TECHNOLOGY ASSESSMENT OF RENEWABLE ENERGY SUSTAINABILITY IN SOUTH AFRICA

By

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DECLARATION

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ABSTRACT

Technology assessment has changed in nature over the last four decades. It changed from an analytical tool for technology evaluation, which depends heavily on quantitative and qualitative modelling methodologies, into a strategic planning tool for policy-making concerning acceptable new technologies, which depends on participative policy problem analysis. The goal of technology assessment today is to generate policy options for solutions of organisational and societal problems, which at the operational level, utilise new technologies that are publicly acceptable; that is, viable policy options.

Energy technology assessment for sustainability is inherently a complex and dynamic process that requires a holistic and transdisciplinary approach. In the South Africa context, specifically, there is no formal and coherent approach to energy technology assessment from a sustainability perspective. Without a formal comprehensive or well integrated technology assessment approach to evaluate the sustainability of any technology, the policy-makers, technology designers, and decision-makers are faced with difficulty in terms of making reasoned decisions about the appropriate technology options.

This study developed a framework that incorporates a technology assessment approach, namely, system dynamics, within the broader scope of technology development for sustainability. The framework, termed the Systems Approach to Technology Sustainability Assessment (*SATSA*), integrates three key elements: technology development, sustainable development, and a dynamic systems approach. The study then provides a guiding process of applying the framework to energy technology assessment theory and practice within the context of sustainable development. Biodiesel, a cleaner burning replacement fuel, argued to potentially contribute to sustainable development, is used for the demonstration. Biodiesel development entails complex interactions of actors such as the technology developers, government at different levels, communities, as well as the natural environment. Different actions or responses in the greater system might hinder or undermine the positive effects of such a development.

Based on the *SATSA* framework, a Bioenergy Technology Sustainability Assessment (*BIOTSA*) model was developed. The *BIOTSA* model was used to test the outcomes of a proposed biodiesel production development in the Eastern Cape Province of South Africa on selected sustainability indicators. In addition, some policy scenarios were tested to compare how they assist in improving the selected indicators. The *BIOTSA* model results are useful in comparing dynamic consequences resulting from a proposed biodiesel production development and the respective policies and decisions that may arise from such a development.

The testing and validation of the *BIOTSA* model was carried out based on structural validity, behavioural validity, and expert opinion. Potential policy scenario outcomes and their implication, on the selected sustainability indicators, were also tested. The opinions of the selected stakeholders indicated that the *BIOTSA* model was useful in providing an understanding of the potential impacts of the biodiesel development on selected sustainability indicators in the Eastern Cape Province. Thus, the *SATSA* framework can be applied for assessing sustainability of other renewable energy technologies. In addition, system dynamics provide a useful and a feasible dynamic systems approach for energy technology sustainability assessment.

Finally, the model building process and transdisciplinary nature of this study enabled the identification of the potential problems that could arise during the biodiesel production development. In addition, gaps in data and knowledge were identified and the recommendation for future work in this field is highlighted. Nevertheless, the findings of the *BIOTSA* model could inform policy- and decision-making in biodiesel production development in South Africa. The development of similar models for other renewable energy development efforts is thus recommended. The current efforts to facilitate the large-scale roll out of concentrated solar thermal technologies in Southern Africa, for example, would require the development of a Solar Thermal Technology Sustainability Assessment (*SOTTSA*) model.

OPSOMMING

Die aard van tegnologie assessering het in die afgelope vier dekades verander. Dit het verander ten opsigte van ’n analitiese hulpmiddel vir tegnologie evaluering, wat hoofsaaklik staatmaak op kwalitatiewe en kwantitatiewe modelleringsmetodiek, na ’n strategiese beplanningshulpmiddel vir beleidvorming met betrekking tot nuwe aanvaarbare tegnologieë, wat afhanklik is van ’n deelnemende beleidsprobleem analise. Vandag se doel vir tegnologie assessering is om beleidsopsies vir oplossings van organisatoriese en sosiale probleme te genereer, wat op operasionele vlak gebruik maak van nuwe tegnologieë wat deur die publiek aanvaar is; met ander woorde, lewensvatbare beleidsopsies.

Energie tegnologie assessering vir volhoubaarheid is sonder twyfel ’n komplekse en dinamiese proses wat ’n holistiese en transdisiplinêre benadering benodig. In die Suid-Afrikaanse konteks is daar geen formele en samehangende benadering tot tegnologie assessering vanaf ’n volhoubaarheidsperspektief nie. Beleidsmakers, tegnologie ontwerpers en besluitnemers mag sukkel om beredenerende besluite te neem oor die toepaslike tegnologie opsies sonder ’n formele omvattende of goed geïntegreerde tegnologie assesseringsbenadering om die volhoubaarheid van enige tegnologie te evalueer.

Hierdie studie het ’n raamwerk ontwerp wat die tegnologie assesseringsbenadering inkorporeer binne die breë bestek van tegnologiese ontwikkeling vir volhoubaarheid naamlik, stelsel dinamika. Die raamwerk, genoem die Sisteem Benadering tot Tegnologie Volhoubaarheidsassessering (*SBTVA*) integreer drie sleutelelemente: tegnologiese ontwikkeling, volhoubaarheidsontwikkeling, en ’n dinamiese stelsels benadering. Verder verskaf die studie ’n leidende proses te opsigte van die toepassing van die raamwerk tot energie tegnologie assesseringsteorie en praktyk binne die konteks van volhoubaarheidsontwikkeling. Biodiesel word gebruik vir die demonstrasie omdat dit gereken word as ’n skoner plaasvervanger vir brandstof en daar aangevoer word dat dit ’n potensiële bydraer tot volhoubaarheidsontwikkeling is. Die ontwikkeling van biodiesel behels komplekse interaksie tussen verskeie akteurs soos tegnologiese ontwikkelaars, die regering op verskillende vlakke, gemeenskappe asook die natuurlike omgewing. Verskeie aksies of reaksies in die groter sisteem mag dalk die positiewe effek van so ontwikkeling ondermyn of verhinder.

’n Biodiesel Tegnologiese Volhoubaarheidsassessering (*BIOTVA*) model is ontwerp gebaseer op die *SBTVA* raamwerk. Die *BIOTVA* model is gebruik om die uitkomste op geselekteerde volhoubaarheidsaanduiders van ’n voorgestelde biodiesel produksie ontwikkeling in die Oos-Kaap Provinsie van Suid-Afrika te toets. Buiten vir die voorafgaande is sekere beleidtoekomsblikke ook getoets om te vergelyk hoe hulle sal help om die geselekteerde aanwysers te verbeter. Die *BIOTVA* model resultate is behulpsaam in die vergelyking van dinamiese gevolge wat voortspruit uit die voorgestelde biodiesel produksie ontwikkeling asook die onderskeie beleide en besluite wat mag ontstaan van so ’n ontwikkeling.

Die toetsing en bekragtiging van die *BIOTVA* model was uitgevoer gebaseer op strukturele geldigheid, gedragsgeldigheid, en kundige opinie. Potensiële beleidtoekomsblikke uitkomste en die nagevolge, ten opsigte van die geselekteerde volhoubaarheidsaanduiders, is ook getoets. Die opinies van die geselekteerde aandeelhouers het aangedui dat die *BIOTVA* model bruikbaar is om ’n beter begrip te verskaf ten opsigte van die potensiële impak wat die biodiesel ontwikkeling op geselekteerde volhoubaarheidsaanduiders in die Oos-Kaap Provinsie sal hê. As gevolg hiervan kan die *SBTVA* raamwerk toegepas word om die volhoubaarheid van ander herwinbare energie tegnologieë te assesseer. Buiten die voorafgaande kan stelsel dinamika ’n bruikbare en uitvoerbare dinamiese stelselbenadering vir energie tegnologie volhoubaarheidsassessering verskaf.

Ten slotte, die model bouproses en transdisiplinêre aarde van die studie het gehelp om potensiële probleme wat kan voorkom tydens die biodiesel produksie ontwikkeling te identifiseer. Daarby is gapings in data en kennis ook geïdentifiseer en die aanbevelings vir verdere studie in die veld is uitgelig. Nieteenstaande kan die bevindings van die *BIOTVA* model beleidmakers en besluitnemers in die biodiesel produksie ontwikkeling van Suid-Afrika inlig. Die ontwikkeling van soortgelyke modelle vir ander herwinbare energie ontwikkelingspogings word aanbeveel. As voorbeeld sal die huidige pogings om die grootskaalse uitrol van gekonsentreerde son termiese tegnologieë in Suider-Afrika te fasiliteer die ontwikkeling van ’n Son Termiese Tegnologie Volhoubaarheidsassesering (*SOTTVA*) model benodig.

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LIST OF ABBREVIATIONS

BIOSSAM	Bioenergy systems sustainability assessment and management
BIOTSA	Bioenergy technology sustainability assessment
BPS	By-product use scenario
BSS1	Biodiesel support scenario 1
BSS2	Biodiesel support scenario 2
BSS3	Biodiesel support scenario 3
CPS	Community perception scenario
CSIR	Council for scientific and industrial research
ERC	Energy research centre
ETA	Energy technology assessment
EU	European Union
FUS	Fertilizer use scenario
GDP	Gross domestic product
GHG	Greenhouse gas
GNP	Gross national product
IDZ	Industrial development zone
IIED	International institute of environment and development
ITA	Innovative technology assessment
ITAS	Institute for technology assessment and systems analysis
LCA	Life cycle analysis
LCC	Life cycle costing
MFA-SFA	Material and substance flow analysis
NERSA	National energy regulator South Africa
O & M	Operation and maintenance
OTA	Office of technology assessment
PBMR	Pebble bed modular reactor
PSBPS	Perception, support biodiesel & by-product scenario.
R & D	Research and development
SADC	Southern African Development Community
SANERI	South Africa national energy research institute
SATSA	Systems approach to technology sustainability assessment
SDM	System dynamics model

SBPS	Support biodiesel & by-product scenario
T21	Threshold 21
TA	Technology assessment
TIA	Technology innovation agency
TSA	Technology sustainability assessment
TSAMA	Transdisciplinary sustainability analysis modelling and assessment
UNEP	United Nations environmental program
WBCSD	World business council for sustainable development
WCED	World commission on environment and development
WDI	World development indicators

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND INFORMATION

Energy services are recognized as essential to meet the basic human needs as well as to support economic growth. The expenditure on energy represents a significant contribution to the gross national product (GNP) and the cost of living in a country (Sagar and Holdren, 2002). Energy extraction, conversion and use have a major impact on the environment; this ranges from local to global levels. In addition, international energy flows affect the world trade and are potential sources of tensions and conflicts. Given these factors, energy systems are crucial to society and to the prospects for improving it.

Technological development has long been a key driver in the energy sector (Sagar and Holdren, 2002). Technology development is regarded as an interaction of the technology with the system in which the technology is embedded (Hekkert et al., 2007) as is illustrated in Figure 1.1.

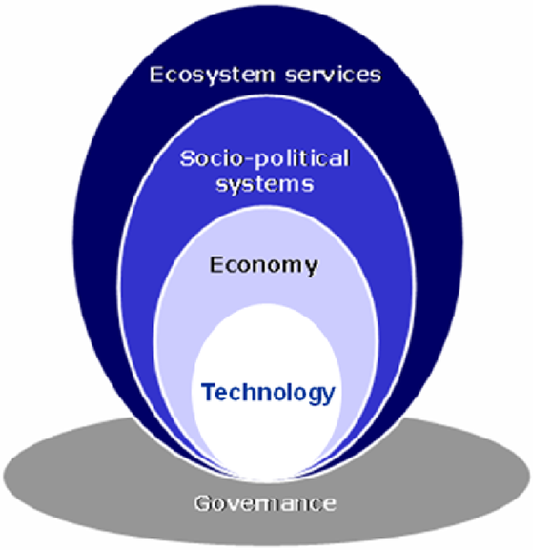

Figure 1.1: Interactions of technology with other systems (adapted from Department of Environmental Affairs and Tourism (2008); Mebratu (1998)

Technology development has shown the capability of providing not only the advantage of economic growth and societal benefits, but also minimizing the negative effects on the natural environment. The relation between the environment and technology is, however, complex and paradoxical (Grübler, 1998; Grübler et al., 2002). Firstly, technologies use resources and impose environmental stress. On the other hand, technologies can also lead to more efficient use of resources, less stress on the environment, and even cleaning the environment. The latter approach is referred to as sustainable technology development (Weaver et al., 2000). Since technology development is not autonomous, its management is necessary. In order to make technological development sustainable, technical change alone is not sufficient and changes in the social and institutional dimensions, such as the user practices, regulations, and industrial networks, are inevitable (Geels, 2002).

One of the important disciplines in technology management is technology assessment (TA), which has evolved over the past four decades (Tran and Daim, 2008). TA enables the evaluation of the aggregate technology capability and facilitates strategic technology planning. Although TA does not necessarily provide policy-makers and managers 'the answer', it does increase the odds that the maximum benefits of technology will be achieved (De Piante Henriksen, 1997). TA can reduce the risks inherent in the competitive process by providing information in support of decision-making and can be important in determining: research and development direction; new technologies adoption; incremental improvement in existing technologies; level of technology friendliness; 'make or buy' decisions; optimal expenditure of capital equipment funds; and market diversification (De Piante Henriksen, 1997).

While TA has found value in many technology-related problems, there is still a strong need of finding more effective methods of assessment (Tran and Daim, 2008) especially in Africa. This is because TA does not feature in many African government policies (Musango and Brent, 2011a). Providing support for the development of sustainable energy innovations therefore remains a difficult task for decision-makers with a need to influence the course of technological change.

Sagar and Holdren (2002) provide three aspects for understanding energy sector technologies. Firstly, it is an evolving system, which is characterized by fluctuating energy prices. Low prices for conventional energy have a direct effect on the market interest in technological development and vice versa; new technologies need to compete with the established technologies. Secondly, the research and development (R&D) budgets provide a hazy picture, since the range of the R&D activities in the energy sector is very broad. Thirdly, there is a need to look beyond the R&D in the assessment of innovation capability, specifically focussing on the energy innovation system. Above all, the accurate assessment of an energy innovation system is a prerequisite for judging the system adequacy in relation to the challenges facing the energy sector, and for suggesting policies to improve the innovation system performance. Gaps in the energy innovation systems are not likely to be filled until the gaps in our understanding of this system are filled (Sagar and Holdren, 2002), hence the need for improved TA. This study therefore focuses on the technology sustainability assessment, with the aim of providing improved assessment practices for renewable energy technologies in South Africa.

1.2 RATIONALE FOR TECHNOLOGY SUSTAINABILITY ASSESSMENT

TA enables the evaluation of the aggregate technology capability of the enterprise and facilitates strategic technology planning (De Piante Henriksen, 1997). Policy-makers and managers therefore require a comprehensive TA technique in order to obtain meaningful information for decision-making and maintaining a viable position in the globally competitive market place.

Classical TA faces considerable challenges. One of the common criticisms is that TA has unrealistic ambitions to predict future technological developments (Palm and Hansson, 2006). Firstly, the lack of clear criteria for how a proper assessment should be conducted has made it difficult to improve assessment practices and to compare and evaluate the quality of different assessments. Secondly, the classical TA concept is treated as universal while it is in fact strongly tied to the western world[1]. Current TA practices have emerged in the Western world in the last few decades and are formed by a relatively homogenous social, political and economic climate. The interests of non-Western nations are seldom taken into consideration as emphasised by Goonatilake (1994):

---

[1] This argument is most often held forth to show the importance of social interactions in the developmental process of new technology, namely social-shaping of technology.

> *"The emergent of technology assessment did not occur in a societal vacuum; neither did its practice. Today's TA expertise is the outcome of historically located concerns, still unique to a particular narrow space and narrow time frame".*

Thirdly, TA focuses mainly on the outcomes or impacts of a technology, which can only be performed at later stages of technology development, when societal implications are easily determined and identifiable (Fleischer et al., 2005). On the other hand, policy-making and decision support require information on the potential consequences of the introduction of new technologies before they are widely implemented. In other words, the information is required at early stages of technology development when the direction of the innovation process can be influenced, but its implications can hardly be foreseen. This is best illustrated in the work of Brent and Pretorius (2008) that provide a framework of technology life cycle interventions and the associated evaluated systems as shown in Figure 1.2.

Fourthly, classical TA was dominated by qualitative methods from social sciences. Quantification was limited to the economic analyses, mostly, by utilising the cost benefit approach (Durbin and Rapp, 1983). The inspiration from the efforts to develop sustainable development indicators to measure social phenomena in the mid-1990's implied the importance of quantitative analysis. Sustainability indicators can thus be useful in testing the relevance and quantity of the various actions, including the development of new technologies (Assefa and Frostell, 2006).

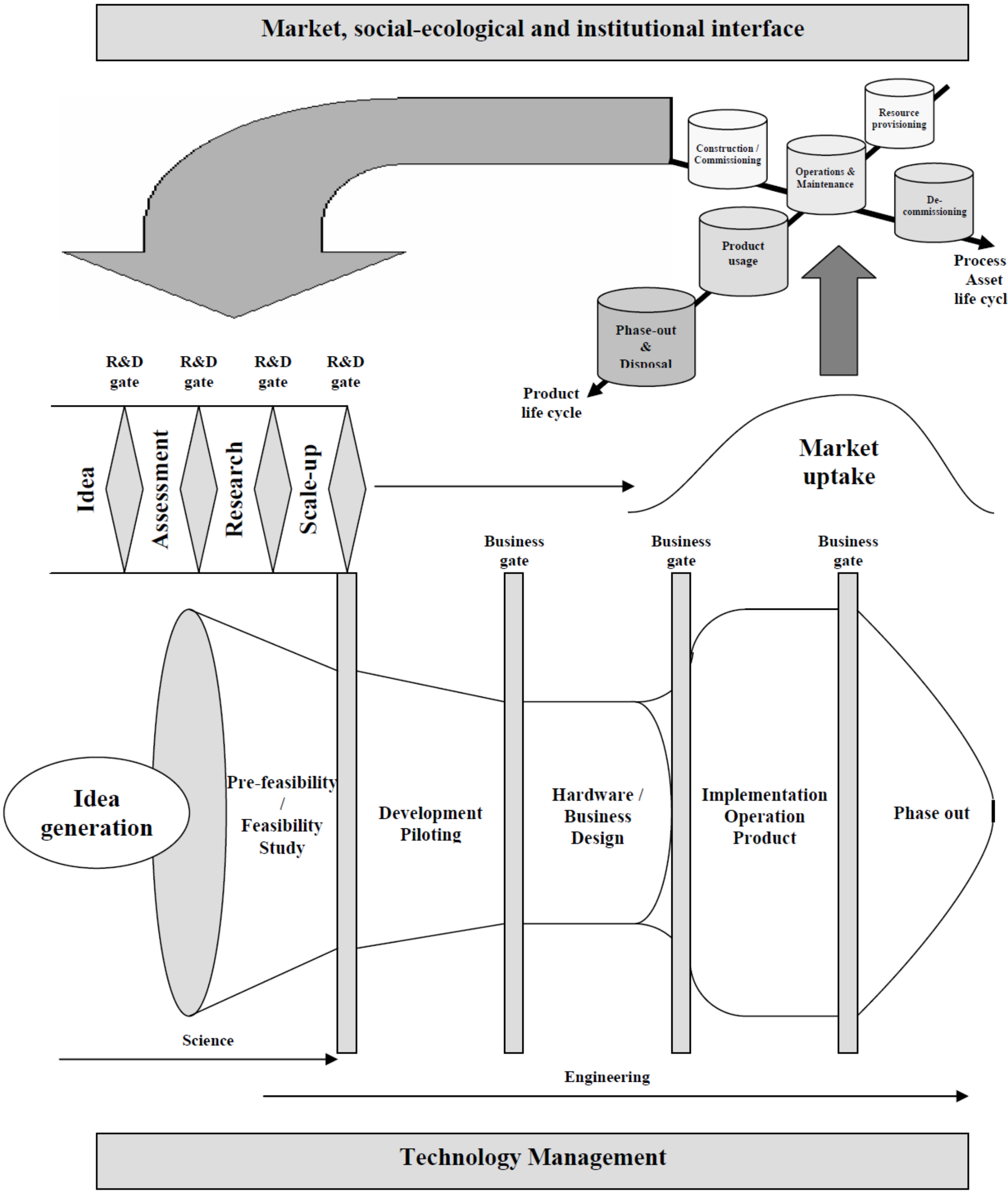

Figure 1.2: Technology life cycle interventions and associated evaluated systems (Brent and Pretorius, 2008)

Fifthly, in terms of disciplinary organization, TA suffers from relatively poor coordination, integration and overall balance. The TA categories[2] are discipline-based (Palm and Hansson, 2006) with little or no integration between the different categories. A diverse literature addresses the integration within one category or within two categories. For instance, Ulvila (1987) combined economic analysis with the decision analysis to assess the profitability of alternative technologies. Brent and Pretorius (2008), however, call for the modification of the technology assessment methods to incorporate the dynamic interactions between nature and society. This also raises the need of considering transdisciplinarity and other principles of sustainability science (Brent, 2009).

Sixthly, most of the TA tools do not take a holistic view and are static in nature and are either high level and 'simplistic', or low level and complex (Wolstenholme, 2003). Further, they tend to evaluate technology in terms of itself rather than the domain it is intended to support. Wolstenholme (2003) advocates the use of system dynamics as a means for intermediate level technology assessment, which is a key contribution to his work. He highlighted the potential benefits of TA through a system dynamics approach as follows Wolstenholme (2003):

i. It provides an indication of the way technology interacts with its domain of application. The benefits of this type of new technology from this type of assessment can be surprising and counter-intuitive. This contrast strongly with other static analysis which mostly assumes each part of technology is independent and the combined effect of the technology is a linear summation of its parts.

ii. It also provides a way of sharing thoughts about the technology between policy-makers and managers in different functional areas at an early enough time for all to be involved in the analysis.

iii. It provides for experimental learning about the technology and the domain of its application and their interaction by providing a quantitative basis for 'what if' analysis.

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[2] Technology assessment tools and methods have been categorized in the literature according to the following: economic analysis; decision analysis; systems engineering/systems analysis; technology forecasting; information monitoring; technical performance assessment; risk assessment; market analysis; and externalities/impact analysis. This is further discussed in Chapter 2.

iv. Finally, it provides a way of determining the overall merits of a technology and in particular, its possible side effects, prior to a full and costly commitment.

The approach of Wolstenholme (2003) involves the creation of maps and dynamic simulation models of the anticipated domain of application of the technology as a test bed to evaluate its impact at a global level rather than local level. In addition, he fails to consider the integration of sustainability-based evaluation criteria.

Within the South African context, there is no formal TA practice to support energy policy formulation. Although the South African governance system is developing national measures of sustainability (Brent and Rogers, 2010), serious application of sustainability based criteria is not common in TA or other decision-making on important energy technology developments. Studies in South Africa that have applied sustainability assessment methodologies on energy technologies include that of Brent and Rogers (2010). They developed a model based on the principles of sustainability science for renewable energy technologies by investigating a particular mini-hybrid off-grid project in rural South Africa. Their model integrates:

i. a life cycle perspective and systems thinking;
ii. learning methods for management of information in the paradigm of sustainable development;
iii. conditions for sustainability to reduce the complexity of systems by clarifying the magnitude cause and effect on systems; and
iv. technology innovation and what is feasible within constrains of time, finances and institutions.

They conclude that changes in the integrated system over time, which was not accounted for in their model, could identify adaptive strategies for the management of renewable energy technologies. They recommend further research in understanding the complexity of the socio-institutional (and ecological) systems as they relate to technological systems to reduce the uncertainty for technology designers and decision-makers.

The recommendation of Brent and Rogers (2010) is critical and timely for South Africa, since a Technology Innovation Agency (TIA), which is a state-owned body, was recently established (www.tia.org.za). The agency has three critically important objectives (Campbell, 2007; South African Government, 2008). Firstly, it aims to stimulate technology development; secondly, to stimulate the development of technological enterprises; and, finally, to stimulate the broader industrial base. However, without a formal comprehensive or well-integrated TA method to evaluate the sustainability of any technology, the policy-makers, technology designers and decision-makers are faced with difficulty in terms of the appropriate technology options for the country. There is therefore a need to develop, verify and validate an appropriate technology sustainability assessment method, which is the key focus of this study.

1.3 ENERGY TECHNOLOGY DEVELOPMENT AS A COMPLEX SYSTEM

The development of energy technologies involves interaction with the environment. For instance, most renewable energy systems require land for their development and also have the potential to reduce emissions of energy production as a whole. Renewable energy may also have a social function in human life and interactions may be established between the energy development and social system. Further, there are numerous actors that are involved, especially in the development of renewable energy. These may range from the local communities, to technology developers and policy-makers in the public entities. These factors thus display the characteristics of a complex system that constitutes renewable energy development. To this end some studies in the literature acknowledge the need to evaluate the energy technology development as a complex system (Afgan and Carvalho, 2002; Jones, 2008; Synder and Antkowiak, 2010).

It is also important to note that, in renewable energy development, projections are not limited to the technology development, but also expectations in the market place and the potential impacts of different policies made by the government or in the market place (Synder and Antkowiak, 2010). Thus, the approach to use in assessing the renewable energy technology development for sustainability will need to be in a position to account for the assumptions regarding the economic, social-ecological and other changes that might influence the development towards the desired sustainable path. By combining a dynamic system approach such as system dynamics with transdisciplinary research, provides potential for such an approach (Jones 2008; Kilham and Willetts, undated). One of the main features of transdisciplinary research is the collaboration and communication with the scientific and non-scientific communities (Pohl and Hirsch Hardon, 2007).

Literature on both the dynamic systems approach and transdisciplinary research do recognize modelling as an integral tool. System dynamics is one of the modelling approaches that have gained popularity due to its focus on the structure of a system and its flexibility. While the potential of system dynamics as an intermediate level tool in technology assessment is recognized (Wolstenholme, 2003), there is, however, a need to examine its potential for improving technology assessment for sustainability that can guide in sustainable technology development policy analysis and informed decision-making.

1.4 TRANSDISCIPLINARY RESEARCH IN TECHNOLOGY ASSESSMENT

Recent studies in the technology management community are recognizing the need for transdisciplinary research in technology assessment. Decker and Fleischer (2010) argue that TA requires transdisciplinary research since it is generally classified as problem-oriented. TA is problem-oriented because it attempts to provide an understanding of problems outside science and provides advice mainly to policy-makers, decision-makers, the academic community and general members of society. All the activities in TA always relate to a particular societal, scientific and political situation, which becomes a starting point of any TA (Decker and Fleischer, 2010). In a similar manner, the transdisciplinary research community already identifies TA as one of the disciplines for the application of transdisciplinary research (Nowotny et al., 2001; and Decker 2007 as cited in Decker and Fleischer, 2010).

Transdisciplinary research is thus a holistic and integrated approach and it involves collaboration with academic and non-academic stakeholders (Pohl and Hirsch Hardon, 2007). Figure 1.3 is a modification of Wolfenden's (1999) concept, which illustrates transdisciplinary research in technology assessment. Monodisciplinary research is always partial and fragmented, and combining different disciplines may result in multi- and interdisciplinary research, but the disciplines still remain distinct. A more integrated and holistic approach is gained from transdisciplinary research. Integration in transdisciplinary research may occur in three ways: deliberation among experts, common group learning and integration by individual or sub-group (Rossini and Porter, 1979: cited in Pohl et al., 2008). Modelling tools can facilitate such integration.

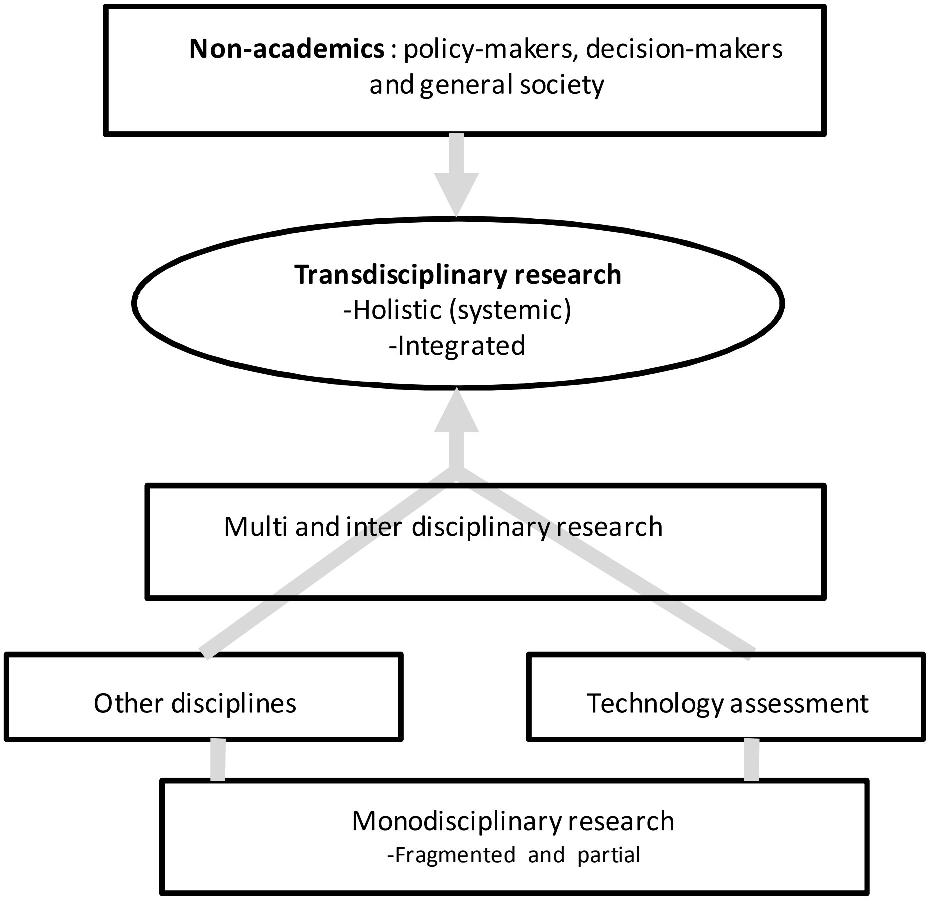


Figure 1.3: Transdisciplinary research in technology assessment

1.5 SYSTEM DYNAMICS MODELLING AS AN INTEGRATIVE TOOL IN TECHNOLOGY SUSTAINABILITY ASSESSMENT

System dynamics places an emphasis on the structure of a system and assumes that this best represents the dynamic behaviour of the 'real world' (Flood and Jackson, 1991). System dynamics can capture the complex real-world behaviour of uncertainties that result from non-linear feedback structures (Forrester, 1994; Sterman, 2000). As a result, system dynamics modelling has a wide application in different disciplines including, among others, technology assessment, business marketing and management, environmental management and health care.

Technology sustainability assessment requires a complex and multidimensional evaluation in order to take into account different sustainability indicators. This complex and multidimensional evaluation can be performed using system dynamics. While system dynamics is among the methods that are identified in the technology assessment literature (De Piante Henriksen, 1997; Tran, 2007), the main benefit of using it for technology assessment is the increased realism in the assessment itself. Modelling the structure that produces this complex behaviour with system dynamics may improve the accuracy of technology assessment. Another advantage of using system dynamics is its flexibility in defining complex feedback systems and separate stochastic effects, which is quite beneficial in dealing with multiple and potentially interacting sources of uncertainty. In addition, describing the distribution of uncertainty around system dynamics variables is intuitive (Sterman, 2000). As a result, system dynamics provides clearer insights into the drivers of the effects of strategic action (Johnson et al., 2006).

From a technology sustainability assessment perspective (Assefa and Frostell, 2006), system dynamics recognizes sustainability as a whole systems concept concerned with human activities in the context of naturally occurring systems that provide the sources and sinks for the flows of materials and energy associated with them (Chan et al., 2004). It also shows the ability of those systems to sustain human activities. The starting point is the current state of the system; the stock of artifacts that are accumulated as a result of human activities and the state of natural systems as they are impacted on by human activities over time (Chan et al., 2004).

Some studies have also recognized system dynamics modelling as an essential tool and well suited in transdisciplinary research (Wolfenden, 1999; Hirsch Hardon et al, 2008). System dynamics modelling is not only useful in simplifying and integrating various aspects of a complex problem, but also facilitates communication and understanding between scientific, non-scientific and management actors. Thus, the system dynamics approach was deemed appropriate for this study because it provides a means to investigate complex and dynamic situations involved in sustainable technology development, communication and understanding of these situations.

1.6 PROBLEM STATEMENT AND RESEARCH QUESTION

The current energy technology assessment approaches in South Africa, and elsewhere, do not provide a holistic view in generating and making choices for technology policy analysis and practices, to ensure effective diffusion and adoption of appropriate and sustainable technologies. Technology assessment of renewable energy development should be guided by not only the economic short-term gains, but also its long-term repercussions on the social-ecological systems in which technologies are embedded. A holistic technology assessment is only possible by incorporating this long-term perspective, which is intrinsically tied to the concept of sustainability. Disciplinary approaches to technology assessment offer piecemeal information for technology development management. However, these have drawbacks and make limited understanding of the sustainability of the technology development. To this end, an improved technology sustainability assessment requires a transdisciplinarity approach that manifests three key elements at the same time, that is, technology development, sustainable development, a dynamic systems approach; and their interaction (see Figure 1.4). The conceptual framework forms the basis of this study and is termed the systems approach to technology sustainability assessment (*SATSA*) (Musango and Brent, 2011b).

The underlying research question of this study is then whether the implementation of the *SATSA* framework and particularly the system dynamics approach thereof, has the potential to improve technology sustainability assessment practices in the South African energy sector, with a specific emphasis on renewable energy technologies.

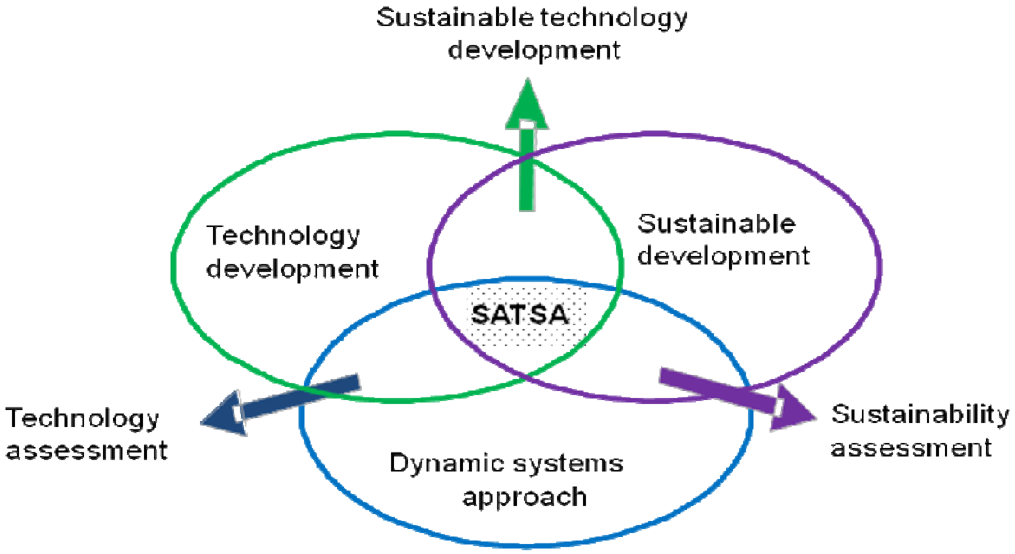


Figure 1.4: Schematic representation of a systems approach to technology sustainability assessment (*SATSA*) (Musango and Brent, 2011b)

1.7 OBJECTIVES OF THE STUDY

The objectives of this study are:

i. to critically review the elements of the systems approach to technology sustainability assessment *(SATSA)* framework;
ii. to determine the technology assessment approaches for the energy sector in South Africa; and
iii. to develop, populate and validate a system dynamics model for bioenergy technology sustainability assessment in South Africa with particular focus on biodiesel development in the Eastern Cape Province of South Africa.

The study aims to demonstrate the application of the *SATSA* framework and the appropriateness of the developed model for its intended use in energy technology assessment for sustainability.

1.8 RESEARCH STRATEGY AND SCOPE OF THE STUDY

The research strategy that was followed is presented in Figure 1.5. It encompassed, first, the critical review and analysis of the past studies on the main elements of a systems approach to technology sustainability assessment. The intent of this component was to understand the intrinsic properties of the elements and their interactions in relation to developing an improved technology sustainability assessment framework. In addition, the study provides a critical review of energy technology assessment for sustainability with specific focus on the approaches used in South Africa. Thirdly, the application of the developed *SATSA* framework is limited to one case study, which focused on bioenergy development in the Eastern Cape Province of South Africa with a specific case of biodiesel production development. The intent is to understand the extent of achieving sustainability goals for developing biodiesel production in South Africa using the *SATSA* framework. The study acknowledges the acclaimed vagueness and ambiguity in the sustainable development concept but does not discuss the whole debate around the concept. Thus, the focus is not on the development of new indicators for energy technology sustainability, but discussing the grounds for using selected indicators. In addition, this study does not deal with the physicochemical processing details of technology assessment (for biodiesel production development). This level of detail was neither necessary, nor desirable, for the level of resolution in the system dynamics model. Finally, the study is limited to consultative transdisciplinarity where the non-scientists were contacted to respond to the work carried out, particularly on the development of the system dynamics model.

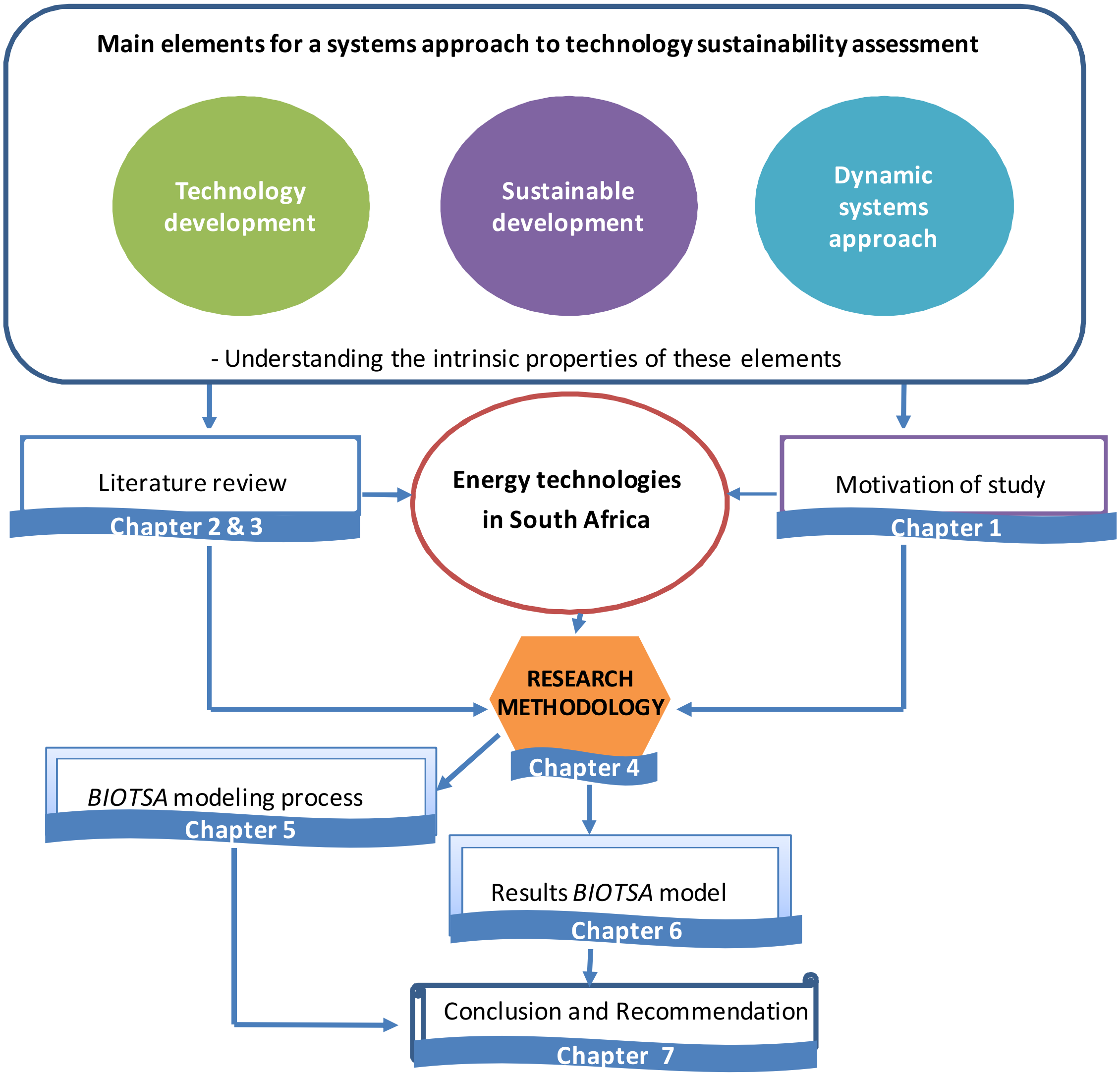
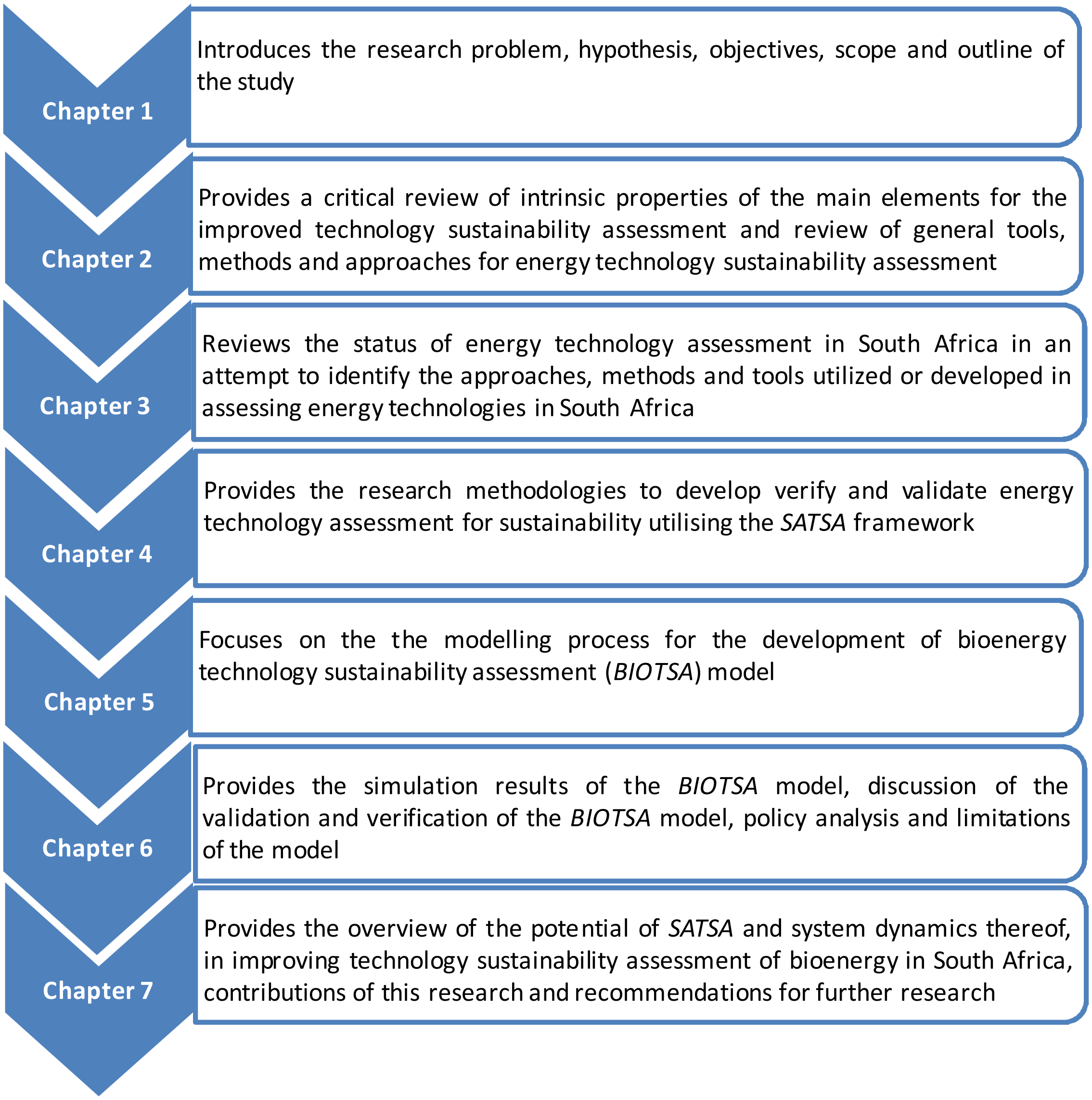


Figure 1.5: General overview of research strategy

1.9 LAYOUT OF DISSERTATION



Introduces the research problem, hypothesis, objectives, scope and outline of the study

Provides a critical review of intrinsic properties of the main elements for the improved technology sustainability assessment and review of general tools, methods and approaches for energy technology sustainability assessment

Reviews the status of energy technology assessment in South Africa in an attempt to identify the approaches, methods and tools utilized or developed in assessing energy technologies in South Africa

Provides the research methodologies to develop verify and validate energy technology assessment for sustainability utilising the *SATSA* framework

Focuses on the the modelling process for the development of bioenergy technology sustainability assessment (*BIOTSA*) model

Provides the simulation results of the *BIOTSA* model, discussion of the validation and verification of the *BIOTSA* model, policy analysis and limitations of the model

Provides the overview of the potential of *SATSA* and system dynamics thereof, in improving technology sustainability assessment of bioenergy in South Africa, contributions of this research and recommendations for further research

Figure 1.6: General content of thesis chapters

CHAPTER 2: LITERATURE REVIEW ON THE SUSTAINABILITY ASSESSMENT OF RENEWABLE ENERGY TECHNOLOGIES[3]

2.1 INTRODUCTION

Many different approaches to TA have been adopted in practice depending on the specific aims and scope of the application and its context; institutional, private firms, private or public research centres, or specific industries (Van Eijndhoven, 1997; Góralczyk, 2003; Spreng, 2002). Energy technology assessment is extensively performed from environmental and economic aspects (Hondo and Baba, 2010). These include: energy analysis (Chapman, 1975), life cycle greenhouse gas emission analysis (Hondo, 2005) and externality assessment, to name but a few. It is evident that for sustainable development and the subsequent introduction of new energy technologies, it is important to incorporate the economic, environmental and social concerns, and other goals, in the assessment.

As indicated in Chapter 1 (and Figure 1.4), an improved technology sustainability assessment framework, referred to as the systems approach to technology sustainability assessment (*SATSA*), has been developed (Musango and Brent, 2011b). This chapter reviews the intrinsic properties of the three main elements of the introduced *SATSA* framework, namely: sustainable development, technology development, and dynamic systems approach. The outcome of the three paired elements, namely: sustainable technology development, technology assessment, and sustainability assessment were also reviewed. The review provides substantial understanding of the theoretical background into the development of the improved technology sustainability assessment framework. In addition, the constraints and limitation of the current energy technology assessment needs to be clearly understood. Therefore, this chapter also provides a critical review of general tools, methods and approaches for energy technology sustainability assessment. As a result the literature review provides a fundamental understanding of certain aspects of the improved energy technology sustainability assessment.

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[3] A conceptual paper for the *SATSA* framework based on this chapter has been published: MUSANGO, J.K. & BRENT, A. C. 2011 A conceptual framework for energy technology sustainability assessment. *Energy for Sustainable Development Journal* 15: 84-91.

2.2 TECHNOLOGY DEVELOPMENT

2.2.1 What is technology?

The term technology originates from two Greek words namely '*techne'* meaning art, the capability to create something; and '*logos*' meaning word or human reason. Thus, '*technologia'* is the science and systematic treatment of practical arts. In a most general definition, technology is a system of means to particular ends that employs both technical artifacts and social information (knowhow). Grübler (1998) presents the conceptualisation of technology as a broad spectrum, hence emphasising its inseparability with the economy and social context in which it evolves. In turn, the social and economic context is shaped by the technologies that are produced and used.

The last 300 years has experienced more momentous technological changes than any other period and is considered as the *'age of technology'* (Grübler, 1998). Anthropologists, historians and philosophers were the first to have an interest in understanding the role technology plays in shaping societies and cultures. Individuals from other disciplines such as economics only followed later to study technological change (Rosegger, 1996).

Thorstein Veblen and Joseph A. Schumpeter pioneered the thinking on technology. Veblen (1904; 1921; 1953) was the first to focus on the interactions between humans and their artifacts in an institutional context and to regard technology as part of material and social relationships. Technology was deemed to be developed and shaped by social actors while at the same time shaping social values and behaviour.

Schumpeter (1934) in turn, considered the sources of technological change as endogenous to the economy. This is well illustrated using Schumpeter's waves (Figure 2.1), whereby the duration in which the utilization of new technology knowledge influences the characteristics of economic development decreases. Technological change therefore arises *within* the economic system as a result of newly perceived opportunities, incentives, deliberate research and development efforts, experimentation, marketing efforts and entrepreneurship (Grübler, 1998).

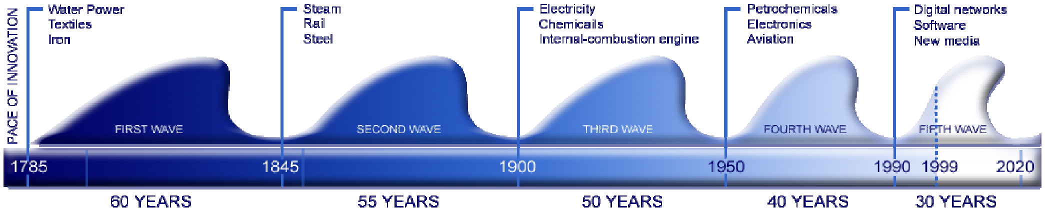

Figure 2.1: Schumpeter's waves of impact of the technological change on the economy

Currently, numerous technology studies acknowledge the feedback loops affecting technology development and a common conclusion that technology development is neither simple nor linear, is shared. Grübler (1998) identifies four important characteristics of technology development that are relevant in guiding the development of the improved technology sustainability assessment; these are: *uncertainty*, *dynamic*, *systemic* and *cumulative*.

Technological *uncertainty* arises due to the existence of a number of solutions to achieve a particular task. It is therefore uncertain to which of these solutions might be the '*best'* when all economic, social, technical, environmental (and other) factors are taken into account. *Uncertainty* also exists at all stages of technology development, from the initial design choices, through success or failure in the market place. Failure of the technology during the early stages of development increases the uncertainty given the chasm between the early technology adopters and the early majority. Secondly, technology is *dynamic* implying that it exhibits an s-curve as it changes over time as a result of improvements or modifications. Plotting the performance of a technology against the cost of investment initially shows a slow improvement, which is then followed by an accelerated improvement and finally diminishing improvement, as is illustrated in Figure 2.2. The main factors contributing to the *dynamic* nature of technologies is due to either (i) the new inventions or (ii) continuous replacement of capital stock as it ages and economies expand.

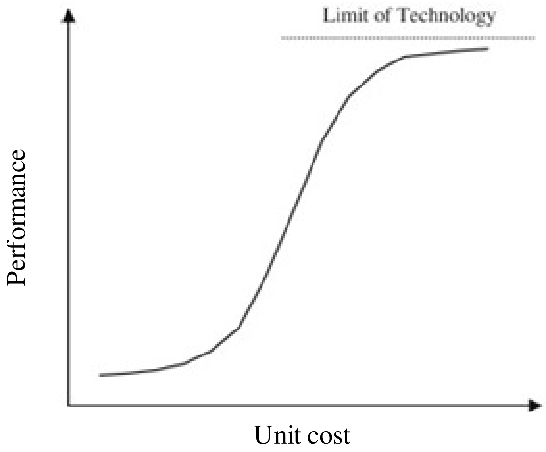

Figure 2.2: Technology S-curve

Thirdly, technology development is *systemic* and cannot be treated as a discrete, isolated event that concerns only one technology. The interdependence of technologies causes enormous difficulties in implementing large-scale changes. The mutually interdependent and cross-enhancing "socio-technical systems of production and use" (Kline, 1985) cannot be analyzed in terms of single technologies, but should be considered in terms of the mutual interactions among the concurrent technological, institutional and social change. Finally, technology change is *cumulative*, and builds on previous experience and knowledge. This implies that an increase in productivity, and thus a reduction in specific production costs, is a function of the life cycle stage of a technology.

Although, the technology development characteristics discussed above are recognized in the literature, two fundamental features are still ignored by macro-economic (Grübler, 1998) and other models. These are: (i) evolution from *within*, and (ii) the inherent dynamic and non-equilibrium nature of technological change, which the static equilibrium models fail to capture.

