofuels, made from food crops, can offer some CO_2 benefits and can help to improve domestic energy security. But concerns exist about the sourcing of feedstocks, including the impact it may have on biodiversity and land use and competition with food crops (Botha and von Blottnitz, 2006). The two main types of first-generation biofuel used commercially are ethanol and fatty acid methyl-esters (derived from vegetable oils). Second-generation biofuels are made from non-food feedstocks, such as waste from agriculture and forestry. The benefits of second-generation biofuels include the ability to achieve significant ‘well-to-wheel’ reductions in greenhouse gas (GHG) emissions, combined with dramatically reduced land requirements compared with first generation biofuels since most biomass, including many organic wastes, can be used as feedstock. Additionally, second generation biofuels are better internal combustion (IC) engine fuels than first generation fuels since they should not present any of the technical problems of degradation and material incompatibility associated with first generation biofuels (DTI, 2006). However, this technology will not be available in significant commercial quantities for five to 10 years in Africa (Shell, 2006).

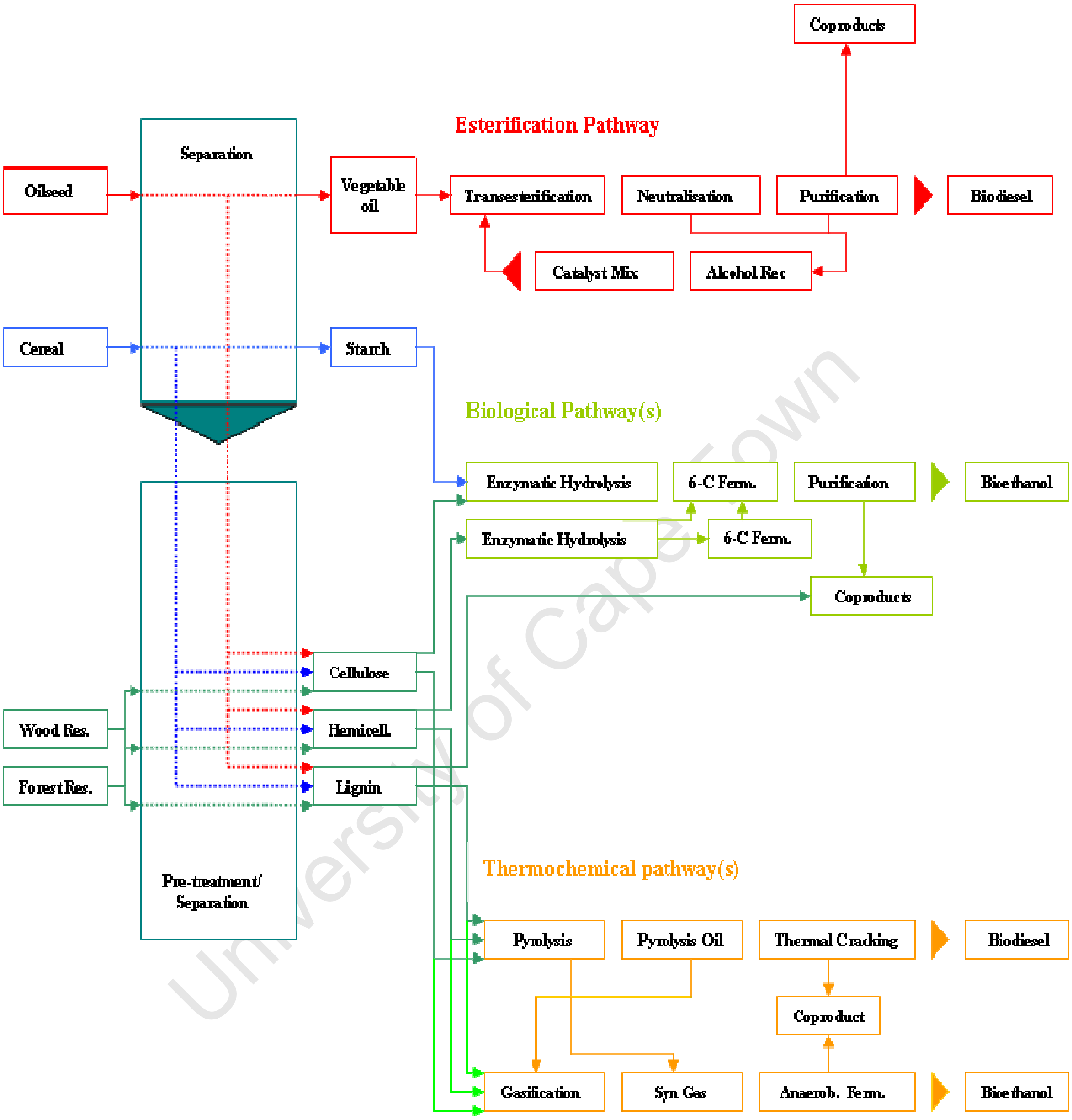


Figure 2.5: Biomass-to-Fuel Pathways (Mabee, 2006)

'Third generation' biofuels rely on biotechnological interventions in the feedstocks themselves. Plants are engineered in such a way that the structural building blocks of their cells (lignin, cellulose, hemicellulose), can be managed according to a specific task they are required to perform. For example, plant scientists are working on developing trees that grow normally, but that can be triggered to change the strength of the cell walls so that breaking them down to release sugars is more easy (Zinoview *et al.*, 2007). Notably, this latter generation of biofuels is only gradually being explored.

The possible uses of biofuels by far exceed most of other regenerative energies. While hydro-energy, wind power, and photovoltaic are used primarily for electricity generation, biofuels are not only suitable for power generation but also for generating heat and motive power. A crucial advantage of biofuels is that they, unlike photovoltaic and wind power, can be stored and made available as needed.

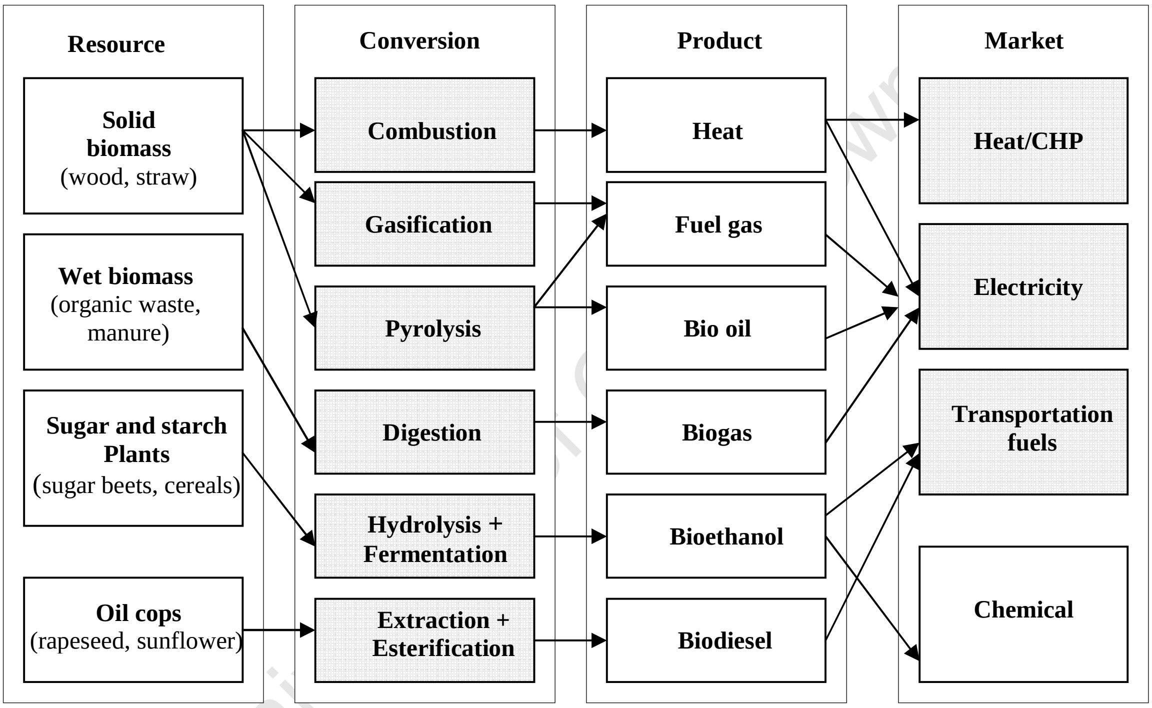


Figure 2.6: Overview of biomass conversion and application routes (Eubia, 2005)

Biofuels are made from biomass through biochemical (fermentation of sugar to alcohol, and anaerobic digestion or fermentation) or thermochemical processes (gasification, pyrolysis, liquefaction). Although the eventual depletion of fossil fuel lurks in the background as a long-term incentive for development of biofuel technology, the growing seriousness of the global energy problem and associated environmental pollution are substantially increasing the importance of the development and commercialisation of biofuel industry in Africa. Industrial countries see biofuels as a way of reducing greenhouse gas (GHG) emissions from the transport sector and diversifying energy sources. Developing countries see biofuels as a way to stimulate agricultural development, create jobs and save foreign exchange (Kojima and Johnson, 2006). Both developed and developing countries view biofuel as a means of achieving energy security. These concerns taking together and highlighted by recent surges in the world oil price, have prompted a wide range of countries to consider biofuel programs. Canada, the European Union (EU), India, the United States to mention but few have adopted new targets, some mandatory, for increasing the contribution of biofuels to their transport fuel supplies. The production and commercialisation of biofuels in Africa could provide an opportunity to diversify energy and agricultural activity, reduce dependence on fossil fuels (mainly oil) and contribute to economic growth in a sustainable manner. Several studies have reported significant decline in the unit cost of renewable energy technology over the past two decades. Further reduction in cost can be expected with technical progress and market growth (Karekezi, 2001). Whilst the topic of “bioenergy” has received significant public and legislative attention in several developed countries such as Germany , Canada, USA and New Zealand and developing countries like Brazil and India, relatively little effort has gone into promoting modern bioenergy in African countries, despite the estimated large resource base in many of them (Marrison and Larson, 1996). For example, in South America, Brazil's sugar-cane based ethanol industry now produces about 160,000 barrels (1072 GJ) of oil-equivalent a day, assisting the country in achieving self-sufficiency in oil (The New York Times, 2006). Also, Kåberger, (2004) reported that bioenergy use in Sweden has grown into the second largest source of energy. The use alone in 2003 was 378 PJ (105 TWh), or 42 GJ/capita, contributing to 20% share of the total energy use. There is lack of coherent biofuel strategy in Africa despite the increase in the price of conventional fuel on a daily basis, and their rising demand mainly due to psychological fear of geopolitical uncertainties compared to the dwindling convertible currency earning and rising evidence of climate change (2006 has been declared by the United Nations as International year of desserts and desertification). There are very few operational commercial biofuel systems in Africa. Existing bioethanol plants are concentrated mostly in the Southern African Development Community (SADC): with plants operating in South Africa, Malawi, Swaziland, Mauritius, and Zimbabwe, but mainly producing for the chemical and beverage markets. Other commercial ethanol producing countries are Ethiopia and Kenya. By way of example, ethanol programmes that produce a blend of ethanol and gasoline (gasohol) for use in existing fleets of motor vehicles have been implemented in Malawi, Zimbabwe and Kenya. Various biofuel projects are now been considered in different countries across Africa. There are strong indications that

Nigerian cars may start running with a combination of petrol and 10 per cent ethanol by the end of 2007, signalling a breakthrough in efforts to find alternative fuel sources (Punch Newspaper, 2006). Available evidence indicates that these programmes have registered important economic benefits. In the case of Zimbabwe ethanol plant (Triangle Ethanol Plant), 60% of the whole plant is locally produced. The building was erected by local workers trained specifically for the job. It is estimated to be the lowest capital cost (the plant was designed to produce 120,000 liters ethanol per day with a capital cost of $6.4 million at 1980 prices) per litre for any ethanol plant at that time. However, in 1994-95, Triangle refinery decided to stop production of ethanol in favour of rectified spirit (an industrial alcohol used widely in printing solvent and capable of being refined to portable alcohol) which is exported to European destinations, and the blending of ethanol with petrol in Zimbabwe stopped at that time. This is attributed mainly to reduced government support (Johnson and Matsika, 2006).

Small scale biogas plants are located all over the continent but very few of them are operational. It is estimated that only 25% of 300 units installed between 1980 and 1990 in Kenya are operational today. The high failure rate can be traced to the following main reasons (Njoroge, 2002):

- Poor design and construction of digesters, wrong operation and lack of maintenance by users
- Poor dissemination strategy by the promoters
- Lack of project monitoring and follow-up by promoters
- Poor ownership responsibility by users
- Failure by government to support biogas technology through a focused energy policy

The growth of large-scale anaerobic digestion (biogas) technology in the region is still at embryonic stage, but the potential is promising. The Kigali Institute of Science, Technology and Management (KIST) has developed and installed large-scale biogas (830 m^3 system in 2003 and 1,430 m^3 system in 2005) plants in prisons in Rwanda to treat toilet wastes and generate biogas for cooking. A recent initiative to tap energy from waste landfills was the US $ 2.5 million Global Environment Facility (GEF)-financed project in Dar-es-salaam, Tanzania which was expected to utilize an estimated 23,000 m^3 of methane generated by the process of anaerobic digestion. It was estimated that large-scale replication of the pilot GEF

Tanzania biogas project could result in the generation of electricity equivalent to over 10% of the Tanzania's total electricity generating capacity. This promising initiative was, however, ended prematurely primarily due to problems of cost escalation which were partially linked to technology selection problems. The project also faced significant institutional constraints (Karekezi, 2001). It is pertinent to note that most of the biogas plants in Africa are set up not only for the purpose of producing energy (cooking and lightning, fuel replacement, shaft power) but also as environmental pollution abatement systems. Some of these are located in South Africa, Rwanda, Kenya, Tanzania, Burundi and Ghana, Lesotho, Zimbabwe.

Biodiesel technology can be regarded as an emergent technology in Africa. To date, no commercial biodiesel plant has been built. In Ghana, a biodiesel plant by Anuannom Industrial Projects Limited (1.2 million-dollar factory, 360,000 tons/annum production) which has been under construction since 2003 would have been the first commercial biodiesel plant in Africa, but the construction was stalled probably due to lack of capital base to complete the construction, as well as political dispute (Ghana Review International, 2006; African News, 2004). There is an unknown but rapidly growing number of micro to small scale biodiesel plants in Africa, mostly operating on waste cooking oil in the cities, or on a part of the oil crop harvest on commercial farms. This is partly due to government subsidy which is lacking in almost all the African countries. By way of example, Biofuel industry in South Africa has been claimed to suffer from a lack of subsidies to build large facilities combined with an apparent lack of raw material for large scale production (Reichardt, 2007). Presently, many countries in Africa are busy cultivating Jatropha Curcas (physic nut), a drought-resistant and frost hardy plant – but it is worth noting that South Africa has placed this plant on the list of invasive species. The seed of Jatropha curcas contain high percentages (30%-35%) of oil, which can be extracted for further processing.

There has been a tremendous increase in biofuel technology development and commercialization in other continents. One of the reasons for this is sustained government support (in France, tax exceptions for biofuels is 0.35 EUR per liter for biodiesel and 0.50 EUR per liter for bioethanol, whilst the US government offers bioethanol subsidies of US$0.51/gal) (ESMAP, 2005). For example, American output of maize-based ethanol is rising by 30% a year; Brazil, long the world leader in bioethanol production is pushing ahead as fast as the sugar crop from which ethanol is made will allow; China, though late to start investing into bioenergy technology, has already built the world’s biggest ethanol plant (The Jilin Tianhe Ethanol Distillery has an initial capacity of 600,000 tonnes a year - 2.5 million liters per day and potential final capacity can be raised to 800,000 tonnes per year) (World Fuel Ethanol, 2004); Germany, the big producer of biodiesel, is raising output by 40-50% a year while France aims to triple output of the two fuels (bioethanol and biodiesel) together by 2007; Britain, taking a backward stance has already embarked on investment into biodiesel industry. Also after a long research on biofuels, a Canadian firm has plans for a full-scale ethanol plant that will replace today’s grain or sugar feedstock with straw. China, India and Nepal have extensively utilised biogas as a source of energy and as liquid fertilizer for soil enhancement since the 1950’s (The Economist, 2005).

2.5 The NEPAD link and other energy access targets for Africa

The New Partnership for Africa’s Development (NEPAD) provides the pragmatic framework for the attainment of United Nations (UN) Millennium Development Goal (MDG) and the World Summit on Sustainable Development (WSSD) plan of implementation. NEPAD “….is a pledge by African leaders, based on a common vision and a firm and shared conviction, that they have a pressing duty to eradicate poverty, place their countries both individually and collectively, on a path of sustainable growth and development and to halt the marginalisation of Africa in the globalisation process and enhance its full and beneficial integration into the global economy…” (NEPAD, 2005a). The extent of the challenge is dramatically illustrated by the fact that about 500 million people in sub-Saharan Africa do not have ready access to modern energy, and almost 600 million are dependent on traditional biomass sources for daily survival (IEA, 2002). Africa is in the early stage of its development journey, and has a wide range of options regarding development pathways and resources utilisation (NEPAD, 2005b). Energy is an essential consideration in this development, and options taken in the near future will have far-reaching consequences on development, impacts on global change and the sustainable use of ecosystems and non-renewable resources on a continental scale.

Energy specific objectives within the infrastructure initiative of NEPAD include:

- To increase Africans' access to reliable and affordable commercial energy supply from 10 to 35 per cent or more within 20 years;
- To improve the reliability and lower the cost of energy supply to productive activities in order to enable economic growth of 6 per cent per annum;
- To reverse environmental degradation that is associated with the use of traditional fuels in rural areas;
- To exploit and develop the hydropower potential of the river basins of Africa;
- To integrate transmission grids and gas pipelines so as to facilitate cross-border energy flows;
- To reform and harmonise petroleum regulations and legislation on the continent.

These objectives clearly highlight the lack of reliable and affordable energy as a barrier to economic and technological development on the continent. But Africa faces critical issues in overcoming this barrier (this is explained in section 2.6): There has been inadequate research and development (R&D) to support decision-making on energy. This is recognized in the WSSD plan of implementation, which advocates the promotion of technological development, transfer and diffusion to Africa, and to further develop technology and knowledge available in African centers of excellence. Meeting the NEPAD energy goals will require investments in scientific research and technological innovation.

2.6 Barriers to biofuel commercialisation in Africa

For developed countries, renewable energy sources primarily serve as a means to diversify the national energy supply and a means by which the concept of sustainable development can be implemented, and Green House Gases (GHG) emissions reduced. However, for developing countries, renewables in general and biomass energy in particular play a very different role. There is a great difference of background motives and a resulting performance gap between the South and the North in terms of harnessing renewable energy products such as biofuel. Therefore, it has become important to fill this gap with experiences gained in the developed world, but adapted to the needs of developing countries.

The fundamental problems to commercialisation of biomass derived energy exist in both developed countries and developing countries. However, the magnitude and characteristics is more pronounced in developing countries. The multi-dimensional differences among regions and countries make the analysis of the magnitude of these hurdles more complex. Despite national differences, it is possible to generalise some barriers. The Table below (Table 2.3) gives the schematic view of barriers to accelerated adoption and commercialisation of biofuel technology in Africa

Table 2.3: Schematic barriers assessment on a classified country basis

Country-type	Institutional/policy hurdle	Technical hurdle	Economic hurdle	Financial hurdle	Information hurdle	Capacity hurdle
Type A	**	*	**	**	*	*
Type B	**	**	**	**	**	**
Type C	***	**	***	***	***	**
Type D	***	***	***	***	***	***

Low:*, Medium: **, High: ***

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The classification of African countries is made in line with the economic and technical development status by Bhagavan, (2003). Various generic barriers currently identified to hinder the adoption and commercialisation of biofuel technologies in Africa apart from the high cost of raw materials and other economics related constrictions can be categorised as technological and non-technological (policy, legal, financial, institutional, cultural, social e.t.c.) constraints. These barriers are in a way general for renewable energy.

- **Type A**: Technologically advanced developing countries, with well diversified and fairly comprehensive industrial, energy and R&D infrastructures: only South Africa
- **Type B**: Technologically advancing developing countries, which are industrialising fairly fast, but are still quite limited in the diversification of their industrial, energy and R&D infrastructure e.g. Egypt, Morocco, Algeria
- **Type C**: Slowly industrialising developing countries, with still very limited infrastructure in industry, energy and R&D, such as Nigeria, Mauritius, Libya

- **Type D**: Technologically least developed countries: Most Sub-Saharan Africa countries, e.g. Ethiopia, Chad, Burundi, Mozambique, Ivory Coast, Niger, DR Congo, Somalia, Mali, and Sudan.

2.6.1 Policy, institutional and legal hurdles

The commercialisation of biofuel systems requires adequate institutional support and corroboration. Lack of coordination among institutions involved in renewable energy (RE) development and commercialisation (excessive bureaucratic bottleneck) such as government ministries of energy/science and technology, research institutes, and financial institutions, hinders efforts for the accelerated adoption of renewable energy technologies. Ghana established the National Energy Board (NEB) in 1983 with one of its mandate to develop and demonstrate renewable energy in the country. The NEB ceased to operate in 1991 and the renewable energy activities were later taken on by the Energy Sector Development programme (ESDP) established in 1996. The ESDP closed down in 2002 and has in its place the DANIDA supported National Renewable Energy Strategy (Amigun *et al.*, 2008).

A major argument against renewable energy in general and biofuel in particular is the large subsidies requirements. Subsidies conceal the commercial energy cost. This badly allocates scarce capital resulting to imbalanced competition between energy sources. Failure on the part of government to extend the subsidies enjoyed by the conventional energy to renewable energy technology is also a hurdle that needs to be resolved. In addition, very few of the African countries have in place clear strategies and targets for renewable energy development generally and specifically. The increase in biofuels utilisation and development in other continents over the past years is due to government policy decision. In North America, policies that help grain based ethanol compete in the market were extended, and additional strategies to increase biodiesel utilisation are being considered. In 2002, German parliament decided to exempt all biofuels from gasoline tax until the end of 2009. In Europe, guidelines to incorporate certain level of alternative fuels into the existing motor fuel have been established and biofuels are expected to be the primary means of achieving these goals (Demibras and Balat, 2006).

Many developing countries are characterised by a weak legal system, with problems ranging from lack of appropriate legislation, little respect for the judicial system to weak legal enforcement. Investors may be discouraged by difficulties in upholding and enforcing contracts. Lack of positive legislation that would encourage investors (especially the sugar companies) in Kenya to diversify into alcohol production is a typical example. However, due to the surging crude oil prices (from US$ 28 to US$ 62 over the past 14 months) key producers of sugar like Brazil and India have scaled back their sugar production in favour of ethanol, which uses the same raw material. The increase in Germany and Italy in biodiesel production from 450,000 and 210,000 tons in 2002 respectively to 1,088,000 and 419,000 tons is due to favourable legislation (Demibras and Balat, 2006). In some African countries, the hostile social climate and political instability prevent opportunities of international collaboration and support.

2.6.2 Financial limitation

The high initial cost of production of biofuels and inadequate financing arrangements for biofuel technology has been identified to be an important barrier to biomass energy commercialisation in most African countries. Existing capital markets do not favour small-scale investments as normally required for some biomass energy. This is however not peculiar only to African countries (Elauria *et al.*, 2002).

Some of the factors contributing to the formation of this barrier are:

- Lack of available credit facility with low interest rate;
- Bias against biomass energy and lack of adequate information of the potentials of biofuels project;
- The perceived risks of biomass energy projects also act as a major barrier to investments;
- Unfavourable government policies.

2.6.3 Technical/Infrastructure hurdles

Within the category of technical barriers, different renewable energy technologies present distinct barriers related to technical issues (Elauria *et al.*, 2002). The supply of feedstock (feedstock currently used for commercial biofuel production is agricultural crops) is crucial to the success of biofuel industry. Obtaining agricultural yields predicted to produce a percentage of biofuels for transport in Africa will be problematic. By way of example, to supply 30% by volume of the petrol used in South Africa would require of the order of 5 million tons of maize. This is a large amount as it is only half the maximum available capacity (Akinbami, 2001). Another factor is development of biofuel technology is likely to be based on the developed world for the foreseeable future. This is because only industrialised countries (including the BRIC countries-Brazil, Russia, India and China) have the technological base, the capital, infrastructure required to push large scale new development in the energy sector (von Blottnitz and Chakraborty, 2006). This is probably due to lack of technical and marketing infrastructure for the effective unpacking and adaptation of available technologies and effective social marketing of the products. Low to lack of cooperation/partnership with international bodies such as Renewable Energy and Energy Efficient Partnership (REEEP), a Public-Private partnership launched by the United Kingdom along with other partners at the Johannesburg World Summit on Sustainable Development in August 2002. This partnership actively structures policy initiatives through concerted collaboration among its partners for clean energy markets and facilitates financing mechanisms for sustainable energy projects. An example of how the partnership will boost biofuel commercialisation is the recent grant of 70,000 Euros gotten by the Nigerian National Petroleum Corporation (NNPC), from Renewable Energy, Energy Efficiency Partnership (REEEP) from Germany to support detailed feasibility study (research analysis on how to achieve improved target yield performance for cassava whose current national average of 15 tons per hectare is considered marginal to feed the proposed ethanol plant in the country) at different target locations (This Day Newspaper, 2006). Attempt to import the biofuel technology from the developed countries (technology transfer) to Africa has failed in many African countries due to lack of proper understanding of peculiar African features (the technology being transferred is not appropriate to the local context and demands, or is not adapted to the local environment). On the positive side, the nascent biofuels industry should look at how the brewing and the sugar industry manage to do well in Africa. Inadequate maintenance and bad quality of products (lack of standardization and quality control) is due to the fact that the technology and option are not suited to local African resources and need. Technical success of biofuel project will be a function of capacity/manpower availability to operate and carry out maintenance operation on the plant and of course spare part availability. This is obviously lacking in most African countries. It has been discovered that the capital cost of a plant varies significantly from place to place depending on the infrastructure already in place. The surrounding infrastructure will therefore influence the profitability of the project.

2.6.4 Information hurdles

Lack of awareness and limited information on the national renewable energy resource base, their benefits both economically and environmentally is a barrier to the market penetration of renewable energy in general and biofuels projects specifically in most African countries. The public is therefore not educated to influence the government to begin to take more decisive initiatives in enhancing the development, application, dissemination and diffusion of biomass energy resources and technologies in the national energy market. The fact that the stakeholders and the consumers are not sensitised to the potentials of biomass energy is another issue. This will probably affect the view of investing as risky.

Poor telecommunications infrastructure (especially poor internet access, and lack of adequate telephone access-this is changing with the advent of mobile telecoms) and high cost of services is also a source of barrier to biofuel commercialisation. Among the benefits of telecommunications for improving efficiency and productivity are the following:

- Reduction of travel cost: in many cases telecommunications can be substituted for travel, resulting in savings in personnel time and travel costs.
- Energy savings: telecommunications can be used to increase the efficiency of shipping so that trips are not wasted and consumption of fuel is minimized.
- Decentralization: availability of telecommunications can help attract industries to rural areas, and allow decentralization of economic activities away from major urban areas.

There is often no industrial association or other co-ordinating body that can help to develop networks of actors in the renewable energy sector.

2.6.5 Capacity/Manpower hurdles

The limited availability of correctly trained and skilled manpower is one of the most critical requirements to the development and market penetration of biofuels in Africa. This is largely due to the exodus of highly trained manpower from developing countries most especially Africa to industrialized nations. The increased number of this exodus attributed to the deteriorated political, economic, and social conditions in Africa reduces the availability of skilled manpower (human resources) which African countries need so badly for self-reliant and sustainable development. This has led to increased cost of doing business in Africa as expatriates to carry out installation, operation and maintenance of biofuel technology need to be imported.

2.7 Biofuels and the sustainable development debate

Links between biofuels and sustainable development are varied and complex. On the one hand, biofuels may imply improved energy security, economic gains, rural development, greater energy efficiency and reduced GHG emissions compared to standard fuels. On the other hand, there is the risk that the continued commercialisation of biofuel through increased production of energy crops utilising practices such as mono-cropping and Genetically Modified Organisms (GMOs) could lead to deforestation, water pollution, food security problems, poor labour conditions and unfair distribution of benefits along the value chain. The positive impacts and trade-offs involved vary depending on the type of energy crop, cultivation method, conversion technology and country or region under consideration.

A major criticism often levelled against biomass, particularly against large-scale fuel production, is that it could divert agricultural production away from food crops, especially in developing countries. According to a recent briefing report by Oxfam International, (2008), tthirty per cent of price increases are attributable to biofuels, suggesting biofuels have endangered the livelihoods of nearly 100 million people and dragged over 30 million into poverty. The basic argument is that energy-crop programmes compete with food crops in a number of ways (agricultural, rural investment, infrastructure, water, fertilizers, skilled labour etc.) and thus cause food shortages and price increases. This rise in food prices is also aggravated by the rising food demand in China and India. On the other hand, there are those that argue that massive production of biofuels would not impose food security trade-offs.

Among the main arguments supporting this are the fact that food shortage and famine problems are more related to poor distribution and shortage of jobs and disposable income to buy food rather than agricultural production. In this sense, the livelihoods created by biofuel revenue could increase affordability in producing areas. Another one is the fact that there are possible synergies between fuel and food production as certain perennial energy crops like trees and grasses require fewer inputs and they can sometime be grown on very degraded land too marginal for food crops and can promote land restoration before food production is able to take place (Dufey, 2006). The extent to which higher crop prices will affect poor people in developing countries will likely vary from region to region. Overall, a more careful analysis of this issue is urgently required, including closer examination of the right balance between food and fuel co-production in different regions and global and local impacts of expanded biofuels demand. However, it is outside the scope of this dissertation to make a contribution to this debate.

2.8 The economics of biofuels

The production and use of biofuels have entered a new era of global growth, experiencing acceleration in both the scale of the industry and the number of countries involved (Woldwatch and GTZ, 2006**.** However, the data are so sparse, that there are few relevant published journal articles on the subject. There are a number of recent working and briefing papers, but the biofuels industry has grown faster than even these papers foretold. The main contentious problems of biofuel commercialisation in Africa relate to economics and political will. The economics of biofuel production and consumption will depend on a number of factors specific to the local situation. These factors include (a) the cost of biomass materials, which varies among countries, depending on land availability, agricultural productivity, labour costs, e.t.c.; (b) biofuel production costs, which depend on the plant location, size and technology, all of which potentially vary a great deal among countries; (c) the cost of corresponding fossil fuel (e.g. gasoline, diesel) in individual countries, which depends on fluctuating petroleum prices and domestic refining characteristics; and (d) the strategic benefit of substituting imported petroleum with domestic resources. The economics of biofuel production and use, therefore, will depend upon the specific country and project situation (Thomas and Kwong, 2001). The cost of the plant in a developing country compared to one in a developed country depends upon the complexity of the technology and the source of technical know-how. The following factors are significant in analyzing capital cost differences between similar plants in different locations or countries:

- **Location**: There is evidence that higher location factors are partly due to the need of importing specialized equipment. In heavily industrialized countries, the equipment is often fabricated in the same area where the plant is constructed; in developing countries, depending on level of technology needed, equipment is generally imported along with specialized personnel to install it, at premium prices (Bridgewater, 1984). Besides, specialised equipment tends to originate from a few well-identified locations where the necessary technology has been extensively developed, such as USA, UK and Germany (Miller, 1984).

- **Equipment**: Material and equipment costs include the effects of tariffs, scale taxes and rates of currency exchange (Miller, 1984). Basic equipment costs do not vary significantly, and location differences in construction costs are largely due to labour costs, specialised equipment and local factors.

- **Indirect construction costs, transportation and handling:** Construction costs depend on the availability of skilled labour and material of construction.

- **Legislation:** Due to the standards of most industrialised countries environmental protection typically adds 20% to plant costs and can in extreme case exceed 50% (Bridgewater, 1984).

- **Climate:** Additional costs for insulation in building and on piping and equipment (Miller, 1984). Particularly cold climate increases construction requirements, as well as the level of thermal conservation needed. Hot climate boosts costs because of additional cooling requirements. Possible lower air conditioning costs and reduction in equipment costs because of colder cooling water at the new location may occur.

- **Labour productivity**: Differences in productivity due to differences in wage ratios, extensive overtime, material factors or indirect factors, such as culture, religion and local weather condition will have a considerable effect on investment costs (Bridgewater, 1984). Even when investment costs are smaller in developing countries, production costs are usually increased. Capital costs diminish due to the technical system that is characterized by collection of rather old machines with a low manufacturing velocity and a low accuracy level.

Owen (2006) illustrated that estimates of damage costs resulting from combustion of fossil fuel, internalised into the price of the resulting output of electricity from renewable energy, could clearly lead to a number of renewable energy including biofuels being financially competitive with conventional energy. He also suggested that the principle of internalising the environmental externalities of CO2 emissions (and other pollutants) could be achieved directly though imposition of a universal carbon tax and emission charges, or indirectly as a result of ensuring compliance with Kyoto targets and other environmental standards.

Economic competitiveness against mainly fossil fuel is a very common argument against renewable energy (RE). The cost of producing very low CO2 biofuels such as cellulosic ethanol and methyl ester (biodiesel) are still higher than the cost of gasoline and conventional diesel. The gap is expected to narrow with the current hike in the price of oil. The costs could also probably decline in the future, especially if new processes being developed for producing cellulosic ethanol are successful, and subsidies as well as tax exemptions, which are currently applied in Europe and USA are used (The economist, 2005). Subsidies to biofuels are large and growing rapidly. For example, there has been a tremendous increase in biofuel technology development and commercialization in other continents such as France due to sustained government support (tax exceptions for biofuels is 0.35 EUR per liter for biodiesel and 0.50 EUR per liter for bioethanol), whilst the US government offers bioethanol subsidies of US$0.51/gal) (ESMAP, 2005).

For many products and services, unit costs decreases with increasing experience. This effect is often referred to as learning by doing, progress curve, experience curve or learning curve. The learning curves are empirical and represent graphically how market experience reduces prices for various technologies and how these reductions influences the dynamic competition among technologies. In nearly all production operations, some change in cost structure occurs as plant size is changed. Thus the theory of economy of scale pre-supposes that there exists and optimum size plant for most production operations (Alam and Amos, 2004). Economies of scale and technological advancement can lead to increased competitiveness of these renewable alternatives, thereby reducing the gap with conventional fossil fuel. One of the most important examples is the one provided by Brazilian Alcohol Program (PROALCOOL), established in 1975 with the aim of reducing oil imports by producing ethanol from sugarcane. This program has been claimed by Goldemberg *et al.*, (2004) to have positive environmental, economic and social aspects and has become the most important biomass energy program in the world. However, while the Brazilian ethanol program is often viewed as a success in environmental policy circles, it has faced a great deal of domestic criticism (Lizardo and Ghirardi, 1987). The Brazil ethanol production cost became cost-competitive at a crude oil price of 36 $/bbl, from close to 100 US dollars a barrel at the initial stage of the program in 1980. Figure 2.7 illustrates a remarkable example of the “learning curve” effect for a renewable energy such as ethanol in Brazil (Goldemberg *et al.*, 2004).

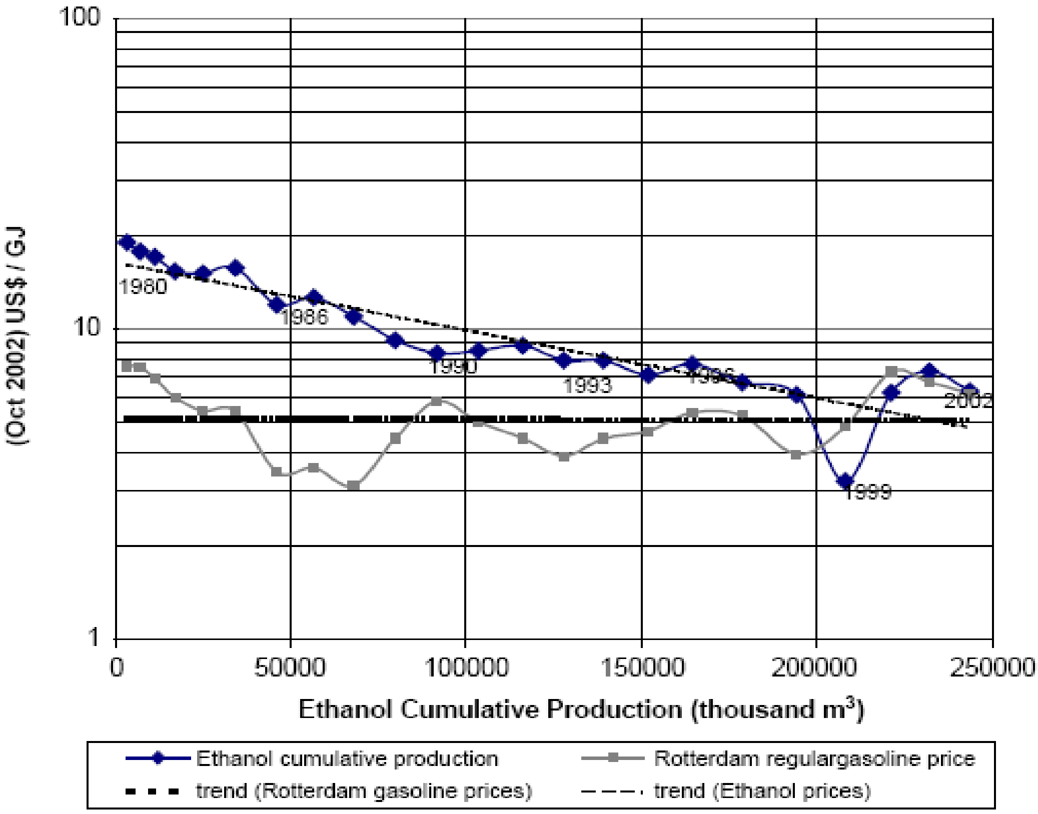

Figure 2.7: Brazilian sugarcane ethanol international competitiveness (Goldemberg *et a.*, 2004)

The learning improvement is measured in terms of progress ratio (PR) of the technology which is the variation of prices according to cumulative sales. Thus, an efficient technology penetration is one that achieved low PRs. In US dollars, sugarcane ethanol produced in Brazil has shown progress ratio of 93% (1980-1985) and 71% (1985-2002) (Goldemberg, 2006). Cardona *et al.,* (2007) suggested that the relatively higher production cost of biofuel and specifically ethanol is the main obstacle to be overcome and proposed that process engineering could provide the means to develop economically viable and environmentally friendly technologies for the production of fuel ethanol. An important part of the research trends on fuel ethanol production is oriented to the reduction of feedstock costs, especially through the utilisation of less expensive lignocellulosic biomass. The authors later concluded that process intensification through integration of different phenomena and unit operations as well as the implementation of consolidated bio-processing of different feedstocks into ethanol will offer the most significant outcomes during the search of the efficiency in fuel ethanol production.

Coelho *et al*. (2006) established that production costs of ethanol from sugarcane are low not only due to geographic conditions but also because of the extremely favourable energy balance. This favourable energy balance is due mainly to the fact that all energy needs in sugarcane mills are provided without any external energy source through burning of sugarcane bagasse in boilers to produce steam and electricity/mechanical energy to fuel the process (cogeneration process).

The feedstock cost for the first generation biofuels has been identified as the major cost barrier. Feedstock accounts for 50 to 80 percent of biofuel production cost, so it has a huge effect on the producers' returns (Caesar *et al.,* 2007). In the United States, for example, every dollar increase in the price of a bushel of corn raises the production cost of bioethanol by $0.35 a gallon and reduces the producer's operating margin by 20 per cent (Caesar *et al.*, 2007). Nelson *et al.*, (2006) performed an economic analysis to determine the cost of production associated with producing methyl tallowate (biodiesel), using commercially available continuous-flow transesterification technologies in the USA. They presented cost-sensitivities data with respect to the two varying inputs; feedstock cost and glycerine credit price and later suggested that feedstock cost had significantly greater impact on production cost, while the effect of glycerine by-product credit was minimal. Also, a review of 12 biodiesel economic feasibility studies by Bender (1999), suggested that cost of feedstock is the most significant cost input factor. This claim is also corroborated in a recent study by Radich, (2006). Warren *et al*. (1994) and Kwiatkowski *et al*. (2006) proposed that the primary feedstock cost has the greatest impact on the cost of producing ethanol. They further suggested that an increase in the cost of corn causes a direct increase in the cost of ethanol production and that changes in the composition of the feed also greatly impact the cost of ethanol production.

Nguyen and Prince (1996) have proposed rules for optimisation of the size of a bioethanol plant (reduction of the cost of ethanol production) in Australia. They derive a simple model of general applicability by balancing crop transport costs (which increase with plant size) against the production costs which decrease as economic of scale. The relationship is generally applicable to all bioenergy conversion plant in general which requires biomass to be transported from surrounding area. At the optimum, the cost of transporting crop, per unit quantity of fuel, must be a predictable proportion of the unit cost of production. The ratio allows an easy check as to whether a design or operating plant is near the optimum size, and if not what action would improve the economy of the operation. This relation can also be used to predict the consequences of cost changes. This principle is explained in the succeeding section.

Johnstone (2005), proposed that American cost data are not always directly applicable to British conditions even with a correction factor, since relative costs in the two countries differs. As a result of the problems associated with the use of existing cost models, there is thus a need to develop indigenous (reflecting the local situation) cost estimation relationship for better understanding of biofuel economics. The key issues considered included ‘parametric’ ability to maximize the use of historical data in the estimating process, increase estimate realism, and reduce the costs associated with proposal preparation, evaluation, and negotiation.

To buttress the need for development of African cost estimation model, in a study of biofuel production in Africa, Ilori *et al.,* (1996) investigated the “Economics of small scale ethanol production from breadfruit and cassava flours via plant enzyme and acid hydrolysis. The working capital required for the plant process was estimated with the method reported by Lyda, (1972) while the estimation of equipment running costs was based on the method of Degarmo *et al*., (1979) and reported in Degarmo *et al.,* (1996), in which case it was assumed that maintenance and repairs costs would increase by a uniform amount (G) and would constitute an arithmetic series. Not only are these methods old but they are also developed for a different location.

2.9 Bioenergy conversion plant size optimisation

Biofuels for transportation, including bioethanol and biodiesel, and several other liquid and gaseous fuels (such as biogas), have the potential to displace a substantial amount of petroleum around the world over the next few decades, and a clear trend in that direction has begun (IEA, 2004). The production and commercialisation of biofuels in Africa could provide an opportunity to diversify energy and agricultural activity, reduce dependence on fossil fuels (mainly oil) and contribute to economic growth in a sustainable manner (Amigun *et al.*, 2008).

Several studies have reported significant decline in the unit cost of RET in general and biofuels specifically over the past two decades. Further reduction in cost can be expected with technological improvement and market growth (Karekezi, 2001). Nguyen and Prince, (1996) discussed ways to reduce bioenergy (bioethanol) costs by finding an optimum economic plant capacity. This is based on the principle that the unit cost of producing any product, such as ethanol decreases with plant size. On the other hand, the biomass required increases, which lead to a longer average biomass transportation distance and subsequently an increase in transportation cost. There may therefore be an optimal plant size that will minimize the total production cost. In order to estimate the change in raw materials transport costs with increases in plant capacity, it would be desirable to find a scale factor similar to the scale factor for capacity costs. Nguyen and Prince, (1996) model assumed a circular biomass supply when calculating the distance from biomass supply to the bioenergy plant. However, this will not often be the case. Other factors, such as biomass moisture and road quality can also be included in the model as these will affect the transportation costs. Kumar *et al.*, (2003) determined the power cost and optimum plant size for power plants using three biomass fuels, agricultural residue-grain straw, whole boreal forest and forest harvest residues from existing lumber and pulp operations-limbs and tops in western Canada. They reported that power cost versus size from whole forest is essentially flat from 450 MW (\$47.76 MWh^{-1}) to 3150 MW (\$48.86 MWh^{-1}), hence optimum size is better thought of as a wide range. They also revealed that all biomass cases show some flatness in the profile of cost versus plant capacity and that this occurs because the reduction in capital cost per unit capacity with increasing capacity is offset by increasing biomass transportation cost as the area from which biomass is drawn increases. This means that smaller than optimum plants can be built with only a minor cost penalty.

Jenkins (1997) also proposed that a biomass facility accepting fuel from a surrounding region may be shown to have an optimum size when the assumption of a positive economy of scale (decreasing cost with increasing size) in capital and non-fuel operating costs is combined with an increasing delivered fuel cost as the facility size increases. The optimisation procedure put forward by Jenkins (1997), generally concludes that the optimal capacity is quite large, and that the smaller sizes of existing biomass utilisation facilities are sub-optimised or will be under intensive energy crop production systems. However, the output pricing functions tend to be quite flat with respect to facility size beyond some small capacity, leading to insensitivity in the price around the optimum. This relative insensitivity of output cost to scale around the optimum suggests that above some small size, finding the true optimum is not especially critical in any case, and that other sitting factors, such as traffic loading and other site specific variables may be considered more important. Hence, determining the optimal facility size remains a site specific task.

The whole bioenergy chain is represented by a five system components as illustrated in Figure 2.8. However, the bioenergy chain described in the Nguyen and Prince (1996) model covers only the biomass production, transportation and conversion.

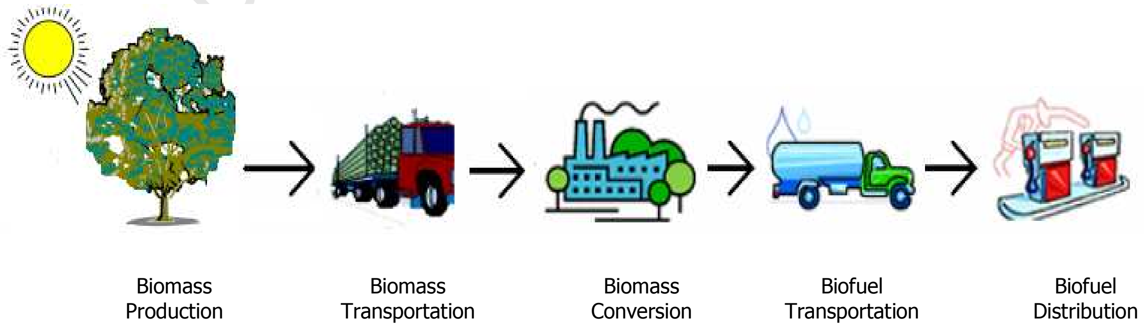

Figure 2.8: The bioenergy chain from biomass production to distribution of biofuel

Consider crop at a distance x to ($x+dx$) from the factory;

Quantity of crop $dM = 2\pi x\,dx\,Ya$ (2.1)

where, x is the average direct distance from factory, a is the fraction of useful land and Y equals the agricultural yield per unit area.

Transportation possibilities may restrict the supply of biomass. When the biofuel plant has local biomass supply, tractor and truck transportation is the most commonly used method of transportation. For longer distances, the wood can be transported by train and ship after been harvested.

The model used in this dissertation is described by Nguyen and Prince (1996) and Dornburg and Faaij (2001). They defined the total transport cost, c, for the biomass to be:

Cost of transport $dc = 2\pi x dx\ Ya\ kbx$ (2.2)

where, k equals the transport cost per unit distance and unit mass and b = ratio of actual length to direct distance, taken as constant.
Hence, total transport cost for all crops up to a distance x from the factory is

$$c = \int_0^x 2\pi Yakbx^2 dx = \frac{2}{3}\pi Yakbx^3 \tag{2.3}$$

Now, the total quantity of crop to this distance

$$M = \int_0^x 2\pi aYxdx = \pi aYx^2 \tag{2.4}$$

This may be related to the plant capacity P (for example tonnes per annum)

$$P = M/y \tag{2.5}$$

Where y = fractional product yield from raw materials.

Hence the required x for a given P is

$$x = \left(P/\pi Yay\right)^{0.5} \quad or \quad x \infty P^{0.5} \tag{2.6}$$

And since $c \propto x^3$ (from equation 2.3), therefore $c \propto P^{1.5}$

Transport cost then varies with capacity to the power of 1.5

The total cost (TC) of a factory operation may be represented as:

$$TC = AP^m + BP^n + k'P \tag{2.7}$$

Where *A* = transport cost factor; *m* = capacity exponent for transport, found as 1.5;
B = production costs factor; *n* = capacity exponent for production costs, *k'* = factors for costs which are constant per unit of product (such as overhead).

Hence, *C*, costs per unit quantity of product can be expressed as

$$C = TC/P = AP^M + BP^{-N} + k' \tag{2.8}$$

Where *M* = *m*-1, *N* = 1-*n*;

At optimum (least cost) plant capacity *P*, $dc/dP = 0$,

Hence, $dc/dP = MAP^{(M-1)} - NBP^{(-N-1)} = 0$ (2.9)

$$MAP^{(M+N)} = NB,$$

$$P^{(M+N)} = NB/MA.$$

2.10 Theory of cost estimation

Practical engineering is very largely a matter of cost and the subject of cost estimation deserves as much study as any other empirical practice, since however technically ingenious a project may be, the decision to proceed will depend ultimately on the estimated costs and profits. Hence, a cost estimate can have a major impact both on project profitability and on the identity of the technical solution.

2.10.1 The need for cost estimation

A need exists for adequate cost estimation and cost control during the planning phases of the product development cycle. Cost estimation is the ‘art’ or a ‘process’ of approximating the probable cost or values of manufacturing a product before all stages of the development cycle have been executed, based on information available or that can be collected at the early stage of product development cycle, (Garrett, 1998). The most significant magnitudes concerning the cost estimation of an industry are:

- The fixed capital cost which is paid during the installation period and
- The annual operating cost which is paid during the operation.

Good cost estimation has a direct bearing on the performance and effectiveness of a business enterprise because overestimation can result in loss of business and goodwill in the market, whereas underestimation may lead toward financial losses to the enterprise. Because of this sensitive and crucial role in an organization, cost estimation has been a focal point for design and operational strategies and a key agenda for managerial policies and business decisions (Niazi *et al.*, 2006). Both fixed capital and annual operating cost estimates are also important in project evaluation, product pricing, process optimization and other techno-economic studies (Marouli and Maroulis, 2005). A realistic cost estimate is an essential element in the decision making process because it can help decision makers determine the optimal course of action necessary to meet operational requirements. An organisation’s future often depends on the accuracy of its cost estimate. Both overestimate and underestimate can be as damaging as over and under design. The Freiman curve (Figure. 2.9) succinctly illustrates that:

- The greater the underestimate, the greater the actual expenditure
- The greater the overestimate, the greater the actual expenditure
- The most realistic estimate results in the most economical project cost

Underestimates may result in a project approval, but they also frequently lead to financial loss and business failure. Overestimates serve an organisation as poorly as underestimates. Rather than resulting in greater profits, as one might hope, it reflects a ‘Parkinson’s Law’ application. Realistic estimates result in most economical cost. They remind managers to control the excess resources.

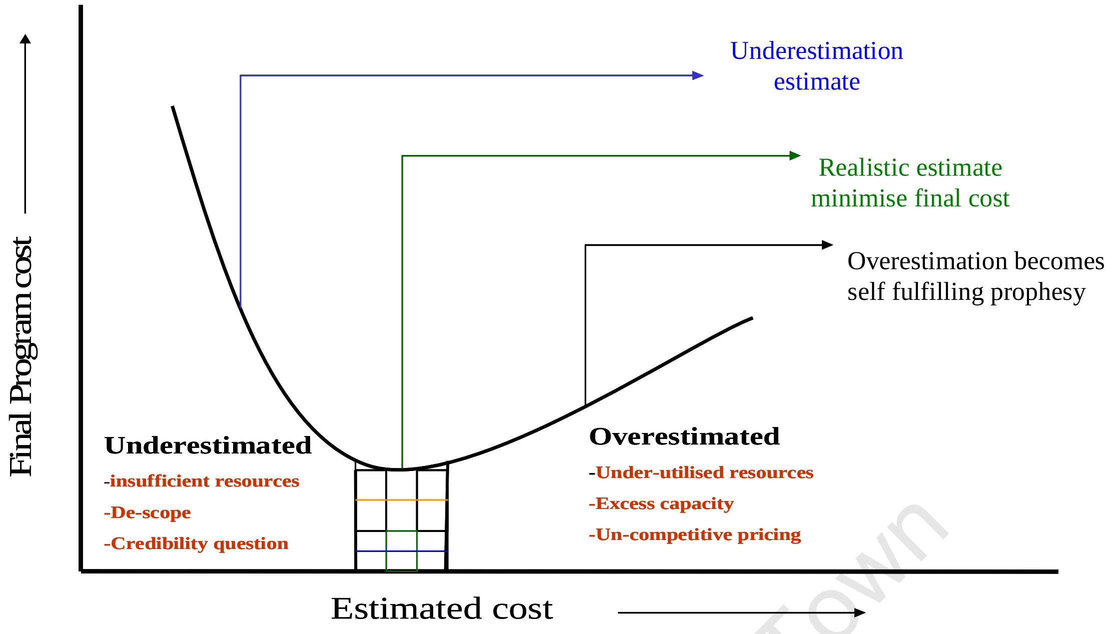

Figure 2.9: The Freiman curve (Daschbach and Agpar, 1988)

Underestimates may result in a project approval, but they also frequently lead to financial loss and business failure. Overestimates serve an organisation as poorly as underestimates. Rather than resulting in greater profits, as one might hope, it reflects a ’Parkinson’s law application. Realistic estimates result in most economical cost. They remind managers to control the excess resources.

2.10.2 Approaches to cost estimation

Cost estimating is one of the most important steps in project management. Cost estimation is the procedure of approximating the cost of manufacturing a product before all stages of the product development cycle have been executed based on the information available or that can be collected at the stage of the product development cycle (ten Brinke, 2002). Two basic approaches for cost estimation can be distinguished: generative cost estimation and variant based cost estimation. Variant based cost estimating depends on the similarity between the product under consideration and previously manufactured products. The cost record of the previously manufactured products can be used as a template in the cost estimation process of the new products. There are certain compensating advantages in basing preliminary estimate on known prices of particular plant items rather than on generalised graphs. The starting data are closer to reality, and at least one knows the source of the information. Generative cost estimating is based on the fact that the costs of manufacturing a product depend on the required production operations. By determining the required operations it is therefore possible to estimate the production costs. This method is closely related to process planning and will usually be applied for new product elements for which no variants exist (ten Brinke, 2002). It is easier to estimate costs accurately when more detailed information is available. Since design fixes about 70% of the product costs, it is required to make accurate cost estimates during design. However, during the design process the product information is not yet available in full detail, so it is difficult to make accurate estimates. This phenomenon is known as the cost estimation paradox. The difference in applicability of both variant and generative approaches is illustrated by means of the cost estimation paradox depicted in Figure 2.10.

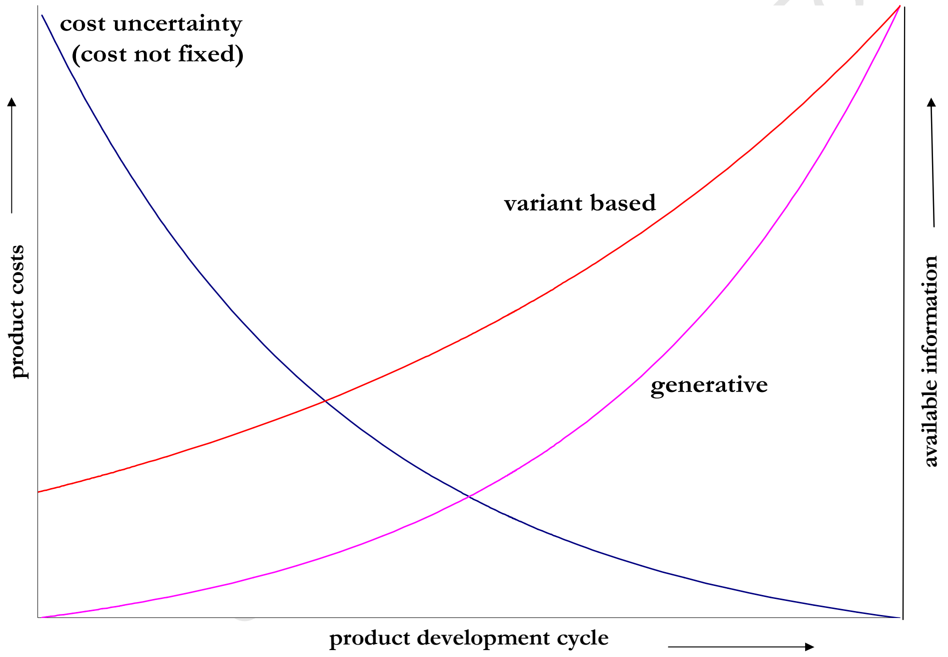

Figure 2.10: The cost estimation paradox for generative and variant-based cost (adapted from ten Brinke, 2002)

Because variant based cost estimation uses information from products manufactured in the past, more information is available in the beginning on the development cycle than in the case with generative cost estimation. Both variant based and generative cost estimation can be applied at the same time for one product resulting in hybrid cost estimation. In the development cycle of products, it can occur that different parts of a product will be in a different phase of the product development cycle.

Therefore, the available information of different parts of the product will be different. When the costs of different parts of a product are calculated in a different way, the total product costs can be calculated by summing the costs for the different parts. The next sections will elaborate on the cost estimation techniques using the approaches mentioned above.

2.11 The anatomy of a process industry project

Following the identification of an investment opportunity, the evaluation of markets, available feedstocks and appropriate technology are undertaken. A key aspect of bringing these elements together successfully is the choice of a suitable location for manufacture. As the various elements of the project are refined and integrated, the project scope and characteristics can be defined. These include not only the markets, feedstocks, process technology and site location, but the production capacity, the extent of integration with other manufacturing, transport and material handling, storage, utilities supplies and labour requirements. Based on these variables, more detailed market forecasts can be conducted, and the process and engineering design carried out to allow cost estimates, safety and environmental appraisal to be carried out (Brennam, 1998). This “process industry anatomy” is illustrated in Figure 2.11.