2.2.2 Technology in socio-ecological systems

Technologies are depended on the natural resources for raw materials, energy and to assimilate waste (Smith and Stirling, 2008). In terms of beneficiation, four roles of technologies in relation to ecosystems are identified in the literature (Berkhout and Goudson, 2003):

(i) technologies provide information and sensors about the state of ecological systems such as satellite imaging of land use - monitoring technology facilitates an appreciation of socio-ecological systems;

(ii) technological change stimulates economic growth and re-structuring of social development that impact upon multiple socio-ecological systems;

(iii) cleaner technologies improve efficiency with which material resources are invested and transformed into valued outputs - for example, liquid fuels from biomass; and

(iv) technologies may be developed with a specific aim of repairing the environmental impacts of existing activities.

The literature also recognizes the influence that technology has on socio-ecological systems (Andries et al., 2004). Technology mediates relationships between key elements of the system as presented in Figure 2.3. Institutions coordinate investments in infrastructure and production technologies with consequent influences on the ecosystems. Technology choices affect the production function that influences relations between users and the ecosystem. In turn, governance strategies for promoting greater socio-ecological systems resilience should consider technology choices, its patterns of use and its control.

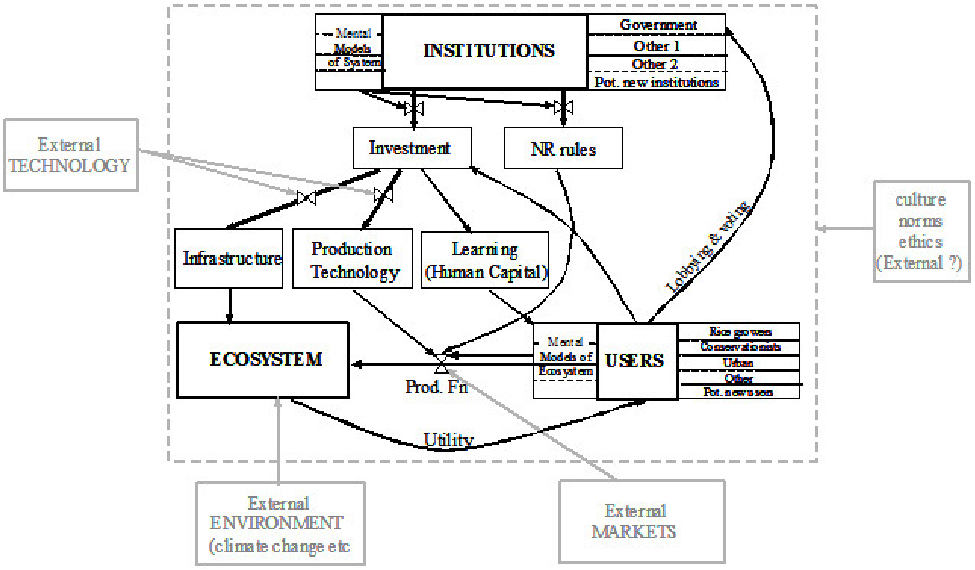

Figure 2.3: Exogenous driver and the exogenous mediating roles of technology in socio-ecological systems (Resilience Alliance[4])

Figure 2.3 conceptualizes technology as exogenous, which implies that the processes that shape and select an array of available technologies are seen to operate outside the social-ecological system. Thus, technology development is somewhat out of focus. However, studies in the literature argue that technology carries implications that are of focal concerns for the resilience of socio-ecological systems.

2.2.3 Technology as a socio-technical system

There are a growing number of studies that attempt to provide frameworks for understanding the factors that shape the course of technology development from a socio-technical systems perspective (Rip and Kemp, 1998; Geels, 2005). Socio-technical systems analysis has its roots in sociological studies (Bijker and Hughes, 1997) and historical accounts of technological change (Hughes, 1983), as well as the evolutionary economics and other influences. The key argument provided in these frameworks (Rip and Kemp, 1998; Geels, 2005) is the notion that large technical systems co-evolve with the associated social, cultural and political institutions.

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[4] http://www.resalliance.org/563.php [accessed 11 January 2010]

Technologies that achieve market dominance and widespread application call for social formations with strong incentives to protect and promote the entrenched regime. Hence, within these frameworks, socio-technical transition occurs when a niche technology gains enough traction to compete with and, to a certain extent, replace the entrenched socio-technical regime (Stephens and Jiusto, 2010). Public policy decision, however, plays a critical role in influencing the prospects for technology development. Therefore, there is a need to provide a means that contributes to the better understanding of the policy choice of technology-oriented sustainable development.

2.3 SUSTAINABLE DEVELOPMENT

2.3.1 Sustainability: a conceptual analysis

The concept of sustainability has enjoyed widespread coverage in the literature and in discussions at different levels (Assefa and Frostell, 2007). The Brundtland Report, *Our Common Future* (World Commission on Environment and Development, 1987) and, from an energy perspective, Goldemberg et al. (1988), are taken as a starting point of the concept. Mebratu (1998) reviewed the historical and conceptual precursors of the concept of sustainable development and categorized it into three historical periods: (i) pre-Stockholm, covering the period until the Stockholm Conference on Environment and Development (1972); (ii) from Stockholm to World Commission on Environment and Development (1972-1987); and (iii) post-WCED (1987-1997). Since the definition of the sustainable development concept by WCED in 1987 and subsequent popularization, different groups of people, organizations and individuals have attempted to capture the meaning of the concept.

The most widely used definition of sustainability refers to three dimensions: ecological, economic and social systems. The concept of sustainability derives from a shift in perspective - from a focus on economic development that is often defined as the expansion of consumption and GDP, to a new view of development called sustainable development (Harris and Goodwin, 2001). The Brundtland Report defines sustainable development as development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). According to Mebratu (1998), this definition contains two key concepts: (i) the concept of ‘needs’, particularly the essential needs of the world’s poor, that should be given a paramount priority; and (ii) the idea of limitations imposed by the state of technology and social organization on the ability of the natural environment to meet the present and future needs.

The term 'needs' can therefore be considered in the context of aspirations and expectations that nations or regions or communities may have of a development process and how these may be met sustainably. Sustainable technology development therefore seeks to effect some improvement in the *quality of life*, as measured by the provision of key indicators such as employment, income and education (access to resources) without exceeding the capacity of the environment to support such technology. This places technology management, in the sense of technology assessment, at the centre of sustainable technology development.

Sachs (1999) distinguishes between partial sustainability and whole sustainability. According to him, the following criteria, along the lines of four dimensions, should be met:

- *ecological sustainability:* conservation of the natural capital of nature supplemented by environmental and territorial sustainability - the former is related to the resilience of natural ecosystems used as sinks, the latter is about evaluating the spatial distribution of human activities and rural-urban configurations;
- *economic sustainability:* taken broadly, the efficiency of economic systems to ensure continuous socially equitable, quantitative, and qualitative progress;
- *social sustainability*: including its corollary, cultural sustainability; and
- *political sustainability:* providing a satisfying overall framework for national and international governance.

In much of the literature, issues that are dealt with in the sphere of Sachs' political sustainability are often included in social sustainability, thereby reinforcing the argument to restrict the discussion to three dimensions, namely, environmental/ecological sustainability, economic sustainability, and social sustainability. Harris and Goodwin (2001) clarify the three dimensions of sustainability from the perspective of important features of a sustainable system:

(i) *ecological/environmental sustainability*: work on this dimension leads to an environmentally sustainable system that maintains a stable resources base, avoids over-exploitation of renewable resources only to the extent that investment is made in adequate substitutes. This includes maintenance of biodiversity, atmospheric stability, and other ecosystem functions not ordinarily classed as economic resources;

(ii) *economic sustainability:* this dimension ensures that an economically sustainable system is able to produce goods and services on a continuing basis. It also maintains manageable levels of government and external debt; and avoids sectoral imbalances that damage agricultural or industrial production; and

(iii) *social sustainability:* efforts to deal with this dimension lead to a socially sustainable system that result in fairness in distribution and opportunity, and adequate provision of social services including health and education, gender equity, and political accountability and participation.

Some studies have argued that, sustainable development is neither a fixed condition nor is there a final sustainable state, but it is inherently a dynamic process (Mog, 2004). Kemmler and Spreng (2007) illustrated this point by arguing that future generation, with greater knowledge and sophisticated technology and different needs, will define sustainable development in their own way and set different development goals. In addition, Meadows (1998) recognizes that sustainable development is dependent on a society's worldviews and values.

Mebratu (1998) categorizes the existing variety of definition of sustainable development into three major groups: (i) institutional version; (ii) ideological version; and (iii) academic version. The institution version entails those given by the World Commission on Environment and Development (WCED), the International Institute of Environment and Development (IIED) and the World Business Council for Sustainable Development (WBCSD). All these definitions share the same definition of sustainable development, but with different focus areas as reflected in Table 2.1.

Table 2.1: Comparative analysis of the institutional version of sustainability

Institution	**Drivers**	**Solution epicenter**	**Solution platform**	**Instruments (leadership)**
WCED	Political consensus	Sustainable growth	Nation-state	Governments and international organizations
IIED	Rural development	Primary environmental care	Communities	National and international NGO's
WBCSD	Business interest	Eco-efficiency	Business and industry	Corporate leadership

The dominant ideological versions of sustainable development include the liberation theology, radical feminism and Marxism (Mebratu, 1998). The major comparison of these different versions is provided in Table 2.2. Finally the economist, ecologist and sociologists reflect the response of the scientific community to the challenge of the environmental crisis of the twentieth century. The differences in the academic version are presented in Table 2.3.

Table 2.2: Comparative analysis of the ideological version of sustainability

Ideology	**Liberation theory**	**Source of environmental crisis**	**Solution epicentre**	**Leadership**
Eco-theology	Liberation theory	Disrespect to divine	Spiritual revival	Churches and congregation
Eco-feminist	Radical feminist	Male-centred (andocentric)	Gynocentric value	Women's movement
Eco-socialism	Marxism	Capitalism	Social egalitarianism	Labour movement

Table 2.3: Comparative analysis of the academic version of sustainability

Academic discipline	**Drivers (epistemological orientation)**	**Source of environmental crisis**	**Solution epicenter**	**Instruments (mechanism of solutions)**
Environmental economics	Economics reductionism	Undervaluing of ecological goods	Internalization of externalities	Market instrument
Deep ecology	Ecological reductionism	Human domination over nature	Reverence and respect for nature	Biocentric egalitarianism
Social ecology	Reductionism-holistic	Domination of people and nature	Co-evolution of nature and humanity	Rethinking of the social hierarchy

Other studies maintain that sustainable development is better defined in the form of normative judgements such as goals and targets coded in formal judgements, treaties, and declarations, not in form of semantic and philosophical clarifications (Parris and Kates, 2003). Despite the debates and argument around the concept of sustainability, the issue itself has prompted policy-makers to formulate new strategies for achieving a balanced economic and technological pathway that would safeguard the environment, not only here and now, but also elsewhere in the future (Nijkamp and Vreeker, 2000). New technologies may affect all the three sustainability dimensions through their influence on environmental, social and economic development. In addition, sustainability is context-specific and may ultimately be determined by the needs and opportunities in a given region as part of a broader spatial system. Therefore, it is indispensible to provide measurements to operationalize the concept of sustainable technology development.

2.3.2 Sustainable development model

The prevailing sustainable development model (Mebratu, 1998) is based on the supposedly separate existence of natural, economic and social system as shown in Figure 2.4. According to Holmberg (1994) this type of model suggests that: (i) the three systems are independent systems and may be treated independently (reductionist); (ii) where the three systems interact is the solution area of integration where sustainability is achieved, whereas outside the interactive area is assumed to be an area of contradiction (bivalent); and (iii) the objective of sustainability requires full integration of the economic, social and environmental systems and can be achieved through the summation of the objectives in the different systems (linear thinking).

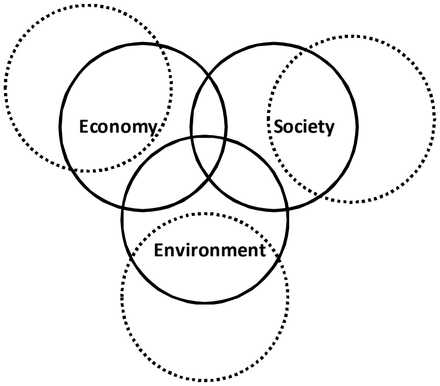

Figure 2.4: The dominant model (adapted from Mebratu, 1998)

On the contrary, Mebratu (1996) draws a number of conclusions on sustainability from the cosmic interdependence model, developed based on the holistic-reductionist-holistic approach (see Figure 2.5(a)). The conclusions of Mebratu (1996) that are relevant to this investigation are:

(i) the social and economic cosmos have never been, and will never be, a separate system independent from the natural system;

(ii) numerous conflict and harmony arise in the intersection area, serving as a seedbed for the process of co-evolution of the natural and human systems;

(iii) the means of interaction within the interaction zone results from numerous systems that cannot be exclusive to one cosmos; and

(iv) the environmental crises result from cumulative effect, or human neglect of one or important systemic parameters resulting in numerous feedback deficient systems.

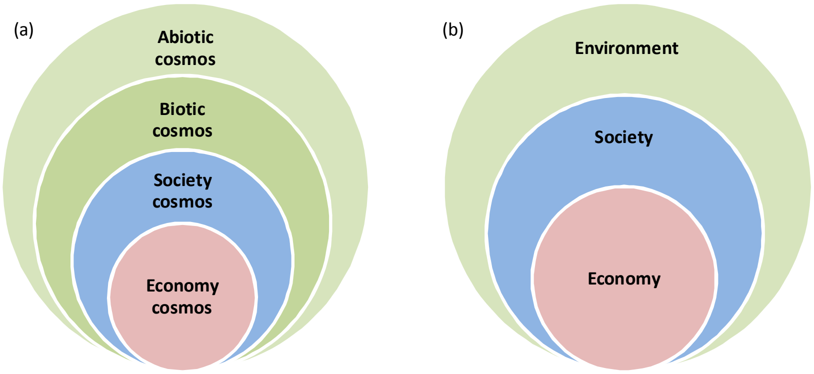

Figure 2.5: Interdependence and prioritization: (a) the cosmic interdependence; (b) operational priority of sustainable development model (adapted from Mebratu, 1998)

Despite this conceptual priority of sustainable development, the irreversible hierarchical interdependencies dictate the environment as the operational priority, as depicted in the cosmic interdependence model of Mebratu (1998). This is because both the society and economy are dependent on the environment as the provider of resources necessary to live and produce. The time frame for use when planning for sustainability is debated in the literature, but the concept intrinsically requires long-term future orientation. According to the operational context, the long-term coverage should change. The operational priority of sustainable development model is presented in Figure 2.5(b), with technology being embedded in the economy sphere (see Figure 1.1). It is then the dynamic interactions of all the spheres that must be understood to ensure the sustainable development of the system as a whole.

2.4 DYNAMIC SYSTEMS APPROACH

2.4.1 The concept of dynamic systems

According to Luenberger (1979) the term *dynamic* refers to a phenomenon that produce patterns that change over time, where, the characteristic of the pattern developed in one time situation is interrelated with those of another time. The term is also thought to be synonymous with *time evolution* (Katok and Hasselblatt, 1995) and *pattern of change*. On the other hand, the origin of the term *systems* was a result of the recognition of the need for accounting the environment surrounding the phenomena under investigation (Luenberger, 1979). The particular phenomena of interest usually represent one component of complexity comprised of several other components. Various definitions of the systems concept are found in the literature (see Van Gigch, 1974; Rosnay, 1979; Dorny, 1993; Flood and Jackson, 1997; O'Connor and McDermott, 1997; and Close et al. 2002). Following Close et al. (2002) a *system* is defined as any collection of interacting elements for which there is a cause-and-effect relationship among the variables. While the definition that Close et al. (2002) provide is a broad one, the most important feature in the definition is the interactions among the variables rather than treating individual variables separately. Other studies in the literature emphasise that these interactions are oriented towards a specific purpose or goal (Dorny, 1993). Similar arguments of the term *system* are found in O'Connor and McDermott (1997) and they summarize the characteristics of a system as follows:

i. interconnecting parts functioning as a whole;
ii. a system is changed if one takes away or adds pieces to it;
iii. the arrangements of the pieces is crucial;
iv. the parts are connected and work together; and
v. systems behaviour depends on the total structure; the behaviour changes once the structure is changed.

According to Flood and Jackson (1997) the general conception of the system consists of boundary, variable/element, relationship, feedback loop, and input and output, as shown in Figure 2.6.

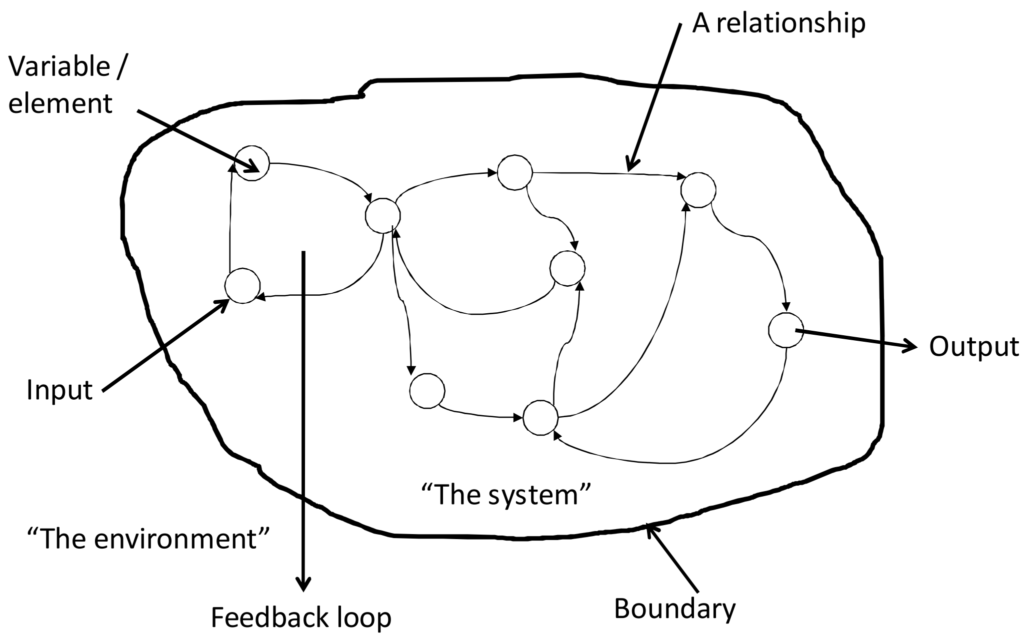

Figure 2.6: General conception of system (adapted from Flood and Jackson, 1991)

Dynamic systems theory thus argues the need for considering the entire system in order to provide a meaningful analysis. Systems, however, are likely to involve large numbers of interrelated variables and the problem under consideration can facilitate in defining the systems boundary. In the process of analysing a problem in a system, two tasks are performed (Close et al., 2002:2): modelling the problem of a system, and solving for the model's response.

Katok and Hasselblatt (1995) point out three key characteristics that define dynamic systems: (i) a 'phase space' of variables representing the possible states of the systems; (ii) time; and (iii) time evolution. Most commonly, dynamic systems are represented mathematically in terms of either differential or difference equations (Luenberger, 1979). It is these equations that provide the structure for representing time linkages among variables. The use of the differential or difference equations depends on whether the dynamic system behaviour is viewed as occurring in continuous or discrete time. Dynamic behaviour viewed in continuous time is usually described in differential equations, which relate to the derivative of a dynamic variable to its current value. Discrete time on the other hand consist of an ordered sequence of points rather than a continuum. Discrete time application is on events and consequences are accounted for only at discrete time periods.

The main structural components of a dynamic system are *levels/stocks* and *rates/flows* (Forrester, 1969; Hanneman, 1988). Levels or stocks can also be thought of as accumulators, in that whatever is contained in the stock is conserved over time. The rates or flows represent the processes by which conserved quantities move from one level to another.

From a dynamical systems perspective, sustainable technology development systems are both dynamic and highly intricate networks of co-dependent sub-systems. In addition, their dynamic behaviour is observed in continuous time. The characteristics of sustainable development and technology development thus enable them to fit well with the concept of dynamic system and hence their assessment requires the application of the dynamic systems approach.

2.4.2 Application of the dynamic systems approach

The dynamic systems approach is a technique for the computational modelling of complex, nonlinear systems. The aim of using the dynamic systems approach is to understand the ways in which the systems function, and the consequences that may follow as a result of the interconnectedness of system states (Auerhahn, 2008). Changes taking place in one part of the system may manifest impacts in others. The dynamic systems approach differs from other applications, due to their ability to model a wide variety of processes and relationships (linear, nonlinear, monotonic or non-monotonic) in a *dynamic* manner (Auerhahn, 2008). The dynamic systems approach also allows the modeller to analyse the feedback processes of the system. In this way, the events and processes occurring at a later point in time can be directly or indirectly influenced by the nature of relationships of the systems at an earlier state of the system.

The dynamic systems approach is often used in multi-domain problems. It has a wide application in control engineering where it originates. Recently, however, it has been widely adopted in other disciplines such as the ecological-economic field where conducting an experiment or a long-term study is not possible. It is also gaining recognition in technology assessment (Wolstenholme, 2003) and sustainability assessment (Singh et al., 2009). This is because with the dynamic systems approach, it is possible to decompose a large complex problem into smaller sub-models, while maintaining the time dependent properties.

2.5 TECHNOLOGY ASSESSMENT

2.5.1 Technology assessment: its evolution and definitions

The evolution of technology assessment (TA) has occurred because of the concept changing its meaning and also due to the struggle towards institutionalizing the concept (Smits and Leyten, 1990). Different authors and authorities have therefore defined TA in a variety of ways. The concept was first developed in the United States in the late 1960's, when the large-scale application of technologies began to (noticeably) affect the citizens (Berloznik and Van Langenhove, 1998; Tran, 2007). The origin of TA was to support the policy needs of the US congress and its goal was to provide an early warning and understanding of what might be the social, economic, political, ethical and other consequences of the introduction of a new technology, or the substantial expansion of an existing technology (Berloznik and Van Langenhove, 1998). TA was hence conceived as a concept to assist in public policy decision-making.

As the concept evolved from its inception, its perspectives and definition has changed as new considerations were taken into account (see Table 2.4) .During the early years, TA was defined as: "the name for a class of policy studies which attempts to look at the widest possible scope of impacts in society of the introduction of a new technology. Its goal was to inform the policy process by putting before the decision-maker, an analysed set of options, alternatives and consequences" (Coates, 1976).

Table 2.4: Technology assessment concept development

Period	USA	Europe	Other countries
1960's	The term 'technology assessment' used for the first time		
1970's	TA becomes synonymous with office of technology assessment (OTA) praxis-classical TA	Technology assessment is started with OTA as the role model	
1980's	The OTA continues to dominate in the field	TA developed as a strategic framework concept and innovative TA (ITA) is first introduced Participatory TA (pTA) emerges in Denmark and constructive TA in Netherlands	
1990's	In 1995, the OTA is closed down	ITA becomes influential. Interactive TA is discussed under various names	Privacy impact assessment becomes common
2000's			Tentative attempts to introduce ethical issues in technology assessment UNEP introduces environmental technology assessment (EnTA)

Source: adapted from Palm and Hansson (2006)

Armstrong and Harman (1980) presented four different definitions that reflect a wide variety of views. They distilled five points that could be identified as underlying features in the different definitions. Three of these features are relevant for the scope of this study:

i. a useful TA should produce a comprehensive, even-handed evaluation and comparison of valid alternative choices;
ii. TA should provide specified stakeholders with comparisons of the broad range of advantages and disadvantages of the alternatives; and
iii. TA as a multidisciplinary effort requires participation of social as well as physical scientists; this study however regards TA as a transdisciplinary effort rather than multidisciplinary.

The United Nations Environmental Program (UNEP) broadly defines TA as a "category of policy studies, intended to provide decision-makers with information about the possible impacts and consequences of a new technology or a significant change in an old technology. It is concerned with both direct and indirect consequences, both benefits and disadvantages and with mapping the uncertainties involved in any government or private use or transfer of a technology. TA provides decision-makers with an ordered set of analyzed policy options, and an understanding of their implications for the economy, the environment and the social, political and legal processes and institutions of society" (CEFIC, 1997). TA is useful when a new technology is introduced or when the existing technology is significantly modified.

According to Durbin and Rapp (1983), TA is not a completely new phenomenon. It was performed implicitly and on an intuitive basis, not explicitly and by means of methodology, even before the establishment of the US Office of Technology Assessment (OTA) in 1972. Coates (2001), however, later redefined the concept as a "policy study designed to better understand the consequences across society of the extension of the existing technology or the introduction of a new technology with the emphasis on the effects that would normally be unplanned and unanticipated".

The term TA is used in a variety of institutions and contexts that differ largely in scope and depth (Assefa and Frostell, 2006). To date, five institutional forms of technology assessment are distinguished. These include academic, industrial, parliamentary, executive power and laboratory (Refer Berloznik and Van Langenhove, 1998). Businesses and their executives have also used the concept, and Tran and Daim (2008) provide a detailed study on how it was adopted and evolved in the commercial sectors.

The problem of dealing with a variety of issues that are many and complex motivated Brooks (1994) to develop TA typologies. He subsequently formulated eight dimensions of TA, namely:

i. the degree of specificity of the object of assessment;
ii. the scope of the system included;
iii. the degree of confinement to hardware and technical characteristics;
iv. the type of impact categories;
v. the geographical and temporal scope of the impacts considered;
vi. the degree to which the likely political and behavioural responses are explicitly considered;
vii. the degree of 'neutrality' aimed at the assessment; and
viii. the stage of development in the 'life cycle' of the technology being assessed.

Recent studies in TA recognize that technology systems are embedded within the broader socio-ecological systems. In this context, TA uses a conceptual framework defined by the three dimensions of sustainability: ecological, economic and social dimensions (Assefa and Frostell, 2006). TA was thus redefined as the evaluation of an object, function, or sequence of functions – created by human society to assist in achieving a goal – with respect to sustainability in comparison of other solutions providing the same function(s) (Eriksson and Frostell, 2001). The technology is assessed from a perspective of a certain defined setting within which it is supposed to operate. TA is thus important in relation to the operational level of sustainability because, in its practical sense, sustainability demands measurement and performance comparisons (Assefa and Frostell, 2006).

2.5.2 Technology assessment approaches, tools and methods

Numerous studies provide extensive literature reviews that attempted to categorize and explain the aims of different types of TA. For instance, Krichmayer et al. (1975) reviewed the fundamental issues in TA such as the TA concept, why it is necessary, its scope, and some examples of TA. Brooks (1994) classified TA into five types, namely: project assessment TA, generic TA, problem assessment TA, policy assessment TA, and global problematique TA. Project assessment TA is concerned with a concrete project while generic TA focuses on a general class of technologies without reference to a particular project, or site, environment or social setting. In the problem assessment TA, the approach is to examine a broad problem area and assess a variety of technologies as well as non-technical measures that might be used to cope with the problem. Policy assessment TA is very similar to problem assessment TA, except that it takes greater account of non-technological alternatives to achieving social goals for whose realization new technology is only one of the many options. Finally, in the global problematique TA, a number of closely interrelated social, political, economic and technical problems that coexist, resulting in a cluster of problems affecting the world as a whole, are considered as a single system. This TA type is different from the rest because no single scientific report, no single decision and no single nation will have the last word.

The Institute for Technology Assessment and Systems Analysis (ITAS) in Germany distinguishes among three types of TA namely: project-induced TA, problem-induced TA and technology-induced TA (Berg, 1994). From the point of view of TA objectives, Van Den Ende et al. (1998) identifies four TA types: awareness, strategic, constructive and backcasting. They further classify these TA types as traditional and modern approaches. The traditional approaches focus on forecasting, impact assessment and policy studies, while the modern approaches, e.g. constructive technology assessment, aim at explicitly influencing the shape of new technologies.

Armstrong and Harman (1980) divided TA into three steps with specific components: technology description and alternative projections, impact assessment, and policy analysis, as depicted in Figure 2.7. The impact assessment step is the central part of the whole process. The more value-laden policy analysis step relates the impact assessment to the concerns of society (Durbin and Rapp, 1983).

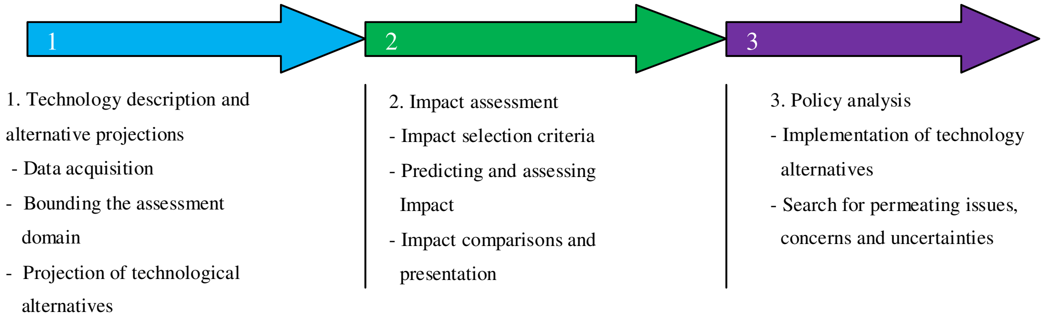

Figure 2.7: The three functional elements of the TA process based on Armstrong and Harman (1980)

Tools and methods enter TA under the latter two steps of impact assessment. Armstrong and Harman (1980) formulated a different grouping of impact assessment techniques as (i) established tools from the scientific disciplines involved in TA; (ii) methods of futurology and systems research; (iii) techniques for social impact; and (iv) tools focussing on organization of the impact assessment process. The tools for impact comparison and presentation of the impacts are categorized as: (i) tools for subjective and objective impacts; (ii) methods for quantifiable and non-quantifiable impacts; (iii) approaches for evaluating and summarizing comparisons; and (iv) ways of organizing the presentation of impacts.

De Piante Henriksen (1997) on the other hand extended the presentation of the toolkit of TA techniques, ranging from economic techniques to impact assessments. Table 2.5 presents the range of these assessment tools for each of the categories and each category is briefly explained as follows.

Table 2.5: Tools and methods for technology assessment

Economic Analysis
- Cost benefit analysis
- Cost effectiveness analysis
- Life cycle cost assessment
- Return on investment
- Net present value
- Internal rate of return
- Breakeven point analysis
- Payback period analysis
- Residue income
- Total savings
- Increasing returns analysis
- Technology value pyramid
- Real options
- Technology balance sheet

Decision analysis
- Multicriteria decision analysis
- Multiattribute utility theory
- Scoring
- Group decision support systems
    - Delphi/group Delphi
    - Analytic hierarchy process
    - Q-sort

Systems engineering / systems analysis
- Technology system studies
- System dynamics
- Simulation modelling and analysis
- Project management techniques
- Systems optimization techniques
    - Linear, integer & non linear Programming

Technology portfolio analysis

Technology forecasting
- S-curve analysis
- Delphi/ analytic hierarchy process/ Q-sort
- R & D researcher hazard rate analysis
- Trend extrapolation
- Correlation and causal methods
- Probabilistic methods
- Monte Carlo simulation
- Roadmapping

Information Monitoring
- Electronic database
- Internet
- Technical / scientific lit reviews
- IP Asset valuation

Technical performance assessment
- Statistical analysis
- Bayesian confidence profile analysis
- Surveys/questionnaire
- Trial use periods
- Beta testing
- Technology decomposition theory
- S-curve analysis
- Human factors analysis
    - Ergonomics studies
    - Ease-of-use studies
- Outcomes research
- Technometrics

Risk assessment
- Simulation modelling and analysis
- Probabilistic risk assessment
- Environ, health and safety studies
- Risk-based decision trees
- Litigation risk assessment

Market analysis
- Fusion method
- Market push/pull analysis
- Surveys/questionnaires
- S-curves analysis
- Scenario analysis
- Multigenerational tech diffusion

Externalities/impact analysis
- Externalities analysis
- Social impact analysis
- Political impact analysis
- Environmental impact analysis
- Cultural impact analysis
- Life cycle analysis

Sources: adapted from De Piante Henriksen (1997) and Tran (2007)

Economic analysis is an important component of a complete TA, as a comprehensive understanding of the relationship of a technological decision to the balance sheet is important to corporate decision-makers. The assumptions made in the economic analysis should be well understood. Although **Decision analysis** does not 'make decisions' it provides information that managers of technology can use to make more informed decisions. Often, the decision analysis process itself can be of more value than the answer it produces, because a decision analysis forces a systematic assessment of alternatives, which otherwise would not occur.

Systems engineering/systems analysis provides a systems view to TA. In this case, it "assesses appropriate technologies within the overall system in which they will function, including environment, interfaces with ancillary equipment, and human factors" (Crepea, 1995). System dynamics is a special application of systems principles with the additional capability to probe dynamic cause-and-effect relationships. **Technological forecasting** examines the dynamics of technological change and attempts to 'predict' future technological direction. It is important to be able to carry out a credible technology forecast.

Information monitoring is a process of gathering, processing and analyzing facts and data of a particular technology, which is critical to technology management. Data must be properly evaluated. **Technology performance assessment** aims at determining how well the technology performs as promised, because if it does not, nothing else really matters. **Risk assessment** in TA is a process of analyzing a technology to determine if it will incur any risks. Technological risk assessment is a vigilance activity designed to keep the firm in business and out of trouble.

Market analysis is a systematic pursuit by technology providers of information regarding the features and characteristic of technology that potential customers desire and the cost-benefit trade-offs that they are willing to make to obtain them. Market analysis should be done prior to, or together with, new technology development. Technology must satisfy the market need with an acceptable level of quality at an acceptable cost.

Finally, **externalities/impact analysis** are incidental effects caused by a technology that impact members of the society or the ecosystem, which may not cost the responsible enterprise directly, but which may reflect upon it as a citizen, community or a nation. The grouping shown in Table 2.5 is not a clear-cut categorization because some tools fit in more than one category.

A recent study by Tran and Daim (2008) also provides a review of the tools applied in TA. Although there is an overlap between the groups of tools they identified with the previous literature, their main contribution lies in their distinction made between methods used in public, business and non-governmental areas. In their conclusion, they further uncovered the need for modification and development of methods that are well suited to a particular TA research, which was not addressed in their study. This study argues the need to make use of system dynamics as the dynamic systems approach within the *SATSA* framework.

2.5.3 System dynamics

System dynamics is among the tools and methods for TA as listed in Table 2.5. It is an interdisciplinary and transdisciplinary approach that is based on the theory of system structures (Sterman, 2000). System dynamics represents complex systems and analyses their dynamic behaviour over time (Forrester, 1961). According to Coyle (1996): "system dynamics deals with the time dependent behaviour of managed systems with the aim of describing the system, and understanding, through qualitative and quantitative models, how information feedback governs its behaviour, and designing robust information feedback structures and control policy through simulation and optimization". Thus, the main objectives of system dynamics approach are: (i) to clarify the endogenous structure of a particular system of interest under study; (ii) to identify the interrelationships of different elements of the system under study; and (iii) to account for different alternatives for simulation and explore the changes in the system under consideration.

System dynamics models (SDMs) therefore are *causal* mathematical models (Barlas, 1996) whose underlying premise are to understand the structure of a system under consideration and gives rise to observable and predictable behaviour (Forrester, 1968; Forrester, 1987). The initial step in system dynamics modelling is to determine the system structure consisting of positive and negative relationships between variables, feedback loops, system archetypes, and delays (Sterman, 2000; Wolstenholme, 2004). This is followed by *ex ante* projection where future system states are replicated from this model. *Ex ante* projection implies that uncertainties with regards to future changes in system structure can be more easily addressed as there is a better understanding of system structure in the first place (Sterman, 1994). This understanding of system structure requires a focus on the system as a whole and it is argued that a holistic system understanding is a necessary condition for effective learning and management of complex systems as well as consensus building. These are important goals in their own right. Additionally, systems modelling and simulation supports policy analysis and evaluation (Morecroft, 1988).

SDMs consist of qualitative/conceptual and quantitative/numerical modelling methods (Dolado, 1992). Qualitative modelling, for example, using causal loop diagrams or hexagons (Hodgson, 1992), improves conceptual system understanding. Quantitative modelling, for example using stock-and-flow models, allows the investigation and visualisation of the effects of different intervention strategies through simulation. Quantitative modelling also requires making explicit statements about assumptions underlying the model, identifying uncertainties with regards to system structure, and identifying gaps in data availability. This promotes model transparency.

Different authors in the literature have organized system dynamic modelling in different arrangements, varying from three to seven different stages, as shown in Table 2.6. At one extreme, Wolstenholme (1990) visualises the process in three stages while on the other extreme Richardson and Pugh (1981) conceptualize the process as consisting seven different steps. Although the ways of groupings vary across the different authors, the activities considered along the different stages remain fairly constant across them. Regardless of the differences in the way of grouping the activities all the authors conceptualize them as an iterative process.

Table 2.6: System dynamics modelling process across the classic literature

Randers (1980)	Richardson and Pugh (1981)	Roberts et al. (1983)	Wolstenholme (1990)	Sterman (2000)
Conceptualization	Problem definition	Problem definition	Diagram construction and analysis	Problem articulation
	System conceptualization	System conceptualization		Dynamic hypothesis
Formulation	Model formulation	Model representation	Simulation phase (stage 1)	Formulation
Testing	Analysis of model behaviour	Model behaviour		Testing
	Model evaluation	Model evaluation		
Implementation	Policy analysis	Policy analysis and model use	Simulation phase (stage 2)	Policy formulation and evaluation
	Model use			

Source: Luna-Reyes and Anderson (2003)

Commonly listed purposes for the development of system dynamics models are improved system understanding, the development of a tool to analyse and evaluate strategies and policies, and the testing of theories (Barlas and Carpenter, 1990; Sterman, 2000). Often, modelling and simulation are aimed at providing valuable insights into the problem structure rather than giving precise answers. They are thus suited to investigate dynamically complex processes that have important short- and long-term effects. Further advantages of system dynamics have been categorised under three broad headings: flexibility, ease of uptake and adaptability, and on-going testing and learning. These are summarised in Table 2.7.

The key factor influencing the acceptance and success of system dynamics models is their practical usefulness. A system dynamics model is useful when it serves the purpose for which it was developed (Coyle, 1996; Sterman, 2000); it addresses the right problem at the right scale and scope, and it represents system response correctly. While the former refers to a model's breadth and depth, the latter addresses model validity (Barlas, 1996). Models are an abstract representation of our limited understanding of reality, and reality in an open system can never be fully defined. Hence, according to Oreskes et al. (1994) and Sterman (2002), the concept of validity is flawed and models are never valid. The challenge becomes to find more appropriate measures of model quality.

Table 2.7: Overview of some strengths of SDM

Category	Explanation
Flexibility – can be used for a wide range of applications and supports working with multiple bottom line dimensions	Multidisciplinary projects: supports use of qualitative and quantitative variables in models; relationship between variables can be defined on an ordinary scale e.g. low, medium, high, as often used in the modelling of social system components Cross-scalar: a nested set of models can be developed to address the problem at different scales Modular objective-oriented models: models often consist of different sub-models (or modules) increasing interchangeability and re-usability Supports a variety of project goals: the focus of any project can be on the model development process itself to support consensus building and team learning, the final model and its use in simulating system behaviour under different scenarios or both
Established methodology, ease of uptake, transparency and adaptability	The dynamic nature of the model allows users to quickly become familiar with modelling and simulation as they are encouraged to alter the model structure, parameters and data on their own, and explore model capabilities and outcomes. Transparency is achieved through interaction –during the model development process as well as the experimentation with the model output. It is crucial factor in client understanding and thus in building of trust, acceptance, and sense of ownership in the model and its results (Meadows and Robinson, 2002; Cockerill et al., 2004) Computer software, e.g. Vensim, Stella, Powersim, Simile, are widely available though not in-expensive and intuitive interfaces significantly reduce the need for programming. Compilation and simulation are fast. There is a wide variety of model outputs including tables, graphs and diagrams, wide range of sensitivity analysis capabilities and in-built error checking capabilities (Eberlein, 1989). Parameters do not necessarily need to be fixed before simulation. They can be either manually or dynamically adjusted.
Foresighting, on-going testing and learning, and stakeholder participation	Simulation allows for the continuous testing of assumptions and sensitivity analysis of parameters, with few restrictions on problem presentation so long as variable can be identified and relationships defined (Morecroft, 1988). Assumptions can be implicit or explicit and are used to make problems mathematically traceable and no objective function needs to be specified. Methods are available to support consensus building and team learning throughout the different stages of the model development process (Vennix, 1996; Meadows and Robinson, 2002)

Source: Winz et al. (2009)

Model usefulness and quality are subjective concepts that do not lend themselves easily to a definition of objective measures. Moreover, the greater the level of uncertainty and complexity of the problem, the more superficial objective comparisons between projected results and observed data become. As a result, model validation becomes a social process where model structure and outcome are negotiated until judged valid and useful by all involved parties (Barlas and Carpenter, 1990). This concept of model usefulness requires transparency of the model development process and the model itself. *Ex post* statistical forecasting models do not provide this level of transparency, but often require expert knowledge in order to understand and use them. Although this may increase confidence in the model in the short term, any dependence on experts will decrease model usefulness either because of the expense and time required or because of the model's lack of adaptability to new parameters, questions, and concerns. In the longer term continuous testing can provide system dynamics model developers and users with better confidence (Barlas, 1989; Barlas, 1996).

Technology assessment practitioners and decision-makers need to be aware of a number of limitations of system dynamics before considering its use. Due to the uncertainties inherent in complex open systems, system dynamics models do not provide exact solutions and answers. It is thus not suited to address well-defined operational problems. Concerns for model depth may be evident, reflecting the level of aggregation. Clearly, in light of existing uncertainty, a detailed system description is pointless. The level of detail should mirror the problem description and be effective in addressing the problem in its entirety while striving to be parsimonious to aid model transparency and ease of understanding (Saeed, 1992). The quantification of qualitative variables may be challenging but qualitative data collection and analysis techniques exist (Luna-Reyes and Anderson, 2003). Furthermore, the definition of the problem boundary, that is, the model breadth, can be problematic (Sterman, 2000). Modellers are advised to be parsimonious and only include variables if they contribute to generating the problem behaviour as experienced in reality (Sterman, 2000). This highlights the fact that system dynamics modelling is more of an art than a science. Indeed, providing rigour in the light of complexity and uncertainty seems to be the main challenge of this approach. The likelihood that two individuals will develop the same system dynamics model given a complex problem statement is small (Ansoff and Slevin, 1968).

It is important to be aware that system dynamics primarily aids analyses of dynamically complex problems (Vennix, 1996), which are interdisciplinary and transdisciplinary with inherent uncertainty. The number of studies that use system dynamics in technology assessment within the framework of sustainable development is limited. Chambers (1991), for example, used system dynamics to investigate the Australian chemicals, fuels, and energy industries. He used Forrester's system dynamics simulation model, coupled with the linear programming routine, for system optimization (Forrester, 1961). In recent years, the literature of technology assessment is recognizing the benefits of using system dynamics. Wolstenholme (2003), for example, describes a holistic and dynamic method based upon system dynamics modelling for the early evaluation of technology at an intermediate and balanced level. The framework of Wolstenholme (2003), however, does not consider the sustainability framework in the technology assessment.

2.5.3.1 System dynamics paradigm

This section provides the basic assumptions of system dynamics and its classifications in a paradigmatic framework that will inform the ontological and epistemological position for this study. The need for a broader and deeper debate about the underlying philosophy of system dynamics was highlighted in the early years of its development (Forrester, 1980). This has resulted in recent debate on understanding whether system dynamics is a paradigm, philosophy, a theory of structure, a methodology, a method, a set of techniques or tools is (Lane, 2001a; Lane, 2001b; Pruyt, 2006). The discussion of this debate is however not the focus of this literature since this is detailed elsewhere (Pruyt, 2006).

Developing the philosophical perspective requires one to make several core assumptions about the nature of science (*philosophy of science*) and the nature of the society (*theory of society*) (Burrell and Morgan, 1979). According to Burrell and Morgan (1979) all the social theories are based upon a particular *philosophy of science* and a *theory of society*. Different paradigms constitute a set of consistent basic assumptions underlying the ontology. The two major philosophical traditions, subjective and objective view, and their respective assumptions are depicted in Table 2.8.

Table 2.8: Subjective versus objective poles on the nature of science

	Subjective	**Objective**
Ontology: what is the nature of phenomena	Nominalist: real world exists as a product of appreciation	Realist: external world exists outside of appreciation
Epistemology: what knowledge can we obtain? And how	Anti-positivist (humanist): knowledge is subjective meaning	Positivist: causal laws deducted by objective observer
Human nature: what is the nature of human actions?	Voluntarist: free will allows human to shape their environment	Determinist: humans react mechanically to their environment
Methodology: how can we obtain knowledge?	Ideographic: access unique individual insights and interpretations	Nomothetic: measurement of general concepts

Source: Burrell and Morgan (1979) and Lane (2001a)

System dynamics is claimed to 'build models of social systems' (Forrester, 1961). The implication is that, it is not an engineered machine or natural system that is modeled. Instead, modeling is aimed toward understanding problems in which, human agents receive information and take decisions in accordance with the policies (Lane, 2001a).

The system dynamics literature had barely articulated its social theory, and recent studies are recognizing this gap and attempting to formulate such theory. This is reflected in Forrester's (1985) who comments that '*the present [system dynamics] paradigm is not sharply defined*" (Lane, 2001a). The initial attempts to place system dynamics within a social theory in order to compare it with other paradigms is found in Lane (2001a), Lane (2001b) and Pruyt (2006). Lane (2001a) and (Lane, 2001b) discuss how the ideas of system dynamics relate to the traditional social theoretic assumptions (Table 2.8). His discussion entails the assumptions of how human beings behave, how societies hold together and how knowledge about such processes can be acquired. Pruyt (2006) on the other hand attempts to extend the frameworks by Tashakkori and Teddlie (1998) and Mertens (2003), in order to account for situations requiring mixing and matching of methods. These three studies (Lane, 2001a, Lane, 2001b, Pruyt, 2006) thus form the basis of the discussion on the ontological and epistemology stance of system dynamics which are relevant for this study.

2.5.3.2 Social theoretic assumptions of system dynamics – Burrell-Morgan framework

In an attempt to relate system dynamics to traditional social theories, Lane (2001a) identifies some of the system dynamics literature that have clearly articulated their social theory. While not much of the literature have done so, Checkland's (1981) soft systems methodology took a subjective stance (Lane, 2001a), utilizing Burrell and Morgan (1979) framework for social theories Similarly, Lane (1994) used the Burrell-Morgan framework, to compare system dynamics with other problem structuring methods, particularly the 'soft' operations research (OR) as observed in Figure 2.8.

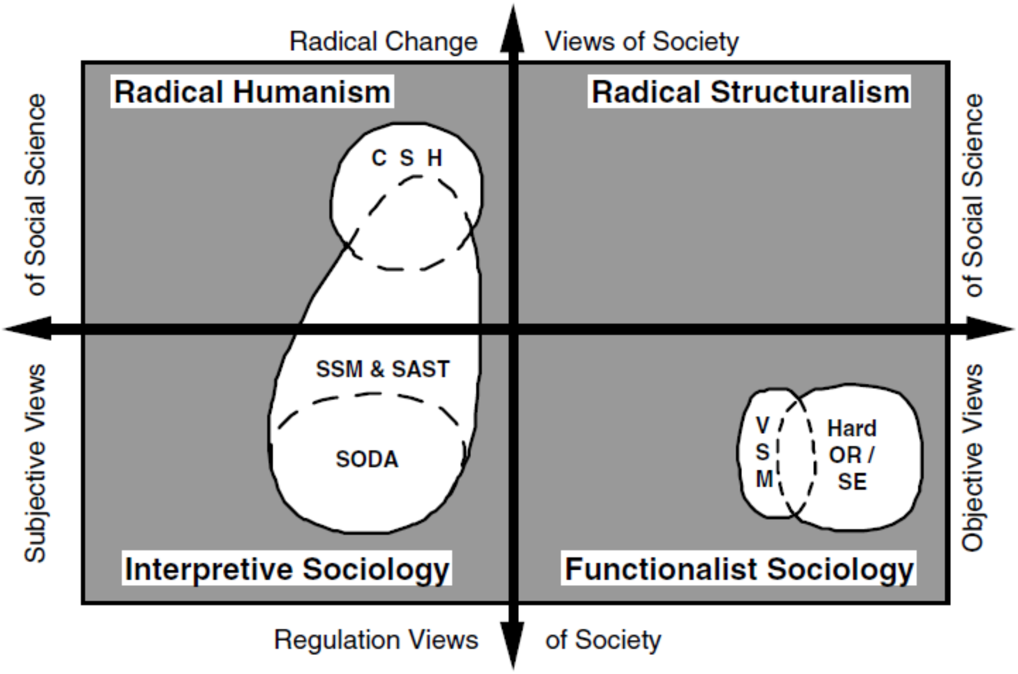

Figure 2.8: Simplified version of the framework for social theories showing placement of various systems and OR modelling approaches; Lane (2001a) as redrawn from Checkland (1981) and Lane (1994)

Notes: VSM = viable systems model; SE = systems engineering; SODA = strategic options development and analysis; SSM = soft systems methodology; SAST = strategic assumptions surfacing and testing; CSH = critical systems heuristics

According to the Burrell and Morgan (1979) framework, wide ranges of social theories are located within two paradigms (Figure 2.9). The assumption concerning the nature of science is represented by the horizontal axis, which can be subjective or objective, and contain four strands of assumptions.

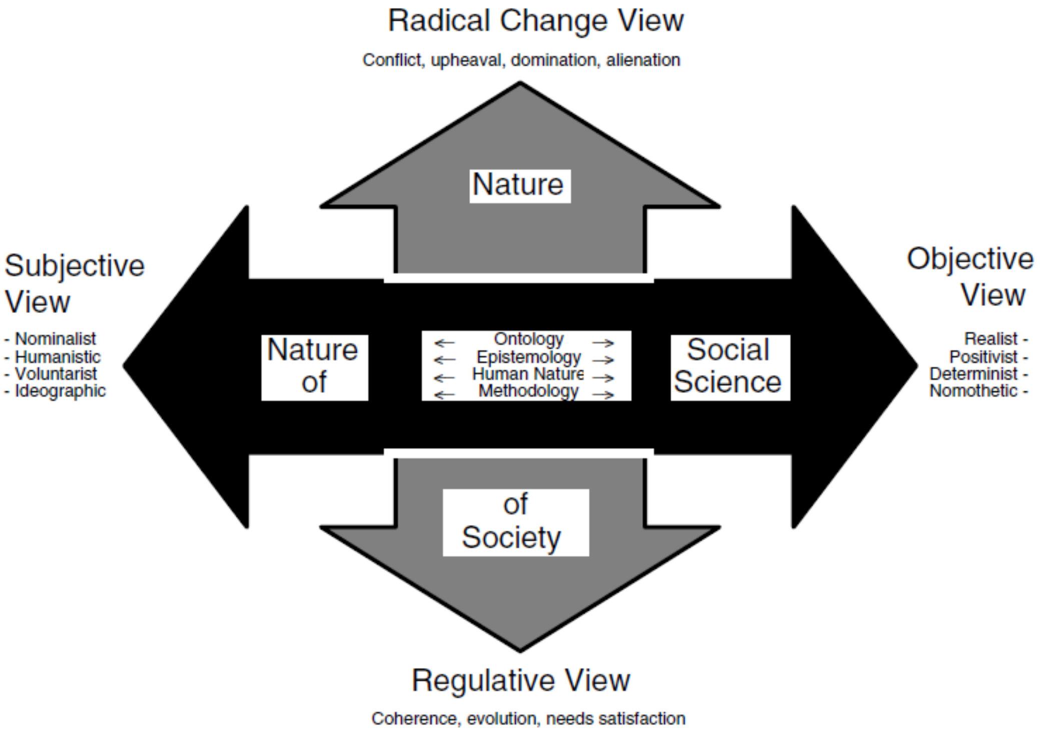

Figure 2.9: Illustration of Burrell-Morgan framework; Burrell and Morgan (1979)

Ontology concern the nature of the phenomena being studied which can be realist or nominalist. Realist view the social world as existing separate from individual human and their appreciation of it, while nominalist view is that the social world is purely a product of human description, consciousness and action. The epistemology concerns the knowledge type that can be viewed. For positivist, causal laws perceivable by an objective observer may be deduced, while for humanistic view that knowledge is concerned with the significance and the meaning that human ascribe to their actions, which are drawn through interpretation. The human nature entails the model of human and their relationship with the environment. The deterministic view has people responding in almost a mechanistic way, functioning as products of an environment that form both the situations they encounter and the conditioning they imbibe while the voluntarist ascribes on a more creative, free-will approach to humans, hence treating them as agents who are able to create an environment by their thoughts and actions. Lastly, a situation may be investigated utilizing two different methodologies – nomotheticism, which promotes measurements of general concepts, and ideographic, which aim at accessing the unique insights and interpretations that individuals have concerning the world.

The nature of society according to Burrell and Morgan (1979) can take regulative or radical view (see Figure 2.9). Regulation ascribes the theories that emphasize the essential cohesiveness of society which seeks to understand the maintenance of the status quo and describes processes of needs satisfaction. On the contrary, radical change concerns theories describing societal conflict, the use of power to dominate and states of alienation.

Burrell and Morgan (1979) concludes that the existing social theories can be seen to exist in one of the four paradigm (Figure 2.10): (i) functionalist sociology – which views the social world exists outside of human and can be observed, and the structural laws that sustain it can be uncovered; (ii) interpretive sociology – which views social world is what agents interpret it to be; (iii) radical structuralism – which views social world as a prison of structural economic forces; and (iv) radical humanism – which views social world as a psychological prison of economic alienation. A number of schools of theories were placed in the Burrell-Morgan framework (Figure 2.10).

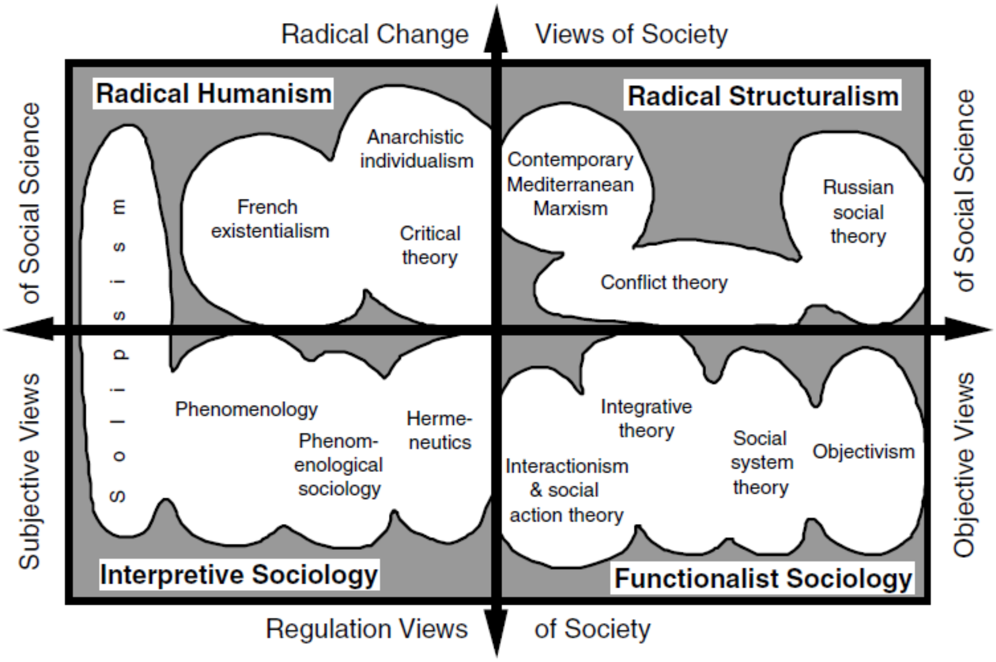

Figure 2.10: Schools of social theories in the Burrell-Morgan framework; Burrell and Morgan (1979); Lane (2001a)

Given that system dynamics has no explicit social theory, Lane (2001a) inferred its social theoretic assumptions from system dynamics literature and its practice. This led to him mapping the system dynamics, within the Burrell-Morgan framework, as observed in Figure 2.11.

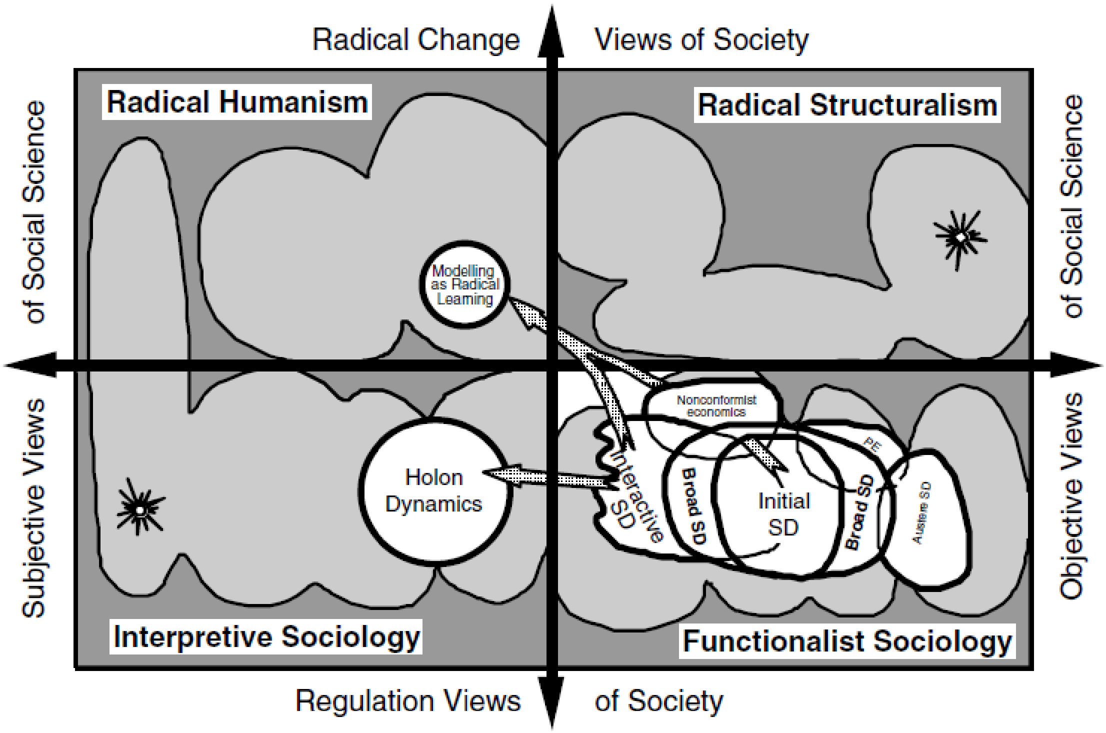

Figure 2.11: Various forms of system dynamics in Burrell-Morgan framework; Lane (2001a)

Notes: PE = Policy Engineering; SD = system dynamics

According to Lane (2001a), the *initial system dynamics* mainly entails Forrester's core ideas (e.g. Forrester, 1961), which is placed away from the objectivist extreme due to the importance of subjective mental models, confidence in the models, and insights gained. Lane (2001a) also groups the *interactive system dynamics* is still characterized by the realist ontology but with stronger anti-positivist epistemology. He also classified many of the system dynamics practices within the functionalist sociology with an exception of *holon dynamics* and *modeling as a radical learning*, which are identified as subjective approaches. Holon dynamics entails modeling as a personal nominalist experience to make sense of the world; while the modeling as radical learning is aimed to further open debate in groups and deal with ideology, power and coercion.

As observed in Figure 2.11, Lane (2001a) finds it difficult to place the domain of system dynamics as a *whole* unequivocally, particularly on the *human nature dimension*; this is because some form of system dynamics seem to be deterministic while others voluntarist. He therefore concludes that system dynamics as a whole cannot fit in the dichotomous framework of Burrell-Morgan. He further provides support this argument by exemplified how it is difficult to classify the mainstream system dynamics by Sterman (2000) into one pole of the ontological, epistemological, methodological and nature of society dimensions. At first sight, the mainstream system dynamics takes a realist ontology and anti-positivist epistemology (systems exists in external reality, but can only be accessed through subjective mental models), although nominalist and positivist aspects are also available. Methodologically, this is ideographic because system dynamics models are made in close cooperation with the stakeholders on specific problems. The nature of society becomes problematic because while it is appropriate to model regulative views of society, it is also appropriate to model the dynamics of radical change views of society.

Lane (2001a) therefore argues that three possible alternative conclusions can be drawn: (i) system dynamics is grounded in functionalist sociology; or (ii) the domain of system dynamics cannot be located in this paradigmatic framework; or (iii) system dynamics does not have an underlying social theory. Pruyt (2006) rejects the last hypothesis by showing that there are aspects that could be said to have its own paradigm or social theory. He actually support the argument that system dynamics does not fit well in the restrictive Burrell-Morgan framework, since it is not possible to claim that system dynamics breaks through the paradigm incommensurability. In addition, Jackson (1990) argues that, no place for structuralist[5] approaches within Burrell-Morgan framework, in which system dynamics is one of these approaches. Pruyt (2006) therefore criticizes Lane (2001a) for even attempting to relate system dynamics within the Burrell-Morgan framework, and to make it worse, not even trying to modernize the framework.

Pruyt (2006) argues that paradigmatic frameworks evolve just like the philosophical and scientific theories and thoughts. They are artifacts of human mind and they influence thinking, and therefore impacting the real world either directly or indirectly, and can be used

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[5] Structuralism […] concerned with the uncovering and understanding the underlying structures of the systems of relationships which generate the surface phenomena perceived in the world.

to elicit the basic assumptions. This is supported by Meadows and Robinson (1985): "*different modeling paradigms cause their practitioners to define different problems, follow different procedures and use different criteria to evaluate results*". Paradigms therefore bias the way modelers view the world, hence influencing the content and shape of the models.

2.5.3.3 Social theoretic assumptions of system dynamics – another paradigmatic framework

Given the underlying limitations of placing system dynamics within Burrell-Morgan framework, Pruyt (2006) developed a framework that could potentially be helpful in positioning system dynamics social theoretic assumptions. His framework is founded, extended and adapted from Tashakkori and Teddlie (1998) and Mertens (2003) frameworks, which are not detailed here since they are not relevant in this study in guiding the positioning of system dynamics in social theoretic paradigm.

Pruyt (2006) classified system dynamics in his extended paradigmatic table which is categorized into six paradigms: positivist, postpositivist, critical pluralism, pragmatism, transformative-emancipatory critical and constructivism (see Table 2.9). These paradigms are further discussed below according to Pruyt (2006) categorization.

(i) Positivist system dynamics

The ontological position for this paradigm is that, the modeled systems correspond to the existing systems in the real world. The epistemological position is that stock and flow diagrams and causal loop diagrams are good objective representation of the external reality and that quantitative system dynamics is the methodological approach to replicate the real world systems. For their axiology, positivists assume that values should and could be avoided as much as possible which is achieved by modeling the physical flows and following the scientific method. The assumed human nature is mostly deterministic and somewhat voluntarist in that, individuals might change their behaviour when insight is gained from the structure-behaviour dynamics. One of the main assumptions in this practice is that real causes, which are temporarily precedent or simultaneous with effects, may be pinned down.

Table 2.9: Extended paradigm table

	Positivist	**Postpositivist**	**Critical pluralism**	**Pragmatism**	**Transformative Emancipatory critical**	**Constructivism**
Ontology	(Naïve) realism	(Transcendental) realism	(Critical) realism	(Pragmatism) realism	Relativism	Relativism
Epistemology	Objective	(Probably) objective	Subjective	Objective and subjective	Subjective (and objective)	Subjective
Axiology	Value-free	Controllable value-ladenness	Concerned by value-ladenness	Unconcerned by value-ladenness	Non-neutral value-ladenness	Value-bound
Method [ologie]s	Purely quantitative	Primarily quantitative	Quantitative and qualitative	Quantitative and qualitative	Qualitative, qualitative, mixed	Qualitative
Causality	Knowable real causes	Reasonably stable causal relationships (not necessarily used)	Causality is key to understanding of real world	Maybe causal relationships but not exactly knowable		Indistinguishable causes and effects
Logic	Deductive	Primarily deductive	Deductive and inductive	Deductive and inductive	Deductive and inductive	Inductive
Appropriateness of model	Refutable but not refuted	Validated models, results closest to the real world	Do models lead to real insight and understanding	Closest to goal or own value system?	Advancing justice, democracy and oppressed?	Confidence in constructed model
Appropriateness of strategies	Optimal strategy	Probably optimal strategy or most appropriate strategy	Potential to structural transformation?	Close to goal or own value system	Advancing justice, democracy and oppressed?	Any strategy (if agreed to)

Source: Pruyt (2006)

The main operations and measurement is quantitative, and the qualitative scales are quantified. The interpretation of the results is positivist, quantified and objective and models are refutable if not corresponding to reality. The implication is that, validation is a scientific process of comparing real world facts with simulation results. The main manifestation of the modeling are forecasting, prediction, neo-classical economics modeling, optimization, and engineering for control of real world system structures. Examples of the positivist system dynamics practice are marginal.

(ii) Postpositivist system dynamics

The ontological position of postpositivist is realist and they are objective in epistemologically, though entail some nominalist / subjective elements to a lesser extent. The method is rigorous scientific modeling, which is assumed that it guides in getting close to the real world. Thus, models are mainly micro-hypothesis that are to be tested, validated or refuted. In their axiology, it is recognized that knowledge is influenced by the theories and values of the researcher, and the modeling and interpretation is value laden. The degree of value-laden may be controlled using scientific methods and skillful modeling. The methodology is mainly quantitative and the qualitative that are used may be quantified. The qualitative causal loop diagrams are mainly used to aid the simulation (quantitative modeling), which is the core of postpositivist. Generalizations may be made in terms of structure but context-free and time generalizations are thought not to be possible. The practice of system dynamics by postpositivist assumes that there are lawful, reasonably stable causal relationships among social phenomena, which may be probabilistically known. The axiology is deductive and the best model is the one that produces the results closest to the real world. Human nature is assumed to be deterministic at the aggregated level. Only a small part of contemporary system dynamics practice is postpositivist.

(iii) Critical pluralist system dynamics

Ontological position is realist in that, external real world exist. However, the epistemological position is subjective in the sense that, the real world can be accessed through subjective mental models. It is therefore assumed that external reality can be known to a certain extent since it is necessarily approached by means of subjective mental models. The axiology is one of the awareness and concern by the value-ladenness of the methodologies and choice of the research, basic assumptions and boundaries among other things. The models are context and time dependent and are developed with close contact with decision-makers, and therefore are ideographic. The methodology is quantitative and qualitative, and the quantitative simulation is interpreted in a qualitative manner. This is because the interest is in increasing the understanding concerning the general dynamics assumed underlying the structures. The critical pluralist tries to discover the underlying structures that generate particular pattern of events (or non-events). Therefore, this allows for exploration and understanding of reality. Modeling here is taken as an iterative process of construction, simulation and interpretation; hence, it is bot inductive and deductive. The models are also appropriate if they are useful in changing mental models and real world structures and generate confidence. The main goal of system dynamics for critical pluralist is to increase understanding of the link between the underlying structures and resulting dynamics. The strategies are appropriate if they seem to have real potential to structurally improve behaviour. The mainstream system dynamics belong to this paradigm.

(iv) Pragmatist system dynamics

The ontological / epistemological position of pragmatism is realist / objective particularly in simulation, and nominalist / subjective in modeling and interpretation phases. The assumption is that reality exists but it is interpreted and partially (re)constructed. Pragmatist assumes that it is not possible to know the model that is close to reality; hence models are chosen that produce desired outcomes, or are closest to personal perceptions of world-views and value systems. It is accepted by pragmatists that the choice of research, theory used, modeling, models and interpretation are value-laden, but they attach different consequences to it. The axiology is inductive and deductive since the model is induced from perceptions and assumptions, and simulation deduces simulation results. Pragmatism philosophy at first sight seems to be incompatible with system dynamics since it questions causality – that is, it assumes that there is no: universal causality; unidirectional and temporal causality, and no single study can be used. At second sight, pragmatism are not concerned about these criticism because (i) system dynamics does not assume universal causality (Lane, 2001a); (ii) system dynamics is based on feedback loops; and (iii) potential criticism of single method use does not hold out as system since it is recognized that system dynamics is only appropriate for very specific issues. Real causality in socio-economic system is thus assumed that it can never be exactly pinned down. Pragmatism is not interested in structural causality to guide in understanding but rather in the use of system dynamics language, techniques, tools, and models to make models that just work or help to reach goal or correspond to values. This is a distinguishing inconsistency feature with the mainstream system dynamics. The operation and measurement values are quantitative and qualitative. However, the interpretation is not constructivist because of the micro-hypothesis is chosen that fits the research question, the desired results and value of the stakeholders and modelers. The pragmatism practice of system dynamics is found in the use of soft variables and reference modes.

(v) Constructivist system dynamics

The ontological position is relativist in that, systems are viewed not to exist in reality, and that only holons of concepts can be ascribed, which are intimately linked to the knower. The epistemological position is thus subjective, that is, models and concepts describe how things are might be, from a particular perspective. The axiology is value bound and human nature is assumed to be voluntarist, the methodology ideographic and mainly qualitative. However, this could be quantitative, whereby, the simulation are used to understanding dynamics views or holon. The constructivist also assumes that real world causality is not distinguishable but subjective interpretation give meaning to the world. The operations and measurements are mainly qualitative, and the quantitative measurements are rendered qualitative through interpretation. The interpretation of the results is qualitative and constructivist. Qualitative and quantitative modeling may help in understanding interpretation. However, a holon of one individual is not better than a holon of another individual. The techniques and tools emphasized in constructivist include subjective articulated mental models of a dynamic systems and subjective causal loop diagrams. The main practice of this paradigm include among others: modeling for learning and modeling for shared interpretation

(vi) Transformative-emancipatory-critical system dynamics

The specific goal of this paradigm is of helping the disadvantaged and oppressed, and to advance democracy and justice using system dynamics tools. The ontological / epistemological position is thus relativist / subjective. This is marginally developed and points out to general weakness of system dynamics, mainly, poor ability to represent interpersonal power and social levels and the disaggregated level.

2.5.3.4 Limitations of system dynamics

System dynamics limitations result from its main application of the approach as a modelling tool, as reflected in the expression that "the assumptions of any model determine its goodness" (Sterman, 1988). A number of limitations of system dynamics have been highlighted in Sterman (1988; 2000) which are as follows:

i. **Description of the decision rules**

System dynamics modelling normally begins with two key processes namely: problem identification (Sterman, 2000) which should be a specific problem oriented; and determination of the dynamic hypothesis (Sterman, 2000) which are the preposition of the dynamic behaviour of the problem being modelled with the system. The main shortcoming lies in the decision rules used in the determination of the dynamic hypothesis which are not obtained directly from data. In addition the model should be capable of responding to the decision rules of the actors in the real situation. The determination of the dynamic hypothesis and the decision rule of the actors are however ascertained from the observations which may be limited by the modeller's perception on the system under study.

ii. **Choice of model boundary**

The validity of any model is affected by the model boundary and hence it is an important factor in system dynamics modelling. It is the model boundary that determines the variables that will be endogenous, exogenous or excluded in the model. Similar to the decision rule, the model boundary is limited to the modeller's perception on the system that is being studied.

iii. **Quantification of soft variables**

There are a number of variables that a fundamental in understanding the complexity of the systems but are immeasurable. These are known as soft variables and in most cases are discarded from the quantitative models. Currently, the best approach is to at least include some reasonable estimates of these variables (Forrester, 1980) if at all it is possible rather than totally ignoring them.

Despite the above limitations, system dynamics is still useful in technology assessment of complex systems. Thus, this study provides a further example of how technology assessment can be incorporated into system dynamics models for an intermediate level assessment accounting for sustainability criteria.

2.6 SUSTAINABILITY ASSESSMENT

The main purpose of sustainability assessment is to provide decision-makers with an evaluation of global to local integrated environment, economy and society systems from both short- and long-term perspectives (Kates et al., 2001). The aim of such an assessment is to provide guidance on policy actions that are intended to achieve sustainable development goals.

Singh et al. (2009) identify two distinct methodologies for sustainability assessment. These are the monetary aggregation, mainly used by the mainstream economists, and physical indicators, which are used by scientist and researchers in other disciplines. Mainstream economists prefer monetary valuation simply because it represents the scarcity value of resources (Singh et al., 2009). Spangenberg (2005) considers this a "restriction of economic thinking" to monetary valuation of functions of different types of capital as "a serious limitation for the analytical capacity of the discipline". Citing criticisms about the assumption of strong sustainability between different types of capital in economic models, Spangenberg (2005) concluded that from a scientific point of view, there cannot be such thing as a comprehensive measure or index of sustainability.

Many approaches for sustainability assessment have led to detailed frameworks from which long lists of indicators have been derived. For instance, the United Nations Department for Policy Coordination and Sustainable Development provides over 130 indicators (UN CSD, 1996a). Such large indicator sets have the advantage of covering most sustainable development issues and providing detailed insights. However, due to the high number of indicators, these sets are complicated, difficult to interpret, and cannot provide a concise general overview of system behaviour. Therefore, they are not useful for decision-making purposes, because without any aggregation, such sets do not provide a measure of progress (Hardi and Barg, 1997). For decision-making purposes, less complex frameworks with small sets of a few lead indicators (flagship indicators) have more promise.

Criteria in developing adequate sustainability indicators were proposed by several authors. According to Hardi and Zdan (1997), the selection of indicators should be based on policy relevance, simplicity, validity, availability of time series data, good quality, affordable data, the ability to aggregate information, sensitivity to small changes and reliability. Another issue in developing indicators is the number of indicators, typically exemplified in the so called information pyramid. While these considerations should be taken into account, some authors warn of the difficulty in finding indicators that comply with a subgroup of the criteria (Levett, 1998).

Despite these limitations of sustainability indicators, individuals, organizations and societies still widely recognise the need to find models, metrics and tools for articulating the extent to which, and the ways in which, current activities are unsustainable. In an effort to define and introduce sustainability science, Kates et al. (2001) provide seven core questions of research which are presented in Table 2.10. These questions are aimed to assist in determining which actions should be taken in an attempt to make society sustainable.

Table 2.10: Core questions of sustainability science

i. How can the dynamic interactions between nature and society – including lags and inertia be better incorporated into emerging models and conceptualization that integrate the earth system, human development and sustainability?
ii. How are long-term trends in the environment and development, including consumption and population, reshaping nature – society interactions in ways relevant to sustainability?
iii. What determines the vulnerability or resilience of the nature-society system in particular kinds of places and for particular types of ecosystems and human livelihoods?
iv. Can scientifically meaningful ‘limits’ or ‘boundaries’ be defined that would provide effective warning of conditions beyond which the nature-society systems incur a significantly increased risk of serious degradation?
v. What systems of incentive structures—including markets, rules, norms, and scientific information can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?
vi. How can today’s operational systems for monitoring and reporting on environment and social conditions be integrated or extended to provide more useful guidance for efforts to navigate a transition toward sustainability?
vii. How can today’s relatively independent activities of research planning, monitoring, assessment and decision support be better integrated into systems for adaptive management and societal learning?

Source: Kates et al. (2001)

Bossel (1999) also recognizes the need for an integral systematic approach to indicators definition and measurement in order to provide well-structured methodologies that are easy to reproduce, and to assure that all important aspects are included in the measurement. However, before developing the methodology, what is needed is a clear definition of the policy goals towards sustainability. In any case, an indicator should refer to specific targets that are chosen, be able to indicate the success or lack of it in approaching them, and be sensitive and robust in their construction (UN CSD, 1996b).

From a TA perspective, quantitative assessment of technological systems during research and development, planning and structuring, and implementation and management phases of technological development is important for identifying and prioritising overall contributions to sustainability. According to Levett (1998), one should take a modest ‘fitness-for-purpose’ approach in developing indicators; that is, using different indicator sets for different purposes, rather than straining to produce a single definitive set of sustainable development indicators. In this sense, the development of technology can take advantage of a set of environmental, social, economic (and other) sustainability indicators.

2.7 SUSTAINABLE TECHNOLOGY DEVELOPMENT

Technology is of major importance for the sustainability of mankind’s development (Huber, 2004). The ambivalence of technology with regard to the concept of sustainable development is highlighted in the literature (Fleischer and Grunwald, 2008). As an illustration, technology is one of the sources and origins of sustainability deficits, as can easily be seen in the fields of environmental pollution. On the other hand, technology has enabled many positive sustainability developments. Many innovative technologies are regarded as highly promising in terms of sustainability. In particular, those that permits much higher resource productivity, lower emissions and de- or immaterialisation of economic processes (Weaver et al., 2000).

Fleischer and Grunwald (2008) argue that the diagnosis of a general ambivalence of technology concerning sustainable development can be transformed into a request for adequate shaping of technology: “technology and its societal environment should be developed further and formed in a way that positive consequences for sustainable development can be realised and negative ones be prevented or minimised”. They claim this is a reformulation of the initial motivation of technology assessment: “to enable society to harvest the benefits of a specific technology without running into situations of severe risks". Thus, the importance of a reliable approach of assessment of technology stems from the need to find an economically and environmentally viable and socially acceptable path towards sustainable society.

2.8 ASSESSING SUSTAINABLE ENERGY TECHNOLOGY DEVELOPMENT

2.8.1 General tools and approaches for energy technology assessment

The technology assessment tools and methods provided by De Piante Henriksen (1997) and Tran and Daim (2008) (refer to Table 2.5) can also be used for energy technology assessment. In addition, computer models have been developed and become standard tools for energy planning and for the optimization of energy system. Table 2.11 provides a summary of the common energy planning models.

These models (Table 2.11) were developed for different purposes, namely cost minimization, increasing the use of renewable energies, and reduction in greenhouse gas (GHG) emissions, amongst others. The models incorporate different technologies and focus on different sizes of energy systems (Segurado et al., 2009). For instance, HOMER (National Renewable Energy Laboratory, 2009) was particularly developed for small isolated powers stations, although it allows for grid connection. The model includes most of the relevant technologies, but not all of them. HYDROGEMS (Institute of Energy Technology, 2009) on the other hand includes precise physical details of specific energy technologies. Such models are too detailed for energy planning purposes and lack some relevant energy technologies. The RETScreen Clean Energy Project Analysis Software (Natural Resources Canada, 2009) can be used to evaluate the energy production, life-cycle cost and GHG emission reductions for various types of proposed energy efficient and renewable energy technologies, but it does not provide tools for joint energy balancing with different renewable energy sources. The model EnergyPLAN (Lund et al., 2007) was developed for national and regional analyses. It is a deterministic input-output simulation model. The H_2RES model (Lund et al., 2007) simulates the integration of renewable sources and hydrogen in the energy systems of islands or other isolated locations.

Table 2.11: Summary of selected energy planning models

AEOLIUS: power-plant dispatch simulation tool	BALMOREL: open source electricity and district heating tool
BCHP Screening Tool: assesses CHP in buildings	COMPOSE: techno-economic single-project assessments
E4cast: tool for energy projection, production, and trade	EMCAS: creates techno-economic models of the electricity sector
EMINENT: early stage technologies assessment	EMPS: electricity systems with thermal/hydro generators
EnergyPLAN: user friendly analysis of national energy-systems	energyPRO: techno-economic single-project assessments
ENPEP-BALANCE: market-based energy-system tool	GTMax: simulates electricity generation and flows
H2RES: energy balancing models for Island energy-systems	HOMER: techno-economic optimisation for stand-alone systems
HYDROGEMS: renewable and H2 stand-alone systems	IKARUS: bottom-up cost-optimisation tool for national systems
INFORSE]: energy balancing models for national energy-systems	Invert: simulates promotion schemes for renewable energy
LEAP: user friendly analysis for national energy-systems	MARKAL/TIMES: energy-economic tools for national energy-systems
MESAP PlaNet: linear network models of national energy-systems	MESSAGE: national or global energy-systems in medium/long-term
MiniCAM: simulates long-term, large-scale global changes	NEMS: simulates the US energy market
ORCED: simulates regional electricity-dispatch	PERSEUS: family of energy and material flow tools
PRIMES: a market equilibrium tool for energy supply and demand	ProdRisk: optimises operation of hydro power
RAMSES: simulates the electricity and district heating sector	RETScreen: renewable analysis for electricity/heat in any size system
SimREN: bottom-up supply and demand for national energy	SIVAEL: electricity and district heating sector tool UREM
STREAM: overview of national energy-systems to create scenarios	TRNSYS16: modular structured models for community energy-systems
UniSyD3.0: national energy-systems scenario tool	WASP: identifies the least-cost expansion of power-plants
WILMAR Planning Tool: increasing wind in national energy-systems	

Source: Connolly et al. (2010)

Early forms of energy models such as those provided in Table 2.11 were mainly linear programming applications in which the assessment focussed on the optimization of energy systems. In addition, feedbacks across the economy, society and environment using the conventional energy planning computer models is difficult to identify, manage and quantify. Thus, the main objective of many of the models listed in Table 2.11 is to provide guidance in energy planning. They are therefore not used to assess energy technologies, but incorporate the technologies used by the user in order to complete the energy chain (Segurado et al., 2009). Despite their limited scope, some of these models are still in use (Martinsen et al., 2006).

In the recent past, due to the need to investigate, among other things, technology development, some of the linear programming models have further been developed to include non-linear programming components in order to allow for the interaction of ’bottom-up’ technology modules with ‘top-down’ simplified macro-economic modules (Messner and Schrattenholzer, 2000; Loulou et al., 2004). Examples of such models include: MARKAL (Loulou et al., 2004); MESSAGE (Messner and Strubegger, 1995); and NEMS (International Energy Agency, 2003). These models have evolved and currently they include econometric components of Computable General Equilibrium models to account for the macro-economic conditions in an optimization structure representing energy system. Apart from providing projections on energy prices, demand and supply, the use of medium to longer term energy planning models such as MARKAL (Seebregts et al., 2008), IKARUS (Martinsen et al., 2006), E3database (Agator, 2003) and EMINENT (Segurado et al., 2009) have the capacity to assess and compare technologies.

A more comprehensive model that integrates a larger number of economic components with respect to MARKAL is the General Equilibrium Model for Energy-Economy-Environment interactions (GEM-E3). The GEM-E3 model includes the economic frameworks used by the World Bank (national accounts and social accounting matrix) as well as projections of full input-output tables by country/region, employment, balance of payments, public finance and revenues, household consumption, energy use and supply, and atmospheric emissions (Capros et al., 1997). Being a full CGE model, there is no objective function in GEM-E3, and the equations underlying the structure of the model define the actors’ behaviour identified with the social accounting matrix (SAM) (Drud et al., 1986). The production function of the model uses capital, labour, energy and materials, and properties of the system such as stock and flow relationships, capital accumulation delays and agents' expectations are considered (Capros et al., 1997). The main exogenous inputs to the model are population, GNP and energy intensity. The GEM-E3 model resembles the structure of Threshold-21 (Bassi, 2009), a causal-descriptive model, where system dynamics (SD) is employed and where society, economy and environment are represented.

Threshold-21 (T21) and other system dynamics models are able to combine optimization and market behaviour frameworks, and the investigation of technology development into one holistic framework that represents the causal structure of the system (Bassi, 2009). SD models offer a complementary approach that allows the assessment of energy technologies while concurrently simulating the interaction of a large number of feedback loops with the major factors in the economy, society and the environment. This provides useful insights for policy formulation and sustainable energy technology development analysis. Examples of SD models applied to energy issues include the IDEAS model (AES Corporation., 1993), an improved version of FOSSIL models originally built by Roger Nail (Backus et al., 1979), the energy transition model (Sterman, 1981), the petroleum life cycle model (Sterman et al., 1988; Davidsen et al., 1990), and the Feedback-Rich Energy Economy model (Fiddaman, 1997). However, according to Bassi and Baer (2009), these models do not encompass the interactions between energy, economy, society and environment. The T21 model was therefore developed by the Millennium Institute to fill this gap. Nevertheless, both FOSSIL and IDEAS models made important contributions, such as their use by the US Department of Energy for policy planning in the eighties.

Recently, several studies have used system dynamics to analyse renewable energy related issues. Flynn and Ford (2005) modelled and simulated carbon cycling and electricity generation from energy crops. Tesch et al. (2003) developed a system dynamics model of global agricultural and biomass development. Bantz and Deaton (2006) used system dynamics to envision possible growth scenarios for the US biodiesel industry over a course of a decade. Scheffran et al. (2007) developed a spatial-dynamics model of energy crop introduction in Illinois. Although bioenergy system dynamics models have already been developed for several regions and for bioenergy related aspects, this does not seem to be the case for all regions and all aspects (Pruyt and De Sitter, 2008). The use of system dynamics in studies related to renewable energy technology policies at local, national and regional levels (seemingly) becomes indispensable.

2.8.2 TA for sustainable energy development

Sustainable energy technology systems are progressively becoming an important issue for policy- and decision-makers (Streimikiene, 2010). New energy technology development, particularly renewable technologies, is seen as key to achieving sustainable energy systems. There are, however, a number of renewable energy technologies that decision-makers have to choose from an increasingly diverse mix of new energy technologies. Identification of these technologies that can comply with the emerging needs and opportunities in the three sustainable development dimensions, namely, economic, environmental and social, is a complex problem.

There is no unique or generally accepted criteria and indicator set for measuring the sustainability of energy technologies. The issue at hand is the key determinant of the selection of the criteria or indicators. While international institutions have proposed or applied sustainable development indicators in the past, Voß et al. (2005) provides three categories which are relevant for the selection process:

(i) indicators for the assessment of sustainable development in general;
(ii) indicators for the assessment of sustainable development of the energy sector; and
(iii) indicators for the assessment of energy technologies.

According to Assefa and Frostell (2006), a TA with an established framework is paramount for assessing the sustainability of technologies. The three dimensions of sustainability can be addressed with the aid of the TA tools. They further argue that, one possible cost effective way of reinforcing conventional TA from sustainable point of view is to use the well established tools, methods and concepts of systems analysis in an integrated manner. They regard such a systematic combination of different tools of systems analysis and other relevant tools as a *technology sustainability assessment* (TSA) framework, as illustrated in Figure 2.12.

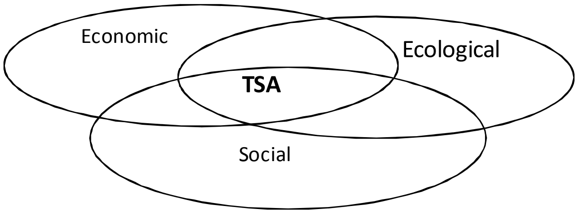

Figure 2.12: A technology sustainability assessment (TSA) tool that can address ecological, economic and social impacts of technology in an integrated manner (Assefa and Frostell, 2006)

A number of studies in the literature account for only a single sustainability dimension, namely the economic, social or environmental dimension. Historically, the primary focus was on the ecological dimension and the economic and social dimension were dealt with as secondary. While the economic and ecological sustainability of energy systems are a common place, modest literature that considers social sustainability is available.

Dewulf and Van Langenhove (2005) focuses on the environmental component of the sustainability of technology, taking into account the role of industrial ecology. They argue that the traditional assessment of environmental sustainability of technology only focuses on the immediate impact of technology on the environment by quantifying resource extraction and generated emissions. However, the technology does not only exchange materials with the environment, but also with the industrial society as a whole. They argue that, a high compatibility of a specific technology with the industrial system, as studied in industrial ecology, can result in lower resource extraction and reduced waste emission, indirectly contributing to a better environmental sustainability. Their study presents a set of five environmental sustainability indicators for the assessment of products and production pathways integrating industrial ecology principles; these indicators were scaled between 0 and 1, taking into account of: (i) renewability of resources; (ii) toxicity of emissions (iii) input of used materials; (iv) recoverability of products at the end of their use; and (v) process efficiency.

Raven et al. (2009) consider social assessment by investigating the social acceptance of a technology in energy projects. They developed a framework, termed ESTEEM, to facilitate a participatory technology assessment. In a similar manner, Carrera and Mack (2010) only focus on the social indicators for sustainability assessment of energy technologies in order to provide input for future energy strategies.

Palm and Hansson (2006), on the other hand, propose a new form of technology assessment that focuses on the ethical implications of new technologies at an early stage. Nine checklists were identified as crucial ethical aspects of technology: (i) dissemination and user information; (ii) control, influence and power; (iii) impact on social contact patterns; (iv) privacy; (v) sustainability; (vi) human reproduction; (vii) gender, minorities and justice; (viii) international relations; and (ix) impact on human values.

The use of a single dimension for sustainability assessment is however criticized in the literature. Begic and Afgan (2007) argue that the evaluation of a complex system based on a single criterion analysis in decision-making is unacceptable. All the sustainability dimensions need to be considered in decision-making (Voß et al., 2005).

According to Maldonado and Márquez (1996) renewable energy options for sustainable development entail the following:

(i) Reliable, timely and cost-effective supply. Failure to meet these requirements would adversely affect the economic growth, competitiveness, quality of life and equity.

(ii) Reducing system vulnerability. Within the context of sustainable development deficiency in energy resources is normally related to greater vulnerability. However, lack of energy independence needs to be interpreted as reduction in the ability to design and implement an energy policy that can aid in answering questions such as: what is the desirable energy profile? Which conditions are possible to achieve those options and what economic and environmental price are people willing to pay?

(iii) Minimum environmental impacts. Energy production and use cause important environmental impacts. The severity of the impact will depend on the technology employed, the fuel quality and the maintenance of the equipment.

(iv) Equity-oriented energy supply. Insufficient energy supply adversely affects the quality of life both domestically and at community level. This reduces the ability of certain essential services.

Dincer (2007) examines hydrogen and fuel cell technologies with regards to sustainability. The study defines the concept of energy as "the confluence of energy, environment and sustainable development". Dincer (2007) emphasises the necessity of renewable energy technologies in maintaining global power supply in the long-run. According to his conception, the availability of affordable and reliable energy supply is a necessary precondition for societal development. Thus, he adheres to a model of four pillars of sustainability, including a dimension of energy resource and resource sustainability. However, his empirical model fails to incorporate any social indicators.

Rösch et al. (2009) investigate the applicability, economic efficiency and sustainability of different techniques for energy production from grasslands as well as grasslands converted into maize fields or short-term rotation poplars under German conditions. According to Ludwig (1997), TA needs to fully examine the unintentional impacts and interactions of the primary energy carriers in order to ensure a sustainable supply in the energy systems. He therefore present a fuzzy logic based assessment method, which he claims can be used as a decision tool.

Afgan and Carvalho (2000) developed the concept of a multi-criteria sustainability assessment of energy systems. This approach focuses mainly on the technical aspects of the energy systems, but also accounts for social indicators. While this approach provides some theoretical groundwork, it is somewhat sparse. However, numerous studies have applied the framework. For instance, Begic and Afgan (2007) assess energy power system of Bosnia and Herzegovina in order to determine options for the selection of new capacity building. Their sustainability indicators were divided into four namely: resource indicator, environmental indicator, economic indicator, and social indicator (see Table 2.12).

Table 2.12: Sustainability indicators

Name of indicator	Type of indicator	Units
Resource indicator	Fuel indicator	Kg/kWh
	Carbon steel indicator	Kg/kWh
	Stainless steel indicator	Kg/kWh
	Copper indicator	Kg/kWh
	Aluminium indicator	Kg/kWh
	Insulation indicator	Kg/kWh
Environment indicator	CO_2 indicator	Kg/kWh
	SO_2 indicator	Kg/kWh
	NO_x indicator	Kg/kWh
Economic indicator	Energy costs indicator	Eur/kWh
	Investment indicator	Eur/kWh
	Efficiency indicator	1/kWh
Social indicator	Job indicator	h/kWh
	Diversity indicator	-

Source: Begic and Afgan (2007)

Elghali et al. (2007) developed a sustainability framework for assessment of bioenergy systems life cycles. They apply multi-criteria decision analysis (MCDA) and decision conferencing to explore how such a process is able to integrate and reconcile the interests and concerns of diverse stakeholder groups. They argue that, sustainable energy technologies should meet the three well known pillars of sustainability: economic viability, ecological performance, and social acceptance. The latter is sought to be achieved through the involvement of stakeholders in assessing different criteria so as to fully assess the social, economic and ecological impacts. A similar argument is made by Assefa and Frostell (2007) who attempt to analyse the sustainability of energy technologies with the Swedish technology assessment tool called ORWARE. They characterize a sustainable technical system by assessing its overall system health as a sustainably functioning system. They portrayed this in a form of a 'social being' where: the *processing* feature of technical systems sustainability represent its abdomen; and the function and *balance* features of ecological sustainability represent its head; and the *relevance* and *context* features of social sustainability and the drivers of economic sustainability are the two legs as shown in Figure 2.13.

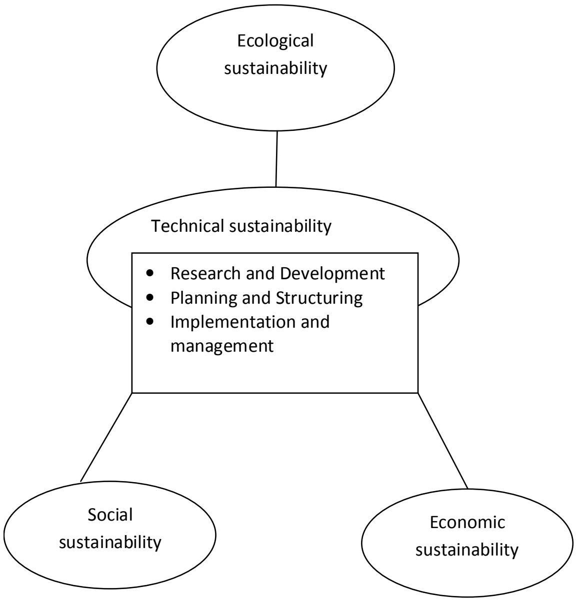

Figure 2.13: The systems health of a sustainable, functioning technical system (Assefa and Frostell, 2007)

Assefa and Frostell (2007) approached the social sustainability from one of its ingredients 'social acceptance'. The study further discusses the importance of assessing social indicators by engaging members of the society and the need for presenting the results together with the ecological and economic indicators is outlined, in order to avoid sub-optimization.

Evans et al. (2009) and Evans et al. (2010) assess the non-combustion based renewable electricity generation technologies against a range of sustainability indicators. The indicators they used for each of the technology include: the price of generated electricity, greenhouse gas emission during life cycle of the technology, availability of the renewable resources, efficiency of energy conversion, land requirements, water consumption, and social impacts. Their justification for use of each of the indicators was:

i. price of electricity generation unit must be considered since unfavourable economics are not sustainable;
ii. greenhouse gas emission are increasingly becoming one of the key parameters that define sustainability of energy generation;
iii. availability and limitations of each technology must be considered since some technologies or fuels may be heavily resource constrained;

iv. efficiency of energy transformation must be known for meaningful comparison. Efficient processes will typically have lower process requirements, capital, and operating costs. Less efficient processes may have more significant room for technological advancement and innovation;

v. land use requirements are important as renewable energy technologies are often claimed to compete with agriculturally arable land or to change biodiversity;

vi. water consumption is particularly important in arid climates and water scarce countries. It is not sustainable to have high water consumption and evaporation rates to support the energy generation process when already water shortages are problematic; and

vii. social impacts are important to correctly identify and quantify the human risks and consequences. This would allow better acceptance and understanding of some technologies that are often subject to public objection.

They ranked the renewable energy technologies against each indicator with the assumption that each indicator has equal importance for sustainable development. Varun et al. (2009) also assess the performance of renewable energy technologies using the cost of electricity generation, greenhouse gas emissions and energy pay-back time as the sustainability indicators.

In a similar manner, Silva Laro et al. (2011) highlight the following key issues to consider in assessing the sustainability of biofuels:

i. productivity: which depends on the type of biomass crop related with the efficiency of the soil utilization and the specific productivity (kg/ha);

ii. greenhouse gas emission (GHG): this is because GHG emissions is one of the justification for biofuel development;

iii. land use: this is due to the increasing concerns of land use changes resulting from the growing demand for biofuels (Bringezu et al. 2009a). There are other human activities particularly food production requiring land use besides energy crops. Thus, land availability is critical issue in many countries (Fargione et al. 2008; Bringezu et al. 2009a);

iv. costs: this is important in order to identify the balance between the biofuel production costs and market price (Hill et al., 2006);

v. impacts of water resources / water depletion: this is due to the considerable water requirements during biofuel feedstock production and industrial processing (Eisentraut, 2010);
vi. co-product and residue utilization: as animal feed, energy, fertilizer, production of chemicals;
vii. impact on the biodiversity: which is associated with the loss of habitats due to land use changes and deforestation (Bringezu et al., 2009a; Bringezu et al. 2009b); and
viii. social impacts: including among others impact on the communities, employment, rural development and food prices (Gacez and Vianna, 2009).

Although Evans et al. (2009), Varun et al. (2009) and Silva Laro et al. (2011) provide useful indicators for renewable energy sustainability indicators, they do not provide cross sector impacts of the various indicators. Other studies have combined a number of methodologies in assessing sustainable energy technologies. Kowalski et al. (2009) combine scenarios and participatory multi-criteria analysis. They appraised five renewable energy scenarios for Austria for 2020 against seventeen sustainability criteria. All these assessment are, however, static snapshots of assessing the sustainability of energy technologies.

2.8.3 Systems dynamics as an energy technology sustainability assessment tool

The static snapshots of technology sustainability assessment have a powerful capacity of providing a system account of the impact of a technology development, but it is not designed to make projections of sustainability consequences. Therefore, this fails to elicit policy implications from a temporary explicit perspective. As a complimentary tool, the forward-dynamic models are useful to explore possible sustainability prospects and facilitate the understanding of the impact of the anticipated energy technology development. Some studies in the literature that account for system dynamics in energy modelling were observed.

For instance, Tan et al. (2010) proposed to adapt the real options methodology to value the potential return from developing alternative energy technologies using stochastic system dynamics models representing the uncertainty in both the learning curve and the fossil fuel price cycles. This approach was further developed to more accurately reflect the value of alternative energy projects (Tan et al., 2009). In this case, they used binomial decision trees and real options theory to evaluate system dynamics models of risky projects, using the wind power industry as a case study. Similar to Wolstenholme (2003), Tan et al. (2010) and Tan et al. (2009) also do not consider the sustainability framework in the technology assessment.

Chan et al. (2004) examine the role of the systems modelling for sustainable policy analysis in Canada using bioethanol as a case study. Their model boundary is, however, on the supply and demand dynamics of the liquid fuel in the transport sector as shown in Figure 2.14. In addition, the study has a limited consideration of sustainability indicators and is biased towards an environmental indicator of greenhouse gas emission. In most cases, governments in developing countries are faced with conflicting goals of economic and social development, as well as environmental protection. Hence, there is need to account for the economic and social goals in the technology assessment.

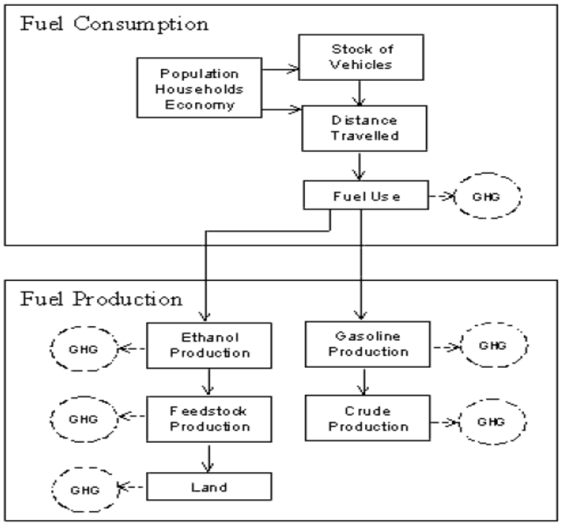

Figure 2.14: Bio-ethanol model boundary (Chan et al., 2004)

2.9 CONCLUSION

The findings on the intrinsic properties of technology development, sustainable development and dynamic systems approach provided a platform in which a new systems approach to technology sustainability assessment (*SATSA*) framework was established. The review of the current energy technology assessment tools and methods are also summarised. The knowledge gained from the critical literature review provides an insight into the application of the developed framework in assessing renewable energy technology development for sustainability.

2.9.1 Systems approach to technology sustainability assessment *(SATSA)*

The theory of technology development and sustainable development indicates that these concepts are dynamic and highly intricate network of co-dependent sub-systems. The characteristics of sustainable development and technology development enable them to fit well with the concept of dynamic systems and hence their assessment requires the application of the dynamic systems approach. While the dynamic systems approach is gaining recognition in the field of technology assessment, there is however no framework for guiding technology assessment for sustainability; hence the introduction of the *SATSA* framework in Chapter 1.

Technology development and sustainable development present a dynamic behaviour that can be viewed in continuous time. The dynamic behaviour viewed in continuous time is usually described in differential equations as found in system dynamics.

Model usefulness and quality are subjective concepts that do not lend themselves easily to a definition of objective measures. The literature also indicates that the key factor influencing the acceptance and success of system dynamics models is their practical usefulness. Thus, in order to build confidence and determine the usefulness of developed model, the process of verification and validation is essential.

2.9.2 Energy technology sustainability assessment

The literature highlights that classical technology assessment studies view technology assessment as a multidisciplinary effort. However, technology assessment for sustainability requires an inter- or transdisciplinary design. This is because of the different actors that are involved in technology development and also because technology assessment is problem orientated.

The review also shows the extensive methods, tools and models that exist in energy technology assessment. Most of these models are developed for specific purposes such as the reduction of greenhouse gas or cost minimization, amongst other things. From the literature, while the current technology assessment approaches and models for renewable energy development do provide guidance in energy planning, they are however constrained with regards to renewable energy technology assessment for sustainability. Thus, to achieve sustainable renewable technology development, there is a need to develop approaches or methods that account for the characteristics of the technology development and sustainable development sub-systems. It is argued that system dynamics is the proposed dynamic systems approach that can guide in energy technology assessment for sustainability.

Indicators are important for measuring the sustainability of energy technologies. However, there is no unique or generally accepted criteria and indicator set. While large indicator sets covering most sustainable development issues provide detailed insights, they are however complicated, difficult to interpret, and cannot provide a concise general overview of system behaviour. For decision-making purposes, less complicated frameworks with small sets of a few lead indicators have more promise.

2.9.3 Conclusive remark

The findings of the literature review have provided the pertinent characteristics of the systems approach to technology sustainability assessment *(SATSA)* elements. In this light, the methodological framework in the context of energy technology sustainability assessment was designed, which needs to be scrutinised in terms of energy technology assessment practices in South Africa.

CHAPTER 3: ASSESSING THE SUSTAINABILITY OF ENERGY TECHNOLOGICAL SYSTEMS IN SOUTH AFRICA: A REVIEW[6]

3.1 INTRODUCTION

The field of technology assessment (TA) is not new, but it continues to be relevant today more than ever, especially in the energy sector (Daim et al., 2009). Issues related to climate change, energy security and sustainability in general are at the core of all energy policies and strategies. The development of new and more sustainable energy technologies are needed to address these challenges. As part of this, energy technology assessment tools can help decision-makers with the identification of sustainable energy solutions, in order to integrate them in long-term energy policies and strategies. The concept and practice of sustainable development has subsequently manifested in the technology assessment field.

This study aims to improving the energy technology sustainability assessment practices in South Africa. However, in order to achieve this aim, there is a need to understand the extent to which the general tools, approaches and methods reviewed in Chapter 2 have been used to assess the sustainability of the energy technology development in South Africa. This chapter provides such a review. Undertaking this review provided an understanding of the concerns that need to be addressed to improve the technology sustainability assessment practices in the South African energy sector.

3.2 DEVELOPMENT OF ENERGY TECHNOLOGY ASSESSMENT

Formal energy technology assessment (ETA) began after the establishment of the USA Congressional Office of Technology assessment (OTA) in 1972. Generally, technology assessment was defined as a “comprehensive form of policy research that examines the short- and long-term social consequences of the application or use of technology” (Janes, 1996). In the energy sector, the OTA recognized that the assessment would emphasise ‘efficiency’ in production and use of energy. This is because energy is important for economic and social development of any country.

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[6] This chapter is based on work that was presented at the 19th International Association for Management of Technology (IAMOT), 8-11 March, 2010, Cairo, Egypt. A paper based on this work has been published in *Technology in Society*. See Appendix A for details.

The OTA devoted much time and resources conducting assessments of energy technologies (e.g. Office of Technology Assessment, 1994a; Office of Technology Assessment, 1994b). One study of the OTA actually did an energy assessment for developing countries with an aim of: examining the extent to which technology can provide energy services that the developing countries need for social and economic development in a cost effective and socially viable manner; and evaluating the role of the US in accelerating the adoption of such technologies by developing countries (Office of Technology Assessment, 1991). The main application of energy technology assessment was to make specific decisions pertaining to particular policies. However, since 1990, the concept and practice of sustainable development has dominated different levels of global discussions. There was hence some initial attempt of presenting technology assessment in the context of sustainable development (Weaver et al., 2000).

In the South African context, specifically, there is no formal and coherent approach to energy technology assessment from a sustainability perspective. The government finds it challenging to establish national policies that are concerned with energy technology development for sustainability. A number of research centres focussing on energy issues have however been established, which is an important step towards fostering sustainable energy. Some examples include: (i) the Energy Research Centre (ERC) based at the University of Cape Town[7]; (ii) the Centre for Renewable and Sustainable Energy Studies at Stellenbosch University[8]; (iii) the Graduate School of Technology Management of the University of Pretoria[9]; and (iv) the South African National Energy Research Institute (SANERI)[10]. In addition, industry plays a part by being the key partner in funding energy technology evaluation research, much of which is required in the regulatory process. Good examples are Sasol[11], Eskom[12] and the Pebble Bed Modular Reactor (PBMR)[13] company.