The cost estimate provides knowledge about the consequences of decisions during the planning phases of product development cycle. Interaction with government and community is initiated and the foundation laid for acceptance of the project by the wider community. Project approval or rejection is usually the decision of the board of directors of a company who require detailed, well-documented proposal, referred to as expenditure proposal (feasibility appraisal of the project). Much iteration of design and evaluation are often necessary before sanction is granted.

After approval is granted, further detailed design, equipment and material procurement and plant construction are implemented followed by commissioning.

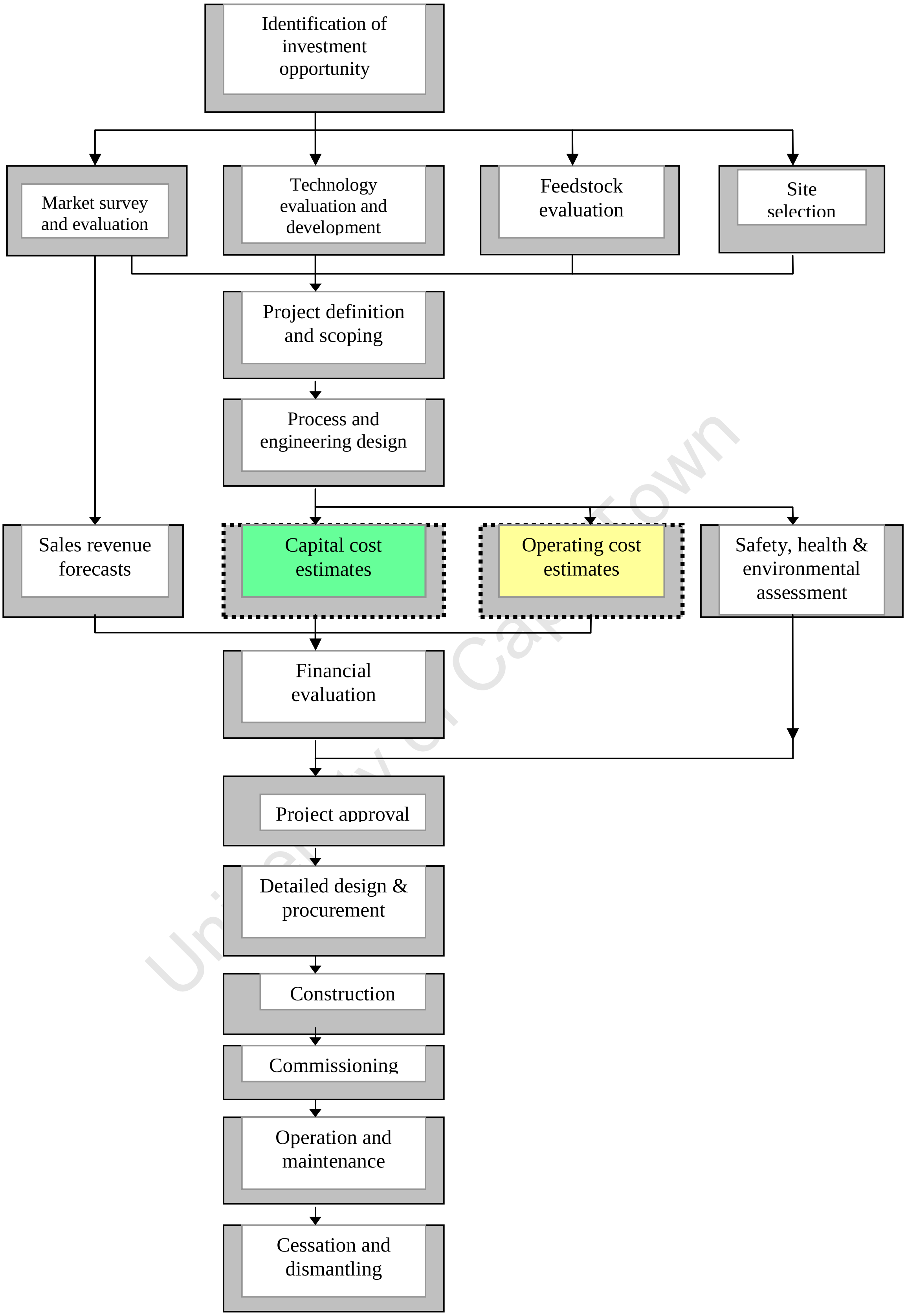

Figure 2.11: The anatomy of a process industry project (adapted from Brennam, 1998)

Time spans from project approval to plant commissioning vary considerably depending on the market pressure, size of the plant and complexity. After plant commissioning, when the production and plant efficiency of the plant is proven, the operating life of the plant starts. It continues until a further major decision is made to terminate operation, when the plant is decommissioned and either ‘mothballed’ or dismantled.

Typical operating lives for process plants are 15 to 20 years but may exceed this. There are situations where short lives are proposed, matching short-term market demands or opportunities to use cheap feedstock for a limited period.

An acceptable plant design must present a process that is capable of operating under conditions that will yield a profit. Since net profit equals total income minus all expenditure, the knowledge of different types of cost involved in the manufacturing processes is essential for engineering estimators. Capital must be allocated for direct plant expenses, many other indirect expenses are also incurred and these must be included if a complete analysis of the total cost is to be obtained. Some examples of these indirect costs are administrative, salaries, and product distribution cost. A capital investment is required for any industrial process, and determination of the necessary investment is an important part of a plant design project.

The total investment for any process consists of fixed capital investment for physical equipment and facilities in the plant plus working capital which must be available to pay salaries, stock raw materials and keep products on hand, and handle other special items requiring a direct cash outlay. Thus, in an analysis of costs in a biofuel process industry, capital investment costs and operating (manufacturing) costs must be taken into consideration.

2.12 Capital cost estimation

Estimation of capital cost (sometime also referred to as Installed Cost or Investment Cost) is the first thing that is to be done for assessing the attractiveness of a proposed project. Capital investment can be regarded philosophically as deferred consumption of wealth in the expectation of greater wealth in the future. Investment cost in the process industries is required for entirely new plants, for modifications to existing plants (retrofitted plant), for sustaining that plant during its operating life. An accurate estimate of capital cost is fundamental to the success of a project.

The capital cost estimate apart from the fact that it indicates the magnitude of the proposed investment, helps to provide other information, including the profitability of the project, which is crucial for management's decision and approval (Pascoe, 1992).

The capital cost estimate has three main functions in relation to capital investment, at various stages in the development of a project. These are:

- To compare an adequate range of possible alternatives
- To provide a more accurate estimate of the investment in a viable project
- To facilitate cost control of the project during implementation

There are of course other uses incidental to the three outlined above, such as rendering assistance in detailed design decisions, facilitating the appraisal of quotations from suppliers or contractors, and assessing of claims. In recent years, not only has the rate of technological innovations increased rapidly but this has been accompanied by sharp fluctuations in market conditions, interest rates, raw material cost e.t.c. One immediate result of these factors is the increasing inability to make quantified prediction with any confidence for more than a very limited period ahead of any decision point in time (Gerrard, 2000). This is especially true when there are wide and rapid changes in currency exchange rates, which necessitate very careful choice of the currency to be used in any estimate (Ulrich, 1984).

The purpose and timing of a capital estimate determines the type of estimate that is appropriate to the purpose. On the other hand, the information that is available determines the accuracy that is possible and the type of estimate that is feasible. It is costly and wasteful to produce a better estimate than is required but misleading to produce an estimate that purports to be better than can be justified by the data available (Turton *et al.*, 1989).

2.13 Types and classification of capital cost estimates

The classification of capital cost estimates is still not universally standardised despite efforts that have been made to overcome this problem (Institution of Chemical Engineers, 1998). The Cost Estimate Classification System maps the phases and stages of asset cost estimating together with a generic maturity and quality matrix that can be applied across a wide variety of industries. Table 2.4 (Perry and Chilton 1973), even though made a long time ago still shows well various types of estimates useful for capital project investments.

Table 2.4: Classification of cost estimate and usual basis

Types of estimate	Usual basis
Order of magnitude (ratio estimate)	Previous similar cost information
Study (factored estimate)	Knowledge of flowsheet and major equipment
Preliminary (initial budget, scope)	Sufficient data for budget preparation
Definitive (project control)	Detailed data but not complete drawings
Detailed (firm, contractor’s)	Complete drawings and specification

A very similar five-level cost estimate system based on the amount of project information available has been developed by the American Association of Cost Engineers (AACE) as follows:

- Order of magnitude,
- Study estimate (factored estimate),
- Preliminary estimate (generally for authorisation),
- Definitive estimate (more detailed information) and
- Detailed estimate (contractor’s estimate).

The international classification is illustrated in Table 2.5. Each of the five-level cost estimate classification is discussed in standard textbooks (Bauman, 1964; Peters and Timmerhaus, 1980; Ulrich, 1984; Garrett, 1989; Brennan, 1998; Turton *et al.*, 1998; Coulson and Richardson, 1999; Gerrard, 2000).

Table 2.5: Cost estimate classification: International classification (AACE International, 2005)

<table>
<tr><th>AACE Classification Standard</th><th>ANSI Standard Z94.0</th><th>AACE Pre-1972</th><th>Association of Cost Engineers (UK) ACostE</th><th>Norwegian Project Management Association (NPM)</th><th>American Society of Professional Estimators (ASPE)</th><th>ADCO EMPD Classification</th></tr>
<tr><td rowspan="3">Class 5</td><td rowspan="3">Order of Magnitude Estimate -30/+50</td><td rowspan="3">Order of Magnitude Estimate +40% to -20%</td><td rowspan="3">Order of Magnitude Estimate Class IV-30/+30</td><td>Concession Estimate</td><td rowspan="4">Level 1</td><td rowspan="3">Class 4 +40/-20% Screening / Feasibility</td></tr>
<tr><td>Exploration Estimate</td></tr>
<tr><td>Feasibility Estimate</td></tr>
<tr><td rowspan="2">Class 4</td><td rowspan="4">Budget Estimate -15/+30</td><td rowspan="2">Study Estimate +30% to -20%</td><td rowspan="2">Study Estimate Class III -20/+20</td><td rowspan="2">Authorization Estimate</td><td rowspan="3">Class 3 +30/-15% Conceptual / Prelim. Budget</td></tr>
<tr><td rowspan="2">Level 2</td></tr>
<tr><td rowspan="2">Class 3</td><td rowspan="2">Preliminary Estimate +25% to -15%</td><td rowspan="2">Budget Estimate Class II-10/+10</td><td rowspan="2">Master Control Estimate</td></tr>
<tr><td>Level 3</td><td>Class 2 +20/-10% Master Budget</td></tr>
<tr><td rowspan="2">Class 2</td><td rowspan="4">Definitive Estimate -5/+15</td><td rowspan="2">Definitive Estimate +15% to -7%</td><td rowspan="4">Definitive Estimate Class I-5/+5</td><td rowspan="4">Current Control Estimate</td><td>Level 4</td><td rowspan="4">Class 1 +10/-5% Definitive / Control Budget</td></tr>
<tr><td rowspan="2">Level 5</td></tr>
<tr><td rowspan="2">Class 1</td><td rowspan="2">Detailed Estimate +6% to -4%</td></tr>
<tr><td>Level 6</td></tr>
</table>

2.13.1 Exponential capacity-adjustment (scaling method) and basis

Exponential methods permit cost estimate to be made rapidly by extrapolating cost data from one scale to another. Thus the total cost of a plant can be derived from historical cost data (a variant capital cost estimation approach) by using:

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

The capital cost of a project does not always vary linearly with plant capacity. The cost of a specific item depends on size or scale and can usually be correlated by the approximate relationship (Bauman, 1964, Brennan, 1992; Brennan, 1998; Sinha, 1988; Remer and Mattos, 2003; Marouli and Maroullis, 2005):-

$$\frac{C_1}{C_2} = \left(\frac{Q_1}{Q_2} \right)^n \tag{2.10}$$

where,

C_1 = Cost of the item at size or scale Q_1

C_2 = Cost of the reference item at the size or scale Q_2

n = Scale exponent or cost capacity factor

k = A correlation constant (normal cost of the item at unit size or scale)

More generally, if one assumes constant prices for capital, this can be written as

$$C_k = \alpha_K Q^{\beta_K} \tag{2.11}$$

where C_K and Q denote the capital cost and capacity, respectively, and α_K and β_K are constants. The term β_K is usually called the scale coefficient (capacity factor) of capital. The dimensions of Q must be chosen to suit the type of item. The value of k and n depend upon the type of item and the characteristic dimension used, they can be derived from historical costs and using appropriate escalation factors known as cost index, the ratio of costs at a particular time to costs at a specified base year such as Chemical Engineering Plant Cost Index (CEPCI), Engineering New Record (ENR), the Nelson refinery cost index (NR) e.t.c. to update from previous installations. The use of the “correct” value for n is critical. This value can be calculated by plotting the logarithm of costs of similar projects versus the logarithm of project capacity. The slope of the best-fit line produced (as illustrated in Figure 2.12) represents the value of n for that type of plant, and costs for the plants of other capacities can be interpolated or, with caution, extrapolated. However, this does not always happen, and curves might be obtained which show the presence of two or more cost capacity factors, each covering a certain range, and providing better results than overall average factor (Montaner, 1995).

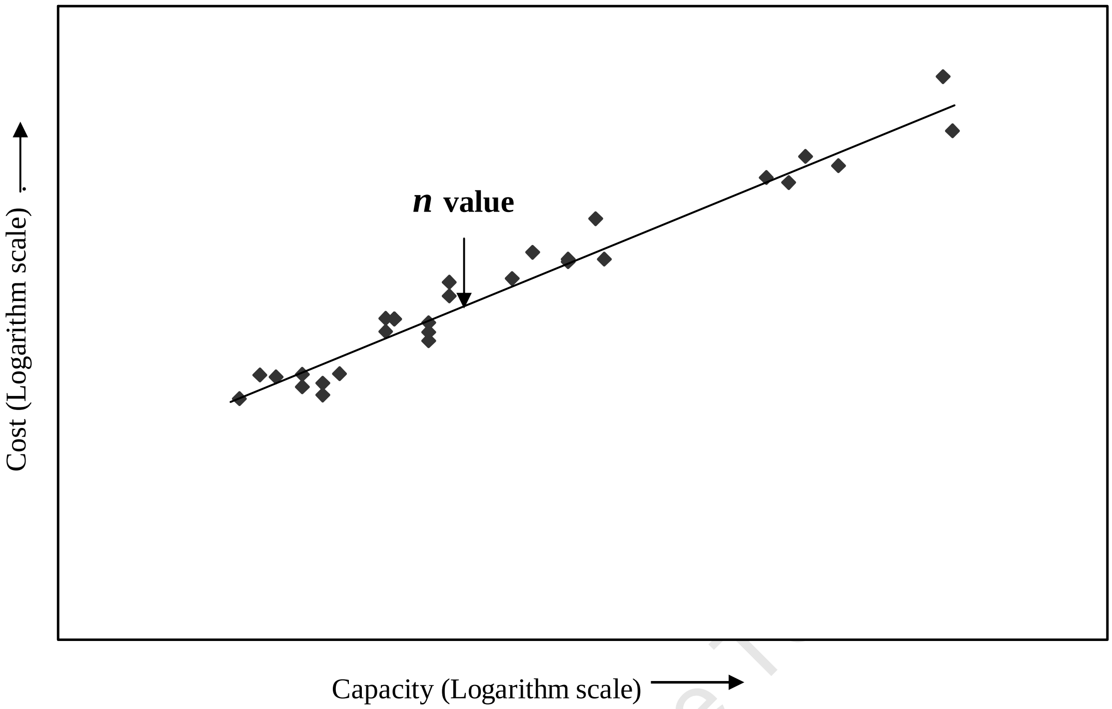

Figure 2.12: Relationship between plant capacity and capital cost

The *n* value of 0.6 is typically used for chemical plants, and for this reason, the relationship is often dubbed the '6/10 rule'. This method was first applied to equipment cost estimates by R. Williams in 1947 and then later to plant costs by C.H. Chilton in 1950 (Remer and Chai, 1990). The application of "six-tenths" rule is an oversimplification with the actual values of cost capacity varying from less than 0.2 to greater than 1.0 (Remer and Chai, 1990; Brennan, 1992; Montaner *et al*,1995) because of this 0.6 should only be used in the absence of other information. However, n value of $n = 0.85$ has been reported to be more appropriate for processes involving the handling of solids plant (Tribe and Alpine, 1968; Garret, 1998). Values of *n* are based on a large volume of accumulated empirical experience. Some discrepancies in the published cost capacity factors *n* are apparent due to variation in definition, scope, and size. Technology has also advanced over time, making it cheaper to produce larger machinery now than in years past. In addition, new regulations dictate expenditures for environmental control and safety not included in earlier equipment. For example, in a study by Remer and Chai, the average n value for 200 chemical processes was found to be 0.7 (Guthrie, 1970).

The existence of economies of scale in capital input was tested statistically by Moore (1959), with data obtained from records of plants built during World War II and also during the mobilization period beginning in 1950. Using data limited to completely new plants and large "balanced additions," estimation was carried out for five industries: alumina, aluminum reduction, aluminum rolling and drawing, cement, and oxygen. In almost all cases, the estimated value of β_k was less than unity although t-tests could not reject the hypothesis of constant returns to scale, that is $\beta_k = 1$, at the 95 percent confidence level.

Komiya (1962) studied economies of scale and technical progress in the generation of steam-electric power in the United States with two alternative specifications of production technology: the Cobb-Douglas substitution model and the "limitational model." The latter was represented by a set of three input-output relationships termed capital, labor, and fuel input functions. The input functions were given as

$$C_i = \alpha_i \overline{Q}^{\beta i} N^{\mu i} \qquad (2.12)$$

where $\overline{Q}$ denotes the average size of the generating unit, *N* the number of generating units in the same plant, and at μ_i a constant expected to be small, and *i* = *K*, *L*. and *E*. It is assumed that the scale effects apply at the generating unit level. Komiya found the substitution model to be unsatisfactory. The limitational model gave a better fit, with the values of β_k and β_E between 0.80 and 0.85, and β_L between 0.50 and 0.60.

In another study, Haldi and Whitcomb (1967) analysed cost data for 103 complete chemical plants of different capacity. He estimated not only β_k but also β_L, β_E, and β_R, the scale coefficient of labor, energy, and raw material inputs, respectively, using engineering estimates of costs (as opposed to actual operating costs). The same functional form for each input,

$$C_i = \alpha_i Q^{\beta i} \qquad (2.13)$$

where X_i denotes the *i*th factor cost, *Q* capacity, α_i a constant, and β_i (also a constant) the scale coefficient of the *i*th factor, for *i* = *K* (capital), *L* (labor), *E* (energy), and *R* (raw materials), was used. The resulting distribution of the β_k's for cross-industry plant investments costs was centered between 0.70 and 0.80. While more than 70 percent of plants had a value of β_L smaller than 0.40, β_E and β_R were almost equal to unity.

Amigun *et al.,* (2007), proposed a cost capacity factor of 1.2 for small and medium scale biogas installations in Africa. Also, Gallagher *et al.,* (2005) suggested that capital costs typically increase less than proportionately with plant capacity in the dry mill ethanol industry in the USA because the estimated power factor is 0.836. In general, exponents depend on the phase that is being processed and *n* increases along the sequence gas phase, liquid phase, solid phase. As with plant costs, there is a tendency for the exponent *n* to increase with larger equipment capacities until some practical limit to equipment capacity is reached. There may also be a lower capacity limit below which it is not practical or economic to purchase or construct (Brennan, 1992).

Cost correlations are published for various items of equipment, e.t.c but preferably they should be built-up within each company from data for items in regular use. Historical cost must be updated to the date of the estimate using appropriate Cost Indices e.g. due to inflation or deflation (in rare instance) e.t.c. However, costs that are more than five years old should be escalated with extreme caution and as a last resort. Because the exponential method is an approximation, it can give significant error if it is used to estimate the cost of a single item. This should be of little importance if the final cost is the sum of many single estimates because in this case the error tends to cancel out.

When a project is based on modifying a previous design, a lot of data will be available from earlier projects, including cost information. If the project involves an identical process, but different scale, an initial cost estimate can be made on the basis that the total plant cost is related exponentially to plant capacity. A better estimate is possible if the total plant cost can be broken down into broad categories and 'Exponential' method applied to each category, separately, using different exponents for each. The total plant is then the sum of the cost of all the separate categories.

Very early in process design, it is possible to specify the approximate size, and therefore the approximate purchase price, of all the main items of equipment, i.e. the Main Plant Items (MPI). The total cost of purchasing the main items can be converted to a Total Erected Cost if it is multiplied by an overall Installation factor that is known to be typical of the types of process (Gerrard, 2000). A better estimate is possible if the purchased cost of each item is converted, separately, to an Erected Cost using an Installation factor that is known to be typical of that type of item. Total Erected Cost is then the sum of all the separate erected costs. This ‘factorial’ method can be extended by dividing the Installation factor for each item of equipment into sub-factors that represent the different engineering activities that go into the erection of each item (Garret, 1998).

2.13.2 Factorial methods of capital cost estimation

Factorial methods can be used to produce study estimates and preliminary estimates discussed earlier. This estimation method is far less expensive than is incurred for definitive and detailed estimates. These generative capital cost methods are generally considered to be more accurate than pre-flowsheet estimates (Sinha, 1988), due to efforts spent in the study and analysis of the process prior to preparing the equipment list. They are based on a historical knowledge of the relative cost of the various purchases and activities that are necessary to build a plant. All factorial methods start by listing and rating the Main Plant Items. The installed cost of an entire process plant is often estimated in preliminary project work as a multiplier or factor of the total purchased cost or installed cost of all the equipment items (Brennan and Golonka, 2002). The factorial (cost ratio) method involves the following stages:

- The drawing of a plant flowsheet involving all major items of equipment
- The calculation of equipment sizes using knowledge of the estimated plant mass balance
- The costing of individual equipment items and
- The factoring of equipment costs to calculate capital cost.

It is obvious that there must be a clear definition of what constitutes a main Plant Item and what state it is assumed to be purchased, e.g., complete or incomplete, delivered or awaiting transportation. Main Plant Items (MPI) is usually defined as all the vessels, columns, other fabricated equipment, heat exchangers and machinery that are needed for the project. They are usually evaluated as if delivered to the site and all the other costs that are necessary to convert them to a functional plant must be accounted for by the installation factors.

For process plant, fixed capital investment can be divided into outside battery limit or off sites (OBL) or inside battery limits (IBL) (Brennan, 1998). “Battery limits” comprises one or more geographic boundaries, imaginary or real, enclosing a plant or unit being engineered and/or erected, established for the purpose of providing a means of specifically identifying certain portions of the plant, related groups of equipment, or associated facilities. It generally refers to the processing area (inside battery limits (IBL)) and includes all the process equipment, and excludes such other facilities as storage, utilities, administration buildings, or auxiliary facilities (OBL). It is important that the scope included within a battery limit should be well-defined for better understanding. The difference between IBL and OBL cost areas is illustrated in Figure 2.13.

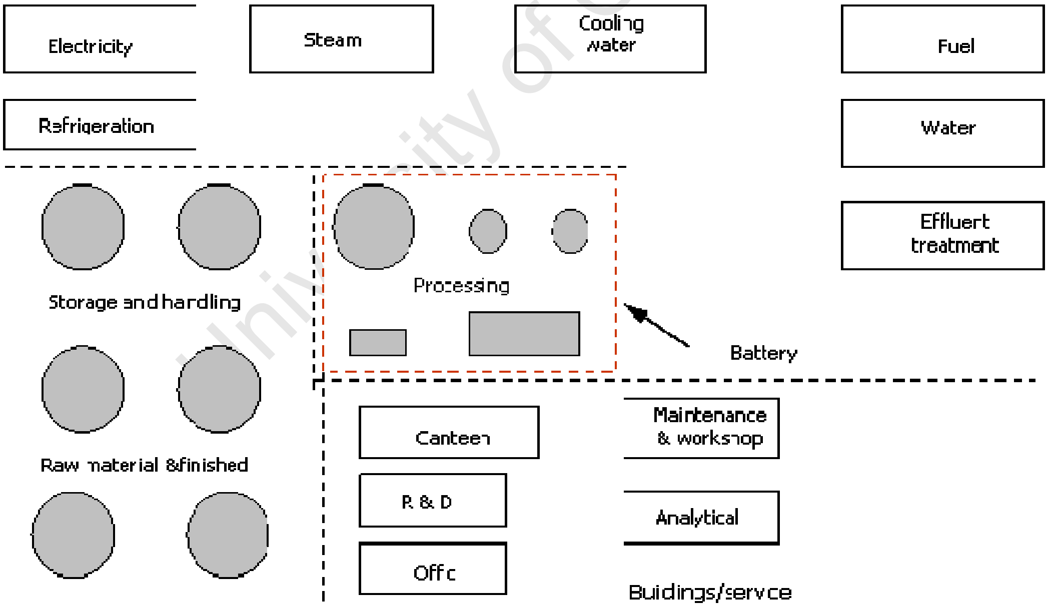

Figure 2.13: Inside and outside battery limits investment (Brennan, 1998)

According to Brennan, design and cost of storage depend on the properties of materials stored. Also consumption of raw materials and utilities depend on the process technology and capacity of the IBL plant. Storage and utilities costs are far more dependent on project operation method, particularly in relation to transport of raw materials and product and its integration with other production facilities. For instance, if the raw materials is been supplied by an adjacent plant, this can be piped with minimal storage. On the other hand, raw material been imported will result to substantial storage requirements depending on the transportation frequency. Surplus steam may in some cases (such as ethanol plant annexed to a sugar mill) be available from an adjoining plant. If the utilities generation and building facilities are shared with other manufacturing plants, scale economies should result. Hence, the decision to generate or purchase a utility has evident effect on utilities investment (Brennan, 1998).

For a given IBL capital investment reflecting a particular plant capacity and process technology, the magnitude of the related OBL capital can vary considerably depending on how the project is implemented and sited. OBL capital can usually range between 5 and 100% of IBL capital depending on the process technology, site location and project implementation (Brennan, 1998).

2.13.2.1 Total plant cost using an overall installation factor

Estimating the fixed capital investment of a plant can vary from a quick estimate to a very carefully prepared, detailed calculation using a complete flow chart, with specifications, depending on how much is known about the product and how much time and effort is available to do the estimate. The total fixed capital cost of a process plant may be estimated as the sum of the fully installed costs for each item of equipment, based on estimate of purchased equipment cost and the additional cost of any associated plant by using appropriate factor (factor methods) (Brennan and Golonka, 2002; Marouli and Maroulis, 2005). These factors often known as 'Lang factor '- f_L, named after their originator (Sinnott, 1996). This approach is attractive to process engineers, since equipment specification is a major function of process engineering and represents an important interface between process design and more detailed plant design.

The ratio of the complete plant cost (C_{fx}) to the sum of the purchased costs of all equipment termed Lang factor can be represented by the equation:

$$C_{fx} = f_L (\sum \text{MPI}) \tag{2.14}$$

Where f_L *is* called the Lang factor and MPI is the main plant equipment costs. The Lang factor depends on the type of industry, the average cost of equipment items used and hence on plant capacity and location (Lang, 1948). For chemical processes, the following values are often used (Lang, 1948; Sinnott, 1996; Brennan and Golonka, 2002; Marouli and Maroulis, 2005).

3.10 for predominantly solids processing plants
f_L = 4.70 for predominantly fluids processing plant
3.60 for a mixed fluid-solids processing plants

This is a common rule of thumb' and a useful yardstick for chemical engineers. The values of f_L are given by a few authors, but most of them are from American or European sources, and are fairly old (Jebson and Fincham, 1994). They have been applied to either individual items of equipment or to whole plants.

Lang factors vary widely. While a Lang factor in the range of 3 to 5 was proposed by Sinnott (1996), an f_L of about 2-10 depending on the process, scale, material of construction, location and degree of innovation (sophistication/automation level) of the plant were reported by Patterson, (1998) and Brennan, (2002). Jebson (2002), although based on a very small number of projects indicated that application of Lang factor based on cost data from American and European sources will lead to inconsistency when applied to New Zealand plants. Lang factors of 1.6 (Marouli and Saravacos, 2003), and 1.8 (Marouli and Maroulis, 2005) have been determined for food industries. This has a lower value because of the higher equipment costs. In view of their large influence on the total estimated cost, it is important that the Lang factor be as accurate as possible. The Lang factors above relate to the overall plant. For improved accuracy, categories of equipment can be multiplied by their own factor, that is, by applying individual installation factors to individual MPI's. The erected cost of one main Plant Item (c) is given below:-

$$C_{fx} = MPI \times \left[(1 + \sum f_{dir}) + (\sum f_{ind}) \right] \tag{2.15}$$

where:

C_{fx} = Fixed investment for the complete system

MPI = Costs of main equipment once installed

f_{dir} = Multiplication factors for estimation of direct costs, such as piping, instrumentation, buildings, e.t.c

f_{ind} = Multiplication factors for estimating indirect costs, such as engineering fees, contractors, e. t. c.

Fixed capital is usually divided into the following components; as represented in Table 2.6 Other categories divisions of capital fixed costs are considered in the literature (Kharbanda and Stallworthy, 1988; Peter and Timmerhaus, 1991; Clark, 1997; Sinnott, 1999; Brennam, 2002). A sample of the MS Excel model employed for the determination of the Lang factors in this dissertation is illustrated in Table A2.1 (appendix).

Table 2.6: Components of fixed capital investments

Direct Costs	Indirect Cost
1. Pre-project study and analysis expenses	13. Engineering and Supervision
2. Main equipment	14. Construction expenses
3. Equipment installation	15. Contractor fees
4. Instrumentation and control	16. Contingencies
5. Piping (installed)	
6. Electrical installation	
7. Civil	
8. Construction (including services)	
9. Auxiliary services	
10. Insulation/fireproofing	
11. Land and land improvement	
12. Starting-up costs	
13. Interest during construction	
14. Non-typical (specialty) cost	

2.14 Operating cost estimates

Of equal importance to the capital cost estimate in an economic evaluation is the operating cost or recurrent cost or manufacturing cost. It predicts the expense of producing the desired product, and thus, together with the capital cost and sale realization, allows the profitability and potential attractiveness of an operation to be evaluated (Garret, 1989). It is the cost associated with the day-to-day operation of a plant, (Brennan, 1998; Coulson and Richardson, 1999). In other words, operating cost encompass all those costs associated with the production, distribution and marketing of products, together with the ongoing cost of developing or purchasing the necessary technology. Operating costs also include all the management and business costs extended over the operating life of a plant, but are normally evaluated for a stipulated period, which is normally taken for convenience sake as one year. Operating costs are generally broken down into two broad categories: variable cost or controllable cost, and fixed cost (see Table 2.7). The plant manager has some ability to control the former items; the plant itself determines the later. Operating (manufacturing) cost encompasses a list of identifiable costs, which may be broadly classified as:

- Raw materials
- Utilities
- Personnel (frequently referred to as manning);
- Capital – related cost

These costs may be conveniently grouped in the following simplified model for production costs. The model is useful as a means for making a quick, approximate estimate of manufacturing cost, in identifying the dominant contribution to cost and to help understanding of some of the way in which operating costs are classified, (Brennan, 1992):

$$C = \sum Rr + \sum Eg + (Mm)/Qu + (kI)/Qu \qquad (2.16)$$

where:

C = production cost,
R = raw material consumption
r = unit cost of raw material
g = unit cost of utility

E = utility consumption
M/QU = number of employees per weight of product
I/QU = fixed capital per weight of product
k = factor to account for number of costs dependent on fixed capital
QU = annual production
m = average cost per employee
U = capacity utilization
Q = production capacity

Table 2.7: Partial checklist for manufacturing costs

Variable costs (controllable)	Fixed Costs
Raw materials, additives, catalysts	Depreciation
Utilities: fuel, electricity, water, steam, air	Taxes, licensing fee, insurance
Labour: operating, supervision, technical Services, engineering, safety, environmental, laboratory, clerical, legal, security, e.t.c.	General and administrative expenses corporate overhead
Indirect labour charges; fringe benefit such as: health insurance, retirement, social Security vacation, sick leave, overtime, Payroll taxes, bonuses, e.t.c.	Patent and royalties
Maintenance: material, services, contract maintenance	Interest
General: office, plant, safety, laboratory supplies, books, Travel, meeting, environmental, miscellaneous	
Transportation, freight	
Distribution, packaging, storage and sale expense	

It is constructive to distinguish between performance parameters *R, E, M/QU* as distinct from unit parameters r, g, m. Performance parameters depends on the technology adopted and on plant management, while unit cost parameters depend largely on influences outside the control of the company operating the plant. In describing changes in cost areas, it is important to analyse whether the change has arisen because of a change in performance or in unit cost, or in both. Fixed capital investment per unit of capacity is a function both of performance (technology and management) and unit costs (labour and materials). The fixed capital-dependent costs likewise functions of both performance and unit costs.

Production costs are scale (or capacity) dependent, because of the dependence of both fixed and capital and some personnel requirements on plant capacity. Thus while R and E are generally independent of capacity, *M/QU* and *I/QU* generally decreases with increasing capacity, thus providing economies of scale. The degree of dependence of total production cost on capacity depends both on these relationship and also on how large the personnel and fixed capital dependent costs are in relation to raw material and utility costs. Since utility cost is energy intensive, it may often be convenient to substitute energy consumption (and unit costs) for utilities consumption in the model. Performance parameters, *R, E, M/QU* depend on the technology adopted and on plant management, while unit cost parameters r, g, and m depend largely on influences outside the control of the company operating the plant.

Productions (and all operating costs) are also classified according to their dependence on production rate. For a plant having a given design (or rated) production capacity, those costs expressed in dollars per year which vary with change in production rate are described as variable, while those which are unaltered with change in production rate are described as fixed. In this context, the simplified model of equation (2.16) is expressed in terms of costs per time interval (or dollar per year) as:

$$C(QU) = \sum Rr(QU) + \sum Eg(QU) + Mm + KI \tag{2.17}$$

Production = Raw material + Utilities + Personnel + Capital related cost

For a continuous process plant, raw materials and energy costs are classified as variable, and personnel and capital related costs as fixed.

2.14.1 Factorial method of operating cost estimation

As with capital costs estimating, detailed breakdowns and item-by-item accurate manufacturing costing are lengthy and expensive procedures, so for most preliminary estimates, a more abbreviated method is required. Often this involves the use of estimating factors as represented in Table 2.8 (Garret, 1989). In this table, the items have been listed for estimating convenience and not for the more logical or useful sequence desired by future managers of the potential operation. The cost components are shown in four generalised groupings. The first represents items that are totally specific to the process under study, and must be estimated directly energy and material balance, operating labour estimates, e.t.c. Each requires individual, detailed estimates; the remaining items may be either factored or estimated in detail as desired.

Table 2.8: Manufacturing cost estimating factors

1		Raw materials	Itemise
2		Utilities	Itemise
3		Operating labour	Itemise
4		Interest (on loans, if any)	Itemise
5		Labour related costs	
	A	Payroll overhead	22-45 % of labour
	B	Supervisory, miscellaneous labour	10-30% of labour
	C	Laboratory charges	10-20% of labour
	D	Total	42-95% of labour
		(Typical total)	60% of labour
6		Capital related cost	
	A	Maintenance	2-10% of plant cost
	B	Operating supplies	0.5 -3% of plant cost
	C	Environmental	0.5 -5% of plant cost
	D	Depreciation	5-10% of plant cost
	E	Local taxes, insurance	3-5% of plant cost
	F	Plant overhead cost	1-5% of plant cost
	G	Total	12-38% of plant cost
		(Typical cost)	26% of plant cost
7		Sales related cost	0-5% of sales
	A	Patents and royalties	0-7% of sales
	B	Packaging, storage	2-10% of sales
	C	Administrative costs	2-10% of sales
	D	Distribution and sales	0.5-4% of sales
	E	R & D	4.5-37% of sales
	F	Total	20% of sales
		(Typical cost)	

The second category is labour related costs, in which operating labour only is used to estimate other labour and manufacturing costs that depend directly or indirectly (sometimes only vaguely) upon it . As with each of the other cost categories, many additional items (other labour requirements, e.t.c) could be added, but these are the more important ones. The typical cost is also shown for each group to provide guidance that each individual estimate is similar to the norm, or if not, that there is a good reason for the difference.

The next grouping of cost (capital related cost) are linked to the total plant capital, generally based upon all of the plant costs, including start-up, auxiliary, or off-site facilities, but not working capital. Many of the items in this category are directly tied to the plant cost, such as depreciation, taxes, and insurance, while others are only indirectly related. The final category is sales related cost, where some items are directly related to sales (royalties, packaging, e.t.c.) and others such as overhead items are only directly related.

2.15 Summary and concluding remarks

This chapter has aimed to discuss process engineering cost estimation theory in the context of the development of an African biofuels industry, and to review prior related work as part of this discussion. The introductory sections have established the relationship between energy availability and poverty on the continent, as well as the regional diversity in terms of uneven energy resources distribution. From this has followed the establishment of the need for the implementation of biofuels technology and their commercialisation in Africa. A simple rule for bioenergy conversion plant size optimisation which underscores ways to reduce the manufacturing costs by finding an optimum economic plant capacity was presented. The lack of a good understanding of the economics of the biofuel process industry as a hindrance to these goals was then established. Economic considerations which are necessary when preparing estimates of capital investment costs or total product cost for a biofuel project have been outlined. Methods for obtaining pre-design cost estimates have purposely been emphasized because these are extremely important for determining the feasibility of a proposed investment and to compare alternative designs.

Appendix A2

Table A2.1: Simplified model for Lang factor analysis of African biogas plant

Lang factor (f_L) model

	Purchased Equipment Items	Quantity	Cost (USD)	Lang Factor	% Direct cost	% Total cost
1				0.0	0%	0%
2				0.0	0%	0%
3				0.0	0%	0%
4	material costsfor Masonry work			0.0	0%	0%
5				0.0	0%	0%
6				0.0	0%	0%
7				0.0	0%	0%
8				0.0	0%	0%
9				0.0	0%	0%
10				0.0	0%	0%
11				0.0	0%	0%
12				0.0	0%	0%
13				0.0	0%	0%
	Total Major equipment		$ -	0.0	0%	0%
14	Equipmment Installation			0.00	0%	0%
15	Piping			0.00	0%	0%
16	Instrumentation and control			0.00	0%	0%
17	Electrical			0.00	0%	0%
18	Civils			0.00	0%	0%
19	Structural steels			0.00	0%	0%
20	Structures & Buildings			0.00	0%	0%
21	Insulation/fireproofing			0.00	0%	0%
22	Painting			0.00	0%	0%
23	Yard improvement			0.00	0%	0%
24	Land (if purchased is required)			0.00	0%	0%
25	Non-typical cost			0.00	0%	0%
26	Legislation cost			0.00	0%	0%
	Total field cost		$ -	0.0	0%	0%
	Total direct cost		$ -	0.0	0%	0%
27	Engineering & Supervision			0.0	0%	0%
28	Construction Expenses			0.00	0%	0%
	Total Indirect cost		$ -	0.00	0%	0%
	Total direct & indirect costs		$ -	0.00	0%	0%
29	Contractor's fee			0.00		0%
30	Contigency			0.00		0%
	TOTAL ESTIMATED CAPITAL COST		$ -	0.00		0%

Lang factor model	**PPC/PEC**	**Process Plant Cost/purchased Equipment Cost**	▨

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3

Approach to the Development of Cost Estimation Relationships and Data Acquisition

3.1 Introduction

Many companies implement cost estimating relationships (CERs) to streamline the costs and cycle time associated with proposal preparation, evaluation and negotiation processes. In most cases, CERs are used to price low-cost items or services that take significant amount of time and resources to prepare using the traditional techniques. Proper CER development and application depends on understanding certain statistical and mathematical techniques. The first objective of this chapter provides general guidance employed in developing CERs focusing on implementation, maintenance, evaluation techniques and framework for analyzing the quality or validity of a statistical model. In addition, this chapter introduces the approach used for selection of cases for analysis and demonstration, presents the method used in data gathering and discusses the difficulties encountered during the collection of primary data from a range of African countries.

3.2 Developing cost estimation relationships

The widespread use of Cost Estimation Relationships (CERs) or Parametric Estimation Methods (PEMs) in the form of simple cost factors, equations, curves, and rules of thumb attest to their value and to the variety of situations in which they can be helpful. CERs are mathematical expressions of varying degrees of complexity expressing cost as a function of one or more driving variables (SCEA, 2007). The relationship may utilise cost to cost variables (for example, using manufacturing costs to estimate quality assurance costs) or cost to non-cost, in which case, the characteristics of an item is used to predict the cost. An example of a cost to non-cost CER may be to estimate the capital investments by using the capacity or size of an item. Parametric estimating methods (PEMs) are defined as estimating methods based on theoretical, known or proven relationships between items characteristics and the associated item cost. For cost estimation to be valid, they must be developed using sound logical concepts, typically based on the notion that one of the variables in the relationship (the independent variable) causes or affects the behaviour in another variable (the dependent variable). Once valid CERs have been developed, their quality is determined. Figure 3.1 pictorially depicts a parametric estimating system (ISPA, 2003) while the CER development process is illustrated in Figure3.2.

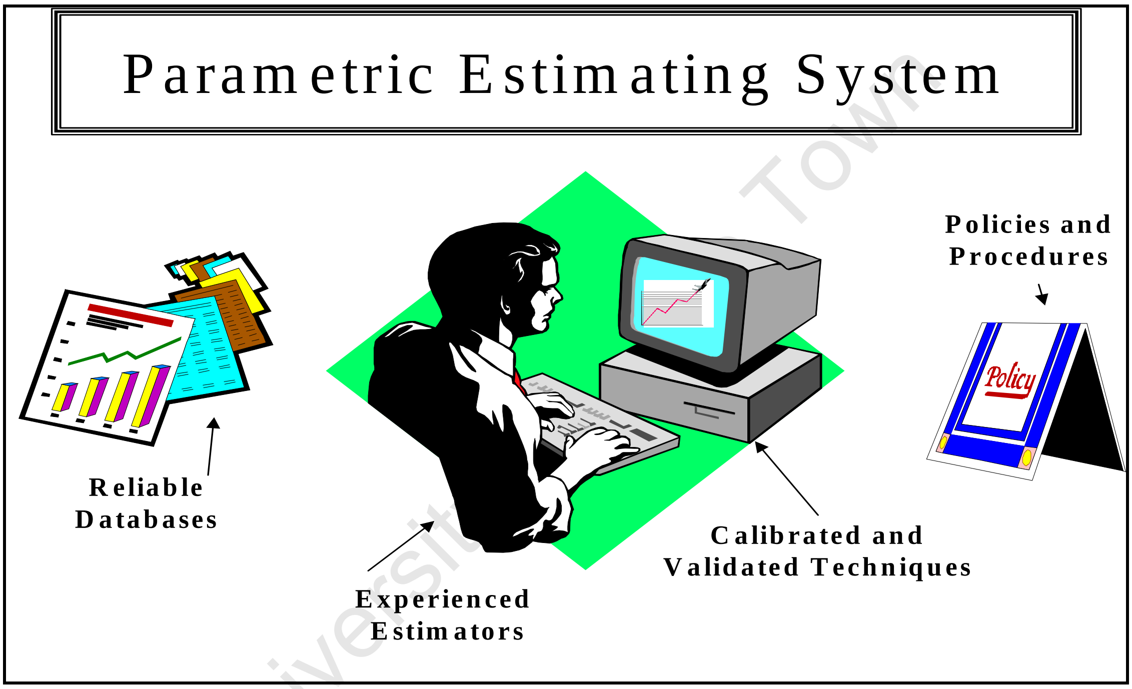

Figure 3.1: Pictorial representation of parametric estimating system elements (ISPA, 2003)

The beginning of a CER development process is the identification of the need to develop or improve the estimating process through the use of CERs. The outcome of this step is a scheme describing the opportunity, the data needs, the analysis tools and the CER acceptance criteria.

Parametric estimating requires that statistical analysis be performed on data points to correlate the cost drivers and other system parameters (US.DOE, 2003). Hence, the ‘goodness’ of a CER depends on the soundness of the database from which the CER is developed. Regardless of the degree of complexity, developing a CER requires a concerted effort to assemble and refine (adjust) the data that constitute the empirical basis so that comparable relationship can be developed.

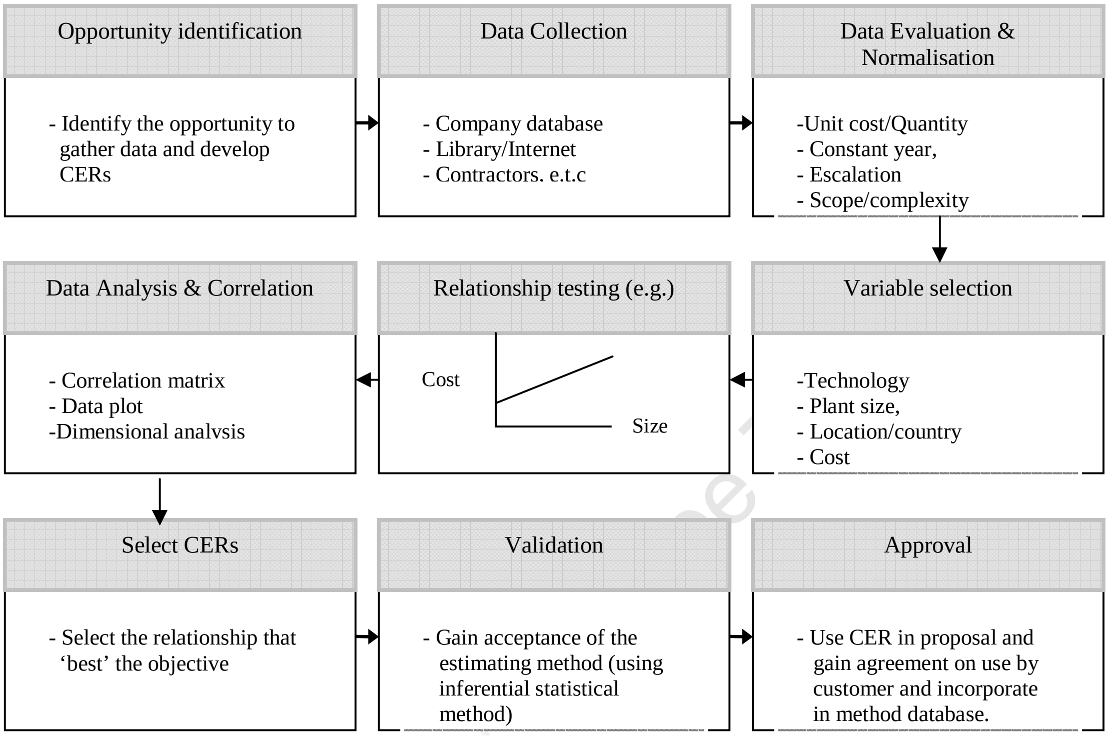

Figure 3.2: CER development process (modified from ISPA, 2003)

Assembling a credible data base is the most time consuming activity. This makes the task of CER developing to be difficult and number of valid CERs to be less than one might expect. To obtain data necessary to develop CERs, it is important to identify common or similar procedures among projects. While there are many reasons for lack of valid CERs, the most prominent is the lack of appropriate database. It is also important to note that the cost of individual projects is affected by site specific conditions.

3.2.1 Data collection

The specification of an estimating methodology is an important step in the estimating process. The basic estimating methodologies are all data-driven. Credible and timely data inputs are required to use any of these methodologies. If data required for a specific approach is not available, then that estimating methodology cannot be used. Because of this, the estimator must identify the best sources for the method to be used.

Parametric techniques require the collection of historical cost data and the associated non-cost information and factors that describe and strongly influence those costs. Data should be collected and maintained in a manner that provides a complete audit trail with expenditure dates so that costs can be adjusted for inflation. Non-recurring and recurring costs should be separately identified. While there are many formats for collecting data, this dissertation employs the use of Work Breakdown Structure (WBS), a results-oriented family tree that captures all the work of a project in an organized way (provides for the uniform definition and collection of cost and certain technical information). The data used for the development of the CER in this dissertation is sourced from both primary and secondary sources. Table 3.1 below explains the nine basic sources of data and their classification (ISPA, 2003; GAO, 2007). Primary data are obtained from the original source, can usually be traced to an audited document, they are considered the best in quality and the most reliable. Secondary data are derived rather than obtained from a primary data. Since they are derived, and thus changed from the original data, their overall quality is lower.

3.2.2 Data normalisation

Cost data must be adjusted to eliminate any bias or “unevenness” which other factors may cause in it. This is called normalisation and is intended to make the data set homogeneous, or consistent, or comparable and in most cases the data collected are neither (Roy and Kerr, 2003). The data set were questioned to ensure that it is free from the effects of:

- the changing value of the currency over time
- cost improvement as the organization improves its efficiency
- various production quantities and rates during the period from which the data were collected

Non-recurring and recurring costs are also segregated as part of the normalization process.

The primary activities followed in data normalisation in this dissertation are briefly explained:

Table 3.1: Data Sources and Classification

Data Sources	Classification	
	Primary source	Secondary source
Basic Accounting Records	x	
Experimental Data	x	
Data collection input forms	x	
Cost Reports	x	x
Historical Databases	x	x
Interviews	x	x
Program briefs	x	x
Subject matter experts	x	x
Technical databases	x	x
Other Information Systems (internet)	x	x
Contract or contractor estimates		x
Cost Proposals		x
Cost studies		x

3.2.2.1 Adjustment for consistent scope

Adjustments are necessary to correct for differences in program or product scope between the historical data and the estimate being made. For example, for the order of magnitude type of cost estimation, the fixed capital investment cost (which is paid during the installation period), for each of the biofuel technologies (biogas, biodiesel and biodiesel) is used as the basis. The influence or presence of factors that might cause problems with redundancy, inaccuracy, consistency, and concurrency of the database should be removed. For example, suppose two out of the ten plants investigated for order of magnitude cost estimation were found to experience delay during construction, to normalise the data, the additional effect of the delay must be deleted from the two plants to create a data set with constistent program scope.

3.2.2.2 Inflation/Escalation

Data were collected from several projects which did not all occur at the same time. Thus the cost data must be normalised to the same base year prior to developing the CER. Inflation is defined as a rise in the general level of prices, without a rise in output or productivity. There are no fixed ways to establish universal inflation indices (past, present, or future) that fit all possible situations. A cost index is a dimensionless number that represents the ratio of a cost at the present to some cost back in time. Inflation indices generally include internal and external information and factors. Examples of external information are: the Consumer Price Index (CPI), Producer Price Index (PPI), and other forecasts of inflation from various econometric models. Cost indexes, most of which are web-based but require a subscription fee to access detailed values are appropriate to the scope of the technology is used. Some of the widely used cost indexes are the Chemical Engineering Plant Cost Index (CEPCI), Engineering News Record (ENR), and the Marshall and Swift Equipment Cost Index (M&S).

3.2.2.3 Cost-quantity and currency adjustment

Costs are usually a function of quantity; they also are not represented in the same currency value due to difference in the plant location. The data should be first converted from the local currency to usually US$ at the rate applicable in the year of construction. However, it is to be noted that the data are not corrected for regional difference as this will be one of the primary characteristics of the developed CER.

3.3 Statistical methods

Once data have been gathered in support of a hypothesis formulated for a specific cost relationship, statistical analysis of the CER is carried out. The form of the relationship can take several forms, both linear and non-linear. The Least Squares Best Fit (LSBF) approach can be taken in all cases, and will be discussed in this dissertation. LSBF techniques are contained in spreadsheet and statistical computer packages such as Excel, SPSS, and Statistica. The following sections review LSBF equations, and discuss the regression analysis process used for model development.

3.3.1 Regression Analysis

Regression Analysis is a statistical forecasting model, that is concerned with describing and evaluating the relationship between a given variable – the response (usually called the dependent variable, e.g. investment cost) and one or more other variables-predictor (usually called the independent variables, e.g. plant capacity). The mathematical model of their relationship is the regression equation. The dependent variable is modelled as a random variable because of uncertainty as to its value, given values of the independent variables. A regression equation contains estimates of one or more unknown regression parameters ("constants"), which quantitatively link the dependent and independent variables. Uses of regression include prediction (including forecasting of time series), modelling of causal relationships, and testing scientific hypotheses about relationships between variables.

The relationship between variables may be linear or non-linear. Linear relationship means that the functional relationship can be described graphically (on a common X-Y coordinate system) by a straight line and mathematically by the common form:

$$y = b_0 + b_1 x \tag{3.1}$$

Where y = the calculated value of y (the dependent variable) which depends on the variation in

x = the predictor (or dependent or explanatory) variable

b_0 is the intercept, b_1 is the slope and they are unknown parameters to be estimated from the data.

For a bivariate regression equation a situation exists in which there is one response or dependent variable, and one predictor or independent variable, and the relationship between the two is represented by a straight line. The equation consists of two distinct parts, the functional part and the random part. The equation for a bivariate regression population is:

$$Y_i = b_0 + b_1 X_i + \varepsilon_i \tag{3.2}$$

Where $b_0 + b_1 X_i$ is the functional part (a straight line) and ε_i is the random part or the error (due to human limitation and the limitations associated with real world events) part which picks up the unpredictable part of the response variable. The error term is usually taken to be normally distributed. b_0 and b_1 are estimates of parameters of the population while $y_i{}' s$ and $x_i{}' s$ stand for deviation of X_i and Y_i about their respective means, i.e.

$$x_i = X_i - \overline{X} \tag{3.3}$$

$$y_i = Y_i - \overline{Y} \tag{3.4}$$

There are a number of other quantities that are important in the analysis, including:

- the 'fitted' or predicted values of the response variable Y_i (called "Y-hat")

$$\hat{Y} = b_0 + b_1 X_1, \tag{3.5}$$

$$= Y + b_1 (X_i - \overline{X}) \tag{3.6}$$

- the residuals or prediction errors

$$e_i = Y_i - \hat{Y}_i \tag{3.7}$$

- the sum of squared deviation and their cross products

$$S_X = \sum_{i=1}^{n} \left(X_i - \overline{X}\right)^2$$

$$= \sum_{i=1}^{n} x_i{}^2 \tag{3.8}$$

$$S_Y = \sum_{i=1}^{n} \left(Y_i - \overline{Y}\right)^2$$

$$= \sum_{i=1}^{n} y_i{}^2 \text{, and} \tag{3.9}$$

$$S_{XY} = \sum_{i=1}^{n} \left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)$$

$$= \sum_{i=1}^{n} x_i y_i \tag{3.10}$$

- and the residual sum of squares

$$SSE = \sum_{i=1}^{n} e_i{}^2 \tag{3.11}$$

3.3.1.1Fitting the regression equation (i.e. estimating parameters)

The regression equation is "fitted" by choosing the values of b_0 and b_1 in such a way that the sum of squares of the prediction errors are minimized, i.e.

$$Min\, D = \sum_{i=1}^{n} e_i^{\,2} \tag{3.12}$$

$$= \sum_{i=1}^{n} \left(Y_i - b_0 - b_1 X_i\right)^2 \tag{3.13}$$

The specific values of b_0 and b_1 that minimize *D* could be found iteratively, or by trial and error, but it is known that the following "ordinary least-squares" (OLS) estimates of b_0 and b_1 do in fact minimize *D*:

$$b_1 = \frac{S_{XY}}{S_X} \tag{3.14}$$

$$= \frac{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)\left(Y_i - \bar{Y}\right)}{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)_i^2} = \frac{\sum_{i-1}^{n} x_i y_i}{\sum_{i=1}^{n} x_i^{\,2}}, \text{ and} \tag{3.15}$$

$$b_0 = \bar{Y} - b\bar{X} \tag{3.16}$$

3.3.1.2Goodness-of-fit statistics

The 'goodness of fit' of the regression equation, or a measure of the strength of the relationship between Y and X can be described in several ways. Analysis of variance of the dependent variable Y can be decomposed into two components.

$$Total\ SS = \mathrm{Re}\, gr\ SS + Error\ SS$$

$$\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)^2 = \sum_{i=1}^{n}\left(\hat{Y}_i - \bar{Y}\right)^2 + \sum_{i-1}^{n}\left(Y_i - \hat{Y}_i\right)^2 \tag{3.17}$$

Where $Total\,SS$ is the “total sum of squares” (of deviations of individual dependent variable values of the mean), $\operatorname{Re} gr\,SS$ is the “regression sum of squares” or that component of the total sum of squares “explained” by the regression equation, and $Error\,SS$ is the “residual sum of squares,” or the sum of squares of the residual,

$$\sum_{i=1}^{n} e_i^{\,2} \tag{3.18}$$

The coefficient of correlation (R) and the related coefficient of determination (R^2) are used in this dissertation. Correlation analysis consider how closely the observed values are to the regression equation, the better the fit, hence, the more confidence we can expect to have in the forecasting capability of the regression equation. Correlation analysis is expressed by the equation:

$$R = \frac{1}{n-1}\sum_{i=1}^{n}\frac{x_i - \bar{x}}{\sigma_x}\,\frac{y_i - \bar{y}}{\sigma_y}\,, \tag{3.19}$$

where σ_x and σ_y are standard deviation of variable x and y respectively.

The coefficient of determination (R^2) whose value varies from 0 to 1 represents the proportion of variation in the dependent variable that has been explained or accounted for by the regression line. A coefficient of determination of zero (0) signifies that none of the variation in Y is explained by the regression equation. R^2 value equal to 1 indicate that 100 percent of the variation of Y has been explained by the regression equation. R^2 is the total variation that is explained by the regression equation (it is a relative measure of the ‘goodness’ of fit of the observed data points to the regression line. This is also calculated by the equation:

$$R^2 = \frac{(\sum xy - n\bar{x}\bar{y})^2}{(\sum x^2 - \bar{x}\sum x)*(\sum y^2 - \bar{y}\sum y)} \tag{3.20}$$

3.3.1.3Testing the significance of the CER (regression coefficients)

There are a number of other statistics apart from R and R^2 that can be used to expand the knowledge and confidence in the regression equation and the assurance of its forecasting capability. Statistical validation of a CER can be carried out using the t-statistic for each explanatory variable to evaluate the variable's significance in the relationship. The significance of the entire equation can be carried out by the F-statistic. This is the most common statistic used to assess the quality of the entire equation. Standard error (SEE) or coefficient of variation (CV) provides insight to the size and proportion of the equation's estimating error. There are a number of other quantities that are useful in interpreting a regression equation. These include standard errors for the slope and intercept

$$se(b_0) = s\left(\frac{1}{n} + \frac{\overline{X}^2}{S_x}\right)^2 \text{, and} \qquad (3.21)$$

$$se(b_1) = s/S_x \qquad (3.22)$$

Using these standard errors, t-statistics that can be used to test hypotheses about the regression coefficients can be constructed

$$t(b_0) = \frac{b_0 - b_0^*}{se(b_0)} \text{, and} \qquad (3.23)$$

$$t(b_1) = \frac{b_1 - b_1^*}{se(b_1)} \qquad (3.24)$$

where b_0^* and b_1^* are hypothesised values of the regression coefficients, which are usually taken to be 0, so that large values of the t-statistics (t test > t critical) will signal that b_0 and b_1 values are not significant. The standard error or standard deviation of the predicted value of the response variable $\hat{Y}_*$, given a particular value of the predicted variable, X_*, is:

$$se\left(\hat{Y}_* \middle| X_*\right) = s\left[1 + \frac{1}{n} + \frac{\left(X_* - \overline{X}\right)}{S_x}\right] \qquad (3.25)$$

3.4 Approach to selection of cases for analysis and demonstration

Three distinct sets of data are required to achieve the aims of this dissertation as set out in chapter 1. For the development of CERs at the order of magnitude level, total investment cost for a larger number of plants (as well as the plant location, plant size and temporal information) is required. Before applying the cost-capacity factor, it is important to verify that the process under question does not represent significative technology variations. The development of capital CERs at the study estimate level requires detailed data sets that are carefully chosen and compiled. Lastly, for operating cost analysis, process information provided on the process flow diagram (PFD), an estimate of the fixed capital investment and an estimate of the number of operators required to operate the plant are required. Of these three, the approach taken to select cases for factorial capital cost analysis is the most complex and is discussed in this section.

To test the theory of Lang factor analysis in capital cost estimating, it is necessary to carry out a detailed analysis of plant costs for a smaller number of distinct processing plants. Cases of installed bioethanol and biogas plants needed to be selected based on their ability to replicate or extend the distinct features of Africa. In addition, the distinct characteristics of the plant itself had to be clear. As the dissertation aims to comment on Africa in general, the case studies had to be drawn from a range of different countries across the continent. The most critical location drivers for investments costs are identified.

In each of the selected cases, the presence of unusual cost, non-typical cost and non-standard cost is of interest. Data of interest in the analysis of each case focuses on the cost of the various purchases and activities that are necessary to build a plant, such as:

- Direct costs such as, purchased equipment delivered, purchased equipment installation, instrumentation and control, piping (installed), electrical (installed), buildings (including services), yard improvement, service facilities (installed), land (if purchase is required).
- Indirect cost, such as, engineering and supervision, construction expenses, contractor’s fee and contingencies.

In general, these factors will depend on several factors including process type and plant location.

3.4.1 Desirable features for case selection

The different biofuels may be produced at different scales. In the case of ethanol, large scale industrial installations are more typical. For biogas installations on the other hand, smaller scale plants are a necessity due to the nature of the feedstock which cannot readily be transported. This serve to constrain variation due to size differences in the case studies since Lang factor analysis have been asserted to be dependent on plant type or its capacity. The case studies that possesses extreme situation are selected based on the following factors (i.e. the plant or facility should have the following attributes):

(a) The case must be that of a first build of the facility (i.e. not an extension or retrofit) as the Lang factor method is a rapid or quick method of determining the total estimated cost of a new plant or facility.

(b) For a selected case it must be possible to access the basic process data (proper documentation of information when it was built) (e.g. equipment data sheet and costs, detail of plant location, plant capacity, capital investment e.t.c.) and engineering design data (e.g. schedule of piping, instrument loop sheet, piping isometrics e.t.c.) and the information should be accessible

(c) Within each selected biofuels class, the selected cases must be similar in terms of plant sophistication (level of automation), technology, geographical location, year of construction (recently built plant will be preferred), This is to make the case studies homogeneous by eliminating the effects of anomalies in the historical data. Also recently plants were preferred due to rapidly changing technical environment, both cost and non-cost data generated for a given period or class of technology can quickly become obsolete.

(d) The studied cases must be complimentary in as many attributes as possible such as geographical positioning (coastal and landlocked locations), and it must to a large extent be representation of “Type C and D” classification of African countries (section 2.6). Most African countries belong to this group.

(e) The analysis will focus on both Inside Battery Limit (IBL) and Outside Battery Limit (OBL) of the facility. IBL are the cost which are governed by the plant capacity, the qualities of the raw materials and product, and the process technology employed while the OBL refer to cost associated with storage and handling facilities for raw material and finished products, utilities generation facilities and buildings and services facilities for process plants such as laboratories, workshop, and warehouse.

(f) The selected cases must have a sufficient suspicion of non-typical cost such as legislation cost and permit, PRO (bribe).

3.4.2 Hypotheses to be tested

The criteria for evaluating and testing the theory of Lang factor analysis in capital cost estimating are listed below. In order to formulate such a test, usually some theory needs to be put forward, either because it is believed to be true or because it is to be used as a basis for argument, but has not been proved. The criteria are as follows:

- Biogas plant will follow closely the attributes of gas plants
- Bioethanol process plant follows liquid plant characteristics
- Higher Lang factors for small plant
- Lower Lang factors for large scale plant due to high percentage of purchased equipment cost
- Higher Lang factors for politically unstable location
- Opposing cost drivers in economically weak countries

3.5 Approach to data gathering and difficulties encountered during data collection

Good data underpin the quality of any estimating system or method. Since much of the analysis presented in this dissertation relies on historical data, a credible dataset relevant to the history of each studied project needed to be assembled.

Several techniques were employed for data collection, as listed below.

- Searches for secondary data sources, typically available in electronic form on the internet. Such data can be used to get a good understanding of the organisation, its industry setting, and the scope and objectives of the project to be studied.
- Questionnaires

- Interviews
- Observations during site visits to obtain first-hand understanding of the processes, activities, physical environment and working conditions
- Networking via the African Roundtable on Sustainable Consumption and Production (ARSCP)
- Institutional collaboration

Interviewing, which is a systematic attempt to collect information from responsible personnel was found to be the most successful data gathering approach. However, this needed careful planning and the steps used are highlighted below:

- **Planning and scheduling the interview**: This entails preparing a list of topics and questions to be covered to help ensure that important points are not overlooked and that the interview follows a logical progression. Scheduling interview was carried out from the top down. For example making sure that head of departments or sections are usually interviewed before employees who report to them. The purpose of the interview, the general area to be covered and the approximate amount of time required to cover all areas are also explained.

- **Opening and Closing the interview**: This starts with self introduction, stating the purpose of the interview. Often, interviewees are concerned that an analyst is trying to find fault with the way they work. This was overcome by allowing them to talk about processes which they are familiar with. Closing the interview was done by briefly summarising the areas that have been discussed, highlighting the important facts and my understanding of them. This lets the interviewee know that you have been listening carefully during the interview and provides an opportunity for clarifying any misunderstandings. A posture of objectivity was maintained during the interview while personal comments, observation, or conclusion were avoided. In closing the interview, I thanked the interviewee for his time and ask if shorter follow-up interview can be scheduled at a later date if necessary.

- **Conducting the interview**: Semi-structured interview was employed. Semi-structured interview is a mix of structured and unstructured interview. Semi-structured interviews are conducted with a fairly open framework which allow for focused, conversational, two-way communication. Unlike the questionnaire framework, where detailed questions are formulating ahead of time, semi structured interviewing starts with more general questions or topics. Relevant questions are initially identified and the possible relationship between these topics and the issues such as availability, expense, effectiveness become the basis for more specific questions which do not need to be prepared in advance. Not all questions are designed and phrased ahead of time. The majority of questions are created during the interview, allowing both the interviewer and the person being interviewed the flexibility to probe for details or discuss issues.

Difficulties encountered in data gathering ranged from a lack of well documented data especially in the small scale biofuel industries, to a lack of willingness to release information for those that have documented data. In many cases, the information presented on corporate websites were found to be obsolete making it very difficult contacting them for information. One major reason for lack of willingness to release data (that was obvious from most of the plant contacted) is that the industry is so competitive that company representatives are reluctant to divulge information that might compromise their ability to compete (because of confidentiality concerns). In some facilities, the data set were only released after receipt of a statement declaring that the data set will not be used in any way that threatens the confidentiality of the industry.

3.6 Summary and concluding remarks

The specific aim of this chapter was to present general guidance for use in developing and employing CERs focusing on implementation and evaluation techniques and a framework for analysing the quality or validity of statistical model. The chapter also discussed the methods employed in selecting cases for analysis and demonstration, methods employed in data gathering and the difficulties encountered during the collection of the primary data from a range of African countries. The chapter has established that the ‘goodness’ of a CER depends on the reliability of the database from which the CER is developed followed by a detailed review of the techniques used to assemble and refine (adjust or normalise) the data that constitute the empirical basis. Barriers to successful data gathering in the biofuel industry in the range of African countries vary from a lack of well documented data especially in the small scale biofuel industries to a lack of willingness to release information for those that have documented data have been outlined. This restricted the analysis in certain industry sectors as well as a prevented a full accounting of the resources at specific facilities. In some facilities, the data sets were only released after receipt of a statement declaring that the data set will not be used in any way that threatens the confidentiality of the industry.

In the following chapters (4-6), the application of the generalised methodologies and criteria developed in chapters 2 and 3 were applied to the three biofuel technologies-biogas, biodiesel and bioethanol. The selection of these biofuel case studies were based on the fact that they have the potential to contribute to sustainable development by reducing green-house gas emissions and the use of non-renewable resources thereby contributing to MDGs, NEPAD, FEMA, ECOWAS/UEMOA objectives/targets on energy. The biofuels case studies were analysed at different levels of details based on the methodology discussed in previous chapters yielding different quality of results and insights.

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4

Biogas Capital Cost Analysis and Estimation

How we generate our energy will determine our quality of life ……………. *BiofuelMarketplace 2007*

Thus far, the thesis has developed criteria, protocols and technical guidelines for predicting the capital and operating costs of biofuel process industries in Africa. The following three chapters (4-6) will demonstrate the application of the generalised methodologies and criteria developed in the previous chapters to biogas, bioethanol and biodiesel process industries.

4.1 Introduction

Biogas technology can serve as a means to overcome energy poverty which poses a constant barrier to economic development in Africa. This technology can be built on a wide range of scales, and conventional financial wisdom is that larger installations have advantages resulting from economies of scale. One important feature of biogas technology is that virtually the entire cost is expended for installation with very low running costs, about 4 -7.5% of the capital cost for a farm scale plant (Murphy, 2004), as the feedstock is usually a waste and there are no moving parts and little operating labour. This chapter therefore focuses on capital cost estimation techniques. The chapter starts with a brief description of biogas technology and specific features of its deployment in Africa (sections 4.2), highlighting the characteristics of anaerobic digestion and its methane potential (section 4.3). It then proceeds in section 4.4 to analyse the statistical evidence bearing on the existence of economies of scale in the small to medium scale production and use of biogas to support faster estimation (at the order of magnitude level) of investment costs for different plant sizes. The significance of scale economies with increasing capacity, and the effect of location (viz: coastal and landlocked African countries) on the capital investment cost of African biogas plants are investigated. Finally, in section 4.5 dealing with the next level of capital cost estimation (the study estimate), the factorial method (Lang factor approach) is investigated for selected biogas installations around Africa to determine the level of deviation from proposed default factors.

4.2 Biogas technology in Africa

Many rural African communities (about 62% of the population live in rural areas) (Population Reference Bureau, 2007) are characterised by low population densities and are remotely situated, making centralised energy generation and transmission prohibitively costly and inefficient due to greater transmission and distribution losses. Beyond certain breakeven distances from the grid, implementation of decentralised energy provision, such as direct use of biogas, or electricity generation distributed via a local mini-grid could be more cost effective. Biogas technology represents one of a number of village scale technologies that offer the technical possibility of more decentralised approaches to development. In addition, this technology offers a very attractive route to utilise certain categories of biomass for partially meeting energy needs.

Some of the first biogas digesters were set up in Africa in the 1950s in South Africa and Kenya. In other countries such as in Tanzania, biogas digesters were first introduced in 1975 and in others even more recently (South Sudan in 2001). To date, biogas digesters have been installed in several sub-Saharan countries including Burundi, Botswana, Burkina Faso, Cote d'Ivoire, Ethiopia, Ghana, Guinea, Lesotho, Namibia, Nigeria, Rwanda, Zimbabwe, South Africa and Uganda (Winrock International, 2007). Biogas digesters have utilized a variety of inputs such as waste from slaughterhouses, waste in urban landfill sites, industrial waste (such as bagasse from sugar factories), water hyacinth plants, animal dung and human excreta. Biogas digesters have been installed in various places including commercial farms (such as in chicken and dairy farms in Burundi), a public latrine block (in Kibera, Kenya), prisons in Rwanda, and health clinics and mission hospitals (in Tanzania) (Winrock International, 2007). However, by far the most widely attempted model is the household biogas digester – largely using domestic animal excreta (Table 4.1). The biogas produced from these household-level systems has been used mostly for cooking, with some use for lighting.

Table 4.1: Countries with documented biogas producing units in Africa as at 2006

Country	Geographical characteristic		Region	No of small/medium digester ($\leq$100m^3)	No of Large scale digester (>100m^3)	Level of technology development
	Landlocked	Coastal				
Botswana		*	Southern Africa	Several	Few	Low
Burkina Faso	*		West Africa	Few	-	Low
Burundi	*		Central Africa	Several	Several	High
Cameroon		*	Central Africa	Few	-	Low
Congo-Brazzaville		*	Central Africa	Several	Few	Low
Côte d'Ivoire		*	West Africa	Several	Few	Low
Egypt		*	North Africa	Several	Few	High
Eritrea		*	East Africa	Few	-	Low
Ethiopia	*		East Africa	Few	-	Low
Ghana		*	West Africa	Several	Few	High
Guinea			West Africa	Few	-	Low
Kenya		*	East Africa	Several	Several	High
Lesotho	*		Southern Africa	Few	-	Medium
Malawi	*		Southern Africa	Few	-	Low
Mali	*		West Africa	Several	Few	High
Morocco		*	North Africa	Several	-	Medium
Namibia		*	Southern África	Few	-	Low
Nigeria		*	West Africa	Few	Few	Low
Rwanda	*		Central Africa	Several	Few	High
Sierra Leone		*	West Africa	Few	-	Low
South Africa		*	Sothern Africa	Several	Several	High
Sudan		*	East Africa	Few	-	Low
Swaziland	*		Southern Africa	Several	-	Medium
Tanzania		*	East Africa	Several	Several	High
Tunisia		*	North Africa	Few	-	Low
Uganda	*		East Africa	Few	-	Low
Zimbabwe	*		Southern Africa	Several	Few	Medium

Sources: Karekezi, (2002), Allafrica.com, (2000), Akinbami *et al*, (2001), Spore, (2004), Amigun and von Blottnitz, (2007).

Global experience shows that biogas technology is a simple and readily usable technology that does not require overtly sophisticated capacity to construct and manage. It has also been recognized as a simple, adaptable and locally acceptable technology for Africa (Gunnerson and Stuckey, 1986; Taleghani and Kia, 2005). There are some cases of successful biogas intervention in Africa, which demonstrate the effectiveness of the technology and its relevance for the region. The lessons learned from biogas experiences in Africa suggest that having a realistic and modest initial introductory phase for Biogas intervention; taking into account the convenience factors in terms of plant operation and functionality; identifying the optimum plant size and subsidy level; and; having provision for design adaptation are key factors for successful biogas implementation in Africa (Biogas for better life, 2007). Biogas technology has multiple beneficial effects. The use of biogas technology can improve human well-being (improved sanitation, reduced indoor smoke, better lighting, reduced drudgery for women, and employment generation) and the environment (improved water quality, conservation of resources –particularly trees, reduced greenhouse gas emissions) and produce wider macroeconomic benefits to the nation (Figure 4.1). Of the eight Millennium Development goals, domestic biogas has a very direct relation with four: MDG 1, MDG 3, MDG 6 and MDG 7.

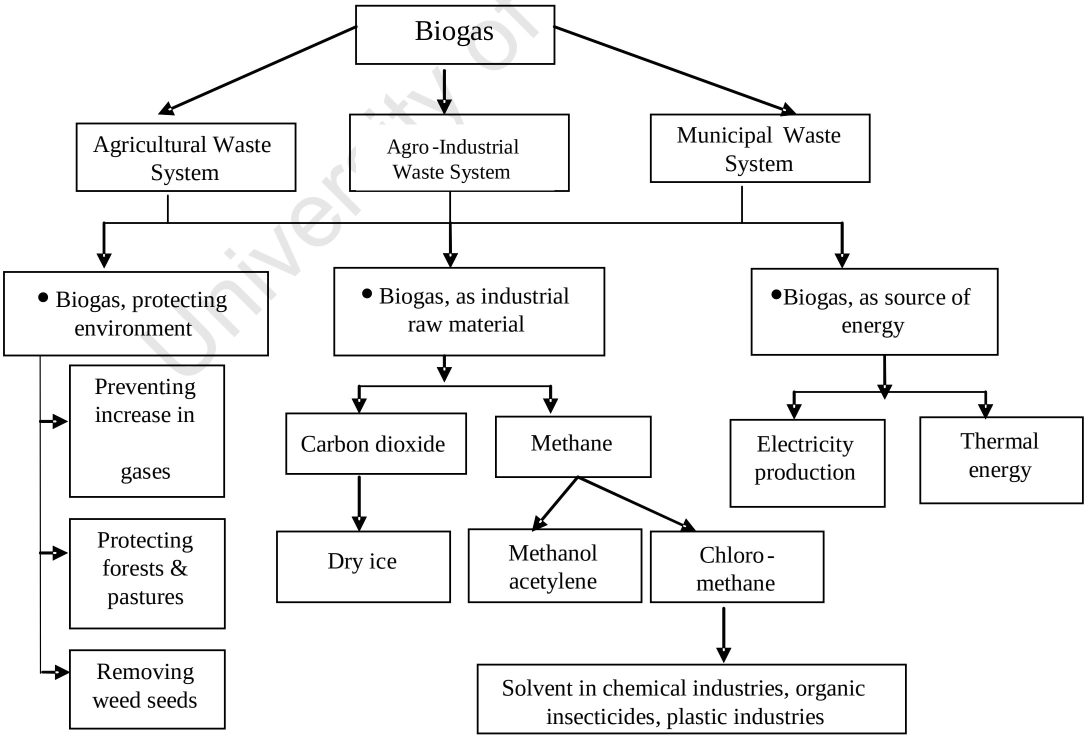


Figure 4.1: Benefits, Application and Usage of Anaerobic digester system (adapted from Shabani and Taleghani, 2006)

- **MDG 1-Eradicate extreme poverty and hunger**

Target 1: To halve extreme poverty

- Biogas plants reduce financial and economic costs expended on fuel for cooking and, to a lesser extent, also lighting. The produced bio-slurry is a potent organic fertiliser and may reduce the use of chemical fertiliser. In general, biogas households are not typically the ones in developing countries that suffer from extreme poverty, although many of them are poor. However, the biogas dissemination process and the resulting reduced claim on common ecosystem services do affect the livelihood conditions of (very) poor non-biogas households through:
- Construction and installation of biogas creates employment for rural people.

- Biogas saving on the use of traditional cooking fuels increases the availability of these fuels for (very) poor members of the community.

- **MDG 3-Promote gender equality and empower women**

Target 4: Eliminate gender disparity in education

Women and girls predominantly spend time and energy on providing traditional energy services. Housekeeping and absence of proper illumination creates barriers for women and girls in accessing education and information, as well as their mobility and participation in ‘public’ activities.

- Domestic biogas reduces the workload – collection of firewood (reduced drudgery for women), tending the fire, cleaning soot of cooking utensils - by 2 to 3 hours per household per day.
- Biogas illumination is highly appreciated for lighting, facilitating reading / education / economic activities during the evening.

- **MDG 6-Combat HIV/AIDS, malaria and other diseases**

Target 8: Halt / reverse the incidence of malaria and other major diseases

Half of the world’s population cooks with traditional (mostly biomass-based) energy fuels whose collection becomes increasingly cumbersome. Indoor air pollution from burning of these fuels kills over 1.6 million people each year, out of which indoor smoke claims the lives of nearly one million children under age 5 per year. Diseases that result from a lack of basic sanitation, and the consequential water contamination, cause an even greater death toll, particularly among young children:

- Biogas stoves substitute conventional cook stoves and energy sources, virtually eliminating indoor smoke pollution and, hence, the related health risks (e.g. respiratory diseases, eye ailments, burning accidents).
- Biogas greatly reduces the workload involved in the collection of traditional cooking fuels like wood.
- Biogas significantly improves the sanitary condition of the farm yard and its immediate surrounding, lowering the exposure of household members to harmful infections generally related to polluted water and poor sanitation.

- **MDG 7-Ensure environmental sustainability**

Domestic biogas can help to achieve sustainable use of natural resources, as well as reducing greenhouse gas (GHG) emissions, which protects the local and global environment. Application of bio-slurry improves soil structure and fertility (will improve agricultural production (e.g. vegetable gardening), thus contributing to food security for the community, and reduces the need for application of chemical fertilizer).

Target 9: Integrate the principles of sustainable development into country policies and program and reverse the loss of environmental resources.

- Biogas dissemination programmes, particularly larger ones, have a considerable governance component. As such, they positively influence national policies on sustainable development (e.g. agriculture, forestation) as well as promote participatory governance involving women and other disadvantaged groups.

Target 10: Halve the proportion of people without sustainable access to safe drinking water and basic sanitation.

- Biogas reduces fresh water pollution as a result of improved management of dung. Connection of the toilet to the biogas plant significantly improves the farmyard sanitary condition.

Despite the recognized technical viability and acceptability of biogas technology in sub-Saharan Africa; the multiple benefits recognized by users, governments and NGOs; and the estimates of large potential markets, the technology has not been widely adopted by sub-Saharan African households. An examination of the literature on constraints to household biogas promotion reveals many site-specific issues that have limited the scope of biogas in sub-Saharan Africa – particularly availability of water and organic materials for effective biodigester operation. Limited water availability poses a constraint for biogas operation because plants typically require water and manure to be mixed in an equal ratio; a household typically would need about 4 buckets of water per day for a biogas plant. In some cases animal urine has been used as an effective replacement. Small-scale farmers frequently lack sufficient domestic animals to obtain enough manure for the biodigester to produce sufficient gas for lighting and cooking. Even where households keep sufficient numbers of animals, nomadic, semi nomadic or the free grazing system of many communities in sub-Saharan Africa makes it difficult to collect dung to feed digesters.

Other reasons identified for lack of widespread use of biogas systems at the rural households were, urbanisation and socio-cultural constraints, poor ownership responsibility by users, immature technical properties of plants themselves and on the other hand, a dissemination strategy which was only minimally developed and which did not recognise the importance of user training and follow-up services (Aklaku, 2005), high initial investment costs (for example, the cost of a family size floating drum plant in most African countries is US$1667. This is beyond the means of most given that more than half the African population is living belowUS$1 /day. This is compounded with lacking credit schemes, negative image caused by failed biogas plants and limited private sector involvement (Akinbami *et al*, 2001, Njoroge, 2002) and failure by government to support biogas technology through a focused energy policy (subsidy). A survey of 25 existing biogas plants in 1986 in Kenya found only 8 of the 25 functional and 13 of the 25 not functional or never finished (Day *et al.,* 1990).

Biogas initiatives in Africa could benefit from the success story of biogas technology in countries like Nepal, India and Vietnam. India has placed far more emphasis on the survival of small-scale farmers than ensuring their efficiency and growth in a competitive environment through various policy instruments like the biogas programme (Njoroge, 2002). The Nepal biogas experience is a good example of how a national program can, through linked subsidy and quality control mechanisms create conditions that stimulate demand for biogas digesters, encourage entry of commercial companies to produce them, and provide incentives for high quality installations. Free market conditions, particularly when regulations are weak and the customer does not have full information regarding the product, often result in competition between suppliers based on price alone, at the expense of quality. For a national program like Nepal’s Biogas Support Program (BSP) to succeed, a major prerequisite is that it be independent and free from political interference. A second lesson learned from the Nepal experience is that standardization of technology to a single approved design makes quality control easier. At the same time it allows a large number of competing companies to enter the market, with everyone working towards the same quality standards. Nepal’s BSP can be described as subsidy-led while being demand-driven and market-oriented. A simple, transparent, and sustained subsidy policy has been instrumental in increasing the adoption of biogas plants. Subsidies have been justified to make up for the difference between ability to pay and the higher societal benefits (maintenance of forest cover, prevention of land degradation, and reduction in emissions of greenhouse gases) and private benefits (reduction in expenditure for firewood and kerosene, savings in time for cooking, cleaning, and firewood collection, increase in availability of fertilizer, and reduction in expenditure to treat respiratory diseases) accruing to users. A progressive subsidy structure, which provides larger subsidies to smaller plants, has made smaller household plants more affordable to poorer households. Over the years, many companies have devised credit programs for households wishing to install biogas plants. Companies must thus market themselves aggressively to generate demand for plants. BSP encouraged the number of participating companies to grow from a single semi-government entity in 1991 to 40 today. In the past 10 years, the real price of installations has decreased by 30%, demonstrating fierce supply-side market competition. In order to reduce initial investment costs, households are encouraged to contribute their own labour and provide local construction materials. In some instances, simultaneous construction of a number of biogas units in the same vicinity (e.g. bulk construction) has reduced costs further, particularly material transportation costs. Productive end use of biogas has also been promoted to enable households to generate additional income, further increasing the affordability of biogas to poorer households (Winrock International, 2007).

4.3 Anaerobic digestion

Biomass may be converted to a variety of energy forms including heat (via burning), steam, electricity, hydrogen, ethanol, methanol, biodiesel, and methane. Selection of a product for conversion is dependent upon a number of factors, including need for direct heat or steam, conversion efficiencies, energy transport, conversion and use of hardware, economies of scale, and environmental impact of conversion process steams and product use (Chynoweth, 2001). Under most circumstances, methane derived from anaerobic digestion is an acceptable fuel. Considered in its basics, biogas technology emulates the natural process by which organic material is broken down in the absence of oxygen (anaerobic biodigestion). In the absence of oxygen, which is the case, for example, when organic matter is buried underground (as in landfills) or submerged in water, the microbial action on it produces a methane-rich gas. Production of biogas is facilitated by biological processes that occur under anaerobic conditions. Anaerobic microorganisms convert biodegradable organic materials into methane (CH_4) and carbon dioxide (CO_2). The process is typically operated in closed reactors at elevated temperatures; however, it does also occur naturally in soils or old landfills at ambient temperatures.

The conversion of biodegradable organic material to CH_4 (heat content of 18.6 MJm^{-3} – 26.04 MJm^{-3}) and CO_2 is facilitated by three major groups of bacteria (Fig. 4.2). The fermenting bacteria (group I) convert the organic material to short-chain fatty acids (especially acetic acid) through hydrolysis by extracellular enzymes and subsequent fermentation of the hydrolyzed products. Other products of the fermentation process are alcohols CO_2 and H_2. The short-chain fatty acids that are longer than acetate are oxidized by the hydrogen producing, acidogenic bacteria (group II) under production of H_2, formic acid, acetic acid and CO_2. The end products from the fermenting and the acidogenic bacteria (formic acid, acetic acid, and H_2) are converted to CH_4 and CO_2 by the methane producing bacteria (group III). Two additional groups of microorganisms are active in the conversion processes. One is the homoacetogens (group IV) which ferments a broad range of components under production of acetic acid. Acetic acid oxidizers (group V) oxidize acetic acid to H_2 and CO_2 if the H_2 is removed at the same time by other processes. The homoactogens can reverse their action and produce other types of fatty acids than acetate if the concentration of acetate, hydrogen or ethanol is high.

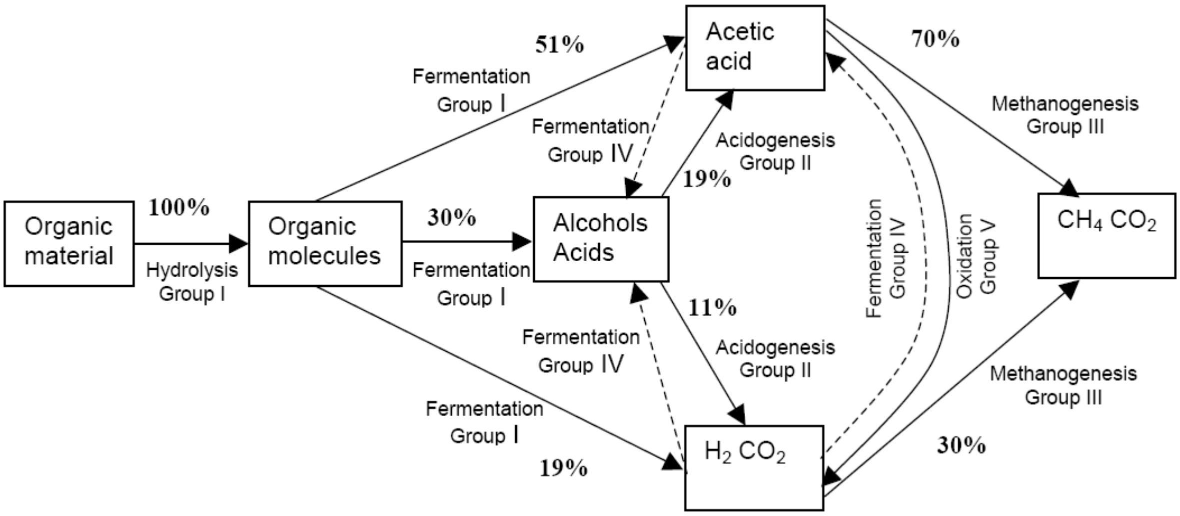


Figure 4.2: Schematic of the processes and microorganisms responsible for conversion of complex organic material to CH_4 and CO_2 under anaerobic conditions [††††] (polulsen, 2003)

The hydrolysis step (group I) converts the organic material into components that are useful for the bacteria. Therefore hydrolysis can become potentially limiting. This is the case if the organic material contains high amounts of cellulose that are hydrolysed slowly. Most of the hydrolysed organic material is converted to acetic acid and subsequently to methane and carbon dioxide (Figure 4.2), the concentration of acetic acid therefore plays an important role in anaerobic conversion of organic matter. Under normal conditions most of the hydrolysed matter will be converted by group I organisms into materials that are directly usable for methane production (CO_2, H_2, acetic and formic acid). If the process is out of balance and the hydrogen is not consumed fast enough the quantity of alcohols and other types of fatty acids produced will increase. Oxidation of fatty acids and alcohols into hydrogen, carbon dioxide and acetic acid by group II only yields very limited amounts of energy. It is therefore important that the partial pressure of hydrogen and the concentration of hydrogen ions is low (Poulsen, 2003)), this will help drive the process with a net energy output.

[††††] Percentages indicate relative quantity of organic matter converted by the different processes).

4.3.1 Characteristics of biogas technology

Biogas technology as envisioned in this dissertation is a decentralised, low maintenance technology producing biogas from domestic organic wastes, in particular animal dung, food wastes and sewage wastes (Figure 4.3).

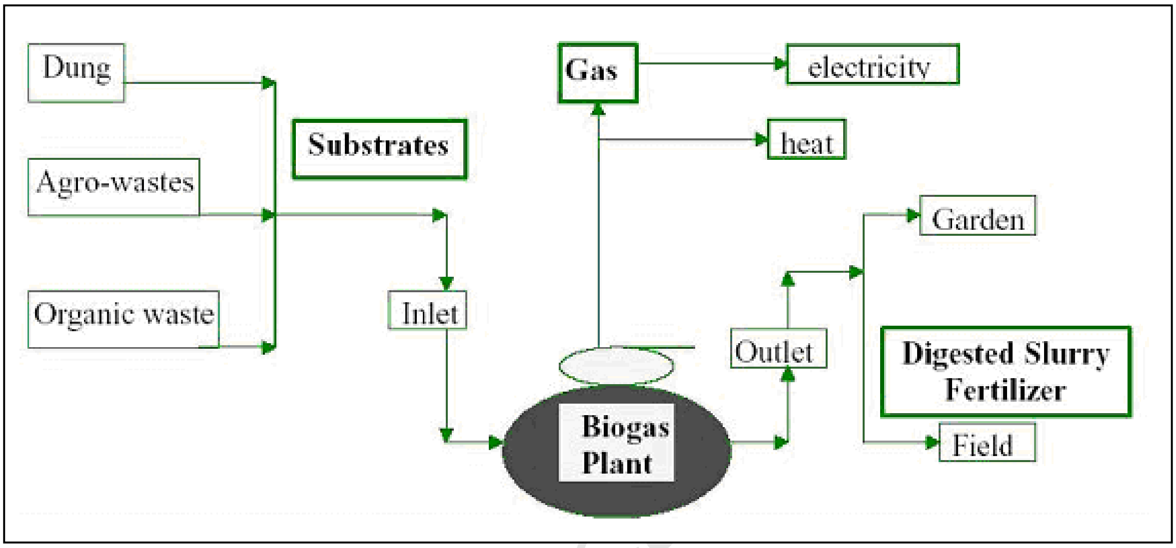
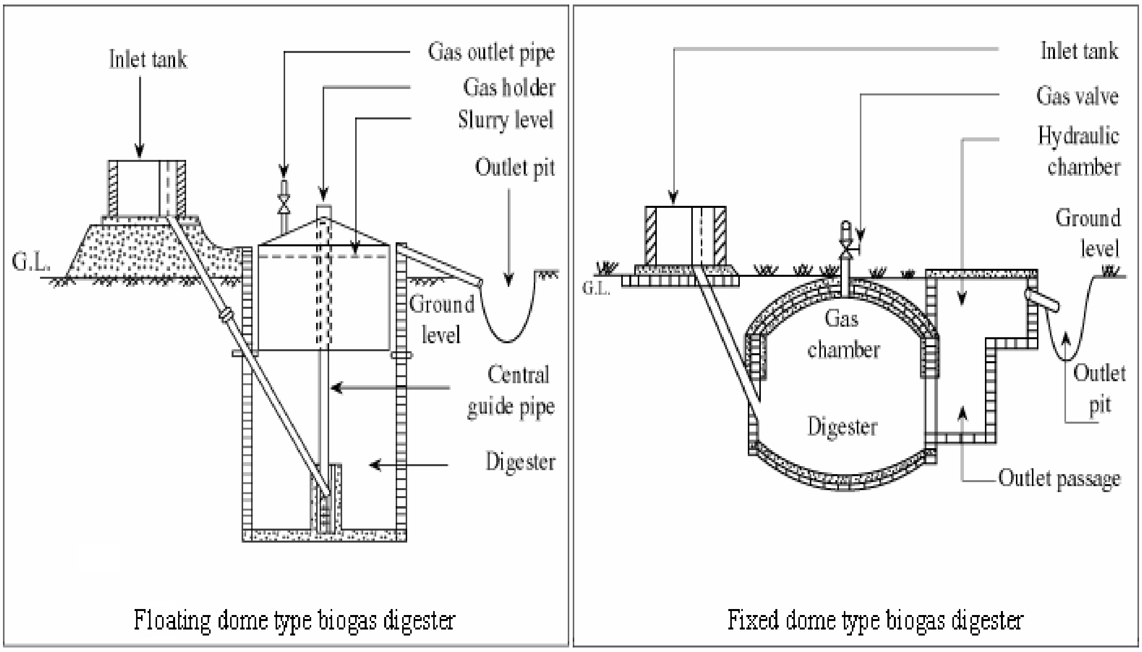


Figure 4.3: Biogas flow diagram

A biogas plant consists of two components: a digestion chamber (or fermentation tank) and a gas storage chamber (gas holder) (Litchman, 1987; Asiatic Society of Bangladesh, 2006). The digester is a cube-shaped or cylindrical waterproof container with an inlet into which the fermentable mixture is introduced in the form of liquid slurry. The gas holder is normally an airproof steel container that, by floating like a ball on the fermentation mix, cuts off air to the digester (anaerobiosis) and collects the gas generated. Two popular simple designs of digester (the Chinese fixed dome digester and the Indian floating dome biogas digester) are illustrated in Figure 4.3. A typical representation of biogas technology in Africa is also illustrated in Figures 4.4. The digestion process is the same in both digesters but the gas collection method differs in fixed dome type biogas digester, where the gas holder is equipped with a gas outlet, while the digester is provided with an overflow pipe to lead the sludge out into drainage. There are two different types of biogas plants: the batch plant, where the organic waste stays in the tank for some time and is then replaced after production; and the continuous digester, where new slurry is fed every day. The continuous type is more efficient with a higher gas production rate per digester volume.



Floating dome type biogas digester

Fixed dome type biogas digester

Figure 4.4: A typical biogas plant floating dome and fixed dome (Banglepedia, 2006)

Figure 4.5: Biogas construction plant in Zimbabwe (Mavunganide Kennedy, 2005)

The biogas system uses a number of individual digesters, with varying volume and built in an excavated underground pit. The technology produces biogas from domestic organic wastes, in particular animal dung, food wastes and sewage wastes. The organic wastes are directed into the biodigester, where they remain for a period of time to allow for the bacteria in the vessel to biologically break them down.

This mixed substrate approach to the technology is termed ‘codigestion’. At the small digester scale the solid wastes – dung and food – are emptied into the digester manually. Sewage is flushed into the digester through a closed channels which minimise smell and contamination- a conventional waterborne sewerage approach (this would be the institutional digester approach, and that of the residential digesters if appropriate), or by building a typical pit-type dry toilet above the inlet.

The digester is shaped like a beehive, and built up on a circular, concrete base using bricks made from clay or sand-cement. The large scale biogas plant emphasis has been pollution control and ecological reasons, rather than maximum biogas production.

The sides taper gradually and eventually curve inward towards a half-metre diameter man-hole at the top. It is crucial to get the bricks laid in exactly the right shape, and to make the structure water-tight so that there is no leakage of material or water out of the digester. Biogas is stored on the upper part of the digester. On the outside, the entire surface is well plastered and backfilled with soil, then landscaped. A particular feature of the plant design is a compensating chamber that acts as a reservoir of methane bacteria for enhanced gas generation. At first, gas pressure displaces the liquid to the compensating chamber. Consumption of gas leads to backflow of the waste from the compensating chamber into the bio-digester; this agitates the waste, circulates the bacteria, and releases trapped gas. Throughout the world, a countless number of designs of biogas plants have been developed under specific climatic and socio-economic conditions. The performance of a biogas plant is dependent on the local conditions in terms of climate, soil conditions, the substrate for digestion and building material availability. The design must respond to these conditions. In areas with generally low temperatures, insulation and heating devices may be important. If bedrock (boulders) occurs frequently, the design must avoid deep excavation work. The amount and type of substrate to be digested have a bearing on size and design of the digester and the inlet and outlet construction. The choice of design will also be based on the building materials which are available reliably and at reasonable cost.

4.3.2 Biogas and methane potential

One of the most important issues in anaerobic digestion is the quantity and composition of gas produced. Often the economy of the biogas facilities depends on the end use of gas produces (sales of gas or energy (heat, electricity) derived from the biogas). The biogas potential (the amount of gas that can be produced from a given quantity of organic waste) is therefore an essential parameter. The following section discusses biogas potential and gas composition as related to the design and operation of the digester as well as composition of the organic material digested. Because biogas typically is a mixture of different gases and methane is the compound that is of interest (seen from an energy perspective at least) the term methane potential will be used rather than the more diffuse term biogas potential. The gas composition (biogas yield) varies depending on the type of feedstock used. The range of performance and the operational reliability of a biogas plant are influenced greatly by the type of substrate used, its quality and its quantity (the ingredients and substrate properties are responsible for the volume of gas generated). This is due to the percentage of dry matter (DM or total solids), and in turn, the percentage of volatile solids (VS) within the feedstock.

The net formula for biogas production based upon the stoichiometry of the degradation (input organic matter) reaction using Buswells formula is as shown below (Vezigolu, 1991):

$$C_aH_bO_cN_d+\left(\frac{4a-b-2c+3d}{4}\right)H_2O \longrightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4+\left(\frac{4a-b+2c+3d}{8}\right)CO_2+dNH_3$$

The specific theoretical methane yield (B_{th}) in terms of normal cubic meters, Nm^3 CH_4 per ton volatile solids (VS defined as ignition loss at 550^{o}C) under standard conditions (0^{o}C, 1 atm.) can be calculated from:

$$B_{th}=22400\,\frac{\left(\frac{4a+b-2c-3d}{8}\right)}{12a+b+16c+14d} \tag{4.1}$$

The actual methane yield from digesters is always lower due to the following factors: Part of the organic input (substrate) will be used for generation of new biomass (bacteria). This fraction is typically on the order of 5-10 % of the input VS. Part of the organic matter will exit the reactor without being degraded. This fraction is typically on the order of 10%. The lignin containing part of the organic matter cannot be degraded under anaerobic conditions. For lignin containing materials the biodegradable fraction (BF) can be estimated as

$$BF = 0.83 - 0.028LC \quad (4.2)$$

Where LC is the lignin content as a percentage of VS (Table 4.2).

Part of the organic matter is bound to inorganic particles and will not be available for microbial degradation. The degradation of the organic matter may be restricted due to lack of sufficient nutrients for microbial growth. It is therefore in general advisable to use actual measured methane potentials under the conditions that one wishes to run the digester.

Table 4.2. Lignin content of selected organic materials (Richard 2000)

Component	Lignin content % of VS
Food wastes	0.4
Newspaper	21.9
Office paper	0.4
Cardboard	12.9
Yard wastes	4.1
Chicken manure	3.4
Pig manure	2.2
Cow manure	8
Wheat straw	13
Whey acid	0
Pine wood	28

Such measurements can be difficult to carry out in practice as many full-scale biogas plants are using mixtures of different organic materials as substrates. Table 4.3 presents measured values of methane potential for a thermophillic digester for a range of different organic materials from various sources. An overview of materials from each group of the well-defined substance groups and methane potentials of selected biodegradable wastes are illustrated in Figure 4.6.

Table 4.3: Methane potentials for selected biodegradable wastes from industry, farming and households (Poulsen, 2003)

Source	Type of waste	% dry matter	VS (% of dry)	Nm^3 CH_4 per ton VS
Cosmetic prod.	Fat-alcohol	95	100	685
Chewing gum prod.	Talc-sugar dust mixture	95	100	137
Alcohol production	Alcohol	95	100	618
Sausage production	Flotation sludge	7.6	100	512
Dairy production	Whey	7.5	100	694
Oil mills	Bleaching soil	95	45	342
Communities	Residential organic waste	35	100	279
Animal feed prod.	Feed residue (grain, fat etc.)	80	100	81
Heparin prod.	Mucosa	17	100	229
Restaurants etc.	Fat from fat separator	50 - 52	100	124 – 130
Brewery	Yeast solution	12	100	426
Dairy production	Sewage sludge	2.0	100	1649
Slaughter houses	Slaughter wastes	15	100	260
Bakery	Bread etc.	60	100	108
Farms	Manure (pigs cattle)	6.0	100	239
Oil mills	Fat sludge	31 – 60	100	488 – 527

The substrate used is dependent on both ecologic and economic conditions of the location. In Germany, agricultural fertilizer still has the greatest share in the substrate use for the majority of biogas plants. For example, for more than 80 % of the biogas plants the mass fraction of agricultural fertilizer used is a minimum of 50 %. In Nigeria, identified feedstock substrate for an economically feasible biogas programme includes, dung, cassava leaves, urban refuse, solid (including industrial) waste, agricultural residues and sewage (Akinbami and Akinwumi, 1996). Also, in Kenya, cattle waste has been the primary substrate (Egerton Newslink, 2006). The most available raw material especially in many sub-Saharan Africa is animal dung.

Substance group				
Basic substrate	(Co-) substrate			
Agricultural fertilizer	Renewable raw material	Plant residues	Animal residues	Industrial wastes
Cattle manure Hog manure Poultry manure Solid muck	Corn silage Grass silage Beet leave silage Corn, whole plant silage	Fodder residues Harvest residues Grass cuttings	Grease Food residues Organic waste	Breweries Wineries, Confectionaries Industrial organic wastewater

Figure 4.6: Substrate examples, organised by substance group

4.4 Biogas economics

A central feature of biogas technology (as for many other renewable energy technologies (RETs), and other than for conventional energy sources) is that almost all expenses need to be financed upfront, with very low operating expenses thereafter. This is problematic where poverty is endemic. In addition, the investment in a biogas unit will result in savings, mainly non-monetary, rather than earnings – which further complicate recovery of capital invested. The quantification of social, environmental and economic benefits would depend on factors such as the size of the unit, the location (environmental conditions), availability and cost of alternative energy sources. In assessing the economic viability of biogas programmes one should distinguish three major areas of applications: individual household units, community/institutional plants, large-scale commercial operations. In each of these cases, the financial feasibility of the facility depends largely on whether outputs in the form of gas and slurry can substitute for costly fuels, fertilizers or feeds which were previously purchased, while at the same time abating pollution. The feasibility also includes indirect benefit such as the reduced time to collect fuel wood and decreased health costs. Still, the potentials of the technology are often assessed in economic terms. There have been some studies providing information on design and investment of methane digesters in developed countries and in some cases, some returns and operating cost data. For example, Nelson and Lamb (2002) presented a comparison of projected and actual costs of constructing a biogas digester on a Minnesota dairy farm in the USA. They calculated the net returns from electricity, annually and also estimated a payback period for the investment of the digester. Meyer and Lorimor (2003) evaluated the construction costs for two biogas digesters. They estimated an 11.4 per cent "return on investment" and proposed that most of the return would go toward depreciation, interest, repairs, taxes and insurance. Engler *et al.,* (1999) analysed the feasibility of the digester investment focusing on the refurbishing of an existing non-operating digester. Although no cost data existed, the authors estimated potential return from the sale of electricity.

Good understanding of the relation between capital costs and plant size (already discussed in section 2.13.1) can provide useful information in assessing economic viability of biogas plants, and providing means whereby decisions are taken on developmental of a new project. In a developing economy, local market opportunities frequently restrict the size of a process plants. Scale effects influence costs per unit of capacity (specific cost). The scale economies concept is therefore of key concern because it can help in determining the optimal size of a biogas digester. The extent to which economies of scale exist varies greatly according to the industry. In some industries, it might be insignificant, and thus, such industries would likely be characterised by numerous small firms (Norman, 1979). For most industries, economies of scale usually do not necessarily exist over the entire possible range of outputs. Rather it occurs only to a certain level of output, or plant size, and then diseconomies of scale or decreasing return to scale can set in. Economies of scale arise from the advantages of operating at a higher scale than at lower scale. Therefore, the decision to build either small/medium scale decentralised or large scale centralised biogas plant should be carefully considered.

Both economies and diseconomies of scale have been reported in anaerobic digester systems. Schwart *et al.,* (2005) reported both economies and diseconomies of scale in digester investment. After adjusting the investment data to animal units, they found that there are some economies of scale up to 4,500 animal units after which diseconomies of scale were observed. They also reported diseconomies of scale of investing in a digester for smaller dairies. Ernest *et al.,* (2000) reported that there are diseconomies of scale affiliated with anaerobic digestion systems on swine farms. Kobayashi and Masudu (1993) and Mehta (2002) reported that there are potential economies of scale associated with anaerobic digestion systems. A recent report by Itron (2004) claimed that transactional costs and uncertainty of payback, coupled with higher unit capital costs associated with diseconomies of scale, render smaller biogas projects less attractive.

A breakdown of the first cost of the biogas plant designed by Adeoti (1998) in Nigeria revealed that construction costs took about 65% while facilities, installation, labour and land accounted for the remaining 35%. The construction cost was high, primarily because cement and steel are used in construction. In a related study, the cost of a family sized biogas plant in India was between 5–10 times higher than a similar Chinese plant which was even about 2–4 times bigger in size. This is due to the fact that the Indian digester was constructed with bricks and industrially advanced materials which were mostly unavailable locally, while the Chinese plant (digester) was constructed with locally available cement, stones, and a mixture of quicklime, sand and clay and no industrially advanced materials. Table 4.4 show a comparison of an 8m^3 biogas system in Kenya with one in Vietnam. The table demonstrates that the system in Kenya is about three times as expensive as one in Vietnam, mainly due to very expensive construction materials, such as cement, bricks, piping.

Table 4.4: Construction cost for 8m^3 biogas system with international benchmark

	Kenya	Vietnam
Cement	90	30
Bricks	103	27
Other materials	136	20
Unskilled labour	43	27
Skilled Labour	43	38
Total	€415	€142

(Source: Winrock, 2007)

Biogas technology in Africa appears to be implemented by technologically driven oligopolies - an economic situation where there are so few suppliers of a particular product that one supplier’s action can have a significant impact on price and its competitors (Butare, 2005; Cawood, 2006, Mojaki Biogas Technology, 2008). The price which the typical firm charges depends on the number of firms in the industry. The less the number of suppliers, the less the competition, and hence the higher the charge. This concept is represented in the equation 4.3. The higher capital cost experienced in African biogas industry is aggravated by the fact that the current market for biogas in Africa is slow. Contractors therefore tend to lump all of their costs into the unit they are constructing because they may not get another order for months (Biogas for better life, 2007).

$$Q = \left(S/n + S \times b \times \overline{P} \right) - S \times b \times P \quad (4.3)$$

where

Q = firm sales; S = total sales of the industry; n = number of firms in the industry; b = constant term representing the responsiveness of a firm's sales to its price; P = price charged by the firm itself; $\overline{P}$ = average price charged by its competitors.

However, a substantial cost reduction could be obtained through design optimisations and efficiencies created through economies of scale, as well as smart implementation and planning. In planning, the concept of clustering installations, where a number of orders for digesters within a defined geographic area would accumulate until a threshold is reached could provide substantial reduction of costs.

There is evidence that higher location factors are partly due to the need of importing specialized equipment (World Bank, 2007). In heavily industrialized countries, the equipment is often fabricated in the same area where the plant is constructed; in developing countries, depending on level of technology needed, equipment is generally imported along with specialised personnel to install it, at premium prices leading to increased investment costs. The investment costs are believed to be affected by the geographical location of the country viz: coastal and landlocked locations. Out of the world's total 28 countries without a sea coast, Africa's disproportionate share is 14. Landlocked countries (countries without direct costal access to the sea and also to maritime trade) face very specific challenges of being dependent on one or more transit countries. A report by the World Bank, (2007) revealed that landlocked economies are affected by the high cost of freight services as well as the high degree of unpredictability in transportation time. The main sources of costs are not only physical constraints but also widespread corruption and severe flaws in the implementation of transit systems, which prevent the emergence of reliable logistics services. By way of example, shipping cost for a standard container from Baltimore (United States) to the Cote D'Ivoire amount to US$ 3,000. Sending the same container to the Central African Republic will cost up to US$ 13,000 (Hausmann, 2001). Also, to send a standard container from Rotterdam in the Netherlands to Dar es Salam in Tanzania over an air distance of 7,300 km costs US$ 1,400 and then transport it to Kigali over a distance of 1,280 km by road costs twice as much (Sachs and Mellinger, 2001).

Further, Radelet and Sachs (1998) used Cost-Insurance-Freight/Freight-on-Board (CIF/FOB) ratios as the dependent variable for a sample of 92 developing countries and found that: each 10 percent increase in sea distance is associated with a 1.3 percent increase in shipping costs; an extra 1000 miles of sea distance tends to increase the CIF/FOB ratio by about 0.6; landlocked countries pay about 5.6 percent more for shipping than a coastal economy, representing an increase of 63 percent in freight and insurance. Their results also indicated that overland transport costs tend to be considerably higher than sea freight costs. Thus, for a given distance from main markets, countries with a higher proportion of transit by land tend to have higher overall shipping costs. This implies the importance of cross-border road transport infrastructure for landlocked countries (Fujimura, 2004).

As mentioned earlier, most biogas programmes in Africa are based on small to medium scale technology. These plants use locally available materials and as such the geographical placement of the plant is expected to have little or no effect. Labour and materials costs differ within region and countries. For comparison purposes, the cost of materials and labour for a 6m^3 fixed-dome digester in South Africa (coastal country) and Rwanda (landlocked country) is illustrated in Table 4.5.

It can be observed from the table that, in the case of South Africa, the 6 m^3 household biogas digester of the GGC 2047 design can be constructed for approximately US$ 1,150 while that of Rwanda can be constructed for US$ 860. The costs of materials in Table 4.5 are comparable but the labour cost associated with the digester construction in South Africa is more than four times that of Rwanda. The overall cost of construction in South Africa is about 35% higher than a similar plant in Rwanda despite the inclusion of farmer own cost. However, the construction costs for South Africa scenario could be reduced by US$ 100 if PVC pipes were to be used instead of galvanised iron (GI). Additionally, a further reduction of US$ 141 would be possible if the Government were to waive the 14% VAT.

Table 4.5: Rwanda and South Africa-6 m^3 GGC 2047 fixed dome digester cost comparison (on the basis of costs for wide-scale implementation)

	Item	Rwanda (US$)	South Africa (US$)
A	**Construction materials**		
	Cement	160.70	76.00
	Lime	6.50	
	Waterproof cement	49.10	
	Sand	40.00	Owner provided
	Stone	54.50	162 (900 bricks)
	Gravel (3/4)	21.80	Owner provided
	Reinforcement (6mm)	10.90	49.50
	Binding wire (2 mm)	0.90	
	Smaller items	25.45	
	Mixer		28.50
	Paint		9.65
	Sub-total construction materials	370.00	325.65
B	**Pipes and fittings**		
	GI pipe (21 mm diameter)	65.50	125.00
	PVC pipe (110 mm)-outlet	27.30	15.40
	GI pipe fitting 21 mm	16.40	16.80
	Sub-total pipe and fitting	109.00	157.20
C	**Appliances cost**		
	Stove	27.30	65.00
	Main valve	5.00	
	Water drain	2.20	
	Gas tap	3.30	19.30
	Inlet, Dome gas + Rubber		71.50
	Sub-total appliances	33.80	155.80
D	**Labour cost**		
	Skilled labour	45.50	228.80
	Unskilled labour	43.60	188.65
	Sub-total labour	89.00*	418.05
E	**Construction charge**		
	Transport cost	98.18	100.00
	Entrepreneur overhead	154.55	120.00
	Company profit		150.00
	Sub-total construction	253.00	370.00
Total		859.00	1008.65
F	VAT (14%)		141.20
	Grand Total	859.00	1149.86

(Source: Biogas for better life, 2007)

* Farmers “own” labour included

4.5 Model development: Order of magnitute estimates

The investment costs for a biogas unit include all expenses and lost income which are necessary for the erection of the plant e.g.: the land, excavation-work, construction of the digester and gas-holder (wages and material), the piping system, the gas utilisation system, the substrate storage system and other buildings. The conventional variation of capital investment cost with plant capacity has been extensively discussed in section 2.13.1 of the dissertation. The dimension of Q is measured in m^3 (cubic meter), while the value of k and n depend upon the type of item and the characteristic dimension used; they can be derived from historical costs. However, this relationship will only be applicable over a certain range of plant capacity, so data is often presented as curves on log-log graphs. A value of n equal unity (n=1), indicates a constant return to scale and capital costs increase proportionately with plant size. Economies of scale exists where the capacity factor value is less than unity ($n < 1$), indicating that capital investment costs per unit of capacity decrease with increasing plant capacity, while a value of $n > 1$ depicts diseconomies of scale. In general, the value of n depends on the phase that is being processed and it increases along the sequence gas phase, liquid phase, solid phase.

4.5.1 Data and method of analysis

The data used in the analysis presented here are from primary sources for recently built biogas plants and consist of fixed capital investment cost for various fixed dome biogas plant sizes in various locations (both coastal and landlocked countries) in Africa. Primary data were obtained from the original sources (exact data cost), and considered the best in quality and the most reliable. Existing biogas plants (Tables 4.6) ranging from small to large scale are described in a uniform format concerning the plant location, the plant size, year built and the cost data. Cost data refer to the fixed capital investment costs in US dollars ($) and both the output and the technology are homogeneous. Hence, there is no problem of comparability. The original data were first converted from local currency to US $ at the rate applicable in the year of construction, then corrected for to an Engineering News record cost index (ENR index) of 6944 (2004) (McGraw Hill Construction, 2006) to account for cost escalation with time. The effect of geographical placement was also carried out by comparing the scale exponents of the coastal and landlocked biogas plants using all the data sets in

Table 4.6 (4 m^3-5000 m^3) according to the country classifications illustrated Table 4.1. However it is important to note that the effect of learning scale is absent in most of the countries. Commonly, the first generation of any technology is significantly more expensive than those that succeed it due to experience gained in commissioning and construction.