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[7] http://www.erc.uct.ac.za

[8] http://www.crses.sun.ac.za/

[9] http://www.up.ac.za/gstm

[10] http://www.saneri.org.za

[11] http://www.sasol.com

[12] www.eskom.co.za

[13] www.pbmr.co.za

3.3 KEY SEARCH ON ENERGY TECHNOLOGY ASSESSMENT IN SOUTH AFRICA

The effort in this chapter consisted of a systematic online search of literature databases (Science Direct, ISI Web of Science and Scopus). Since the review of technology assessment in general is readily available in the literature (De Piante Henriksen, 1997; Tran and Daim, 2008), the main concern of this chapter was to review technology assessment approaches, methods and tools in the energy sector of South Africa. The search was done by combining three keywords as shown in Table 3.1.

Table 3.1: List of the key search words for energy technology assessment in South Africa

No.	Keyword 1	Keyword 2	Keyword 3
1	Technology assessment	Energy technologies	*South Africa*
2	Economic analysis	Energy technologies	*South Africa*
3	Decision analysis	Energy technologies	*South Africa*
4	Systems analysis	Energy technologies	*South Africa*
5	Technology forecasting	Energy technologies	*South Africa*
6	Information monitoring	Energy technologies	*South Africa*
7	Technical performance assessment	Energy technologies	*South Africa*
8	Risk assessment	Energy technologies	*South Africa*
9	Market analysis	Energy technologies	*South Africa*
10	Impact analysis	Energy technologies	*South Africa*

In addition to the list of the keywords in Table 3.1, a specific assessment approach in each broad category listed in Tran and Daim (2008) was done. As an example, there was a search with a combination of the following keywords: "*cost benefit analysis*" AND "*energy technologies*" AND "*South Africa*". The keyword 2, that is "*energy technologies*", was also replaced by the keyword "*energy assessment*. This was to done to ensure, as far as possible, that relevant articles were not missed. Further, a backward search was also conducted using the list of articles of interest that were already identified.

The time frame for the journal articles search was the years 1980 to 2009. This is because, in a preliminary search, a South African related article published in the journal "*Energy*" in 1987 was identified (Pouris, 1987) and the starting date for the search was extended to explore any other earlier studies conducted.

To foster comparison of the assessment approaches in South Africa relative to the other Southern African Countries[14], *Keyword 3* was replaced with the *Southern African country* name. The publication name and the keywords used for each identified relevant study were noted. The studies that address the issues of sustainability in the energy technology assessment were also noted.

3.4 ANALYSIS OF ENERGY TECHNOLOGY ASSESSMENT REVIEW IN SOUTH AFRICA

The articles from peer reviewed journals that were found relevant and hence cited in this review are presented in Table 3.2. It is clear from the list of journals that the studies are not targeted to the technology management community. In fact the issue of renewable energy seems to be high on the agenda as observed by the high number of relevant publication in the *Renewable Energy* journal.

Table 3.2: Journals reviewed and cited in this study

Journal	No. articles reviewed
Energy Policy	4
Energy	3
Renewable energy	10
Nuclear Engineering and Design	1
Biomass and Bioenergy	1
Energy for Sustainable development	1
The Electricity Journal	1
Environmental Modelling and Software	1
Appropriate Technology	1
Development Southern Africa	1
International Journal of Hydrogen Energy	1
South Africa Journal of Industrial Engineering	1
Renewable and Sustainable Energy Reviews	1

The review also revealed the limited use of the term *"technology assessment"* in the South Africa energy technology studies. The use of this terminology is only found in Grover and Pretorius (2008), and Brent and Kruger (2009). In order to specify the technology assessment approach or method used in accordance to the technology management community, the implied energy technology assessment based on De Piante Henriksen (1997) and Tran and Daim (2008) were identified.

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[14] These are: Angola, Botswana, Lesotho, Malawi, Mauritius, Mozambique, Namibia, Swaziland, Zambia and Zimbabwe

Another issue worth mentioning is that only two studies have done a review on energy technologies assessment elsewhere. Tokimatsu and Hondo (2006) did a review on energy technology assessment in Japan, but with a specific focus on the usage of life cycle analysis. More recently, an on-going study is reviewing energy technology assessment but with the specific focus on the scenario analysis literature (International Risk Governance Council, 2009).

The energy technology assessment coverage in South Africa is wide, ranging from national to project level. Comparing it to the other Southern African countries, the published studies were only limited to the following countries: Lesotho, Mauritius, Mozambique, Zambia and Zimbabwe. As observed in Figure 3.1, publications on energy technology assessment in South Africa are high relative to other Southern African countries.

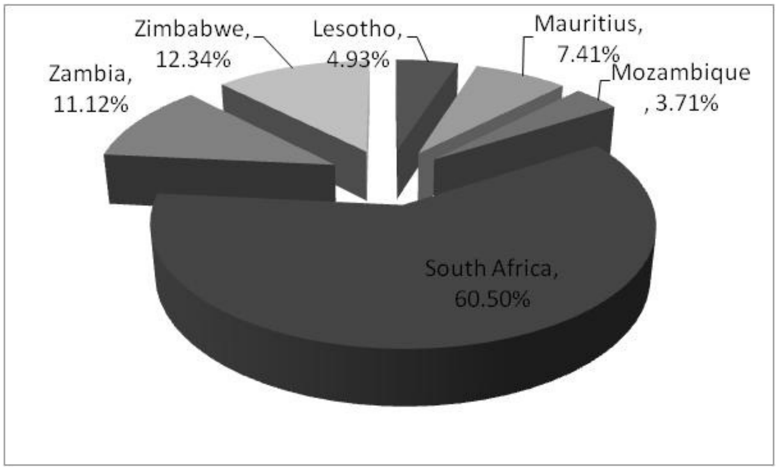

Figure 3.1: Comparison of energy technology assessment publications in South Africa and other Southern African countries

The review is presented in two main separate topics: (i) TA of power generation technologies; and (ii) technology assessment of liquid fuel technologies. In each topic, two issues of special interest of this study are discussed: (i) the approaches, tools and methods used in the energy technology assessment; and (ii) the extent to which these studies assess sustainability of these energy technologies.

3.4.1 Technology assessment of power generation technologies

Power generation technologies are the most assessed in South Africa. These include both conventional and renewable energy technologies. The energy technology assessment categories found in the literature are discussed below.

Economic analysis

There were only three economic analysis studies found for power generation technologies in South Africa. The other six studies that were found were from four different Southern African countries (see Table 3.3). Most of these economic analysis studies for energy technologies consider the question of cost or cost-effectiveness. Pouris (1987) estimates the current and future costs of electricity from photovoltaic cells and compared them with the electricity produced by Eskom, a public electricity utility in South Africa. Mulder and Tembe (2008) provide a cost benefit analysis of a rural electrification programme in Mozambique.

Table 3.3: Summary of economic analysis studies of energy technology

Author(s)	Energy technology	Country
Pouris (1987)	PV cells	South Africa
Spalding-Fecher et al. (2002)	Energy efficiency	South Africa
Mbohwa (2003)	Bagasse	Zimbabwe
Mbohwa and Fukuda (2003)	Bagasse	Zimbabwe
Palanichamy et al. (2004)	Renewable energy	Mauritius
Weisser (2004)	Renewable energy	Rodriguez, Mauritius
Maboke & Kachienga (2008)	Power transmission	South Africa
Mulder & Tembe (2008)	Rural electrification	Mozambique

Spalding-Fecher et al. (2002) use a discounted cash flow analysis to estimate the energy efficient investments in South Africa. In a similar analysis, Weisser (2004) assesses the cost of the various electricity supply options in Rodriguez, Mauritius. Other economic analyses are aimed at identifying the feasibility of investing in a particular energy technology. Mbohwa and Fukuda (2003) and Mbohwa (2003) use a techno-economic analysis to evaluate biogas power development in Zimbabwe. On the other hand, Palanichamy et al. (2004) analyse the feasibility of renewable energy investment projects in Mauritius. The study analysed the Mauritius energy scenario, the earlier and recent renewable energy projects, the current status of such projects, the barriers for renewable energy developments and the suitable renewable energy technology for fruitful investment.

Some studies seek to modify the TA methods by making use of multiple methods in their economic analysis. For instance, Maboke and Kachienga (2008) introduced a new financial evaluation framework to evaluate power transmission investment in South Africa. Their analysis incorporated project options and uncertainties, Monte Carlo simulation, real options analysis and decision analysis based on a foundation of strategic analysis.

Decision analysis

Decision analysis studies which were identified were only carried out in South Africa as shown in Table 3.4. Basson and Petrie (2007) provide an integrated approach for both technical and valuation uncertainties during decision-making supported by environmental performance information based on a life cycle assessment. Their approach includes ‘distinguishability analysis’ to determine whether the uncertainty performance information is likely to make it impossible to distinguish between the activities under consideration, and the use of a multivariate statistical analysis approach (principal component analysis). The approach was demonstrated for a technology selection decision for the recommissioning of a coal-based power station in South Africa.

Table 3.4: Summary of decision analysis studies of energy technology

Author(s)	Energy technology	Country
Heinrich et al. (2007)	Electricity supply	South Africa
Basson & Petrie (2007)	Coal	South Africa
Brent & Kruger (2009)	Renewable energy	South Africa

Heinrich et al. (2007) argue that the complexity in the strategic planning of electricity supply calls for transparent decision support frameworks. They therefore outlined a methodology for ranking power expansion alternatives in South Africa given multiple objectives and uncertainty. Their methodology uses a value function of multi-criteria decision analysis that is augmented with scenario analysis. They demonstrated this framework using South African electricity supply technologies.

Finally, Brent and Kruger (2009) integrated two frameworks, one developed by the Intermediate Technology Development Group and the other one by the Renewable Energy for Sustainable Rural Livelihoods workgroup. Their aim was to assess the applicability of the integrated frameworks for the South African rural renewable energy landscape through a Delphi study with several experts in the energy sector. Their study points out that integrating these frameworks may result in the formulation of more robust community-based renewable energy implementation strategies. The study found possible deficiency in the South African renewable energy industry concerning the environmental and social/human issues. They highlight the need to enhance the sustainability science thinking in renewable energy technology research and development, specifically in technology assessment methods that are appropriate to the research and development phases of technology management.

Impact analysis

A number of studies on power energy technologies in South Africa are also dedicated to impact analysis as summarized in Table 3.5. Only one study on impact analysis was from other Southern Africa countries, namely Zambia. Van Horen (1996) considers the damages caused by electricity generation. In a similar study, Spalding-Fetcher and Matibe (2003) estimate the externality costs of the electric power generation technologies (coal and nuclear) in South Africa. Their main focus for the study was on the air pollution impacts on human health, damages from GHG emissions and avoided health costs from electrification.

Table 3.5: Summary of impact analysis studies of energy technology

Author(s)	Energy technology	Country
Spalding-Fecher & Matibe (2003)	Coal and Nuclear	South Africa
Gustavsson & Ellegard (2004)	Solar home systems	Zambia
Bikam & Mulaudzi (2006)	Solar	South Africa
Greyvenstein et al. (2008)	Nuclear	South Africa
Mamphweli et al. (2009)	Biomass gasification	South Africa

Some studies are intended to provide an understanding of the impact of energy technology access to the rural communities. For instance, Gustavsson and Ellegård (2004) analyse the impact of solar home systems on rural livelihoods in Zambia using surveys. Their aim was to collect information on the impacts of the solar home systems on the rural livelihood as a result of access to electric services such as light. Mamphweli and Meyer (2009) assess the impact of implementation of biomass gasification project at Melani Village in the Eastern Cape, South Africa.

Bikam and Mulaudzi (2006) use a beneficiaries' assessment method to assess the problems related to the sustainable implementation and operation of a solar energy project in Folovhodwe, in South Africa. This was in the form of semi-structured interviews, focus group discussions and direct observations of facilities. The problem of sustainability in this study was related to the inadequate definition of the role of each stakeholder. This is however a narrow sense definition of sustainability. Although the results of this study are limited to the specific project, they recommend the need for considering culture, capacity development, and the level of income at the initial stages of planning and implementing a new technology.

Greyvenstein et al. (2008) proposes a strategy for South Africa in undertaking the global hydrogen economy whilst addressing economic development, environmental concerns and energy diversity by building on national resources and technologies. Their proposed strategy is to use a Pebble Bed Modular Reactor (PBMR) to generate both electricity and process heat for use in generating clean hydrogen.

Potential and technical analysis

Potential analysis studies are similar to resource assessments while technical analysis studies are mostly investigations of the technical performance of the energy technologies. South Africa has had a limited potential and technical analysis studies when compared with the other Southern Africa countries. The studies on potential and technical analysis (see Table 3.6) were mainly aimed at providing an understanding of the feasibility of particular renewable power generation technologies.

Table 3.6: Summary of potential & technical analysis studies of energy technology

Author(s)	Energy technology	Country
Gustavsson (2007)	Solar	Zambia
Taele et al. (2007)	Photovoltaic cells	Lesotho
Hajat et al. (2009)	Solar	South Africa
van Nes & Nhete (2009)	Biogas	South Africa, Lesotho & Zimbabwe
Batidzirai et al. (2009)	Solar water heating	Zimbabwe
Fluri (2009)	Concentrating solar power	South Africa

Gustavsson (2007) analyses the use of solar home systems from both user experiences and technical performance, and its implications on the design of the solar home systems in rural electrification projects in Zambia. Taele et al. (2007) analyse the potential and utilization of renewable energy technologies in Lesotho with an emphasis on the contribution of solar energy technologies. They argue that proper economic support and utilization of renewable energy technologies can help developing countries meet their basic energy demands and alleviate problems of energy shortages.

Hajat et al. (2009) assess the efficacy of solar power units for small business in rural areas in South Africa. They make use of surveys to examine the patterns of use of two 12V and one 24V systems for small-scale enterprises housed in transportable containers. Their results showed that the 12V system was inadequate to meet the requirements of the enterprises while the 24V system performed better. In a similar study, Green et al. (2001) investigate the introduction of solar (photovoltaic) systems and an alternative electrification technology in a rural community in the Kwa-Zulu Natal Province of South Africa.

Batidzirai et al. (2009) discuss the economic, social and environmental benefits of using solar water heating in Zimbabwe. They compare different water heating technologies in three sectors over a period of 25 years and demonstrate the potential for solar water heating in alleviating energy and economic problems that energy importing country like Zimbabwe are facing.

Different indicators determining the potential for implementing power generation technologies were used. This mainly depended on the power generation technology being assessed. For example, Fluri (2009) assessed the potential for implementing large-scale concentrating solar power plants in South Africa, and the availability of water is used as the factor determining the potential for this energy technology. In a different study, van Nes and Nhete (2007) define the technical potential of biogas in Africa as the number of households that can meet two basic requirements namely, sufficient availability of dung and water to run a biogas installation. South Africa was considered as among the leading nations with the potential for biogas. In their conclusion, van Nes and Nhete (2007) recommend the need to relate this potential to finance and economy, and the potential to make progress on a number of Millennium Development Goals.

Other energy technology analysis

This section includes other analysis of energy technology that appeared once in the literature and its assessment/implied assessment is provided (see Table 3.7).

Table 3.7: Summary of other energy technology analysis

Author(s)	Energy technology	Implied assessment	Country
Green et al. (2001)	Solar	Market analysis	South Africa
Alfstad (2005)	Electricity supply	TIMES	South Africa
Grover & Pretorius (2008)	Electricity – DSB[1]	Technology forecasting/ market analysis	South Africa
Winkler et al. (2009)	Renewable energy	MARKAL	South Africa

Note: [1] Demand side bidding

Grover and Pretorius (2008) assessed the energy demand side bidding measure that Eskom introduced in order to reduce the power energy peak load demand in South Africa. Their aim was to determine the future position of demand side management as a technology product in South Africa making use of a technology balance sheet, roadmapping and scenario analysis.

Alfstad (2005) developed an energy model for the Southern African Development Community (SADC) region using TIMES (The Integrated MARKAL-EFOM System) framework, focussing on the supply side only. Winkler et al. (2009) analyse the technology learning for renewable energy technologies for the electricity sector in South Africa. They considered scenarios implemented in a MARKAL energy model used for mitigation analysis. These tools, as mentioned earlier, are mainly optimization models aimed at providing least cost options.

3.4.2 Technology assessment of liquid fuel technologies

There are limited published studies that investigated liquid fuel technologies in South Africa and other Southern African countries. This is surprising given the existence of companies such as Sasol in South Africa, which is one of the largest liquid fuel producers in Africa. However, the literature review, which only focuses on the publication in the academic domain, may be partly a contributing factor for such a finding. The studies that were found either focus on economic analysis or potential analysis of liquid fuel technologies as summarized in Table 3.8.

Table 3.8: Summary of other energy technology analysis

Author(s)	Energy technology	Implied assessment	Country
Singh (2006)	Biofuel	Economic analysis	South Africa
Amigun et al. (2010)	Methanol	Economic analysis	South Africa
Batidzirai et al. (2006)	Biofuel	Economic analysis	Mozambique
Woods (2001)	Biofuel	Potential analysis	Zimbabwe
Jingura & Matengaifa (2008)	Biofuel	Potential analysis	Zimbabwe

Singh (2006) examines the economics of investment in biofuel production from a national and commercial perspective in the South African transport sector. This includes, among others, the financial investment model in maize to ethanol plant to establish the net present value and internal rate of return. Amigun et al. (2010) assess the optimum and economic performance of methanol production from non-woody biomass (maize residue) in South Africa. They argue that this can be a viable option in the short-term. In a similar analysis, Batidzirai et al. (2006) provide an economic cost of bioenergy supply from biomass in Mozambique.

For the case of potential analysis studies, Woods (2001) assesses the potential for biofuel production from sweet sorghum in Zimbabwe. Jingura and Matengaifa (2008) did a similar study, but accounted for different number of crop residuals in Zimbabwe. In their conclusion, they stress the need of incorporating crop residue in the Zimbabwe energy system.

3.4.3 Energy technology sustainability assessment in South Africa

The assessment of energy technology sustainability in South Africa is limited. In some of the studies that were found, the issue of sustainable technology development is mentioned (e.g. Hajat et al., 2009) but these studies do not assess the sustainability of the technology *per se.* For example, Brent et al. (2009) review the viability of the South African Biofuels Industrial Strategy in terms of the three conditions of sustainability, that is, environmental, social and economic macro-forces. Van der Gaast et al. (2009) discuss an approach to facilitate low-carbon energy technology transfer compatible with the energy development needs and priorities of developing countries.

Engelbrecht and Brent (2008) model the energy system by combining a set of macro level indicators from various sustainability and energy studies. They further applied multi-attribute utility theory to determine utilities for economic, social, institutional and environmental macro-influencing factors. Their study lays a foundation for sustainable energy system decision-making for policy-makers and technology managers based on the macro-influencing factor landscape.

Brent and Rogers (2010) applied a sustainability assessment methodology on a renewable energy technological system in South Africa. The assessment predicts outcomes of wind, solar and lead-acid battery energy storage technologies. Discipline-based models in the field of economics, sociology, ecosystem sustainability, institutional governance, and the physics and chemistry of energy conversion were utilised. The renewable off-grid electrification system was found not viable since the electricity supply costs were higher than the available subsidies. Brent and Rogers (2010) however point out that the failure of the integrated system may also be attributable to the complexity of the socio-institutional sub-system, which resulted in uncertainty for the project planners and system designers. Additional factors include the lack of resilience of the technological system to the demands from the socio-economic and institutional sub-systems.

Praetorius and Bleyl (2006) point out that successful technology dissemination needs appropriate institutional structures to reduce the related transaction costs. They argue that the implementation of innovative institutional structures in the form of an energy agency can improve the situation. They used South Africa to examine the appropriateness of this concept in the emerging nations.

3.5 CONCLUSION

This chapter provided a review of the energy technology assessment approaches and tools in South Africa. In addition, the review also compares the energy technology assessment studies in South Africa with the other Southern African countries. The review observed that the studies that have been published are not dedicated to the technology management community and the term "*technology assessment*" is also not common. In fact, the studies that were identified can generally be implied to be directed for policy guidance in the development of the energy technologies in both South Africa and the other Southern African countries. In addition, almost all the studies mainly focused on power generation technologies and limited studies are carried out on liquid fuel technologies. This, however, does not come as a surprise because power energy access is a key priority to the many of the Southern African governments. On the other hand, a limited number of publications were found, and this is attributed to the systematic literature review which focussed on the publications in the academic domain.

Taking a closer look at the studies that provide an implication of energy technology assessment in South Africa, they all seem to provide a partial analysis which might limit, rather than stimulate, a deeper understanding of energy technologies that contribute to the sustainability goals. They either display a strong technical and quantitative bias and sometimes simplistic ideas about the dynamics of energy technology development. Unfortunately, none of the studies investigated explicitly and comprehensively evaluates the extent to which energy technology development in South Africa can contribute to sustainability. This seems odd considering the fact that most technology developments attempt to ultimately address the social-economic goal of access to energy and the environment goal of contributing to cleaner energy technologies. This study therefore argues that a comprehensive technology sustainability assessment is highly needed for not only South Africa but also in the other Southern African countries. Although a number of studies in South Africa are familiar with systems thinking, none include the causal relations and feedbacks existing within energy technology development, and how these relations and feedbacks might be addressed through a comprehensive system dynamics approach. This study therefore utilizes a system dynamics approach to a biodiesel technology development in the Eastern Cape Province as a case study.

CHAPTER 4: RESEARCH METHODOLOGY

4.1 INTRODUCTION

The problem relating to the technology assessment for sustainability was discussed in Chapter 1, which was followed by a critical review of technology assessment in Chapter 2. The issues relating to the extent of energy technology assessment in South Africa and the need for an improved energy assessment framework was highlighted in Chapter 3. Thus, the need for an approach that accounts for the complexity of energy technology development was realised.

The *SATSA* framework is argued to fulfil this need, and the demonstration of this framework, using a case study, is subsequently required. Thus, the aim of this chapter is twofold. Firstly, this chapter provides a discussion on the research design for this study. Secondly, this chapter provides the research methodologies that were used to:

i. develop, verify and validate an appropriate energy technology assessment model using biodiesel production development in the Eastern Cape Province of South Africa as a case study (simulation methodology); and
ii. demonstrate the appropriateness of the developed model for improved energy technology assessment practices in the South African energy sector (survey methodology).

The rationale for using both simulation and survey methodologies is due to the transdisciplinary nature of this study, which was motivated in Chapter 1. Therefore, the research design of this study, which is transdisciplinary, is first discussed. This is then followed by the discussion of the two methodologies used and finally the summary of the chapter is provided. As a summary, the main objectives of this study are provided in Figure 4.1.

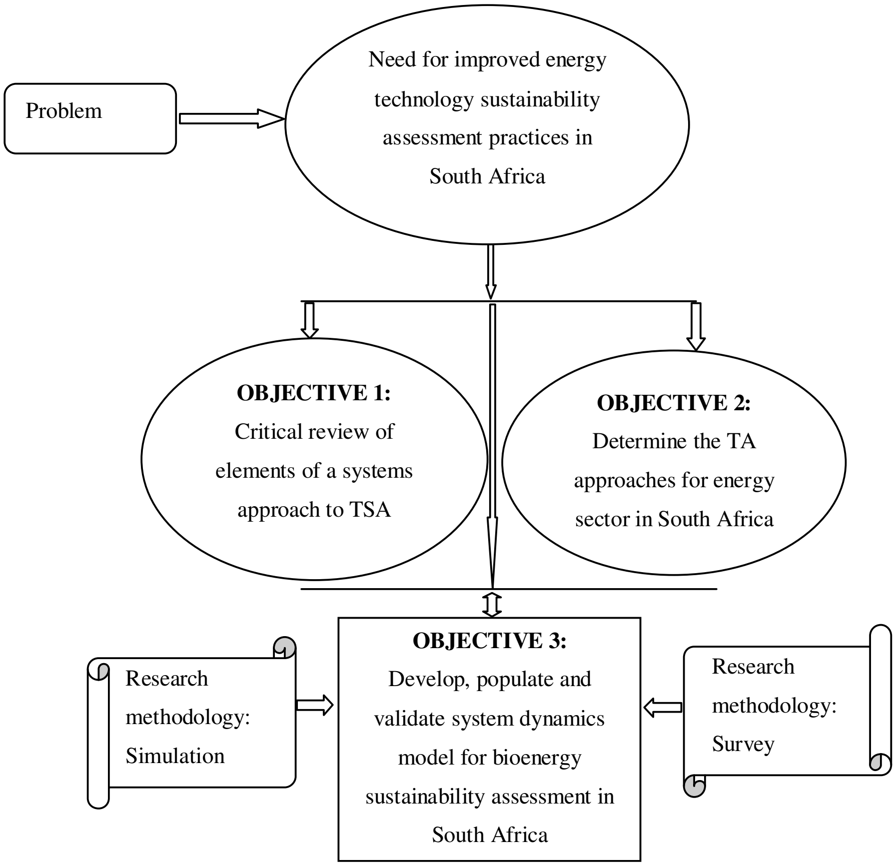

Figure 4.1: Summary of the study objectives

4.2 THE RESEARCH DESIGN

Transdisciplinary emerged in the early seventies as an approach to solve complex, interconnected problems of the world, when it was discovered that multi-and interdisciplinary approaches were not enough (McGregor, 2011). The problems were becoming complex to be solved within disciplinary boundaries or using conventional empirical methodology. According to Hirsch Hadorn et al. (2008), the underlying motivation for application of transdisciplinary approach lies in the art of the research problem:

> *There is a need for TR [transdisciplinary research] when knowledge about a societally relevant problem field is uncertain, when the concrete nature of problems is disputed, and when there is a great deal at stake for those concerned by problems and involved in dealing with them. TR deals with problem fields in such a way that it can: a) grasp the complexity of problems, b) take into account the diversity of life-world and scientific perceptions of*

problems, c) link abstract and case specific knowledge, and d) constitute knowledge and practices that promote what is perceived to be the common good.

Several studies have attempted to provide the definition of transdisciplinary. Mittelstraß (1992:250) defines transdisciplinarity as "knowledge or research that frees itself of its specialised or disciplinary boundaries, that defines and solves its problems independently of disciplines, relating these problems to extra-scientific developments". According to Scholz et al. (2006) transdisciplinary research:

i. deals with relevant, *complex* societal problems;
ii. compliments traditional disciplinary and interdisciplinary scientific activities by *integrating actors from outside academia*;
iii. organizes processes of *mutual learning* among science and society; and
iv. does not constitute research for society but *research with society* (mutual learning).

Pohl and Hirsch Hardon (2007) on the other hand distinguish four dimensions of transdisciplinary research as:

i. transcending and integrating disciplinary paradigms;
ii. participatory research;
iii. relating to life-world problems; and
iv. searching for a unity in knowledge.

While transdisciplinary is still young to be able to generalize the overall transdisciplinary movement, Hirsch Hardon et al. (2008) implies that transdisciplinary is a reaction against the dissociation of scientific knowledge, and the recent need for reshaping the conception of science and the distinctions of science and the life-world. McGregor and Volckmann (2011) identifies that, the current practice in the application of transdisciplinary approach can be classified into two fundamental views:

(i) It is an exclusive concentration on joint problem solving of problems that concern the science-technology-society triad. This notion was largely expressed at Zurich congress held in 2000, and rejects the notion of a transdisciplinary methodology (Nicolescu, 2010).

(ii) It is a methodology in its own right, in addition to empirical, interpretive and critical methodologies. This notion originated in the first world congress on transdisciplinarity held in Portugal, 1994.

Looking at transdisciplinary as a methodology, this is deeply informed by new sciences of quantum theory, chaos theory and living systems theory (McGregor, 2011). Grounded in these new sciences, Nicolescu (2007; 2002; 2005; 2008) provided his own interpretation of three axioms of transdisciplinary methodology: (a) multiple levels of reality and the hidden third; (ii) the logic of included middle, and (c) epistemology – knowledge as an emergent complexity. According to Nicolescu (2006), there are multiple levels of reality, at least ten, organized in three macro levels: internal (consciousness, subjective); external (information, objective) and the hidden third, the mediated interface between the internal and external realities. Recent literature, particularly Cicovacki (2004, 2009) argues for the need of an explicit fourth axiom in transdisciplinary, that is, theory of value. He argues that value provide an axis of orientation of lives, attitudes and deeds for decision making. Cicovacki (2004) supports his argument by referencing Nicolescu (1997) assertion that transdisciplinary "*is a way of self-transformation, oriented towards the knowledge of self, and the creation of a new art of living'*. Similarly, Glasser (2006) argue that due to the concern on the level of reality in transdisciplinary, there is need to pay attention on what people consider to be of value to them. Further, van Breda (2007) urges the need to look for agreement in axiology, in order to develop tolerance of different viewpoints, in order to stay engaged in conversations about complex problems shaping human mind.

Following McGregor and Volckmann (2011) fundamental classification of transdisciplinary approach, this study belonged to the exclusive concentration on joint problem solving of problems pertaining the science-technology-society. The intention of the study was not to utilize transdisciplinary as a methodology but rather, to address a contemporary and complex societal problem in a creative way, while engaging with different disciplines and non-academic actors. Technology assessment for sustainability is one of the issues that cannot be properly be dealt with by one disciplinary perspective. Thus, disciplinary reduction is 'undercomplex' and does not cope with 'new, complex wicked problems'(Schmidt, 2008).

Taking the position of joint problem solving, transdisciplinary research has been described as a process of collaboration between scientists and non-scientist on a specific real-world problem. A large number of such problems are strongly linked to sustainable development (Blattel-Mink and Kastenholz, 2005). Thus, any planning and learning process for sustainable development requires a transdisciplinary research approach (Meppem and Gill, 1998). In addition, technology assessment attempts to provide solutions outside the academic domain and as a result requires a transdisciplinary approach (Decker and Fleischer, 2010). Transidisciplinary approach therefore takes the challenge of integration of 'inside' (academics) and 'outside' (non-academics), and the researcher becomes an active part of the research field.

The extent of collaboration is one issue that is raised, when taking the view of joint problem solving. In addition, one may even wonder whether it is really possible to conduct transdisciplinary research as a solo project – particularly in the case of a PhD study! While individual forms of research are not ruled out, this study positioned itself in a collaborative manner as that was one of its intentions. Mobjörk (2010) identifies two kinds of transdisciplinarity in terms of the extent of collaboration between scientist and non-scientists. These are consultative and participatory transdisciplinarity. In the case of consultative, the non-scientist actors are not actively incorporated into the knowledge production process. On the other hand, participatory transdisciplinarity fully incorporates the non-scientist actors in the knowledge generation process. Elaborating on Mobjörk (2010), participatory transdisciplinary imply engaging in the whole research process, while consultative is engaging in some part of the research process. This engagement may take place in problem-framing and problem definition, when one wants to understand a field and grasp a problem; or in the learning and studying phase, that is, during part of research process where the problem is examined and the results to the problem (s) are searched for. During the process of PhD study, the author established contact and network with local, regional and national actors (see Figure 4.3) who were technology assessment practitioners, developers, policy makers and fellow PhD students. While agreeing that participatory collaboration seems most advantageous, this study found it worthwhile to be limited to consultative transdisciplinarity where, the non-scientist actors were engaged to respond on the work carried out. This limitation was due to the fact that participatory transdisciplinary requires a lot of time and funding which was a constraint for this study.

Transdisciplinary research is characterized by an ontology, epistemology, methodology and organization that go beyond disciplinary research (Scholz et al., 2006). Each of these characteristics in relation to this study is briefly discussed in the subsequent sections.

4.2.1 Ontology

The transdisciplinary ontology seems to be one of the contested characteristic (McGregor, 2011). Ontology attempts to answer the question concerning the conceptualization of the phenomenon or problem or case study in which a researcher is engaged (Scholz et al. 2006). Generally, transdisciplinary research is often, but not always, concerned with real-world and real people's problems, whereby, framing the problem within disciplinary science does not seem to fit. The ontological axiom supporting this need is that, in nature and knowledge of nature, there are different levels of reality, which corresponds to different levels of perception (Nicolescu, 2006). These different levels of reality and perceptions usually do not compete and can be complementary. In transdisciplinary research, this complementarity is used explicitly to achieve a more inclusive perspective on reality.

Given the different levels of reality and levels of perceptions, it is therefore not possible to deal with problems using the routine expertise and professional knowledge and arguments, and lack of value compromises the ability to determine the underlying causes of the world crises, understand them and also attempt to overcome them (Funtowicz and Ravetz, 2008). Van Breda (2007) regards this as polycrisis, which is a situation where there is no single big problem that exists, but a series of overlapping, interconnected problems. This complexity implies the need for more than a single expert solution. The author is aware and acknowledges the possibility of not been able to achieve a shared or common decision because of the individual uniqueness, differences in priorities and different motivations. Adopting different values thus does not imply that people have no values but rather display confrontational values (Hartman, 1967). According to Hartman (1967), problem solving can be augmented if the unique patterns of each person are observed and compared to patterns of others.

Based on the discussion above, it is clear that, the object of the transdisciplinary is to deal with a complex *ill-defined* (or 'wicked') real-world problem (Pohl and Hirsch Hardon, 2007). In the context of this study, managing energy technology development for sustainability is a 'wicked' problem, in the sense that there is no definitive formulation of sustainable development and no conclusively 'best' energy technology solutions. In addition, the problem related to sustainable development is constantly changing (Laws et al., 2004). For the case of this study, the question regarding whether a particular renewable energy technology development would contribute to sustainable technology development in South Africa, is unclear.

Ontological considerations also unfold the type, or nature of phenomenon or case that one is dealing with (Scholz et al., 2006). In this study, a case of biodiesel production development in the Eastern Cape Province of South Africa was used to demonstrate the *SATSA* framework presented in Chapter 1 (refer to Figure 1.4). This was done to illustrate how the *SATSA* can be used as a guiding framework for assessing the sustainability of the renewable energy technologies, given specific energy technology development needs. The analysis represented:

i. a structure of the biodiesel production development in the Eastern Cape Province and its linkages with the economy, society and environment;
ii. the dynamics of how the biodiesel production development in the Eastern Cape Province develops or could be developed;
iii. biodiesel production development with regards to its impacts on sustainable development indicators in the Eastern Cape Province;
iv. the initial state of biodiesel production development in the Eastern Cape Province; and
v. the target state that is aimed for biodiesel production development in the Eastern Cape Province with regards to the sustainable development goals.

4.2.2 Epistemology

Scholz et al. (2006) defines epistemology as the science of generating, integrating and using knowledge with a special focus on structure, scope and validity. In addition, epistemology includes individual, social and cultural differences (Goldman, 1986). There are three forms of knowledge that characterize transdisciplinary research: systems knowledge, target knowledge and transformation knowledge (Pohl and Hirsch Hardon, 2007:36). Table 4.1 summarizes these forms of knowledge and their respective research questions that are considered while Figure 4.2 illustrates the relation between these different forms of knowledge.

Table 4.1: Three forms of knowledge

Forms of knowledge	***Research questions***
Systems knowledge	Questions about genesis and possible further development of a problem and about interpretations of the problem in the life-world.
Target knowledge	Questions related to determining and explaining the need for change, desired goals and better practices.
Transformation knowledge	Questions about technical, social, legal, cultural and other possible means of acting that aim to transform existing practices and introduce desired ones.

Source: Pohl and Hirsch Hardon (2007)

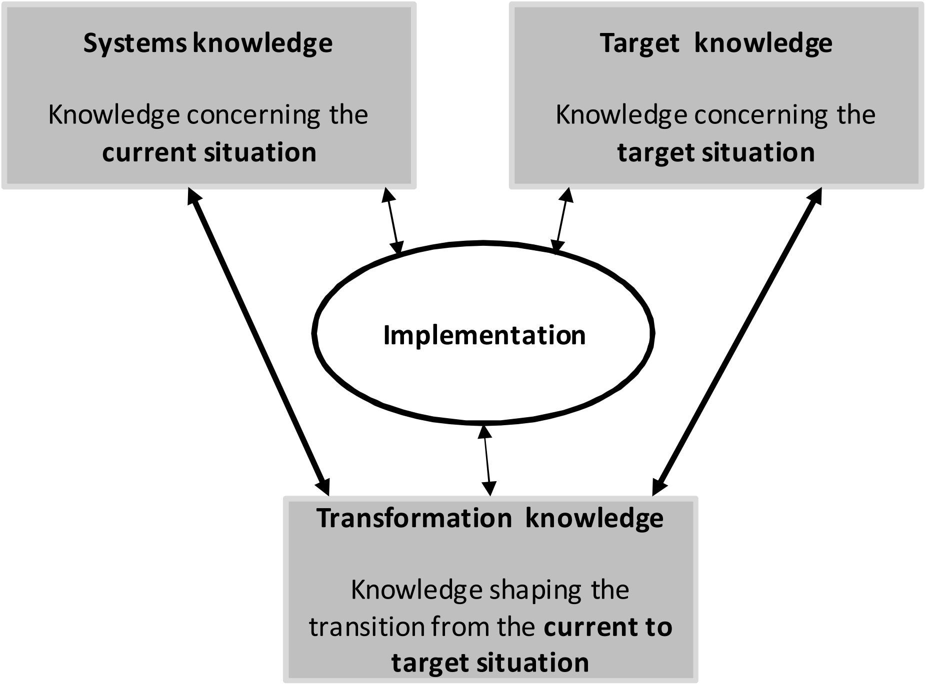

Figure 4.2: Types of knowledge in a transdisciplinary research and their relation (adapted from Messerli and Messerli (2008)

According to Hirsch Hadorn et al. (2006), transdisciplinary research is thus devoted to a wide integration and acknowledgment of pluralistic in knowledge generation (see Figure 4.2). Reflecting on the knowledge generation, these sounds very appealing, but at the same time, this is exceedingly demanding – particularly for a PhD student – to think of a research accomplishing all these knowledge generation.

All in all, with regards to these knowledge forms, this study can be positioned as both systems and transformation knowledge. As systems knowledge, the study is composed of concepts and data concerning the relevant systematic and dynamic structures of the biodiesel production development, aimed at providing an integrative understanding of these systems. In addition, the current situation of the potential biodiesel technology development was considered in this study. As transformation knowledge, the research question for the study is about a means of acting to transform the current energy technology assessment practices and introduce desired ones. The main challenge in this form of knowledge is learning how to make the existing energy assessment practices more flexible.

To answer the research question, this study engaged in a number of disciplines namely: energy policy, environmental and resource economics, technology assessment, socio-economics and system dynamics. This was through the use of concepts, methods or ideas from these disciplines. In addition, the non-academic experts that were contacted included: (i) public agencies such as the Technology Innovation Agency, Department of Energy and government departments in the Eastern Cape Province involved in the biofuel development such as the Accelerated Shared Growth Initiative of South Africa, the Department of Economic Development and Environmental Affairs, the Eastern Cape Socio Economic Council and the Eastern Cape Appropriate Technology Unit; (ii) technology developers such as PhytoEnergy, the East London Industrial Development Zone, the Coega Industrial Development Zone and Sasol; and (iii) technology assessment practitioners such as the Energy Research Centre at the University of Cape Town. Figure 4.3 provides a summary of the expertise/and or the disciplines involved in this study.

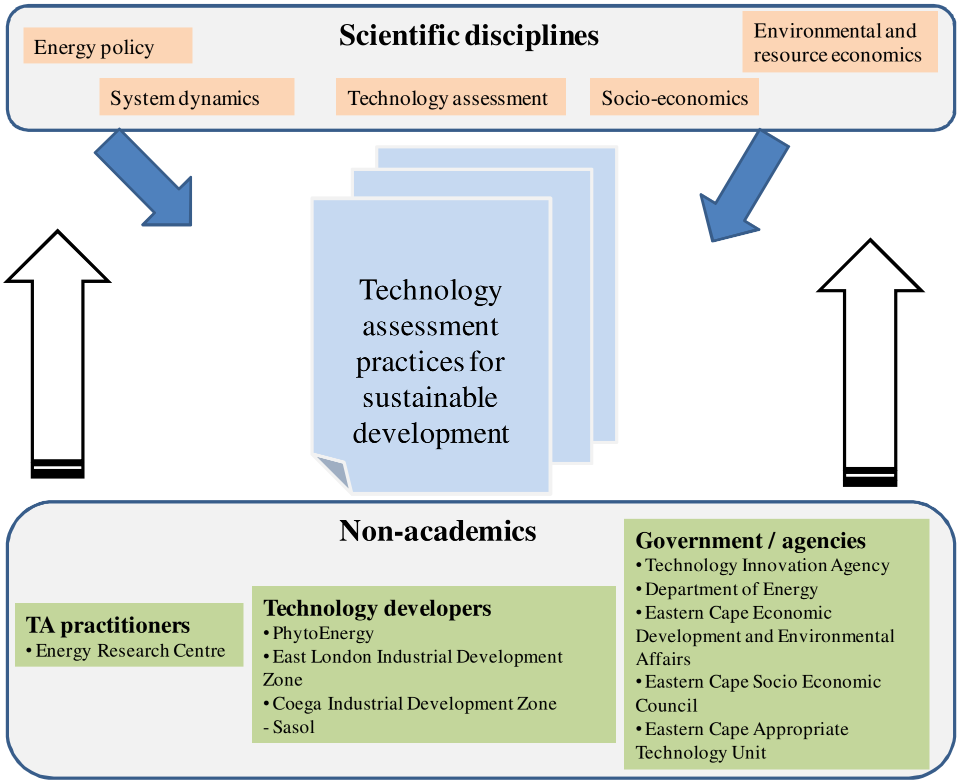

Figure 4.3: Summary of expertise and/or disciplines involved

In transdisciplinary research, different modes of explanation will be involved, since knowledge from both different scientific disciplines and non-scientific sources is integrated. These modes usually do not compete and can be complementary. In transdisciplinary research, this complementarity is used explicitly to achieve a more inclusive perspective on reality. One of the main challenges in transdisciplinary research is how non-scientific knowledge can be validated and integrated in the scientific enterprise. Testing of non-academic explanations on the basis of validation criteria can occur in different ways. It can occur implicitly in society, for example, when many people subscribe to the adequacy and appropriateness of an explanation, resulting in a degree of intersubjectivity. It can also be carried out explicitly in a scientific setting.

4.2.3 Methodology

Methodology is conceived as precepts of methods and procedures formulated and elaborated to tackle problems (Checkland, 1999). Transdisciplinary research is supported by the flexibility regarding the choice of methods from the different research traditions. Thus, the transdisciplinary research process involves moving into other research designs (e.g.

interdisciplinary, multidisciplinary and disciplinary) over the period of this study, especially in the search of the appropriate methodology to analyse the research question (see Figure 4.4). This ranged from a critical literature search to systematic literature search, simulation modelling and a survey. This thesis applied the developed systems approach to technology sustainability assessment (*SATSA*) framework to evaluate biodiesel production development in the Eastern Cape Province in South Africa. The aim of the modelling was to provide a guiding process for an improved technology sustainability assessment practices in the South African energy sector. The validity of the developed model, however, depends on the demonstration of its appropriateness for its intended use of improving energy technology assessment for sustainability. Hence system dynamics was used to develop the model and the modelling process was complemented with a survey in order to determine the usefulness of the developed model. A more detailed discussion of this is found in section 4.3.

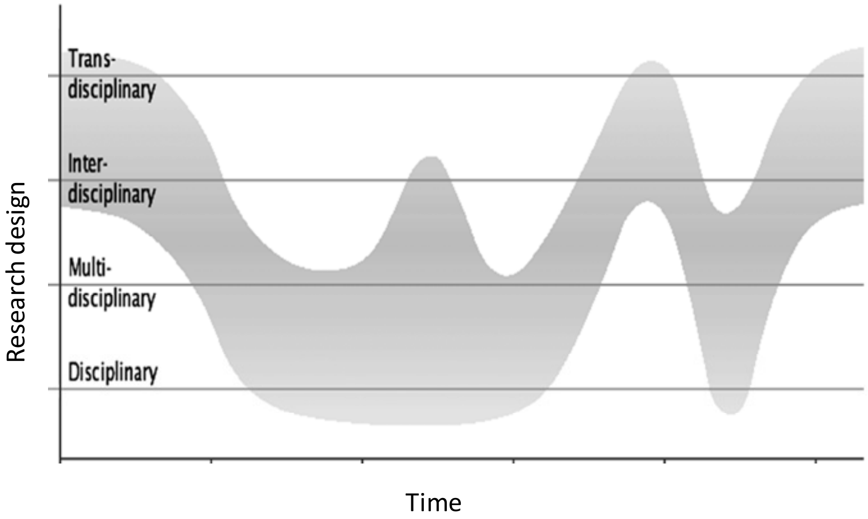

Figure 4.4: Transdisciplinary research process (Hurni and Wiesmann, 2004:40)

4.2.4 Organization

Organizational considerations entail the general procedural of undertaking a project / research and the general organizational setting (Scholz et al., 2006). The general systematic procedure for undertaking transdisciplinary research is not yet developed. However, within transdisciplinary field, the interactive and constructive approaches have been developed in order to guide in the involvement of end users with other societal actors, particularly in the decision-making process, with regard to evaluating new technologies or development (Grin et al., 1997; Broerse, 1998; Rip et al., 1995). Thus, these framework procedures can be used to guide the implementation of transdisciplinary research, since it is aimed at integrating knowledge in an interactive process with non-academics. Flinterman et al. (2001) suggests this procedure for utilization in all the transdisciplinary research (see Table 4.2)

Table 4.2: Procedural elements of transdisciplinary research

Definition of a research field
Identification and contacting of all relevant actors
Literature research
In-depth interviews with participants
Discussion meetings or focus groups
Interactive workshops
Repeated feedback on all kinds of results by all participants
Development of shared constructions and an integral vision

Source: Flinterman et al. (2001)

All the procedural elements were followed within the limitation that the collaboration was consultative. The process of identification of definition of the research question was guided and facilitated by the Transdisciplinary, Sustainability, Analysis, Modelling and Assessment (TSAMA) hub[15] of Stellenbosch University. The Hub officially started in 2009 and it is facilitated by a Programme Manager. TSAMA currently has about 10 PhD students with their respective supervisors from different disciplines. Invited guest speakers on various topics such as complexity theory, sustainable development and transdisciplinary research provided theoretical foundations of transdisciplinary in order to guide the TSAMA Hub PhD students frame there research problems. In addition, the programme consisted of formal and informal meetings, each of which was held twice a month for 2 hours. Hence, in total, there were four meetings a month and this nurtured discussion and interaction with fellow students, supervisors from different disciplines, and invited guest. Given the mix of students with different backgrounds, these discussions guided in viewing ourselves as both actors within and outside the academics, and furthered the organization of the research problem within the transdisciplinary design. How the other procedural activities were undertaken – that is: identification and contacting all the relevant actors; literature search; interviews; discussion and meetings; workshops; feedback; and development of the shared understanding are discussed in the various sections of the thesis and thus not repeated in here (Chapter 2, 3, 4 & 6).

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[15] www.tsama.org.za

Concerning the organizational setting, transdisciplinary research requires an institutional structure for its successful implementation. This is because most universities are still strongly organized within the disciplinary structures. Thus, this study was facilitated within the TSAMA hub. Since TSAMA is not yet a department per se, the PhD students are required to register within a specific faculty / department in which specific supervisors have accepted to participate within the transdisciplinary framework. For instance, this study is registered within the Faculty of Economics and Management Sciences. TSAMA however provides a platform for crossing the disciplinary boarders and further, transcending beyond disciplines by organizing educational core modules, and forums for discussion of PhD projects and other issues / challenges of being a transdisciplinary PhD researcher.

4.3 RESEARCH METHODOLOGY

4.3.1 Simulation research methodology

Simulation is the methodological approach that was used for the objective of developing and populating a system dynamics model for energy technology sustainability assessment (objective 3, refer to Figure 4.1). According to Bratley et al. (1987: ix) "simulation means driving a model of a system with suitable inputs and observing the corresponding outputs". Simulation research allows the assumption that the inherent complexity of the system under consideration is given. While other research methods attempts to answer the questions "what happened, and how, and why", simulation research guides in answering the "what if" question. Thus, simulation research allows the study of complex systems since it creates forward-looking observations (Dooley, 2005).

Axelrod (1997) describes simulation research methodology as a new way of conducting scientific research, which can be contrasted with the two standard methods, namely, induction and deduction. Induction is the discovery of patterns in empirical data while deduction involves specifying a set of axioms and proving consequences that can be derived from those assumptions. The similarity of simulation with deduction is that it starts with explicit assumptions; however, unlike deduction, it does not prove theorems, instead, it generates data that can be analyzed inductively (Axelrod, 1997). On the other hand, simulation differs from induction in that the simulated data comes from rigorously specified set of rules rather than direct measurement of the real world. While induction can be used to find patterns in data, and deduction can be used to find consequences of assumptions, simulation modelling can be used to aid intuition.

Dooley (2005:829) identifies three main simulation research practices namely: discrete event simulation, system dynamics and agent-based simulation. Discrete event simulation entails modelling the system of concern as a set of entities that evolve over time. This is dependent on resource availability and the events that trigger a system. System dynamics simulation identifies the key 'state' variables defining the system behaviour and further relates these variables through coupled differential equations. In agent based simulation, the agents attempt to maximize their utility through their interaction with other agents and resources. The behaviour of agents is determined by schema in which they are embedded which in nature is both interpretive and action oriented. Table 4.3 provides a summary of the key characteristics of these methods and their main conditions for use.

Table 4.3: Characteristic of the three different simulation approaches

Simulation approach	***Conditions for use***	***Main characteristics***
Discrete event	System described by variable and events that trigger change in those variables	Events that trigger other events sequentially and probabilistically
System dynamics	System described by variables that cause change in each other over time	Key system variables and their interactions with one another are explicitly defined as differential equations
Agent-based	System described by agents that react to one another and the environment	Agents with schema that interact with one another and learn

Source: Dooley (2005:834)

The selection of the simulation modelling method is an important decision that is mainly based on a number of factors that relate to the purpose of the model, desired outcomes and scenarios explored. In this study, the aim is to assess energy technology development for sustainability. System dynamics is the dynamic systems approach that fits well with the intrinsic properties of technology development and sustainable development discussed in Chapter 2. In addition, system dynamics provides a tool for integrating different issues and concepts of a transdisciplinary research. Other benefits of using systems dynamics were discussed in Chapter 2.

4.3.2 Reflection on the ontological position of system dynamics for this study

According to Meadows and Robinson (1985) the primary ontological assumption of system dynamics is that, '*the persistent dynamic tendencies of any complex social system arise from its internal causal structure'*. Having reviewed the literature of the system dynamics paradigm, the discussion of the placement of this study based on Pruyt (2006) is provided. This is mainly intended to provide the ontological stance of the system dynamics which is taken in this study. The ontological / epistemological position for the system dynamics that is taken in this study is realism / subjective, which is categorized within critical pluralism paradigm. Thus, the researcher's view is that, systems, stock, flows and feedback loops exists, and they are interesting devices to structure, describe and make sense of perception of complex real world issues such as the one being investigated in this study – that is – technology assessment for sustainability. The subjective epistemology position taken in this study is due to the view that, the perceptions of the complex real world can be grasped through mental models. For the case of this study, the complex real world view about technology assessment for sustainability can only be of accessed through subjective views of the different actors and stakeholders ranging from technology assessment practitioners, technology developers and public agencies. This influenced the goal of modeling and research in which, for the case of this study, the goal was for learning; that is, enhancing the understanding of whether systems approach improves the technology sustainability assessment in South African renewable energy, with a specific case of biodiesel production development. The learning on the interventions to improve the sustainable biodiesel production development was also of interest in this study.

The author of this study was aware that the investigation was value-laden, that is, it was influenced by the researcher's theories and values. The system dynamics methodology was a combination of quantitative and qualitative techniques and variables, and there was consultation with the selected actors on the model, hence in a sense, ideographic. This study also undertook a rigorous scientific validation process of the model. At first sight, it might seem to take a positivist operations and measurements. In positivist, models should be refutable particularly if not corresponding to reality. This implies that validation is a process of comparing simulation results with real-world facts. It should however be noted that, the purpose of validation in this study was not to examine whether the model is refutable, but rather, due to the concerns of value ladenness, and the need to keep in practice with the mainstream system dynamics. Thus, this delineates the study from positivist operations and measurement.

4.3.3 System dynamics method

System dynamics is the simulation research methodology that was used to achieve the objective of developing a technology assessment model for sustainability. Different authors in the literature (Chapter 2) indicate different steps that are followed in developing a systems dynamics model (Randers, 1980; Richardson and Pugh, 1981; Roberts et al., 1983; Wolstenholme, 1990; Sterman, 2000). In dealing with technology assessment for sustainability, this study incorporated an additional step before the beginning with the system dynamics modelling. Thus, the procedure that was followed was STEP 1 and STEP 2 as shown in Figure 4.5. Each of these activities in each step as they pertain to the selected case study is explained in subsequent sub-sections.