The capital investment costs were then plotted against plant capacity on a log-log scale using the exponential rule (section 2.13.1). By means of the least square method (section 3.3.1), the points were approximated to a straight line to find if there exists any empirical relationship between the plant capacity and the installation cost (fixed capital investment cost). Validation of the developed model was carried out to determine the limit of its usefulness. This is achieved by testing the model against evidence recorded in the field to verify that predictions are robust, general and unbiased. Model predictions must be compared with independent data sets having the same basis as the data used to build the model. The magnitude of relative error (percentage) = *MRE* (degree of estimating error in an individual estimate) given by equation 4.4 was used to accomplish this task.

$$MRE = \frac{|Estimate - Actual|}{|Actual|} \times 100\% \tag{4.4}$$

The quality of the capacity factor (*n*) obtained was also evaluated using inferential statistic (t-test), using a level of significance of 0.05. The t-value corresponding to the appropriate degree of freedom was used as the critical point to accept or reject the hypothesis of constant return to scale.

Applying equation (2.10) to Tables 4.6 and using least square estimation, the cost exponent n power factors were obtained. Inferential statistics, F and heteroscedastic t test were performed on the data in Table 4.6 based on the classification of coastal and landlocked African countries represented in Table 4.1 to ascertain if the data in both locations (group) are significantly different from each other. The F test analyses the differences in the standard deviations of the data sets while the t test analyses differences in the means of the data sets.

Table 4.6: Fixed capital investment cost for biogas installations in some African countries.

S/N	Plant location	Capacity (m^3)	Year built	Original cost	Original cost (normalised to ENR index 2004) US$
1	Namibia	4	1999	750 US$	860
2	Ethiopia	4	2000	554 US$	618
3	South Africa	5	2002	5000 Rand	504
4	South Africa	5	2003	5000 Rand	685
5	Nigeria	6	1999	763 US$	874
6	Rwanda	6	2004	1016 US$	1016
7	Ghana	6	2004	1358 US$	1358
8	Uganda	6	2004	1005 US$	1005
9	Burkina Faso	6	2004	1029 US$	1029
10	Kenya	8	2004	1535 US$	1535
11	Nigeria	10	2005	492,100 Naira	3565
12	South Africa	10	2001	20,000 Rand	2541
13	South Africa	11	2004	23,000 Rand	3487
14	South Africa	11	2004	23,000 Rand	3487
15	South Africa	11	2004	23,000 Rand	3487
16	South Africa	11	2004	23,000 Rand	3487
17	Rwanda	16	2004	2,000 US$	2000
18	Rwanda	16	2004	2,5000 US$	2500
19	Zimbabwe	16	2004	2,212,804 Zim$	3173
20	Kenya	16	2004	2198 US$	2918
21	Kenya	16	2004	2793 US$	2793
22	Ghana	20	2000	7,974 US$	8901
23	Ghana	20	1996	750 US$	6334
24	Lesotho	31	2004	7132 US$	7132
25	South Africa	40	2002	97,000 Rand	9784
26	Burundi	50	2002	18,000 US$	19118
27	Kenya	54	2004	12176 US$	12176
28	Rwanda	74	2002	7150,000 RWF	15943
29	Rwanda	74	2003	7,800,200 RWF	15050
31	Rwanda	84	2004	9,188,010 RWF	15,990
30	Ghana	100	1999	39,120 US$	44,835
32	Kenya	124	2004	26,090 US$	38,090
33	Rwanda	650	2002	50,870,000 RWF	127,318
34	Rwanda	830	2003	58,086,270 RWF	112,073
35	Rwanda	1000	2004	220,000 US$	220,000
36	Rwanda	1430	2005	96,466,000 RWF	173,835
37	South Africa	4500	2004	1,671,429 US$	1,671,429
38	Nigeria	5000	2004	420,000 US$	420,000

4.5.2 Results and discussion

4.5.2.1 Scale factor for total capital investment

Three figures summarise the results of the present analysis. In each figure, the resulting fitting equations are included. Figure 4.7 presents the variation of escalation adjusted capital investment with plant capacity for the biogas installations represented in Table 4.6 for plant size ranging from 4 m^3-124 m^3 (32 data sets). The cost capacity factor, n for biogas installations from Figure 4.7 is 1.20 which indicates diseconomies of scale. Although from a visual inspection of the result, it appears that the correlations are very high, statistical appraisal is nevertheless needed to support the evidence of diseconomies of scale.

The plant-capital expenditure relation was estimated using Equation (4.5).

The estimate is shown below:

$$\ln(C) = -9.84 + 1.20 \ln(Q) \tag{4.5}$$

The "goodness of fit" of the regression equation, or a measure of the strength of the relationship between the capital investment cost and plant capacity can be explained by the value of coefficient of determination, $R^2 = 0.92$ which mean that 92% of the variation in the capital investment cost (dependent variable) is explained or accounted for, by the relationship with plant capacity (independent variable). A t-test applied to the slope (n) testing it against the hypothesis $n = 1$ (hypothesis of constant return to scale), gave a value of 2.593. Using a 5% critical probability level (significance level), $t_c = 2.042$. Hence, the constant returns to scale hypothesis is rejected as the value is significantly different from 1. This result illustrates that the average cost-size relationship is statistically significant.

This is also synonymous to saying that the correlation coefficient is also significant. It can therefore be deduced that the value of 1.20 obtained from the exponential rule is really indicative of diseconomies of scale in the household and community scale biogas industry because a 1% (percent) increase in plant size increases capital cost by 1.20 percent.

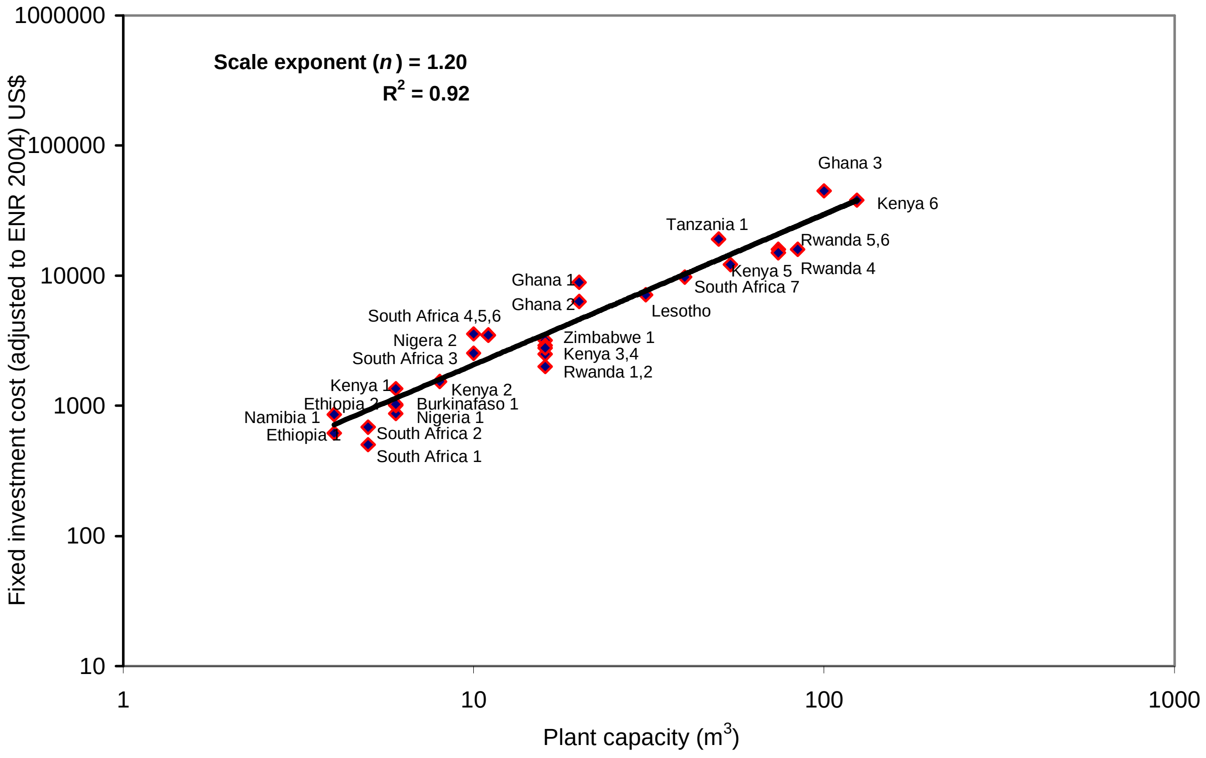


Figure 4.7: Cost Capacity Factor for Biogas Plants in some African countries

In order to develop an understanding of the likely accuracy of cost estimates made on the basis of the above analysis, the standard error of the estimate (SEE) was determined. The SEE indicates the variability of the observed (actual) points around the regression line (predicted points), i.e., the extent to which the observed values (Yi) differ from their calculated value (*Yc*). The SEE thus is the average estimating error when using the equation as the estimating rule. From the regression analysis an SEE value of 0.34 was determined. The average estimating error when using the cost capacity factor n (1.20) thus is ± 34%. This is in agreement with the suggested variable accuracy of -20% to -50% for class 5 estimates published by the American association of Cost Engineers (Chilton, 1950; Sinnott, 1996; AACE, 2003) and indicates that the model can be used within the error limit.

As discussed in chapter 3, an important component of model development is validation. The independent data used for validation are primary data obtained from biogas technology providers in each of the countries. The data in their original format were converted to the same basis with the data used to generate the cost model. The validation result using the magnitude of relative error (%) showed good to fair predictive performance on independent validation. The model demonstrated a good prediction at low scale digester size and fair prediction as the capacity increases. It is of some concern that the model appears to overpredict at larger sizes; on the other hand, the relative error is within the bounds found above. This is reported in Table 4.7 below:

Table 4.7: Model validation using magnitude of relative error (%).

Location	Digester size (m^3)	Model prediction (Estimate) (US$)	Actual data (US$)	Relative error (%)
Kenya	6	1145	1179	-2.8
Burkina Faso	8	1596	1702	-6.2
Lesotho	12	2551	2844	-10.3
Kenya	16	3559	3173	+12.2
Rwanda	56	15149	13091	+15.7

Further, the cost capacity factor obtained is notably greater than the widely used 0.6 factor rule, the use of which would thus lead to significant estimation errors. The result illustrates that the average cost-size relationship is statistically significant and that doubling the size of a plant increases its cost by about 130%, and tripling the size boosts its cost by about 270%.

This finding suggests strongly that application of the 0.6 rule to the analysis of investment costs is not applicable to small and community/institutional biogas installations in African countries. The errors that occur from using a cost capacity factor of 0.6 (the rule of thumb) instead of the actual value of 1.20 obtained in this study are summarised in Table 4.8. This is calculated by the method proposed by Remer and Chai (1990) for chemical plants.

Table 4.8: Potential errors from using the 0.6 or 0.7 as cost capacity factors instead of the value of 1.2 found in this research

Scale up	2 times	3 times	5 times	10 times
Cost-capacity factor n =0.6 (Error %)	- 44	- 60	- 74	- 85
Cost-capacity factor n =0.7 (Error %)	- 40	- 55	- 69	- 81

However, despite the significance of an average cost-size relationship and the good predictive performance of the model, average capital cost for plant of a given size at a particular location could still be highly variable due to costs associated with unique circumstances, possibly labour and productivity, availability of material of construction, soil condition (presence of boulders resulting to high excavation cost), utility access, climate, legislation (environmental) and management practices. This concept has been explained in section 2.8. It could therefore be deduced that the model will not be predictively valid over the full range of conditions that can occur in the biogas industry.

4.5.2.2 Capital cost relationship for small-large scale biogas systems

Figure 4.8 presents the fixed capital investment cost versus the plant capacity for different scale (class) of biogas technology from the data sets presented in Table 4.6.

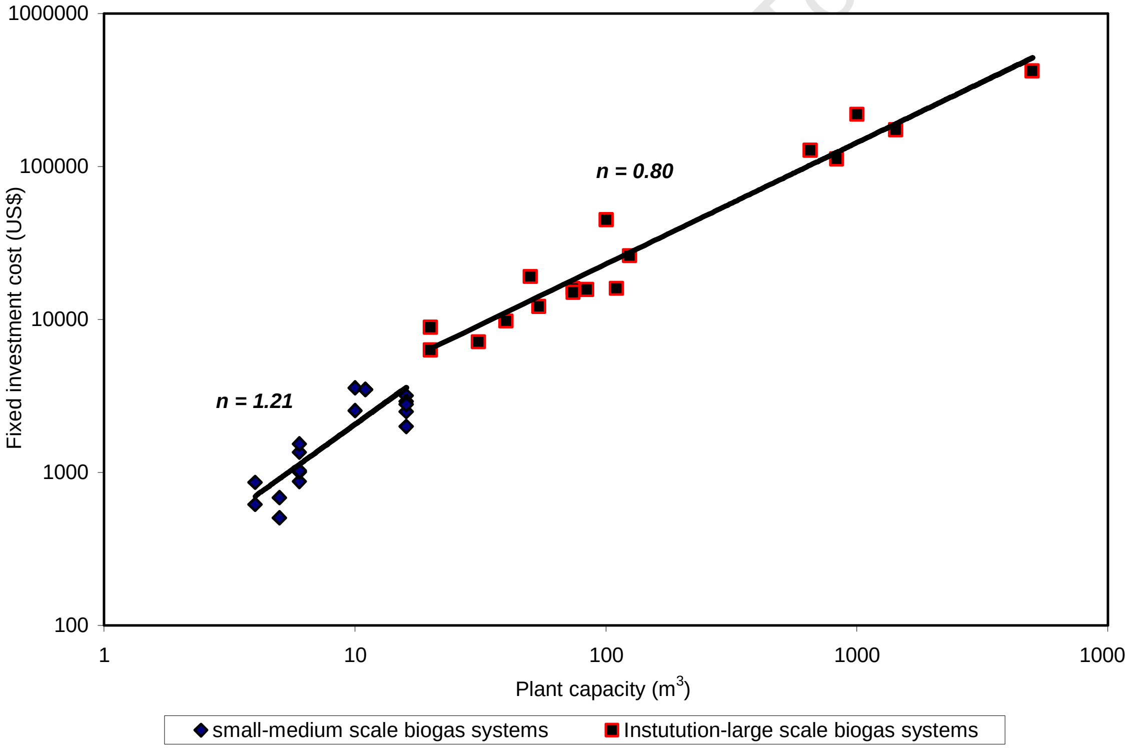


Figure 4.8: Size: Capital cost relationship for small-medium scale biogas & community – large scale biogas plants

For the family/small scale - medium biogas plant (2-16m^3 size range), the cost exponent (capacity factor), n, is 1.21; this is analogous to the scale factor of 1.20 reported above for the small –institutional (community) scale systems. In the case of institutional to large scale biogas technology (> 20 m^3 size range), the cost capacity factor is 0.80 indicating economies of scale. This is an indication of decrease in marginal cost of investment when the plant capacity (output) is increased. Statistical analysis (t-test) indicated that the scale exponent is significantly greater than sixth tenth rule-0.6 ($t_{test} > t_{critical}$: 4.128 >2.145). Although the estimated value of scale exponent in community – large scale biogas systems was less than unity, t-tests could not reject the hypothesis of constant returns to scale, that is $n = 1$, at the 95 percent confidence level. Since the benefits from a community-large plant can be shared by poorer households that would not be able to afford the investment and operating cost of household units, community plants may be more socially viable than the smaller units.

4.5.2.3 Geographical location influence

The influence of location on the fixed capital investment cost of biogas technology (coastal and landlocked biogas plants) in Africa is evaluated in Figure 4.9.

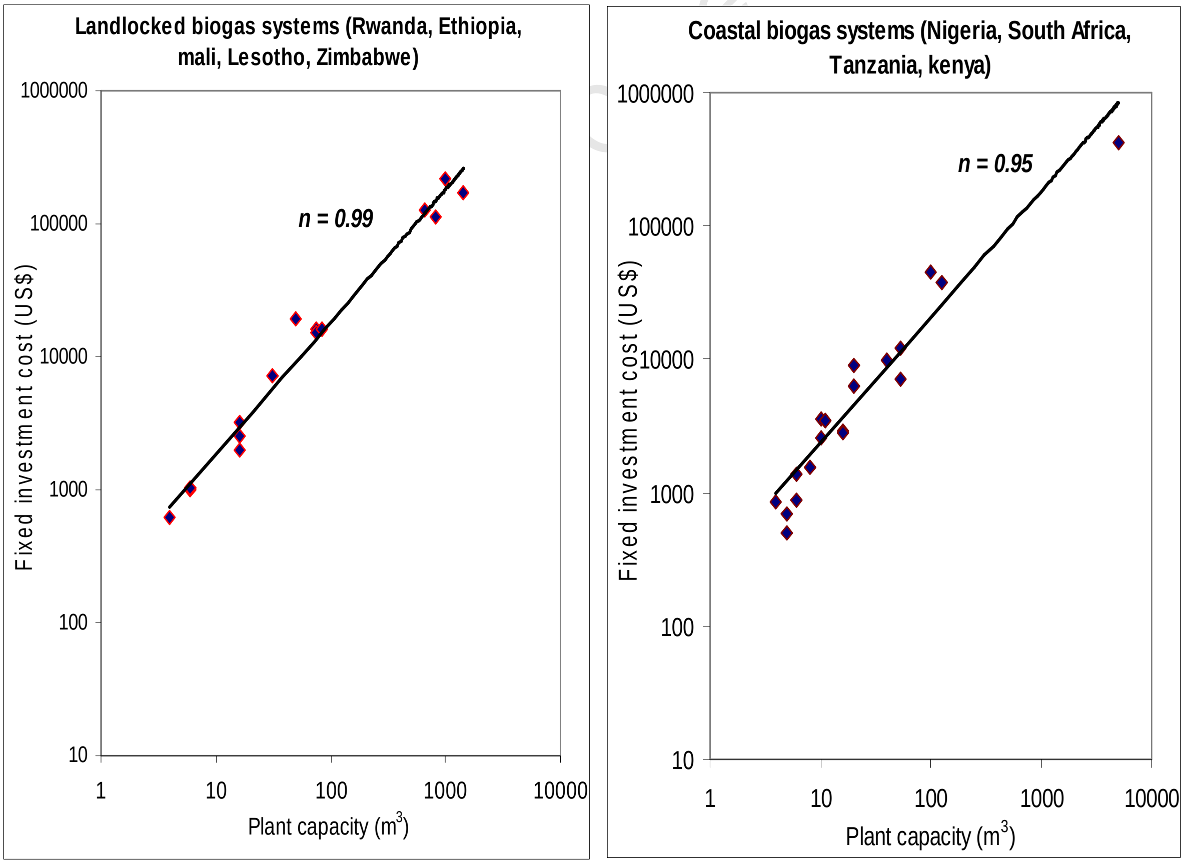


Figure 4.9: Investigation of location difference on biogas technology in coastal and landlocked African countries using cost-capacity factor approach

The cost exponent of the coastal biogas plant is 0.95 while that of landlocked is calculated to be 0.99. An inferential statistic, t (heteroscedastic) test performed on both the coastal and landlocked biogas plants data at an alpha value of 0.05 against the hypothesis that the mean differs ($\mu_c \neq \mu_l$), gives a P value (two tailed) of 0.50 which is higher than alpha value of 0.05 (P (T<=t) two tail = 0.50 > α value 0.05). Therefore, there is not enough evidence to reject the null hypothesis, and we conclude that there is evidence that the means are not different. The result of one way ('single factor") Analysis of variance (ANOVA) with a significance level of 95% (α = 0.05), against the hypothesis that there is no difference between the variances also indicates that, the calculated F value (0.47) is less than the critical value of 4.11.

Hence, we conclude that the means are not significantly different and that the samples come from distributions with equal population means (the fixed investment cost of biogas systems has no significance between the coastal and landlocked African locations). Therefore, the difference in the observed value of *n*-capacity factor is due to random sampling error (chance). Fixed investment costs of biogas systems are not dependent on the geographical placement (coastal or landlocked) as most small-medium scale biogas systems use locally available construction materials.

4.6 The study estimate

Factorial method of capital cost estimation using the Lang factor (f_L) approach as described in section 2.13.2, have been developed over a number of years. A number of textbooks (Bauman, 1964; Ulrich, 1984; Institution of Chemical Engineers, 1988; Breuer and Brennan, 1994; Jebson and Fincham, 1994, Brennan, 1998) and research articles (Brennan and Golonka, 2002; Jebson, 2002; Marouli and Maroulis, 2005) have been written on the subject. It is the purpose of this section to estimate the fixed capital investment cost for the biogas industry in Africa by fitting simplified cost factor models to actual (primary) data from two African countries. A sample of the MS Excel model employed for the determination of the Lang factors has previously been illustrated in Appendix A2.1. This estimate is used in its own right first as an estimating tool and also to further examine the evidence pertaining to evidence of diseconomies of scale in small to medium scale biogas plants in the African continent. The outcome of this estimate will be useful for predicting total plant construction cost based on the delivered cost of plant equipment and also for checking estimates of process plant construction costs.

4.6.1 Data collection and method of analysis

Detailed capital investment cost data were collected for three small/medium scale biogas plants located in Ghana and South Africa, and one large scale biogas installation (brownfield plant) located in South Africa. The small/medium scale biogas plant size ranges from $20m^3$ to $60m^3$, whilst the digester of the large plant has a volume of 4500 m^3. A detailed cost breakdown of the investment could not be obtained partly due to non-availability of the data and lack of willingness by the owners to release the data. The cost distribution of the small/medium biogas plants and the corresponding Lang factor (f_L) analysis are contained in Appendix A4.1. The installed cost defined for the large scale biogas plant located in South Africa includes that of the equipment item purchased, the installation of the equipment item (predominantly labour), the foundations and other civil, steel structures and buildings, piping and cost of project management. In Appendix A4.2, the original data for the large scale biogas plant were multiplied by a uniform factor to protect its confidentiality. Equations (2.14) and (2.15) described in section 2.13.2.1 were fitted to the data for all the plant types described to obtain their individual Lang factors.

The model was tested with independent data (historical data), i.e. running the model with normal inputs against items for which the actual costs are known. The validation of the model was done out using Conte's Criteria (Conte *et al.*, 1986) based on the following statistics:

Here the Magnitude of Relative Error (MRE) is computed (degree of estimating error in an individual estimate) for each data point. This step is a precedent to the next step and is also used to calculate PRED (e). An MRE of 25% or less indicates satisfactory results

$$\text{MRE} = |\,\text{Estimate} - \text{Actual}\,| \,/\, \text{Actual} \qquad (4.6)$$

Calculate the mean magnitude of relative error (average degree of estimating error in a data set) for each data set.

Calculate the mean magnitude of relative error (MMRE) (the average degree of estimating error in a data set) for each data set. According to Conte *et al.*, (1986) the MMRE should have a value of 25% or less (i.e. MMRE <0.25)

$$MMRE = (\Sigma MRE) / n \tag{4.7}$$

where n = total number of estimates.

Calculate the root mean square (model's ability to accurately forecast the individual actual effort) for each data set. This step is a precedent to the next step only. Again, satisfactory results are indicated by a value of 25% or less.

$$RMS = \left[1/n * \sum (Estimate - Actual)^2 \right]^{1/2} \tag{4.8}$$

According to Conte criteria, a model should be within 25% accuracy, 75% of the time. To find this accuracy rate PRED (e), divide the total number of points within a data set that has an MRE = 0.25 or less (represented by *n*) using the equation below:

$$\text{PRED (e)} = k/n \text{, where e= 0.25} \tag{4.9}$$

The result of the analysis is illustrated in appendix A4.3.

4.6.2 Discussion of results

Table 4.9 represents the compilation of factors for individual cost categories in the three small/medium scale and one large scale biogas plants respectively.

A marked difference is observed between the Lang factors obtained for biogas plants and chemical plants. This is probably due to a larger auxiliary infrastructure in chemical plants, not often existing in biogas industries. For all cases (plant sizes 20, 40, 60 m^3), the purchased cost of the equipment is about a third of the capital cost of the plant. The Lang factor (f_L) increases as the plant capacity increases for the small/medium scale biogas plants studied. A Lang factor (f_L) of 2.63 was observed in the case of 20 m^3, f_L of 2.91 in the case of 40m^3, while a factor of 3.04 was observed for the 60m^3 biogas plants. There appears to be corroboration between the increased values of f_L as the capacity size increases and the diseconomies of scale obtained for small/medium scale biogas plants (as discussed in section 4.5.2.1 of the dissertation). It is striking that the strongest diseconomy of scale appears to reside in the indirect costs, with this component of the Lang factor increasing with size in the three cases analysed. The slightly higher total physical cost observed in the 40m^3 could be attributed to higher labour rate in South Africa.

Table 4.9: Breakdown of cost factors for small/medium and large scale biogas plant

	Multiplying factors			
Item	20 m^3 (Ghana)	40 m^3 (South Africa)	60 m^3 (Ghana)	4500 m^3 (South Africa)
Purchased equipment cost (I_E)	1.0	1.0	1.00	1.00
Installation cost				0.21
$\therefore$ Installed equipment cost (IEC) =				$I_E \times 1.21$
Piping , instrumentation & control	-	-	-	0.06
Electrical	-	-	-	0.07
Civil and structural cost	-	-	-	0.24
Structures and building	-	-	-	0.04
Yard improvement/service facilities	-	-	-	-
$\sum f_i$	0.78	1.0	0.93	0.60
Total Physical Cost, $I_E\left(1+\sum f_i\right)$	1.78	2.0	1.90	1.60
Total Direct Cost	-	-	-	
Engineering & supervision	-	-	-	0.10
Contractor’s fee	-	-	-	0.05
Contingency	-	-	-	0.04
Total Indirect Cost, $\sum f_{I\ indirect}$	0.85	0.93	1.11	0.19
Total Fixed Investment, $I_F = I_E + \left(1+\sum f_{i\,dir}\right) + \left(\sum f_{I_{ind}}\right)$	2.63	2.91	3.04	1.79

In the case of large scale biogas plant (4500 m^3), an f_L value of 1.78 was computed. The percentage contribution of the purchased equipment cost to the total capital cost of the plant is 56%. The lower value of f_L observed for this plant (which is equivalent to a higher contribution of the purchased equipment costs) clearly results from the fact that this was a brownfields project, with many of the non-equipment direct expenses falling away.

Potential accuracy of factorial method of capital cost estimation has been proved to be much better when using smaller individual factors for the major plant components, such as piping, electrical, e.t.c. This allows a more detailed understanding of where the costs are in a total plant cost estimate so that they may hopefully be reduced, and much better controlled. To validate the Lang factor, independent data (purchased equipment cost (PEC)) from different countries were used to estimate the total project cost of the plant. It was found that an f_L of 2.63 provide a better cost prediction for the small/medium scale biogas plant.

The result of the Conte criteria revealed that the model satisfies all the three criteria, viz., the mean magnitude of relative error (MMRE) < 0.25, relative root mean square of the error (RRMS), which is less than 0.25 and the estimated effort is within 25% of the actual estimates for at least 75% of the time. PRED (e) is greater than 0.75. Therefore, the methodology proposed is sufficient for the purpose of the estimation.

The f_L values obtained for the African biogas plants are lower compared to the value of 3.6 reported in the textbooks for the gas-phase processing plants. This indicates that applying the textbook value to cost prediction in the African continent will lead to inconsistent estimate.

4.7 Chapter summary and concluding remark

Biogas technology represents one of a number of village scale technologies that could offer the technical possibility of more decentralised approaches to development in African. Most current biogas programmes in Africa however, are based on family-sized plants and their dissemination have experienced a number of set backs as a large proportion of the plant erected were not used or only used to an insufficient extent.

A cost-capacity factor of 1.20 of capital investment cost for small and institutional scale biogas industry in Africa has been obtained on the basis of an analysis of 38 projects across 11 countries from 1999 to 2005, after currency conversion and escalation adjustment. A statistically significant result was obtained, suggesting the existence of diseconomies of scale arising from increasing plant size in the small to institutional type biogas systems. The cost capacity factor obtained is notably greater than the average 0.6 factor rule often used in scale up of chemical process plants. A measure of the strength of the relationship between the capital investment cost and plant capacity can be explained by the value of coefficient of determination, $R^2 = 0.91$. The average estimating error when using the cost capacity factor n (1.20) obtained from the regression statistics as the estimating rule is ± 35%. Independent validation of the model shows a good to fair prediction. Despite the statistical significance of an average cost-size relationship, average capital cost for plant of a given size at a particular location could still be highly variable due to costs associated with unique circumstances, possibly labour and productivity, soil condition (presence of boulder resulting in higher excavation cost) utility access, environmental and management practices.

Cost-capacity factors for biogas plant at various scale of production have also been computed. Values of 1.15 and 0.80 have been obtained for small-medium scale biogas plant (2-16m^3) and community-large scale (>16m^3) respectively. It appears that economies of scale are absent for biogas technology in Africa for the small-medium plant sizes investigated. Therefore the use of the rule of thumb (6/10th) rule for capital cost estimation of small-medium scale African biogas installations will lead to underestimation. The estimated value of scale exponent in the community-large scale biogas systems, was less than unity, however, t-tests could not reject the hypothesis of constant returns to scale, that is $n = 1$, at the 95 percent confidence level. Community to large scale biogas plants are therefore not favoured and might not possess the supposed network externalities. Equally, however, they are not strongly disfavoured, indicating that all potential biogas projects have equal merit on a cost basis.

From the trend observed for coastal and landlocked biogas plants, it appears also that the cost of biogas technology is largely independent of geographical location of the plant, which is probably explained by the use of local construction materials in most small-medium scale biogas plants in Africa. The lower the import content of the total plant costs (for example, amount of steel), the less the external diseconomies which may arise in consequence of sliding exchange rates and transportation construction of materials.

Lang factor (f_L) values of 2.63, 2.91 and 3.04 have been obtained for small/medium scale biogas plants in two African locations. The increase of the Lang factor with size corroborates the observation of diseconomies of scale observed at the order of magnitude level. It is striking that the indirect costs category appears to be most susceptible to such diseconomies. Calibration of the factors revealed that f_L value of 2.63 gives a better cost prediction. The verification of the correctness of the performance model also revealed that the model satisfies all the three Conte's criteria indicating that the model is sufficient for the purpose of effort estimation. An estimated f_L value of 1.79 was obtained for the large scale biogas plant. The factored approach to capital cost estimation remains a useful technique in its own right, and also provides a means of checking the validity of estimates made by more detailed methods. The increased f_L as plant capacity increases supports the evidence of diseconomies of scale obtained for small/medium scale biogas plant in some African countries. This is possibly due to the technologically driven oligopolies (described in section 4.1) experienced in the industry in Africa; interestingly, indirect costs appear to increase fastest as the size of the digester increases.

In conclusion, whilst it must be acknowledged that the results presented in this chapter are based on a relatively small number of existing biogas installations, it should be noted that there are no compelling economic reasons for promoting either large centralised or small decentralised biogas solution in African setting. However, small/medium scale facility has a potential advantage in that it improves the prospects for achieving economies of scale in manufacturing and economies of scale in learning through repeated applications. This advantage can only be exploited, however, if there is sufficient demand for the biogas systems.

Appendix A4

Appendix A4.1: Cost distribution of three small/medium scale biogas plants expressed as percentage of total cost of installation[‡‡‡‡].

Digester size m^3/day	Location	Equipment %	Direct expenses %	Indirect expenses %	Lang factor (f_L)
20	Ghana	38	30	32	2.63
40	South Africa	34	34	32	2.91
60	Ghana	33	30	37	3.04

Appendix A4.2: Cost distribution of large scale biogas plant in South Africa

s/n	Items	Cost expressed in US$
1	Purchased Equipment cost (PEC)	
	Main equipment: Inlet Tank, Equilisation Tank, Methane reactor, Biofilter	7,922,328
2	Equipment Installation	1,678,200
3	Piping, Instrumentation and control	458,250
4	Electrical	512,040
5	Civils	1,938,420
6	Structures & Buildings	287,400
7	Painting	151,673
8	Engineering & Supervision	461,760
9	Construction Expenses	357,600
10	Contingency	320,400

[‡‡‡‡] The data represented the level of detail available

Appendix A4.3: Analysis of model validation using Conte Criteria

n	Actual project cost	Equipment cost	f_L calculated $Cfx = f_L$ (MPIC)	Estimated project cost	MRE	RMS	RRMS
1	463	181	2.56	476	0.027	5.319	0.069
2	685	265	2.58	697	0.017	4.879	0.043
3	874	339	2.58	892	0.020	7.173	0.049
4	2610	1000	2.61	2630	0.008	8.165	0.019
5	3565	1350	2.64	3551	0.004	5.919	0.009
6	12104	4529	2.67	11911	0.016	78.682	0.039

MMRE = 0.015	RRMS = 0.228
PRED (e) = 1	

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5

Fuel Ethanol Process Cost Analysis and Prediction

We can get fuel from fruit, from that shrub by the roadside, or from apples, weeds, saw-dust - almost anything! There is fuel in every bit of vegetable matter that can be fermented. There is enough alcohol in one year's yield of a hectare of potatoes to drive the machinery necessary to cultivate the field for a hundred years. And it remains for someone to find out how this fuel can be produced commercially - better fuel at a cheaper price than we know now. *………. Henry Ford*

5.1 Introduction

This chapter starts with a brief background on historical and modern use of fuel bio-ethanol (globally and in Africa) followed by a review of literature on cost analyses and predictions, with a particular focus on the scale factor in capital cost estimates. Detailed analyses of the breakdown of capital and operating costs of one African distillery operating in a landlocked East African country, in a poorly accessible rural area are then presented. Finally, the chapter demonstrates the relevance of the knowledge gained (from literature, the chapter on biogas, and the preceding distillery cost analyses) by means of an illustrative case located in the Niger Delta area of Nigeria

5.2 Background , historical trend and ethanol utilisation

Ethanol utilisation as transport fuel dated back to the origin of the automobile industry. By way of example, Henry Ford's Model T, called the Quadricycle, built in 1908, was aimed at using ethanol. Fords vision was to "build a vehicle affordable to the working family and powered by a fuel that would boost the rural farm economy" (Rosillo-Calle and Walter, 2006). Contrary to general belief, fuel ethanol has been used in enormous quantities since the early 20th century, particularly in Europe (Germany, France and Italy). In 1902, there was an exhibition in France dedicated to alcohol fuels including automobile, farm machinery, lamps, stoves, heaters. To give an idea of the widespread use of fuel ethanol, in Germany alone more than 95,000 stoves and 37,000 spirit lamps were made in 1902 (Kovarik, 1988). Fuel ethanol played an important role in the in the first four decades of the 20th century. By the mid-1920s, ethanol was widely blended with petrol in almost all industrial countries except in the USA. In the Scandinavian countries, 10-20% blend with gasoline was common, and ethanol was typically produced from paper mill waste. While in most continental Europe, ethanol was obtained from surplus grapes, potatoes, wheat, e.t.c., in Australia, Brazil, and a lot of other sugarcane producing countries; ethanol was produced from cane juice and molasses (Kovarik, 1998). In the USA, the combination of increasing taxes (a concerted campaign by major oil producers) and availability of “cheap” petrol efficiently stamped out the use of ethanol as a major transport fuel in the early part of the 20th century. Ethanol attained some importance only during the Second World War, mostly in Brazil and the USA due to fuel shortages. After the conflict was over, the unavailability of petrol effectively ushered in the use of ethanol. In Brazil, the vital role of the sugar cane industry led to frequent government support, as ethanol production was seen as an instrument of policy to achieve the rationalization of the sugar industry since the early 20th century (Rothman et al, 1983) .

The trend towards cleaner, reformulated gasoline worldwide has been largely responsible for the burgeoning ethanol industry. With its clean “green” nature, ease of manufacture and its ability to be blended with petrol, there has been a steady increase and widespread acceptability of its use by both government and consumers (Berndes *et al*., 2001; Cardona and Sanchez, 2007; Farrel *et al*., 2006; Von Siver and Zacchi, 1995;). Demand for ethanol has also increased substantially in recent years for use in ethanol/gasoline blends mostly due to the recent hike in the crude oil price (Economist 2006). Domestic production and use of ethanol for fuel can decrease dependence on foreign oil, reduce trade deficit, create job in rural community, and reduce air pollution and carbon dioxide build-up (Prasaad *et al.*, 2007). At present, the global ethanol production is over 40 billion litre, accounting for less than 2 per cent of the total petrol consumption. The International Energy Agency (IEA, 2006) predicts that ethanol alone has the potential to make up to 10% of world gasoline use by 2025 and 30% in 2050. Brazil is the world largest producer of ethanol driven in part by government policies dating back to 1970s. Brazil with its low sugar cost feedstock is able to produce ethanol for less than US$0.14 cents per liter (c/l). The US is the largest producer and the world largest consumer of ethanol (Ethanol producer Magazine, 2007). Its development is also a direct result of government policies, but its production costs are much higher at US$0.4 c/L with corn (maize) as its main feedstock (Henniges and Zeddies, 2004; Pat *et al.*, 2007).

The sizeable number of sugarcane mills in Africa indicates significant potential for expanded ethanol production (Karekezi, 2002). The recent interest in ethanol production in Africa is driven partly by the increase in oil price and its low convertible currency earnings. Other factors are environmental reasons for example, prevention of water pollution from dumping of waste molasses was cited as one of the motivations for ethanol production in Malawi, and dumping of waste molasses is cited as a continuing environmental problem in Uganda (Kwong and Thomas, 2001). The expanded use of bio-ethanol would have significant health benefits in replacing lead as an octane enhancer in most African countries where leaded fuel is still widely used. Africa represents the largest leaded fuel user in the world. Of a total of 49 countries in Sub-Saharan Africa, 22 countries use leaded fuel only, 14 dual system and 13 unleaded. The fuel status of some of the African countries is illustrated in Table 5.1, (UNEP, 2005 modified).

There are several reasons for current public and private interest and support for the production of bioethanol mentioned earlier. For example;

- It might be possible to establish a local industry to substitute for some portion of the imported crude oil in the continent
- If the economics were favourable, producing ethanol might provide a basis for establishing alternative uses for agricultural land and may generate new sources of employment in the agriculture sector
- If the economics is not based on production of ethanol as a single product, ethanol production might be a viable co-product with other agricultural-based products such as sugar, fibreboard, or diversified agriculture.

Table 5. 1: Leaded and Unleaded Fuel Consumption Pattern in some African countries (Modified from UNEP, 2005)

Country	Leaded fuel	Unleaded fuel	Dual System (leaded and unleaded fuel)
Angola	√		
Benin		√	
Botswana			√
Burkina Faso	√		
Burundi	√		
Cameroon		√	
Cape Verde		√	
Chad	√		
Comoros	√		
Congo (Brazzaville)	√		
Democratic Republic of Congo	√		
Cote d’Ivoire		√	
Djibouti	√		
Equatorial Guinea	√		
Eritrea		√	
Ethiopia		√	
Gabon	√		
Ghana		√	
Kenya			√
Lesotho			√
Liberia	√		
Madagascar			√
Malawi	√		
Mali	√		
Mauritania		√	
Mauritius		√	
Mozambique			√
Namibia			√
Niger			√
Nigeria		√	
Rwanda		√	
Sao Tome Principe	√		
Senegal	√		
Seychelles			√
Sierra Leone	√		
South Africa		√	
Sudan		√	
Swaziland			√
Tanzania		√	
The Gambia	√		
Togo			√
Uganda			√
Zambia			√
Zimbabwe			√

5.3 Types of Ethanol distilleries

There are two main types of distillery used in the production of sugarcane based ethanol: autonomous (stand alone plant) distillery in a cane plantation dedicated to alcohol production, or a distillery annexed to a plantation primarily engaged in production of sugar for export.

Their size can vary considerably, from a few hundred of liters per day (l/day), or so-called mini-distilleries, to about 2.5 million liters/day. The biggest ethanol plant in the world in China, the Jilin Tianhe Ethanol Distillery has an initial capacity of 600,000 tonnes a year or 2.5 million liters per day, and its potential final capacity can be raised to 800,000 tonnes per year (World Fuel Ethanol, 2004). The types and size of distillery is determined by specific requirements of the ethanol (and sugar) market (Thomas and Kwong, 2001).

An annexed distillery is built alongside a sugar cane mill. In this case, the main objective would be to produce sugar rather than alcohol, sharing several common systems such as utilities such as boilers, effluent treatment and personnel. An annexed plant can provide considerable flexibility against price fluctuations and is currently the preferred option. There are different economic strategies for co producing sugar and ethanol. The main choice is whether to produce in fixed or flexible quantities. Fixed quantity production generally means reserving all of the economically extractable sugars for sugar production and using "C" molasses or "final molasses" for ethanol production. C molasses is not valuable for sugar production because the sugar extraction has reached a point of diminishing returns. Such a strategy would be chosen when the market value of sugar is generally higher than that of ethanol in production-equivalent terms, and is expected to remain higher for the foreseeable future. Alternatively, sugar extraction can be halted after the first or second stages, resulting in "A" or "B" molasses, respectively. These molasses streams will have fermentable sugars that can still be economically extracted. However, the presence of additional fermentable sugar increases the efficiency of ethanol conversion. Consequently, if ethanol is expected to have a market value close to or greater than that of sugar, then it makes economic sense to prioritize ethanol production over some sugar production, by using molasses A or B as the ethanol feedstock. A disadvantage is that the distillery is an integral part of a more complex process plant, and that higher capital cost is required.

In an autonomous (stand alone) plant, the primary aim is to produce ethanol. This is only justified where there is a large and highly secure market for ethanol, as in the case of Brazil and India. In recent times in Brazil, most of the autonomous plants have been converted to annexed type. The autonomous ethanol plants use typically cane juice, but also molasses in the case of India, purchased from sugar mills. The capital cost of an autonomous ethanol plant is usually lower than that of an annexed type, but it has little flexibility in the case of price fluctuations, for both sugar and ethanol (Rosalline-Calle and Walter, 2006).

In the USA, corn distilleries predominate, and two different processes are used to produce ethanol or other starch-based products: (i) dry milling (DM) or mash distillation and (ii) wet milling (WM). The primary distinction between the two processes occurs during fermentation. In the DM process type, the grain is cleaned and dry-ground to reduce the particle size and then fermented. The major co-product is distiller's grain (DGs). The WM process extracts the maximum amount of starch from the grain by adding water to enhance starch removal which is converted into dextrose for further refining and is subsequently used to convert enzymes or fermented to produce amino acids, organic acids, e.t.c. WM plants produce corn gluten feed (CGF) and corn gluten meal (CGM), which are high in high protein content, and corn oil as primary co-products. CGF and CGM are the sources for producing ethanol, together with high fructose corn syrup (HFCS). This means that the co-products produced with ethanol in a WM can have more value. There are more dry-mill plants producing ethanol, although wet mill plants account for a majority of the capacity. The primary advantages of the conventional dry mill plant are, lower capital cost and higher ethanol yield on a capacity basis, and simplicity in marketing co-products. These three advantages have allowed this process technology to be commercialized in smaller ethanol plants (40 million gallons (150 million liters) per year or less). Additionally, for U.S. plants having a production capacity of less than 30 million gallons, a small ethanol producer's tax credit is available.

5.4 Ethanol production and use in Africa

Ethanol production in Africa is concentrated at the southern tip of the continent, with the Republic of South Africa accounting for approximately 70 per cent of the total, followed by Mauritius and Zimbabwe. Some countries have facilities that are in very poor conditions due to years of unrest and /or lack of investment, including Angola, Republic of Congo (DR Congo), Madagascar, and Mozambique. The largest player is SASOL, producing industrial alcohol from coal and gas, with a capacity of around 220,000 tonnes a year. All of this is used to make ethyl acetate, high purity ethanol and a small volume for fuel. Production of high purity ethanol has been growing in recent years, with the total in 2001 forecast to reach 126,000 tonnes, against 97,000 tonnes in 2000. Besides synthetic alcohol, South Africa also produces increasing amounts of fermentation ethanol, with molasses being the major feedstock. One of the most interesting import markets in Africa in recent years was Nigeria. The country stopped producing ethanol in 2001, after cheap world market imports and a difficult domestic feedstock situation had undermined the viability of the domestic sector. The total market volume in Nigeria is estimated at around 90 million liters per annum, the largest part of which is now supplied by South Africa, Brazil and Spain.

Fuel ethanol has been produced in Zimbabwe since 1980. The economic sanctions imposed on Rhodesia (the colonial name for Zimbabwe) in the 1970s and foreign-exchange limitations generated the need for an independent, self-sufficient source of automotive fuel. As such, a molasses based ethanol plant began operation in 1980; shortly after the state of Zimbabwe was created at the Triangle sugar refinery. Since 1980 Zimbabwe pioneered the production of fuel ethanol for blending with gasoline in Africa (most gasoline sold in Zimbabwe since 1980 contained 12-15 percent ethanol). Production capacity has exceeded 37.5 million liters since 1983, though actual production stood at only 6 million gallons in 2004. The ethanol plant was designed to operate on a variety of feedstock using different grades of molasses, cane juice, or even raw sugar itself. This flexibility means that the plant is fully integrated with the rest of the sugar production process and can respond rapidly to changes. Thus, the fermentable sugar content, for example, of molasses entering the plant can be adjusted at the expense of sugar production depending on relative market prices, in order to maximise the return on total investment in both sugar and ethanol production (Da Silva *et al.*, 1992). Triangle sugar refinery stopped the production of ethanol for blending with petrol during the 1992 drought when the company could not produce enough sugarcane for ethanol production. However, the company is currently producing about 30 million liters of industrial ethanol for export markets in Europe.

Malawi has very favourable economic conditions for ethanol. Like Zimbabwe, Malawi had been continuously producing ethanol and blending it with gasoline since 1982, although the production volume has fluctuated significantly over the years (Kartha *et al.*, 2005. Ethanol is produced from sugar molasses at Dwangwa Estate Plant on the lakeshore. Because of high freight costs, the wholesale price of gasoline (petrol 95 ULP) is about ZAR 631.30 c/l as of September 2007, and about ZAR 691 c/l retail (Shell Southern Africa, 2007). Moreover, Malawi's molasses has a low value because the cost of shipping it to a port for export typically exceeds the world market price (US AID, 1989b). Malawi's ethanol company Ltd. produces about 10–12 Ml per year, providing a 15% blend for gasoline (US AID, 1988, Thomas and Kwong, 2001).

An ethanol producer in Mauritius, an island east of Madagascar, Africa, began shipping ethanol to the EU in late August of 2004. Alcodis reportedly shipped 3.5 million liters (925,000 gallons) of ethanol made from molasses. According to Europe Energy, Alcodis plans to export up to 30 million liters (8 million gallons) per year. The company has partnered with Swiss group Alcotra, an ethanol producer and distributor, to examine the international market (Ethanol Producer Magazine, 2004).

Molasses distillation plants also exist in such countries as Mozambique, Tanzania, Zambia, Kenya, Angola, Uganda, Egypt, and Ethiopia. Existing information on ethanol plants in Nigeria are scanty. By a way of example, the only government owned commercial bioethanol plant, Nigerian Yeast and Alcohol Manufacturing Company (NYAMCO) which was established in 1973 as an annex to the Nigerian Sugar company (NISUCO) for the purpose of producing ethanol using the molasses generated by NISUCO. The plant was retooled when supply of molasses was running short from the complementary Sugar plant. It however floundered due to management problems (because of problems in organizing the collection of dried cassava roots from scattered smallholders) (Amigun *et al*, 2008).

5.5 Cost analyses and predictions for bio-ethanol

The main cost components of ethanol plants in general are capital and feedstock supply (Solomon *et al.*, 2007). It is difficult to provide a general information about ethanol fuel economics (i.e. precisely model the production technology), because production costs and the product value depend on plant location, feedstock types, production scale and the end use. This uncertainty extends to the degree of or lack of substitutability among factor inputs (i.e. capital, labour, energy, materials, water) and economies of scale, which have been found to be highly variable depending on the production technology (Solomon *et al*, 2007). A key factor is whether the facility is an autonomous distillery in a cane plantation dedicated to alcohol production, or a distillery annexed to a plantation primarily engaged in production of sugar for export (World Bank, 1980).

Thomas and Kwong, (2001) proposed that the economics of biomass ethanol production and use depend on a number of factors specific to the local situation. These factors include:

- The cost of biomass materials, which varies among countries, depending on the biomass source, land availability and agricultural productivity
- Ethanol production costs, which depend on plant location, size, process and particular technology configuration
- The cost of gasoline in individual countries which depends on fluctuating petroleum prices and domestic refining characteristics
- The strategic benefit of substituting imported petroleum with domestic resources.

From the technological perceptive, many scientific studies have been carried out but literature on the economic aspects of bioethanol production such as cost analyses and the potential for further cost benefits are limited (Henniges and Zeddies, 2003).

Some of the existing cost models for ethanol production technology are the Cobb-Douglas model, the Leontiff or CES format, and the Solomon model (Solomon *et al*, 2007). The total cost of producing ethanol is composed of capital related charges, and manufacturing costs (net feedstock costs plus variable operating costs).

Nguyen and Prince (1996) proposed that the cost of producing ethanol decreases with plant size. On the other hand, the area of crop required increases: the average crop transport distance then also increases, so that the transport cost component of the production cost also increases. There will then be some plant size or capacity which will minimise the total production cost. Warren *et al.* (1994) and Kwiatkowski *et al.* (2006) proposed that the primary feedstock cost, has the greatest impact on the cost of producing ethanol. Coelho *et al.* (2006) established that production costs of ethanol from sugarcane are low not only due to geographic conditions but also because of the extremely favourable energy balance. This favourable energy balance is due mainly to the fact that all energy needs in sugarcane mills are provided without any external energy source through burning of sugarcane bagasse in boilers to produce steam and electricity/mechanical energy to fuel the process (cogeneration process).

Economies of scale have been shown to exist in the construction of ethanol plants (Enecon, 2002), Gallagher *et al*., 2005) and the gross production cost of ethanol (Henniges and Zeddies, 2003). A value of 0.6 was proposed by the USDA for a dry milling ethanol facility compared to NREL's average value of 0.63 (McAloon *et al.*, 2000). Gallagher *et al.* (2005) suggested an estimating power factor of 0.86 for dry mill ethanol industry based in the USA. However, average capital costs for plants of a given size at a particular location is still highly variable due to costs associated with unique circumstances such as utility access and environmental compliance. The USDA's experience in the corn industry showed that a Lang factor of 3.0 was reasonable for going from purchased equipment costs to total project investment, while NREL's installation costing method produced a factor of 2.5 (McAloon *et al.*, 2000). Quireshi and Blaschek (2000), in their economic study used a Lang factor of 3.0 to calculate the fixed capital investment cost for an ethanol plant annexed to an already existing corn milling plant in the mid-west region of United States of America.

5.6 Scale factor in capital cost estimates of ethanol plant

Capital costs have been identified (Tiffany and Eidman, 2003) as one of the secondary success factors in ethanol production. Fuel ethanol from starch and sugar has grown rapidly in the United States and Brazil respectively over the past two decades. In both cases, there has been a large reduction in plant capital costs and production costs. In the United States, for example, a 190 million liter per year ethanol plant cost about $ 150 million (US) to build in early 1980. The same plant size cost about $50 million (US) in 2004 (USDA, 2006). There is an overwhelming empirical evidence to suggest that deploying new technologies in competitive markets lead to technology learning, in which the cost of using a new technology falls and its technical performance improves as sales and operational experience accumulates. This concept has been explained in section 2.8 of the dissertation.

In this section, capital cost-plant relationship analysis were carried out for dry-mill ethanol processing plant in the USA based on the principle already explained in section 2.14.1 of this dissertation. The appropriate data for the analysis was retrieved from the report work of $(S\&T)^2$ consultant Inc. (2004) indicating the capital cost of a number of recently built corn ethanol plants (dry mill operations) in the United States. According to the report, the early data were obtained from the company press information, while the more recent data were from the company SEC filings (A document, usually containing financial data, that a company delivers to the security exchange commission) and, thereby, to the public (Table 5.2). The data were analysed by plotting the normalised cost (adjusted to ENR, 2004) against the plant capacity.

Table 5.2 Capital costs of recent US corn ethanol plants (Dry Mill operations)

Location	Year	Design Size	Design Size	Capital Cost (CC)	Relative capital cost
		(Million USG/yr)	(Million Liters/yr)	(Million USD)	Adjusted (ENR-2004)
Benson, MN	1986	15	56.78	24.4	39.45
Luverne. MN	1998	15	56.78	20.5	24.05
Alber Lea, MN	1999	15	56.78	20	22.92
Bingham Lake, MN	1997	11.5	43.53	19	22.65
St. Joseph, MO	2001	15	56.78	21.5	23.54
Wenworth SD	2001	40	151.40	40.5	44.34
Monroe Wisconsin	2002	40	151.40	46.4	49.28
Chancellor, SD	2003	42	158.97	47.4	49.17
Mason City Iowa	2004	40	151.40	50.6	50.60
Plainview, NE	2003	20	75.70	30.7	31.85
Garnett, KS	2004	25	94.63	30.4	30.40
Granite Falls, Mn	2004	40	151.40	46.4	46.40
Rochelle, IL	2004	50	189.25	56.6	56.60
Rensselaer, IN	2004	40	151.40	49.4	49.40
Marcus, IA	2003	40	151.40	50.4	52.28
Milbank , SD	2002	40	151.40	44.2	46.95
Davenport, NE	2003	40	151.40	49.4	51.25
Friesland, WI	2004	40	151.40	51.5	51.50
Campus, KS	2004	30	113.55	35.5	35.50

The resulting capacity factor of $n = 0.62$ (Figure 5.1), support the evidence of economies of scale in the US ethanol industry – and is significantly lower than the factor of 0.86 reported by Gallagher *et al*. (2005). The data points for the smaller plants are older but essentially the same curve results from using the post 2001 data. This significant difference in the scale factor of 0.62 obtained in this analysis and 0.86 reported by Gallagher *et al*. 2005 could be attributed to the effect of technological learning experience. While the ethanol plants plant used in this analysis were mostly recent, the ethanol plants in the report of Gallagher *et al*. 2005 were constructed at different times over the last 25 years and the plant construction cost data were deflated by a plant cost index to 1988.

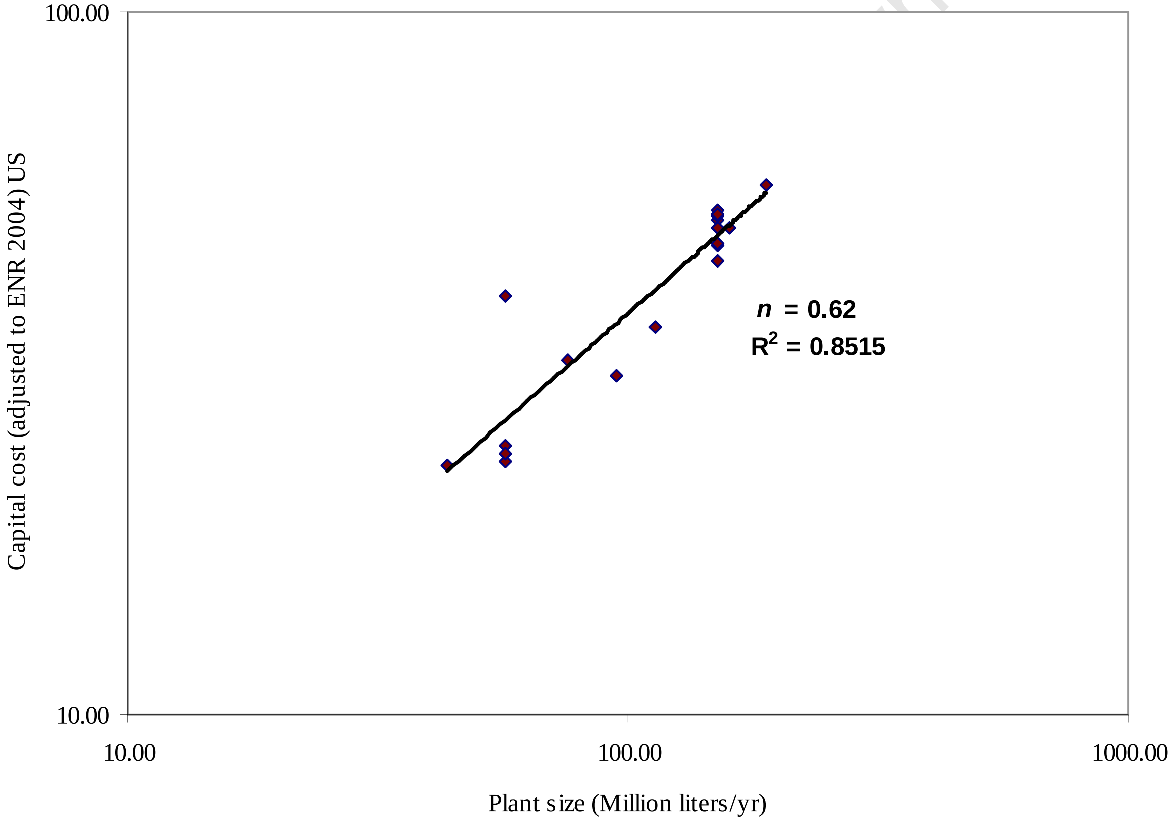

Figure 5.1: Impact of plant size on capital cost

For the capital investment in Africa, a leading ethanol plant construction company was contacted during the study for up-to-date pricing for fuel ethanol plants in different locations (countries) in Africa for a green field molasses-to-fuel-grade-ethanol complex. Analysis of the supplied data revealed that the company works with value of n ranging from 0.56 to 0.59, but for costs excluding land purchase or site development, local taxes and duties, license or permit cost for plant by local authorities, unloading of equipments and other materials at port of destination and local transit cost, cost impacts due to local standards and should therefore be regarded as a ball park estimate. The estimate provided also includes the provision of an effluent treatment, taxes and duties paid in India and FOB and CIF cost.