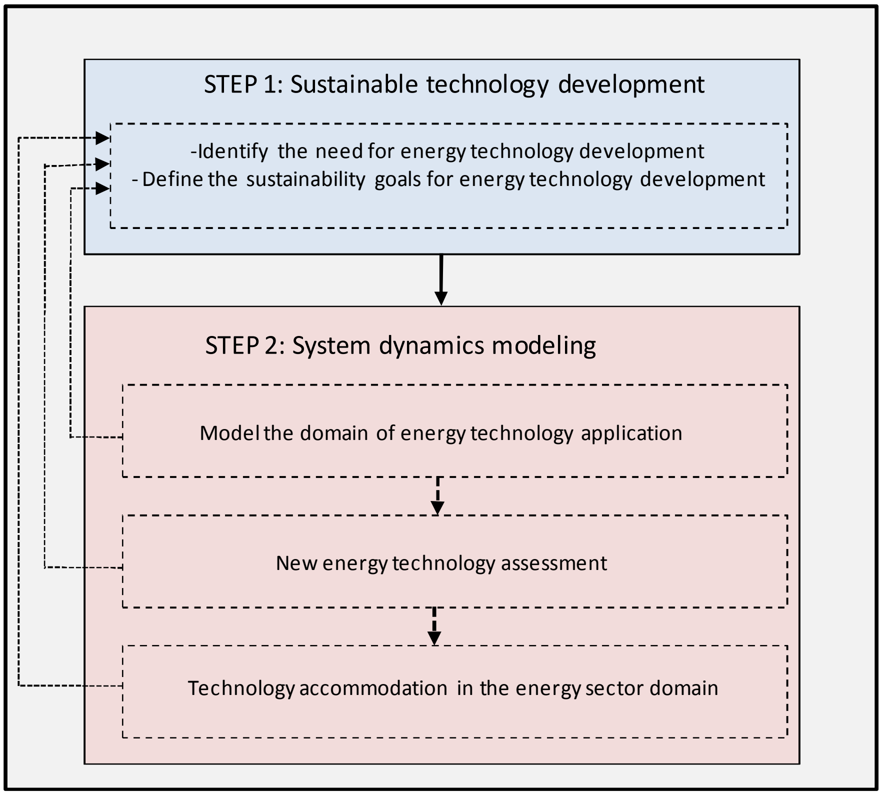

Figure 4.5: Methodological framework

4.3.3.1 STEP 1: Sustainable technology development

STEP 1, which is denoted as *sustainable technology development*, consists of two main activities. The first activity is the identification of the need for energy technology development in South Africa based on the secondary data sources and confirmation of the identified needs with the key actors in the energy sector. This study scope was limited to biodiesel production development in the Eastern Cape Province of South Africa, aimed for export market.

At a national level in South Africa, the driving forces of developing biodiesel include the need to:

i. decrease the dependence on imported fossil fuel;
ii. promote renewable energy;
iii. decrease greenhouse gas emissions/pollution;
iv. meet the Renewable Energy White Paper objectives of achieving 10000 GWh of energy from renewable by 2013; and
v. comply with the Kyoto protocol because South Africa ratified the protocol in 2002.

In the Eastern Cape Province, the identified needs for developing biodiesel production are outlined in the South Africa Biofuels Industrial Strategy (Department of Minerals and Energy, 2007). These needs are mainly to address the issue of rural poverty, rural development and Black Economic Empowerment.

The first activity of STEP 1 also entailed assessing all the existing features of biodiesel production development in Eastern Cape Province. This was also based on secondary data sources, information and data obtained through the desktop searches, personal communication with the researchers at the Department of Agriculture in Bisho and a survey visit in the Eastern Cape Province in South Africa (see Figure 4.6). The Department of Agriculture in Bisho is involved in some trial experiments of crops for biofuel production, and the communication with some of the key researchers facilitated the understanding of the state of the development of biodiesel crops production in the province.

Figure 4.6: Map of the case study location indicating the areas surveyed

The survey visit in the Eastern Cape Province took place in June 2009 where some of the potential areas earmarked for biodiesel crop production were visited. The specific areas visited were (i) Sigidi and Mbizana in Mbizana Municipality; (ii) Port St Johns in Port St Johns Municipality; (iii) Berlin, Zwelitsha, Mdantsane, Tyutyu village and Ndevana in Bufallo City Municipality; (iv) Idutywa in Mbhashe municipality; and Didimana in Lukanji Municipality and East London in Buffalo City Municipality (see Figure 4.6). Three methods were employed to interact with the communities: (i) a questionnaire, which comprised of both quantitative and qualitative data collection; (ii) a series of semi-structured interviews which consisted of a qualitative data only; and (iii) a focus group discussion, consisting of qualitative data only. This combination was used to gauge the attitude of the local community to the proposed biodiesel project through data triangulation: “the use of more than one approach to the investigation of a research question in order to enhance confidence in the ensuing findings” (Bryman, 2001).

These interactions enabled the understanding about the awareness and perception of biodiesel crop production and biodiesel production development in the Province[16]. In addition, a visit was made to the East London Industrial Development Zone, where one of the biodiesel plants was initially planned to be located. The planned location for the plant has, however, been changed a number of times, and it is currently planned to be established in the Coega Industrial Development Zone, which is in Nelson Mandela municipality (see Figure 4.7). During the visit at East London Industrial Development Zone, located in Buffalo City municipality (see Figure 4.7), there was a discussion on the state of the biodiesel plant development.

Figure 4.7: Map of the case study location indicating the location of the two IDZ's

The second activity of STEP 1 was to define the sustainability goals for the energy technology development, particularly the biodiesel production development in the Eastern Cape Province. In this activity, the linkages of biodiesel production development with the sustainable development sub-systems were identified. The Millennium Institute[17] sub-system

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[16] The outcome of the survey visit was published as a Journal article: AMIGUM, B., MUSANGO, J. K., & BRENT, A. C. 2010. Community perspectives on the introduction of biodiesel production in the Eastern Cape province of South Africa: questionnaire survey results. *Energy*, 36: 2502-2508.

[17] http://www.millenniuminstitute.net

diagram of Threshold-21(T21) model (Bassi, 2009), focussing on energy and national development analysis, was a basis for identification of the appropriate variables for consideration in this study. The final variables that were considered were also informed by the survey visit in the Eastern Cape Province and the scope of the study.

Figure 4.8 illustrates the major variables and interactions considered between society, economy and environment systems of biodiesel production development: (i) the society component included population, community perception and employment, which were relevant for the social system in the Eastern Cape Province; (ii) the economic component, which invests capital and labour for biodiesel production in the Eastern Cape economy; and (iii) the environmental component, which determined the key resources used, such as, land, water, energy and biodiesel related wastes.

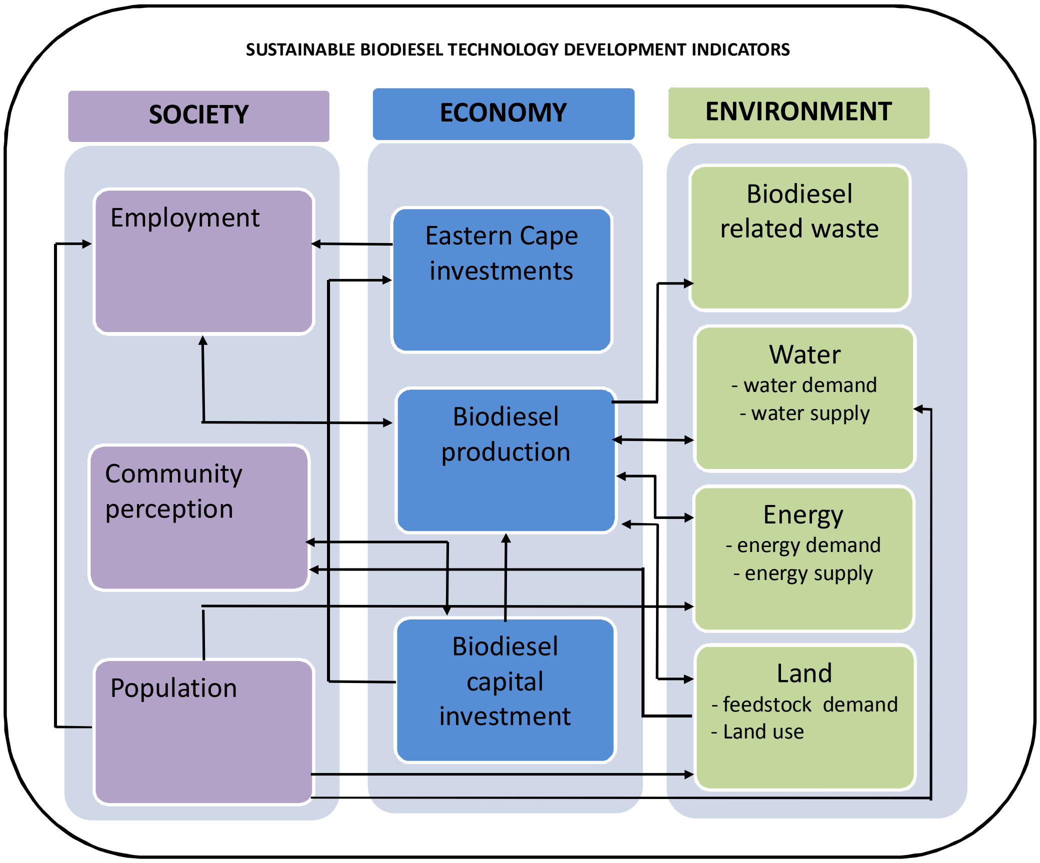

Figure 4.8: Society-economy-environment interactions in biodiesel production development

Information and data on the economic, environmental and social conditions in the Eastern Cape, as presented in Figure 4.8, were gathered from various sources. Data on population, employment, Eastern Cape investments (economy), land use and water demand and supply were obtained from: (i) Statistics South Africa[18]; and (ii) the 2005 development report by the United Nations Development Program, the Development Bank of Southern Africa and the Human Sciences Research Council[19]. Data on biofuels capital investment and biodiesel production were obtained from various websites such as Engineering News[20]; bioenergy site[21]; Department of Minerals and Energy documents, currently the Department of Energy; personal communication with individuals in the East London Industrial Development Zone; and a survey with the community in the Eastern Cape communities by means of person to person semi-structured interviews and a focus group discussion.

This information and data were necessary to populate the environmental, economic and social impact/indicators related to biodiesel technology development. Sustainability indicators involve either direct quantitative measurement and/or qualitative assessments given quantitative rankings. This study focused on quantitative indicators, and used disaggregated indicators.

It is important to note that some indicators are directly related to a specific technology under consideration. Based on the literature review (Chapter 2), some of these sustainability indicators were used as a basis for renewable energy technology assessment were found in Evans et al. (2009), Evans et al. (2010) and Silva Laro et al. (2011) and included:

i. production cost;
ii. greenhouse gas emission;
iii. availability and limitations of each technology;
iv. efficiency of energy transformation must be known for meaningful comparison;
v. land use requirements;
vi. water consumption, which is particularly important in arid climates and water scarce countries like South Africa; and
vii. social impacts that are technology dependent.

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[18] www.statssa.gov.za

[19] http://www.hsrc.ac.za/Research_Publication-18627.phtml

[20] www.engineeringnews.co.za

[21] http://www.thebioenergysite.com/articles/359/south-africa-biofuels-annual-report

Other indicators are dependent on the economic, environmental, social and political context in which the technology is being implemented. Thus, additional energy technology development sustainability indicators were identified during the interactions with the stakeholders. Data limitations are often a significant obstacle to generating large indicator sets, and, this study was not an exception to such a limitation. The final choice of indicators that were used in this study was thus driven by four main factors:

i. indicators that had most relevance to the study subject;
ii. indicators that reflected the Eastern Cape Provincial issues of biodiesel production development;
iii. indicators encompassing each of the environmental, social and economic and other spheres of sustainability; and
iv. ability to quantify the indicators and data availability.

Based on the above criteria, ten indicators were identified and selected for the biodiesel technology assessment and are presented in Table 4.4. This includes three economic indicators: biodiesel production, biodiesel profitability, and Eastern Cape per capita GDP; two social indicators: employment created due to biodiesel plant development, and the community perception of growing crops for biodiesel production; and five environmental indicators: air emissions resulting from biodiesel production, land use changes due to the introduction of the biodiesel production, water and energy use in the biodiesel production, and biodiesel by-products, particularly glycerol.

Table 4.4: Sustainability indicators for bioenergy technology assessment

	Indicator	**Symbol**	**Description**	**Units**
Economic	Biodiesel production	ECO_1	This measures the quantity of biodiesel production	Litre/year
	Biodiesel profitability	ECO_2	This measures the profitability from biodiesel production	Rand/year
	Eastern Cape GDP	ECO_3	This measures the per capita GDP in the Eastern Cape Province	Rand/person/ year
Social	Employment	SOC_1	This measures the labour force participation due to the investment in the biodiesel plant capacity	Person
	Community perception	SOC_2	This is represented by the effect of community perception on land conversion for biodiesel production crops and measures the community acceptance to grow these crops	Dimensionless
Environmental	Land use change	ENV_1	This measure the changes in land use due to the introduction of biodiesel production. This includes changes in fallow land, agricultural land, biodiesel crop land and livestock land.	Ha
	Air emission	ENV_2	This measures the total avoided air emissions due to investment in biodiesel production	kg CO_2/year
	Biodiesel by-product	ENV_3	This measures the amount of accumulated glycerol resulting from biodiesel production.	Litre/year
	Water use	ENV_4	This measures water use as a result of biodiesel production	Litre/year
	Energy use	ENV_5	This measures energy use as a result of biodiesel production	kWh/year

4.3.3.2 STEP 2: System dynamics modelling

STEP 2, denoted as *system dynamics modelling*, consists of three main activities namely: modelling the domain of energy technology application, new energy technology assessment, and technology accommodation in the energy sector domain. These activities are synonymous to the three-stage approach to technology assessment of Wolstenholme (2003). However, unlike Wolstenholme (2003), this study proposed a STEP 1, *sustainable technology development,* whereby there are linkages with the *system dynamics modelling*. This is because the identification of the energy technology options and their respective sustainability indicators should be defined before the *system dynamics modelling*. The VENSIM® software[22] was used to implement the activities in STEP 2. The VENSIM®

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[22] www.vensim.com

software provides a flexible and simple platform for building simulation models for both causal loop diagrams or stock and flow diagrams (Ventana Systems, 2003). The detail of the system modelling process for this study is provided in Chapter 5. In this section, only a brief explanation of the activities involved in the STEP 2 is provided.

Modelling the domain of energy technology application

The first activity of STEP 2 involved the problem definition, conceptualization and dynamic hypothesis. The model developed in this study was for the biodiesel production development in the Eastern Cape Province and was named the bioenergy technology sustainability assessment *(BIOTSA)* model. Based on the intentions of the *BIOTSA* model and the domain of the intended users that need to be influenced, the boundary of the model was selected to focus on a specific project on biodiesel production development that is designated for the export market. Biodiesel production development projects involve diverse actors including among others, the policy-makers, technology developers/investors; technology assessment practitioners; and the community that would be involved in growing crops for the biodiesel production. An appropriate project scope was necessary to ensure that both down and upstream effects of decisions were accounted for. Confining this to a project wide scope also ensured that the scenarios were tested within the realm of the responsibility of the model users. For instance, while a biodiesel technology developer may have influence on the overall biodiesel production level, venturing beyond the boundaries of a biodiesel project level could reduce the relevance and feasibility of scenarios, and as a result reduce the model's usefulness and practicality.

These events of the first activity of STEP 2 took place following a number of discussions and workshops at various levels and with different researchers who were considered knowledgeable in the field.

The first discussion was with three researchers at Council for Scientific and Industrial Research (CSIR), which occurred during September 2009. The discussion was on the Bioenergy System Sustainability Assessment and Management (BIOSSAM) model[23]. It is

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[23] For more detail of the BIOSSAM model, refer to: MUSANGO et al. 2010 Understanding the implication of investing in biodiesel production in South Africa: A system dynamics approach. Paper presented at the 28th International Conference of System Dynamics Society, Seoul, South Korea, 25-29 July 2010.

from the BIOSSAM model that the *BIOTSA* model was extended to provide a case specific for technology assessment for sustainability.

The initial discussion on the BIOSSAM model was followed by a workshop, which was held from the 5th to the 9th of October 2009 at the Council for Scientific and Industrial Research in Stellenbosch. The first four days of the workshop was a meeting with the three researchers from CSIR and a senior systems dynamics modeller from Millennium Institute[24] in the USA. The senior systems dynamics modeller facilitated in providing the technical aspects of the conceptualization of the modelling process. On the last day of the workshop (9th of October 2009), five participants from Energy Research Centre (ERC)[25] who are involved in, among other things, energy modelling joined the workshop. In addition, four other researchers from CSIR also joined the workshop. In total, there were 12 participants on the last day of the workshop. The initial ideas of the problem definition, conceptualization and dynamic hypothesis were presented to the participants. The participants supported the modelling approach and a number of suggestions were made for further model development. The full detail of the *BIOTSA* model problem definition and dynamic hypothesis is discussed in Chapter 5.

New energy technology assessment

The second activity of STEP 2 was the technology assessment of biodiesel production development in the Eastern Cape Province on the sustainability indicators identified in STEP 1 (see Table 4.4). This activity entailed the *BIOTSA* model formulation and model testing. The details of the model formulation are also discussed in Chapter 5. Model testing is an iterative process and begins from the moment the model building starts.

Validation and verification is part of the model testing. There are four aspects of validity that are considered in the system dynamics modelling: *soundness* and *completeness* of the model structure and *plausibility* and *correctness* of the model behaviour (Nguyen, 2005). *Soundness* is based on the valid reasoning and thus free from logical flaws; *completeness* of the model structure implies that the model includes the relevant variables to define the problem and

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[24] http://www.millenniuminstitute.net/

[25] http://www.erc.uct.ac.za

causal relationships that concern stakeholder; *plausibility* of model behaviour implies that the scientific laws are not contradicted by the model behaviour; and *correctness* of behaviour implies that the computed and the measured behaviour are consistent. Validation of the system dynamics model can take place at the end of the model formulation stage. This however does not imply it is the end of the life cycle of the model. There is always the need of adjustment when new knowledge and data becomes available.

According to Barlas (1989), there are three classes of validity tests: (i) structural validity tests; (ii) behaviour validity tests; and (iii) policy implication tests. As part of the validation process for the *BIOTSA* model all these tests were applied and this is fully discussed in Chapter 6, section 6.3. In addition, a qualitative evaluation of the model performance using the expert opinion was used. Thus, the process of validating the *BIOTSA* model structure and behaviour addressed three questions concerned in the validation as stated by Shannon (1975; 1981):

(i) is the structure of the model, its underlying structure and parameters contradictory to the observed reality and / or to those obtained from expert opinion?

(ii) is the behaviour of the model system consistent with the observed/hypothesized behaviour of the real system?

(iii) does the model fulfil its designated task or serve its intended purpose?

The VENSIM® software in which the *BIOTSA* model was compiled facilitated the model testing. In addition, there were also a number of sessions where the initial model results were presented in order to facilitate discussion around the baseline results and gain insights on further model improvements and validation. Some of these sessions were:

i. A seminar at the Energy Research Centre (ERC) of the University of Cape Town, which was held on 13 July 2010. The aim of this seminar was to present the *BIOTSA* model mainly to a large number of participants who attended the workshop at Council for Scientific and Industrial Research and gather their input on the progress of the model. There were 10 participants who attended the seminar. During the seminar, the progress of the model was presented and was followed with discussion of the model, facilitated by a participant from the CSIR. Due to the time constrains, the participants felt there was a need to hold another seminar.

ii. Part of this PhD work was presented at the 28th International Conference of System Dynamics Society PhD Colloquium on 25th July 2010 in Seoul, South Korea. Comments and suggestions were provided by the conference participants. It is worth noting a one hour informal meeting which was held with a system dynamics society member and MIT graduate on the 26th July 2010. During this meeting technical issues for improving the *BIOTSA* model structure was discussed and implemented.

iii. The *BIOTSA* model was presented to a class of participants of a postgraduate bioenergy course on the 17th September 2010 at the Sustainability Institute[26]. The aim was to present the case study which was on bioenergy and illustrate how to assess sustainability within the bioenergy system. During the presentation, the participants were first introduced to systems thinking and system dynamics. This was then followed with the presentation of the *BIOTSA* model. The participants were thereafter requested to discuss on the issues what they thought were omitted from the *BIOTSA* model.

iv. A follow-up lecture with the Energy Research Centre was held on 30th September 2010. It was attended mainly by the participants of the ERC and their postgraduate students doing a course on energy modelling. Thus the total number of people who participated was 15. In this session, the fully developed model, which incorporated previous comments, was presented. Once the presentation was concluded, the participants were given a short questionnaire (see Appendix B) to provide their views on the usefulness of the *BIOTSA* model. The questionnaires were collected after 3 days in order to provide the participants enough time to thoroughly consider and answer the questions. The responses for question two of the questionnaire (see Appendix B) were aggregated using a simple average method. The ranking given to each of the responses is presented in Table 4.5.

Table 4.5: Weights for responses

Response (X)	Weight (w)
High	3
Medium	2
Low	1
No opinion	0

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[26] http://www.sustainabiltyinstitute.net

The final average ranking of the response (X) was calculated using the following formula:

$$X = \frac{1}{n}\sum_{i}^{n} w_i \qquad \text{Equation 4.1}$$

where: n is the number of responses; and w_i is the weight of given to the response. The value of X was rounded to the nearest whole number. The results of the questionnaire are discussed in Chapter 6, sub-section 6.3.3.

Technology accommodation in the energy sector domain

The third activity in STEP 2 (refer to Figure 4.5) is the critical one in the sense that it experimented on the ways in which the biodiesel production development could be accommodated to improve its effect on the selected sustainability indicators. It involved policy formulation and evaluation of the changes in policies and procedures that could help in improving the biodiesel production development impact on the sustainable development indicators. A number of scenarios were thus developed for biodiesel production development in the Eastern Cape Province which is discussed in Chapter 6. Within this activity, a friendly interface for non-users of system dynamics was developed (refer to the accompanied CD).

4.3.4 Survey methodology

A survey methodology was used to a limited extent to achieve the objective of model validation, verification and demonstration of the usefulness of the *BIOTSA* model. The target population for the survey was the non-academic experts highlighted in Figure 4.3. According to Knoke et al. (2005: 788) the target population is a theoretical construction while a sampling frame provides the size of the target population that is included in a study. This study aimed to have a sample that was representative of the non-academic target population. A semi-structured questionnaire was used to gather the information from the representatives. The phases that were involved in the survey were:

4.3.4.1 Identification of the non-academic target population

The identification of the non-academic target population from the point of technology assessment practitioners and technology developers was not difficult. The technology developers that were identified were the East London Industrial Development Zone, the Coega Industrial Development Zone, and Sasol. However, the target population in the public agencies was initially difficult to identify due to: (i) there is no formal technology assessment agency in South Africa; and (ii) biofuel development in South Africa is only entering the growth stage and no large-scale commercial production exists as yet.

The survey visit in June 2009 provided the initial ideas of who would be the potential target stakeholder. In addition, there were several consultations with four key people in the field who guided in identifying the relevant main target population in the public agencies. This target group are the individuals working on the relevant issues of renewable energy technology development in South Africa and particularly in the Eastern Cape Province. Thus, as mentioned earlier, the final target stakeholders in the public agencies were: the Technology Innovation Agency; the Department of Energy; the Accelerated Shared Growth Initiative of South Africa in the Eastern Cape; the Eastern Cape Provincial Department of Economic Development and Environmental Affairs; the Eastern Cape Socio Economic Council, and the Eastern Cape Appropriate Technology Unit.

4.3.4.2 Identification of the specific participants/representatives in the target population

This phase entailed identifying the specific participants/individuals who would be representatives for the target population. The criterion for the selection was that the representative should be in a position to influence policy or decision-making in the biodiesel development. A total of twelve representatives were identified in all the different institutions in which: seven were from the different institutions in the Eastern Cape Province; two were from the Department of Energy; two from Sasol; and one from Technology Innovation Agency. Due to the confidentially of the representatives, their names and position is not disclosed in this study.

4.3.4.3 Contacting the identified representatives

Once the specific representatives were identified, the next step was to contact these individuals. The Eastern Cape representatives were contacted telephonically and were questioned as to their availability during the week of the 8th to the 12th November 2010. Once they confirmed their availability, a letter was sent to each of the representatives confirming the meeting and the activities that would take place (See Appendix C). In addition, a questionnaire was attached to the letter in order for the representatives to prepare themselves of the questions that they were expected to answer (See Appendix C). An attempt was made to ensure that any jargon was excluded in the letter and questionnaire. A similar process was done for the representatives in Department of Energy, Sasol and Technology Innovation Agency. However, these were contacted through an email which provided the purpose of the appointment and a request for indication of the availability. The appointments were set for 18th January 2011 and 16th March 2011; 11th March 2011 and 29th March 2011 for Department of Energy, Technology Innovation Agency and Sasol respectively.

Meeting with the identified representatives

In order to meet with the identified representatives, a visit was made to each of the participant's office on the indicated dates. For instance, the participants in the Eastern Cape Province were visited in the week of the 8th to the 12th November 2010. These meetings began with a brief introduction of the aim of the study, the objective of the meeting with the representative and the required outcome of the meeting which was their views and comments on the *BIOTSA* model relevance, reliability, practicality and importance in assessing biodiesel technology development for sustainability in the Eastern Cape Province. The user friendly *BIOTSA* model was then presented to representatives and each was requested to provide their answers of the questionnaire. The representatives were given time to answer the question which was collected at the end of the meeting; these meetings took about two hours. In the questionnaire, the representatives were also asked to provide additional comments and views on the *BIOTSA* model. This method of obtaining information assumes that the non-academic experts are unbiased and consistent. Given the anticipated outcome of the questionnaire and the voluntary willingness of the non-academic experts to participate in the survey, this method was regarded as appropriate for the case study.

The meetings with the key representatives enabled this study to identify whether the *BIOTSA* model was appropriate for its intended use in biodiesel technology development policy formulation and decision-making in South Africa. The representative's views, concerns and comments are discussed in Chapter 6, section 6.3.3.

Aggregation of the opinions

In a similar manner, the responses of the non-academic experts for question two of the questionnaire were aggregated using the simple average method as shown in Equation 4.1 above.

4.3.5 The use of a case study approach and challenges

Case study is a useful approach when a holistic and in-depth investigation is required (Feagin et al., 1991). Case studies have a wide application in many disciplines particularly in the sociological studies and policy evaluation. Other researchers have developed robust procedures for this methodology (Yin, 1994, Stake, 1995). Yin (1993) identifies three types of case studies namely: explanatory, exploratory and descriptive. Other additional types of case studies included by Stake (1995) are: *intrinsic,* in which the researcher has an interest in the case study; *collective*, where a group of case studies are investigated; and *instrumental,* where the case is used to understand more than what is obvious to the observer.

This study followed the general approach by Yin (2003) whereby, irrespective of the case study type that is used, there can either be a single case or multiple cases. The main application in this study was to explain the complex causal links in real-life interventions, which is one of the four main applications of the case study identified in Yin (1994). Understanding the complex-real life situation involving societal phenomena requires a specific case study or experience (Eisner, 1998). While the use of a case study is not a sampling research (Feagin et al., 1991, Yin, 1994, Stake, 1995), the selection of a case in this study was aimed at maximizing learning for energy technology sustainability assessment practises in the South African context.

The main criticism that is raised in the literature due to the use of the case study is the issue of providing generalizable explanations (Dyer and Wilkins, 1991). This criticism is however refuted by Yin (1984) who provides a constructive explanation of the difference between the statistical and analytical generalisation. While it is unusual for the outcome of the case study to generalise the way the natural science data does, cases however do provide an opportunity for generating and testing theory (Denzin, 2009). According to Flyvbjerg (2007), there is no reason given as to why the knowledge that is generated from a case study cannot enter the collective process of accumulating knowledge in a particular field. Knowledge transfer occurs through a critical process of engagement as ideas appear to the reader (Eisner, 1998). Thus, the use of a case study provides a 'method of learning' (Flyvbjerg, 2007).

4.4 CONCLUSION

The research design used in this study is transdisciplinary research, which entails transcending beyond disciplines. However, this study was limited to consultative transdisciplinarity where the non-academic experts were contacted to respond to the work that was done. The transdisciplinary characteristics of ontology, epistemology, methodology and organization as they relate to this study were discussed.

Three objectives are contained in this study. The first two objectives relate to the literature review and were covered in Chapter 2 and Chapter 3 respectively. This chapter provided a detailed discussion on the research methodology that was employed to achieve the objective of developing, populating and validating the *BIOTSA* model. Simulation, and more specifically system dynamics, is the methodological approach that was used for the objective of developing and populating a system dynamics model for energy technology sustainability assessment. This was complemented with survey methodology, which was used to a limited extent in order to validate, verify and demonstrate the usefulness of the *BIOTSA* model for its intended use in sustainable renewable energy technology assessment in South Africa. Chapter 5 provides a more detailed discussion of the *BIOTSA* modelling process.

CHAPTER 5: BIOENERGY TECHNOLOGY SUSTAINABILITY ASSESSMENT (*BIOTSA*) MODELING PROCESS[27]

5.1 INTRODUCTION

The aim of this study is to improve renewable energy technology sustainability assessment practices in South Africa in which *SATSA* was developed as a guiding conceptual framework. In order to demonstrate the application of the *SATSA* framework, biodiesel technology development in the Eastern Cape Province of South Africa was selected as a case.

Chapter 4 provided the methodological framework that can be followed in energy technology sustainability assessment, which consists of two steps (Figure 4.5). STEP 1 which entails identifying biodiesel development needs and the respective sustainability indicators was detailed in Chapter 4. In STEP 2 of the methodological framework, a system dynamics model for assessing the impacts of biodiesel technology development in the Eastern Cape Province was developed and named as the bioenergy technology sustainability (*BIOTSA*) model.

The *BIOTSA* modelling process was briefly discussed in Chapter 4 and therefore this chapter elaborates on this discussion. While different authors (Randers, 1980; Richardson and Pugh, 1981; Roberts et al., 1983; Wolstenholme, 1990; Sterman, 2000) in the literature have discussed different numbers of steps involved, the content of the system dynamics modelling process is however similar and there is an understanding that the modelling process is iterative. This chapter begins with the discussion of the problem formulation for the *BIOTSA* model which is then followed by the discussion on the dynamic hypothesis. Finally, the description of the model boundary, model structures and equations of selected variables is discussed.

5.2 PROBLEM FORMULATION

According to Sterman (2000), problem formulation is an important step of the modelling process. A clear purpose enables successful modelling and allows the model users to reveal

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[27] The content of this chapter was presented at the 20th International Association for Management of Technology (IAMOT), 10-14 April 2011, Florida, USA. A paper based on this work has been accepted for publication in *Energy*. See Appendix A for details.

the usefulness of the model in addressing the problem (Sterman, 2000). Effective models are those designed for a small problem or account for a part of the system rather than looking at the whole system itself. Identifying the purpose of the model based on the problem is fundamental in guiding the modeller about the boundary of the model. In this study, the problem formulation was guided by the STEP 1 of the methodological framework (refer Figure 4.5), which identified the needs for developing biodiesel production in the Eastern Cape and the sustainability indicators. The key problem in the design of the *BIOTSA* model was to explore policies to ensure sustainable transition in the biodiesel production in the Eastern Cape Province.

The hypothesis of this study is that the *SATSA* framework is appropriate for technology sustainability assessment and the system dynamics is the suitable dynamic systems approach. In order to aid in steering the appropriateness of the model there is however the need to be aware of the intended use of the simulation. The intended use of the *BIOTSA* model is to aid biodiesel technology developers and energy policy/decision-makers with strategic planning by providing them with a model for making informed decisions regarding biodiesel technology development for sustainability. Thus, the *BIOTSA* model would provide insights on the effect of biodiesel production development in the Eastern Cape Province on the selected sustainability indicators, and enabling the comparison of the outcomes on the various scenarios or decisions.

Another important feature in the problem characterization is the time horizon for the model. Many conventional approaches focus on short time horizon due to their event oriented outlook. Assessing sustainability of any technology development needs to be embedded in the system as a whole such that the systems evolution over a long-term can be simulated with/and or without penetration of the targeted technology (Chan et al., 2004). Thus, biodiesel production development for sustainability requires a long time horizon. Most simulation models are set for 30-50 years. However, *BIOTSA* model takes into account of a longer time effect of biodiesel development on the selected sustainability indicators. Thus, the time horizon that was considered runs from 2005-2100.

5.3 FORMULATING DYNAMIC HYPOTHESIS

This step involves developing a working theory to explain the problem that is being considered. This is denoted as dynamic hypothesis because it describes the dynamics of the behaviour of a system based on the underlying feedbacks and interactions between the different parts. The dynamic hypothesis helped in developing an appreciation for the dynamic complexity of the development of biodiesel production for sustainability in the Eastern Cape Province. This study thus formulated a number of causal loop diagrams to provide an endogenous explanation while at the same time portraying the essential components and interactions in the development of biodiesel production in the Eastern Cape Province. This is essentially accomplished using systems thinking approach as suggested by Flood and Jackson (1991), O'Connor and McDermott (1997) and Maani and Cavana (2007).

A causal loop diagram comprises connections of variables by causal links, which are denoted by an arrow. The links usually have either a negative or positive polarity denoted by "**+**" and "**-**" respectively. The negative polarity implies that, if the cause decreases (increases), the effect increases (decreases). On the other hand, a positive polarity implies that, if the cause increases (decreases) the effect increases (decreases). This is exemplified by a simple population diagram as shown in Figure 5.1. The polarity of each of the feedback loops are also specified. If a feedback loop has an even number of "-" signs, then it is a positive loop; and if it has uneven number of "-" signs, then it is a negative loop (Coyle, 1996). A positive feedback loop is also known as a reinforcing loop and is normally marked with "R" (Sterman, 2000) as shown in Figure 5.1. It is known as a reinforcing loop because it is an amplifying or enhancing feedback loop (Meadows, 2008). On the other hand, a negative feedback loop is also known as a balancing loop and is normally marked with "B" (Sterman, 2000) as shown in Figure 5.1. It is a balancing loop because it is stabilizing, goal seeking and regulating feedback loop (Meadows, 2008). This polarity labelling is an important step of qualitative modelling in system dynamics and it is an initial step towards developing the feedback structure described by stock and flow diagrams and finally by equations.

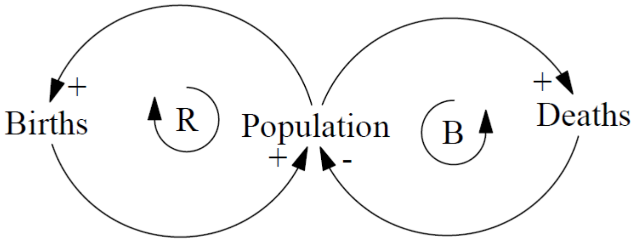


Figure 5.1: Example of a causal link with polarity (adapted from Sterman, 2000)

Biodiesel production development for sustainability involves significant dynamic complexity. The discussion of the feedback structures is systematically discussed according to the economy, society and environmental sub-sectors described in Figure 4.8 in Chapter 4. The investors' concern in the biodiesel production development is mainly the profitability of the operation. Thus, at the highest level of aggregation in the economic sub-sector of biodiesel production development, a simple reinforcing loop is produced as shown in Figure 5.2. In this case, the biodiesel investment promotes the biodiesel plant capacity, which increases the biodiesel production. This in turn increases the biodiesel profitability, which stimulates further investment.

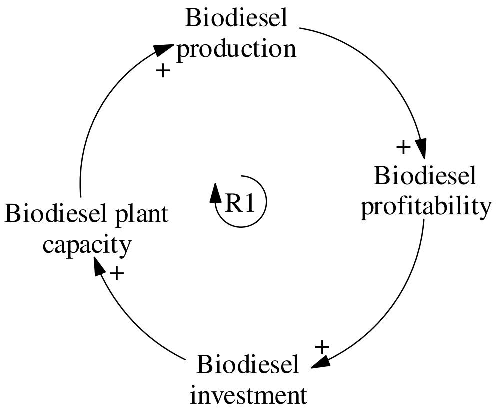


Figure 5.2: Biodiesel production causal loop diagram, economic sub-sector

An expanded overview of the economic sub-sector of biodiesel production development is presented in Figure 5.3 which consists of three reinforcing loops (R1, R2 and R3) and two balancing loops (B1 and B2). From Figure 5.3, balancing loop B1 shows that biodiesel production also leads to an increase in the biodiesel operations and maintenance costs which in turn decreases the biodiesel profitability. A decrease in profitability reduces the incentive for biodiesel investment, and this means that after a delay, the biodiesel plant capacity is reduced hence decreasing the biodiesel production.

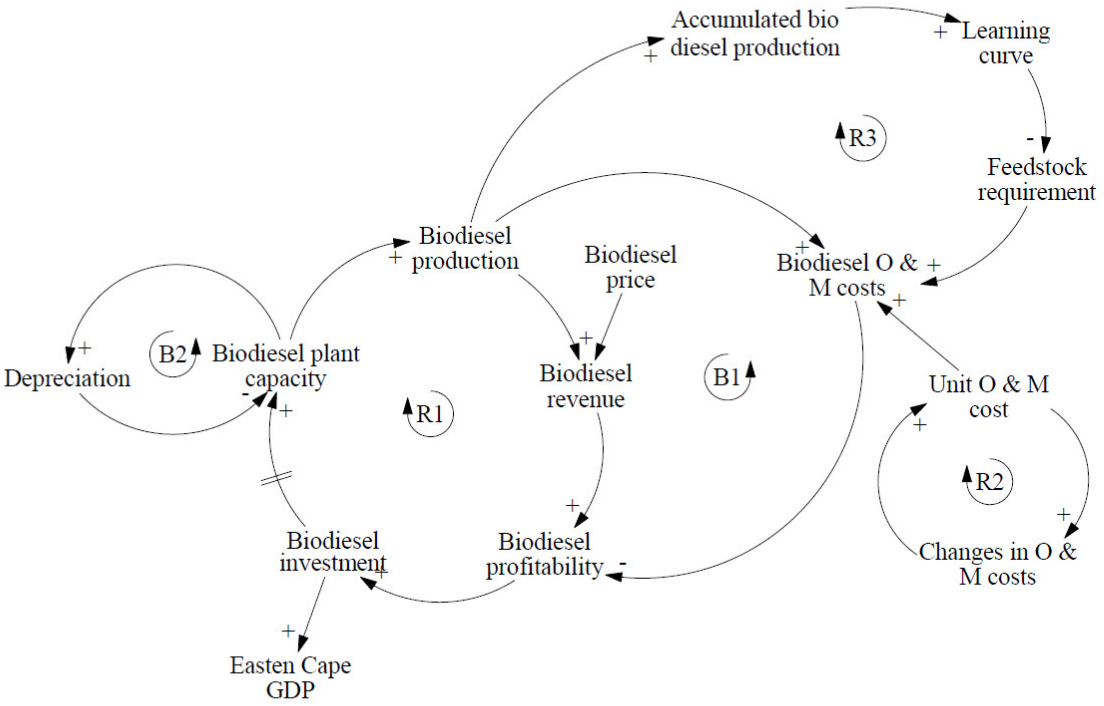


Figure 5.3: Expanded biodiesel production causal loop diagram, economic sub-sector

Given that biodiesel production is a new technology in the Eastern Cape Province, reinforcing loop R3 shows that increasing biodiesel production increases the accumulated biodiesel production. This in turn leads to an increase in the learning curve resulting from the conversion efficiency of the feedstock. A higher learning curve decreases the feedstock requirement which in turn reduces the biodiesel operations and maintenance costs. The latter increases the profitability of biodiesel production, which then drives up the biodiesel investment, making it more possible to expand the biodiesel plant capacity and thus increase the biodiesel production.

The dynamics of the social context of the biodiesel production development is presented in Figure 5.4. The social sub-system consists of three reinforcing loops (R4, R5 and R6) and three balancing loops (B3, B4 and B5). The feedback loops that are discussed here are R4, B4 and B5. Reinforcing loop R4 in Figure 5.4 shows that higher biodiesel plant capacity increases the desired employment in the biodiesel plant which increases the number of workforce that requires training. This in turn increases the number of the trained workforce which consequently increases the biodiesel production. Increased biodiesel production implies increased revenue and consequently increased profitability. This increases the biodiesel investment and thus increased biodiesel plant capacity.

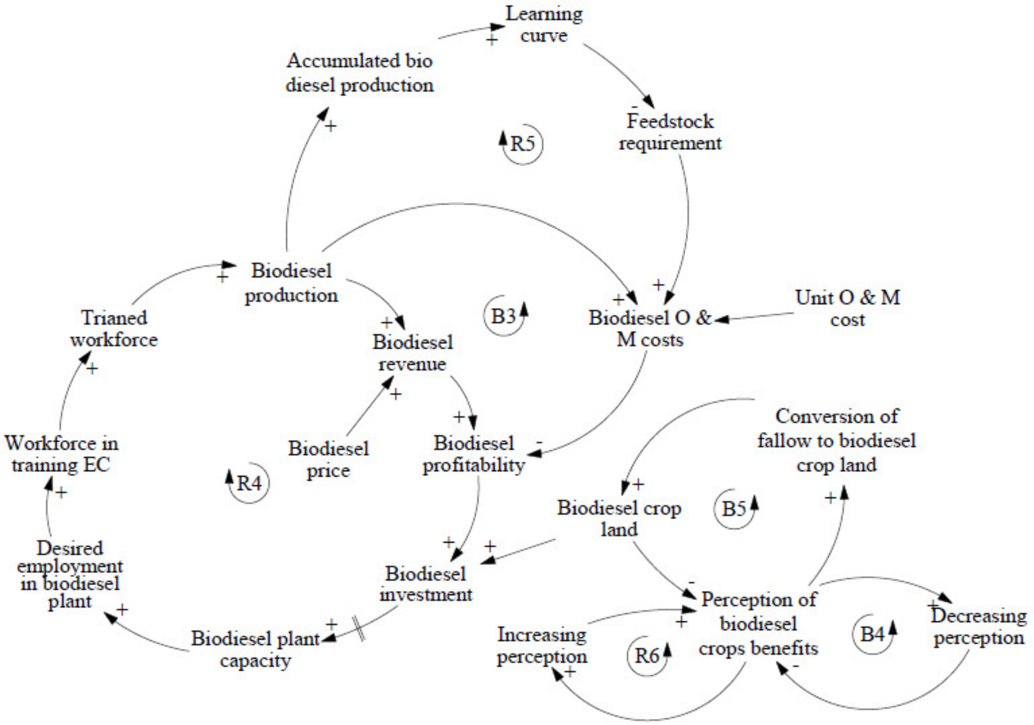


Figure 5.4: Biodiesel production causal loop diagram, society sub-sector

Based on the surveys with the local community in some of the areas that are identified as potential for biodiesel crop production, the community perception on the biodiesel crops benefits was considered an important social variable. According to the balancing loop B4, the higher the level of perception of biodiesel crops benefits, the higher the decreasing in perception. On the other hand, a higher decrease in perception reduces the level of perception of biodiesel crops benefits. In a different view, the balancing loop B5 shows perception of the biodiesel crops benefits increases the conversion of fallow land to biodiesel crop land. This in turn increases the amount cultivated with the biodiesel crop land. Increasing the amount of land under biodiesel crops however decreases the perception about these crops. This relationship is based on the survey and observation at the Eastern Cape, where land is one of the huge concerns. The availability of the biodiesel crop land on the other hand is a key driver of the biodiesel investment decision-making.

Taking a look at the environmental setting of biodiesel production development, Figure 5.5 shows that there are two balancing loops (B6 and B7) and one reinforcing loop (R7). As shown in balancing loop B6, increasing biodiesel production results in higher demand for water, which increases the water stress index. An increase in the water stress index leads to an increase in the effect of the water stress on the crop yield which in turn reduces the amount of feedstock supply and ultimately affecting the biodiesel production. Another interesting dynamics observed is reinforcing loop R7 where an increase in biodiesel production increases the feedstock demand which in turn implies higher biodiesel crop requirement. Having more land dedicated to biodiesel production means that there is an increase in the feedstock supply which in turn influences the biodiesel production.

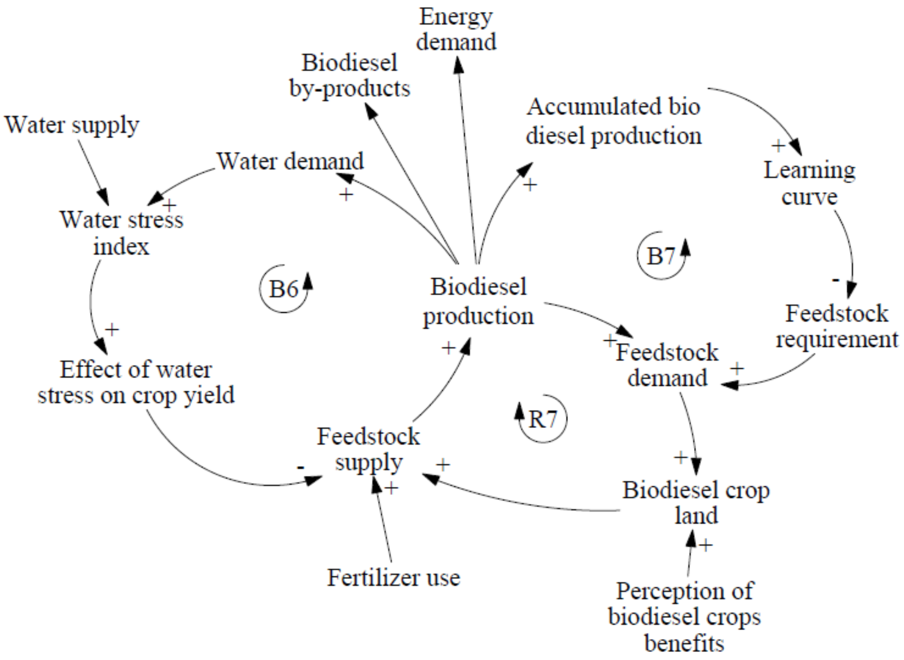


Figure 5.5: Biodiesel production causal loop diagram, environmental sub-sector

The balancing loop B7 in Figure 5.5 shows that increased biodiesel production does lead to increased accumulated biodiesel production, which increases the learning curve. An increase in the learning curve drives down the feedstock requirement which in turn decreases the feedstock demand. A decrease in the feedstock demand thus means a reduction in biodiesel crop land and hence a decrease in feedstock supply. This ultimately decreases the biodiesel production.

Having formulated the dynamic hypothesis for the three sub-sectors the model boundary, structure and equations are discussed in the subsequent Section 5.4.

5.4 *BIOTSA* MODEL BOUNDARY

The main purpose of the system dynamics models is to provide an endogenous explanation of the problem (Sterman, 2000). Therefore, the variables that influence the dynamics of the behaviour of the system should be included in the model. Deciding on what variables to include (endogenous), those to be treated as exogenous variables and the excluded ones is determined by the purpose of the model and or problem being analysed. The relationships between some of the key variables for the *BIOTSA* model were described by the causal loop diagrams which are presented in Section 5.3. The purpose of the *BIOTSA* models is to provide insights on the biodiesel production development in South Africa on selected sustainability indicators. Thus, the model seeks to provide possible implications to the transition towards biodiesel production development in the Eastern Cape Province. It also aimed to provide insights to policy-makers to make proper decisions with regards to this transition. A summary of the *BIOTSA* model boundary, showing the variables that are endogenous, exogenous and excluded ones is presented in Table 5.1. As observed in Table 5.1, many of the important variables were determined endogenously in the model. Several exogenous variables also drive the model behaviour. The list is not exhaustive as some of the exogenous variables are either table functions or time series data. The lists of all the table functions are fully provided in the Section 5.5 which discusses the structure and equations of the *BIOTSA* model.

Table 5.1: *BIOTSA* model boundary chart

Endogenous	**Exogenous**	**Excluded**
Biodiesel crop land	Energy price	Food
Fallow land	Feedstock price	Oil
Crop land	Other operational costs	Other biofuels e.g. bioethanol
Settlement land	Water price	Employment at farm level
Conservation land	Unit capital costs	Community other crop experiences
Livestock land	Feedstock cost growth	Land fertility
Forest plantations land	Capital cost growth	Government investment
Biodiesel capacity construction	Water cost growth	Energy supply
Functional biodiesel capacity	Other operational cost growth	
Biodiesel production		
Desired new biodiesel capacity		
Expected biodiesel profit		
Population		
GDP		
Perception of biodiesel crop land		
Community acceptance		
Feedstock cost		
Unit biodiesel profitability		
Desired employment biodiesel plant		
Workforce in training EC		
Trained workforce EC		

While the excluded variables may be interesting, the reason for their exclusion was either due to the scope of the problem analyzed or lack of data for some of the social variables; or due to an increase in complexity of the model. As an illustration, land fertility may have potential implications on the feedstock demand analysis but was excluded from the *BIOTSA* model. This is because in order to have such a sub-model, one has to clearly understand the different soil types and their fertility. Since the study is looking at a high level of aggregation of the different land uses (provincial level), this was not practical to be included. However, the studies investigating lower level units (e.g. district, municipality, and farm) should take into account of land fertility. Thus, due to the need of appropriate simplicity, these features were excluded at this stage of research.

5.5 *BIOTSA* MODEL STRUCTURE AND EQUATIONS

The *BIOTSA* model was divided into eleven sub-models. These sub-models represent the economy, society and environment interactions of the biodiesel production presented in Figure 4.8 in Chapter 4. These sub-models are: biodiesel production, cost of operation, biodiesel production profitability, GDP, employment from biodiesel plant, community perception, population, land, water, air emissions and energy demand. Each sub-model and selected variables equation is described in the subsequent sub-sections.

5.5.1 Biodiesel production sub-model

The biodiesel production sub-model is one of the core systems of the *BIOTSA* model. Currently in South Africa, there is no commercial large-scale biodiesel production (Amigun et al., 2008a) and only plans are in place to construct the plant. The biodiesel project that was used as a case for this study is based on the proposed biodiesel plant by an international company that will be operational in 2012. The structure of the biodiesel production is partly taken from the generic commodity market model (Sterman, 2000) and adapted to suit the conditions of the proposed biodiesel production in the Eastern Cape. The structure that represents the biodiesel production is demonstrated in Figure 5.6.

This sub-model consists of three key stocks; these are: biodiesel capacity construction, functional biodiesel capacity and the accumulated biodiesel production as shown in Figure 5.6. The biodiesel capacity construction (BC, in litre) is increased by biodiesel plant construction (r_{BC}, in litre/year) and decreased by new biodiesel capacity (r_{NBC}, in litre/year) once the construction is completed. This dynamics of biodiesel capacity construction is mathematically represented as:

$$BC(t) = BC(0) + \int [r_{BC} - r_{NBC}] dt \qquad \text{Equation 5.1}$$

Where $BC(0)$ is the initial value of the biodiesel capacity construction, which is zero.

The new biodiesel capacity is determined by the biodiesel capacity construction (BC, in litre) divided by the biodiesel plant construction time (t_{BC}, in year).

$$r_{NBC} = \frac{BC}{t_{BC}} \qquad \text{Equation 5.2}$$

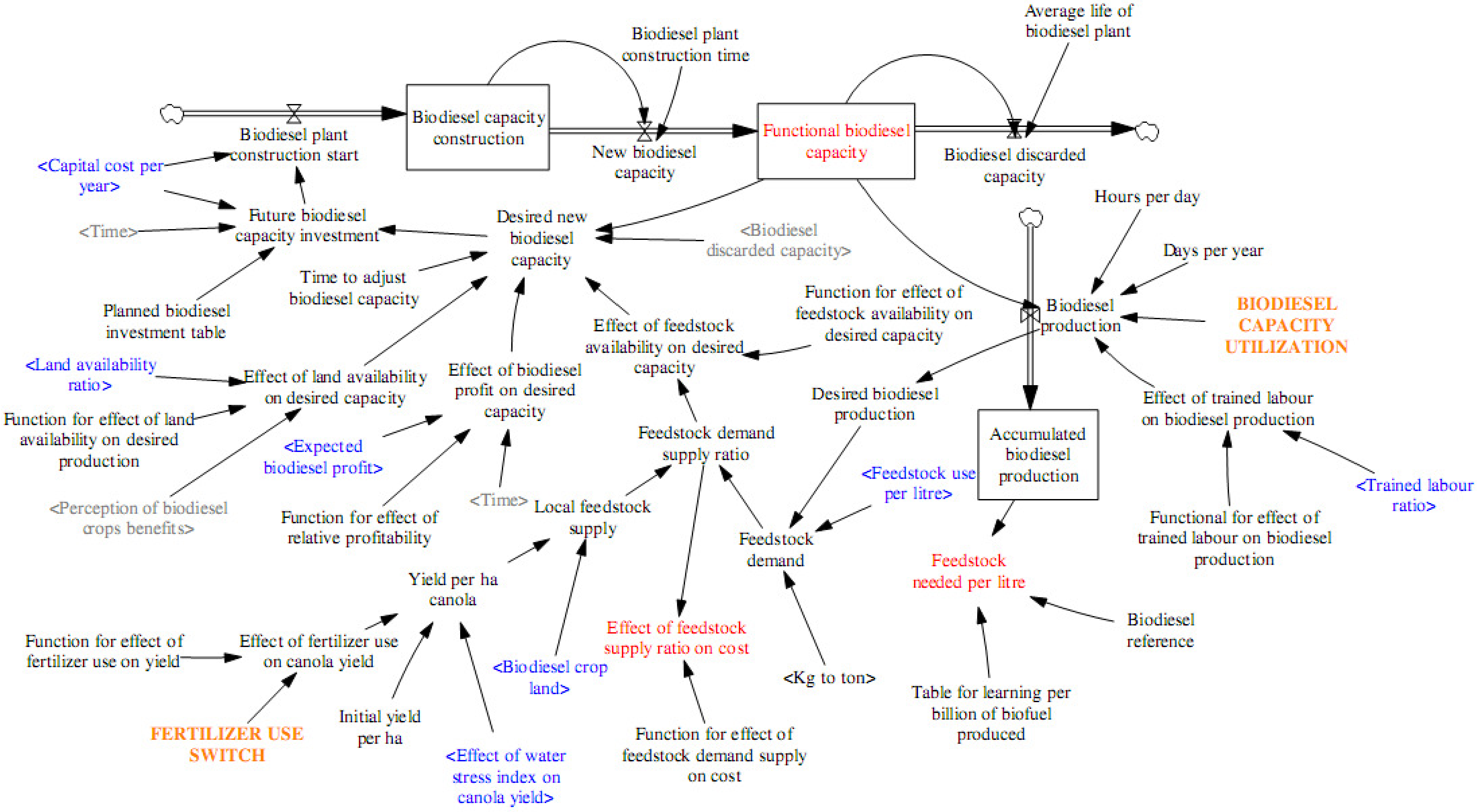


Figure 5.6: The stock and flow diagram of the biodiesel production sub-model of the *BIOTSA* model

On the other hand, biodiesel plant construction start (r_{BC}, in litre/year) is determined by future biodiesel capacity investment ($FBCI$, in Rand/year) divided by the capital cost per year (CC_a, in Rand/litre). Thus:

$$r_{BC} = \frac{FBCI}{CC_a} \qquad \text{Equation 5.3}$$

The future biodiesel capacity investment ($FBCI$, in Rand/litre) is the sum of the endogenously determined desired biodiesel capacity (DBC, in litre/year) and exogenous planned biodiesel investment (PBI, in litre/year), multiplied by the capital cost per year (CC_a, in Rand/litre). Thus:

$$FBCI = [DBC + PBI] * CC_a \qquad \text{Equation 5.4}$$

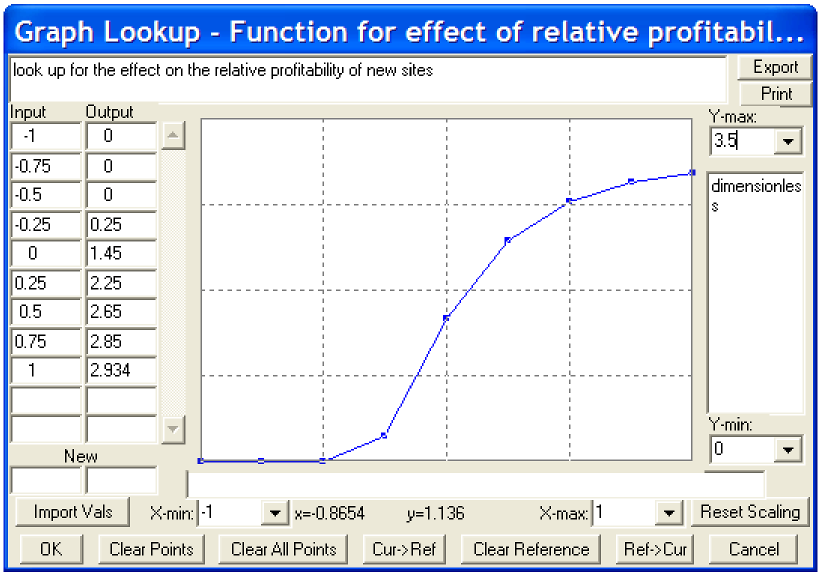
Desired biodiesel capacity (DBC, in litre/year) is an important variable in the biodiesel production sub-model and it is mathematically represented as:

$$DBC = \left(\frac{FBC}{t_{ABC}} + BDC \right) * E_{BPC} * E_{FA} * E_{LA} \qquad \text{Equation 5.5}$$

Where FBC is functional biodiesel capacity (in litre); t_{ABC} is the time to adjust biodiesel capacity (in year); BDC is the biodiesel discarded capacity (litre/year); E_{BPC} is the effect of biodiesel profit on the desired capacity (in dimensionless units); E_{FA} is the effect of feedstock availability on the desired capacity (in dimensionless units); and E_{LA} is the effect of land availability on desired production (in dimensionless units).

The effect of biodiesel profit on desired capacity was assumed as a non-linear function of the expected profit. This is because non-linear relationships are fundamental in all dynamics of a system (Sterman, 2000). Such a non-linear function was made possible by using the VENSIM® software lookup table. Lookup tables are generally tables that stores numerical data in either simple two dimensional or multi-dimensional arrays. Lookup tables are used in system dynamics modelling when a modeller is faced with a situation where a relationship exists between two variables yet a simple algebraic equation that defines the relationship is non-existence. Thus, table functions are preferable to complicated equations since the modeller can have control over the slopes, shapes and saturation points to accurately provide a representation of two variables in a non-linear relationship. In addition, lookup tables can facilitate clear understanding of the model and facilitate participation from non-specialist. Lookup tables are generated by experiments or creating artificial data of input and output of the system. In this study, no experiments were carried out and thus, the lookup were generated artificially based on the expected theoretical behaviour and discussion with some key persons in the field. All the input variables were normalized in order to ensure that the units for both inputs and outputs were dimensionless.

Thus, the table function representing the effect of biodiesel profit on desired capacity is shown in Figure 5.7. The X-axis represents the expected profit and the Y-axis the effect on the desired capacity. As an example, when the unit cost of biodiesel production is equivalent to the price of biodiesel, the expected biodiesel profit is zero and thus, the effect on the desired biodiesel capacity is 1.45 as shown in Figure 5.7.



Graph Lookup - Function for effect of relative profitabil...

look up for the effect on the relative profitability of new sites

Input	Output
-1	0
-0.75	0
-0.5	0
-0.25	0.25
0	1.45
0.25	2.25
0.5	2.65
0.75	2.85
1	2.934

Y-max: 3.5

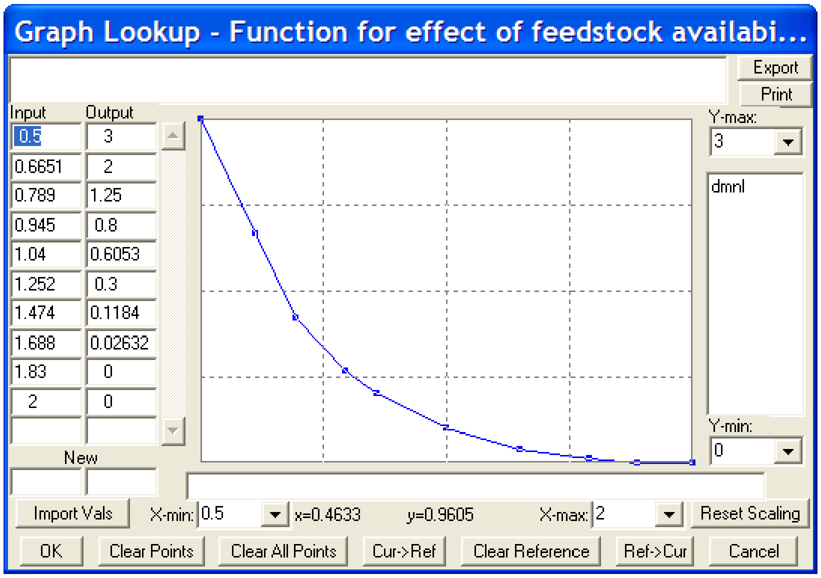
dimensionless

Y-min: 0

X-min: -1 x=-0.8654 y=1.136 X-max: 1

Figure 5.7: Lookup table for the effect of profitability on desired biodiesel capacity

In a similar manner, the effect of feedstock availability on the desired capacity is a non-linear function of the feedstock demand supply ratio. The demand supply ratio represents the availability of local feedstock production/supply relative to the desired feedstock demand. This is shown in Figure 5.8. The X-axis in Figure 5.8 is the demand supply ratio and the Y-axis is the effect of feedstock availability on desired capacity.

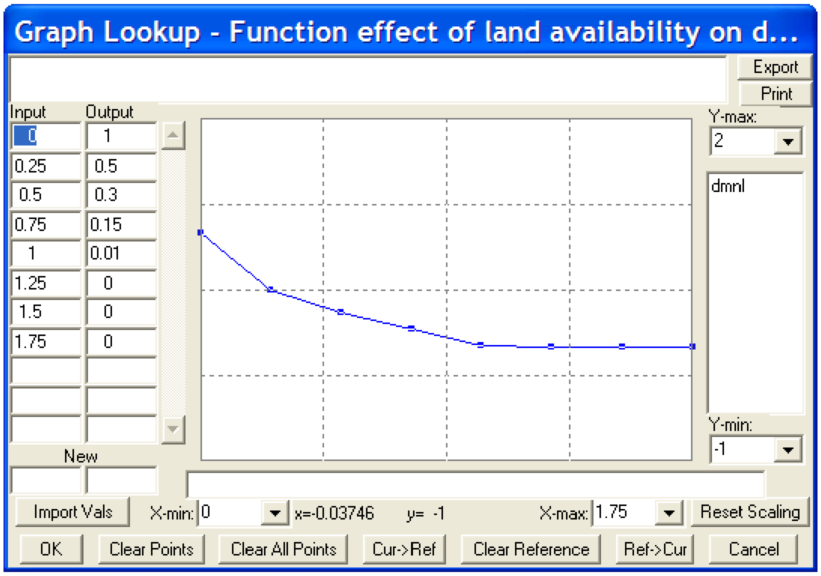

Graph Lookup - Function for effect of feedstock availabi...

Input	Output
0.5	3
0.6651	2
0.789	1.25
0.945	0.8
1.04	0.6053
1.252	0.3
1.474	0.1184
1.688	0.02632
1.83	0
2	0

Y-max: 3
dmnl
Y-min: 0
X-min: 0.5
x=0.4633
y=0.9605
X-max: 2

Figure 5.8: Lookup table for the effect of feedstock availability on desired biodiesel capacity

The values of the effect of land availability, which is a non-linear function of land availability ratio, were derived based on the information from the visit in the Eastern Cape Province. Its table function is presented in Figure 5.9. The X-axis represents the land availability ratio and Y-axis is the effect of land availability on the desired biodiesel capacity. The land availability ratio is given as the amount of land that is allocated for biodiesel crop divided by the maximum available land for biodiesel crop. This is further discussed in the land sub-model section.


Graph Lookup - Function effect of land availability on d...

Input	Output
0	1
0.25	0.5
0.5	0.3
0.75	0.15
1	0.01
1.25	0
1.5	0
1.75	0

Y-max: 2
dmnl
Y-min: -1
X-min: 0
x=-0.03746
y= -1
X-max: 1.75

Figure 5.9: Lookup table for the effect of land availability on desired biodiesel capacity

The biodiesel plant that is in operation in the *BIOTSA* model is regarded as functional biodiesel capacity (FBC , in litre), and it is increased by the new biodiesel capacity (r_{NBC} , in litre/year) and decreased by the biodiesel discard capacity (r_{BDC} , in litre/year). This is represented as:

$$FBC(t) = FBC(0) + \int [r_{NBC} - r_{BDC}] dt \qquad \text{Equation 5.6}$$

The equation for the biodiesel discarded capacity (r_{BDC} , in litre/year) is represented as the functional biodiesel capacity (FBC , in litre) divided by the average life of biodiesel plant (t_{ALBP} , in year):

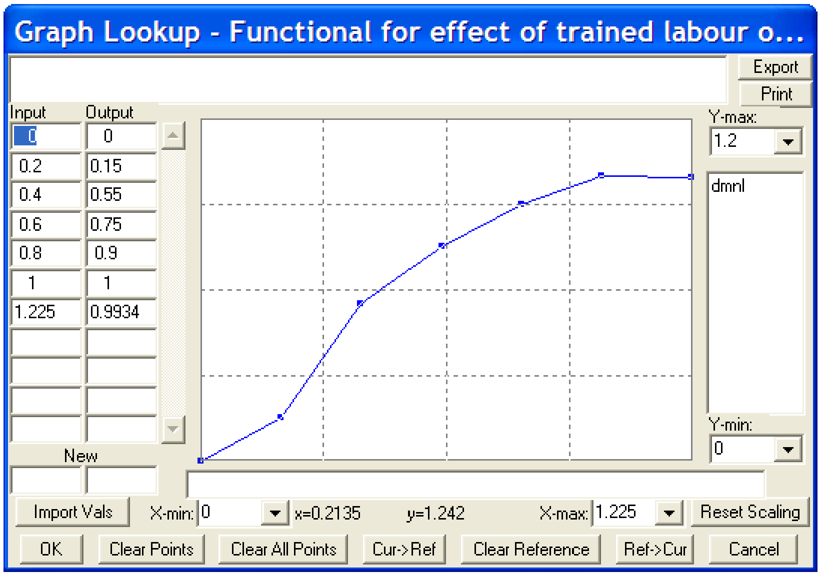
$$r_{BDC} = \frac{FBC}{t_{ALBP}} \qquad \text{Equation 5.7}$$

Given the functional capacity of the biodiesel plant, the biodiesel production can be estimated. This is calculated by multiplying the functional biodiesel capacity with the duration of operation of the plant in a year. In addition, biodiesel production is not only dependent on the functional capacity but also on the labour availability. The assumption is that the labour at the biodiesel plant level comes from the Eastern Cape Province. Since biodiesel production is new to the Eastern Cape, the trained labour is fundamental in influencing the amount of biodiesel production. The *BIOTSA* model initially assumes 100% capacity utilization. However in practice, firms will not produce at 100% utilization as this allows no scope for fluctuation. Effective capacity utilization of about 90% has been recorded elsewhere (Haas et al., 2006). According to Amigun et al. (2008b) the effective capacity utilization for Africa could be lower due to the local specific situation. In addition, the *BIOTSA* model assumes that the biodiesel plant will be operational for 330 days in order to account for shut down due to maintenance purposes. Thus, biodiesel production (r_{BP} , in litre/year) is given as:

$$r_{BP} = FBC \left(\frac{24\,hour}{day} * \frac{330\,day}{year} \right) * E_{TL} * CU \qquad \text{Equation 5.8}$$

Where: E_{TL} (in dimensionless units) is the effect of trained labour on biodiesel production; CU is the biodiesel capacity utilization (in dimensionless units).

The effect of trained labour on biodiesel production is used as a non-linear function following the concept of diminishing returns of the standard production function (Gravelle and Rees, 1993; Mankiw, 2009). The table function of this relationship is presented in Figure 5.10, where the X-axis is the trained labour ratio and Y-axis is the effect of the trained labour on biodiesel production. The trained ratio is given as the employment in the biodiesel plant divided by the desired employment in the biodiesel plant. Thus, the higher the trained labour ratio the higher its effect on the biodiesel production.



Graph Lookup - Functional for effect of trained labour o...

Input	Output
0	0
0.2	0.15
0.4	0.55
0.6	0.75
0.8	0.9
1	1
1.225	0.9934

Y-max: 1.2

dmnl

Y-min: 0

X-min: 0

x=0.2135 y=1.242

X-max: 1.225

Figure 5.10: Lookup table for the effect of trained labour on biodiesel production

While biodiesel production is determined by the functional biodiesel capacity, it is also an inflow to the accumulated biodiesel production (ABP, in litre) which is the third stock of the biodiesel production sub-model. This is an important stock in biodiesel production sub-model because it is used to estimate the learning curve that result from accumulated production. This is represented as:

$$ABP(t) = ABP(0) + \int [r_{BP}]dt \qquad \text{Equation 5.9}$$

The list of all the parameters, input variables and output variables that were used in the biodiesel sub-model are found in Table 5.2, Table 5.3 and Table 5.4 respectively. The input variables are those that were extracted from other sub-models and used in the biodiesel production model. On the other hand, the output variables are those that were determined in the biodiesel production sub-model and used in other sub-models. All the respective equations for biodiesel production sub-model as used in the VENSIM® software can be found in Appendix D.

Table 5.2: Parameters used in biodiesel production sub-model

Parameter	**Type**	**Value**	**Units**	**Notes /Source**
Initial unit capital cost	Constant	7.3	Rand/litre	Estimated based on Amigun et al., 2008
Initial yield per hectare	Constant	1.8	Ton/ha/year	PhytoEnergy website
Planned biodiesel investment table	Time series	57392.1	Litre/year	Calculated based on PhytoEnergy data
Time to adjust biodiesel capacity	Constant	1	Year	
Average life of biodiesel plant	Constant	20	Year	
Biodiesel plant construction time	Constant	3	Year	
Biodiesel reference	Constant	1.5e+009	Litre	Assumption
Biodiesel capacity utilization	Constant	1	Dimensionless	Assumption

Table 5.3: Input variables used in biodiesel production sub-model

Variable name	**Module of origin**
Biodiesel crop land	Land sub-model
Land availability	Land sub-model
Effect of water stress index on canola yield	Water sub-model
Feedstock use per litre	Biodiesel profitability sub-model
Expected biofuel profit	Biodiesel profitability sub-model
Trained labour ratio	Employment biodiesel plant sub-model
Perception of biodiesel crops benefits	Community perception sub-model
Capital cost per year	Cost of operation sub-model

Table 5.4: Output variables from biodiesel production sub-model

Variable name	**Module destination**
Biodiesel production	Biodiesel profitability; and air emissions sub-models
Functional biodiesel capacity	Employment biodiesel plant sub-model
Feedstock needed per litre	Biodiesel profitability sub-model
Desired biodiesel production	Land sub-model
Future biodiesel investment	GDP sub-model

5.5.2 Land sub-model

Land use changes are one of the increasing concerns in the biodiesel production development (Bringezu et al., 2009a). This is because of other human activities particularly food production requiring land use besides growing energy crops. Thus, land availability is critical issue in many countries (Fargione et al., 2008; Bringezu et al., 2009a).

Eastern Cape is the second largest Province in South Africa, with a land size of 168966 square kilometres. The land use in the Eastern Cape Province is divided into six competing land use namely: settlement land (*S*, in ha); forest plantations (F_P, in ha); fallow land (*F*, in ha); food crop land (C_f, in ha); conservation land (C, in ha); and livestock land (*L*, in ha). An expected seventh land use in the Eastern Cape is the biodiesel crop land (C_b, in ha), which is as a result of biodiesel production development. Thus, the land sub-model included the seven different types of land uses in the Eastern Cape Province. The structure representing the land sub-model in this study is presented in Figure 5.11.

Settlement land, crop land and livestock land are influenced by the population dynamics. On the other hand, the South African government plans to establish biodiesel crop land from fallow land. This makes fallow land one of the key land stocks because it can also be converted to other forms of land, depending on the land requirements. Only the dynamics of the fallow land and biodiesel crop land are discussed here. Thus, the stock of fallow land is given as:

$$FL(t) = FL(0) + \int \left[\sum (r_{LF}, r_{C_f F}, r_{C_b F}) - \sum (r_{FC_f}, r_{FL}, r_{FC_b}, r_{FC}, r_{FF_P}, r_{FS}) \right] dt \qquad \text{Equation 5.10}$$

where: r_{LF} is the rate of conversion from livestock land to fallow land (in ha/year); r_{FC_f} is the rate of conversion from fallow land to food crop land (in ha/year); $r_{C_b F}$ is the rate of conversion from biodiesel crop land to fallow land (in ha/year); r_{FL} is the rate of conversion from fallow land to livestock land (in ha/year); r_{FCb} is the rate of conversion from fallow land to biodiesel crop land (in ha/year); r_{FC} is the rate of conversion from fallow land to conservation land (in ha/year); r_{FF_P} is the rate of conversion from fallow land to forest plantations (in ha/year); and r_{FS} is the rate of conversion from fallow land to settlement land (in ha/year).

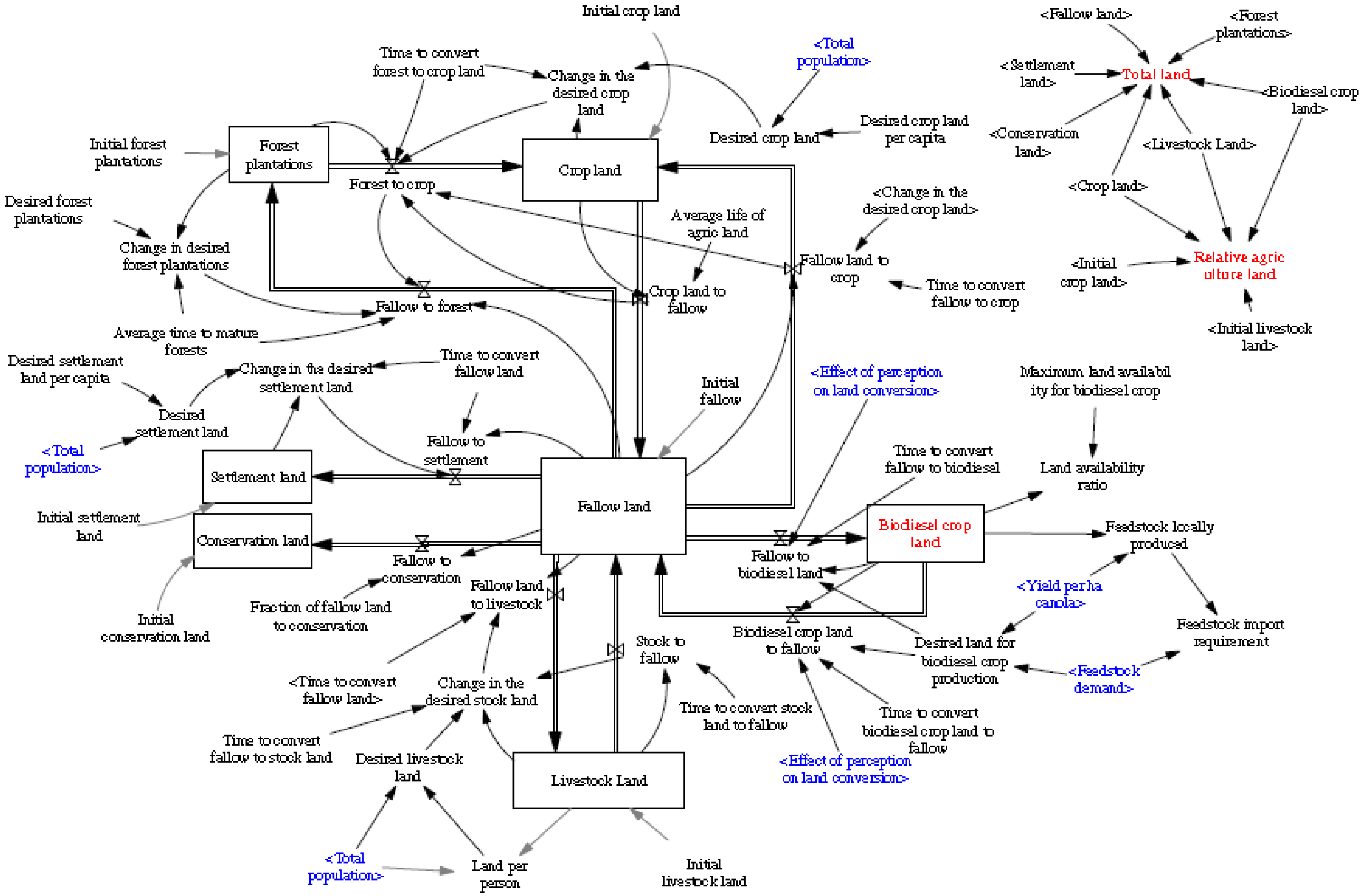


Figure 5.11: The stock and flow diagram of land sub-model of the *BIOTSA* model

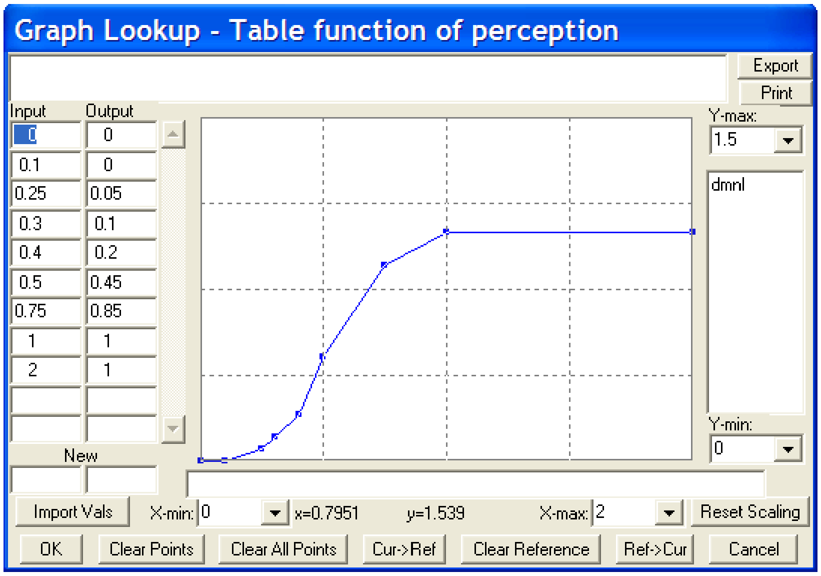
The stock of biodiesel crop land on the other hand is mathematically represented as:

$$BCL(t) = BCL(0) + \int \left[r_{FC_b} - r_{BC_f} \right] dt \qquad \text{Equation 5.11}$$

$$r_{FC_b} = Max\left[0, \left(\frac{DBCL - BCL}{t_{FC_b}} \right) * E_{PBL} \right] \qquad \text{Equation 5.12}$$

Where, $DBCL$ is the desired biodiesel crop land (in ha); BCL is biodiesel crop land (in ha); t_{FC_b} is time to convert fallow land to biodiesel crop land (in year); and E_{PBL} is the effect of perception on land conversion (in dimensionless units).

The effect of perception on land conversion is represented as a non-linear function as shown in Figure 5.12. The figure shows that increases in community perception on biodiesel crops benefit increases the conversion rate from fallow land to biodiesel crop land. However, a point is reached where additional perception does not increase the conversion anymore.



Input	Output
0	0
0.1	0
0.25	0.05
0.3	0.1
0.4	0.2
0.5	0.45
0.75	0.85
1	1
2	1

Y-max: 1.5

dmnl

Y-min: 0

X-min: 0 x=0.7951 y=1.539 X-max: 2

Figure 5.12: Lookup table for the effect of perception on land conversion

The list of the parameters, input variables and output variables for the land sub-model are presented in, Table 5.5, Table 5.6 and Table 5.7 respectively, and all the equations for the sub-model are found in Appendix D.

Table 5.5: Parameters used in land sub-model

Parameter	Type	Value	Units	Notes/ Source
Initial forest plantations	Constant	844430	Ha	STATS SA
Initial settlement land	Constant	1.0138e+006	Ha	STATS SA
Initial conservation land	Constant	169896	Ha	STATS SA
Initial livestock land	Constant	1.08138e+006	Ha	STATS SA
Initial fallow land	Constant	675864	Ha	STATS SA
Initial crop land	Constant	3.37932e+006	Ha	STATS SA
Initial biodiesel crop land	Constant	0	Ha	
Maximum land availability for biodiesel crops	Constant	500000	Ha	PhytoEnergy website
Desired crop land per capita	Constant	0.48	Ha/person	Estimate
Desired settlement land per capita	Constant	0.15	Ha/person	Estimate

Table 5.6: Input variables used in land sub-model

Variable name	Module of origin
Yield per ha canola	Biodiesel production sub-model
Feedstock demand	Biodiesel production sub-model
Total population	Population sub-model
Effect of perception on land conversion	Community perception sub-model

Table 5.7: Output variables from land sub-model

Variable name	Module destination
Biodiesel crop land	Biodiesel production
Total land	Water sub-model
Relative agriculture land	GDP sub-model

5.5.3 Biodiesel profitability sub-model

Profitability of any production activity is important in determining the future investments. Some of the most important factors determining the biodiesel plant profitability are the cost of production, particularly the feedstock costs, biodiesel production and the biodiesel plant capacity (Fortenbery, 2005; Bantz and Deaton, 2006). This sub-model represents the profitability in biodiesel production and consists of one stock, the expected biodiesel profit; and one flow rate, that is, changes in expected biodiesel profit. The expected biodiesel profit represents the balance between price and cost and is expressed by a dimensionless number.

The expected biodiesel profit is an important driver of the desired new biodiesel capacity. Figure 5.13 shows the stock and flow diagram of the dynamics of the expected biodiesel profit (EBP, in dimensionless units), driven by the changes in expected biodiesel profit (r_{CBP}, in dimensionless units/year). This is mathematically represented as:

$$EBP(t) = EBP(0) + \int [r_{CBP}]dt \qquad \text{Equation 5.13}$$

$$r_{CBP} = \left(\frac{UBP - EBP}{t_{AP}} \right) \qquad \text{Equation 5.14}$$

Where UBP is unit biodiesel profitability and t_{AP} is the time it takes to adjust profit.

The unit biodiesel profitability is determined by the unit total cost of production (UTC, in Rand/litre) and the biodiesel price (P_b, in Rand/litre). Hence:

$$UBP = \left(\frac{P_b - UTC}{P_b} \right) \qquad \text{Equation 5.15}$$

The biodiesel unit total cost of production is the sum of costs such as: electricity cost, water use cost, feedstock cost, labour cost, maintenance cost and other administration costs. The support for biodiesel is subtracted from these costs. The potential support of 0.53 Rand/litre for biodiesel production as stated in the South Africa Biofuels Industrial Strategy (Department of Minerals and Energy, 2007) is not accounted for in the initial analysis in order to test the effect of this policy. Following Amigun et al. (2008b), this study used the selling price of the conventional fuel as proxy for biodiesel price. This is because there is no current data that exists for biodiesel price. A switch was also used for the unit total cost of a production in order to test a scenario where the biodiesel plant sells its by-products such as glycerol and cake. A switch takes a value of 1 if the glycerol is part of revenue generation and zero if not.

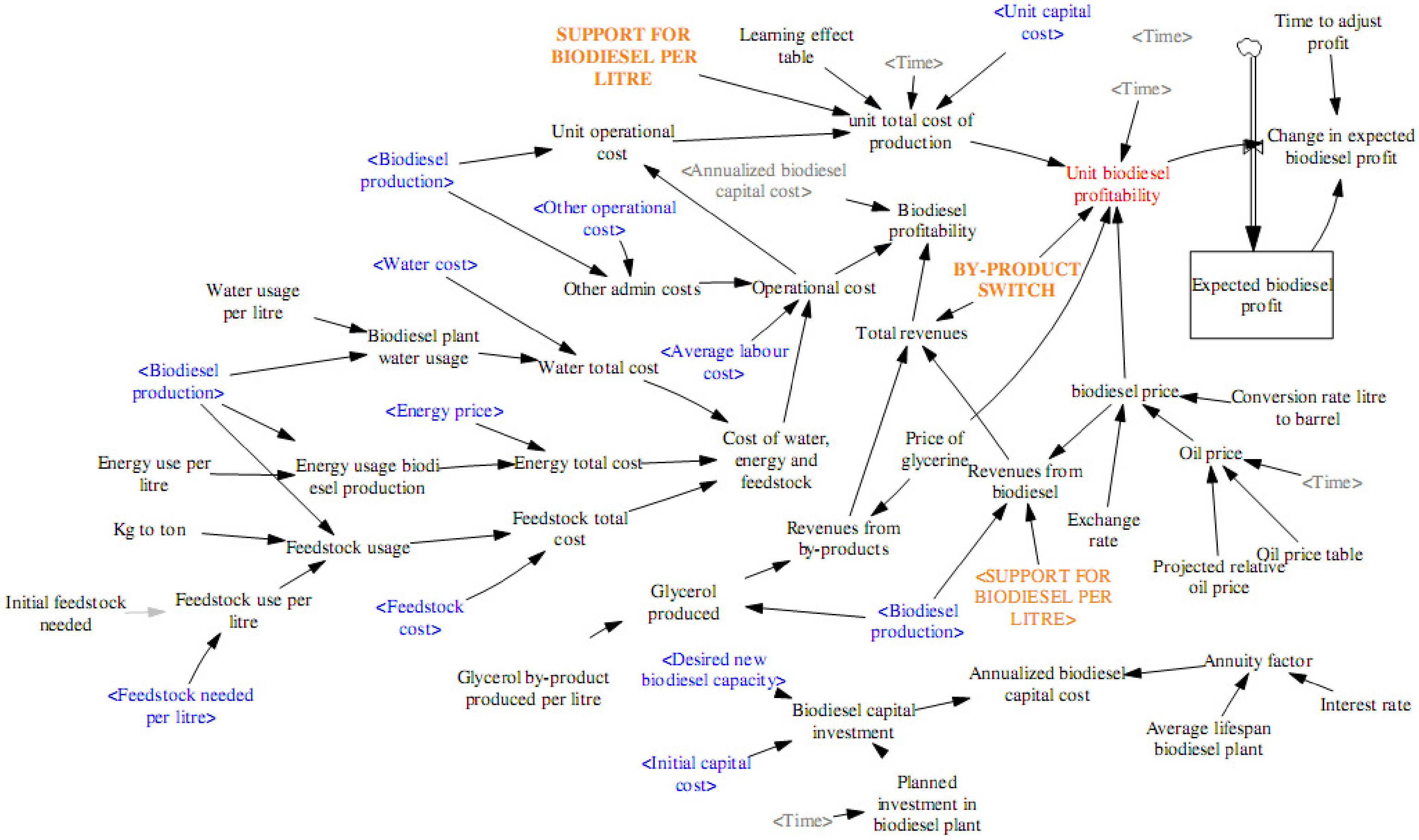


Figure 5.13: The stock and flow diagram of biodiesel profitability sub-model of *BIOTSA* model

All the parameters input and output variables for the biodiesel profitability sub-model are presented in Table 5.8, Table 5.9 and Table 5.10 respectively. In addition, all the equations for the sub-model are found in Appendix D.

Table 5.8: Parameters used in biodiesel profitability sub-model

Parameter	**Type**	**Value**	**Units**	**Notes/Source**
Initial feedstock needed	Constant	2	Kg/litre	
Energy use per lire	Constant	0.04	KWh/litre	Amigun et al., 2008
Water use per litre	Constant	1.2	Dimensionless	Amigun et al., 2008
Support for biodiesel	Constant	0	Rand/litre	DME, 2007
Glycerol produced per litre	Constant	0.075	Dimensionless	Amigun et al., 2008
Price of glycerol	Constant	2	Rand/litre	Nolte, 2007
Oil price	Time series		USD/Barrel	http://www.ioga.com/Special/crudeoil_Hist.htm
Projected relative oil price	Time series		Dimensionless	Amigun et al., 2008

Table 5.9: Input variables used in biodiesel profitability sub-model

Variable name	**Module of origin**
Biodiesel production	Biodiesel production sub-model
Feedstock needed per litre	Biodiesel production sub-model
Average labour cost	Employment biodiesel plant sub-model
Other operational cost	Cost of operation sub-model
Feedstock cost	Cost of operation sub-model
Energy price	Cost of operation sub-model
Water cost	Cost of operation sub-model
Unit capital cost	Cost of operation sub-model

Table 5.10: Output variables from biodiesel profitability sub-model

Variable name	**Module destination**
Expected biodiesel profit	Biodiesel production sub-model
Effect of feedstock supply ratio on cost	Cost of operation sub-model

5.5.4 Cost of production sub-model

This sub-model is important since high cost of biodiesel development is recognized as a major barrier to large-scale commercialization (Canakci and Van Gerpen, 2001). There are a number of costs that are involved in the biodiesel production including capital costs and operational costs such as feedstock, water cost, energy cost and other operational costs. Feedstock cost is the dominant cost in biodiesel production (Amigun et al., 2008b). This sub-model represents such costs and consists of four stocks: feedstock cost, water cost, other operational costs and unit capital cost, which are influenced by an exogenous fractional rate. All the four costs have more or less similar structure and are presented in Figure 5.14.

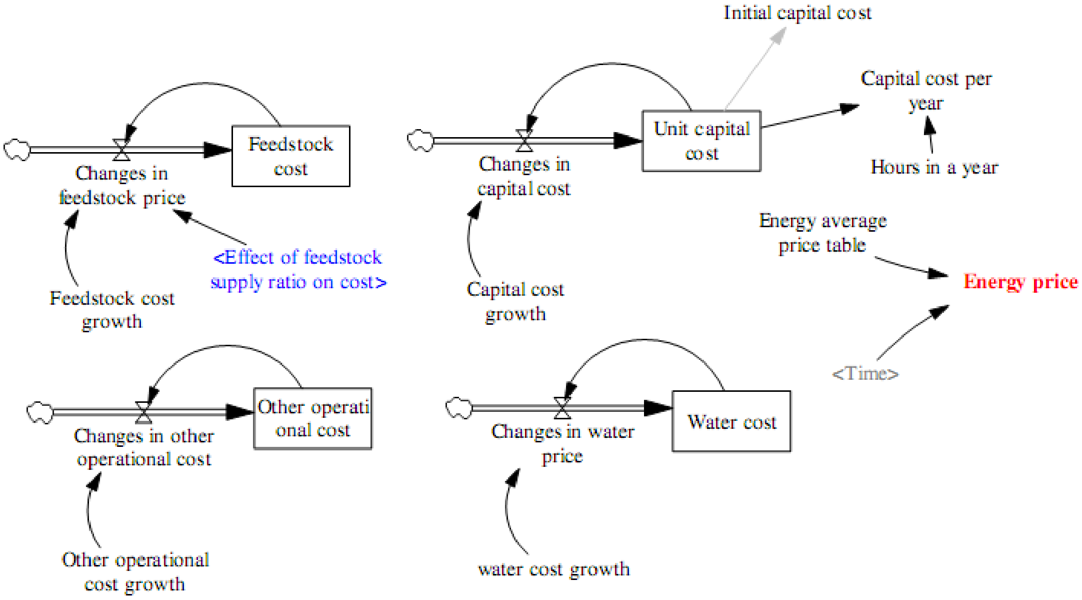


Figure 5.14: The stock and flow diagram of cost of operation sub-model of *BIOTSA* model

To avoid repetition only the dynamics of the feedstock costs are explained in this study. Feedstock cost is influenced by the changes in the feedstock price. On the other hand, the changes in feedstock price are determined by both feedstock cost growth and feedstock demand-supply behaviour. This is based on the notion that, if the feedstock is not produced locally, the demand for feedstock is met from imports which has a cost implication.

$$FDC(t) = FDC(0) + \int [r_{FP}]dt \qquad \text{Equation 5.16}$$

Where: FDC is feedstock cost; and r_{FP} is the change in the feedstock price. The parameters and output variables for the biodiesel profitability sub-model are presented in Table 5.11 and Table 5.12 respectively, and all the respective equations for the sub-model are found in Appendix D.

Table 5.11: Parameters used in biodiesel profitability sub-model

Parameter	Type	Value	Units	Notes/Source
Initial feedstock cost	Constant	2600	Rand/ton	
Initial water cost	Constant	0.7	Rand/litre	
Initial other operational cost	Constant	0.3	Rand/litre	
Initial unit capital cost	Constant	6.6	Rand/litre	Estimated from Amigun et al., 2008
Energy average price	Time series		Rand/kWh	DME/Estimated
Feedstock cost growth	Constant	0.1%	Dimensionless/year	
Capital cost growth	Constant	0.1%	Dimensionless/year	
Water cost growth	Constant	0.1%	Dimensionless/year	
Other operational cost growth	Constant	0.1%	Dimensionless/year	

Table 5.12: Output variables from biodiesel profitability sub-model

Variable name	Module destination
Feedstock cost	Biodiesel profitability sub-model
Other operational cost	Biodiesel profitability sub-model
Unit capital cost	Biodiesel profitability sub-model
Energy price	Biodiesel profitability sub-model
Water cost	Biodiesel profitability sub-model
Capital cost per year	Biodiesel production sub-model

5.5.5 Employment from biodiesel plant sub-model

The employment in biodiesel plant is explored to determine the number of jobs that are created as a result of establishing the biodiesel plant in the Eastern Cape. Therefore, the employment sub-model (Figure 5.15) is designed to calculate the desired employment in a biodiesel plant ($DEBP$, in person) and the process of recruiting the desired employment in order to achieve a trained workforce that matches with the desired employment. There are two stock variables, workforce in training (WiT, in person) and employment in a biodiesel plant (EBP, in person); and two flow rates, recruiting for training (r_{rt}, in person/year) and new trainees (r_{NT}, in person/year).

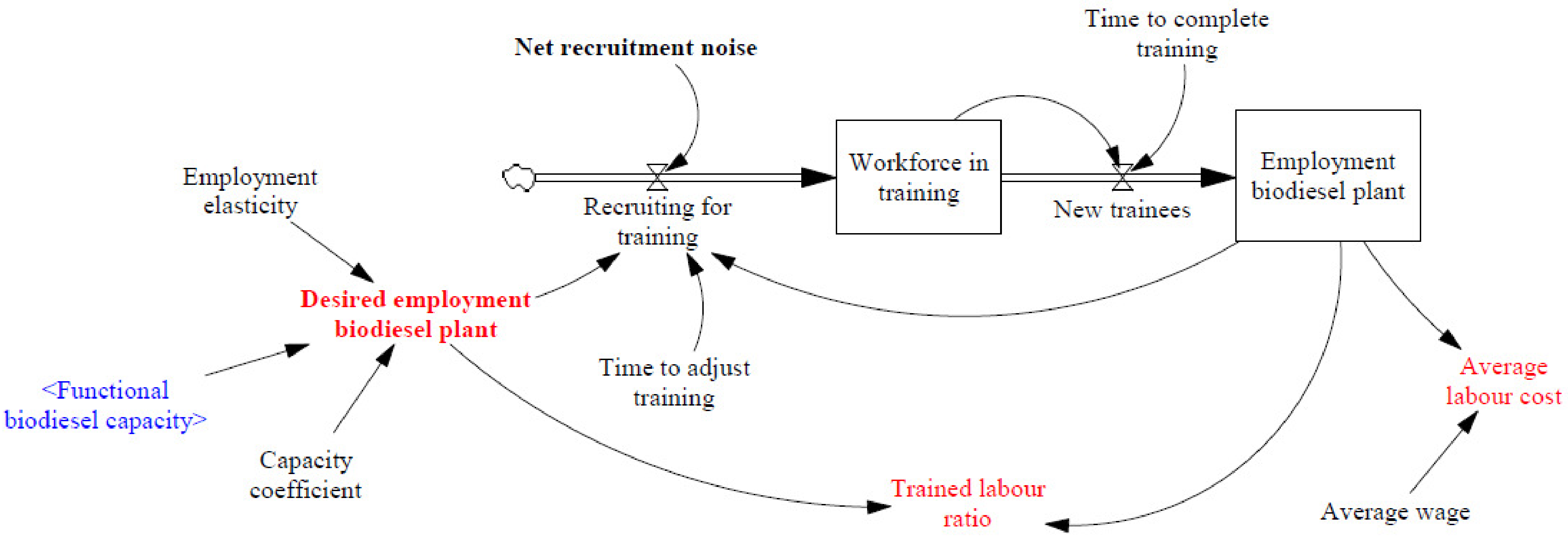


Figure 5.15: The stock and flow diagram of employment biodiesel plant sub-model of *BIOTSA* model

The desired employment in the biodiesel plant is limited to the plant size and it makes use of an equation developed by Amigun et al. (2008b). Thus:

$$DEBP = \alpha\left(FBC\right)^{\beta} \qquad \text{Equation 5.17}$$

Where: α is the capacity coefficient; and β is the employment elasticity.

The information on the desired employment in a biodiesel plant is fed into the recruiting for training (r_{rt}, in person/year), which determines the dynamics of the workforce in training (WiT, in person). In addition, employment in a biodiesel plant (EBP, in person) and net recruitment noise (NRN, in person/year) determines the recruitment for training. These relationships are represented as:

$$WiT(t) = WiT(0) + \int\left[r_{rt}\right]dt \qquad \text{Equation 5.18}$$

On the other hand, the recruiting for training is given as:

$$r_{rt} = \left(\frac{DEBP - EB}{t_{AT}}\right) + NRN\left[RANDOMUNIFORM(-0.5, 0.5, 0)\right] \qquad \text{Equation 5.19}$$

Where t_{AT} is the time to adjust training (in year).

The net recruitment noise (NRN, in person/year) in the Equation 5.19 is assumed as random uniform, with a minimum value of -0.5 and maximum value of 0.5. The employment biodiesel plant on the other hand is represented as:

$$EBP(t) = EBP(0) + \int\left[r_{NT}\right]dt \qquad \text{Equation 5.20}$$

$$r_{NT} = \left(\frac{WiT}{t_{NT}}\right) \qquad \text{Equation 5.21}$$

Where r_{NT} are new trainees (in person/year); and t_{NT} is time to complete training (in year).

The parameters, input variables and output variables for the employment biodiesel plant sub-model are presented in Table 5.13, Table 5.14 and Table 5.15 respectively and all the equations for the sub-model are found in Appendix D.

Table 5.13: Parameters used in the employment biodiesel plant sub-model

Parameter	**Type**	**Value**	**Units**	**Notes/ Source**
Average wage	Constant	12000	Rand/person/year	Estimate; STATS SA
Employment elasticity	Constant	0.5	Dimensionless	Amigun et al., 2008
Coefficient capacity	Constant	1	Dimensionless	Amigun et al., 2008
Initial employment baseline plant	Constant	0	Person	
Time to complete training	Constant	0.5	Year	Assumed

Table 5.14: Input variables used in the employment biodiesel plant sub-model

Variable name	**Module of origin**
Functional biodiesel capacity	Biodiesel production sub-model
Biodiesel capacity utilization	Biodiesel production sub-model

Table 5.15: Output variables from the employment biodiesel plant sub-model

Variable name	**Module destination**
Average labour cost	Biodiesel profitability sub-model
Trained labour ratio	Biodiesel production sub-model

5.5.6 Water sub-model

Water is one of the resources required for both the biodiesel plant and the biodiesel crop production level. These two types of water requirements form part of the water demand. Water consumption is however significant at the biodiesel crop production stage, which can rely on irrigation or rainfall. The production of biodiesel crop in the Eastern Cape Province is expected to rely on rainfall. The water sub-model structure (Figure 5.16) is customized from Millennium Institute T21 model (Bassi, 2009).

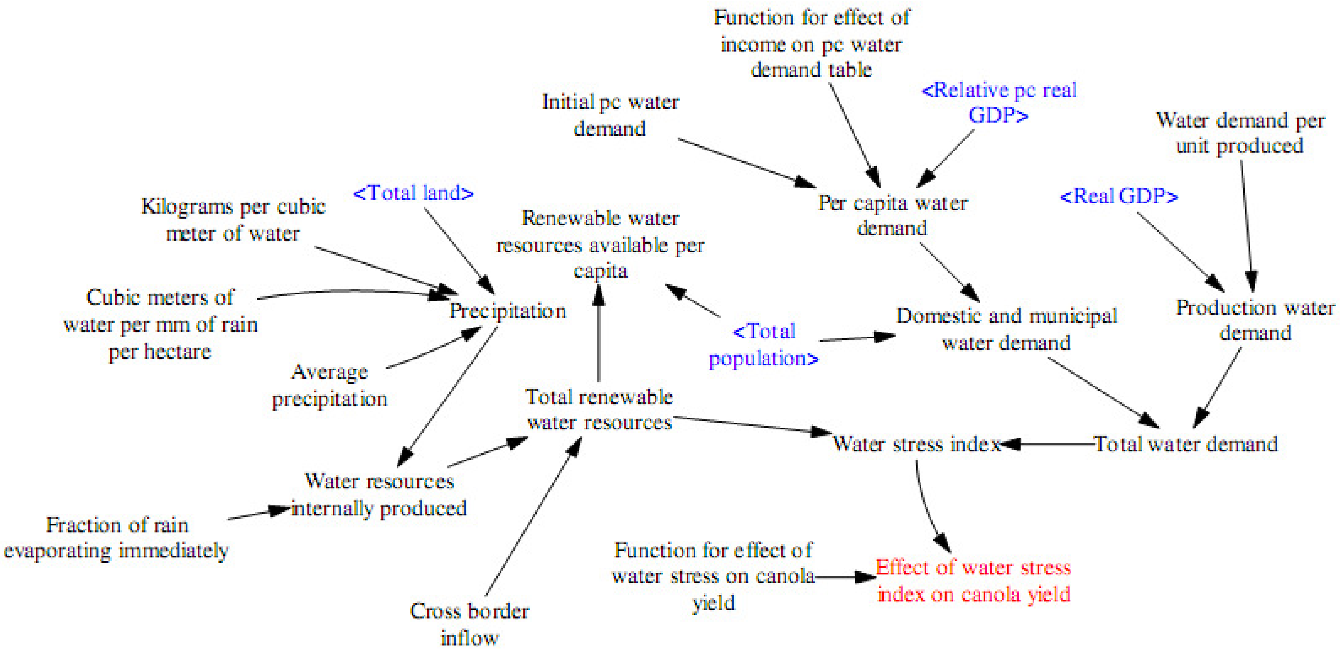


Figure 5.16: The stock and flow diagram of water sub-model of *BIOTSA* model

This sub-model aims to calculate the water stress index (WSI, in dimensionless units) in the Eastern Cape Province, which influences the production yield and therefore determines the land requirements for biodiesel crop production:

$$WSI = \left(\frac{TWD}{TRWR} \right) \qquad \text{Equation 5.22}$$

Where TWD the total water is demand (in kg/year); and $TRWR$ is the total renewable water resources (in kg/year). Total water demand is the sum of domestic and municipal water demand ($DMWD$, in kg/year) and the production water demand (PWD, in kg/year) represented as:

$$TWD = \sum (DMWD, PWD) \qquad \text{Equation 5.23}$$

Total renewable water resource on the other hand is depended on the precipitation, the total land area, any cross border inflow and the proportion of evaporation. The rest of the parameters, input variables and output variables for the water sub-model are presented in Table 5.16, Table 5.17 and Table 5.18 respectively. The equations for the sub-model are also found in Appendix D.

Table 5.16: Parameters used in the water sub-model

Parameter	**Type**	**Value**	**Unit**	**Notes/ Source**
Cubic meters of water per mm of rain per hectare	Constant	10	Mm^3/mm/ha	Estimate
Fraction of rain evaporating immediately	Constant	0.25	Dimensionless	http://www.idrc.ca/en/ev-31152-201-1-DO_TOPIC.html
Cross border inflow	Constant	0	Kg/year	Assumed
Initial pc water demand	Constant	9125	Kg/year/person	Estimated
Water demand per unit produced	Constant	1	Kg/Rand	
Average precipitation	Constant	650	Mm/year	STAT SA

Table 5.17: Input variables used in the water sub-model

Variable name	**Module of origin**
Total land	Land sub-model
Total population	Population sub-model
Relative pc real GDP	GDP sub-model
Real GDP	GDP sub-model

Table 5.18: Output variables from the water sub-model

Variable name	Module destination
Effect of water stress index on canola yield	Biodiesel production sub-model

5.5.7 Energy demand sub-model

Energy, particularly electricity is an important input in the biodiesel production process and thus necessary to represent its contribution to the existing electricity demand. The energy demand sub-model (Figure 5.17) therefore shows the demand for electricity in the Eastern Cape which is driven by the economic activities, including the biodiesel production and population.