5.7 Capital and operating cost analyses of a rural African distillery

The study of economic parameters involved in the functioning of an ethanol plant has rarely been carried out from an engineering point of view, and there are no publications in this regard for ethanol plants in Africa. This section aims to present an analysis of the breakdown of the capital and operating costs of one African distillery, operating in a landlocked country, in a poorly accessible rural area. The fixed capital investment cost is analysed so as to test the applicability of a factorial method (the Lang factor (f_L) approach), while the operating cost is studied with a view of interrogating the multiplication factors proposed by Turton *et al.* (1998). Both techniques are regularly used for quick cost estimation.

5.7.1 Plant description

The fuel ethanol distillery studied here is located about 350 kilometres away from the country's capital city. The region in which it is located has an altitude ranging from 1350 meters to 1600 metre above sea level. Its temperature varies from the highest 31^{o}C to the lowest 15^{o}C and its average annual rainfall is 1,300 mm. The plant is rurally located, with no access to electricity nor to landline telephone.

The ethanol plant which is annexed to a sugar factory produces a power alcohol (99.5%) and has a design capacity of 45,000 Liters/day. The ethanol plant makes use of the by-product molasses from the adjoining sugar factory which has a daily crushing capacity of 40,000 quintals (40 million kg) of cane to produce 850,000 quintals (850 million kg) of high quality commercial sugar per annum. Therefore there is no cost incurred on the raw material and its transportation. The ethanol produced can be blended with gasoline (90%) to be used as a motor fuel (power ethanol) without any engine modification and also blended with kerosene (50%) to be used as household cooking fuel. The ethanol distillery was built by a Brazilian construction company in 1999. Based on a reliable production process, the plant was meant to produce 450 hectolitre of pure alcohol per day at 100% capacity utilisation.

The distillery is in good operating condition, as would be expected from the limited amount of time it has operated. The plant operates 24 hr/day, 7 months in a year, with the remaining 5 months (down time allowance) due to seasonality of the harvest, equipment repair and maintenance. Therefore, a basis of 212 days per year (4464 hours) operating time was used in all cost analyses. The plant is semi-automated and the energy consumption is fairly high. The distillery was not designed for energy efficiency, since excess bagasse and excess steam are readily available from the sugar factory. A simplified flow diagram of the process is shown in Figures 5.2. The actual process contains more than 200 pieces of equipment and unit operations.

5.7.2 Fixed capital investment cost analysis: The Lang factor (f_L) approach

Factorial analysis of fixed capital investment costs by means of the so-called ‘Lang factor’ was introduced in section 2.13.2. Most of the existing Lang factors are from American and European sources, and are fairly old. In most African countries typically characterised by low labour rates for semi and unskilled personnel and very few locally established engineering equipment suppliers and or specialist support services, the purchased equipment is mostly imported, leading to increased cost due to additional freight, legal, administrative, custom and import duties and insurance fees.

The use of Lang factors, which are based on high labour cost, on project with no additional cost of equipment importation, may well result in a preliminary capital cost which is unrealistic, and the project may probably not proceed. The greater the uncertainties of capital cost, the more cautious investors are likely to be. Hence, the more accurate these factors are, the greater the likelihood of the more marginal projects proceeding to the benefit of all concerned.

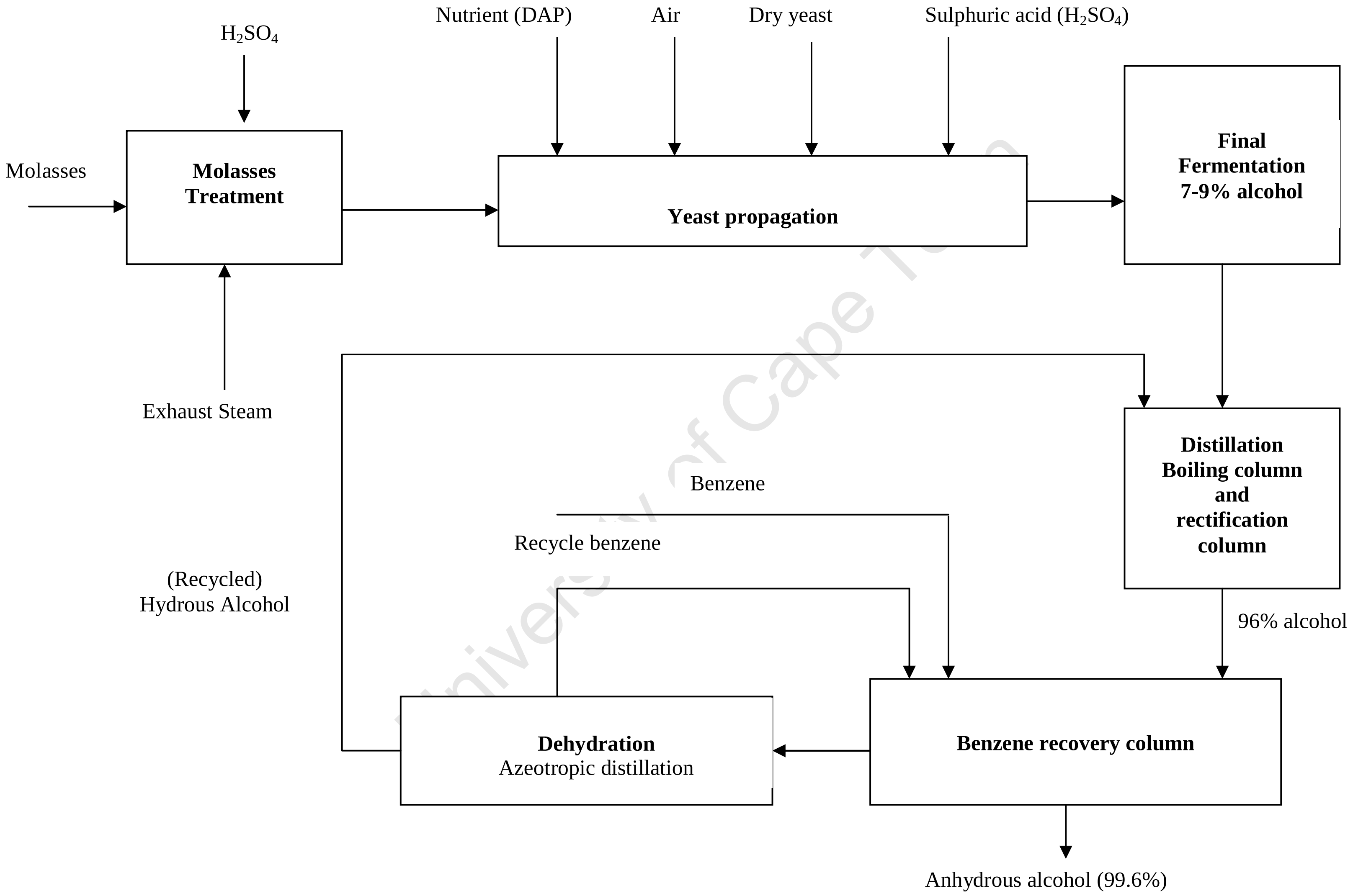

Figure 5.2: A simplified flow diagram of the distillery

5.7.3 Data and method of analysis

Cost data were collected on-site in a visit that lasted for one week. The visit included review of construction and operational cost records, collection of information from interviews with key plant personnel, with the help of an interpreter, a trained process engineer. A draft report was then prepared for the plant summarising the information obtained. The draft reports were cycled back to the distillery management for their review and were updated as needed. The process was time consuming and resource intensive, but we believe it produced high-quality cost data that were comprehensive in scope.

The cost structure, multiplied by a uniform factor to protect confidentiality, was used to create an econometric model using generally acceptable methods for conducting conceptual economic evaluation as described in section 2.13.2. The descriptions of the components of fixed capital investment cost are explained in Appendix B5.1. The main equipment used in the ethanol plant, their specifications and costs are listed in Appendix B5.2. It is pertinent to note that processes and equipment vary greatly, depending on feedstock, ethanol end use, available support utilities, process energy source, by-product use and plant scale. Fixed capital cost (FC), as defined in section 2.12, is the amount of money necessary to completely construct a processing plant with auxiliary services, and to bring it to the point of start-up production. It is basically the total value of all the assets of the plant. Assets can be tangible or intangible. Tangible (or fixed) assets comprise machinery (including the cost of assembly), buildings, auxiliary installations, etc., and the intangible assets include patents and technical knowledge.

To make a more accurate estimate, the cost factors that are compounded into the Lang factor are considered individually. The cost items, already described in section 2.13.2.1 (Table 2.6) that are incurred at the construction phase of a process plant, in addition to the purchased equipment costs, can be arrayed into the following two categories (Marouli and Maroulis, 2005):

- Civil work cost (C_{cv}), including site improvements, building and structure
- Mechanical and electrical work cost (C_{me}), including equipment installation, piping, instrumentation and control, electrical equipment, engineering and supervision.

The above division is selected for the purpose of the present analysis, which is appropriate for the available data. As the definition of these terms given by various authors are generally different, Table 5.3, is introduced to make clear the definition used. Based on the cost division, the detailed factorial method can be expressed by the following equations:

Table 5.3: Definition of cost items

	C_{eq}	C_{me}	C_{cv}
Fixed capital investment cost			
Purchased equipment	*		
Equipment installation		*	
Piping, Instrumentation and control		*	
Electrical		*	
Civil and structural cost			*
Structures and building			*
Yard improvement/service facilities			*
Engineering and supervision		*	

$$C_{FX} = C_{eq} + C_{CV} + C_{me} \tag{5.1}$$

$$C_{CV} = f_{cv} C_{eq} \tag{5.2}$$

$$C_{me} = f_{me} C_{eq} \tag{5.3}$$

where:

C_{eq} = purchased equipment cost

C_{cv} = civil work and structural cost

C_{me} = mechanical and electrical cost

f_{cv} = civil works cost factor

f_{me} = mechanical and electrical cost factor

The above models can be represented in the format below:

$$C_{FX} = (1 + f_{cv} + f_{me}) C_{eq} \tag{5.4}$$

5.7.4 Result and discussion

Tables 5.4 and B5.3 in the Appendix shows a compilation of values of Lang factors (f_L) obtained for the distillery described above. f_L was computed for both OBL and IBL plant according to the illustration in section 2.13.2. For IBL plant, factors for individual cost categories of piping, instrumentation and control, electrical, civil and structural cost, structures & building and yard improvement/service facilities are 0.40, 0.09, 0.31, 0.11 and 0.14 respectively. Factors for corresponding individual cost categories of piping, instrumentation and control, electrical, civil and structural cost, structures & building and yard improvement/service facilities for OBL plant are 0.53, 0.12, 0.40, 0.14 and 0.19 respectively. It is evident from the Tables that the ratio of the installed cost to purchased cost for an equipment item depends on the magnitude of purchased equipment costs and hence on plant capacity. The implied dependence of Lang factor f_L on average equipment cost PEC is consistent with work of others (for example, Montfoort and Meijer (1983), reported that $f_L \alpha PEC^{-0.22}$) (Brennan and Golonka, 2002). A value of Lang factor f_L = 2.81 was obtained for IBL distillery with an equipment installation cost factor of 0.26 while for OBL distiller, a f_L = 2.39 was obtained with an equipment installation cost factor of 0.20. Using installed equipment cost as basis, the corresponding factor f_L is 2.22 for IBL plant and 1.99 for OBL plant. This plant is integrated with an existing sugar mill factory making it an annexed ethanol plant. The estimated f_L values of 2.81 and 2.39 in this study are lower than the values proposed in the textbooks (Brennan, 1998; Garret, 1998; Guthrie, 1969; Kharbanda and Stallworthy, 1988; Turton *et al*., 1998). The difference in the f_L values for IBL and OBL distillery support the fact that the scope included within a battery limit of a process plant must be well-defined. The magnitude of the OBL as a percentage of IBL in this study is ≈ 20%. This value is in the range of the typical value of 5% -100% reported by Brennan, (1998). The raw material requirement for the distillery (molasses type "C") is supplied as the product of an adjoining sugar mill. This is piped with minimal intermediate storage. Utilities such as steam, effluent treatment facilities and building and service facilities are also shared with the annexed sugar mill. This ratio will be higher for a stand-alone or a grass root distillery. Therefore, rules of thumb giving OBL capital as a percentage of IBL capital, even for a given technology must be approached with caution as this depend on project implementation, scope and location.

Table 5.4: Values of Lang factors (f_L) obtained for the (OBL) African distillery located in a landlocked and poorly accessible rural location

Item	Multiplying factor	Cost of item Units	% Direct cost	% Total cost
Installed equipment cost (PEC)	1.00	28,555,318	53	50
• Purchased equipment cost (I_E)	1.00	23,748,593	44	42
• Installation cost	0.20	4,806,725	9	8
∴ Installed equipment cost (PEC) =	$I_E \times 1.20$			
Piping , instrumentation & control	0.40	9,615,084	18	17
• Basis of installed equipment cost	0.34	9,615,084	18	17
Electrical	0.09	2,095,911	4	3
• Basis of installed equipment cost	0.07	2,095,911	4	3
Civil and structural cost	0.31	7,363,871	14	13
• Basis of installed equipment cost	0.26	7,363,871	14	13
Structures and building	0.11	2,587,717	5	5
• Basis of installed equipment cost	0.09	2,587,717	5	5
Yard improvement/service facilities	0.14	3,391,423	6	6
• Basis of installed equipment cost	0.12	3,391,423	6	6
$\sum f_i$	1.3	29,860,731	56	53
• Basis of installed equipment cost	0.9	25,054,006	47	44
Total Physical Cost, $I_E \left(1+\sum f_i\right)$	2.3	53,609,324	100	95
• Basis of installed equipment cost	1.9	53,609,324	100	95
Total Direct Cost, $\sum f_{dc}$		53,609,324		
Engineering & supervision	0.06	3,087,241	6	6
• Basis of installed equipment cost	0.06	3,087,241	6	6
Total Indirect Cost, $\sum f_{ic}$	0.13	3,087,241	6	6
• Basis of installed equipment cost	0.11	3,087,241	6	6
Total Fixed Investment, $I_F = I_E [\left(1+\sum f_i\right)+\left(\sum f_{ic}\right)]$	2.39	56,696,565		
• Basis of installed equipment cost	1.99	56,696,565		

The estimated value 2.81 (IBL plant) is also a very close to the value of Lang factor $\left(f_L = 3.0\right)$ used for ethanol plant annexed to an already existing corn milling plant in the mid west region of the USA (Qureshi and Blaschek, 2000) and f_L = 2.75 used for calculating total capital investment cost for an annexed dry-mill plant located in the USA (McAloon *et al*., 2000). A value of f_L = 4.5 has been used by Di Luccio (2002) and Wasewar and Pangarkar (2006) for grass-roots plant.

The low value of f_L obtained in this study for the OBL plant is probably due to the higher equipment cost (53 % of total plant cost) and lower labour rate. The higher equipment cost could be attributed to the landlocked characteristic of the plant location. Generally in countries other than the USA and Europe, especially those without a chemical manufacturing industry, the purchased equipment is mostly imported, with additional freight, customs and import duties, agents' fees, and insurance, thereby making the price higher.

The percentage of purchased equipment cost (53%) obtained in this study for OBL distillery is closely related to the value of 50-65% of the total investment /project cost, given by one of the leading molasses based ethanol construction companies in the world with proven African experience. The purchased equipment installation of 20% of equipment cost is in the range (18-20%) provided by the same source. The plant location is characterised by low labour rate for semi-skilled and unskilled labour categories. This may offset to some extent the high transportation expenses. In a related industry, a recent investigation also reported lower Lang factor than the values used in chemical industries: $\left(f_L = 1.6\right)$ and $\left(f_L = 1.8\right)$ have been recorded for food plants by Maroulis and Saracos (2003) and Marouli and Maroulis (2005), respectively. The level of automation of the ethanol plant is low. In modern ethanol plants, the Lang factor may be higher than 2.39, due to the cost of process control and instrumentation.

The ranges of Lang factor for individual capital cost components as shown in (Table 5.5) were provided by a leading fuel ethanol technology provider in the world with proven track records in Africa.

Table 5.5: Lang factor ranges[§§§§]

Component	Range, %
Direct costs	
Purchased equipment	50-65 % of total investment or project cost
Purchased equipment installation	18-20 % of the equipment cost
Piping &Instrumentation	10-15 % of the equipment cost
Electrical (installed)	2-8 % of equipment cost
Civil work and structural cost	18-22 % of total investment
Indirect costs	
Engineering and supervision	4-6 % of the equipment cost
Contractor's fee	This has a broad range and depend on contractor and location
Contingency	0-5 % of equipment cost

This was used to benchmark the result of this study. These factors may be selectively used to check aspects of detailed estimates in order to identify irregularities in the estimate which may reflect unusual aspects of design or cost structure or in some cases may result from errors or oversight.

For a stand alone plant, there may be significant additional costs involved. Co-location reduces initial capital costs associated with facility development as much of the required infrastructure for the ethanol facility may already be in place. Therefore, total fixed investment necessary for a new plant located in a remote area, can be almost 100% greater than that of an annexed plant (FAO, 1995).

[§§§§] Lang factor range data were provided by a leading ethanol technology provider in the world with proven track record in Africa. The company prefers to remain anonymous.

5.7.5 Operating cost analysis of the distillery

5.7.5.1 Process model description

A simplified distillery process description of the distillery has already been illustrated in Figure 5.2. The actual process contains more than 200 pieces of equipment and unit operations (Appendix B5.2). The molasses (86° Brix[*****]) is received from the factory molasses storage tank and pumped by means of molasses pumps in to a scale receiving tank with an overflow facility to the molasses tank. The molasses flows by gravity from the molasses scale in to a weight molasses tank. The next stage is the heating of the molasses. However, for this to be more efficient, it is necessary to reduce the molasses viscosity. For this purpose, pre-dilution should be done to a concentration close to 50° Brix. Pre-dilution is done with process water and condensate water, which under normal working conditions, comes from vaporizer (L) of the Dehydrating column, the molasses heater themselves as well as the molasses pre-dilutors. The advantage of using condensate water in pre-dilution is that there will be a pre-heating of the diluted molasses to about 50°C, therefore diminishing its viscosity and reducing steam consumption for final heating. Before entering the pre-dilutors, the molasses (86° Brix) goes through an instant measuring and totalizing instrument for process and yield control purposes. After measuring, the concentrated juice goes to a pre-dilutor bottle which has an internal centrifugal type to facilitate dilution.

The pH of molasses is adjusted to ensure precipitation by the dilution of the sulphuric acid. The diluted, acidified molasses is then heated to 95°C and held at this temperature for approximately twenty minutes in order to sterilize it before being pumped into molasses settling tanks, where it is allowed to settle for approximately 8 hours. The clarified molasses is decanted into a clarified molasses tank and the sludge from settling tank flows into sludge mixing and dilution tank, where it is diluted using cooling water.

From the mixing and dilution tank, the diluted sludge is transmitted to sludge settling tank where after a settling period, the sweet water is decanted in to sweet water tank while the sludge flows to drain. The decanted diluted juice (50-52° Brix) at a temperature of between 90 and 95°C is diluted and cooled to about 18 - 20 m^3/hr of cold water is further consumed for a

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[*****] Brix is a unit of measure which is related to the sugar (sucrose) content of a sugar solution.

final concentration to 20-22^o Brix, this operation is done in the pre-fermentation section. From this moment onward, this raw material is called Mash, the temperature of which is from 55 to 60^{o}C. Mash is cooled to 30-32^{o}C in a plate heat exchanger, and its water consumption is around 60-65m^3/hr. The final volume of mash (20-22^o Brix) is 31 - 33 m^3/hr adequate for obtaining a good fermentation. Since it is free of a large part of the impurities, blockage of the centrifugal nozzles and eventual scaling at the distillation stage is avoided. It is not possible to obtain absolute alcohol[†††††] by simple fractional distillation, because a mixture containing around 95.6% alcohol and 4.4% water becomes a constant boiling mixture (an azeotropic mixture). To obtain absolute alcohol, a small quantity of benzene is added to rectified spirit and the mixture is then distilled. Absolute alcohol is obtained in the third fraction that distils over at 78.2 °C (351.3 K). Because small quantity of the benzene used still remains in the solution, absolute alcohol produced by this method is not suitable for consumption as benzene is carcinogenic.

5.7.5.2 Operating cost data

Operating costs, as described in section 2.14 are costs associated with the day– to–day operation of a chemical plant and must be estimated before the economic feasibility of a process can be assessed. This section introduces the important cost factors affecting the manufacturing cost of the distillery. The data were obtained from process information provided on the process flow diagram (PFD), and the information on the number of operators required to run the distillery.

- **Raw material**

The primary raw material used in the distillery is molasses. The molasses is being supplied by an adjoining sugar plant; hence the transportation cost (US$ 0.053/km) is not included. Generally, the composition of molasses varies depending on the variety of cane, composition of soil, climatic conditions, harvesting practices, sugar manufacturing process and method of handling and storage. Tropical climatic conditions may also influence the technical aspects of

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[†††††] Absolute or anhydrous alcohol generally refers to purified ethanol, containing no more than one percent water.

molasses to ethanol fermentation. The Table 5.6 gives an indication of characteristics of molasses obtained from distillery.

Table 5.6: Characteristics of Distillery Molasses type "C"

Item	Composition of molasses (%)	
	Range	Mean
Sucrose	30 – 35	33
Reducing Sugar	15 – 20	18
Unfermentable sugar	3.5 – 4.5	4
Sulphited Ash	12 – 13	13
CaO	1 – 2	2
$CaSO_4$	2.9 – 3	3
Potassium Ash (K_2O)	3.5 – 5	4
Nitrogenous compounds	1.2 – 1.5	1.4
pH	5.2 – 6.0	5.6

Other inputs are yeast (*Saccharomyces cerevisiae*[‡‡‡‡‡]) to convert the sucrose in the molasses

Other inputs are yeast (*Saccharomyces cerevisiae*[§§§§§]) to convert the sucrose in the molasses to ethanol and carbon dioxide, and a small amount of Nutrient (DAP) for yeast propagation, sulphuric acid (H_2SO_4) for sterilization of molasses to avoid contamination. The volumes of materials utilized and their costs have been incorporated into the model. The breakdown of the direct raw material for the fuel ethanol production is illustrated in Table 5.7.

- **Product value**

Three products are produced in the conversion of "C "molasses (or "final" molasses) for ethanol production. They are ethanol, carbon dioxide (CO_2 gas) and vinasses (spent washes). There were no local markets for the blending of fuel ethanol produced with gasoline. The denatured ethanol is exported to Italy and Germany. This is despite the fact that the government imports fuel by truck from Sudan and from Djibouti. This constitutes a huge drain on foreign exchange of the country which is rated as one of the poorest in the world. The major local use for the ethanol produced is for household cooking purpose by mixing it with kerosene (50-50 ratio).

[‡‡‡‡‡] a specie of budding yeast

[§§§§§] a specie of budding yeast

Table 5.7: Direct raw material consumption

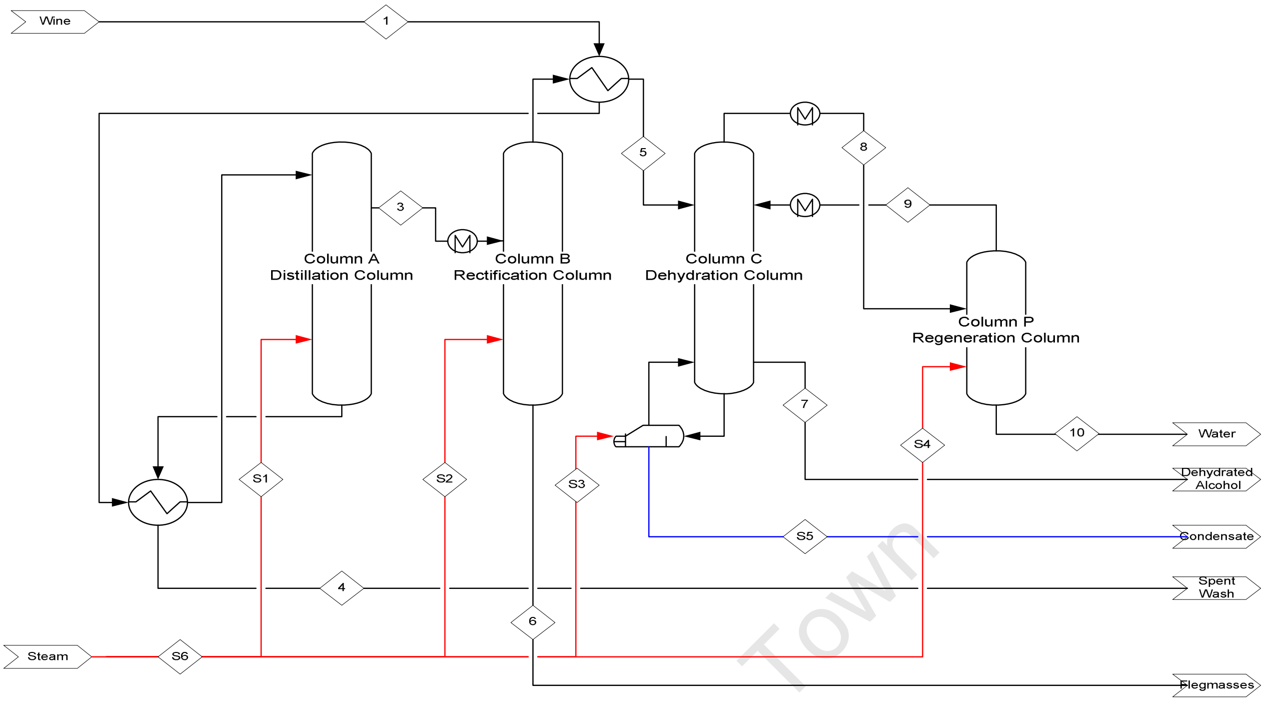
S/N	Item	Quantity	Unit
1	Molasses	207600	kg/day
2	Yeast	10	kg/day
3	Nutrient (Di-ammonium phosphate (DAP)	166.40	Kg/day
4	Antifoam (oil based)	9	L/day
5	Sulphuric acid	600	Kg/day
6	Benzene	50	L/day

There was no end use for the vinasses produced, but efforts are in place to utilise it as a source of fertilizer by spreading it in the cane plantation. The carbon dioxide is often vented to the atmosphere since the cost of purifying and transportation to the end user, often out-weighs any economic gain from selling it. Nevertheless, if the distillery was planning to install a calco-carbonic epuration (installation of a back end refinery), the pure CO_2 can be used for carbonation (in usual installations, CO_2 gas comes from the boiler exhaust). The mass of CO_2 produced is close to the mass of the alcohol produced simultaneously.

- **Utility costs**

Costs for utilities are based on the utilities required in the production process which includes electricity, steam, process water and cooling water. The distillery was not designed according to energy saving principle, since excess bagasse and excess steam were available from the adjoining sugar factory. This is the main drawback of the ethanol distillery. The energy consumption is about 600 kg of steam per hectoliter of pure alcohol (PA). These utilities are treated as purchased utilities in this study and as such, the capital costs associated with their generation are not included.

The distillery is heated by direct injection of steam in the distillation column A, rectification B, dehydrating column C and by heating surface on regeneration column P (Figure 5.3).



1: wine feed; 3: Distilled alcohol; 4: Spent Wash; 5: Rectified Alcohol; 6 Fleg-masses; 7: Pure alcohol; .8: Wet Benzene; 9: Dry Benzene; 10: Removed Water; S1: Column A Steam; S2: Column B Steam, S3: Column C Steam; S4: Column P Steam; S5: Column C Condensate; S6: Steam Header.

Figure 5.3: Distillation plant layout of the distillery

The consumption of the steam is as follows:

- 175kg of steam per hectoliter of pure alcohol for Distillation column A
- 85kg of steam per hectoliter of pure alcohol for Lutter column (rectification) B ;
- 150 kg of steam per hectoliter of pure alcohol for the Dehydrating column C;
- 30kg of steam per hectoliter of pure alcohol for benzene Recovery column P, regeneration of the heavy phase.
- 160 kg of steam for the must preparation.

The distillery water utilisation is illustrated in below

• Process water	193,236 m^3/annum
• Cooling water (fermentation)	34,119 m^3/annum
• Cooling water (distillation)	46,526 m^3/annum

The electric consumption of the distillery is reported to be 246 kWh; the motor list received from the factory is illustrated in Table 5.8.

Table 5.8: Electricity consumption at the distillery

Item No.	Description	Installed power		Consumed power
	Distillery	Working **HP**	Standby **HP**	Power **KW**
1.	Diluter for nutrient	0.25		0.2
2	Sulphuric acid pump	2	2	1.3
3	Benzene motor pump	2	2	1.3
4	Alcohol loading pump	1	1	0.6
5	Motor pump for slurry	3	3	1.9
6	Diluter continuous	3		1.9
7	Batch slurry pump	3		1.9
8	Motor pump for 1st grade alcohol	3	3	1.9
9	Motor pump for 2nd grade alcohol	3	3	1.9
10	Condensate water pump	3	3	1.9
11	Prefermenter	5.5		3.4
12	Prefermenter	5.5		3.4
13	Prefermenter	5.5		3.4
14	Continuous diluter for molasses	7.5		4.7
15	Continuous diluter for molasses	7.5		4.7
16	Motor pump for treated molasses	7.5		4.7
17	Motor pump for diluted molasses	7.5	7.5	4.7
18	Motor pump for treated molasses	7.5	7.5	4.7
19	Mash/beer pump	7.5		4.7
20	Mash/beer pump	7.5		4.7
21	Mash/beer pump	7.5		4.7
22	Mash/beer pump	7.5		4.7
23	Mash/beer pump	7.5		4.7
24	Mash/beer pump	7.5		4.7
25	Mash/beer pump	7.5		4.7
26	Stillage/exhaust flegma motor pump	7.5	7.5	4.7
27	C/P solution motor pump	7.5		4.7

28	Motor pump for molasses	7.5	7.5	4.7
29	Mash pump	10	10	6.3
30	Beer to distillation pump	12.5	12.5	7.8
31	Beer to distillation pump	15	15	9.4
32	Centrifugal separator	50	50	31.3
	Sub total	239.75	134.5	150.0

Item No.	Description	Installed power		Consumed power
		Working	Standby	Power
	Tank farm area	**HP**	**HP**	**KW**
1	Molasses transfer pump	15	15	9.4
2	Fuel oil transfer pump	15		9.4
3	Technical alcohol delivery pump	3		1.9
4	Gasoline unloading pump	3		1.9
5	Gasoline blend pump	1		0.6
6	Gasoline blend pump	1	1	0.6
7	Denatured ethanol delivery pump	2		1.3
8	Denatured ethanol delivery pump	2	2	1.3
	Sub Total	42	18	26.3

Item No.	Description	Installed power		Consumed power
		Working	Standby	Power
	Effluent treatment	**HP**	**HP**	**KW**
1	Effluent recycle pump	40	40	25
2	Effluent recycle pump	40	40	25
	Sub Total	80	80	50

Item No.	Description	Installed power		Consumed power
		Working	Standby	Power
	Lighting consumption	**HP**	**HP**	**KW**
1	Lighting fixture	24.6		12.9
2	Laboratory electrical equipment	13		6.8
	Sub Total	37.6	0	19.7

- **Capital recovery**

The time value of money and cost of capital is normally accounted for in cash flow estimates using the present value criterion. However, it is sometimes convenient to allow for this using a capital recovery factor, which accounts for the annual cost of recovering a capital investment over a life of *n* years where the interest cost of capital is *i* % per annum. The capital recovery factor *f*, which is applied as a factor of capital investment to give an annual cost is defined as:

$$f = i(1+i)^{n} \Big/ (1+i)^{n} - 1$$

The base borrowing rate of *i*, expressed as a decimal fraction is 8%. For investment life, *n*, of 20 years, *f* = 0.102.

- **Maintenance**

Maintenance and upkeep of the facility components is also considered in the operating cost estimate. This cost includes costs for labour, materials, and supervision for facility equipment and vehicles used at the facility, buildings and their infrastructures at the facility, including phone lines and power generators and regular housekeeping service. A value corresponding to 1% of fixed capital investments (≈ 1.22 of purchased equipment cost) per year was obtained. The cost of maintenance is very low as the distillery is in good condition, as would be expected from the limited amount of time it has operated.

- **Downtime allowance**

Facilities will not operate 100 percent of the time. Weather-related shutdowns, equipment repair and maintenance, emergencies, and employee work schedules will affect the number of hours operated per year. Some facilities may be prevented from operating pending acceptance of the facility work plan or other permit. Proper allowance for downtime is important if the operating costs were estimated on a percentage of hours operated basis. For conventional construction facilities, this is not a significant factor unless the facility's operating budget is dependent upon the number of hours operated. Maintenance and repair costs may also be a function of the number of hours of facility operation. The total number of downtime is 5 months (between June and October). This is due to heavy rainfall experience around time which makes transportation of sugarcane from the field to the adjoined Sugar factory difficult.

Labour Costs

The labour requirements are a function of plant size. The distillery employs various types of labour, including operations, technical, administrative, and clerical labour. This cost includes provisions for salaries and labour burden, including medical benefits, vacation and holidays, and other employee compensation items. Labour overhead will consist of administrative costs for scheduling, payroll, etc., as well as costs for employee workspace maintenance. Labour overhead will be present regardless of the facility operating schedule, but labour costs may be a function of the facility's operating schedule, especially if shift work is involved.

- **Distillery human resources management and organisational chart**

The organizational chart (Figure 5.4) presented below illustrates the distillery's needs in term of human resources. The figures provided by the distillery for the total labour costs for one year are distributed as shown below. The breakdown of the figures is illustrated in Table 5.9. It is important to note that the Production Manager is primarily responsible for the sugar factory but the Ethanol Technologist reports to him.

• Management:	25,714 US$
• Other staffs:	42,857 US$
• Total labour cost:	68,571 US$

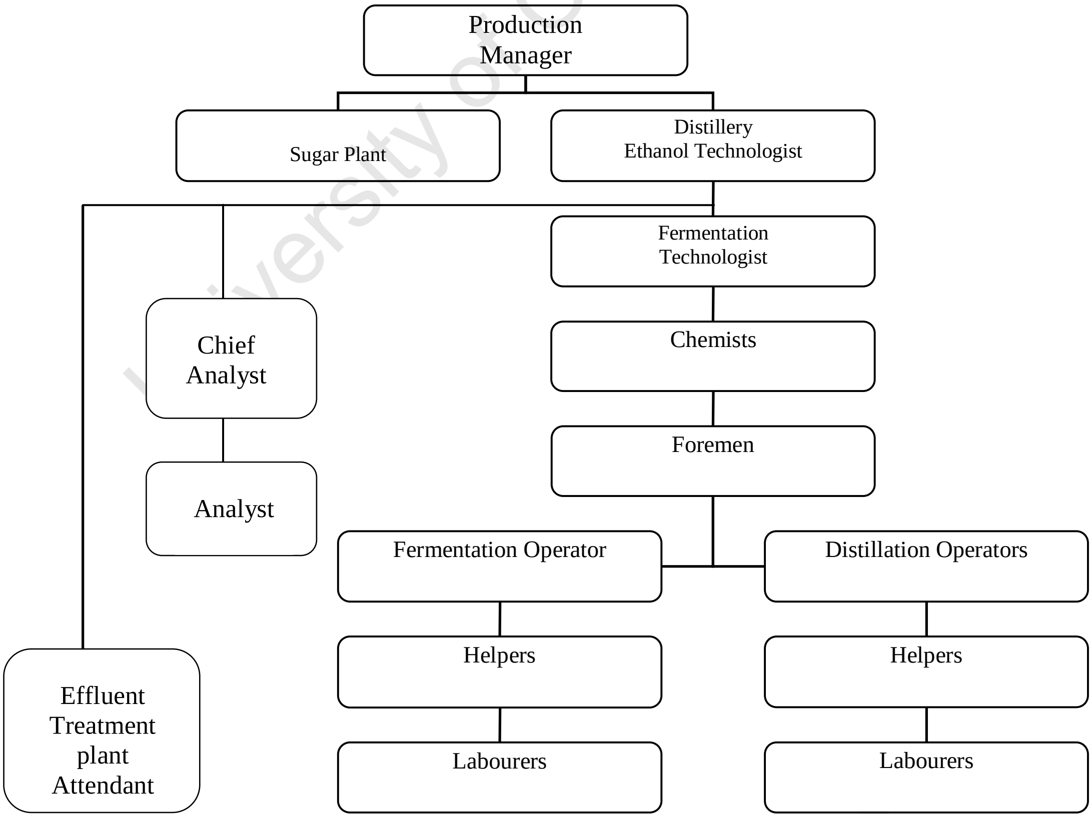


Figure 5.4: Organisational chart of the distillery

Table 5.9: Breakdown of labour cost per month at the distillery

Labour description	Personnel cost (US$)
Ethanol Technologist	427
Fermentation Technologist	365
Shift Chemist	309
Foremen	233
Chief Analyst	187
Laboratory Analyst	147
Fermentation Operators	147
Distillation Operators	128
Fermentation and Distillation Helpers	95
Labourers	28

The Ethanol technologist and fermentation technologist oversee the plant at every shift. There are twelve (12) staffs working in the distillery per shift. The breakdown of the operating labour per shift is as follows:

- 1 Ethanol technologist } (Oversee the distillery)
- 1 fermentation technologist
- 1 Senior fermentation operator
- 1 Junior fermentation operator
- 1 Senior distillation operator
- 1 Junior distillation operator
- 1 Supervisor
- 1 Process foreman
- 4 Seasonal workers (Labourers)

5.7.5.3 Method of analysis

The method of analysis employed is the factorial method of operating cost estimation (using the multiplication factors proposed by Turton *et al*. (1998). This approach is similar to that presented in other chemical engineering design texts (Peters and Timmerhaus, 1990; Ulrich, 1984; Valle-Riestra, 1983). The process information provided on the PFD, the actual costs for the operating personnel in addition to that of the actual fixed capital investment (already covered in 5.8.4) were appropriately analysed, and correlated using the multiplication or factored approach for operating cost model development. This approach has in common the factoring of process labour and fixed capital investment costs in addition to the costs of raw materials and utilities.

5.7.5.4 Results and Discussion

Figure 5.5 represents the breakdown of the operating costs of this distillery expressed in US$ per year. The total ex-distillery cost for the produced fuel ethanol includes a significant cost component for feedstock supply. Utilizing sugar molasses “type C” which is the case in this analysis as feed at $ 0.12/kg, and a 450 hl distillery (45,000 liters) at 90% capacity utilisation, operating 7 months in a year, the cost of ethanol production has been estimated at $19.57/hl, excluding annualised cost of capital investments (ethanol production cost of $30.43/hl was obtained with the inclusion of annualised capital cost). This production cost is a little higher than the net production cost of $16.37/hl for 550,000hl bioethanol plant in Brazil (Henniges and Zeddies, 2004). However, ethanol market value depends on end use. The market value of ethanol as a replacement fuel would generally be measured relative to gasoline prices using the Basic Fuel Price (BFP) approach. BFP linked or tied the domestic retail price of ethanol to international crude oil prices. Because of the lower energy content of ethanol compared to petroleum, the fuel grade ethanol is valued at 75% of the monetary value of petroleum. The market value of ethanol when blended with gasoline may be higher that gasoline because of the increased octane value of ethanol/gasoline blend. The breakdown of the ethanol unit cost is illustrated in Figure 5.10.

The major economic factor to consider for input costs of ethanol production are feedstock cost which constitute one third of the cost of production, depreciation of capital cost, which is represented by cost on annual basis and energy related expenses. The type, availability, and price of molasses all factor into the profitability of producing ethanol. The energy costs include that of steam and electricity, with costs being critical for profitability. Energy expenses are one variable in location selection that can affect the success of the ethanol plant.

Hence, ethanol plants located near an existing manufacturing plant that produces excess steam or that have some type of cogeneration potentials, as is common in the sugar industry will result into a better economics. Intermediate economic factors include the cost of labour, both in operating expenses and administrative costs. These costs are expected to be directly related to economies of size for ethanol plants. Other minor economic input factors include the cost of enzymes, water, denaturant and waste treatment.

Table 5.10: Ethanol plant unit cost

Input[******]	Cost (US$/year)	Cost (US$/kl)
Molasses	492,961	64.90
Yeast	13,077	1.72
Nutrient (DAP)	77,745	10.24
Antifoam	10,128	1.33
Sulphuric acid	37,317	4.91
Benzene	16,579	2.18
Steam	225,981	29.75
Electricity	71,185	9.37
process water	27,605	3.63
Waste treatment	25,320	3.33
Cooling water (fermentation + distillation)	11,521	1.52
Labour cost	68,571	9.03
Maintenance	41,502	5.46
Laboratory charge	13,714	1.81
Insurance & Admin. Cost	18,607	2.45
Depreciation[††††††]	335,941	44.23

According to the distillery, about ten volume of effluent will be generated for each volume of fuel ethanol produced. A portion of the effluent is been recycled for use in the distillery. This quantity is however unknown. Factors that influence the volume of wastewater include the quality of the water, the treatment process and the amount of water recycling. The cost of waste treatment depends on the environmental regulation condition in the location. The cost of effluent treatment is shared by the sugar mill and the ethanol distillery. Minor economic input factors have little to do with economies of scale. Minor economic concerns have little impact on either the location of a plant or the economies of size associated with large plants.

Other factors, aside from ethanol production costs and the market value of ethanol, may also be significant to the economic analysis. Displacement of imported petroleum with domestically produced renewable fuel may improve balance-of-payment deficits and may be economically advantageous despite relatively higher ethanol costs.

[******] Price of molasses = 0.0112 US$/kg (1.12 US$/Quintals)@ conversion = 270 L/ton; Electricity = $0.07 /KWh; Process water = $0.21/m3; Benzene = $2.0 /l; Yeast = $5.0 /kg, Urea = $2.33/kg

[††††††] Depreciation is a non cash expenses

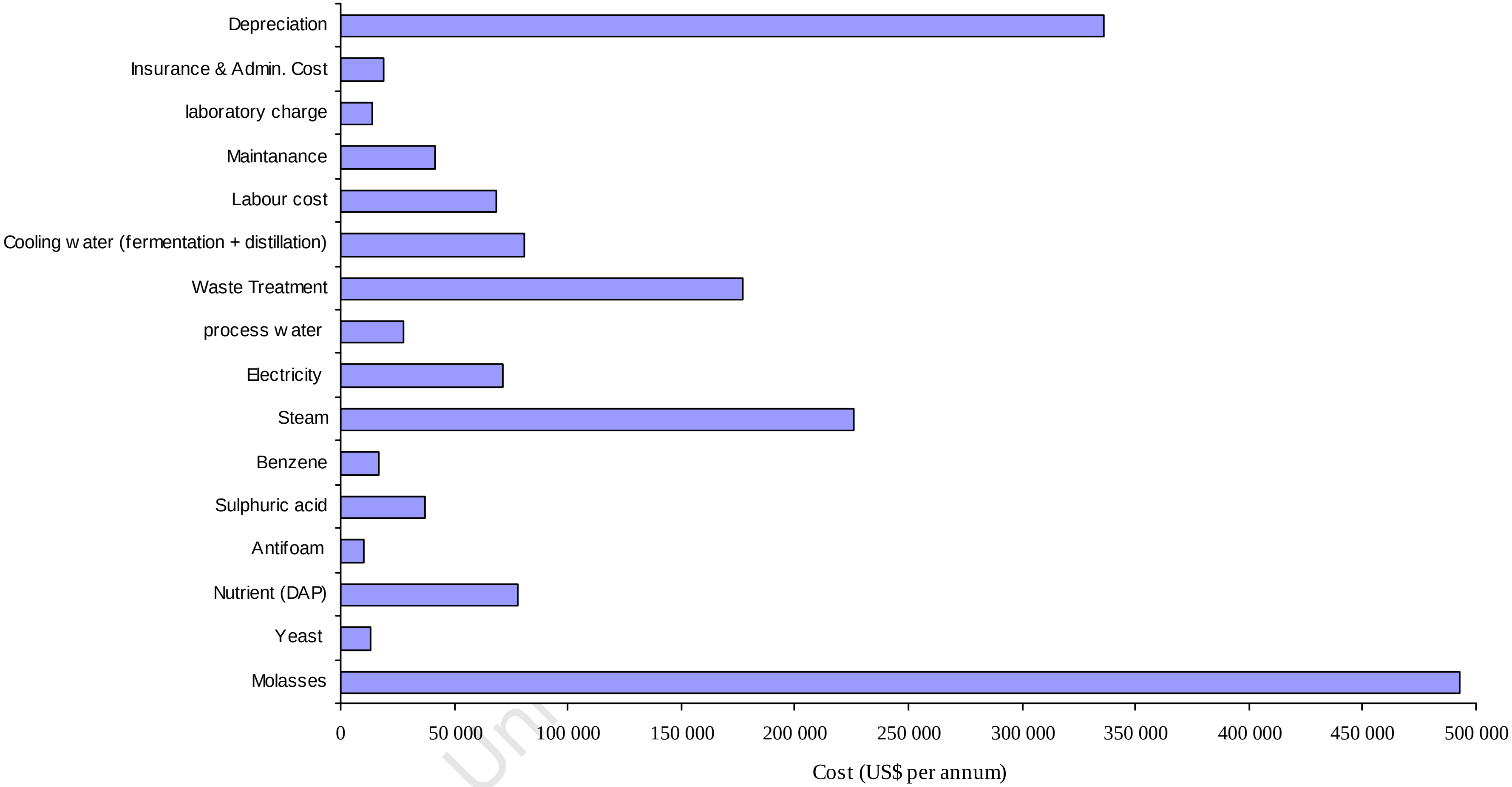


Figure 5.5: Distillery operating expenses (without by-product value)

The type, availability, and price of molasses all factor into the profitability of producing ethanol. The energy costs include that of steam and electricity, with costs being critical for profitability. Energy expenses are one variable in location selection that can affect the success of the ethanol plant.

Opportunities for rural employment, alternative markets for agricultural commodities, and energy independence may provide significant economic advantages in addition to a direct accounting of plant profitability.

Important factors although not covered in this dissertation, that need to be considered when determining the profitability of ethanol plant are the competition threat from future technologies such as converting woody products, herbaceous plant like switchgrass, municipal waste materials, and agricultural resources , government subsidies, which is a driving force in ethanol production in some countries, technology of production and the availability of water as production from sugar cane crops uses significant amount of water in the agricultural and industrial processing phases.

A sensitivity analysis was performed by calculating the ethanol price required for molasses cost ranging from 10% increase in the original cost ($0.12/kg) to 200% increase, keeping all other parameters constant. The result of the analysis is illustrated in Figure 5.6. A 10% raise in the molasses cost increase the cost of ethanol produced from $0.19/liter to $0.20/liter; while a 200% increase in the molasses cost will increase the cost of the ethanol produced by $0.13/liter (or 65%). It is therefore concluded that the price paid for molasses is an important but not over-riding determinant of product cost.

The predominant energy requirement of an ethanol production plant is the steam required for the distillation process. The distillery was not designed according to energy saving principle, since excess steam was available from the sugar factory. The total distillery steam consumption per hectolitre (hl) of pure alcohol is 600kg, which translates to 7.x kg of steam per kg of ethanol, more than double the theoretical value (Mouris estimate) of 3.5kg of steam required per kg of ethanol (Enecon Pty Ltd, 2002).

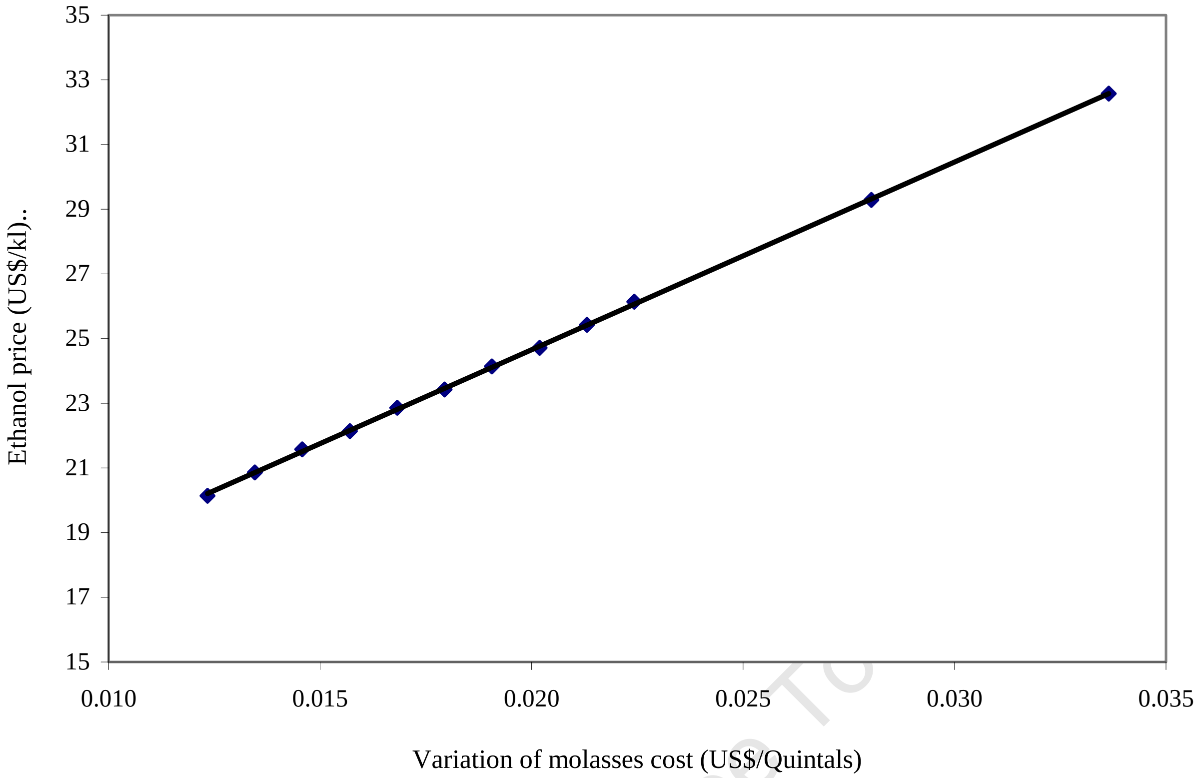


Figure 5.6: Effect of changing feedstock cost on fuel ethanol

Fixed operating costs are generally incurred whether or not the plant is producing at full capacity. These costs include labour and various overhead items. The total production period per annum at the distillery is 212 days. The operating labour of 480,000 constituting about 5% of total cost of production is low due to low labour cost at the plant location as well as possible sharing of labour (managerial) with the adjoining sugar mill.

The theoretical estimation of operating labour requirement was calculated to ascertain if the method of estimating operating labour requirement proposed by Ulrich and reported in Turton *et al.*, 1998 will work for the distillery. This method assigns a number to different types of equipment categorised as auxiliary and process equipment as illustrated in Table 5.11.

This analysis would indicate a requirement of 11-12 operators employed in the ethanol plant per shift. This does agree with the total number of staff working on a shift in this distillery, but it is worth pointing out that only 8 of the shift positions correspond to those expected from the analysis in Table 5.10, with the remainder being supervisory.

Table 5. 11: Textbook estimation of operator requirements for the distillery

Unit Operations	Number	operator	Total number of operator
Tower	14	0.35	4.9
Reactors	8	0.5	4
dryer (vaporizer)	1	0.5	0.5
heat exchanger	17	0.1	1.7
Total	40		11.1

It therefore appears that the use of Ullrich’s method would overestimate the labour requirement – an error that is more likely to be specific to the nature of this industry than the African location (where rather, one would expect a first world estimating tool to result in an under-estimate).

Annual maintenance materials were calculated as 1% of capital investments (1.22% of the total equipment cost). Possible explanation for this could be due to the limited amount of operating time. Maintenance costs are generally higher for corrosive, abraisive severe duty process and plants pushed to capacity limit. Additionally, insurance and taxes were estimated at 1.3% of the total cost.

Table 5.12 presents the multiplying factors calculated in the dissertation and the corresponding factors reported by Turton *et al.*, 1998. The cost items for each of the three categories from the breakdown of the distillery cost data were added together to provide the total cost for each category as follows:

$$DC = C_{RM} + C_{UT} + C_{WT} + 1.83C_{OL} + 0.005FCI \quad (5.5)$$

$$FC = 0.05C_{OL} + 0.043\ FCI \quad (5.6)$$

$$GE = 18C_{OL} + 0.0006FCI + 0.014COM \quad (5.7)$$

We can then obtain the total manufacturing cost by adding these three cost categories together and solving for the total manufacturing cost (COM).

Table 5.12: Multiplication factor for estimating manufacturing cost determined for the rural African distillery and the corresponding factor from Turton *et al*, 1998.

Multiplication Factors Estimating Cost			
1	**Direct Manufacturing Costs**	Value of multiplying factor (Distillery analysis)	Typical range of multiplying factor (Turton *et al.*)
A	Raw material	C_{RM}	C_{RM}
B	Utilities	C_{UT}	C_{UT}
C	Operating Labour	C_{OL}	C_{OL}
D	Direct supervisory labour	$0.63C_{OL}$	$(0.1\text{-}0.25)C_{OL}$
E	Maintenance and repair	0.01FCI	(0.02-0.1)FCI
F	Laboratory Charge	$0.2C_{OL}$	$(0.1\text{-}0.2)C_{OL}$
G	Patent and Royalties	0	(0-0.06)COM
H	Waste Treatment	C_{WT}	C_{WT}
2	**Fixed Manufacturing cost**		
I	Depreciation	0.040FCI	0.1FCI
J	Local Taxes and Insurance	0.002FCI	(0.014-0.05)FCI
K	plant overhead (distillery analysis)	0.03 (Line 1C + Line 1D + Line 1E)	
	plant overhead (Turton *et al.*)	(0.5-0.7) (Line 1C + Line 1D + Line 1E)	
3	**General Manufacturing Expenses**		
L	Ethanol departmental cost (distillery analysis)	0.11(Line 1C + Line 1D + Line 1E)	
	Administration costs (Turton *et al.*)	0.15(Line 1C + Line 1D + Line 1E)	
M	Distribution and selling cost	0.014COM	(0.02-0.2)COM
N	Research and Development	-	0.5COM

Cost of manufacturing (COM) =

$$COM = C_{RM} + C_{UT} + C_{WT} + 2.06C_{OL} + 0.044FCI + 0.014COM - C_{BP} \tag{5.8}$$

The equation for the manufacturing cost categories proposed by Turton et al, 1998 is illustrated below:

$$COM = C_{RM} + C_{UT} + C_{WT} + 2.215C_{OL} + 0.246FCI + 0.190COM \tag{5.9}$$

It appears that there is a remarkable difference in the supervisory labour, which is high for the distillery compared with the Turton *et al*. prediction. The higher supervisory labour attests to annexed nature of distillery. The remarked difference observed between the manufacturing cost model obtained from the dissertation and that proposed by Turton et al, (1998) could be due to the sharing of utilities and support systems in the annexed distillery plant. However, variables like laboratory charge fit very well with the Turton *et al.,* prediction. This variable is assumed to be independent of the plant type. The low maintenance and repair cost could also be associated with the high distillery downtime. The local tax and insurance factor for the distillery is also very low compared to the literature value. Non cash expenses such as depreciation depend on first cost and whatever depreciation methodology employed. This analysis used a straight line method which is often the case in preliminary cost estimation. A value of 4% of capital investment cost was obtained in the analysis compared to a value of 10% reported by Turton *et al*. The low depreciation rate (4%) and low maintenance material factor calculated as 1% of fixed capital investments (1.22% of purchased equipment cost) will influence the observed scale dependence of operating costs.

5.8 Size optimisation and location-cost analysis of a bio-ethanol project

5.8.1 Introduction

How could improved understanding of relevant capital and operating cost estimation techniques benefit planning for future fuel bio-ethanol industries in Africa? A key planning question in any bio-ethanol project is how many processing plants of what size to locate where, in relation to overall feedstock production limits and projected productivities. The following case study of potential bio-ethanol production from cassava in the Niger Delta area of Nigeria illustrates how knowledge of key cost estimation parameters affects the optimal outcome in terms of plant size and numbers of plants.

5.8.2 The Optimisation model: Cost analysis

The Nguyen and Prince (1996) optimisation model as discussed in section 2.9 is based on the principle that the unit processing cost of any product decreases with plant size, whilst the biomass required increases, which leads to a longer average biomass transportation distance and subsequently an increase in transportation cost. There may therefore be an optimal plant size that will minimize the total production cost. In any area having different scattered places (sources) of biomass, settling up a bioethanol plant(s)/distilleries which will take biomass and convert it into bio-ethanol which will also be further transported to market like petrol (gasoline), the following steps must be taken:

- Collection of biomass (cassava)
- Transportation of biomass to the bio-ethanol plant
- Processing of biomass
- Production of ethanol and
- Transportation of bio-ethanol to the market.

The optimisation model of Nguyen and prince (Nguyen and Prince, 1996) was used for this case study. The principle has been extensively discussed in section 2.9 of the dissertation. The model finds application to reduce the ethanol costs by finding the optimum economic plant capacity. It can also be used to predict the consequence of changes in different locations. The model calculations include both scale dependent quantities and fixed costs. However, the emphasis is on scale dependent quantities. The optimisation model was developed in MS Excel based on the following assumptions:

- Three different cassava yields (25 ton[‡‡‡‡‡‡]/ha, 18 ton /ha and 10 ton/ha) were investigated. However, 18 metric ton/ha of cassava is the most realistic yield in Nigeria
- Economies of scale exist in the capital cost of the distillery. A value of n= 0.6 and 0.7 was therefore employed for the size optimisation.
- The fraction of the land area around a distillery used for the production of cassava is assumed to be 90%
- The assumed number of days a plant would be up and running is 300 days /annum
- The transport cost used is 40 US cents/(km/1000kg) = 54 Naira/(km/1000kg)
- Exchange rate used is 135 Naira to 1US$
- 200,000 metric tons cassava per annum is assumed to be needed to feed a 60 kl/day plant (the reference plant capacity referred to as the base case); this is assumed to be the farm product and not cassava chip.
- The cost of ethanol transportation to market has not been included in the ethanol cost calculation.