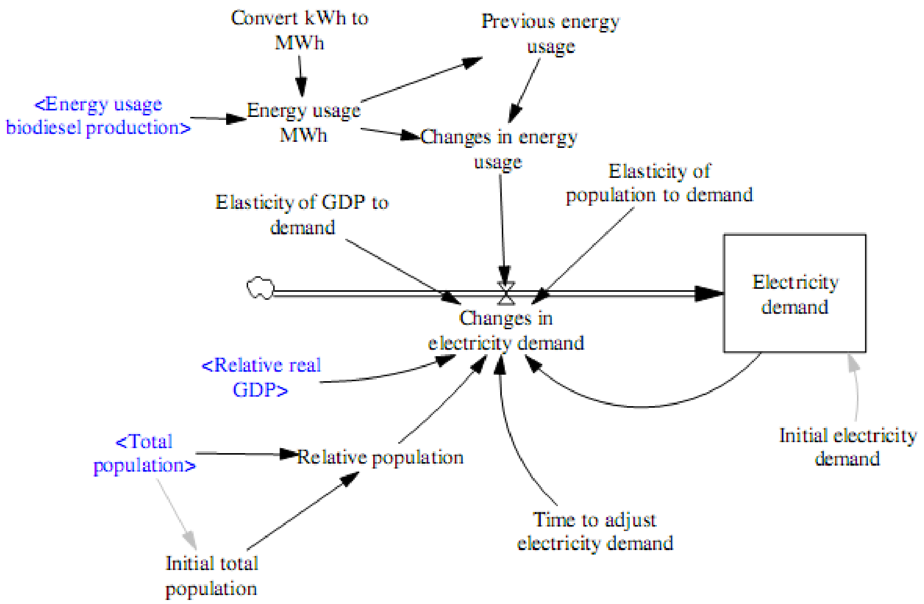


Figure 5.17: The stock and flow diagram of the energy demand sub-model

The dynamics of the electricity demand (ED, in MWh) is determined by the changes in the electricity demand (r_{ED}, in MWh/year). These relationships are represented as:

$$ED = ED(0) + \int [r_{ED}]dt \qquad \text{Equation 5.24}$$

$$r_{ED} = \left(\frac{\left[ED(RP)^{\varphi} * (RRGDP)^{\mu} \right] - ED}{t_{AE}} \right) + CEU \qquad \text{Equation 5.25}$$

Where RP is the relative population (in dimensionless units); φ is an assumed elasticity of population to demand (in dimensionless units); $RRGDP$ is the relative real GDP (in dimensionless units); μ is an assumed elasticity of GDP to demand (in dimensionless units); t_{AE} is the time to adjust electricity demand (in year); and CEU is changes in energy usage (in MWh/year).

The parameters and input variables for energy demand sub-model are presented in Table 5.19 and Table 5.20 respectively. Similarly, all the equations for the sub-model are also presented in Appendix D.

Table 5.19: Parameters used in the energy demand sub-model

Parameter	**Type**	**Value**	**Units**	**Notes / Source**
Elasticity of population to demand	Constant	0.001	Dmnl	Assumed
Elasticity of GDP to demand	Constant	0.002	Dmnl	Assumed
Initial electricity demand	Constant	7.136E+06	MWh	STATS SA
Time to adjust electricity demand	Constant	1	Year	Assumed

Table 5.20: Input variables used in the energy demand sub-model

Variable name	**Module of origin**
Energy usage biodiesel production	Biodiesel profitability sub-model
Total population	Population sub-model
Relative GDP	GDP sub-model

5.5.8 Air emissions sub-model

While biodiesel is a cleaner technology, there are air emissions that are associated with its production. Biodiesel emissions are mainly dependant on the feedstock used and the biodiesel production model. Generally, these emissions in carbon dioxide equivalent, is relatively lower than its diesel counterpart. The air emissions sub-model (Figure 5.18) therefore calculates the total emissions and the emissions avoided due to biodiesel production which in turn determines the net emissions (NE) from the biodiesel production. The sub-model consist of one stock variable, cumulative net emissions, and two flow rates, air emission generation and air emission decomposition. Thus, the stock of cumulative net emissions

(CNE, in kg CO_2) is increased by air emission generation (r_{EG}, in kg CO_2/year) and decreased by the air emissions decomposition (r_{ED}, in kg CO_2/year).

$$CNE = CNE(0) + \int [r_{EG} - r_{ED}]dt \qquad \text{Equation 5.26}$$

Air emission generation (r_{EG}, in kg CO_2/year) is determined by the net emissions (NE, in kg CO_2/year) and is given as:

$$r_{EG} = NE \qquad \text{Equation 5.27}$$

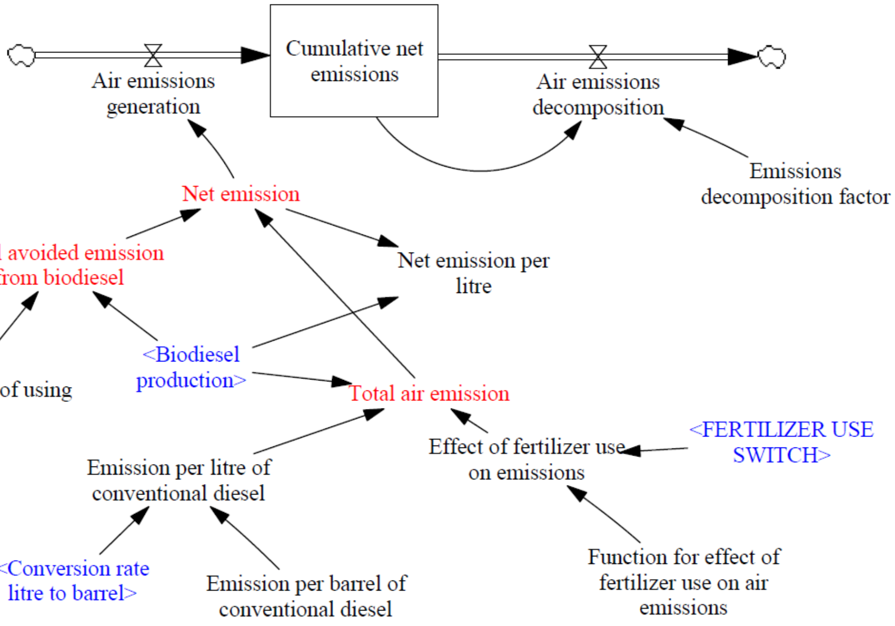


Figure 5.18: The stock and flow diagram of the air emissions sub-model

On the other hand, the net emissions (NE, in kg CO_2/year) is the difference between the total air emissions (TAE, in kg CO_2/year) and the total avoided emission from biodiesel ($TAEB$, in kg CO_2/year). Thus:

$$NE = TAE - TAEB \qquad \text{Equation 5.28}$$

The total air emissions (TAE, in kg CO_2/year) include emissions that would be generated if the conventional diesel was produced and emissions if fertilizer is used in the biodiesel crop production. A switch was used to test fertilizer use and it takes a value of 1 if the fertilizer is used in biodiesel crop production (canola) and zero if not. The total air emissions is thus mathematically represented as avoided emissions per litre of conventional diesel (ECD, in kg CO_2/litre) multiplied by a biodiesel production (BP, in litre/year) and the effect of fertilizer use on emissions (EFU, in dimensionless).

$$TAE = ECD * BP * EFU \qquad \text{Equation 5.29}$$

On the other hand, the total avoided emissison from biodiesel ($TAEB$, in kg CO_2/year) is given as avoided emissions of using biodiesel (AEB, in kg CO_2/litre) multiplied by a biodiesel production (BP, in litre/year).

$$TAEB = AEB * BP \qquad \text{Equation 5.30}$$

Biodiesel production (BP, in litre/year) is obtained from the biodiesel production sub-model and is linked to the air emissions sub-model. The parameters and input variables for the emission sub-model are presented in Table 5.21 and Table 5.22 respectively and all the equations for the sub-model are presented in Appendix D.

Table 5.21: Parameters used in the air emissions sub-model

Parameter	**Type**	**Value**	**Unit**	**Notes/Source**
Emission per barrel of conventional diesel	Constant	430.7	Kg CO_2/ barrel	Personal communication*
Avoided emission using biodiesel	Constant	1.2	Kg CO_2/ litre	Personal communication*
Emissions decomposition factor	Constant	0.1%	Dmnl/year	Assumed
Initial cumulative net emissions	Constant	0	Kg CO_2	Assumed

*with Prof Harro von Blotnitz

Table 5.22: Input variables used in the air emissions sub-model

Variable name	**Module of origin**
Biodiesel production	Biodiesel production sub-model

5.5.9 Population sub-model

Population is an important sub-model and it is used to determine some social and economic indicators. The structure of the population sub-model (see Figure 5.19) is customized from Millennium Institute Threshold-21 (Bassi, 2009) to fit within the scope of this study. The population in the *BIOTSA* model was defined as the Eastern Cape Province population, which was categorized according to sex and age groups. The population sub-model consists of one stock variable, population (P , in person), which was defined by three rate variables namely: births (r_B , in person/year), deaths (r_D , in person/year) and net migration (r_M , in person/year). Population stock dynamics was therefore given as:

$$P = P(0) + \int [r_B - r_D - r_M \;]dt \qquad \text{Equation 5.31}$$

It is estimated that the birth and death rates in the Eastern Cape Province are both influenced by the economic conditions which in turn influence the level of the population stock. Changes in population influence variables in other sub-models such as the water demand, energy demand, and GDP. While the Millennium Institute Threshold-21 population model is more elaborate, for the current exploratory purpose, this population sub-model is sufficient. All the parameters, input and output variables for the population sub-model are presented in Table 5.23, Table 5.24 and Table 5.25 respectively. The equations for the sub-model are found in Appendix D.

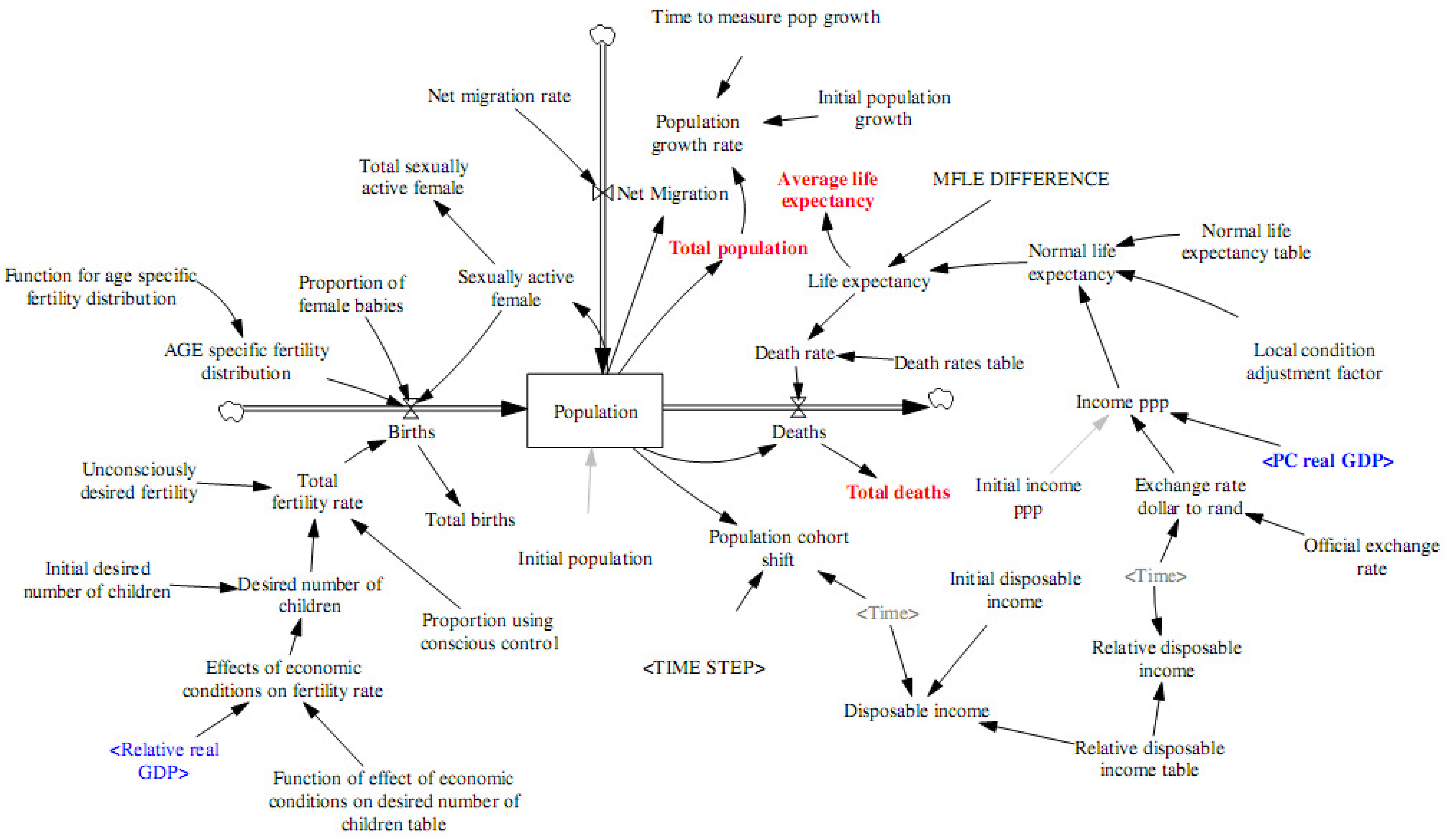


Figure 5.19: The stock and flow diagram of population sub-model of *BIOTSA* model

Table 5.23: Parameters used in the population sub-model

Parameter	**Type**	**Value**	**Units**	**Notes/ Source**
Unconsciously desired fertility	Constant	3	Dmnl	Assumed based on WDI data
Proportion of female babies	Constant	0.525	Dmnl	Calculated
Male Female life expectancy difference	Constant	4.4	Year	
Function age specific fertility distribution table	Lookup			
Net migration rate	Constant	0	Person/year	WDI
Normal life expectancy table	Lookup		Year	
Time for income changes to affect life expectancy	Constant			
Initial disposable income	Constant	900	Rand	Estimate
Initial income PPP	Constant	1580	USD/person/year	www.southafrica.info/business/investing/opportunities/ecape.htm
Initial population growth	Constant	1.25%	Dmnl/year	
Official exchange rate	Timeseries		Rand/USD	WDI
Initial desired number of children	Constant	2	Dimensionless	
Proportion using conscious control	Constant	0.35	Dimensionless	Assumed
Time to measure population growth	Constant	1	Year	

Table 5.24: Input variables used the in population sub-model

Input variable name	**Module of origin**
Relative real GDP	GDP sub-model
PC real GDP	GDP sub-model
Real GDP per capita	GDP sub-model

Table 5.25: Output variables from the population sub-model

Output variable name	**Module destination**
Total population	Energy demand; GDP; and water sub-models

5.5.10 GDP sub-model

One of the main factors of promoting biofuel investments in the Eastern Cape Province is to improve its economy. This is because the Eastern Cape Province contribution to the GDP is among the least in South Africa. An explicit representation of the Eastern Cape GDP was therefore crucial.

This sub-model consists of two stocks as shown in Figure 5.20. The first one is the South Africa GDP, which is driven by an exogenous GDP growth. The importance of this stock is to estimate the total investment in the Eastern Cape (TI_{EC}, in Rand/year). The second stock is, capital stock (K, in Rand). Both total investment in the Eastern Cape (TI_{EC}, in Rand/year) and future biodiesel investments (FBI, in Rand/year) influence the gross capital formation (r_{GKF}, in Rand/year), which in turn influences the capital stock. The capital stock (K, in Rand) is however decreased by the rate of depreciation (r_{DN}, in Rand/year).

$$K = K(0) + \int [r_{GKF} - r_{DN}]dt \qquad \text{Equation 5.32}$$

Based on the Cobb-Douglas production function[28], capital (K) and labour (L) are the key factors determining GDP. Thus:

$$RGDP = RGDP(0) * RP \qquad \text{Equation 5.33}$$

Where $RGDP$ is the real GDP (in Rand/year); $RGDP(0)$ is initial real GDP (in Rand/year); and RP is relative production (in dimensionless units).

On the other hand, relative production is calculated as:

$$RP = \left[(RK)^{\alpha_K} * (RL)^{\alpha_L} * (RAL)^{1-\alpha_K-\alpha_L}\right] * TFP \qquad \text{Equation 5.34}$$

Where RK is relative capital (in dimensionless units); α_K is the capital share (in dimensionless units); RL is relative labour (in dimensionless units); α_L is the labour share (in dimensionless units); RAL is relative agricultural land (in dimensionless units); and TFP is total factor productivity (in dimensionless units).

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[28] http://en.wikipedia.org/wiki/Cobb_douglas

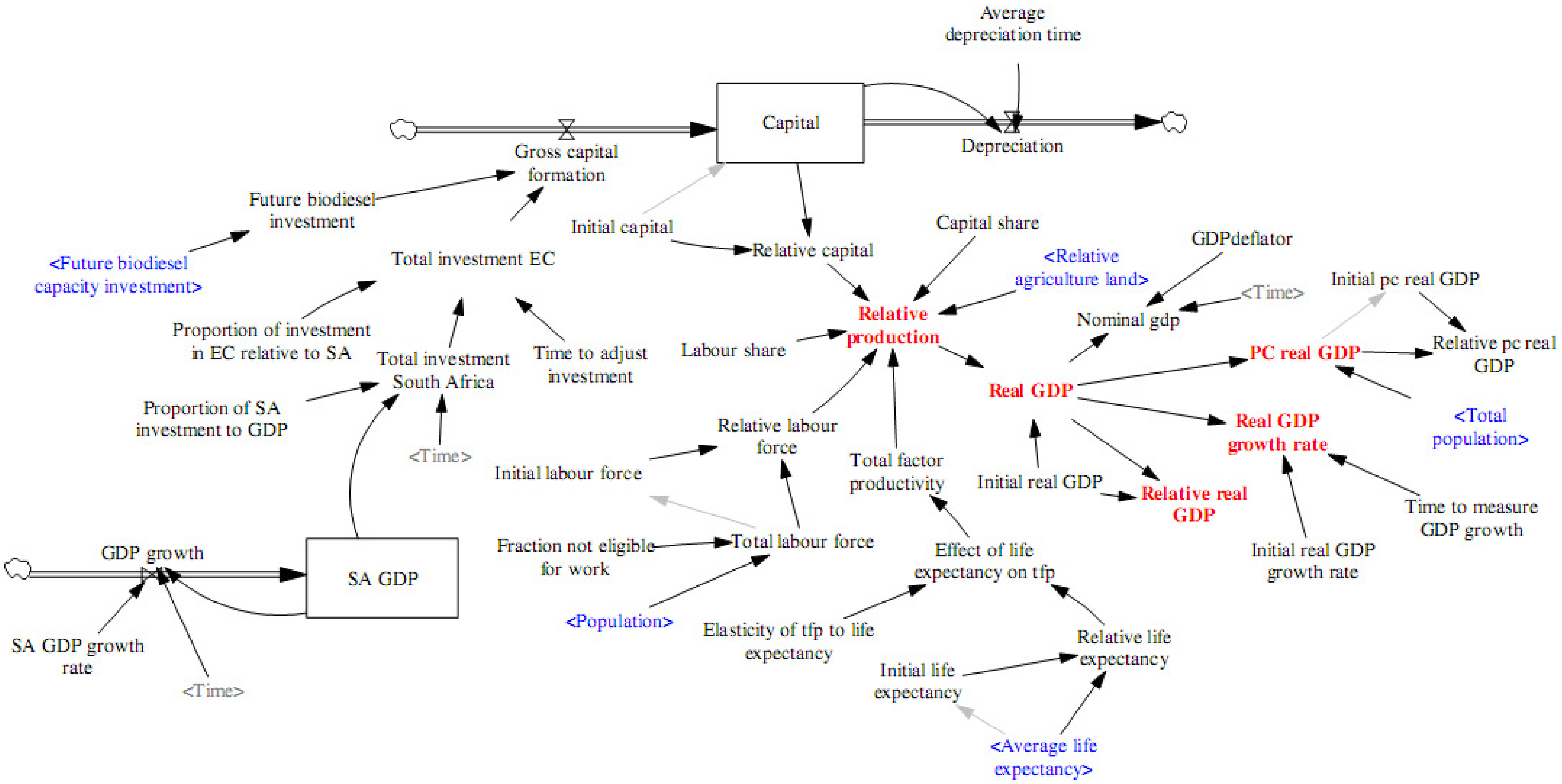

Figure 5.20: The stock and flow diagram of the GDP sub-model of *BIOTSA* model

The parameters, input variables and output variables are presented in Table 5.26, Table 5.27 and Table 5.28 respectively. All the equations for this sub-model are also presented in Appendix D.

Table 5.26: Parameters used in the GDP sub-model

Parameter	Type	Value	Units	Notes/ Source
Proportion of investment in EC relative to SA	Constant	0.06	Dimensionless	STATS SA
Proportion of SA investment to GDP	Time series		Dimensionless	WDI
SA GDP growth rate	Time series		Dmnl/year	EGTSA model
Fraction not eligible for work	Constant	0.2	Dimensionless	Estimate
Capital share	Constant	0.4	Dimensionless	Estimate
Labour share	Constant	0.6	Dimensionless	Estimate
Initial real GDP	Constant	4.85e+10	Rand/year	Development Report 2005
GDP deflator	Time series		Dimensionless	WDI/ projected
Initial capital	Constant	1.08e+11	Rand	Estimate; STATS SA
Initial SA GDP	Constant	1.13E+12	Rand	STATS SA
Elasticity of tfc to life expectancy	Constant	0.08	Dimensionless	Estimate

Table 5.27: Input variables used in the GDP sub-model

Variable name	Module of origin
Future biodiesel investment	Biodiesel production sub-model
Population	Population sub-model
Average life expectancy	Population sub-model
Relative agriculture land	Land sub-model
Total population	Population sub-model

Table 5.28: Output variables from the GDP sub-model

Variable name	Module destination
PC real GDP	Population sub-model
Relative real GDP	Population and energy demand sub-models
Relative pc real GDP	Water sub-model
Real GDP	Water sub-model

5.5.11 Community perception sub-model

Community perception is an important factor in biodiesel production since the local communities are expected to supply feedstock to the biodiesel plant. If the local communities do not see any benefits from growing crops for biodiesel production, then they would not be committed to convert the fallow land to biodiesel crop land. The development of this sub-model is thus mainly based on the survey and observations in the Eastern Cape concerning the community perceptions on growing crops for biodiesel production. This sub-model made use of new data in a unique way for a case that has not been previously done. The community perception sub-model (Figure 5.21) consists of one stock: perception of biodiesel crops benefits (*PBC* , in dimensionless units).

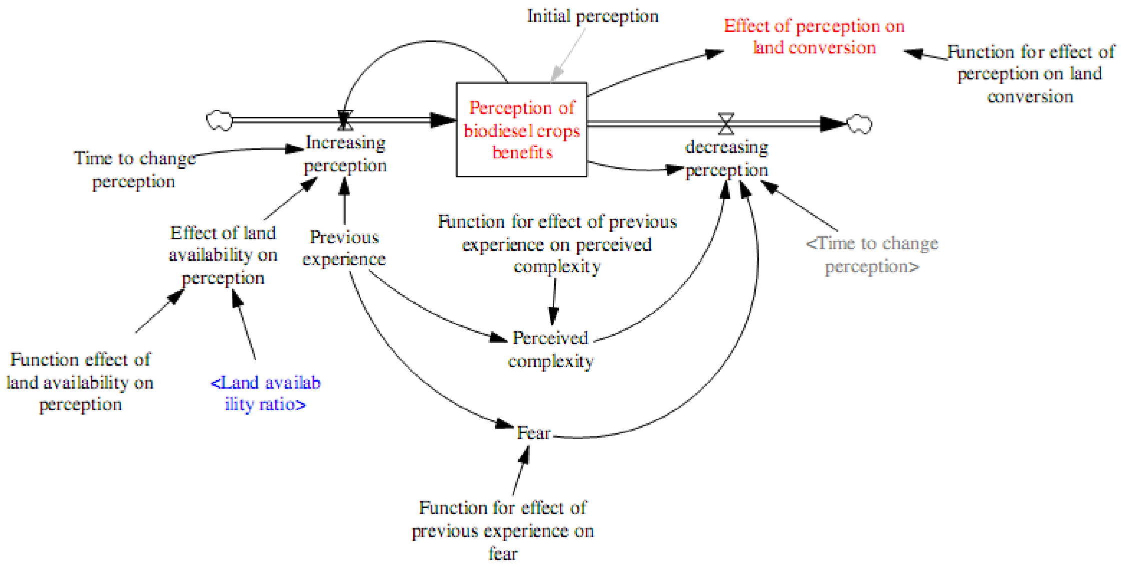

Figure 5.21: The stock and flow diagram of the community perception sub-model

The factors that increase the stock of community perception of the biofuel crops benefits are: the effect of land availability on perception and the previous experiences with the department of agriculture in the introduction of new crops and or species on their farms. On the other hand, the perception of the biofuel crops benefits is decreased by the perceived complexity of these new crops as part of their crop mixes, and the local community fear of introducing new crop in their crop mix. The mathematical relations of the perception of biofuel crops benefits is influenced by the increasing perceptions (r_{CiP}, in dimensionless units/year) and decreasing perception (r_{CdP}, in dimensionless units/year) is represented as:

$$PBC = PBC(0) + \int [r_{CiP} - r_{CdP}]dt \qquad \text{Equation 5.35}$$

$$r_{CiP} = \left[\frac{(PBC * E_{LAP} * \Pr E)}{t_{CP}} \right] \qquad \text{Equation 5.36}$$

$$r_{CdP} = \left[\frac{(PBC * PeC * Fe)}{t_{CP}} \right] \qquad \text{Equation 5.37}$$

Where E_{LAP} is effect of land availability on perception (in dimensionless units); $\Pr E$ is the previous experience (in dimensionless units); t_{CP} is time to change perception (in year); PeC is perceived complexity (in dimensionless units); and Fe is fear (in dimensionless units).

The parameters, input variables and output variables are presented in Table 5.29, Table 5.30 and Table 5.31 respectively. In addition, all the equations for the sub-model are presented in Appendix D.

Table 5.29: Parameters used in the community perception sub-model

Parameter	**Type**	**Value**	**Unit**
Initial perception	Constant	0.1	Dimensionless
Previous experience	Constant	1	Dimensionless
Time to change perception	Constant	10	Year

Table 5.30: Input variables used in the community perception sub-model

Variable name	**Module of origin**
Land availability	Land sub-model

Table 5.31: Output variables from the community perception sub-model

Variable name	**Module destination**
Effect of perception on land conversion	Land sub-model
Perception of biodiesel crops benefits	Biodiesel production sub-model

5.6 CONCLUSION

Insights into the art and science of developing the *BIOTSA* model were presented in this chapter. The *BIOTSA* modelling process enabled the appreciation of the inherent dynamic complexity in the biodiesel production development in the Eastern Cape Province. The conclusion resulting from the modelling process is summarized in this section.

- The problem formulation is an important aspect in setting the boundary of the model. This is because clear purpose enables successful modelling and allows the model users to reveal the usefulness of the model in addressing a problem. The key purpose in the design of the *BIOTSA* model was to explore policies to ensure sustainable transition in the biodiesel production development in the Eastern Cape Province.
- The formulation of dynamic hypothesis shows the complex feedback structures of biodiesel production development which integrates the economic, social and environmental sub-sectors. The use and the process of developing causal loop diagrams in formulating the dynamic hypothesis provided a clear understanding of the nature of effect of biodiesel production development with other variables (e.g. water, GDP, and population) in the different sub-sectors.
- Causal loop diagrams were formulated to provide the endogenous explanation and also to portray the essential elements and interactions in the development of biodiesel production in the Eastern Cape Province. This was essentially accomplished by using systems thinking approach as suggested by Flood and Jackson (1991), O'Connor and McDermott (1997) and Maani and Cavana (2007). The systems thinking approach assisted in the thought process for the causal loop and in describing the case study.
- Causal loop diagrams also enable clear presentation of the causal effect and feedback loop relationships to people with different academic backgrounds and to non-academic community. Capturing the polarity of the effects provided a clear understanding of these relationships and their direction of the effect.
- Based on the economy-society-environment interactions of the biofuel production development, the *BIOTSA* model was divided into eleven sub-models namely: biodiesel production; cost of operation; biodiesel production profitability; GDP; employment from biodiesel plant; community perception; population; land; water; air emissions; and energy demand. The stock and flow structures of the *BIOTSA* model were accomplished using the VENSIM® software.

While Chapter 5 only deals with the problem formulation, dynamic hypothesis and the model formulation, Chapter 6 provides the simulation results of the developed *BIOTSA* model. This is the testing step of the modelling process and includes the baseline simulation results, verification and validation tests. Further, policy testing and evaluation is also discussed in Chapter 6, which is the final stage of the system dynamics modelling.

CHAPTER 6: BIOENERGY TECHNOLOGY SUSTAINABILITY ASSESSMENT (*BIOTSA*) RESULTS[29]

6.1 INTRODUCTION

Future biodiesel production development for sustainability requires an improved approach that can take into account of the sustainability goals of a particular country or region. The *BIOTSA* model was developed following the *SATSA* framework, which provides a guiding process to assessing the sustainability of energy technology development.

This chapter provides the simulation results of the *BIOTSA* model, discussion of the validation and verification of the *BIOTSA* model and policy analysis. Firstly, the baseline results of the sustainability indicators simulated with the *BIOTSA* model is presented. This analysis is followed by the validation and verification tests of the model's behaviour based on structural validity, behavioural validity and expert opinion. In addition to the baseline results, policy design and analysis based on a number of scenarios were tested to compare the performance of the sustainability indicators relative to the baseline results. The simulation results in this chapter should not be seen as "predictions" but rather as possible evolution of the sustainable technology development from which understanding might be derived, which could be used to make more robust decisions.

6.2 BASELINE RESULTS

The goal of the *BIOTSA* model is to demonstrate the appropriateness of *SATSA* framework in assessing sustainable biodiesel development. Thus, the *BIOTSA* model was used to produce various scenarios of how biodiesel technology development might influence the identified sustainability indicators. The baseline scenario represents a situation where the current South African strategy of supporting biofuel production is maintained. In addition, the baseline scenario assumes that a proposed biodiesel investment project by an international company that intents to export biodiesel is also kept. The plant is expected to be operational in 2012. Table 6.1 provides a list of the initial inputs of some key parameters used in the baseline case. Different settings for these parameters are discussed in the scenario analysis. The discussion

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[29] The content of this chapter has been submitted for publication in *TECHNOVATION*. See Appendix A for details.

of the baseline behaviour of the sustainability indicators in the *BIOTSA* model is categorized according to the economic, social and environmental indicators.

Table 6.1: Baseline scenario parameters

Parameter	Units	Baseline values
Fertilizer switch	Dimensionless	0
Cost growth rates	Dimensionless/year	0.1%
Initial perception	Dimensionless	0.1
Support for biodiesel per litre	Rand/litre	0
By-product switch	Dimensionless	0

6.2.1 Economic indicators

The economic indicators in the *BIOTSA* model are associated with the performance of the biodiesel plant and the economy of the Eastern Cape Province. The base case scenarios for the economic indicators are presented in Table 6.2. This is also accompanied by the simulation runs in Figure 6.1.

Table 6.2: Economic indicators[30] simulation output

Year	Biodiesel production (Litre/year)	Biodiesel profitability (Rand/year)	PC real GDP (Rand/person/year)
2005	0.00E+00	0.00E+00	6.89E+03
2012	1.61E+06	-3.34E+08	8.87E+03
2019	3.26E+08	-7.55E+08	1.03E+04
2026	2.61E+08	-4.94E+08	1.11E+04
2033	1.87E+08	-3.31E+08	1.17E+04
2040	1.32E+08	-2.80E+08	1.23E+04
2047	9.29E+07	-2.74E+08	1.24E+04
2054	6.61E+07	-2.77E+08	1.22E+04
2061	5.11E+07	-2.81E+08	1.22E+04
2068	4.55E+07	-2.81E+08	1.24E+04
2075	4.52E+07	-2.78E+08	1.26E+04
2082	4.62E+07	-2.76E+08	1.25E+04
2089	4.61E+07	-2.81E+08	1.24E+04
2096	4.49E+07	-2.96E+08	1.24E+04
Final	4.35E+07	-3.13E+08	1.23E+04

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[30] Average exchange rate in 2010: 1USD = 7.3 Rand (http://www.x-rates.com/d/ZAR/USD/data120.html)

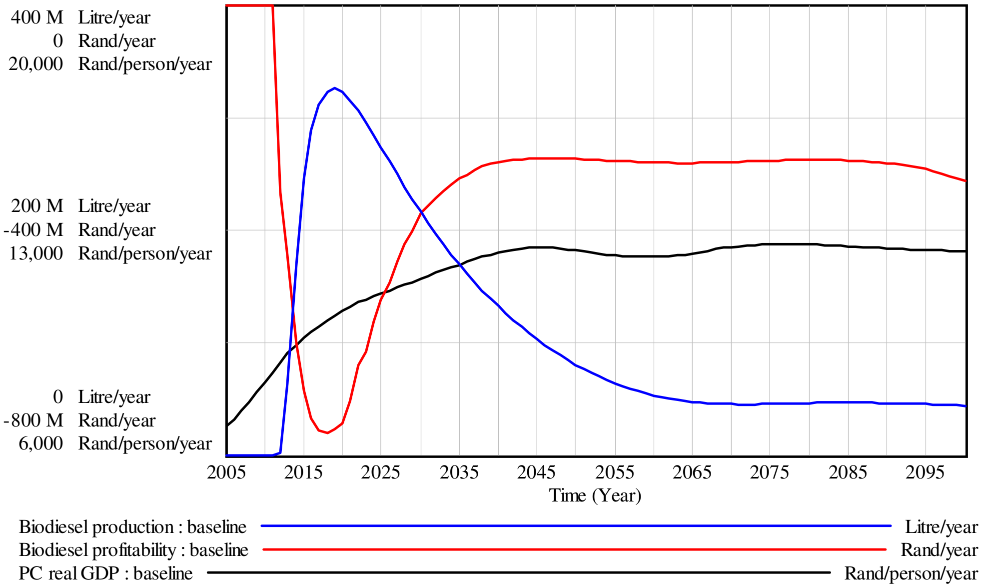

Figure 6.1: Graphical output for economic indicators of the *BIOTSA* model

Large-scale biodiesel production in South Africa is at its infancy. Hence, biodiesel production investment in the *BIOTSA* model is dependent on exogenous planned future capacity and endogenous desired new capacity. The biodiesel production (ECO_1) is projected to start from 2012 and a maximum production capacity of about 326 million litres / year is reached in 2019 and then starts to decrease. There are a number of factors that influence the dynamics of the biodiesel production and future expansion (see Figure 6.2): feedstock availability and cost; land availability; and expected profitability. From 2012 until 2048, the expected profitability is not enough to encourage more desired capacity expansion. Hence the effect of expected profitability on desired capacity is zero as shown in Figure 6.2. This is the key factor resulting to the rapid decline in the biodiesel production. In addition, the biodiesel production declines in order to match with the local feedstock supply.

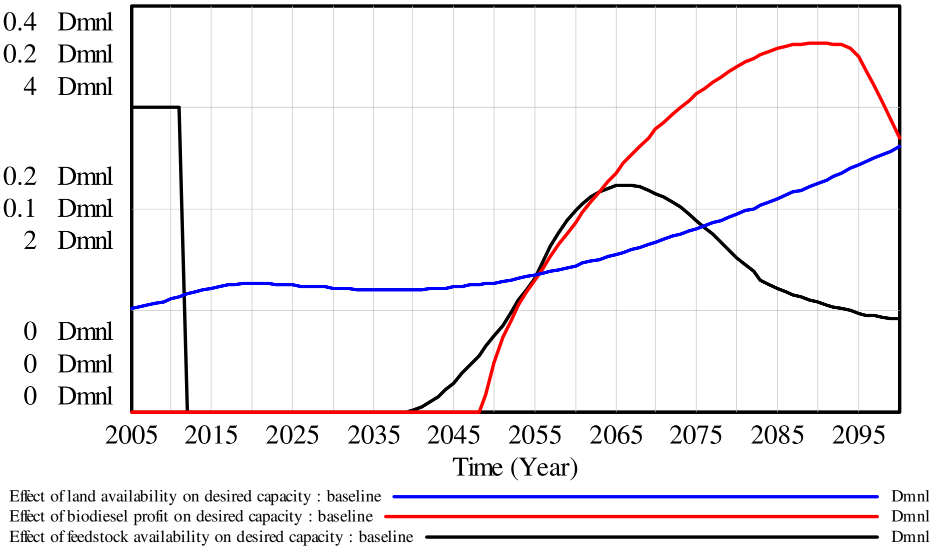

Figure 6.2: Graphical output of effects on desired capacity

The biodiesel plant developers propose to use an agrarian (agriculture) model, whereby they initially expect to source feedstock from imports. The imports would decrease as the local feedstock production increases. However, given the initial low initial perception as indicated in the baseline scenario, local supply of feedstock is constrained resulting in reduction of desired capacity and consequently biodiesel production. The low initial perception used in the baseline scenario is based on the evidence that people are reluctant to implement new activities/technologies that are introduced to them, especially those that involve a paradigm shift. Evidence concerning the low perception includes: lack of trust, incredibility and past bad experiences. This has been reported by Amigun et al. (2011a). It might take some time to change the mindset of the communities so that they would be willing to grow crops for biodiesel production.

Biodiesel profitability (ECO_2) is another economic indicator for the performance of the investment in the biodiesel production (Figure 6.1). The *BIOTSA* model indicates high losses incurred in 2012, which is as a result of the initial capital cost investment incurred. From 2013 however, due to the start of the biodiesel production, the capital cost is covered but still the operation is not profitable. The loss incurred decreases over the simulation period and it is projected to reach -276 million Rand/year in 2081. Thereafter, the loss begins to increase and reaches -313 million Rand/year at the end of the simulation period.

Looking at the per capita real GDP (ECO_3) in the Eastern Cape Province, the *BIOTSA* model projects the growth of Eastern Cape per capita GDP from 8866 Rand /person/ year in 2012 to 12329 Rand /person/ year in 2100 (Table 6.2 and Figure 6.1). This represents an increase of about 39% increase relative to 2012.

6.2.2 Social indicators

The simulation output for the social indicators is presented in Table 6.3 which is also accompanied by the graphical output in Figure 6.3. Given the increases in the baseline biodiesel functional capacity, the employment in the biodiesel plant (SOC_1) is also projected to increase, reaching a maximum of 203 persons in 2020 as presented in Figure 6.3. Thereafter, the employment declines due to the decrease in the biodiesel functional capacity. Thus, without further development in the biodiesel functional capacity, the employment in the biodiesel plant would continue to decline into the future.

Table 6.3: Social indicators simulation output

Year	Employment biodiesel plant (Person)	Perception of biodiesel crops benefits (Dmnl)
2005	0.00	0.10
2012	5.52	0.12
2019	202.53	0.13
2026	185.64	0.15
2033	157.48	0.16
2040	132.35	0.17
2047	111.09	0.18
2054	93.51	0.19
2061	81.51	0.21
2068	76.15	0.22
2075	75.45	0.24
2082	76.35	0.26
2089	76.34	0.28
2096	75.47	0.30
Final	74.49	0.32

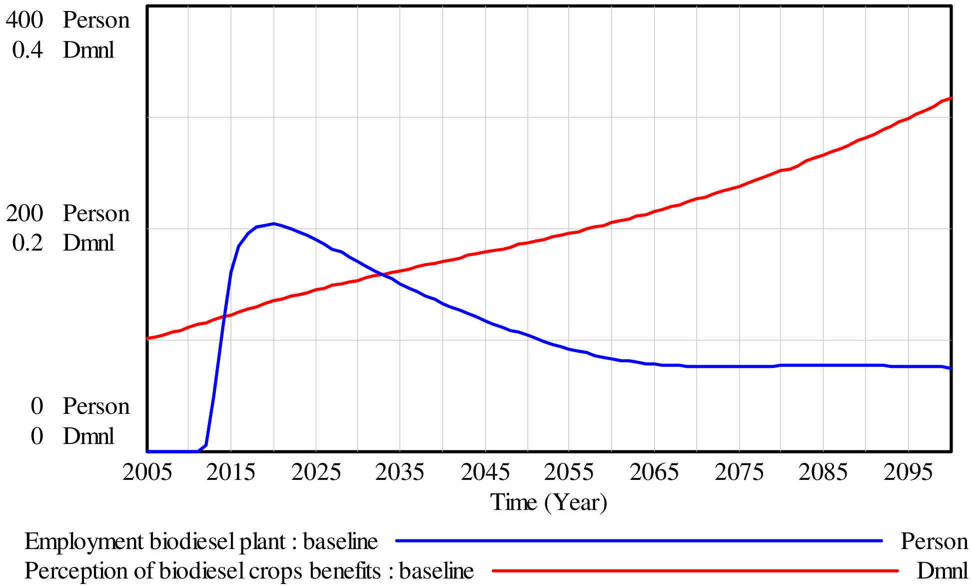

Figure 6.3: Graphical output of social indicators of the *BIOTSA* model

Land is an important asset in the Eastern Cape Province as it is considered as an inheritance (Amigun et al. 2011a). Thus, the community perception on biodiesel crops benefits (SOC_2) is an important social indicator for biodiesel production development. As observed in Figure 6.3, the *BIOTSA* model projects an increase in the perception of biodiesel crops from a very low value of 0.12 in 2012 to about 0.32 in 2100, which is about 2.67 times more relative to 2012. The community perception increases over the simulation period because only a small proportion of fallow land is converted into biodiesel crop land. If large proportion of this land is converted, the community would perceive that the land is being taken away from them which in turn would decrease their perception of biodiesel crops benefits.

6.2.3 Environmental indicators

The five environmental indicators in the *BIOTSA* model are: land use change (ENV_1), air emissions (ENV_2), biodiesel by-products (ENV_3), water use (ENV_4) and energy use (ENV_5). Land use changes are associated with the proposal to acquire biodiesel crop land from fallow land, which also competes with the other land uses. Table 6.4 indicates the values of the land use simulation outputs while Figure 6.4 presents graphically the changes of the different land uses over the simulation period.

Table 6.4: Environmental indicators simulation output

Year	Biodiesel crop land (Ha)	Fallow land (Ha)	Forest plantations (Ha)	Livestock Land (Ha)	Crop land (Ha)	Settlement land (Ha)
2005	0.00E+00	6.76E+05	8.45E+05	1.08E+07	3.38E+06	1.01E+06
2012	1.02E-01	5.03E+05	8.95E+05	1.07E+07	3.45E+06	1.13E+06
2019	1.19E+04	4.69E+05	9.20E+05	1.04E+07	3.65E+06	1.24E+06
2026	3.89E+04	4.38E+05	9.33E+05	1.00E+07	3.94E+06	1.36E+06
2033	6.09E+04	4.16E+05	9.37E+05	9.58E+06	4.27E+06	1.47E+06
2040	7.42E+04	4.03E+05	9.13E+05	9.16E+06	4.60E+06	1.57E+06
2047	7.98E+04	3.93E+05	8.57E+05	8.80E+06	4.93E+06	1.67E+06
2054	7.91E+04	3.86E+05	7.74E+05	8.50E+06	5.23E+06	1.76E+06
2061	7.41E+04	3.85E+05	6.67E+05	8.26E+06	5.51E+06	1.83E+06
2068	6.73E+04	3.89E+05	5.46E+05	8.11E+06	5.74E+06	1.88E+06
2075	6.06E+04	3.89E+05	4.67E+05	8.02E+06	5.88E+06	1.92E+06
2082	5.52E+04	3.80E+05	4.26E+05	7.92E+06	5.98E+06	1.96E+06
2089	5.05E+04	3.69E+05	4.00E+05	7.79E+06	6.10E+06	2.02E+06
2096	4.65E+04	3.59E+05	3.81E+05	7.64E+06	6.23E+06	2.07E+06
Final	4.46E+04	3.54E+05	3.73E+05	7.55E+06	6.31E+06	2.10E+06

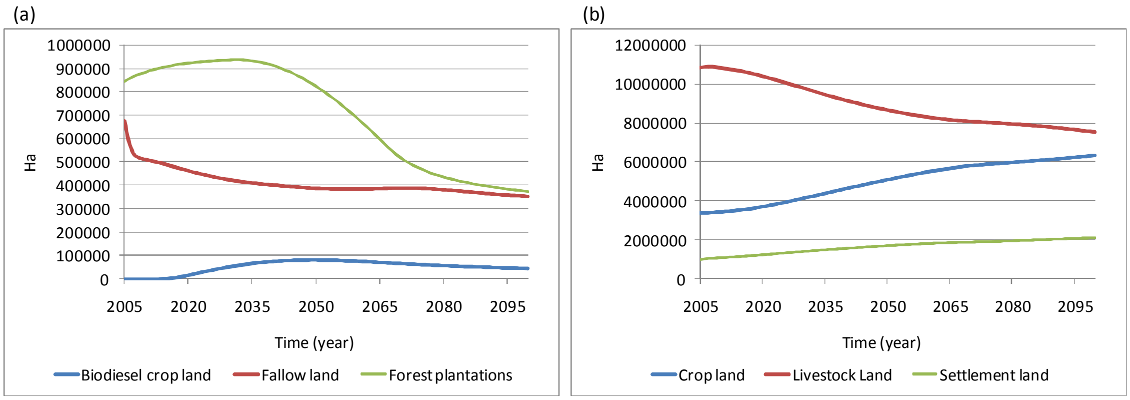

Figure 6.4: ENV_1 indicator of the *BIOTSA* model

According to the *BIOTSA* model, fallow land is the only land type which can be converted to biodiesel crop production. Thus, a reduction in the size of fallow land is observed during the biodiesel production period. This declines from 503426 ha in 2012 and reaches 354346 ha in 2100, which is about 30% reduction relative to 2012. Biodiesel crop land on the other hand increases from zero in 2011 to a maximum of 80142 ha in 2050. Henceforth, the biodiesel crop land declines and reaches 44610 ha in 2100. In a similar manner, forest plantation increases at a decreasing rate from 844830 ha and reaches a maximum of 936668 ha in 2033. Thereafter, the forest plantation declines at a decreasing rate, reaching 373025 ha in 2100. For the case of the crop land, the *BIOTSA* model projects an increase from 3454326 ha in

2012 to 6305304 ha in 2100, which is 83% increase relative to 2012. This increase is largely driven by the increase in population. The same case applies to settlement land, which also increases over the simulation period due to increase in population.

The air emissions (ENV_2) indicator is associated with the air emissions avoided due to biodiesel production. Given that the case considered here is for biodiesel product that would be used outside South Africa, this indicator becomes important in terms of negotiations in the carbon trading market and policy arena. As observed in Figure 6.5, the *BIOTSA* model projects that the emissions follow the biodiesel production behaviour and a maximum air emission avoided of 390.61 million kg CO_2/year is reached in 2019 and declines thereafter as biodiesel production declines as well.

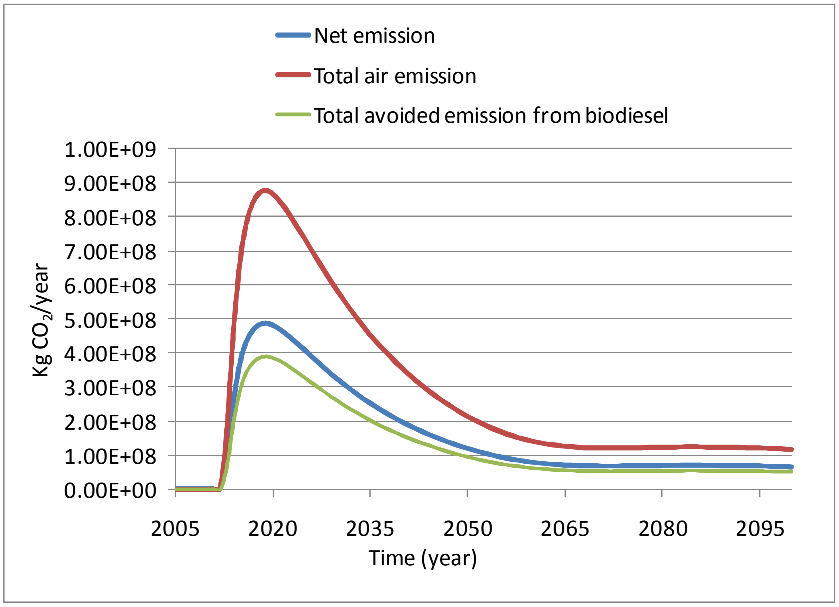

Figure 6.5: ENV_2 indicator of the *BIOTSA* model

The biodiesel by-product (ENV_3) indicator relates to the glycerol that is generated as a by-product in the biodiesel production. The glycerol by-product similarly follows the biodiesel production behaviour as shown in Figure 6.6. The glycerol by-product can be sold to the pharmaceutical companies for use in a productive way, thus generating revenue to the biodiesel plant. This was analyzed as a scenario for the *BIOTSA* model and is discussed in section 6.4.

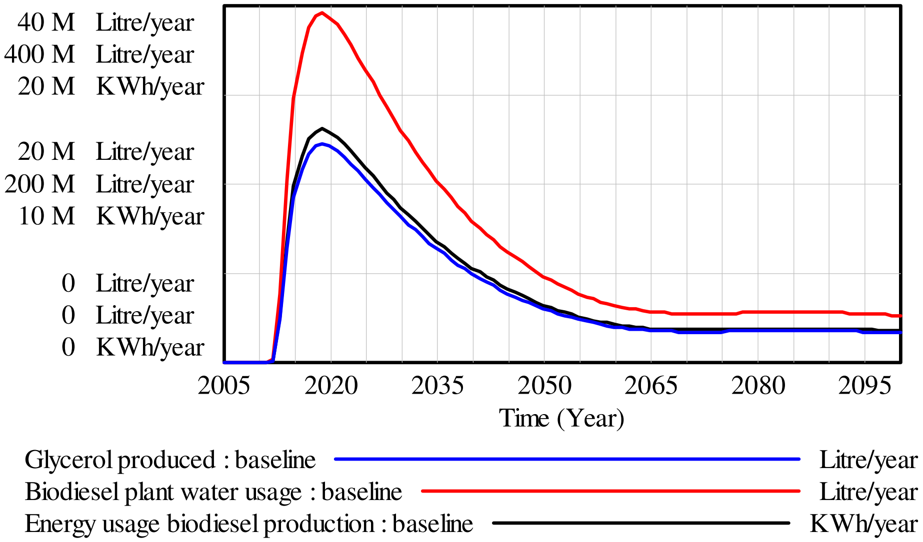

Figure 6.6: ENV_3 indicator of the *BIOTSA* model

The water use (ENV_4) indicator constitutes the amount of water consumption by the biodiesel plant. As shown in Figure 6.6, the *BIOTSA* model projects a maximum water use of approximately 390.61 million litres when biodiesel production is at its highest level in 2019. This value, however, declines following the behaviour of biodiesel production.

Finally, the energy use (ENV_5) indicator similarly represents the amount of electricity needs as a result of biodiesel production. The *BIOTSA* model projected behaviour of the energy usage is shown in Figure 6.6.

In general, all the environmental indicators except land uses are mainly influenced by the biodiesel production development and tend to follow the trend of the biodiesel production.

6.3 VALIDATION AND VERIFICATION

The intention of a system dynamics models is not to produce exact or precise projections but to represent the tendencies and behaviour which may support the process of formulating strategies. Model testing is an iterative process (Sterman 2000) that runs throughout the modelling process. Model testing enables the modeller to understand the limitations and robustness of the model developed. In system dynamics, the process of validation typically relies on different number of tests. The field seems to lack formalized methodology and tools for validation. In addition, there is no system dynamics software that contains a full validation environment. Nevertheless, this does not imply that there are no robust techniques for finding the flaws in the model structure and behaviour.

According to Sterman (1988), validation is a continuous process of testing and building confidence in the model. There is no model that can be validated by a single test or the ability to fit the historical data. Thus, it is not generally possible or plausible to classify the model as correct or incorrect (Barlas, 1996; Sterman, 2000), but the model can be of good quality or poor quality (Barlas, 1996), suitable or not suitable. On a different note, Forrester (1961) argues that the validity of a system dynamics model cannot be discussed without reference to a specific purpose. Thus, in order to make use of the standardized tests, it is always important to keep note of the environment in which the model is designed to operate and the questions it aims to answer.

This study uses among others the three validity tests suggested in the literature. Each of these validity tests and how they were used in the *BIOTSA* model are further discussed in the sections that follow.

6.3.1 Structural validity

Structural validity is considered as fundamental in the overall validation process (Qudrat-Ullah and Seong, 2010). This is because a model's validity is not sufficiently established by merely generating "accurate" output behaviour. What is essential is validity of the internal structure of the model (Barlas, 1989). According to Barlas (1989) s*tructural validity tests* determine how well the structure of the model matches the structure of reality. This is the case when every model component has a real world counterpart and when every key factor contributing to the problem in the real world has a model counterpart. As descriptions of system structure are generally not available, they have to be extracted from the mental models of people familiar with the system. However, system understanding of different actors is usually not identical. One goal of consultative transdisciplinary research was thus to increase the degree to which overlap occurred, that is, building consensus. Furthermore, key factors contributing to the problem may be unrecognised prior to modelling and there is no guarantee that they may be discovered during the model development process. In this study, the structural validation process began at the initial stage of model building when the first few parameters were estimated and their relationships defined. This continued throughout the entire model building and each of this is discussed.

6.3.1.1 *Direct structure test*

The direct structure validity test was carried out to check the model consistency with the knowledge of the real system relevant to the purpose. A number of approaches were applied to test the structural validity tests. Firstly, the *BIOTSA* model utilised a case specific data of Eastern Cape and/or knowledge available about the real system of biodiesel development.