[‡‡‡‡‡‡] Metric ton

The model finds application to reduce the ethanol costs by finding the optimum economic plant capacity.

5.8.3 Result and discussion

The optimisation model here reflects the base case for a 60 kl ethanol plant. By introducing changes ranging from different cassava yield and location of the distillery, it may be used to determine the optimum locator that will minimise the cost of production. The model does not provide a minimum value for the bioethanol unit costs for a specific plant size. This result depends on many different input variables, such as biomass, plant and transportation costs. Cost and energy consumption are strongly dependent on local conditions and it is difficult to find general values.

From Figures 5.7 and 5.8, it can be seen that both the yield of cassava per unit area and the capital cost estimation scale factor have a significant impact on the ethanol cost and optimum plant.

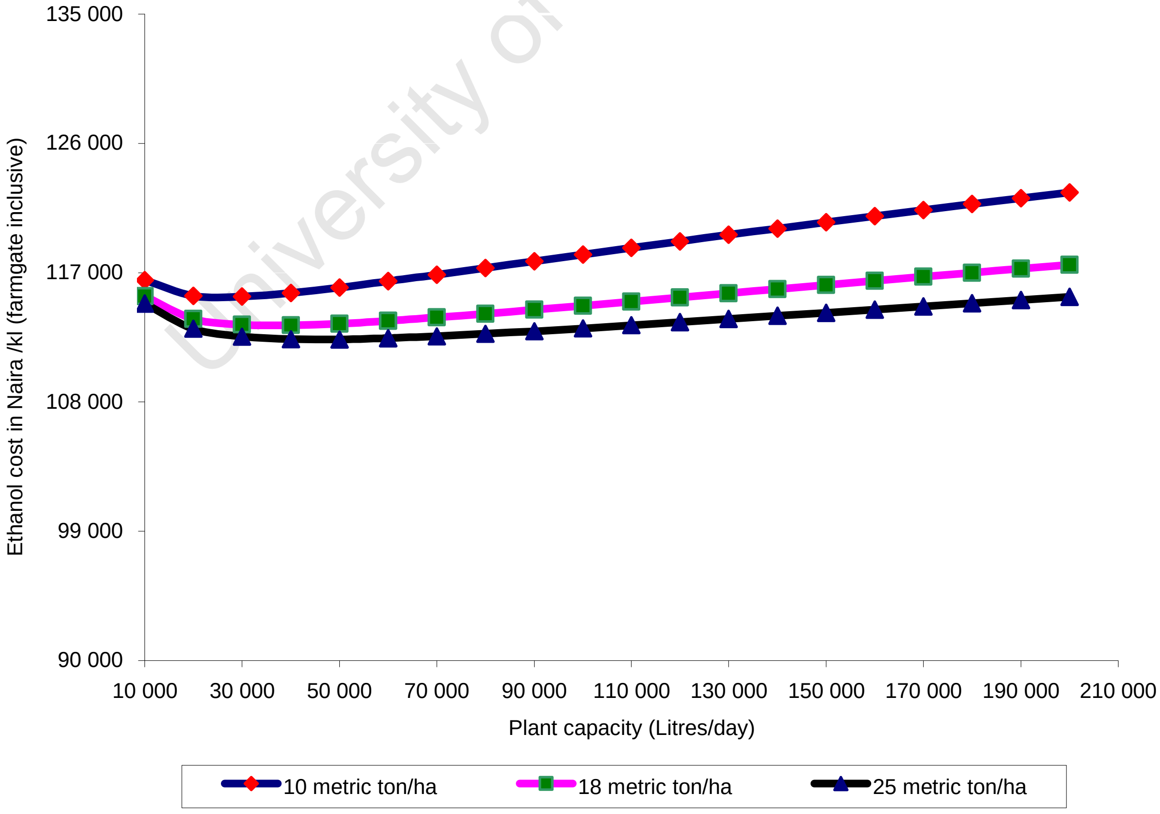


Figure 5.7: Size-cost relation of cassava based ethanol distillery in Delta State using n = 0.6

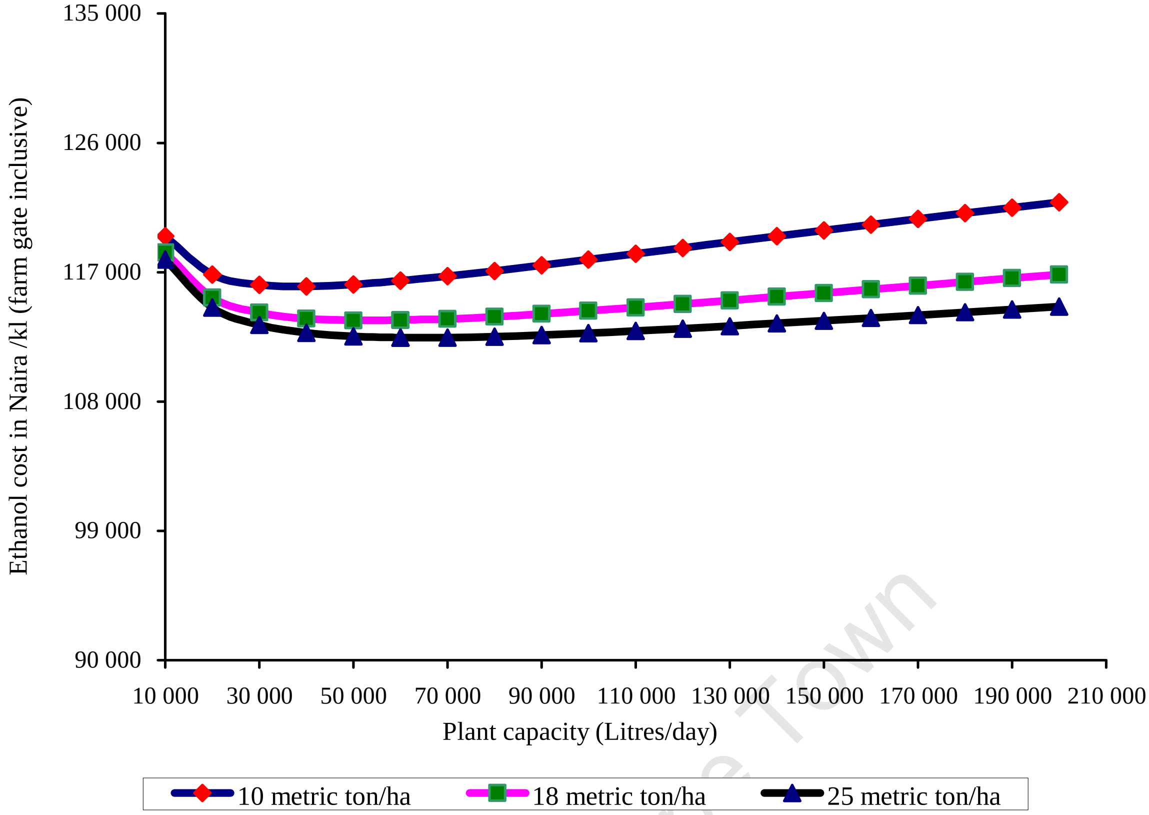


Table 5. 8: Size-cost relation of cassava based ethanol distillery in Delta State using n =0.7

Figures 5.7 and 5.8 representing distilleries located in the Delta with scale factors *n* = 0.6 and 0.7 respectively show some flatness in the profile of ethanol cost versus plant capacity, esp. on the upper side of the optimum. This means that slightly larger than optimum plants can be built with only a minor cost penalty. The scale factor, *n* = 0.7 was introduced to illustrate the impact of capacity factor on the optimum plant size. Clearly, scaling that results from increased economies of scale is offset by increased costs for feedstock collection, as transportation distance increases with feedstock demands.

The intensity of agricultural production (in terms of the yield per hectare) is seen to have a significant impact on the optimum plant size. This implies that for low agricultural productivity, it is better to build smaller distilleries. The larger facilities can achieve economies of scale, but other factors such as increased costs for feedstock collection (increased transportation distance) due to more feedstock demand for the plant comes into play. Producers located near feedstock source have the advantage of lower transportation costs to their plants

When calculating the distance from biomass supply to bioethanol plant, a circular biomass supply is assumed, with the plant located in the middle. However, this will often not be the case. When the biomass transportation distance differs considerably from this assumption, the cost or energy use for biomass transportation can be calculated using equation for additional biomass transportation

It appears that a distillery distant from the crop producing areas would only be feasible if significantly cheaper bulk transportation were available. The quantities transported would be significantly lower than for the cassava chip, but it would require specialised tanker truck.

5.9 Summary and concluding remark

This chapter was aimed at achieving the following results. Firstly to present the analyses of the breakdown of capital and operating cost to inform improvement of cost equations, secondly to analyse which factors most influence the production cost of bioethanol and lastly, to review their application in size-optimisation models (i.e. to demonstrate how bioethanol plant size optimization will benefit from availability of better capital and operating cost estimating techniques).

In the capital cost analysis of the rural East African distillery annexed to an existing sugar mill, a Lang factor f_L of 2.39 was obtained on the basis of the purchased cost of equipment. Using installed equipment cost as basis, the resulting factor is 1.99. The value of 2.39 is significantly lower than general green-fields sites values of 3.6 and 4.5 commonly used in the literature – but not that different to values of 3.0 and 2.75 reported for mill-annexed maize ethanol plants in the US by Qureshi and Blaschek (2000), and Kwiatkokowski et al. (2000) respectively. Whilst no comparative results appear to have been published for the sugarcane based ethanol industry, the evidence supports the notion that Lang factors for African installations (in particular in landlocked and/or rural locations) could be slightly lower than those of corresponding installations elsewhere.

A second important conclusion from the analysis of the distillery's capital cost appears to be that the factored approach to capital cost estimation remains a useful method in its own right, and also provides means of checking the validity of estimates made by more detailed methods.

A very significant cost of commercial scale ethanol plants is the cost of site development such as building and upgrading roads, water supply systems, and pollution control systems and electricity generating capacity. This is expected to be very significant in the case of stand-alone plant while an annexed plant (for example sugar producing plant) will lead to better economics.

From the operating cost analysis of the same East African distillery it emerged that the factorial approach to estimation is principally a sound one, with no indication of untypical cost items. Some of the typical cost items do however display ratios to the base cost that are outside of previously reported limits, notably direct supervisory labour (much higher), maintenance (lower) and local taxes (lower). Additionally, the process flowsheet based approach to operating the labour requirement has been shown to also be appropriate; however, it is worth pointing out that it predicts 11-12 shift positions, where only 8 operators are needed. It is thus of interest to note that textbook approaches in this instance seem to over-predict direct but under-predict supervisory labour requirements.

The greatest single operating cost item in the ethanol production studied is feedstock, which constitutes one third of the total cost of production. Therefore, for ethanol fuel to be profitable, an economical supply of feedstock is essential. However, questions of possible competition for prime agricultural land, and impacts of ethanol production on food supply and distribution are crucial to the social and economic success of ethanol technology. Steam and electricity costs constitute other major components of the operating expenses.

The illustrative case study involving the planning of fuel ethanol production from cassava in the Niger Delta has shown that the successful introduction of ethanol and use in such an African setting requires careful planning. The technology must be integrated with local economic conditions, available resources, and potential end use of both the ethanol and its by-products. The operating efficiency of large scale plants may be greater than that of small scale due to economy of scale but the efficiency may be of little value if the plant is too large for the locally available feedstock (resulting in excessive transport costs). Whilst not investigated in the case study, the availability of suitably sized support utilities would equally become a planning issue for large plants. Finally, the local economics of food production and distribution should not be disrupted by such projects.

Indirect and social economic questions are also very important in the decision to produce and use ethanol. Economic decisions regarding the production may rely more on the ability to meet such objectives as increasing rural employment, achieving energy independence, and providing alternative market for crops than on direct evaluation of production cost and market value. Technical decisions regarding plant scale, process design, and equipment may be influenced by the ability to meet such objectives as the use of local labour, and locally manufactured equipment (which will reduce the investment costs), the creation of alternative markets for agricultural crops as feedstock and the local use of process energy. Ethanol plants should be scaled so that demand for feedstock does not disrupt distribution systems and markets for agricultural commodities. Support utilities and transportation should be able to support the scale of ethanol production.

Even though bioethanol plant costs are expected to display economies of scale more so than biogas plants in the previous chapter, it may be favourable to establish several smaller plants instead of one large plant. Producers in close proximity to feedstock source have the advantage of lower transportation costs to their plants. The total bioethanol unit cost will therefore be less. If a choice has to be made between a location close to biomass supply and a location close to the consumer, the location close to biomass supply should generally be preferred as energy use and costs are higher for biomass transportation than for bioethanol transportation. The energy use and cost of transportation could be reduced for longer distances by changing the transportation mode.

Appendix B5

Appendix B5.1

Direct costs

- **Pre-project study and analysis expenses**

Preliminary economic studies are usually performed before deciding on or supporting construction of a project. These include investigative travel, market surveys, laboratory and pilot plant studies, etc. However, the procedure for charging these costs varies from project to project. In the case of public utility projects, for example, the Government does not usually add these expenditures to the total costs of the project and regards them as unrecoverable promotion costs. All the resources assigned to a project must be considered as part of its cost, including those incurred at the research stage and pre-project costs.

- **Main equipment**

The cost of purchased equipment is the basis of several pre-design methods for estimating capital investment. These vary in details from facility to facility as several technology suppliers provide the process design, equipment, and construction process. In some cases, the pro-forma invoices of the equipment only include their intrinsic value, and in others, the value of the equipment after installation. Where it includes the value of the installed equipment, components (2) and (3) (in Table 6.6) can be calculated together and include all complementary installations. Where equipment or materials have to be imported, details will be given in terms of FOB (equipment price at port of origin), CIF (price including freight and insurance) and at the utilization site (import expenses, freight, etc.). The various types of equipment can often be divided conveniently into (i) processing equipment, (ii) raw material handling and storage equipment, and (iii) finished-products handling and storage equipment. The equipment and machinery used during the assembly and which can be used in the production process should also be included. The value can be found by depreciating the goods according to use, incorporating only the resulting residual value.

- **Equipment installation**

Each piece of equipment requires quite different multiple of its purchase price to pay for its installation. Generally, the costs are fairly specific for and depend on the characteristics of the equipment, with some influence of the local installation conditions for equipment mounting, and the process, location, and size also help determine this cost. The installation costs consist of the freight from the factory, the unloading and handling costs, foundation or supports, physically putting the equipment in place and securing it, and connecting it so that it will run (electric switch gear, e.t.c) and function (connect piping, e.t.c). The cost of installation will often include payment of qualified expatriate personnel. This is convenient for the experience that the personnel of the supplier company should have, and because, in many cases, equipment suppliers will only honour their guarantees if the equipment is assembled, adjusted and started-up by their own personnel or by technicians authorized by them. Knowledge of this installation is necessary if one is considering single pieces of equipment only, or small process additions. However, for a complete plant estimates, installation cost is not considered separately most of the time and is included in other cost items such as the electrical, instrumentation, piping costs e.t.c., all of which are necessary for the equipment in a new plant to function. Table 6.11 presents the general range of installation cost as a percentage of the purchased equipment costs for various types of equipment.

Analyses of the total installed costs of equipment in a number of typical chemical plants indicate that the cost of the purchased equipment varies from 65 to 80 percent of the installed cost depending upon the complexity of the equipment and the type of plant in which the equipment is installed. Installation cost, therefore, are estimated to vary from 25 to 55 percent of the purchased equipment cost.

- **Piping (installed)**

In many estimating methods, this component is calculated separately from the rest of the equipment. In a detailed estimate, calculation of the cost of pipes is made with a diagram of the pipes and their siting. Piping costs can vary greatly in the process industry, from low to relatively high values depending on the dominant phase been transported. Piping in the ethanol industry is utilized, for instance, for the purpose of conducting water (process and waste), compressed air, slurry and liquid effluents, and special gases (e.g., CO_2).

Table B 5.1: Installation cost for equipment as a percentage of the purchased cost (Peter and Timmerhaus, 1991)

Type of equipment	Installation cost, %
Centrifugal separator	20-60
Compressor	30-60
Dryer	25-60
Evaporator	25-90
Filters	65-80
Heat exchangers	30-60
Mechanical crystallizers	30-60
Metal tanks	30-60
Mixers	20-40
Pumps	25-60
Towers	60-90
Vacuum crystallizers	40-70
Wood tanks	30-60

- **Instrumentation and control**

This component includes all auxiliary equipment and instruments for controlling and recording the different variables at each stage of the process. This cost is expected to increase due to rising labour cost and the rapidly increasing use of computers and more complex instrumentation controls. The ethanol plant can be described as a medium automated plant.

- **Electrical installation**

The costs involved in electrical installations consist mainly of labour and materials necessary for supplying power and lighting to the process, while the costs for illuminating the service buildings are normally included in the cost of auxiliary services.

- **Construction (including services)**

Cost of construction includes the expenditure on labour, materials, and supplies needed for the construction of all buildings connected to the plant. They include plumbing costs, electrical installation, ventilation, air conditioning, and similar building services.

- **Yard improvements**

Costs for fencing, grading, roads, sidewalks, landscaping and similar items constitute the portion of the capital investment included in yard improvements. The bulk of the yard improvement cost in this case is attributed to the existing sugar industry.

- **Service facilities**

Service facilities generally include utilities for supplying steam, water, power, compressed air and fuel. It also includes; waste disposal, fire protection and miscellaneous service items such as first aid, cafeteria equipment. For the case of distillery, this variable also covers the cost of waste disposal.

- **Land**

The cost of land and the accompany surveys and fees depends on the location of the facility and may vary by a cost factor per acre. The cost of land is not included in the case of the distillery as the land used for construction is owned by the government.

- **Contractor fees**

These vary according to the peculiar situation of the plant and location. These costs can be zero (nil) in a situation where the same firm or company is handling the construction and setting-up of the project. This is the case for the distillery, hence, the contractor expenses is not included in the Lang factor analysis.

Appendix B5.2

Table B5.2: Fuel ethanol distillery equipment list

No	Description	Qty	Unit price	Total price	Other Forex cost	Final price
1	In-line flow meters	2	5,024	10,049	320	10,369
2	Molasses receiving tank	1	6,050	6,050	368	6,418
3	Dilution, Mixing and treatment tank	2	40,333	80,666	1,359	82,025
4	Carboxyl acid pump	1	3,833	3,833	64	3,897
5	Treated Molasses pumps	2	14,458	28,917	160	29,076
6	Molasses settling tanks	3	19,317	57,952	4,160	62,112
7	Clarified Molasses tank	1	17,395	17,395	807	18,202
8	Clarified Molasses pumps	2	9,010	18,020	185	18,206
9	Clarified Molasses cooler	1	28,298	28,298	704	29,002
10	Static in line mixer	2	6,887	13,774	112	13,886
11	Brix spindle pot	2	790	1,580	160	1,740
12	Nutrient mixing tank	2	12,430	24,860	193	25,053
13	Nutrient pumps	2	9,800	19,600	441	20,041
14	First Stage Yeast Propagation Vessel	1	44,707	44,707	112	44,819
15	2nd Stage Yeast Propagation Vessel	1	60,782	60,782	463	61,245
16	3rd stage Yeast Propagation Vessel	1	140,739	140,739	736	141,475
17	Fermenter vessel	6	43,741	262,446	18,583	281,029
18	Fermenting Mash recirculation pumps	4	14,541	58,362	807	59,169
19	Mash cooler/Heat exchanger	4	7,288	29,154	480	29,633
20	Fermentor Emptying pumps	2	9,541	19,081	175	19,257
21	Fermented wash buffer tank	1	19,270	19,270	1,119	20,390
22	Distillation feed pumps	2	12,277	24,553	160	24,713
23	CO2 Alcohol recovery unit	1	35,768	35,768	320	36,089
24	Ethanol plant process water tank	1	17,572	17,572	688	18,260
25	Sterile air filter	1	13,019	13,019	48	13,067
26	Process water pump	2	3,172	6,345	160	6,504
27	Ethanol plant cooling water tank	1	15,272	15,272	480	15,752
28	Cooling water Transfer pump	2	3,172	6,345	79	6,424
29	Reflux and vent condensers	3	18,444	55,332	2,303	57,636

30	Boiling column	1	155,905	155,905	4,063	159,969
31	Degassing column with condenser	1	35,993	35,993	544	36,536
32	Rectifying column	1	123,472	123,472	4,321	127,792
33	Fusel oil cooler	1	4,104	4,104	544	4,648
34	Fusel oil decanter	1	5,154	5,154	99	5,253
35	Eprouvette (Fusel oil)	1	1,096	1,096	45	1,141
36	Dehydration column	1	125,031	125,031	4,992	130,023
37	Dehydration column reboiler	1	11,676	11,676	544	12,219
38	Regeneration column	1	16,227	16,227	832	12,219
39	Benzene pump	2	4,647	9,293	48	9,341
40	Benzene pump tank	1	5,932	5,932	27	5,959
41	Benzene decanter	1	15,331	15,331	181	15,513
42	Reflux & vent condenser (dehydration column)	2	17,465	34,931	560	35,491
43	Reflux pumps to regeneration column	2	2,323	4,646	152	4,798
44	Reflux heat exchanger	1	5,861	5,861	560	6,421
45	Benzene/ Alcohol pumps	2	4,705	9,410	165	9,576
46	Anhydrous Alcohol pumps	2	4.647	9,293	146	9,439
47	Anhydrous Alcohol cooler	1	9,505	9,505	726	10,231
48	Eprouvette (Anhydrous alcohol)	1	2,819	2,819	335	3,154
49	Technical Alcohol cooler	1	2,925	2,925	726	3,650
50	Eprouvette (Technical Alcohol)	1	1,651	1,651	335	1,986
51	Ethanol plant condensate tank	1	22,100	22,100	343	22,443
52	Ethanol plant cool condensate pumps	2	4,175	8,349	165	8,515
53	Ethanol plant hot condensate pumps	2	2,523	5,047	165	5,212
54	Excess condensate cooler	1	9,375	9,375	99	9,475
55	Lutter water pumps	2	2,795	5,519	181	5,700
56	Reflux & vent condensers (refrigeration column)	2	9,211	18,422	1,451	19,873
57	Distillation control panel	1	249,132	249,132	99	249,231
58	Specified miscellaneous instruments	1	273,396	273,396	229	273,625
59	Boiling column reflux pumps	2	11,522	23,044	335	23,379
60	Rectifying column reflux pumps	2	11,522	23,044	335	23,379
61	Rectifying column reflux pumps	2	11,522	23,044	335	23,379

62	Rectifying column feed drum	1	5,460	5,460	167	5,627
63	Regeneration column reflux pumps	2	11,522	23,044	335	23,379
64	Benzene decanter feed pump	2	11,522	23,044	335	23,379
65	Benzene decanter feed pump	1	19,635	19,635	167	19,803
66	Fusel oil storage tank	1	21,063	21,063	785	21,848
67	Gasoline blending pump	2	6,592	13,185	132	13,317
68	Technical alcohol intermediate storage tank	1	14,305	14,305	386	14,690
69	Ethanol shift storage tank	2	16,003	32,006	2,610	34,615
70	Ethanol blending pumps	2	6,911	13,821	146	13,967
71	Denatured Ethanol storage tank	1	146,577	146,577	24,725	171,302
72	Gasoline unloading pump	1	6,805	6,805	99	6,904
73	Gasoline meter	1	6,251	6,251	104	6,310
74	Gasoline storage tank	1	13,751	13,751	2,325	6,310
75	Denatured ethanol delivery pumps	2	9,765	19,530	120	19,650
76	Ethanol meter	1	2,158	2,158	46	2,204
77	Denatured ethanol meter	1	6,015	6,015	1,859	7,874
78	In-line meter	1	5,483	5,483	99	5,583
79	Technical alcohol main storage tank	1	22,466	22,466	5,665	25,038
80	Technical alcohol delivery pump	1	10,284	10,284	84	10,367
81	Vapour recovery system	1	10,508	10,508	99	10,607
82	Desiccant dryer package	1	5,873	5,873	232	6,104
83	Ethanol plant effluent treatment	1	506,359	232,804	15,445	531,804
	Total Equipment Cost (Local currency)					23,748,593
	Total Equipment Cost (Installed)					28,555,318
	TOTAL EQUIPMENT COST ($USD)					3,392,656

Table B5.3: Values of Lang factors (f_L) obtained for the African distillery (IBL) located in a landlocked and poorly accessible rural location

Item	Multiplying factor	Cost of item Units	% Direct cost	% Total cost
Installed equipment cost (PEC)	1.00	23,024,079		45
• Purchased equipment cost $\left(I_E\right)$	1.00	18,217,354	38	36
• Installation cost	0.26	4,806,725	10	9
$\therefore$ Installed equipment cost $\left(PEC\right)$ =	$I_E \times 1.26$			
Piping , instrumentation & control	0.53	9,615,084	20	19
• Basis of installed equipment cost	0.42	9,615,084	20	19
Electrical	0.12	2,095,911	4	4
• Basis of installed equipment cost	0.09	2,095,911	4	4
Civil and structural cost	0.40	7,363,871	15	14
• Basis of installed equipment cost	0.32	7,363,871	15	14
Structures and building	0.14	2,587,717	5	5
• Basis of installed equipment cost	0.11	2,587,717	5	5
Yard improvement/service facilities	0.19	3,391,423	7	7
• Basis of installed equipment cost	0.15	3,391,423	7	7
$\sum f_i$	1.6	29,860,731	62	58
• Basis of installed equipment cost	1.1	25,054,006	52	49
Total Physical Cost, $I_E\left(1+\sum f_i\right)$	2.6	53,609,324	100	94
• Basis of installed equipment cost	2.1	53,609,324	100	94
Total Direct Cost, $\sum f_{dc}$		53,609,324		
Engineering & supervision	0.06	3,087,241	6	6
• Basis of installed equipment cost	0.06	3,087,241	6	6
Total Indirect Cost, $\sum f_{ic}$	0.17	3,087,241	6	6
• Basis of installed equipment cost	0.13	3,087,241	6	6
Total Fixed Investment,				
$I_F = I_E\left[\left(1+\sum f_i\right)+\left(\sum f_{ic}\right)\right]$	2.81	56,696,565		
• Basis of installed equipment cost	2.22	56,696,565		

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6

Biodiesel Optimum Plant size Determination and Cost Predictions

The use of vegetable oils for engine fuels may seem insignificant today. But such oils may become in the course of time as important as the petroleum and coal tar products of the present time...Rudolf Diesel, 1912

6.1 Introduction

Biodiesel, produced through the transesterification of vegetable oils with methanol or ethanol, is currently considered to be a feasible alternative to conventional diesel, presenting advantages such as the reduction of carbon dioxide, carbon monoxide, hydrocarbon and sulphur oxide emissions (Gerpen, 2005; Marchetti, 2007). From an economic perspective, the continuous increase in the oil market prices and possibility of receiving financial resources through the commercialisation of carbon credits, as it was established by the Clean Development Mechanism, (CDM) are motivations for developing such technology. Moreover, strategic questions as job creation and income generation and energy self-sufficiency in rural areas come to reinforce the need for biodiesel programs. This chapter starts with a demonstrative case study on size-optimisation of a biodiesel processing plant in South Africa using the Nguyen and Prince (1996) optimisation model. This is followed by an analytical assessment of the economic feasibility of producing biodiesel by various industrial configurations, representing the state of art of biodiesel technology in Germany, with the view of applying the result to the African continent where most of the countries are still in the first phase of biodiesel production. This approach is justified by the absence of commercial facilities and the fragmented nature of the non-commercial biodiesel sector at the time of research and writing of the dissertation. The analytical approach is supported by cost reviews of

German biodiesel installations, showing how industry-specific features have contributed to successful commercialisation.

6.2 Background

The concept of using vegetable oil as an engine fuel dates back to 1895 when Rudolf Diesel (1858-1913) developed the first engine to run on peanut oil, as he demonstrated at the World Exhibition in Paris in 1900. Unfortunately, R. Diesel died in 1913 before his vision of a vegetable oil powered engine was fully realized.

Alternative fuels for diesel engines are becoming increasingly important due to diminishing petroleum reserves and the environmental consequences of exhaust gases from petroleum-fuelled engines. A number of studies have shown that triglycerides hold promise as alternative diesel engine fuel (Clark and Wagner, 1984; Muniyappa and Brammer, 1996; Bender, 1999; Ma and Hanna, 1999; Fukuda *et al.*,, 2001; Juergen and Juergen, 2002; Peterson and Auld, 2002; Massimo and Marco, 2003; Zhang and Dube, 2003; Collins-Chase, 2005; Haas and McAloon, 2006; Nelson and Schrock, 2006). However, the direct use of vegetable oils and /or oil blends is generally considered to be unsatisfactory and impractical for both direct-injection and indirect-type diesel engines (Fukuda *et al.*, 2001). The high viscosity, acid composition and free fatty acid content of such oils, as well as gum formation due to oxidation and polymerisation during storage and combustion, carbon deposits, and lubricating oil thickening are some of the more obvious problems (Ma and Hanna, 1999; Strivastana and Prasad, 2000). Thus, considerable research has gone into developing vegetable oil that approximates the properties and performance of hydrocarbon-based fuels. There are four primary ways to make biodiesel, direct use and blending, microemulsions, thermal cracking (pyrolysis) and transesterification (Ma and Hanna, 1999). The most common way is transesterification as the biodiesel from transesterification can be used directly or as blends with diesel fuel in diesel engine (Peterson *et al.*, 1991; Zhang *et al.,* 2003). Transesterification, also known as alcoholysis, is the displacement of alcohol from an ester by another alcohol in a process similar to hydrolysis, except that alcohol is employed instead of water. Biodiesel can be made from two different chemical processes. The most commonly used and most economical is called the base-catalysed esterification of fat with methanol, typically referred to as the “methyl ester process”.

Base esterification is preferred because the reaction is quick and thorough, it occurs at lower temperature and pressure resulting in lower capital and operating cost (Bender, 1999). This process creates four main products namely: methyl ester (biodiesel), glycerine, feed quality fat and methanol that is recycled back through the system. Most, if not all, existing commercial biodiesel plants use the methyl ester process. A generalised representation of this process is illustrated in Figure 6.1.

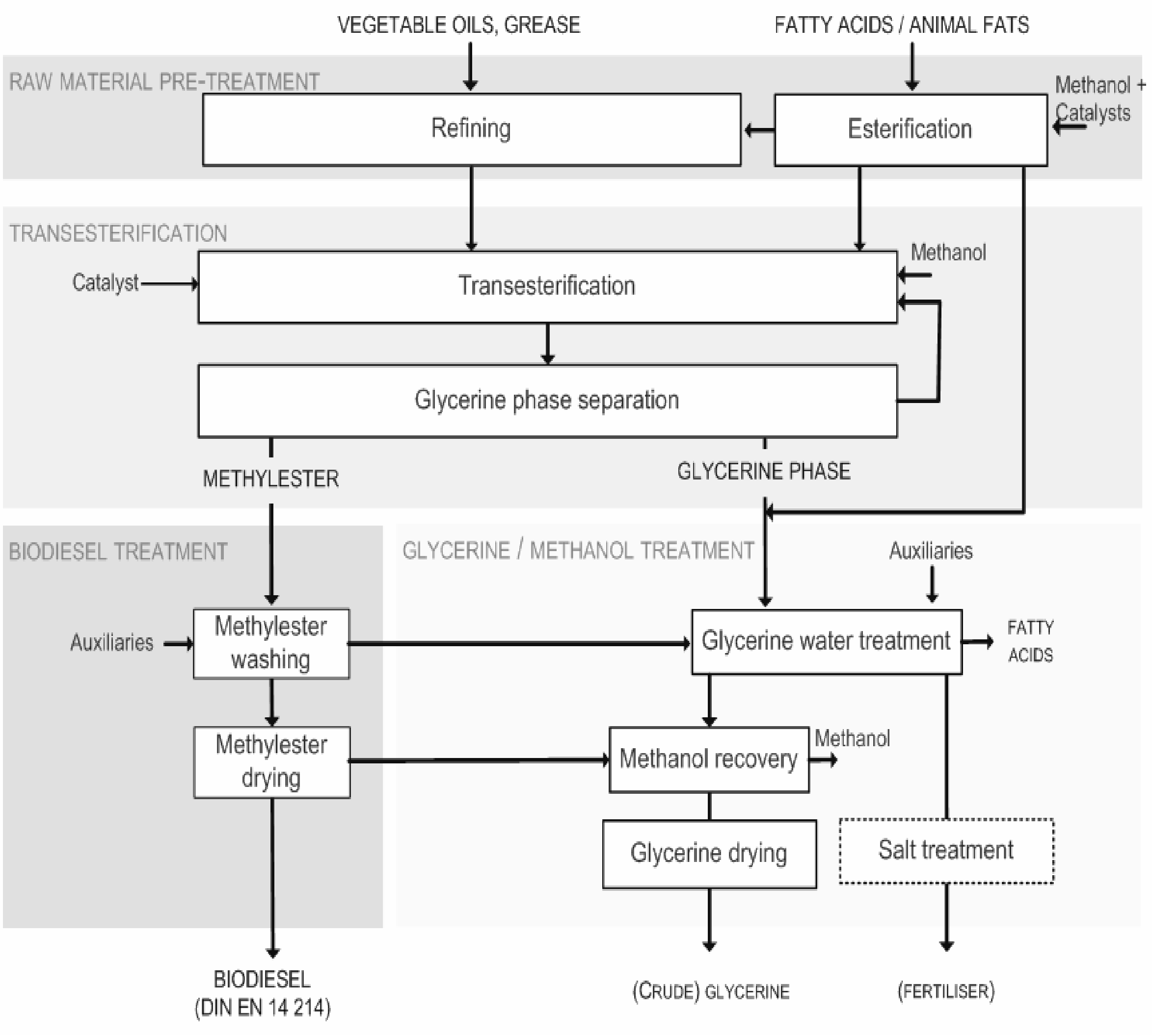

Figure 6.1: General Scheme of biodiesel production (IEE, 2007)

Biodiesel can also be produced using ethanol, oil feedstock, and an enzyme catalyst to make an “ethyl biodiesel”. Enzyme catalysed transesterification is considered as an effective means to overcome the energy-intensive nature of the alakali catalysed transesterification process, the difficulty in the recovery of glycerol, and the need for removing the alkaline catalyst. Some of its drawbacks include slow conversion rates, sensitivity to water, which can result to quality problem in handling and the relatively high production cost per unit (Radich, 2006; Ginder, 2004).

The reaction illustrated in Equation. (6.1), is reversible, and thus an excess of alcohol is usually used to force the equilibrium to the product side. The stoichiometry for the reaction is 3:1 alcohol to lipids. However, in practice this is usually increased to 6:1 to raise the product yield (Encinar and González, 2007).

$$\text{Triglyceride (TG)} + 3\text{ROH} \rightleftharpoons 3\text{R}'\text{CO}_2\text{R} + \text{Glycerol} \qquad (6.1)$$

Transesterification consists of a sequence of three consecutive reversible reactions. The first step is the conversion of triglycerides to diglycerides, followed by the conversion of diglycerides to monoglycerides, and finally monoglycerides into glycerol, yielding one ester molecule from each glyceride at each step. The reactions are reversible, although the equilibrium lies towards the production of fatty acid esters and glycerol (Ma and Hanna, 1999; Meher *et al* 2006).

The catalyst used has a determinant effect on the reaction, raising the rate notably. It is known that basic catalysts require short times (30 min) to complete the reaction even at room temperature, while acid catalysts, such as sulfuric acid, require higher temperatures (100 °C) and longer reaction times (3–4 hrs.) (Gerpen, 2005; Ma and Hanna, 1999; Schwad *et al*, 1987). The alkalis that are used generally include sodium and potassium hydroxides, carbonates, and alkoxides such as methoxide, ethoxide, propoxide, and butoxide.

A major technological issue in the biodiesel production is the question of whether to utilise a batch or a continuous process plant. Most smaller plants currently in operation use batch processing and produce discrete “runs” of product. These plants in general loose the excess methanol into air and/or wash water and do not recapture unused catalysts resulting in high operating cost of the plant and serious environmental risks from the disposal of polluted water. Whilst a continuous flow process with methanol recycling requires only the stoichiometric amount of alcohol, the batch process requires an excess alcohol of at least 75% to drive the reaction to completion (Bender, 1999).

Processing in discrete runs can at times create quality and homogeny problems in the final biodiesel product. However, batch operations have the benefit of being feasible on a small scale and many established processor designs exist. The former benefit of biodiesel will find a better application in the rural areas in Africa due to the financial base from local investors.

Continuous flow plants are not as common as the batch counterpart. Continuous process plants have several important operating cost advantages over the batch process. It is possible to reuse excess NaOH that has not become part of the biodiesel and reuse catalysts which are lost in batch processes. The major obstacle to continuous flow operation appears to be the high initial investment required. Continuous flow generally requires a larger scale plant, thus making the initial capital outlay to build generally higher. Another issue is the availability of feedstock which adds to the high initial costs. Price of crops as well as the season of the year affects the overall cost of the biodiesel. This can be a major problem for a small start-group especially in the developing countries of Africa where the financial institutions lack the understanding of the renewable energy projects and their potential benefits. Also, there are high risks (which is difficult to access accurately), associated with technological immaturity and unpredictable government energy policies; thus, for the smaller start group, it can be excessively difficult to find financing for a larger biodiesel plant.

Most of the larger plants (with production rate of about 4 million liters/year) use continuous flow processes involving continuous stirred-tank reactors (CSTR) or plug flow reactors. The reaction is sometimes carried out in two steps (Gerpen, 2005). In this system, approximately 80% of the alcohol and catalyst is added to the oil in a first stage CSTR. Then the reacted stream from this reactor goes through a glycerol removal step before entering a second CSTR. The remaining 20% of the alcohol and catalyst are added in this reactor. This system provides a very complete reaction with the potential of using less alcohol than single-step systems.

Following the reaction, the glycerol is removed from the methyl esters. Due to the low solubility of glycerol in the esters, this separation generally occurs quickly and may be accomplished with either a settling tank or a centrifuge. The excess methanol tends to act as a solubiliser and can slow the separation process. However, this excess methanol is usually not removed from the reaction stream until after the glycerol and methyl esters are separated due to concern about reversing the transesterification reaction. Water may be added to the reaction mixture after the transesterification is complete to improve the separation of glycerol.

Once separated from the glycerol the alcohol ester is washed to remove any soap formed during the reaction as well as the residual free glycerol and alcohol. The alcohol ester is then dried to remove all water. In some cases, the esters are distilled under vacuum so as to achieve higher purity, reduce colour bodies in the fuel and remove sulphur and/or phosphorus from the fuel. The washing step can be greatly affected by the free fatty acid level of the feedstock, since all the free fatty acids form soaps in the reaction. To further refine the glycerol, it is neutralized with an acid (usually hydrochloric or phosphoric) to form salts.

The properties of biodiesel and diesel fuels are compared in Table 6.1 (Varese and Varese, 1996; Srivastava and Prasad, 2000; Yamane and Ueta, 2001). Biodiesel produced from various vegetable oils have viscosities close to those of conventional diesel. Their volumetric heating values are a little lower, but they have high cetane numbers and flash points.

Among the other attractive features of biodiesel fuel are as follows:

- It is a plant-, not petroleum-derived, fuel and as such it is potentially carbon neutral
- It can be domestically produced, offering the possibility of reducing petroleum imports, hence resulting in foreign exchange saving
- It is biodegradable
- Its combustion products have reduced levels of particulates, carbon monoxide, and, under some conditions, nitrogen oxides relative to conventional diesel fuel. It is well established that biodiesel affords a substantial reduction in SOx emissions and considerable reductions in CO, hydrocarbons, soot, and particulate matter (PM). There is a slight increase in NOx emissions, which can be positively influenced by delaying the injection timing in engines (Varese and Varese, 1996; Körbitz, 1998; Schäfer, 1998; Sheehan *et al.*, 998; Syassen, 1998; Sams, 1998; Yamane and Ueta, 2001).

Yamane and Ueta (2001), reported that a biodiesel fuel with good ignitability, such as one with high methyl oleate content gives lower levels of NO, hydrocarbons, HCHO, CH_3CHO, HCOOH, and soot formation is suppressed, since biodiesel is an oxygenated fuel having an O_2 mass fraction of 10 %. Life cycle analysis carried out by Sheehan and Camobreco (1998), showed that the benefit of using biodiesel is in proportion to the level of blending with petroleum diesel. Substituting 100% biodiesel for petroleum diesel in buses reduces the life cycle consumption of petroleum by 95%, while a 20% blend of biodiesel fuel causes the life cycle consumption of petroleum to drop to 19%. Sheehan ad Camobreco also claimed that biodiesel yields 3.2 units of fuel product energy for every unit of fossil energy consumed in its life cycle while the production of B20 yields 0.98 units of fuel product energy for every unit of fossil energy consumed. Such measure confirm the “renewable” nature of biodiesel.

Table 6.1: Physical and chemical properties of biodiesel

Vegetable oil Methyl ester	Kinematic viscosity (mm^2/s)	Cetane number	Lower heating value (MJ/l)	Cloud point (°C)	Flash point (°C)	Density (g/l)	Sulphur (wt %)
Peanut[a]	4.9 (37.8°C)	54	33.6	4	176	0.883	-
Soybean[a]	4.5 (37.8°C)	45	33.5	1	178	0.885	-
Soybean[b]	4.0 (40°C)	45.7-56	32.7	-	-	0.880 (15°C)	-
Babassu[a]	3.6 (37.8°C)	63	31.8	4	127	0.879	-
Palm[a]	5.7 (37.8°C)	62	33.5	13	164	0.880	-
Palm[b]	4.3-4.5 (37.8°C)	64.3-70	32.4	-	-	0.872-0.877 (15°C)	-
Sunflower[a]	4.6 (37.8°C)	49	33.5	1	183	0.860	-
Tallow[a]	-	-	-	12	96	-	-
Rapeseed[b]	4.2 (40°C)	51-59.7	32.8	-	-	0.882 (15°C)	-
Used rapeseed[c]	9.48 (30°C)	53	36.7	-	192	0.895	0.002
Used corn oil[c]	6.23 (30°C)	63.9	42.3	-	166	0.884	0.0013
Diesel fuel[b]	2-3.5 (40°C)	51	35.5	-	-	0.830-0.840 (15°C)	-
JIS-2D[c] (Gas oil)	2.8 (30°C)	58	42.7	-	59	0.833	0.005

[a] Srivastava and Prasad, 2000
[b] Yamane and Ueta, 2001
[c] Varese and Varese, 1996

6.3 Biodiesel economics

In previous economic studies of biodiesel production, the main economic criteria identified were capital cost, manufacturing cost and biodiesel break-even price (Zhang *et al*, 2003). However, different researchers have used different criteria to assess the economics of a biodiesel production. Total capital cost was used by Nelson *et al.,* (1994), whereas total biodiesel cost (i.e. total manufacturing cost) was used by Noordam and Withers (1996) to represent the economic performance of the plant. Capital equipment cost was used as an economic evaluation criterion by Bender (1999). Zhang *et al.,* (2003) assessed the economic feasibility of four continuous processes to produce biodiesel, including both alkali- and acid-catalysed processes using waste cooking oil and the 'standard' process using virgin vegetable oil as the raw material. They based the economic criteria on fixed capital cost, total manufacturing cost, after-tax rate of return and break-even price for biodiesel and found that the alkali-catalysed process using virgin vegetable had the lowest fixed capital cost, while the acid-catalysed process using waste cooking oil was more economically feasible overall, providing a lower total manufacturing cost, a more attractive after-tax rate of return and a lower biodiesel break-even price. They later concluded based on sensitivity analyses carried out on the economic calculations that plant capacity and prices of feedstock oils and biodiesel were found to be the most significant factors affecting the economic viability of biodiesel manufacture. Krawczyk (1996) and Connemann (1998), reported that approximately 70-95% of the total biodiesel production cost arises from the cost of virgin vegetable oil and animal fats. Therefore, the use of waste cooking oil should greatly reduce the cost of biodiesel because waste oil is available at a relatively low price.

Bender (1999) reported a review of 12 economic feasibility studies in the USA and concluded that biodiesel technology was at the time not economically feasible and that more research and technology would be needed. He proposed that the economics of biodiesel is volatile due to the large effects of feedstock cost and the meal credit and that, factors such as capital costs, electricity costs and glycerine product can appreciably affect production costs for biodiesel. The review also revealed that economies of scale for capital costs exist while the cost of operation does not reflect economy of scale because scale dependent expenses such as labour are only a small part of the operating cost. He concluded that tax credits would be needed to make biodiesel competitive with diesel fuel.

The analysis of Zhang *et al.* concured that raw material costs account for a major portion of the total manufacturing cost. Thus, reduction of the raw material cost should be the first step in optimising the total manufacturing cost. They also proposed that glycerine was a valuable by-product, which could add an appreciable credit to reduce the total manufacturing cost by approximately 10% for a plant with 8000 tonne/year biodiesel capacity. Lang *et al.*, 2001 and Antolin *et al.*, 2002, also reported that in spite of the favourable impact that biodiesel commercialisation could provide, the economic aspect of biodiesel production prevents its development and large-scale use, mainly due to the high feed cost of vegetable oil. Biodiesel usually costs over US$0.5/l, compared to US$0.35/l for normal diesel (Zhang et al., 2003). Exploring ways to reduce the high cost of biodiesel is of much interest in recent biodiesel research, especially for those methods concentrating on minimizing the raw material cost. This trend is rapidly changing with the increase in the price of crude oil. Although the price of conventional diesel fuel, which is about linearly proportional to crude oil price (EIA 2007), is not a direct component of the cost of biodiesel production, it provides the baseline against which the cost of biodiesel production must be compared. From the perspective of the biodiesel producer, the price received for its biodiesel output will most likely bear a close relationship, if not equivalent to the price of diesel and therefore will be a direct influence on the profitability of the producer's operation. Crude oil prices in 2003 are hovering slightly above US$ 30 per barrel[§§§§§§] (nominal value is US$ 27.69). However, in 2008, the partial price of crude oil is about US$ 100 per barrel[††††††].

Dorado *et al.,* (2006) recently conducted research on biodiesel economics using Ethiopian mustard oil seed and waste olive oil. The final cost of both biodiesels, including seed cost, oil extraction, processing, and distribution were compared with the cost of mineral diesel fuel. The final cost of the products was 0.66 €/kg of manufactured biodiesel from Ethiopian mustard, and 0.41 €/kg of manufactured biodiesel from used olive oil, while diesel fuel was in the range of 0.82–0.86 €/kg due to the fluctuations of the petroleum prices during 2004 in Spain. Although, this study shows a good first approach to the economics involved, there is not a full description of the process and the cost associated with it.

[§§§§§§] Prices are adjusted for inflation to April 2008 using Consumer Price Index (CPI-U) as presented by the bureau of labour statistics. The prices are annual average and will not show the absolute peak.

Haas *et al.* (2006) developed a computer model to estimate the capital and operating cost of a moderately-sized continuous process industrial biodiesel production. They proposed that the largest contributors to the equipment cost, accounting for nearly one third of the expenditures, were storage tanks to contain a 25 day capacity of feedstock and product. They also determined that the single greatest contributor to the expenditure was the cost of the oil feedstock, which accounted for 88 % of total estimated production costs and that production cost of biodiesel was found to vary inversely and linearly with variations in the market value of glycerol generated during biodiesel production while analysis of the dependence of production costs on the cost of the feedstock indicated a direct linear relationship. Nelson and Schrock (2006) carried out an economic analysis to determine the cost of production associated with producing methyl tallowate, using commercially available continuous-flow transesterification technologies and found out that feedstock cost had significantly greater impact on production cost, while the effect of glycerine by-product credit was minimal.

In a recent study to determine the scale of biodiesel plant, Collins-Chase (2005) conducted a study on biodiesel production in the Eastern Cape of South Africa. He reported that small scale, community agriculture biodiesel plant fits with rural livelihoods and has generated economic and social benefits for the rural community. Nolte, (2007) reported that a soybean 2500 kg/hr seed extraction biodiesel production plant with an annual manufacturing cost of about ZAR 150 million resulted in a biodiesel production cost of ZAR 6.69/l. This is lower that the current cost of ZAR 11.58 for conventional diesel in South Africa. He also concurred with the report of Collin-Chase and concluded that commercial biodiesel plant in South Africa should not be centralised, but rather be established through greater number of relatively small plants located in oilseed producing region. He further proposed that the local economy, particularly the agricultural economy will only benefit from biodiesel production if feedstock is produced locally.

6.4 Size optimisation of a biodiesel plant: South Africa as case study

Whilst the literature indicates that a major portion of the cost of biodiesel relates directly to the agricultural production cost of the oil feedstock, the chemical processing also adds a significant cost component. As already demonstrated by means of the Cassava-based bio-ethanol production case study (section 5.9), this cost is dependent on plant size, first decreasing with increase in the plant size due to economies of scale, but ultimately increasing due to the impact of transportation cost which increases with increasing transportation distances. This section specifically seeks to examine the sensitivity of key model outcomes to uncertainties in capital and operating cost estimation. The example used is a hypothetical one, located in South Africa, parametrically investigating the response of optimal throughput tonnage and resulting biodiesel cost to a wide range (250%) in variables such as capital cost capacity factor, labour cost model, depreciation factor, transport cost and oil feedstock cost. The results are used to direct the further cost analysis enquiry presented in the remainder of the chapter.

6.4.1 Method and assumptions

This study applies the Nguyen and Prince optimisation model described in section 2.9 to biodiesel production, using data by Zhang *et al.* (2003), who investigated the economic feasibility of the alkali–catalysed continuous process to produce biodiesel, but working with *Jatropha curcas* (physic nut) as the raw material. *Jatropha curcas L* (physic nut) is a perennial plant which can grow very well both in tropical and arid climatic conditions, which makes it a potential contender for use as raw material in Southern Africa.

The study focuses on the common end use of biomass which is energy provision and does not consider the credit from the by-product. Average seed yield of 3900 kg/acre/annum and 40% oil yield from seed are used for the analysis. The fraction of useful land available for cultivation of Jatropha curcas is assumed to be 10% while the plant operating time per annum is 330 days. Also, the capital cost of 8.637 million ZAR for a 1000 kg/hr plant was used as the base case, based on the results of Zhang et al. (2003). All currency are expressed in South African Rand (ZAR) and are used to the base of 2003 using a conversion rate of 1 US$ to 6.438 ZAR.

6.4.2 Result and discussion

Table 6.2 illustrates the biodiesel production cost estimate for the central values of the investigated variables as shown in the footnote to the table. Comparing the capital cost obtained for the different plant sizes shows that the unit capital cost decreases as the plant capacity increases as expressed by the theory of economy of scale (when the capacity factor $n<1$). The results obtained in the study generally, but not always, show a near flat response of biodiesel cost around the optimum plant size and agree with those reported by Jenkin (1996) and Kumar *et al.* (2002) as already discussed in section 2.9 of the dissertation. This is illustrated in Figures 6.2 to 6.6.

Table 6.2: Biodiesel cost estimate using Jatropha curcas as feedstock using Nguyen and Prince optimisation model

Annual Capacity of plants (x 10^3)	2,252	4,505	9,010	13,515	18,020	22,525	45,051	m3/year
Plant Capacity (units)	250	500	1000	1500	2000	2500	5000	kg/hr
Capital cost of plant	0.508	0.825	1.340	1.780	2.177	2.545	4.134	$\$/10^6$
Capital cost of plant	3.269	5.311	8.627	11.459	14.015	16.385	26.617	Rand*10^6
Capital cost in Rand (ZAR)	3.269	5.311	8.627	11.459	14.015	16.385	26.617	ZAR
Feedstock cost	3.167	6.335	12.669	19.004	25.338	31.673	63.346	ZAR*10^6/ annum
Seed Cost	0.561	0.561	0.561	0.561	0.561	0.561	0.561	R/kg
Transport	0.310	0.878	2.482	4.560	7.020	9.811	27.750	ZAR*10^6/ annum
Waste/utilities	0.268	0.453	0.824	1.195	1.566	1.937	3.791	ZAR*10^6/ annum
Chemical e.t.c	0.789	1.577	3.155	4.732	6.310	7.887	15.774	ZAR*10^6/ annum
Labour(Operating)	1.415	2.299	3.734	4.960	6.066	7.092	11.521	ZAR*10^6/ annum
Supervisory and clerical Labour	0.212	0.345	0.560	0.744	0.910	1.064	1.728	ZAR*10^6/ annum
Overhead, packaging and storage	0.849	1.379	2.241	2.976	3.640	4.255	6.912	ZAR*10^6/ annum
Maintenance and insurance	0.147	0.239	0.388	0.516	0.631	0.737	1.198	ZAR*10^6/ annum
Administration	0.212	0.345	0.560	0.744	0.910	1.064	1.728	ZAR*10^6/ annum
Depreciation	0.131	0.212	0.345	0.458	0.561	0.655	1.065	ZAR*10^6/ annum
Capital charge	0.654	1.062	1.725	2.292	2.803	3.277	5.323	ZAR*10^6/ annum
Working capital cost	0.490	0.797	1.294	1.719	2.102	2.458	3.993	ZAR*10^6
Production cost	2.902	4.715	7.659	10.173	12.442	14.546	23.630	ZAR*10^6
Total manufacturing cost	7.436	13.958	26.789	39.663	52.676	65.853	134.290	ZAR*10^6
Transport cost as % Total cost	4.17	6.29	9.27	11.50	13.33	14.90	20.66	%
Cost per litre	**3.30**	**3.10**	**2.97**	**2.93**	**2.92**	**2.92**	**2.98**	**R/l**

The values of the investigated parameters used in this table are: n = 0.7; D = 4%; T = 15 ZAR (ZAR/ton/km); F = 0.56 ZAR/kg; labour cost model = $y = k(x^{0.7})$

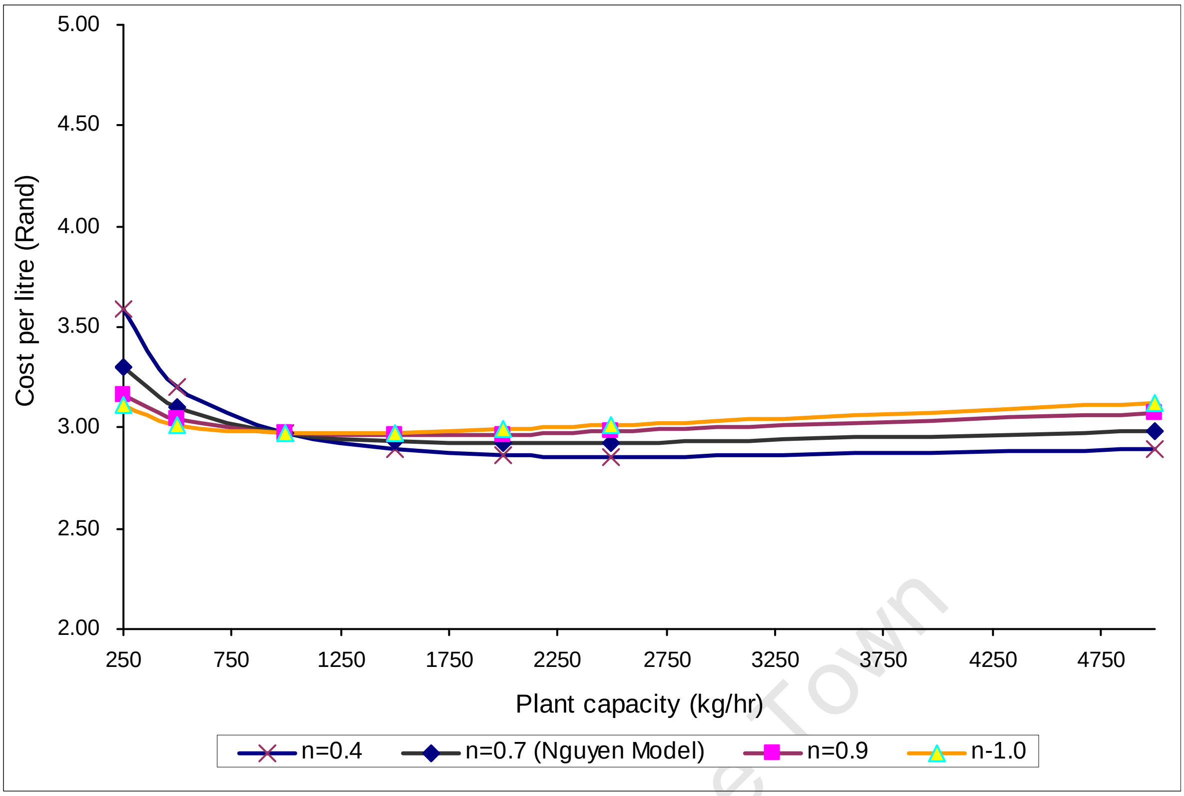

Figure 6.2: Effect of capacity factor (*n*) on cost of biodiesel (D = 4%; T = 15 ZAR/ton/km; F = 0.56 ZAR/kg; labour cost model = y = k($x^{0.7}$))

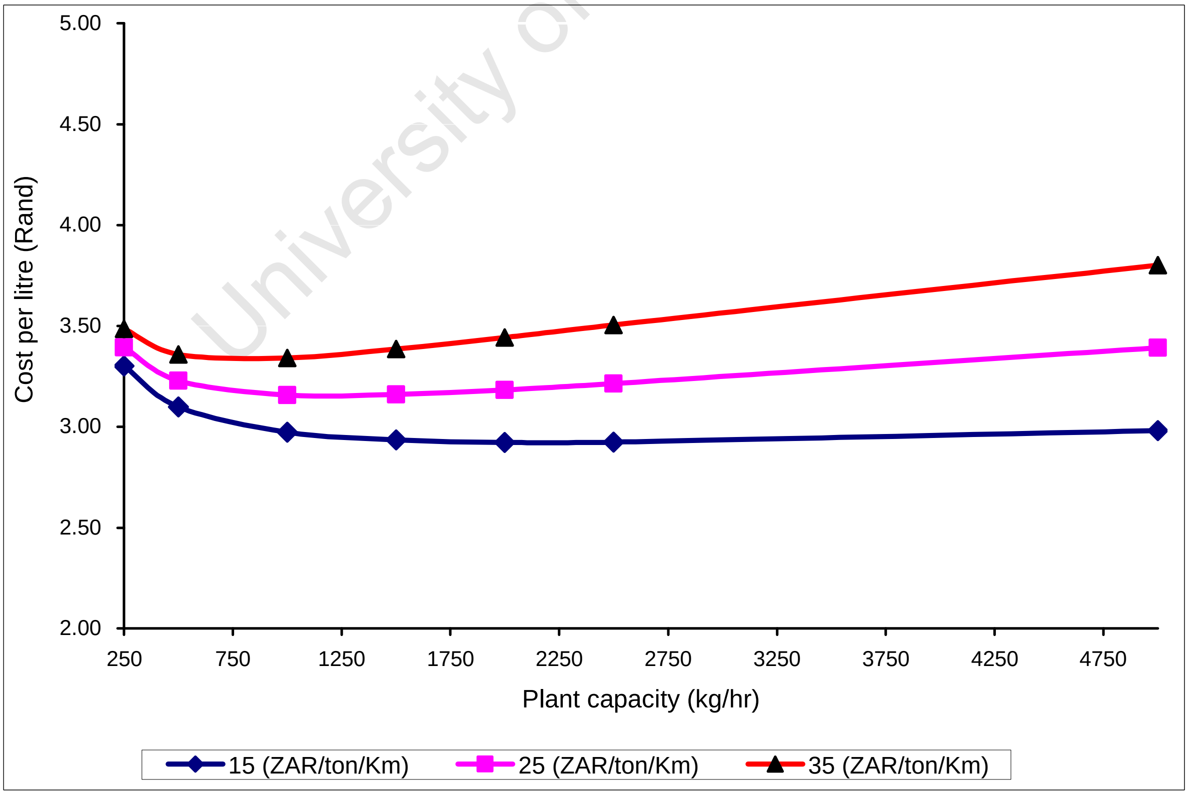

Figure 6.3: Effect of transport cost on cost of biodiesel (*n* = 0.7; D = 4%; F = 0.56 ZAR/kg; labour cost model = y = k($x^{0.7}$)

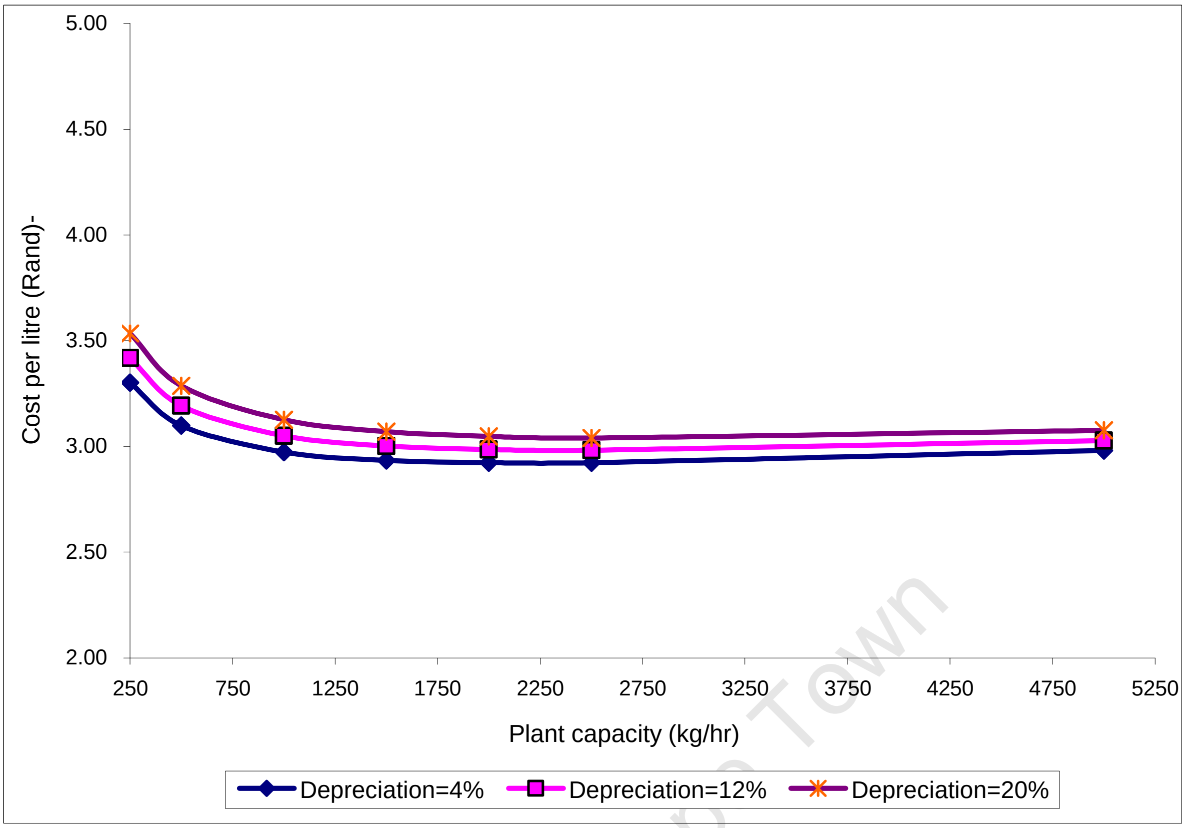

Figure 6.4: Effect of depreciation (using Nguyen labour model) on cost of biodiesel (*n* = 0.7; T = 15 ZAR/ton/km; F = 0.56 ZAR/kg; labour cost model = y = k($x^{0.7}$)

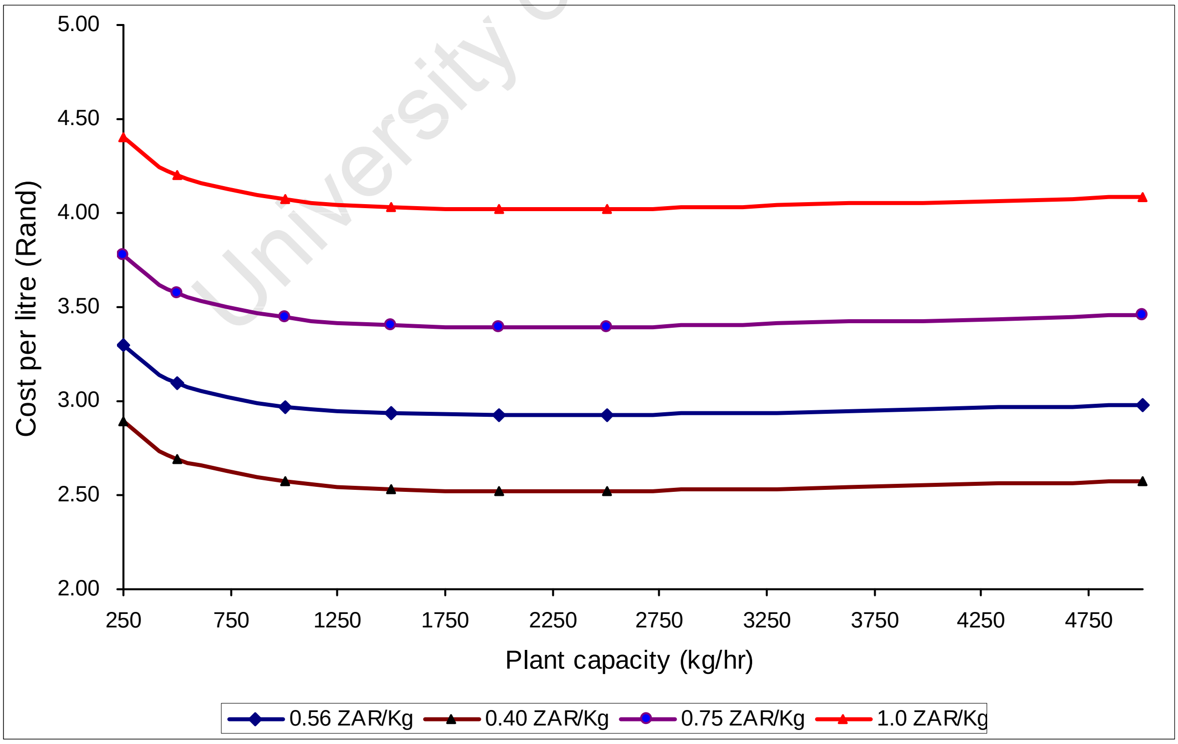

Figure 6.5: Effect of seed cost using Nguyen labour cost model on cost of biodiesel (*n* = 0.7; D = 4%; T = 15 ZAR/ton/km); labour cost model = y = k($x^{0.7}$)

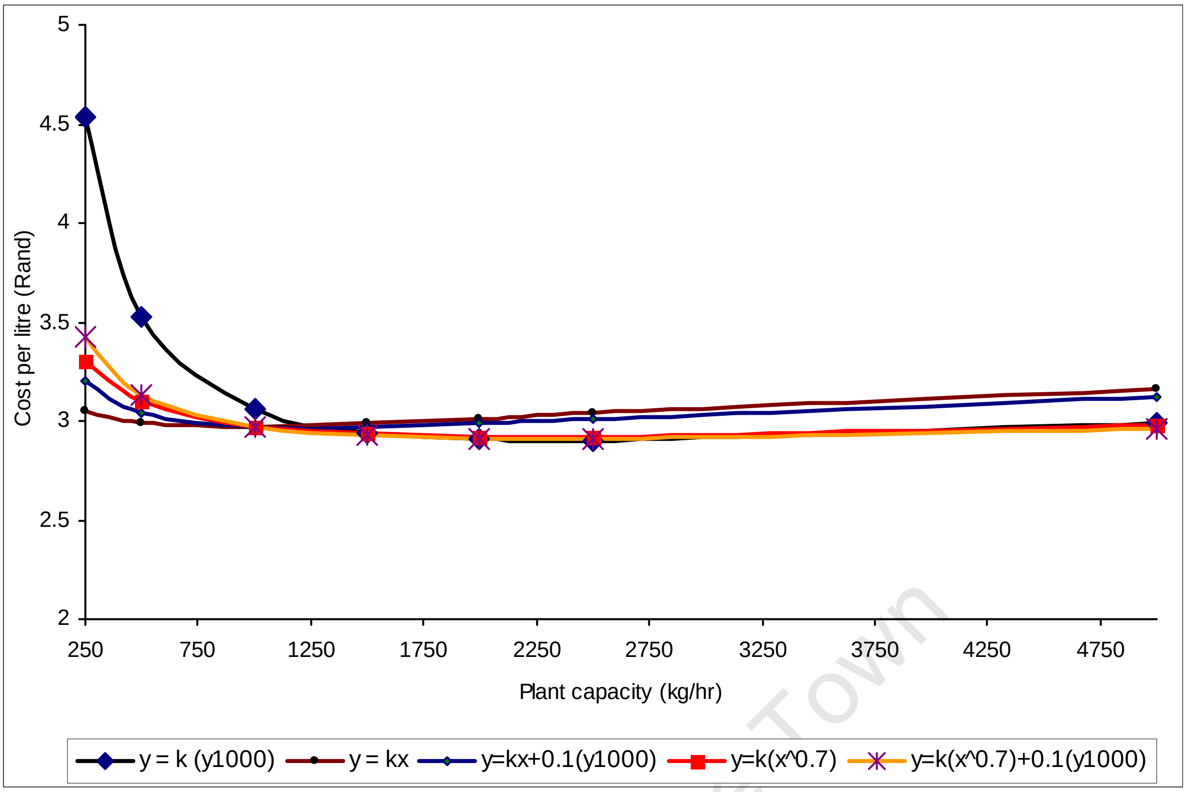

Figure 6.6: Effect of labour cost model on cost of biodiesel (*n* = 0.7; D = **4%; T = 15 ZAR /1000kg/km); F = 0.56 ZAR/kg)**

This near flat profile around the optimum plant size occurs because of the reduction in capital cost per unit capacity with increasing plant size, which is offset by transportation cost as the area from which the biomass is drawn increases, indicating that smaller than optimum plant of between 1500 and 2000 Kg/hr observed can be built with only minor cost penalty. The wide range of optimum plant size obtained in this study is in agreement with the report of Kumar *et al*. (2002). The relative insensitivity of output cost to scale around the optimum suggests that above some small size, finding the optimum is not especially critical in any case and that other siting factors which are site specifics may be considered more important and as such determining the optimum facility size remains a site specific task.

As noted in the result, the transportation costs for the biodiesel production varies with the plant capacity. This arises because of the area from which the raw material is drawn is proportional to the plant capacity, and the transportation distance is proportional to the square root of the area. Therefore, decreasing the transport cost from (ZAR 20/1000 kg/km) to (ZAR 10/1000 kg/km) led to a decrease in the unit capital cost; hence, the production cost decreases, resulting in the lower optimum plant size. Increasing the crop price (Jatropha curcas) from ZAR 0.40/kg through to ZAR 1.0/kg resulted in increased biodiesel price of 4.15 ZAR/l, but did not affect the optimum plant capacity, as the ratio of the transport to production cost is not affected.

The result indicated that the optimal plant size varies widely in the range of plant size explored and show different sensitivities to variations in the various parameters. The optimal size is highly sensitive to variation in the labour cost model, changes in the transport cost and capacity factor (*n*), but fairly insensitive to the oil feedstock cost or the depreciation allowance. The biodiesel cost is dependent on transport cost and highly dependent on the oil feed cost but less sensitive to the labour cost and the depreciation allowance. The cost of biodiesel is also fairly sensitive to the effect of capacity factor (*n*).

Therefore, to further investigate and clarify the outcome of this demonstrative case study, a detailed cost analysis of biodiesel economic feasibility in Germany, the highest biodiesel producer in the world was carried out. This approach is justified by the absence of commercial facilities and the very competitive and fragmented nature of the non-commercial biodiesel sector in Africa at the time of research and writing.

6.5 Biodiesel economics in the European Union (EU): Relevance to the African continent

6.5.1 Predicting the costs of biodiesel in Africa: Lessons from Germany

Commercially motivated biodiesel initiatives in Europe could be observed as early as 1988 predominantly in Austria and also in France, where the first industrial scale biodiesel production plants went into operation in 1990/1991 (Austrian Biofuel Institute, 2002; EIA, 2002). Germany’s focus then was on the development and application of pure vegetable oils as fuels for diesel type engines. Germany recorded tremendous breakthroughs in biodiesel production and utilisation from late 1999 onwards, and they are today the world’s largest producer of biodiesel. Germany’s existing biodiesel production plants in 2006 have a total annual biodiesel capacity of more than 3 million tons (UFOP, 2006). This is aided by higher prices and taxes imposed on petroleum diesel and many government support programs (Thrän, 2006). Also, several developed countries (Austria, France, USA, Canada) and other developing countries

(Brazil, India, Malaysia) have active biodiesel programmes. They also have provided legislative support and have drawn up national policies on biodiesel development. Table 6.3 illustrates the top five biodiesel producers in 2005 (worldwatch, 2006).

Of all the renewable material products, biodiesel is by far the most important for German agriculture (Bockey, 2005). Germany as mentioned earlier is the world's leader in the production of biodiesel and also in developing related plant technologies and automotive concepts of operation with biodiesel as a pure fuel. Biodiesel has been produced in Germany since 1993. Until 1998, the structure of biodiesel production in Germany was still unstable mainly due to uncertainties on the market penetration and the calculation risk involved. Demand in biodiesel as a final energy source grew after 1998 when biodiesel produced from rapeseed, sunflower oil and other oil plants was declared 100% mineral oil tax free. Biodiesel production in Germany is almost exclusively based on rapeseed oil (the final product is called rape seed methyl ester (RME)). This feedstock can be used for both human and industrial purposes. In 2001, about 460,000 ha of rapeseed were cultivated in Germany for non-food purpose. These yielded some 470,000 tons of oil, of which about 300,000 tons were used for biodiesel production amounting to about 1% of Germany diesel fuel consumption (UFOP, 2006).

Table 6.3: Top five biodiesel production in 2005

Country	Production (million liters)
Germany	1,920
France	511
United States	290
Italy	227
Austria	83

In Germany, as in other European countries, a certain percentage (currently about 1%) of agricultural land is taken out of food production every year (set aside) to avoid overproduction of food crops. This land is often used for non-food crops, the most often cultivated in Germany being rapeseed. The costs for re-planting the fallow land effectively became a credit for cultivating rapeseed. The use of this potential area makes the biodiesel rapeseed widely cultivated more than other energy crops, particularly cereal crops.

However, the use of biodiesel in Germany is still controversial, while the federal ministry of finance defends the tax exemption of biodiesel, the federal environmental agency argues that ecological benefits (such as lower net CO_2 emissions) do not justify the disadvantages (such as additional agricultural inputs) and the expenses (Ifeu, 2005; Clean Air Initiative, 2007).

There has been increased awareness and development of biodiesel in other developing countries such as Brazil and India apart from developed countries such as Germany, France, USA, Canada and other developing countries, while the development of biodiesel in Africa is still in its infancy with a total production of approx. 50,000 t in 2006 (F. O. Licht, 2007). To describe the biodiesel scene in Africa, a three-phase development is referred to (Friedrich, 2004; Körbitz, 2003; Amigun *et al.*, 2008).

- Phase I consists of the very first ideas and thoughts of biodiesel being used as a fuel until the actual adaptation of the ideas on the part of decision makers who are then motivated to put these ideas into practice. The end of Phase I is the political decision to invest money and other resources into biodiesel research.

- Phase II is characterised by research efforts, pilot projects, setting of frame conditions (policy/strategy formulation) and financially supported technical trials.

- Phase III is marked by a biodiesel economy based primarily on a feasible economic production, distribution and use of biodiesel.

Most of the countries in Africa except South Africa and Zimbabwe are still at the first stage of biodiesel development. The South African biodiesel market is mainly characterised by several small and medium scale producers while Zimbabwe recently inaugurated the country's and Africa first ever commercial biodiesel plant. The US$6 million biodiesel plant which processes jatropha, cotton seed, sunflower and soya, among others has the capacity to produce 100 million liters annually if fully operational (The Zimbabwe gazette, 2007; ZimOnline, 2007). The plant is expected to save up to US$80 million a year in foreign currency from diesel importation. However, the use of vegetable oil as a source of fuel for energy production has been explored in some African countries such as Mali and Uganda. Mali is at the moment planning on using existing Jatropha nut already on the market to produce biodiesel by first quarter of 2008 for local consumption. The production will employ small scale decentralised biodiesel plants, where there is local production of jatropha nuts to minimise transport (Petroleum Africa, 2007). The production and commercialisation of biodiesel in Africa could provide an opportunity to diversify energy and agricultural activity, reduce dependence on fossil fuels (mainly oil) and contribute to economic growth in a sustainable manner (Amigun *et al*, 2008).

6.5.2 Objectives

The primary objective of this study is to assess the economic feasibility of producing biodiesel by various industrial configurations representing the state of art of biodiesel technology in Germany with the view of applying the result to the African continent where most of the countries are still in the first phase of biodiesel production. Specific objectives are as follows:

(a) Study fixed capital investment costs and evaluate the cost-capacity factor (n), of biodiesel production facilities in Europe in order to gain a better understanding of likely impact that economies of scale will have as this industry is adopted. This capacity factor is useful for the Level I (order of magnitude) type of fixed capital investment estimation. As shown in section 6.4, it is also important in optimal facility size selection.

(b) Evaluate the labour requirement for a typical biodiesel plant and its impact on the whole biodiesel economics, again with reference to the scale of production.

(c) Evaluate the economic impact factors (feasibility) of biodiesel production in Germany and evaluate the relevance of the study to the African continent for a better understanding of its economics.

6.6 Economic model

6.6.1 Capital cost estimation and model development

This section will seek to develop a cost estimation relationship (model) for calculating the capital cost (in a static technological framework) of the biodiesel industry in the EU and also analyse the quality or validity of the developed model. This applies when considering capacity choices in an investment or design decision.

6.6.1.1 Capital cost

The capital costs for a biodiesel plant are relatively modest compared to other biofuel such as bioethanol. The capital cost is influenced by the type of feedstock processed, the technology, location of the plant, the magnitude of the proposed plant. There has been a number of plant cost estimates published in the past years for different plant sizes based on Greenfield sites in Europe (Körbitz *et al.* 2004). The data of plant size and capital investment costs from several sources (both primary and secondary sources) are plotted on a log-log graph using the principle of order of magnitude type of cost estimation to obtain a cost-capacity factor for biodiesel installations in Europe. Cost capacity factor for both modular plant and full plant cost were determined. Land cost for industrial developments and thus for biodiesel plants strongly depends on location and available infrastructure. The capital investment cost obtained from a leading biodiesel technology provider is used in this study. For the modular plant whose cost does not include the project development cost, a capacity cost factor of 0.693 is recommended (Anonymous, 2006). In addition to this, a 15% of the original capital cost is added to the investment cost.

6.6.2 Data collection and method of analysis

The data used in the analysis were collected from accounting records of biodiesel producers in the EU. All the data were in the same currency. The data were normalised by adjusting the cost for inflation difference using an Engineering news record index of 2005 (McGraw Hill Construction, 2006). The capital investment costs were then plotted against plant capacity on a log-log scale using the exponential rule. By means of the least square method (Ordinary Least Squares Best Fit (LSBF) Regression Analysis), the points were approximated to a straight line to find if there exists any empirical relationship between the plant capacity and the installation cost (fixed capital investment cost). The quality of the capacity factor (n) obtained was evaluated by means of inferential statistic (t-test), using a level of significance of 0.05 (alpha value). The t-value corresponding to the appropriate degree of freedom was used as the critical point to accept or reject the hypothesis of constant return to scale.

6.6.3 Operating cost estimation and model development

When evaluating technology and process alternatives, it is important to consider not only the capital costs of the initial investments but the operating costs of running the plant. More attention tends to be focused on the capital expenditure required to build the plant. This is reasonable since it is the first barrier that must be overcome in establishing a biodiesel production plant. However, the long run success of the plant is frequently more dependent on the daily operating performance than on the amount of the initial capital outlay invested. Low quality, inconsistent product quality, poor product yield or high operating costs can cause low efficiency, low plant availability or total failure of the venture.

To calculate the biodiesel production cost and the economic efficiencies of the various reference models, a calculation model was developed on the basis of the annuity method as described by the VDI[*******] guideline "Economic calculation for capital goods and plants" (VDI, 1996). This is illustrated in Figure 6.7. This model guideline deals with all the dynamic methods of calculation of economic efficiency, which are characterised by the following features:

- Explicit allowance for costs and payments which occur at different periods, i.e. doing away with average cost rates per period, in contrast to the static method
- Use of different change rate for various costs or type of payment
- Taking account of the uncertainty or risks of future costs of payment. This is realized by a sensitivity analysis using the annuity model

The economic analysis assumed that the reference plant is a green-field biodiesel plant with an annual plant capacity of 100,000 tons (a large scale biodiesel plant). The plant capacity utilization is considered to be 96%. In general, parameters such as specific taxes (e.g. petroleum tax subsidies) and tariffs, fluctuating revenues and expenditures incurred during start up, salvage and decommissioning of the plant are not taken into account.

The economic lifetime (i.e. typical consideration period for investment sector) is assumed to be about 15 years. The annual inflation rate is in a wide range for different industrial sectors (e.g. metal industry, import/export); moreover, they are subject to fluctuations.

[*******] Association of German Engineers

Regarding the assessment of the general economic feasibility, an average inflation rate of 3.0 % per annum is used. It is assumed that 20% of the capital investment cost is the investor's own capital (interest rate of 15% due to higher risk involved) while 80% is sourced from bank or loan/finance house with an interest rate of 8%.

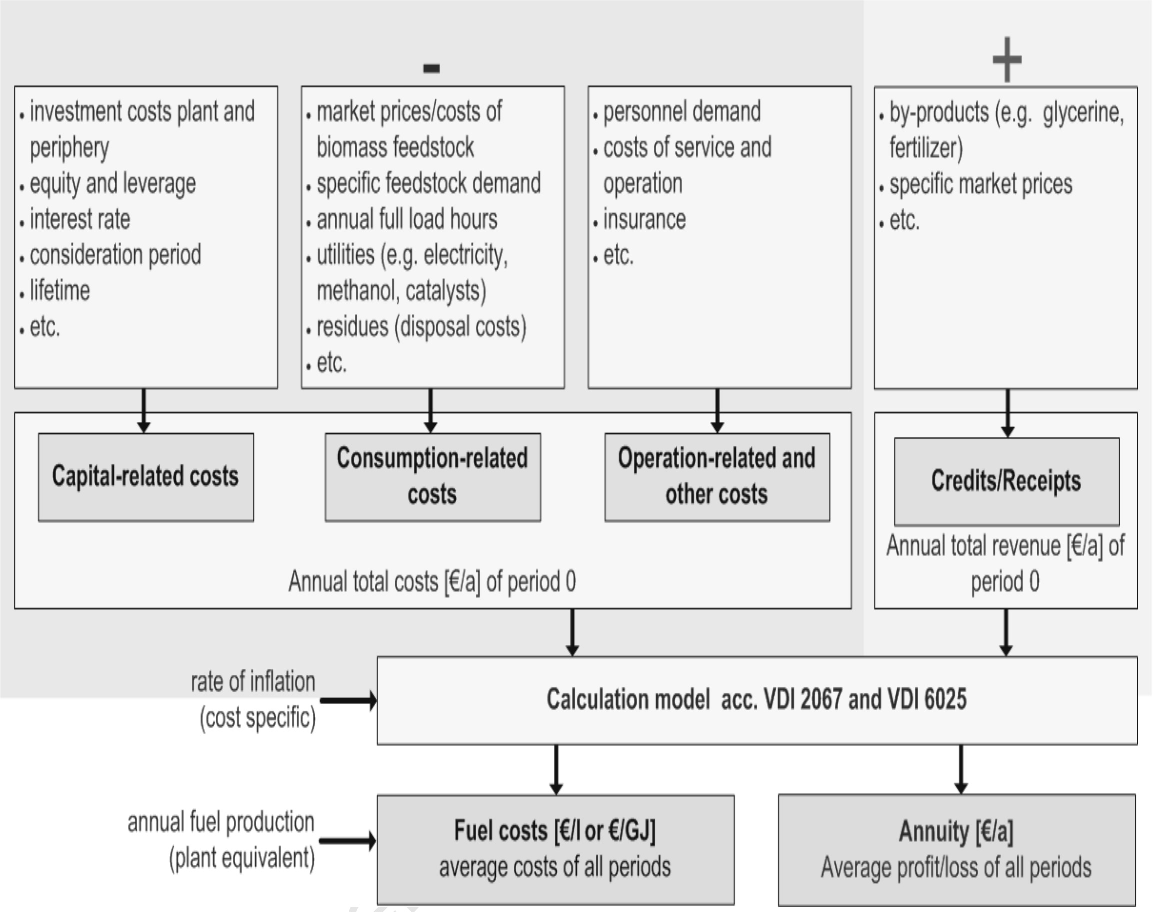

Figure 6.7: Principle of the calculation model for biodiesel production cost (VDI, 1996; IEE, 2007)

It is also assumed that 50% of the total cost of investment, corresponding to equipment replacement and fee will be incurred during the lifetime of the biodiesel plant. This model assumes that no incentives are provided to biodiesel producers as they are in some European countries, where fuel tax exemptions on agriculturally based diesel fuels are applied, effectively closing the gap between renewable and conventional diesels.

6.6.3.1 Feedstock cost

The feedstock costs are the primary component of the cost of biodiesel. Theoretically, the conversion of feedstock triglyceride to methyl ester is very close to one to one on a weight and volume basis. Since the density of fat and oil is about 0.88 kg/liter, that means that 1 kg of feedstock makes 1.14 liters of biodiesel or 0.88 kg of feedstock will produce 1 liter of biodiesel. The conversion rate used in this study is based on the plant conversion rate as illustrated below (equation 6.2):

$$\text{1000 kg rapeseed oil} \longrightarrow \text{980 kg of biodiesel} \tag{6.2}$$

Mustard/rapeseed oil is the third largest edible oil produced in the world after soy and palm oil (Demibras, 2005). At a production volume of 46.7 million tons in 2005, it accounts for about 12% of the total worldwide edible oil production (FAO, 2006). Factors affecting the price of rapeseed oil are among others: availability and price of other vegetable oils, population growth, economic growth, changing consumer preference. Top rapeseed producers in 2005 are illustrated in Table 6.4 (FAO, 2006).

Table 6.4: Top rapeseed producers in 2005

Country	Production volume (million metric ton)
China	13.0
Canada	8.4
India	6.4
Germany	4.7
France	4.4
United Kingdom	1.9
Poland	1.4
Australia	1.1
World total	46.7

6.6.3.2 Energy requirement

Biodiesel plants require electricity and heat to achieve the transesterification process and the purification of the product and co-product as the case may be. The energy requirements used in the model are based on the data provided by a leading biodiesel manufacturer in Germany to the Institute of Energy and Environment, Leipzig, Germany.

6.6.3.3 Labour requirement (operating labour)

The hypothesis proposed is that labour requirement (personnel need) generally depends on the production scale of the plant (plant capacity). It also depends on the level of sophistication of the plant (degree of automation), the type of process (batch or continuous), the type of feedstock processed and technical progress made in the industry. This dependence is usually different for distinct categories of personnel and can be broadly categorised as technical, administrative and clerical. In most process plants, this includes, production, engineering, technical support, technical support staff, accounting, clerical and secretarial functions (Brennan, 1988). The functional dependence between plant size and employment requirements can take a number of forms. Two basic approaches based on the study of Norman were employed (Norman, 1979).

- Hypothesis I: The labour input consists of a fixed element (probably made up of managerial and technical staff) plus an element linear in plant capacity, represented by the equation:

  $$E = a_1 + b_1 C + \varepsilon_1 \tag{6.10}$$

  Where: E is the employment requirement
  C is the plant capacity
  ε is the error term
  a and b are constants

  If economies of scale exist in the labour requirement and equation (6.10) is the appropriate condition, then, $a_1 > 0$

- Hypothesis II: The labour requirement increases proportionately "progressively" with plant capacity, i.e. that the functional form is:

  $$E = a_2 C^{b_2} \varepsilon_2 \tag{6.11}$$

  Economies of scale to labour require, $b_2 < 1$

The data used for the determination of dependence of total labour requirements on investment volume was provided by a leading biodiesel producer in Europe and America.

The estimation is for a standalone plant. The average operating labour is estimated as the slope of the total operating labour versus the plant size.

6.6.3.4 Chemicals

Biodiesel production requires the use of alcohol (usually methanol), a catalyst and minor chemicals such as acid (sulphuric acid-H_2SO_4, phosphoric acid-H_3PO_4). In this study, Sodium methylate is used as the catalyst. This model employs a value of 0.12 liters of methanol per liter of biodiesel produced. This is 10% above the theoretical requirement (10% of weight of feedstock). The prices of methanol can be volatile and they vary depending on location. Prices of methanol are usually expressed as FOB and small scale users (batch plant operators) may pay a price a bit higher than what a large scale plant will pay. Small users might also have a higher methanol use, up to 0.2 l/l.

6.6.3.5 Maintenance

The cost of maintenance for a biodiesel plant will be similar to other processing plants since operation conditions for biodiesel plants are relatively mild and as such a factor of 1.5% of the capital investment cost is used for a standalone plant and 2.5% for a biodiesel plant with an integrated oil mill.

6.7 Revenue

Biodiesel production plant generates revenue from at least two sources namely; biodiesel (FAME) and glycerine. In the case of an integrated crushing (seed) plant, revenue is also generated from the sales of the cake (for protein rich seed/fruit-such as soybean, rapeseed, and peanut). Separated FFAs can also be sold for further processing to the oleo-chemical industry and in some cases potassium sulphate fertilizer is another by-product. The selling price of the produced biodiesel will be determined by the corresponding price of conventional diesel, tax incentives depending on the location (this varies even within countries), and the characteristics of biodiesel such as cetane number or lubricity value.

Other revenue can be obtained from the crude glycerine co-product. This contains unused catalyst and soaps that are neutralised with an acid (typically H_2SO_4 or H_3PO_4).

Moreover, crude glycerine can be further treated to technical or pharma glycerine (i.e. products of higher quality). In some cases, the salt formed during this phase is recovered for use as fertilizers. This is rather possible if potassium hydroxide (KOH) is used as catalyst instead of sodium hydroxide (NaOH). The volume of the salt (recovered) is rather low, about 1% of the biodiesel production. This by-product type is not relevant to the model as Sodium methylate is used as catalyst.

6.8 Biodiesel models

An economic analysis was performed to determine the cost of production (€/L) using commercially available transesterification technologies. These models were selected based on the current state of art technology (IEE, 2006). The reference models are as follows.

- Agricultural biodiesel plant (Reference concept model I)
- Industrial biodiesel plant - stand alone (Reference concept model II)
- Industrial biodiesel plant - with integrated oil mill (Reference concept model III)
- Multi-feedstock biodiesel plant (Reference concept model IV)

Capital cost and operating data used in the study are a compilation of records from 25 current operating biodiesel plants in Europe, with a large percentage from Germany. Cost sensitivity analyses were performed to determine the effect of feedstock, and glycerine credit on final biodiesel cost at the plant.

6.8.1 Reference concept model I

This is a biodiesel plant located very close to an agricultural area with an integrated oil mill. This kind of practice increases the regional creation of value and at the same time, introduces biodiesel production in a closed loop recycling management cycle (see Figure 6.8). This kind of biodiesel plant model reduces the feedstock transportation cost due to its close proximity, making it more efficient from energy and cost point of view. This type of model will be most applicable for wealth creation within a community thereby increasing the standard of living. The press cake and the glycerine can be used as a source of energy generation such as biogas production for combined heat and power (CHP). The steps are further illustrated in Figure 6.9.

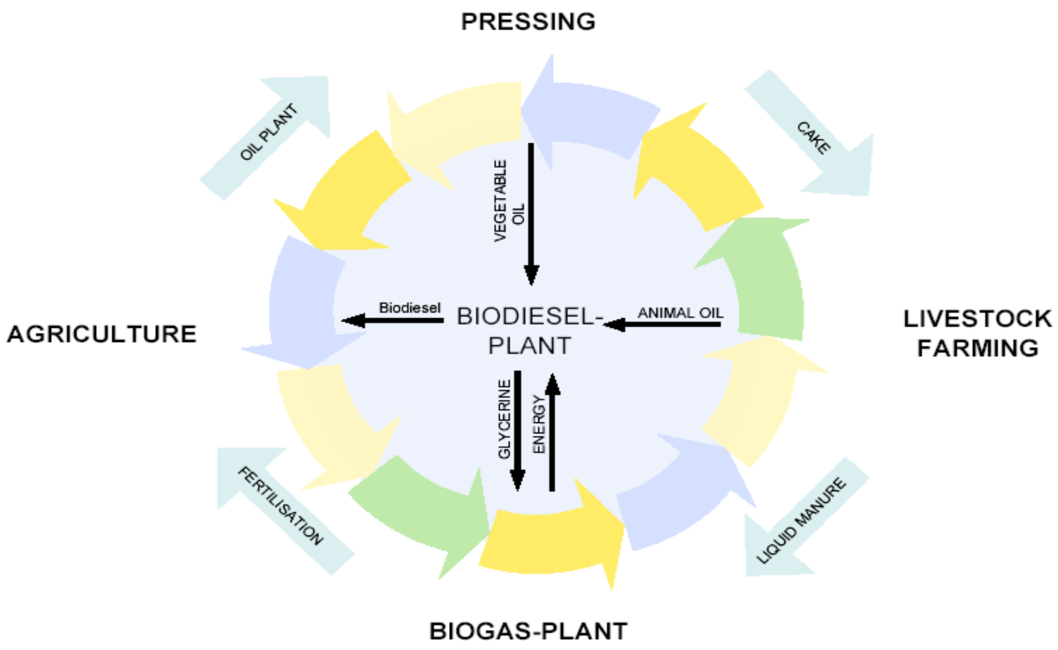

Figure 6.8: Closed loop recycling management of agricultural oil-mill based biodiesel plant (IEE, 2006)

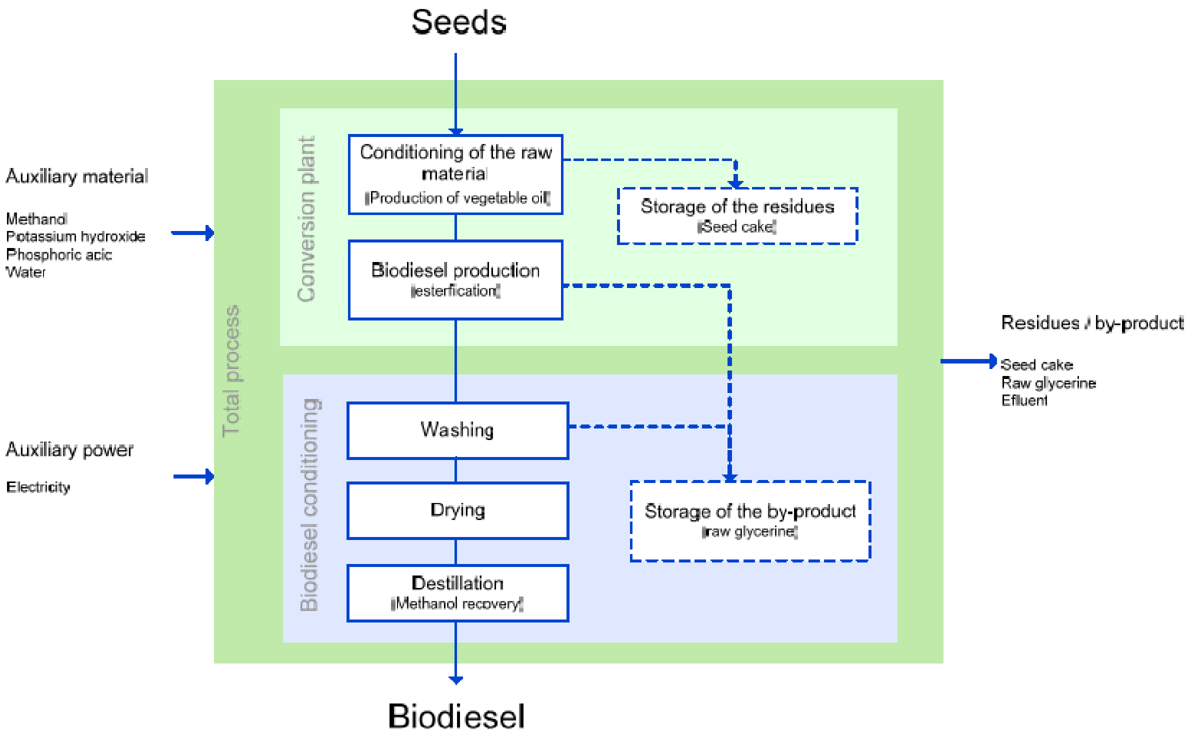

Figure 6.9: Agricultural oil-mill biodiesel plant model (Reference model I)

6.8.2 Reference concept model II and III

The general conception is that large industrial process plant tends to be more economical than small scale due to economies of scale. It is also expected that large scale biodiesel plant will face the problem of limited feedstock availability and other logistic constraints. Most of the large scale biodiesel plants in the USA and Europe have been designed to use clean (high quality) vegetable oil. The large scale model can also be further differentiated based on whether it is a stand alone plant or has an integrated oil crushing/extraction facility. These two types will be represented as model II and III respectively (Figures 6.10 and 6.11). A typical representative of industrial scale biodiesel is 100,000 t/a (Ballestra, 2005; UFOP, 2006).

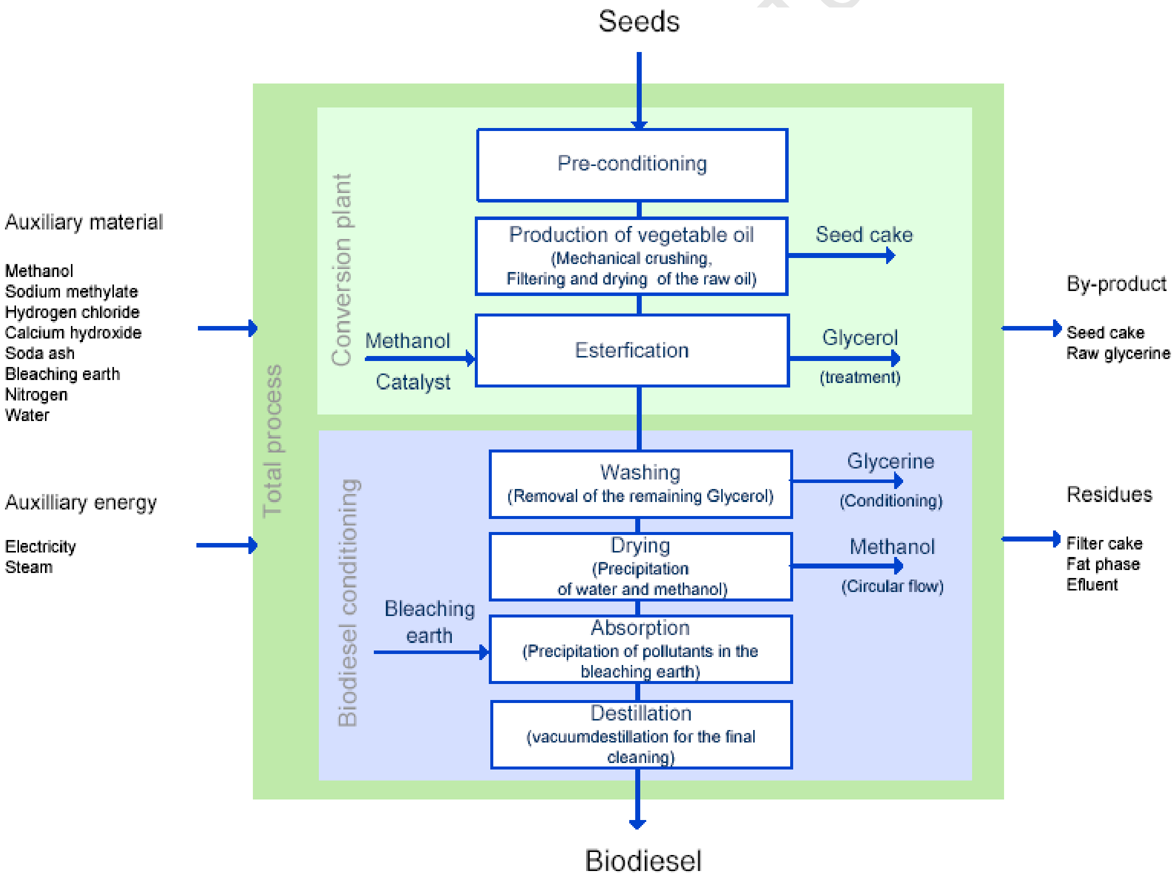

Figure 6.10: Industrial biodiesel plant (Reference mode II)

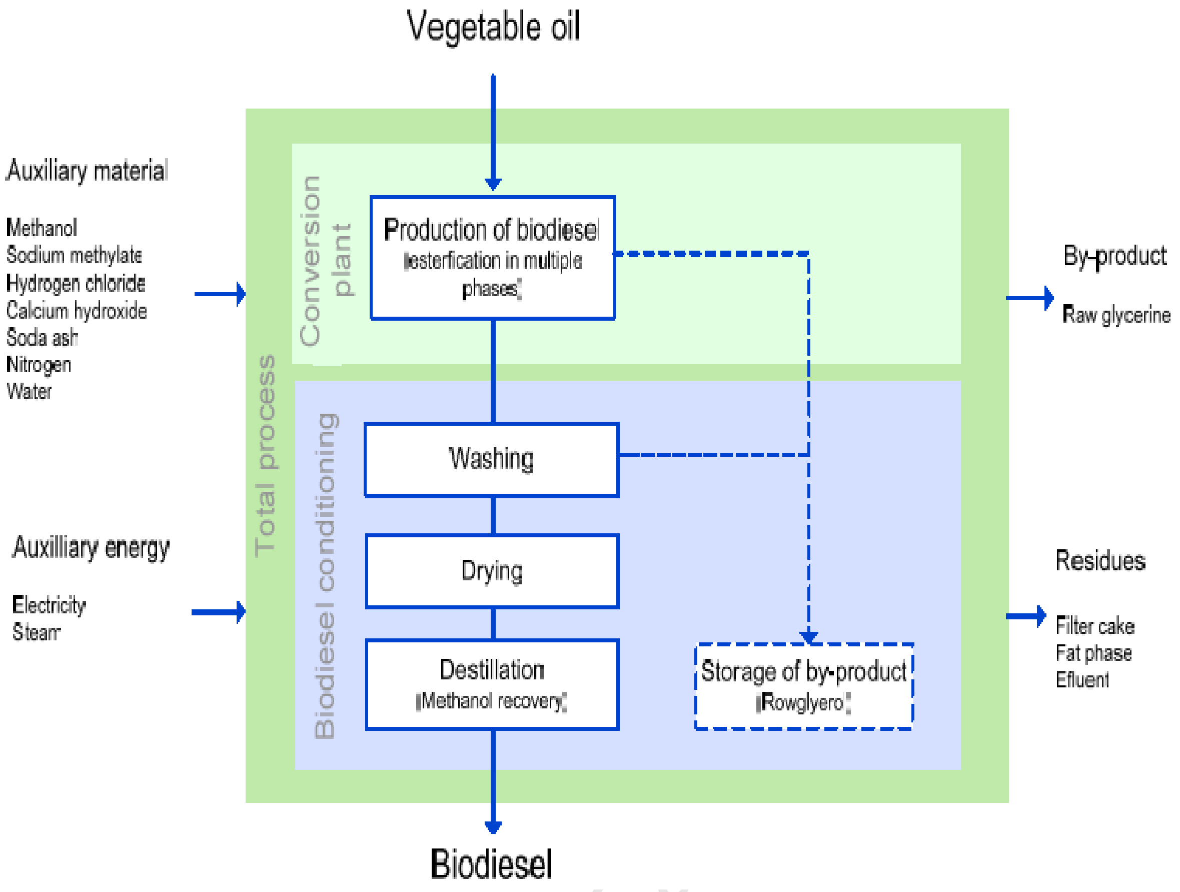

Figure 6.11: Industrial biodiesel plant (Reference model III)

6.8.3 Reference Model IV

New technology in biodiesel production that offers multi-feedstock utilisation without impacting production cost, product quality, or product yield are now on the increase. This technology is driven by the quest to finding solution to the high cost of vegetable oil feedstock. This technology also offers sustainable competitive advantages: the use of low cost multiple feedstock that can help reduce the margin between biodiesel and petroleum diesel without reliance on government subsidies or tax credits. The technology usually has a high degree sophistication to cater for different feedstocks, and handles high free fatty acid (FFA) content up to 20% and uses mainly recycled oil with a typical plant size of around 50,000 tons per annum (Figure 6.12).

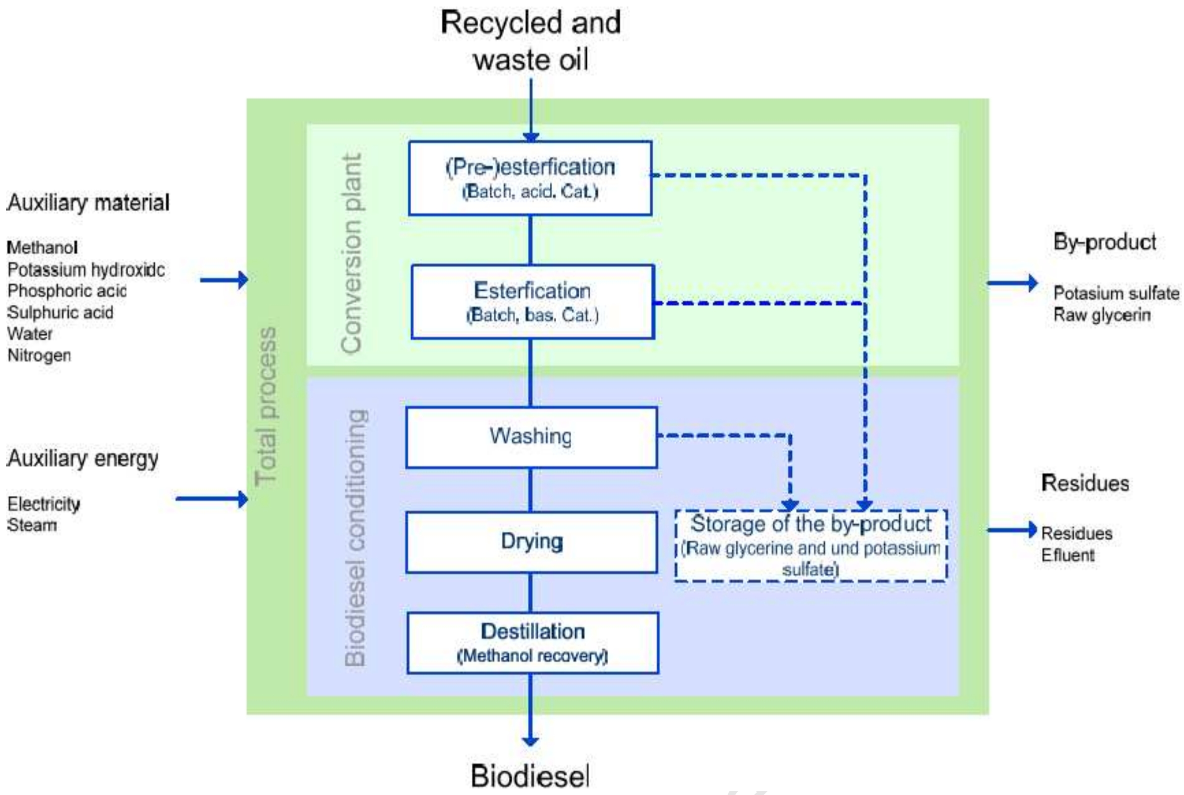

Figure 6.12: Industrial multi-feedstock biodiesel plant (Reference model IV)

The mass and energy balance (process data) for the models (I to IV) are given in Table 6.5. The table represents the input of raw material, utilities, auxiliary energy into the biodiesel production process as well as the main product biodiesel and co-products (press cake from annexed oil extraction plant, glycerine and others)

6.9 Result analysis and discussion

6.9.1 Scale factors for total capital investment and personnel demand

Figure 6.13 represents the variation of escalation adjusted capital investment cost with plant capacity for the biodiesel installations. The estimated power factor of 0.89 (indicating weak economies of scale) for the 25 studied biodiesel plants suggest that capital cost increases more rapidly than for many other categories of processing plants The Coefficient of Determination (R^2) which is used to assess overall CER goodness (the “strength” of the relationship between two variables) is 0.96 indicating that about 96% of the variation in the investment cost is explained by the relationship with the plant size (the independent factor).

Table 6.5: Process data for reference models (Anonymous, 2006 and IEE, 2006, GTZ/SENER, 2006)

Reference Concept	Unit	I	II	III	IV
Characteristic Installation					
Mode of operation		Batch	Continuous	Continuous	Batch
Feedstock	[-]	Oilseed/ fruit	Oilseed/ Fruit	Oil	Multi-feed Tallow/ grease
FFA content (Max)%		< 1	< 1	< 1	< 20
Capacity	[t_{Bd}/a]	4,000	100,000	100,000	50,000
Operating hour	[hr/a]	6,000	7,500	7,500	7,500
Mass and energy flows					
Input	[t/t_{Bd}]	~3.3 –9.1	~2.9 –6.8	~1	~1
Electricity	[kWh_el/t_{Bd}]	~236	~196	~12	~43
Steam	[kWh_{th}/t_{Bd}]	~300	~470	~211	~639
Crude glycerine	[kg/t_{Bd}]	~116	~129	~129	~113

The plant size-capital cost relationship based on equation (1.0) can be represented as:

$$\ln(C) = 6.13 + 0.89\ln(Q) \tag{6.12}$$

The statistical significance of the model was measured using t-statistics, testing it against the hypothesis that the capacity factor obtained in the CER is not significantly greater than n=0.6 ("the rule of thumb or two third rule"). This value of *t*-test = 7.61645 is greater than the value of t_c = 2.069 at 5% critical probability level. Hence, the rule of thumb hypothesis is rejected, indicating that the cost-capacity factor obtained is statistically significant other than 0.6. The standard error which is the average root mean square estimating error over all the CER data points observed from the regression analysis is ± 39% supporting the fact that the model can be used for at the order of magnitude level of estimating the fixed capital investment costs of biodiesel facility.

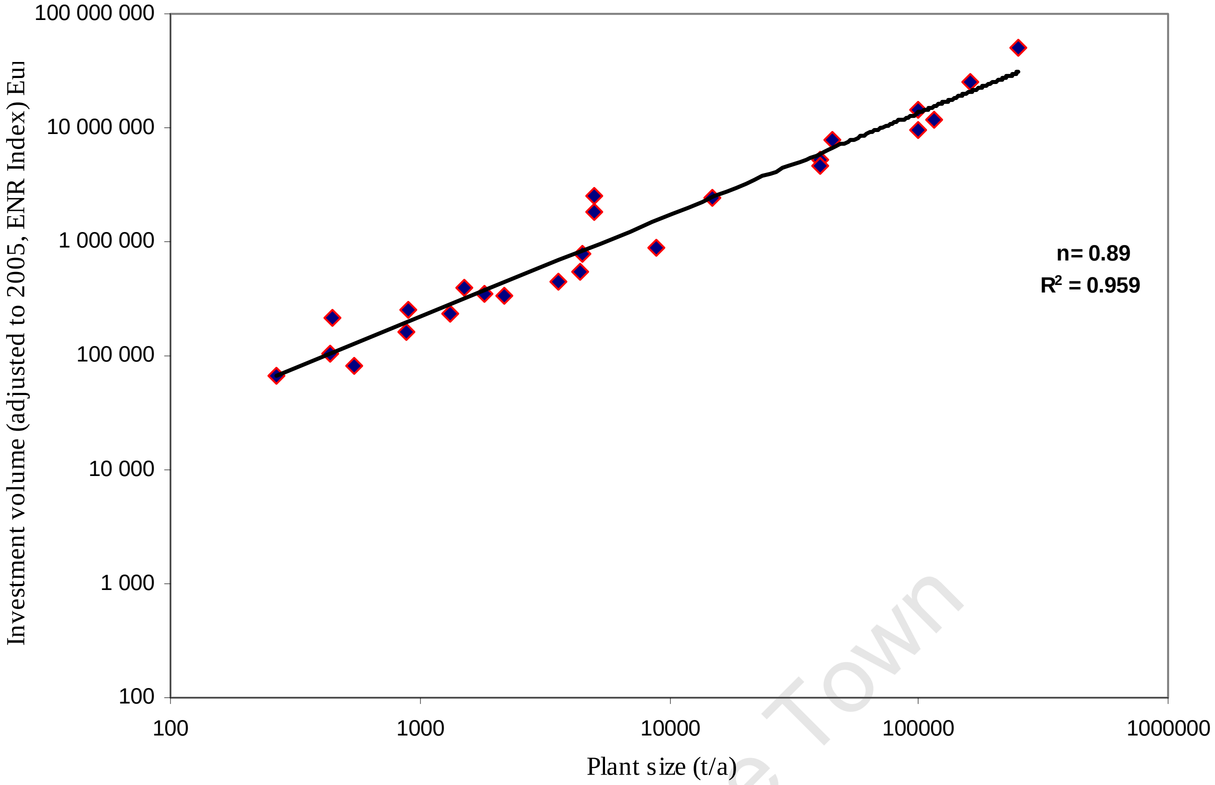

Figure 6.13: Increase cost-capacity relationship for Biodiesel plants in EU

The model was benchmarked against the fixed investment costs of €252,000 and €346,500 for 900 t/a, and 1850 t/a biodiesel plants respectively obtained from 3B-biofuel (biodiesel) GmbH Germany. Using the magnitude of relative error (%) approach explained in section 4.4.1.1, the model gave a predictive fixed investment value of €205,674 for the 900 t/a (18% magnitude relative error) and €382,208 for the 1850 t/a biodiesel plant (10% magnitude relative error).

The total operating labour requirement in a standalone biodiesel plant is illustrated in Figure 6.14. It appears from the scatter diagram in Figure 6.14 that equation (6.10) proposed in hypothesis I is inappropriate for measuring the functional relationship between labour requirements and plant capacity. The distribution of plant capacities as observed in the figure is positively skewed and there is some indication of heteroscedasticity in the data. A model representing the functional relationship between plant capacity and employment is therefore proposed based on hypothesis II, represented in Equation (6.11). The dependence of personnel on capacity for EU biodiesel plant can be represented by $E = a_2 C^{0.50}$ or (M ∞ $n^{0.5}$). The coefficients are significant at the 5% level. The model supports the fact that there are significant economies of scale to labour in biodiesel plant over the range of plants for which we have observations. The value of labour requirements obtained in this study is closely related to the capacity exponent predicted for nominally parallel process stream plant (Brennan, 1992), where n is the number of potlines which maybe taken as a direct indicator of production capacity and M, the number of persons employed. By way of example, the total manning capacity exponent for aluminium smelting has been reported as 0.67, for ethylene plants as 0.35 and for chlorine plants as 0.42 (Brennan, 1998).

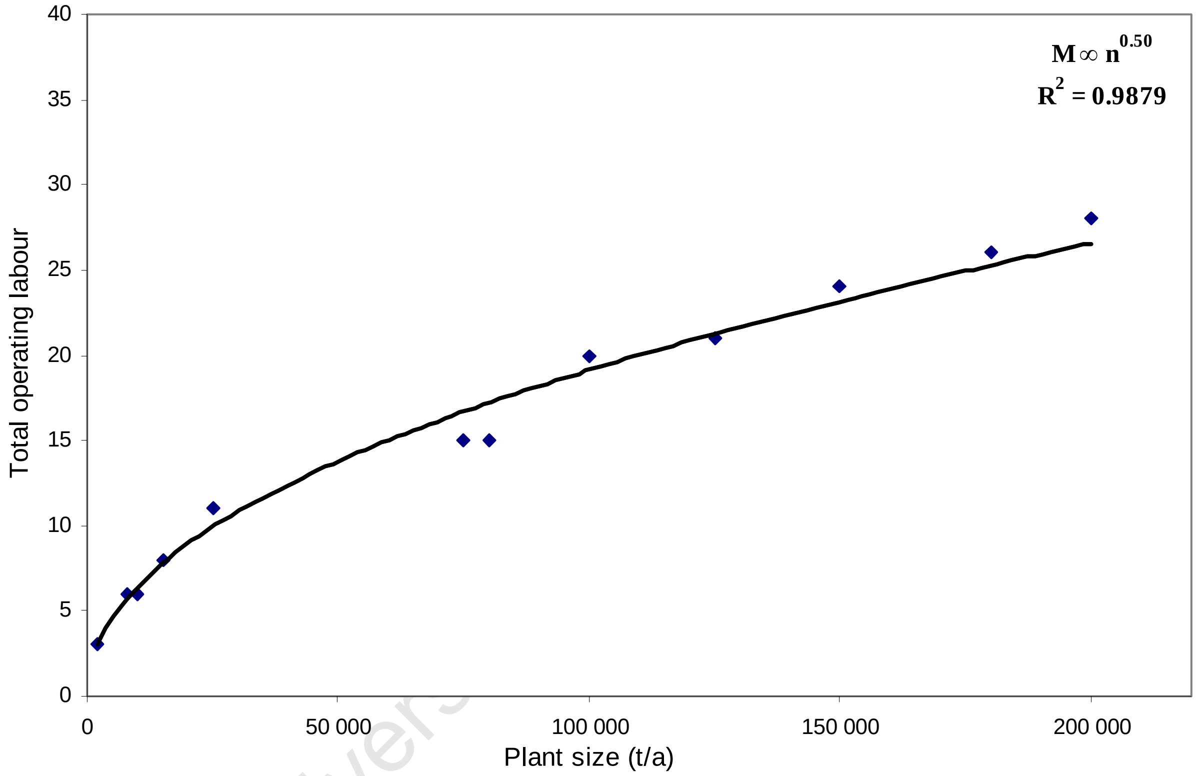

Figure 6.14: Total Operating Labour requirement versus plant size

Production facilities that are integrated with another operation may require fewer employees as some management and administration and other services may be shared between operators. Hence, the total manning capacity exponent of 0.5 obtained in the model may be lesser for a biodiesel plant integrated with oil mill (crushing facility).

6.9.2 Biodiesel production costs

The relative costs of biodiesel from the reference models cannot be determined with absolute certainty because the total costs are affected by assumed values for some input variables. However, the assumed values follow closely the usual practice in the biodiesel and other related industries. Costs of biodiesel production may vary widely depending primarily on feedstock cost (seed and oil yield), and to a lesser extent on co-product credits, and participation in government subsidies (for example, government farm programs as practiced in Germany). The major economic factor influencing the economic viability of biodiesel is feedstock cost. Other important factors include co-product credits from high protein meal and glycerine benefits. Investment in plant and equipment, while extremely significant in establishing biodiesel production potentials, has a minimal influence on the final net cost of biodiesel. The cost of producing biodiesel from the models ranges from €0.49/l to €0.73/l. The estimated net cost of biodiesel for the reference models I, II, III and IV are €0.65/l (19.91€/GJ), €0.63/l (19.30€/GJ), €0.73/l (22.37€/GJ) and €0.49/l (15.01€/GJ) respectively. These values are based on the plant gate feedstock cost price of €200/ton (rapeseed), €220/ton (rapeseed), €600/ton (rapeseed) and €300/ton (yellow grease) for reference concept models I, II, III and IV respectively. These values are closely related to the 2006 cost range for biodiesel production reported by IEA, Reuters and DOE (GTZ, 2006). It is to be noted that the scenarios includes credit for glycerine co-product in the case of stand alone plant and a combination of protein meal and glycerine in the case of integrated biodiesel plant. The cost comparison for the reference models is illustrated in Figure 6.15.

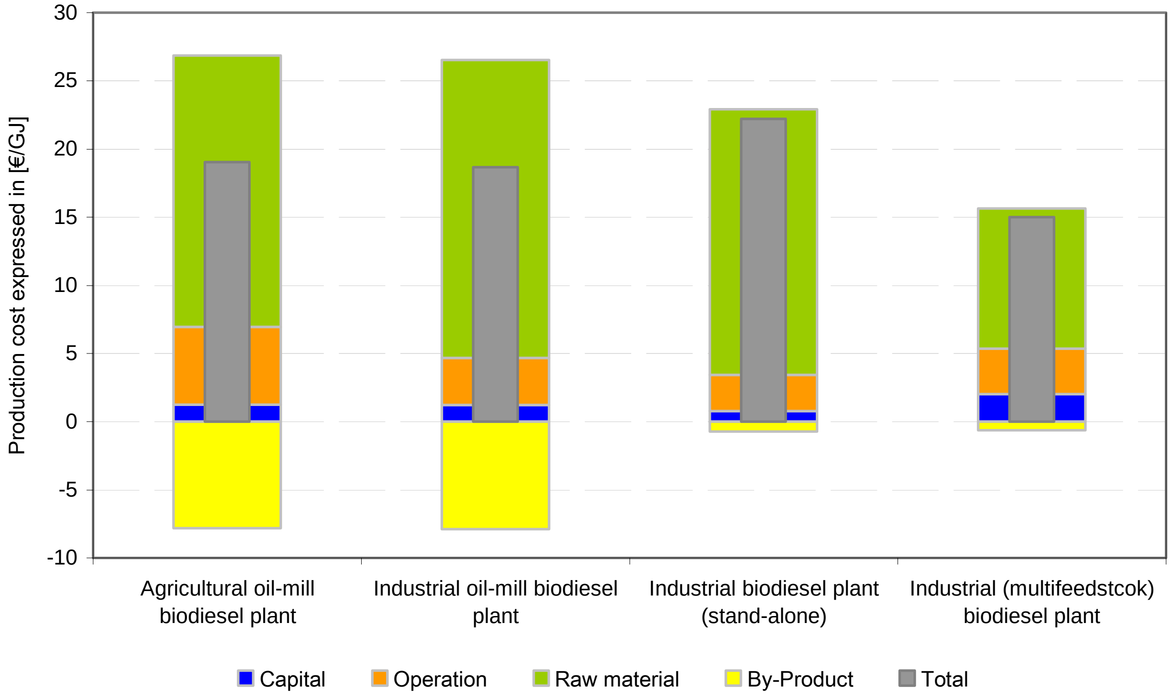

Figure 6.15: Comparison of production cost of biodiesel for the reference models, I-IV

The production scale has an impact on cost, but since capital is a smaller share of the overall cost, it is not significant. Costs are lower for biodiesel produced from waste grease (reference model IV), due to low feedstock price. The limited availability of recycled oil is a big constraint to industrial scale production of biodiesel using this feedstock. However, organised practices could significantly increase their availability. The collecting and recycling of used oils is a highly competitive business. For example, yellow grease is a potential feedstock for the manufacture of soap, textiles, cleansing creams, inks, glues, solvents, clothing, paint thinner, rubber, lubricants and detergents to list a few. It is also possible to use it as a livestock feed additive. It makes the feed less dusty, adds lubrication to the feed reducing wear on milling machinery. It is a dense source of energy, which is important for animals like cattle and horses that have a hard time eating.

There is a considerable reduction in the overall cost of biodiesel production in model I and III, due to the cost reduction provided by the meal cake (especially) and the glycerine sales as well as possible sharing of labour, heat and equipment between the two operations. The distribution of the production cost in model III, shows that effect of raw material is highest (80.7%) followed by operating costs (13.1%) and lastly capital costs (6.2%). Reference model II also follows a similar trend; raw material (84.4%), operating costs (11.6%) and capital costs (4.0%). In the case of agricultural scale model with integrated oil mill, the production price of biodiesel is very competitive with the industrial scale (with integrated oil-mill). The increased cost of production due to higher unit capital cost experienced in the small scale (agricultural model) should be more than offset by savings in transportation cost because the plant is allied to the source of feedstock and/or seed oil processing plant. On the other hand, the industrial scale biodiesel plant enjoys the effect of scale economies on both the capital and the operating costs; the cost of chemicals, for example will be higher in agricultural scale model due to their small amount of consumption.

The cost distribution for the multi-purpose plant (model IV) is as follows: raw material (72%); capital cost (7%) and operating costs (21%). The processing cost in the case of multi-feedstock using yellow grease is high (21%); feedstock (66%); and capital cost (13%). The percentage of capital related cost in the total cost of production is high (13%). This is because very high level of automation is needed. The feedstock costs are the most important cost component and contribute to the expenditures up to about 66 % for biodiesel based on yellow grease, and 84.47% for biodiesel based on rapeseed oil (stand alone plant). The large price differential and the large contribution of feedstock cost to the production cost of biodiesel, highlight the potential value of low cost alternatives to virgin vegetable oils in improving the economic viability of biodiesel. This is further explained in the sensitivity analysis in section 6.11.

When reviewing the cost of biodiesel production, it quickly becomes apparent that it is difficult to typify this cost as its components, notably the principal feedstocks and the by-product glycerol, are subject to considerable and unrelated market price fluctuations. Also, the cost of conventional diesel fuel, which is directly related to the price of crude oil, is subject to similar fluctuations, creating uncertainty in targets for biodiesel production costs. For this reason, sensitivity analysis was carried out to determine the possible impacts of changes in the cost composition on the economics of biodiesel production.

6.9.3 Sensitivity analysis

Sensitivity analysis was carried out to determine the impact of key variables on production cost. This is represented in spider diagrams in Figures 6.16, 6.17, 6.18 and 6.19. A linear relationship is observed between the feedstock cost and the production cost of biodiesel in these figures. In particular, for biodiesel based on oil plants, which have a high content of cake (Rapeseed), the total biodiesel production costs are also dominated by the receipts for by-products. This is relevant to plant with integrated oil-mill facility. The trend will also be applicable to other raw materials such as soybean, peanut, and cotton seed. For stand alone plants only crude glycerine and fertilizer (in some cases) accumulates as by-product with only a marginal impact to the total biodiesel production costs.

The cost of feedstock will have a major bearing on the crushing margin and overall cost of biodiesel production. This has a major impact on production cost. Sensitivity to biodiesel costs from potential changes in fixed capital investment costs was also examined, primarily because of the possibility for reduction in costs with technological innovation and also some uncertainty regarding the equipment complement that would be necessary to install a biodiesel plant in various existing businesses. The impact of capital expenditure on the overall production cost indicates that within reason, the capital cost is not a critical factor.

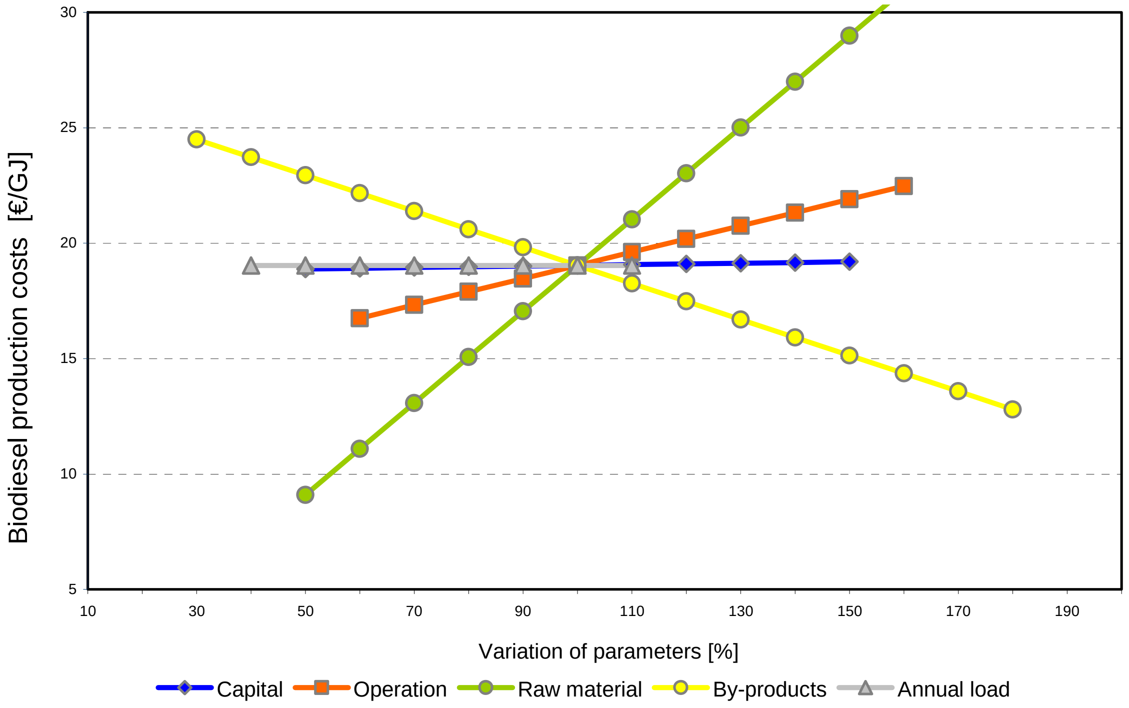

Figure 6.16: Sensitivity analysis – biodiesel (rapeseed) in agricultural scale (Model I)

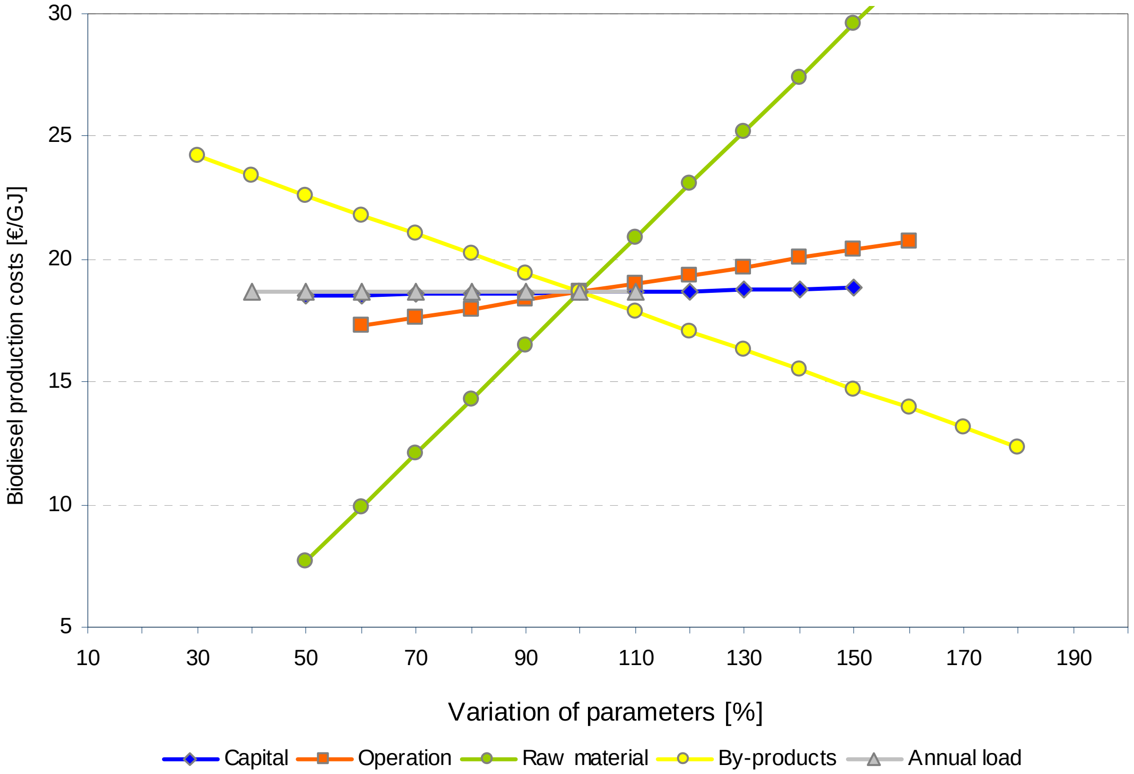

Figure 6.17: Sensitivity analysis – biodiesel (rapeseed) in oil-mill industrial scale (Model II).

This is an indication that improvement in capital costs and process technology will have only a minimal effect on biodiesel competitiveness. The revenue earned from the by-product of the crushing and esterification process make a crucial contribution to the overall viability and competitiveness of the plant. The value of glycerine has little impact on overall production cost.

By way of example, for a 100,000 t/a, standalone biodiesel plant, a 10% increase in the capital expenditure will only increase the cost of biodiesel from €0.730/l (22.37€/GJ) to €0.731/l (22.39€/GJ) while a 100% increase will shift the cost to €0.738/l (22.59€/GJ).

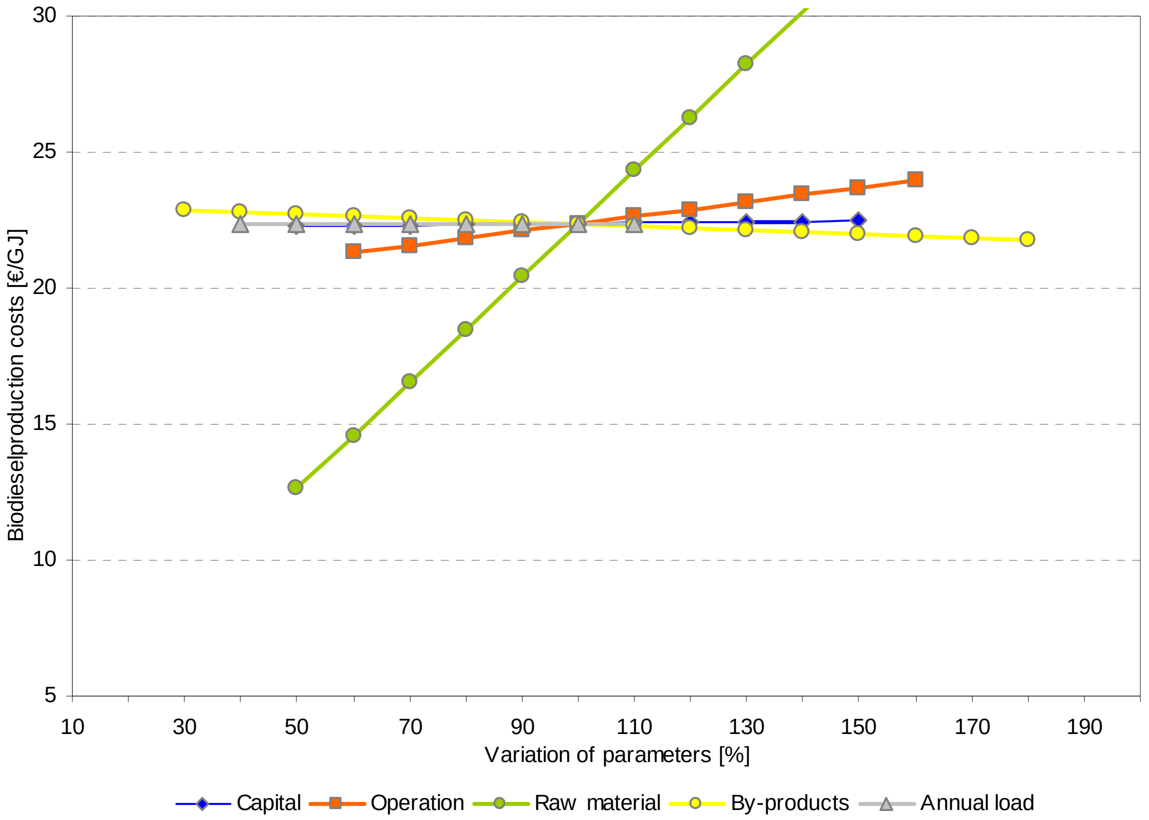

Figure 6.18: Sensitivity analysis – biodiesel (rapeseed) in Oil mill industrial scale-standalone plant (Model III)

The impact of raw material indicates that a 10% increase boosts the cost from €0.730/l (22.37€/GJ) to €0.794/l (24.32€/GJ) while for 100%, the cost shift to €1.354/l (41.46€/GJ).

In the case of operating cost, a 10% increase in the operating expenses causes an upward shift to €0.739/l (22.64 €/GJ) from €0.730/l (22.37€/GJ) while a 100% will raise the cost to 25.05€/GJ. The influence of the by-product on the cost of biodiesel is such that a 10% increase in the by-product worth will decrease the cost of biodiesel from €0.730/l (22.37€/GJ) to €0.728/l (22.30€/GJ) while at 100%, the cost is lowered to €0.706/l (21.65€/GJ). Also, a 50% reduction in the investment cost reduced the biodiesel production cost from the base case (€0.73/l) to €0.70/l, 3 cents per liter reduction.

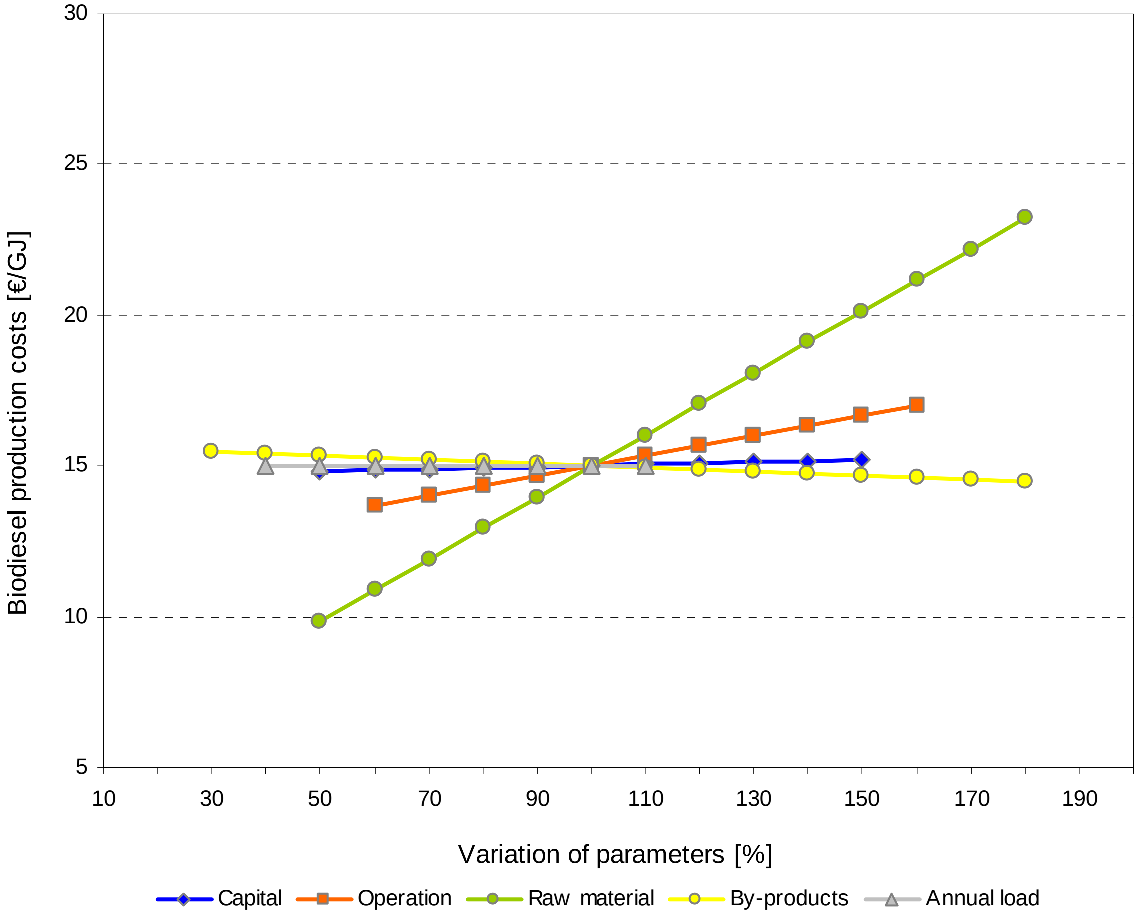

Figure 6.19: **Sensitivity analysis–biodiesel (yellow grease) in multi-feedstock industrial scale plant (model IV)**

Basically for all plants, it can be deduced that (i) feedstock costs are most important, in many cases followed by (ii) receipts for by-products – mainly driven by the credits for cake and the oil plant specific mass content – and/or (iii) plant operation cost; (iv) capital investment is of only marginal influence which is in turn reflected in the low impact of reduced annual load. For the annual load of biofuel plants it is true that the higher the capital investment and thus the fixed costs, the higher the impact of annual load of a plant.

6.10 Relevance of study to the African continent

Biodiesel production cost are mainly driven by the cost of raw material which could be as high as 80% of the total cost of production as observed in the case of industrial scale oil-mill plant. Hence their production costs are by far the biggest component of biodiesel retail price. Adding the costs for transportation, blending and marketing will push further the expected retail price of biodiesel. The competitiveness of biodiesel industries will be primarily dependent on the cost of the local feedstock, transportation and other logistics costs for the distribution of the finished product. Immediate opportunity therefore emerged from the analysis for the use of low cost feedstock, in this case, waste oils as it gives the lowest cost of biodiesel. Methanol (the most widely used catalyst), and other chemical costs should be quite similar in different regions with only the labour costs and energy (utilities) costs expected to vary considerably from one location to the other.

For conventional biodiesel production from oil-seed crops, the technology involved is fairly mature. While incremental cost reductions can be expected, no major breakthroughs are anticipated that could bring costs down dramatically. Costs will likely continue to decline gradually in the future through technical improvements and optimisations, and as the scale of new conversion plants increases. The reason is ascribed to the fact that the cost of feedstock (crops) is a major component of overall costs. This is compounded by the volatility of crop prices. In particular, the cost of producing oil-seed-derived biodiesel is dominated by the cost of the oil and by competition from high value uses like cooking. However, the use of second generation feedstock such as algae could lower the feedstock cost requirements and at the same time provide the answer for today biofuel criticism such as food price increase and deforestation problems. Therefore, an evaluation of the costs of feedstock in any location (especially in major crude oil exporting countries) should provide some insight into the potential competitiveness of biodiesel production in that location. The potential for biodiesel production is particularly large in tropical developing countries, where high crop yields and lower costs for land and labour, which dominates the cost of production, provide an economic advantage that is hard for countries in temperate regions to match. African countries therefore have the potential to be a major player in biodiesel production due to their land availability and low labour rates (IEA, 2004). However, it is to be noted that future intensification of biodiesel feedstock without proper mitigation guidelines, will likely further threaten the high concentration of globally endemic species in this biodiversity hotspots. As such, sustainable biomass production should be employed.

The capital investment cost is influenced by the plant capacity and location (infrastructure availability and geographical placement, e.g. coastal vs. in-land locations). The general conception is that investment cost of a biodiesel plant will be higher in Africa than in Europe due to the additional cost of importation and other logistics associated with it. However, according to some of the leading biodiesel manufacturers, the capital investment cost of the same sized biodiesel plant will be about 15% higher in Germany than in South Africa. This is attributed to the availability of well-established infrastructure of engineering equipment suppliers and support and manpower (South Africa has been classified as Type A. country: technologically advanced developing countries, with well diversified and fairly comprehensive industrial, energy and R&D infrastructures) (Amigun et al, 2008). This classification is explained in details in section 2.6. The cost of energy (provision of which is lacking in more than 70% of the population/areas) is expected to be very high in most African countries as companies might have to provide their own energy. This might noticeably increase the operating cost, thereby possibly increasing the commercial risk.

One inevitable by-product in the biodiesel manufacturing process is glycerol, traditionally used in the medical, food and cosmetic industries. The processing and production of biodiesel creates only a crude form of glycerine (up to 10%), and thus the potential market for this material depends in part on the degree of treatment at the biodiesel facility. While there are existing markets for glycerol, a significant increase in availability of glycerol, resulting from the expanded use of vegetable oils and animal fats, would destabilise the glycerol market (see Figure 6.20) (Procter and Gamble, 2003). The expected glycerol price drop will affect the profitability of biodiesel production in the sense that it will be profitable to refine it only in the case of large-scale biodiesel production. African biodiesel producers should therefore right from the start begin to explore new application/utilisation for glycerine such as in the industrial synthesis of glycerine tetra-butyl ether (GTBE), a glycerine-derived chemical that can be used as fuel (gasoline) additive. GTBE has numerous advantages for making gasoline go farther unlike ethanol that lowers the mileage because of its lower energy content when compared to gasoline, and for cleaning up automobile emissions (GTBE is considered safer than MTBE because it does not readily mix with water and, hence reduce the likelihood of contaminating ground water in case of a spill (Pratt e-press-Duke University, 2006). The use of GTBE in Africa would have significant health benefits in replacing lead as an octane enhancer in most African countries where leaded fuel is still widely used; of a total of 49 countries in Sub-Saharan Africa, 22 countries use leaded fuel only, 14 dual system and 13 unleaded (Thomas and Kwong, 2001; UNEP, 2005).

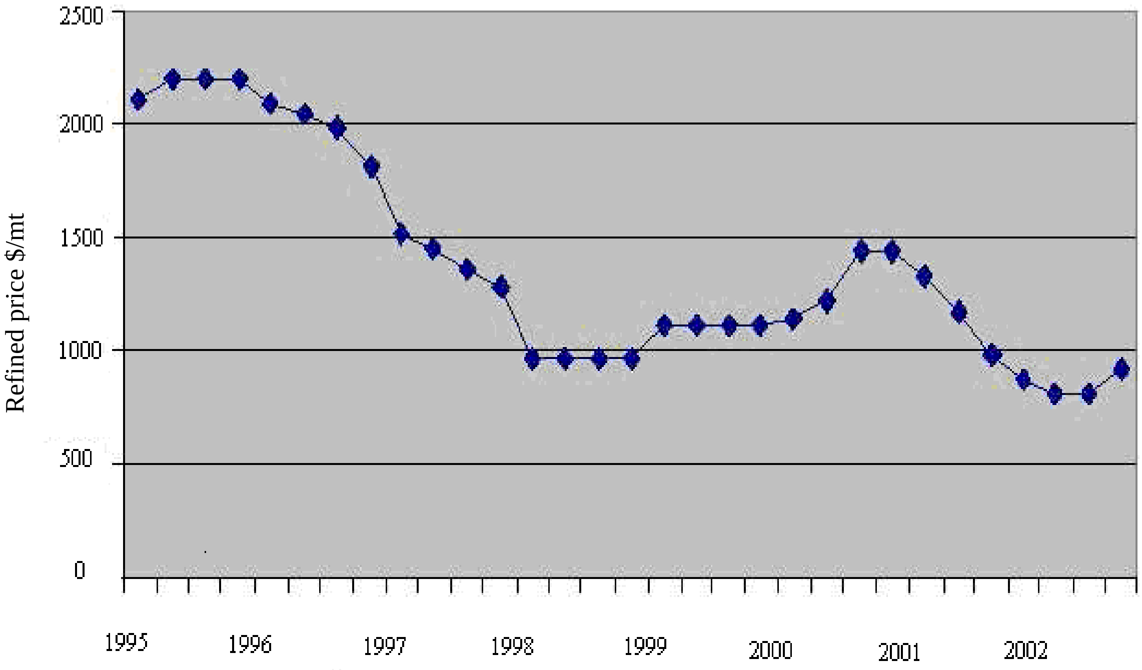

Figure 6.20: Impact of world biodiesel production on glycerine markets

Biodiesel costs the same to transport as oil (they have approximately the same density). Hence, transportation concerns alone do not affect the decision to have a stand-alone or combined facility integrated oil-mill pant). More importantly, the enterprise can capture profits from both the sale of the meal and the sale of the oil, as well as share labor and equipment between the two operations. Economics of biodiesel production will also depend greatly on localised variables. Locations that offer low utility rate (e.g. electricity), existing facilities, and close proximity to large oil seed acreage (farm) would be a good location. Cost savings technologies that will help producers use energy more efficiently, increase yield and convert cheaper feedstock into high quality biodiesel will be of great importance to the African continent. The development of non-toxic varieties of Jatropha curcas by the Agricultural Research Trust (ART) in Zimbabwe, which would make the seed cake following extraction to be suitable as animal feed without detoxification is a good step in improving the value added, and hence the economics of biodiesel production (Biswas et al, 2006).

Given the insensitivity of biodiesel price relative to scale, the limited feedstock availability, and the large contribution of feedstock cost to the production cost and taking note of the significant benefits of job creation, a strong argument emerges for Africa to adopt smaller scale plants that can be embedded into the local economy according to the scheme in Figure 6.10. Therefore, small decentralised biodiesel plant capable of being allied to a source of feedstock or seed oil processing plant may provide logistics advantages in that the feedstock can be used at source, reducing costs to a centralised processing plant. The increased cost of production due to higher unit capital cost should be more that offset by savings in transportation cost.

Based on the findings presented above, it is possible to develop appropriate policy interventions to foster the development of a local biodiesel industry. By way of example, the once off-capital-grant subsidies advertised by the South African Department of Minerals and Energy (DME) for Renewable Energy Projects in 2005-2007, would unlikely be sufficient to push the market penetration of biodiesel, since capital cost constitutes approximately 5% in the industrial scale production of biodiesel. The subsidy would be useful at the construction phase of the plant but would not address the main concern of investors, which resides in the fluctuations of most dominant cost component: the raw material. Incentives that will favour the sustainable production of feedstock should be enacted.

Technology transfer from Germany to Africa should be promoted. This however, should be accompanied by local technology capacity building. This is because technology is one of many factors influencing the market penetration of biofuels at national and international levels. Besides its scientific and technical components, technology embodies a host of choices made relative to social, economic and environmental policies. Examples of such choices are selection of feedstocks for biodiesel and scales of production: urban versus rural development; openness to international trade. Although, the condition that led to biodiesel commercialisation in Germany may not be easily replicated in developing African countries, but at least it would points out to policy initiatives that might be considered. Each country in the African continent interested in the biofuel development in general and biodiesel specifically would do well to consider the strategic approach suggested by the German experience (section 6.9 and 6.10), and decide through interactions amongst its relevant stakeholders on the best way to move forward and how to manage technology transfer to support such development (compatible with sustainable development goal).

6.11 Chapter summary and concluding remark

This chapter analysed costs of biodiesel production, via an illustrative case study exploring sensitivities of a plant size optimisation model to key cost parameters, supported by an analysis of capital cost breakdown of biodiesel plants as recently built in Europe.

The size optimisation analysis of a biodiesel plant processing oil crops in South Africa using the Nguyen and Prince (1996) model revealed that smaller than optimum biodiesel plant size can be built without a significant cost penalty only if there are no strong economies of scale for capital cost expenses (i.e. if $n > 0.7$). The relative insensitivity of output cost to scale around the optimum (when oil-seed crop transport costs are low, and the scale factor $n > 0.7$) suggests that above some small size, finding the optimum is not especially critical, and that other site specific factors may be classified more important, hence, determination of optimum facility size remains a site specific task. This analysis may however be useful in providing insight into different plant sizes for different areas.

The cost analysis of European biodiesel plants found evidence of weak economies of scale arising from increasing plant size. The scale factor of 0.89 obtained suggests that capital costs are indeed not strongly influenced by scale. The economic analysis of biodiesel technology indicate that the order of major costs is as follows: 1) raw material cost, 2) capital cost and 3) other operating costs. The single most important factor influencing the economic viability of biodiesel is feedstock cost. Other important factors include the type of plant configuration, co-product credits for high protein meal and glycerine, plus government program benefits. Investment in plant and equipment, while extremely significant in establishing biodiesel production potentials, has a minimal influence on the final net cost of biodiesel.

Small-decentralised (localised) biodiesel production with standards satisfactory to engine manufacturer could be a feasible option of encouraging biodiesel development in Africa as this model is cost competitive with large plants, and keeps more resources and revenue within communities. In a developing or small economy, local market opportunities frequently restrict the size of manufacturing plants. Very large plants incur economic risks should market or operability constraints limit capacity utilisation. Since biodiesel production facilities are relatively insensitive to economies of scale, it is possible to erect a large number of economically viable small-decentralised plants rather than large-scale centralised facilities. In this way, it is possible to spread the employment and other economic benefits of production as widely as possible since large scale project tend to have lower impact on employment and earnings as opposed small scale plants. For relatively new technologies developed on a local or regional scale, successful ‘learning by using’ and ‘learning by interacting’ may be of major importance of the successful development, therefore, small scale biodiesel plant is recommended to provide the necessary learning by doing in the biodiesel industry.

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7

Conclusion and Recommendations

This dissertation has set out to advance the state of knowledge regarding the costs of biofuel production in African countries, and to suggest ways of using this new knowledge, by addressing three inter-related objectives. Firstly, factors which most influence the processing costs of biofuels were to be investigated and analysed, where possible in African countries. This was expected to yield insights on the possible barriers to implementation that need to be overcome, on the technological improvement options that should be stimulated by research and development, and for the formulation of policies and regulations. The second objective was to translate cost data into indigenous and more robust tools for estimating capital and operating costs of biofuels processing in Africa, enabling easier and more rapid use of the data in numerical and economic models for use in design and optimisation of biofuel process plants. The third objective was stated to demonstrate how knowledge of the dynamics of a specific biofuel as already produced elsewhere can be combined with the newly gained knowledge and developed tools to assist the introduction of such biofuel production into an African country. The objectives of this dissertation were addressed using both analytical and demonstrative approaches.

7.1 Synthesis of findings

In line with the stated overarching research objectives, chapter 1 proposed a parametric cost estimation method using both variant-based and generative approaches for addressing data gaps and inconsistencies pertaining to the use of the currently available cost estimation relationships when applied to the African biofuels industries. Whilst empirical work in the form of the collection of relevant and available cost data and information formed a necessary step in the proposed methodology, it was also realised that the approach is largely underpinned by, and relies to a significant extent on, a deeper understanding of the key factors governing the variation of relative costs in different locations. The development of the qualitative perception, protocols and methodological guidelines together with the subsequent derivation of criteria and generic processes to support the proposed predictive approach, constituted two of the key research aims, and formed the focus of Chapters 2 to 3 of the dissertation.

Chapter 2 contextualized the development of an African biofuels industry, introduced the relevant theory of cost estimation, and reviewed prior related academic work. This chapter established the relationship between energy availability and poverty on the continent, as well as the regional diversity in terms of uneven energy resources distribution. From this has followed the establishment of the need for the implementation of biofuels technology and their widespread adoption in Africa. Chapter 3 provided general guidance for use in developing Cost Estimation Relationships (CERs), focusing on implementation and evaluation techniques and a framework for analysing the quality or validity of a statistical model, as well as the methods employed in data gathering and the difficulties encountered during the data collection stage of the dissertation. This chapter established that lack of quality data is a serious constraint to the development of a robust CER and that barriers to successful data gathering in the biofuel industry in Africa are due largely to the fragmented nature of data in the small scale industries and lack of willingness to release information due to a perceived competitive and confidential nature of the data in the large scale biofuel industries. The chapter therefore proposed substantive capacity programmes in data gathering and management.

Chapters 4 to 6 demonstrated the application of the generalised methodologies and criteria developed in the previous chapters to biogas, bioethanol and biodiesel process industries. The focus on the first generation technologies for biofuel production in each case relates directly to the empirical data gathering approach adopted, and does not imply any argument for or against the desirability or viability of second generation biofuels technologies. The biofuels process systems were analysed at different levels of detail based on the methodology discussed in chapter 3, yielding a different quality of results and insights in each case. The key findings are presented in the following subsections.

7.1.1 The role of feedstock type and cost

Results obtained (Figure 7.1) show that the dominance of feedstock cost diminishes orderly with the use of agricultural feedstock, industrial by-product, and waste materials. The feedstock fraction in a standalone biodiesel factory in the EU (Germany) using rapeseed is about 81% (cf. section 6.10), while the utilisation of molasses in a rural eastern Africa distillery only represents one third of total annual cost of production (cf. section 5.8.5.4). In the case of small/medium scale biogas plant, the use of waste material (sewage) has no contributing cost to the total production cost of biogas. In addition to this cost disadvantage of crop feedstocks for biofuels production, it is worth pointing out that crop-based biofuel projects will also face the many typical challenges of agriculture in Africa.

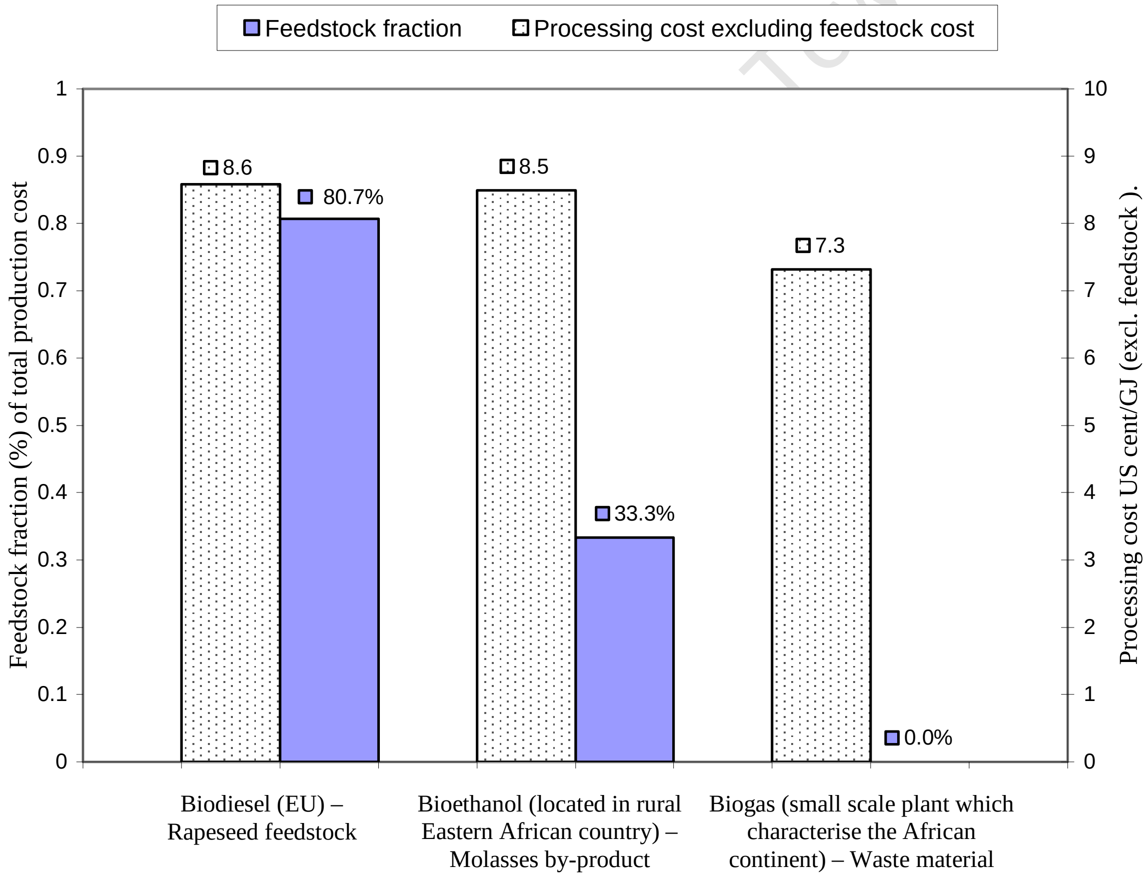

Figure 7.1: Significance of feedstock cost on the total cost of production in three biofuel industries[†††††††]

[†††††††] The processing of the three specific fuels is based on 10% annual depreciation of capital, and processing cost (in biogas industry) of 7.5% of capital investment cost of the plant (Murphy, 2004).

Although the biogas industry is usually characterised by zero to low feedstock cost (if any, it is mostly due to the transportation cost), large scale production will also be limited by local feedstock resource availability. The delivered energy cost of biodiesel, bioethanol and biogas, excluding the feedstock cost were obtained and represented in Figure 7.1 to give a more accurate comparison between the three specific fuels. Biodiesel and bioethanol presented similar processing cost (8.6 UScent/GJ and 8.5 UScent/GJ respectively), while biogas showed a lower value of 7.3 UScent/GJ. It is to be noted that the method used in calculating processing cost in the biogas industry was based on the estimate of 7.5% of capital cost presented by Murphy (2004) and is thus less certain than those for ethanol and diesel.

It may thus be concluded that biofuel programmes on the African continent will benefit from policies designed primarily to develop indigenous industrial capabilities to harness existing low-cost feedstocks for biofuel production. This does not mean that certain special arrangements, e.g. tax reductions and capital incentives, should not be used to establish a biofuel industry. Such incentive schemes are perfectly normal for establishing an emerging industry, provided that the incentives do not constitute structural support, which may distort economic activity, with negative social and environmental effects in the long term.

7.1.2 The questions of scale and decentralisation

Whilst the conventional financial wisdom in the process industry is that larger installations have cost advantages resulting from economies of scale, results obtained for all three biofuels culminate in a different conclusion, albeit for at least two different reasons.

The statistical regression of the investigated small-medium scale African biogas plants, after currency conversion and escalation adjustment, disproved the existence of economies of scale with a probability of > 95%, and suggested the existence of diseconomies of scale (*n* =1.2) arising from the increasing plant size. Possible reasons for this have been explored, and are summarised in section 7.1.3 below.

The application of the published Nguyen and Prince model to size optimisation and location-cost analysis of bioethanol plant in Nigeria, suggested that the cost of producing bioethanol is cheaper in medium size plants, and not in the large plants. This is due to lower feedstock costs for the medium scale plants, because the sites of harvesting are closer and therefore feedstock transportation costs are lower. Whilst it may be considered that the distribution to retailers may be lower from a smaller number of larger scale plants, the lower energy density by weight of the feedstock compared to the ethanol output implies that more effort should be made to reduce feedstock distribution costs rather than the ethanol distribution cost.

Results from the plant size optimisation analysis of biodiesel plant in South Africa equally revealed a relative insensitivity of output cost to scale around the optimum but with transport-cost penalties becoming more significant for larger plants, suggesting that above some small size, finding the optimum is not especially critical and that other siting factors may be considered more important. As such, determining the optimum facility size would remain a project specific task. The appropriate scale of a bioenergy facility will be determined by a variety of factors, including: the feedstock chosen, proximity to markets, project goals and company objectives (e.g. local energy provision vs. production for export), type of bioenergy, and access to finance. This finding was reinforced by the result obtained from the cost reviews of German biodiesel installations, viz. that the cost-capacity factor in this industry is of the order of 0.9.

Given the insensitivity of biofuels processing costs relative to scale, and the possibility of diseconomies of scale when including feedstock transport cost, and taking note of the enhanced benefits of job creation for smaller scale plants, a strong argument emerges for Africa to adopt decentralised biofuels production. Such smaller plants can be embedded into the local economy as such installations keep more resources and revenue within rural communities. The implication is that production for local consumption at present should take precedence over production for international trade. Further, since biofuels are emerging commodity products, the size of the plants will be restricted by feedstock availability. Feedstock plantation is a time consuming and often seasonal exercise and may take a few years before optimum supply can be guaranteed. Hence, in most African countries where feedstock production has not yet been established, small scale/capacity plant may have to be set up initially. The plant size/capacity can be enlarged or replicated as markets grow and as appropriate infrastructure, human management capacity, and awareness are developed.

7.1.3 Adjustments to factorial cost estimation methods

a) Methods for capital cost estimation

A Lang factor (f_L) value of 2.39 (OBL) and 2.81(IBL) was obtained for the analysed annexed fuel ethanol plant located in a rural East African location. The outcome of the factorial cost estimation supports the fact that Lang factor is dependent on average purchased equipment. In the biogas industry, f_L factors of 2.63 (20m^3), 2.91 (40m^3) and 3.04 (60 m^3) were obtained for small/medium scale "greenfields" plant in two African locations while an f_L of 1.79 was obtained for a large scale "brownfield" biogas plant. The increased f_L as plant capacity increases supports the evidence of diseconomies of scale obtained for small/medium scale biogas plant in some African countries. This is probably due to the technologically driven oligopolies experienced in the industry in Africa: interestingly, indirect costs appear to increase fastest as the size of the digester increases.

The analysis also suggests that conventional factorial capital cost estimation and factorial manufacturing cost estimation methods may be employed, but will lead to inaccurate cost predictions if applied in unmodified form to annexed fuel ethanol plant or brownfields facilities. The analysis using a factored approach to capital cost estimation remains a useful technique in its own right, and also provides a means of checking the validity of estimates made by more detailed methods. It also reveals simple equations for rapid preliminary cost estimations needed in various techno-economic studies.

b) Methods for operating cost estimation

The major economic factor to consider for input costs of ethanol production are feedstock cost, depreciation of capital cost (or the equivalent annualised capital financing cost) and energy related expenses. The type, availability, and price of molasses all factor into the profitability of producing ethanol. The energy costs include those of steam and electricity, with these costs being more critical for profitability. Energy expenses are one variable in location selection that can affect the success of the ethanol plant. Hence, ethanol plants located near existing manufacturing plants that produce excess steam or have some type of cogeneration potentials such as commonly found in the sugar industry will result in more favourable economics.

Intermediate economic factors include the cost of labour, both in operating expenses and administrative costs. In this regard it is worth noting that the process flow sheet approach to estimating operating labour requirement (as proposed in standard texts such as Turton *et al.* (1998) has been shown to be appropriate, but that the use of dated factors can lead to over-estimation, even for African installations. Other minor economic input factors include the cost of enzymes, water and denaturant. These costs have little to do with economies of scale.

7.1.4 Location factor

From the evaluation of the influence of location on the fixed capital investment cost of biogas technology (coastal vs. landlocked biogas plants) in Africa, it appears that the cost of this technology is largely independent of geographical location of the plant. Therefore, the use of locally available technology should be promoted where necessary. Most African locations are characterised by cheap labour cost but high capital cost, the latter mainly due to the effect of transportation cost especially in the landlocked African countries and the perceived high risks of investment resulting in requirements for high returns on investment. The increased economic and political reform in Africa is expected to increase the FDI expansion to the continent thus lowering capital cost financing.

African countries attributed with the availability of well-established infrastructure of engineering equipment suppliers and support and manpower could offer lesser investment cost. The cost of energy (provision of which is lacking in more than 70% of the population/areas) is expected to be very high in most African countries as companies might have to provide their own energy. This might noticeably increase the operating cost resulting in increasing commercial risk, unless this aspect is well integrated with the biofuels project from the outset.

7.1.5 Appropriate approaches to cost estimation

Variant cost estimation methods will find better application in small and medium scale plants (such as biogas technology) of relatively standard products. Because no additional information (with the possible exception of indirect costs) has to be generated for the cost estimation process, it is a relatively quick method and very useful in the early product development phases. Generative cost estimation methods, reflecting the fact that the cost of a product depends on the required processes and materials, generate a detailed cost estimate with increased level of accuracy. This method is applicable to both small and medium high variety (standard) to large scale manufacturing plant. Based on the findings of the three fuel-specific chapters, the following is observed:

- For biogas plants, esp. at the small to medium scale, variant approaches to cost prediction should generally be sufficient. Biogas would remain the cheapest clean burning biofuel available even in the unfortunate case of a 200% over-estimate of capital cost becoming a self-fulfilling prophecy.
- For bio-ethanol plants, generative approaches need to be mixed into variant-based approaches fairly early on, as site-specific variables (esp. in terms of feedstock and energy cost) determine, to a significant degree, the final cost of this fuel.
- For biodiesel plants, variant based approaches to capital cost prediction should generally suffice a long way into any project, as by far the majority of the cost of this fuel is feedstock dependent. The corollary to this observation is that generative approaches need to be taken as early as possible to biodiesel feedstock cost predictions.

7.2 Statement of significance

This dissertation makes two important contributions. It has presented the first comprehensive treatise on a subject of process engineering economics in Africa, and thereby proposes some important modifications to cost estimation factors and methods in the domain studied. It also shows that engineering economic analysis concurs with environmental and social analyses concerning the subject of biofuels in Africa: biofuels should firstly be produced from waste materials, and secondly on a small to medium distributed scale.

The ability to present an analysis of the breakdown of the capital and operating costs of a rural African distillery, in an equation format enables easier and more rapid use of the data in numerical and economic models, and in the preliminary design and optimisation of biofuel process plants. This provides insight into different plant sizes for different location in a manner that is both time and cost effective. More specifically, the CERs generated from the relation between capital costs and plant size can provide useful information in assessing economic viability of biofuel plants. Further, it provides means whereby decisions are taken on developmental new project as well as providing adequate and sustainable energy services through commercialisation of renewable energy in general and biofuels specifically. The identification of the economic input factor of production (factors which most influence the production cost of bioethanol and biodiesel industry (biogas installations have minimal operating costs once established) provides insights to both the possible barriers to implementation that should be overcome, and on the technological improvement options that should be stimulated by research and development.

Governments in some developed and developing countries have already enacted policies to support biofuels production, use, and increasingly, trade. Most countries in Africa have no national energy policy, let alone specific policies for the utilization of renewable energy. Hence, decisions will have to be made, including the type of technology, feedstock type, plant site selection, scale and decentralisation, and orientation (i.e. for domestic/national consumption, for international trade, or both) of production. Policies will need to be designed appropriately based on domestic economic and resource situations. Key to shaping such a future, in which biofuels are produced in a sustainable manner and used in multiple locations, is defining clear goals/targets and enacting the policies necessary to achieve them. The outcomes of this dissertation, viz: role of feedstock, scale and decentralisation choices in the biofuels industry and impact of location on the investment cost as outlined in section 7.1 can be used as tools by governments to enact policies, reform and harmonise biomass-based energy regulations and legislations in the African continent.

7.3 The way forward

This dissertation, aimed at generating insights that might help catalyse environmentally sustainable development on the African continent has married within its scope several approaches and methods stemming from different research fields, such as, process engineering, renewable energy technology, engineering economics, information science as well as elements from environmental science and politics. Room for further research has been identified at different levels within this dissertation. This section aims to synthesise these observations and direct future research efforts.

7.3.1 Recommendations for further work

7.3.1.1 Recommendations for industry and government

Key issues that need to be addressed in the local context of any biofuels project are the problems of resource availability and competing uses. A major concern in poor rural areas is the competition of biomass energy systems with the present use of biomass resources (such as agricultural residues) in applications such as animal feed and bedding, soil maintenance and fertilisation, and construction materials. These may be of higher priority to rural populations, as alternatives might not exist. Thus, a very detailed and participatory resource evaluation needs to be carried out before commencing action on bioenergy systems using existing resources.

On the African continent, promoting biofuels technologies, even if established (mature), could face challenges such as obtaining finance from traditional financing institutions, as such initiatives generally have a less favourable risk rating compared to more well-established (but non-sustainable) energy technologies. The risk perception may need to be addressed through government policy such as support for decentralised production, local use of the energy produced and organisation of cooperative or other form of participation and technical support measures in the initial stage.

As concerns approaches to cost estimation to be taken in African biofuels projects, the observations presented in section 7.1.5 are referred to.

7.3.1.2 Recommendations for further research

In terms of robustness, the study has identified the fact that some of the results presented are based on a relatively small number of existing biofuel installations. The availability of a more detailed and reliable empirical database, as well as a better understanding of the data composition will greatly enhance the quality of the cost estimation equations. Furthermore, more detailed estimation of i) financing charges and ii) cost of equipment should be developed based on the classification of African countries in line with their economic and technical development status according to Bhagavan (2003) (cf. section 2.6) to further understand the effect of location. Further work is also recommended to explore possible reasons for the diseconomies of scale observed in the biogas industry in some African countries. This investigation could be carried out at a PhD level.

A major reason identified for lack of willingness to release data was that company representatives were reluctant to divulge information that might compromise their ability to compete (because of confidentiality concerns). This restricted the analysis in certain industry sectors as well as a preventing a full accounting of the resources at specific facilities. A substantive data programme in data gathering and management should be promoted. This could be in form of information exchange and experience sharing amongst institutions and practitioners. This is important as data gathering forms the bedrock of cost estimation relationship development.

Further work to assess and quantify the external benefits derived from biofuels as avoided cost measure should be developed and incorporated into the economics and model development. The knowledge on the performance of biofuels can further be improved by closer assessment of the conversion systems, especially of the whole chain from crop to end product. Economics and cost estimation relationship developments should be extended to other types of renewable energy. Choices of one fuel could block or slow down the development of others; therefore, interacting effects between biofuels and technology development should be mapped.

Finally, it has been observed that the generally held simple conception of 'negligible operating costs in biogas' needs to be challenged. Regular spend on measurement and maintenance could help this industry to overcome some of its implementation barriers, without adding significantly to the final cost of delivered energy. Detailed analyses of the processing cost of biogas operations on the African continent should therefore be undertaken.

7.3.2 Closing remark

The share of renewable energy in general and biofuel specifically in the energy mix in many countries is increasing. Biofuels will certainly play an important role in the future of energy supply in Africa. The weight of the role depends on the importance attached to sustainable development through poverty alleviation, fuel security and the willingness to address greenhouse gas problems and reduce CO_2 emissions. Further, ensuring the provision of adequate, affordable, efficient and reliable high quality energy services with minimum adverse effect on the environment for a sustained period is not only pivotal for development, but crucial for African countries in which most are struggling to meet present energy demands. The data and information provided in the dissertation can be used to identify opportunities to improve economic performance of biofuel process industry and hence, their commercialisation in the African continent.

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