Secondly, the mathematical relationships were evaluated and comparisons made with the real situation of the biodiesel production development. As an illustration, Table 6.5 shows three equations of how this process was carried out for all the equations in the model.

Table 6.5: Selected examples of direct structure test

Equation	Explanation with real situation
$r_{FC_b} = Max\left[0,\left(\left(\frac{DBCL-BCL}{t_{FC_b}}\right)*E_{PBL}\right)\right]$	Land that is converted for biodiesel crops come from fallow land. The conversion of this land is however dependent on the community perception and acceptance of growing these crops and the desired biodiesel crop land by the investors of the biodiesel plant. The fuzzy maximum function (Sterman, 2000) is used because the conversion rate of fallow land to biodiesel crop land must remain non-negative.
$r_{BP} = FBC\left(\frac{24\,hour}{day}*\frac{330day}{year}\right)*E_{TL}*CU$	Biodiesel production is the output from a biodiesel plant and is only possible based on the capacity that is functional, the number of hours in a year it runs, its capacity utilization and the labour.
$DEBP = \alpha\left(FBC\right)^{\beta}$	Employment is the number of people working in the biodiesel plant and this is dependent on the capacity that is functional.

In addition to the mathematical equations, tests were done to ensure that the *BIOTSA* model conforms to the basic physical conservation laws. An example of a common violation of this law entails a stock that becomes negative. For instance, all land stocks can either be zero or a positive number but not a negative value. Thus the outflow tests from these flows should approach zero as any of these stocks approaches zero. The first equation in Table 6.5 provides such an illustration. This was inspected for all the stocks and their respective flows.

Thirdly, some existing structure of some sub-models were adopted and thus served as a "theoretical" direct structure test (Forrester and Senge, 1980) for the *BIOTSA*. The conclusion that was drawn from undertaking these tests was that, the *BIOTSA* model is a robust simplification of the processes occurring in the real world.

6.3.1.2 Dimensional consistency test

This test seeks to verify that the equations in the model are dimensionally consistent without using arbitrary constants that do not represent the real world situation (Sterman, 2000). The test was done by inspecting the dimension of inputs for the equations and also from the actual simulation of the model. The simulation using the VENSIM® software did not generate any dimension consistency error.

6.3.1.3 Parameter confirmation test

This test was performed throughout the model-building phase. Since large-scale biodiesel production in South Africa is in its infant stage, an attempt was made to ensure that all the parameters defined represent the real system of biodiesel development in South Africa. The list of parameters used in each of the sub-models was presented in Chapter 5 and their source or notes about them were highlighted. Some control buttons were included for some parameters which were in question so that they could be specified with a particular range. In doing so, this allowed for prompt and effective extreme condition testing and scenario analyses which are further discussed in this chapter.

The standard statistical test could not be applied in this study because of the lack of historical data. Apart from the data limitation, the test could not be possible even with the availability of data due to the transient, non-stationary behaviour of most of the model indicators. According to Barlas (1996), the modelled problem is of no statistical nature and validating it statistically is unsuitable due to multicollinearity and autocorrelation problems. The appropriate approach suggested by Barlas (1996) is the use of graphical/visual measures to compare the behaviour pattern.

6.3.1.4 Extreme condition test

A model that has the ability to properly function when subjected to extreme conditions contributes to its utility as a policy evaluation tool and increases user confidence. Two types of extreme condition tests are recognized in system dynamics namely: structure-oriented and direct behaviour test. The former was used for the *BIOTSA* model in order to assess the plausibleness of the resulting behaviour against the anticipation and/or knowledge of what is expected to occur under similar condition in the real world (Forrester, 1971). A number of selected parameters were thus assigned extreme values and a comparison made on the model-generated behaviour to the anticipated behaviour of the real system under a similar extreme condition. A selected output of some of the sustainability indicators is discussed below:

Test 1: Extreme initial community perception

The initial community perception of biodiesel crops parameter was set to 1 and the results from such a simulation for the selected sustainability indicators affected by this parameter are presented in Figure 6.7. In reality, if such a situation happens, it implies a high level of community acceptance to grow biodiesel production crops implying larger amount of biodiesel crop land as observed in Figure 6.7a. With large biodiesel crop land available, there would be a higher incentive for the desired biodiesel capacity which obviously increases the overall biodiesel production. However, since land availability is only one component that determines desired biodiesel capacity, this increase is only evident almost at the end of the simulation period as shown in Figure 6.7b. Improved profitability and total avoided emissions increased also follows the dynamics of the biodiesel production (Figure 6.7c and Figure 6.7d respectively). It is thus evident from the result in Figure 6.7 that the simulation properly responds to the set extreme condition.

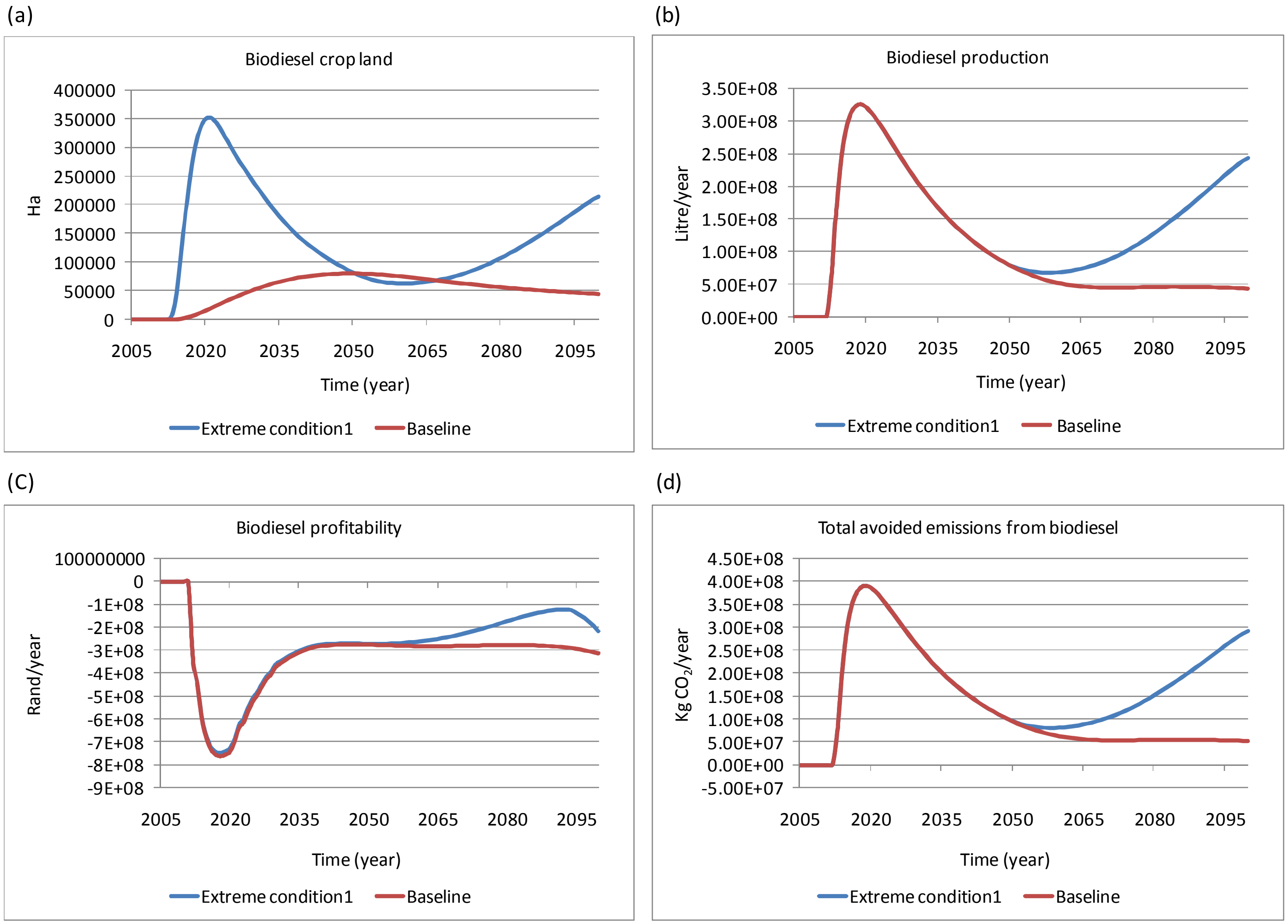

Figure 6.7: Extreme condition 1 of initial community perception results

Test 2: Extreme feedstock cost growth rates

The baseline results of the *BIOTSA* model used the feedstock cost growth rates of 1% which were based on the assumption of an expert opinion. When such cost growth rates are increased to 25% the simulation results are shown in Figure 6.8. With such a condition in the real world, higher increases in the feedstock cost decreases the profitability of biodiesel production (see Figure 6.8a) which in turn reduces the desired biodiesel plant capacity to zero (see Figure 6.8b). The reduction in the capacity implies reduced biodiesel production. Lower biodiesel production implies reduced revenue generation further decreasing the biodiesel profitability. It is also clearly seen that the simulation results in Figure 6.8 responds to the extreme condition of increased costs growth rate.

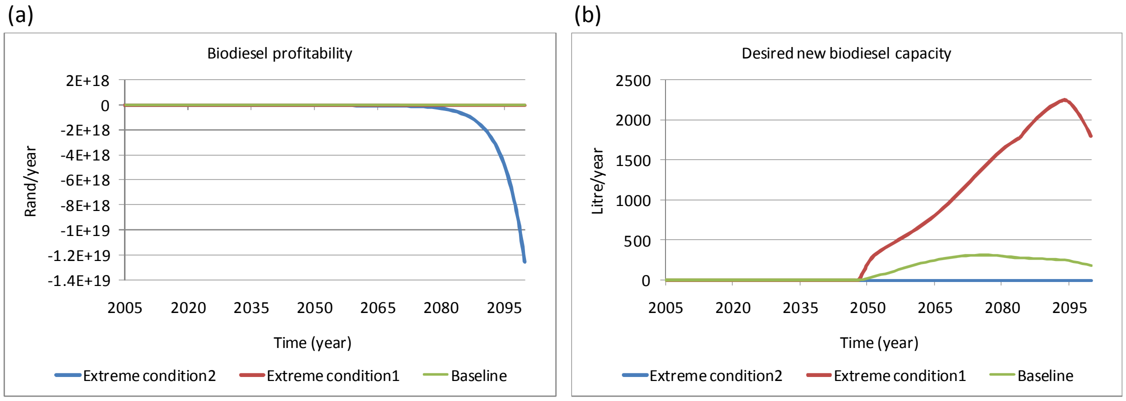

Figure 6.8: Extreme condition 2 of cost growth rates result

Test 3: Planned biodiesel investment table

When the planned biodiesel investment table is set to zero, it is expected that there is no future development of the biodiesel plant, which means no production, no conversion of land and zero profitability. The simulated results accurately respond to this condition as is observed in Figure 6.9.

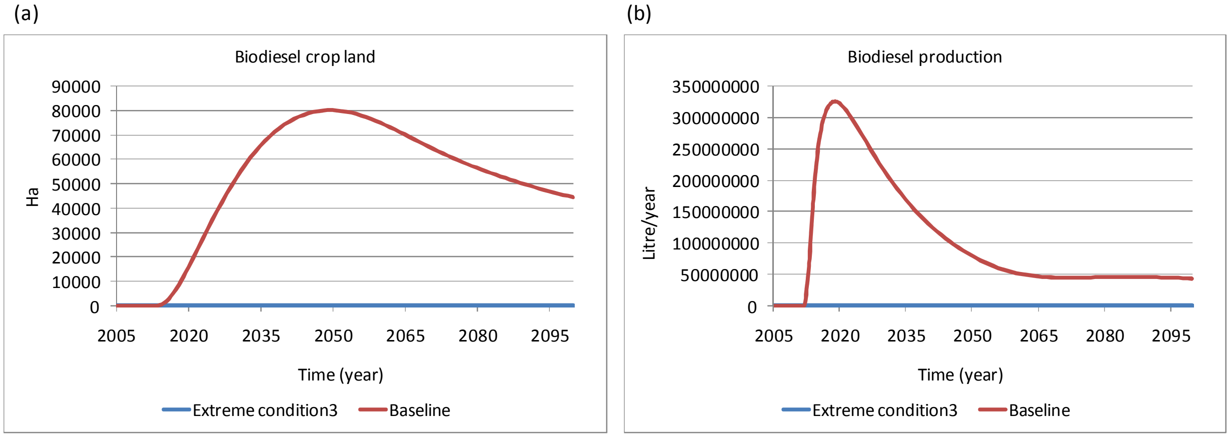

Figure 6.9: Extreme condition 3 planned biodiesel investment table

Generally, it is observed that the *BIOTSA* model yields the expected behaviour of the real system under the extreme condition. Thus, the *BIOTSA* model does pass the extreme condition test and the validity of the model was enhanced.

6.3.2 Behavioural validity

Behaviour tests determine how consistently model outputs match real world behaviour (Barlas, 1996). This can either be based on available time-series data or the correlation of mental models with established reference modes (Sterman, 2000). The usefulness of the former clearly depends on the quality of the available historical data, while the latter necessitates a substantive and coherent overlap in mental models. There are a number of ways of undertaking behavioural tests and how they were carried out for the *BIOTSA* model is discussed below.

6.3.2.1 Reference test

This entails running the simulation a few years or decades in the past and comparing how the model reproduces the key indicators with the actual/historical data. Unfortunately, this test was not possible with the *BIOTSA* model due to the non-existence of the biodiesel development market in South Africa. Thus, no historical data that exists that could be used to undertake the reference test.

6.3.2.2 Sensitivity analysis

It was important to know how the *BIOTSA* model was sensitive to different assumptions. The VENSIM® software does provide a platform for carrying out robust Monte-Carlo sensitivity simulations. Monte-Carlo simulation explores the uncertainty and future possibility of selected output variables through a selected number of repeated simulations, in which the uncertain or unknown parameters are randomly drawn. Given the uncertain parameters, confidence bounds are used for illustrating model validity. As part of the validation process for the *BIOTSA* model, the focus on the sensitivity analysis was on the cost growth rates with particular emphasis on the feedstock. This is because the price of feedstock such as canola seed is determined by the import parity and local supply, which vary not only from year to year, but also from month to month. Thus, biodiesel production and profitability would be greatly influenced by the cost of feedstock due to changes in price and it is necessary to establish how sensitive the production is as a result of the variation in price. Thus, the feedstock cost and other cost growth rates were set between -5% and 5% and the behaviour of the selected sustainability indicators were observed. In addition, it was uncertain on the length of time to change the community perception which was set between 5 and 20 years. Table 6.6 provide the range of the parameters that were to change in order to carry out the sensitivity test. A random uniform distribution was used for all these parameters and the number of simulations was set at 400 scenarios.

Table 6.6: Baseline scenario parameters

Parameter	**Unit**	**Value**	**Range**
Biodiesel reference	Litre	1.5e+009	[1e+009, 2e+009]
Feedstock cost growth	Dmnl	0.001	[-0.05, 0.05]
Other operational cost growth	Dmnl	0.001	[-0.05, 0.05]
Capital cost growth	Dmnl	0.001	[-0.05, 0.05]
Water cost growth	Dmnl	0.001	[-0.05, 0.05]
Time to change perception	Year	10	[5, 20]

Figure 6.10 provides the simulation based confidence bounds for biodiesel crop land, biodiesel profitability, biodiesel production and employment in the biodiesel plant. Figure 6.10 results indicate the percentage test cases in the Monte-Carlo simulation that fall within a particular percentage of confidence bounds. For instance, 100% of biodiesel profitability test cases are located in the 100% confidence bounds. More sensitivity analyses results can be found in Appendix E.

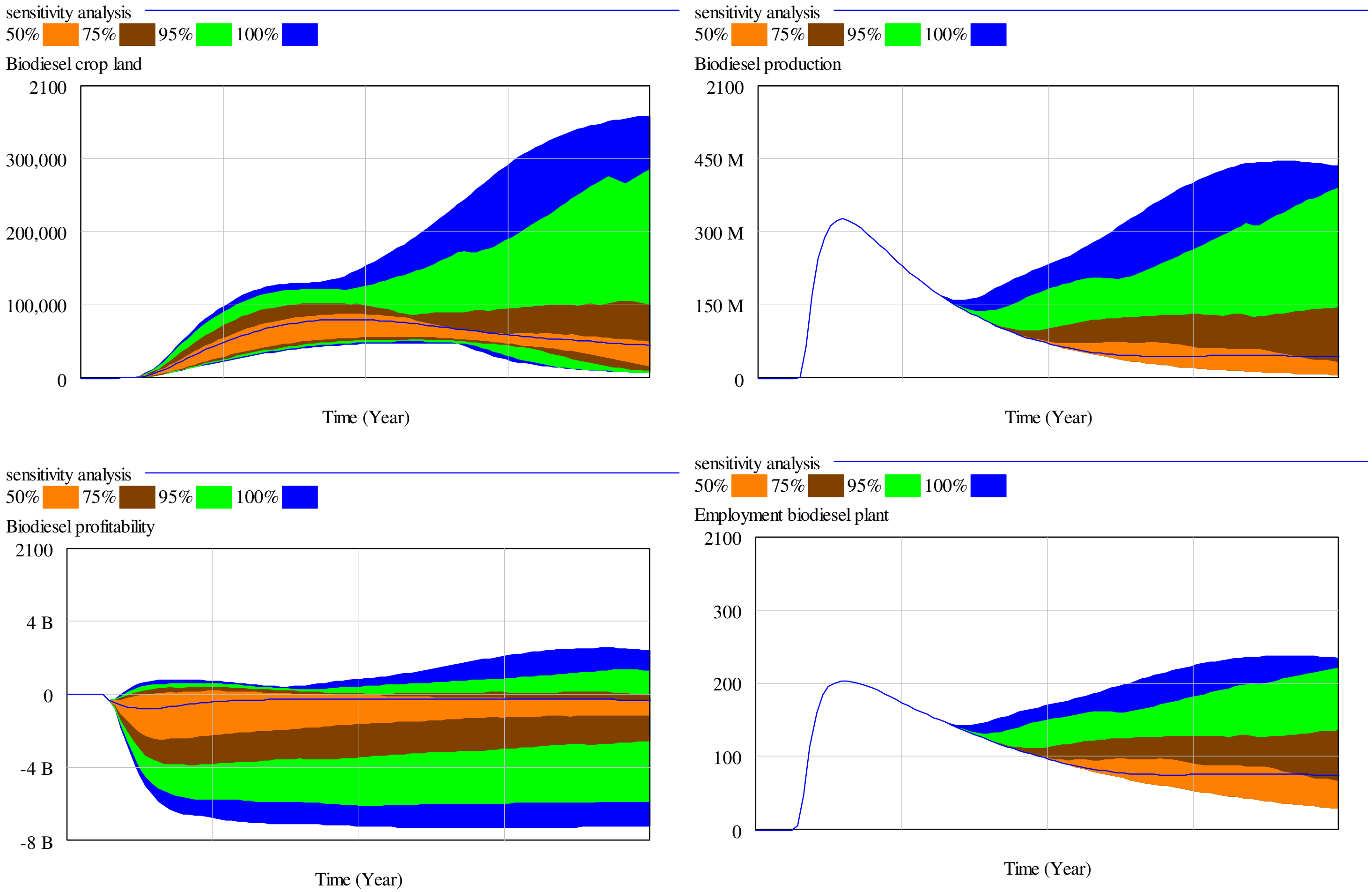

Figure 6.10: Sensitivity analysis of cost growth rates result

6.3.3 Expert opinion

Qualitative validation using expert opinion was also used in this study to assess the model usefulness, importance and quality. The experts surveyed include the technology assessment practitioners, technology developers and the public agencies in the Eastern Cape Province and at a national level.

6.3.3.1 Technology assessment practitioners' opinion

Figure 6.11 presents the Technology assessment practitioners' opinions, which show that relevance and importance of the *BIOTSA* model had more responses (Figure 6.11a) and the model was considered as highly relevant and important (Figure 6.11b). The issue of reliability and practicability received moderate positive responses (Figure 6.11a) and high No response (Figure 6.11b). This is also consistent with the average rankings (see Table 6.7) which show that relevance is ranked high, importance ranked medium, while both reliability and practicability are ranked low.

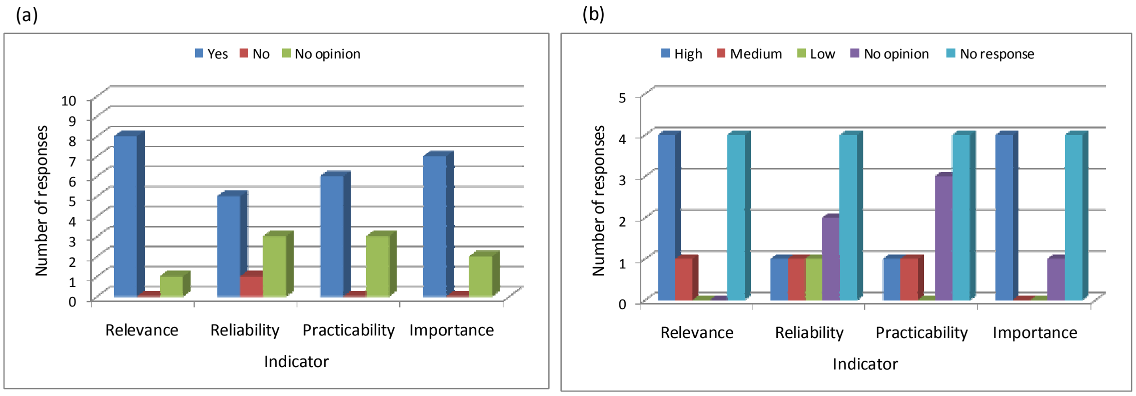

Figure 6.11: Technology assessment practitioners' opinion on the *BIOTSA* model relevance, reliability, practicality and importance

Table 6.7: Average rankings – the technology assessment practitioners result

Indicator	Average	Standard deviation	Rank
Relevance	2.8	0.45	High
Reliability	1.2	1.30	Low
Practicability	1	1.41	Low
Importance	1.8	1.64	Medium

Table 6.7 also show that the importance of the *BIOTSA* model is ranked as medium but with a high standard deviation of 1.64. Similarly, while reliability and practicality of the *BIOTSA*

model is ranked as low, the standard deviation is also higher, indicating a low consensus by the technology assessment practitioners in these responses. This is probably because reliability and practicability was seen as a policy question rather than the energy modeller's question. This conclusion was drawn from a summary of comments that were given on each of the indicator responses and are presented in Table 6.8.

Table 6.8: Summary of the technology assessment practitioners' opinion on relevance, reliability, practicality of the *BIOTSA* model

Relevance

- It seems to take into account of a wide range of input parameters which affect development of the sector
- It showed that the major issue is the buy-in from locals. However, the scenarios show that pay-back is long. This is a long-term social welfare project
- The parameters represented in the model are comprehensive
- Provides understanding of the interactions
- Relevant especially in South Africa which is faced with climate change issues and unemployment
- Creates awareness to land owners, land tenants, government, Eskom

Reliability

- Well researched inputs; transparent methodology with many scenarios
- The technologies represented give a good picture of what to expect
- It depends on the assumptions on which the parameter values are based; some validation and calibration is required
- Some respondents were not sure about the reliability but thought it can be reliable

Practicability

- Good from investment and policy point of view but lacking in terms of a developer point of view. The output should be linked to GIS and technology used
- Some respondents were not sure but mentioned that it incorporates all important issues that need to be considered especially community perspective
- It is practical but needs government buy-in

Importance

- It gives due consideration to multiple factors that will affect future take-up of which community buy-in and participation is a key one
- There is need to diversify the energy supply mix
- Knowledge of projections and modelled estimates is quite valuable and *BIOTSA* does that
- Important to model the interaction between different stakeholders and systems which *BIOTSA* model does it
- It is important from an employment/job creation perspective
- Some respondents were not sure of biodiesel future availability/demand because it was seen as a government policy

6.3.3.2 Technology developers' opinion

The opinions of the technology developers presented in Figure 6.12 indicate that some responses regard the *BIOTSA* model as highly relevant, reliable, practical and important in assessing biodiesel production development in the Eastern Cape Province. On the other hand, some of the respondents provided a No opinion response on the *BIOTSA* model. As a result, the average rankings (see Table 6.9) show that the relevance, reliability and importance of the *BIOTSA* model are ranked medium, while practicability is ranked low.

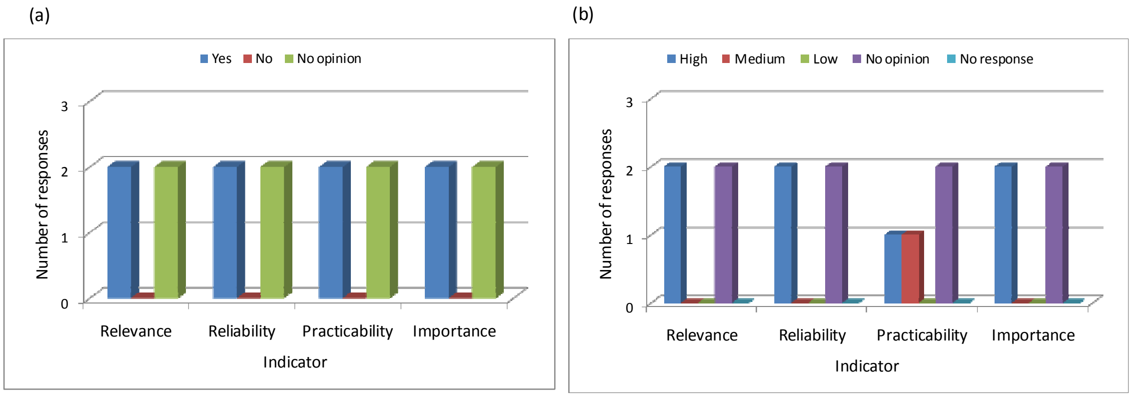

Figure 6.12: Technology developers' opinion on the *BIOTSA* model relevance, reliability, practicality and importance

Table 6.9: Average rankings – the technology developers result

Indicator	Average	Standard deviation	Rank
Relevance	1.5	1.73	Medium
Reliability	1.5	1.73	Medium
Practicability	1.25	1.5	Low
Importance	1.5	1.73	Medium

The standard deviations for the technology developers are higher than those provided by the technology assessment practitioners (see Table 6.9). This indicates a very low consensus among the technology developers than among the technology assessment practitioners. The specific comments that were provided by the technology developers are presented in Table 6.10.

Table 6.10: Summary of the technology developers' opinion on relevance, reliability, practicality of the *BIOTSA* model

Relevance

- Sustainability has to be central to get things off the ground
- Relevant to provide informed policy decision on sustainable biodiesel development and developing guidelines
- The details of the relevance are behind the model

Reliability

- While the model looks reliable, there is limited scope for end value chain (market); it need to be rigorous
- This is dependent on the inputs and assumptions made in the model. For industry, the inputs would be different because for instance, job creation is not a driver in business

Practicability

- The relevant government agencies in the Eastern Cape such as office of the Premier, Accelerated shared Growth Initiative South Africa and Eastern Cape Socio Economic Council will benefit from the model
- Good and usable; it is a good model for use in the industrial development zones (East London and Coega)
- This depends on the level of detail, data availability and capacity/skills availability for such modelling

Importance

- Shows the economic, social and environmental effect of the biodiesel industry
- At the moment there is no biofuels strategy in the Eastern Cape. If results for a model like *BIOTSA* is published before hand, it will be useful in providing policy guidance
- Important for government as they are driving different targets such as job creation and reducing carbon emissions

6.3.3.3 Public agencies' opinion

The public agencies similarly considered the *BIOTSA* model as highly relevant, reliable, practical and important in assessing the biodiesel development in the Eastern Cape (Figure 6.13 and Table 6.11). The public agencies also indicated that this modelling approach is very useful for decision-making at policy level. In Table 6.11, a high value of the average indicates a high ranking of a response and a low standard deviation value indicates a high consensus of the responses in the public agencies. This implies that there is a high consensus of the public agencies' opinion on the relevance, reliability, practicability and importance of the *BIOTSA* model. Although the *BIOTSA* model was considered an important and a practical way of looking into the biodiesel development in the Eastern Cape Province, system dynamics, in which the *BIOTSA* model was developed, is however, unknown to the public agencies. This calls for creation of awareness to this kind of assessment to the relevant people or users of the model. The specific comments that were raised by the public agencies are presented in Table 6.12.

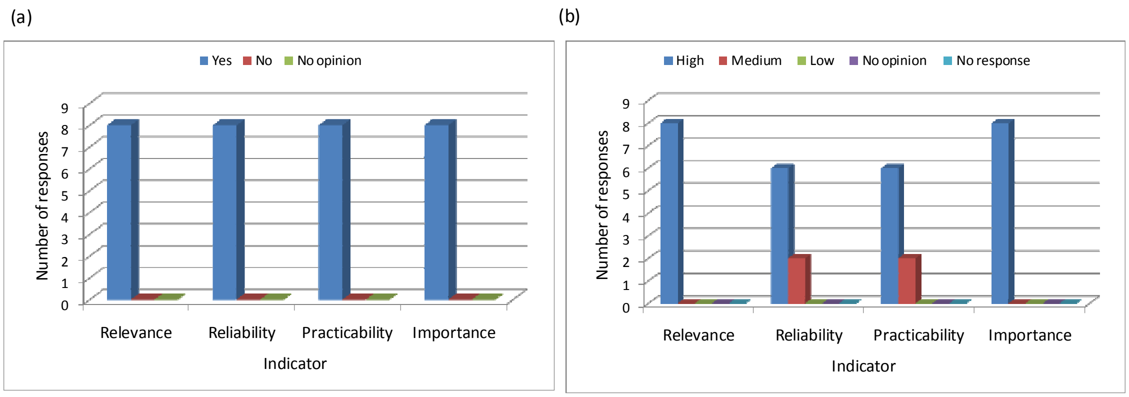

Figure 6.13: Public agencies' opinion on the *BIOTSA* model relevance, reliability, practicality and importance

Table 6.11: Average rankings – public agencies result

Indicator	Average	Standard deviation	Rank
Relevance	3	0	High
Reliability	2.6	0.45	High
Practicability	2.6	0.45	High
Importance	3	0	High

Table 6.12: Summary of the public agencies opinion on relevance, reliability, practicality of the *BIOTSA* model

Relevance

- The model captures most critical elements sufficiently; it is a multivariable approach and accounts the important variables to provide informed results; it is very comprehensive and allows for complexity
- It is a big eye opener in a scary way – in terms of the solutions claimed for alternative energy development
- Biofuels development is a new issue in the Eastern Cape and the model seems to provide relevant information on such development
- The model gives an understanding of the problem particularly to the decision-makers at policy and investors
- Currently there is a limited technical resources in South Africa that interrogates the technology development in this manner

Reliability

- Highlights the critical factors that need to be considered in the biodiesel development; especially the area of community perception
- Questions arose on how long the government can jumpstart for a success of a project
- Analyses policy for investors; better analyses and focus on the land, which is a key issue in the Eastern Cape
- Reliability is dependent on the data used for the model

Practicability

- The model is suitable for use by the Eastern Cape Socio Economic Council
- The user-friendly version has hidden the technical aspects of the model which makes it important for the policy-maker and decision-makers
- Time period for the development might be a challenge for policy-makers

Importance

- The current models used in the Eastern Cape province are not as robust as the *BIOTSA* model
- It is critical to have a model like *BIOTSA* to assess technology for other sectors (e.g. agriculture, health, mining) because in most cases mono-variable models have been used to interrogate technology development

6.3.3.4 Other concerns/opinions

Other concerns/opinions raised by all the different experts were consolidated and are summarized in Table 6.13. These concerns entail issues that would be useful for sustainable future biodiesel production targeted for the local market.

Table 6.13: Summary of other concerns/issues from *BIOTSA* model discussion

- Investment in biodiesel production seems attractive but there is need to actualize the policy interventions
- Regulatory framework for the biodiesel development needs to be in place since there is no mandatory blending given for this market; investment in biodiesel production will thus make sense if there is a legislation and regulation of the market
- Questions arose on whether the Eastern Cape Province is ready for biodiesel production market
- Land in the Eastern Cape is viewed from a social welfare perspective. There is a need to provide an economic objective for the land. Thus there is need for economic policy in agriculture
- It will be important to show if biodiesel crop land will create better opportunity cost in the value chain
- The extent of government involvement in the biodiesel production development needs further investigation
- Getting the community involvement is a key problem
- Lack of willingness to participate in the farming activities in the Eastern Cape Province due to the social welfare policy
- Need a policy to limit the level of mechanization so that can deter the level of employment in the front-end value chain

6.4 POLICY ANALYSIS AND BIODIESEL PRODUCTION DEVELOPMENT

In many instances, models in system dynamics are developed with an aim of providing an understanding of the dynamic hypothesis of the problem and then utilizing this understanding to design leverage for improvement (Sterman, 2000). The dynamic hypothesis for the *BIOTSA* model was clearly discussed in Chapter 5. However, the modelling process was only focused on the evaluation of the impact of the identified sustainability indicators due to the transition in biodiesel production development.

This section discusses the policy design and analysis that is based upon the system dynamics modelling process. Policy design involves either creation of new decision rules, strategies and structures (Sterman, 2000). In this study, this is discussed as an outcome of the simulation process within the biodiesel production development in the Eastern Cape Province of South Africa. Thus, the *BIOTSA* simulation results were evaluated under a number of “what if” scenarios of the potential and/or hypothetical policies for the biodiesel production development in the Eastern Cape Province.

A set of scenarios, relevant for policy making for the *BIOTSA* model were defined aimed to test their effect on the selected sustainability indicators. A summary of the changes in the key parameters for these scenarios is presented in Table 6.14. A brief description of each is provided in the following sections.

Table 6.14: Scenarios analysed in the *BIOTSA* model

Scenario	Fertilizer use switch (dimensionless units)	Support biodiesel (Rand/litre)	By-product use (dimensionless units)	Community perception (dimensionless units)
Baseline	0	0	0	0.1
FUS	1	Baseline	Baseline	Baseline
BSS1	Baseline	0.53	Baseline	Baseline
BSS2	Baseline	1.06	Baseline	Baseline
BSS3	Baseline	8	Baseline	Baseline
BPS	Baseline	Baseline	1	Baseline
CPS	Baseline	Baseline	0	0.8
SBPS	Baseline	1.06	1	Baseline
PSBPS	Baseline	1.06	1	0.8

Notes: FUS = fertilizer use scenario; BSS1 = Biodiesel support scenario 1; BSS2 = Biodiesel support scenario 2; BSS3 = Biodiesel support scenario 3; BPS = by-product use scenario; CPS= community perception scenario; SBPS = support biodiesel & by-product scenario; PSBPS = perception, support biodiesel & by-product scenario.

6.4.1 Fertilizer use scenario (FUS)

The fertilizer use scenario corresponds to a situation where the local community makes use of fertilizer as opposed to the baseline scenario where there is no use of fertilizer. In the *BIOTSA* model this translates into the reduction of the land requirement per hectare for the production of the feedstock. The outcome of the fertilizer use (FUS) show that less biodiesel crop land is required for the production of the same amount of biodiesel (Figure 6.14a and Figure 6.14b). While fertilizer use increases yield and leads to less land use than the baseline scenario, there is however an increase in the net air emissions (Figure 6.14c). Thus, the fertilizer use scenario results in a trade-off in decreasing land use and increasing net air emissions. It should be noted that the study did not consider how the fertilizer would be provided and an assumption was that, an institutional mechanism would definitely need to support local communities.

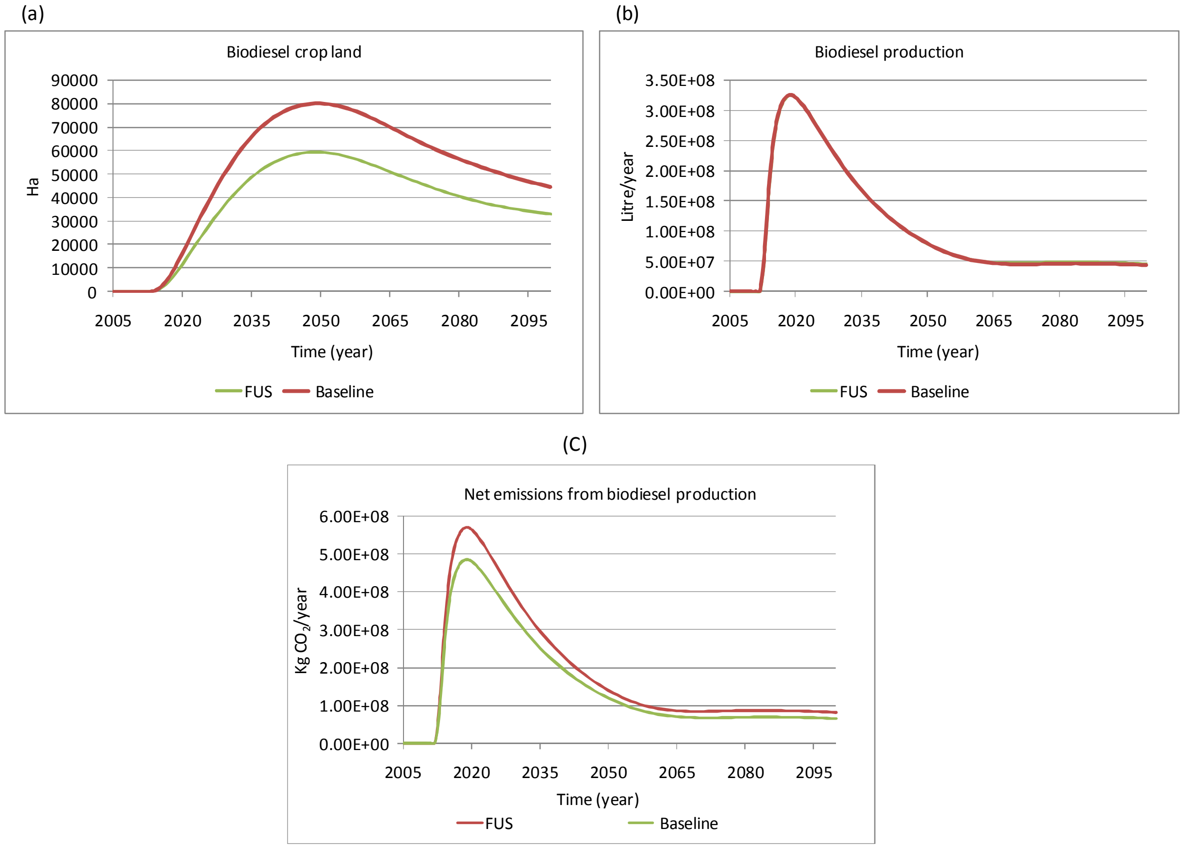

Figure 6.14: Effect of fertilizer use scenario on selected indicators

6.4.2 Biodiesel support scenario (BSS)

This scenario was motivated due to the unprofitability of the biodiesel production in the baseline scenario, which resulted in the low desired biodiesel capacity. In order to model this scenario, two different situations were considered. In the first case, biodiesel support was set at 0.53 Rand per litre (BSS1) as outlined in the South Africa Biofuels Industrial Strategy. The second case is however a hypothetical one and considers a situation where the support is doubled hence becoming 1.06 Rand per litre (BSS2). This scenario is expected to increase the unit biodiesel profitability which, in turn, influences desired biodiesel capacity (Figure 6.15). The result shows that the biodiesel plant does not break-even with the doubling of biodiesel support. Given that BSS1 and BSS2 is not enough to drive the market penetration of large-scale biodiesel development, this prompted an investigation into the support that is needed to ensure that the biodiesel plant is profitable. This is indicated by BSS3 in Figure 6.15, in which the biodiesel support used was 8 Rand per litre. The results show that, with this scenario, the plant is capable of breaking-even from the third year of its operation (Figure

6.15a). In addition, the effect of the biodiesel profit on the desired capacity is also increasing over the simulation period (Figure 6.15b).

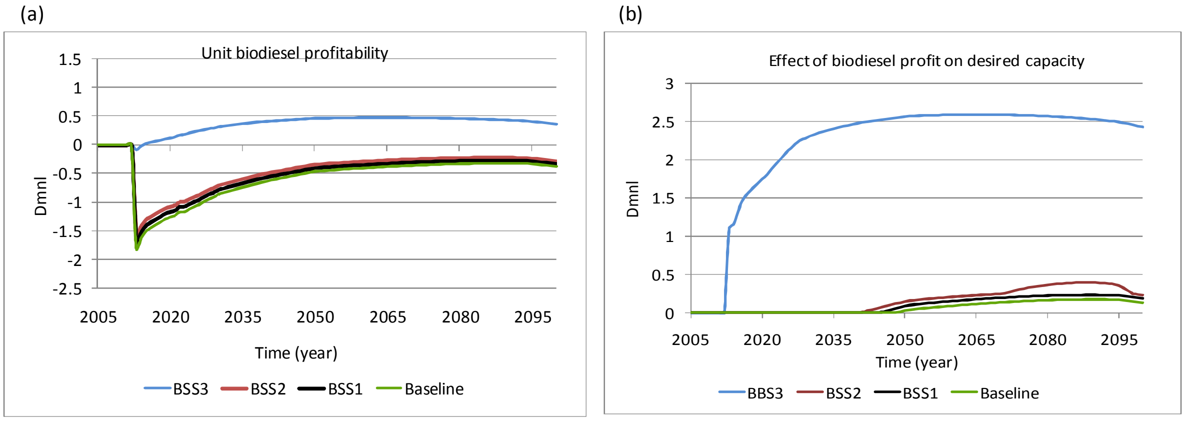

Figure 6.15: Outcome of biodiesel support scenario

The effect of the biodiesel support scenario on selected indicators is shown in Figure 6.16. The slight increase in the desired biodiesel capacity result in a slight increase in the biodiesel production, biodiesel crop land, employment in the biodiesel plant and total avoided emissions. Hence it is clear that this scenario would only result in slight changes in the selected sustainability indicators. The only scenario that makes a visible difference is the hypothetical biodiesel support scenario of 8 Rand per litre (BSS3).

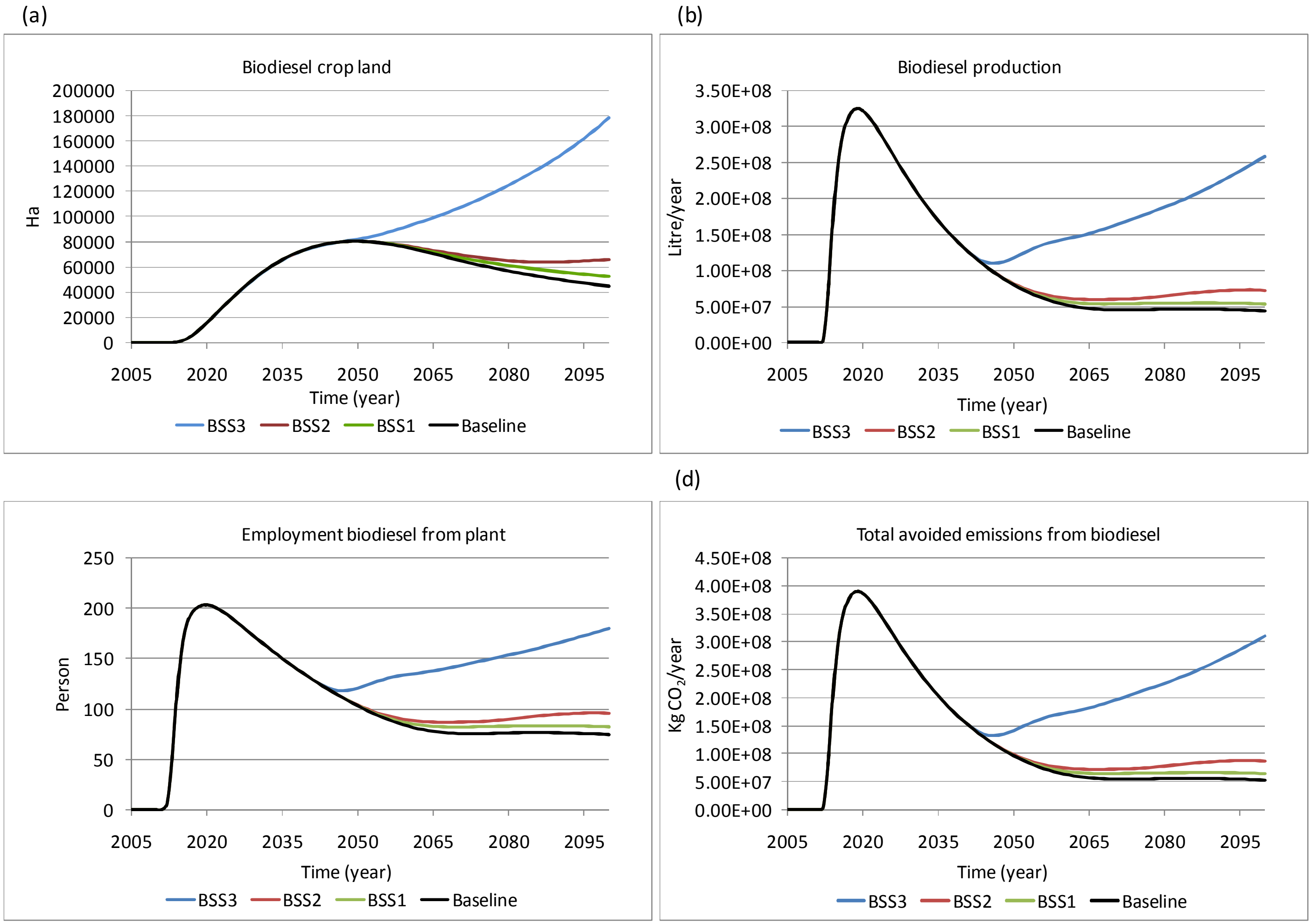

Figure 6.16: Effect of biodiesel support scenario on selected indicators

6.4.3 By-product use scenario (BPS)

Questions might arise in the biodiesel production concerning the effect of using the biodiesel by-product for revenue generation. Thus, this scenario investigated a situation where the biodiesel glycerol by-product was considered as part of the revenue generation in the biodiesel plant. Currently in South Africa, there is no market for locally produced glycerine, which may be attributed to its small to medium-scale production. This study used a large-scale biodiesel production plant and therefore it becomes necessary for the by-product use scenario. Figure 6.17 illustrates an increase in the unit biodiesel profitability in comparison with the baseline scenario and the doubling of biodiesel support. It thus appears that the unit profitability in the biodiesel production would show a greater improvement with the incorporation of biodiesel by-products in the revenue generation process. However, some studies have found that increased biodiesel production will likely lead to the decrease in the value of the by-product (Amigun et al 2008), hence decreasing the biodiesel profitability. The extent of the decrease in profitability due to quality and purity of the glycerine will differ depending on the different stages of feedstock processing (Amigun, 2008b). However, this is beyond the scope of this study.

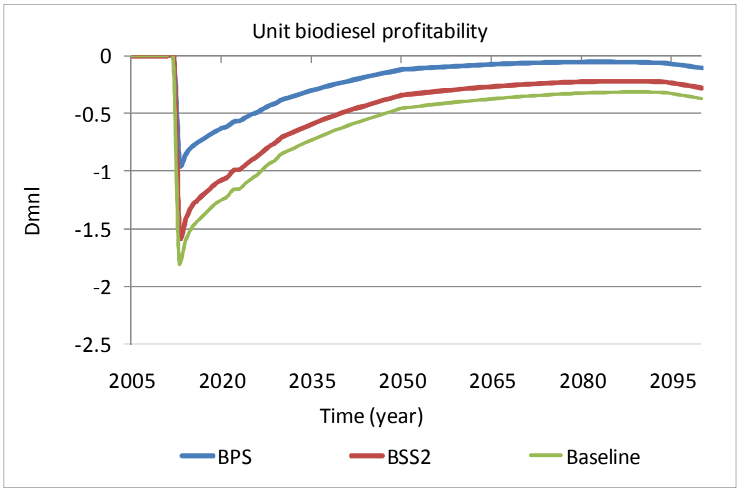

Figure 6.17: Outcome of by-product use scenario

Looking at the specific sustainability indicators that are affected by this scenario, it is observed in Figure 6.18 that there is an increase in all the values of the indicators in comparison with the baseline and the biodiesel support scenario. These increases are however, visible from 2048 and thus indicate the medium- to long-term benefit of utilizing the by-product in comparison to a situation without utilizing the by-product.

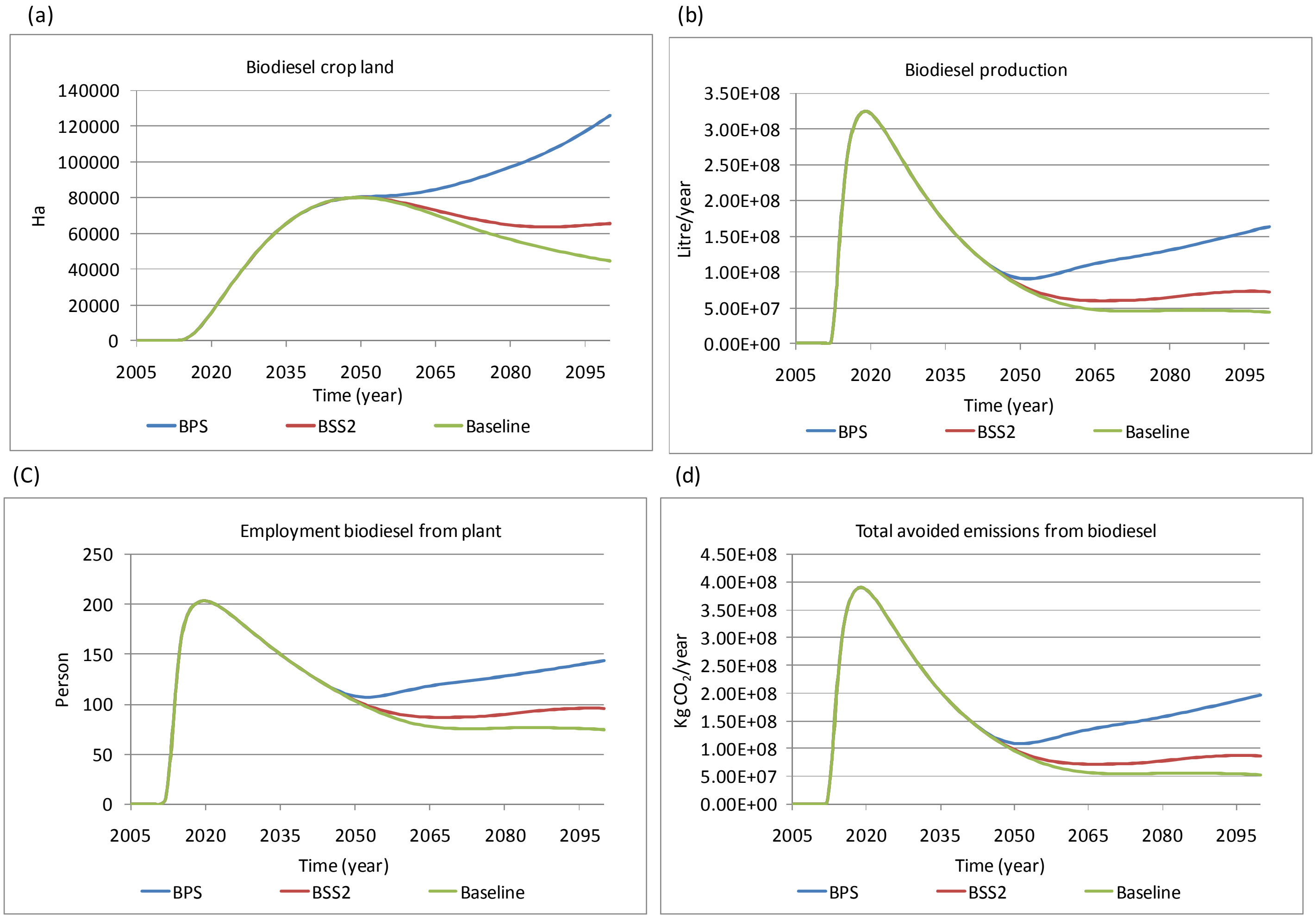

Figure 6.18: Effect of by-product use scenario on selected indicators

6.4.4 Community perception scenario (CPS)

The Eastern Cape survey visit revealed that the communities' knowledge and understanding of the biodiesel crops benefits remains relatively low. In addition, their perception on growing crops for biodiesel production remains relatively low (Amigun et al. 2011a). A scenario was thus tested taking a situation whereby the community perception is relatively high. It is evident in Figure 6.19a that, with a relatively high community perception, there is a large conversion of fallow land to biodiesel crop land. The implication is that, more of the feedstock is sourced locally. While local feedstock production is available, biodiesel production (Figure 6.19b) is not profitable yet and this leads to a reduction in the biodiesel production. However, after 2068, the biodiesel production begins to increase due to the combined effect of land availability, feedstock availability and improving profitability of the biodiesel production. Employment from biodiesel plant (Figure 6.19c) and total avoided emissions (Figure 6.19d) follows a similar trend as the biodiesel production.

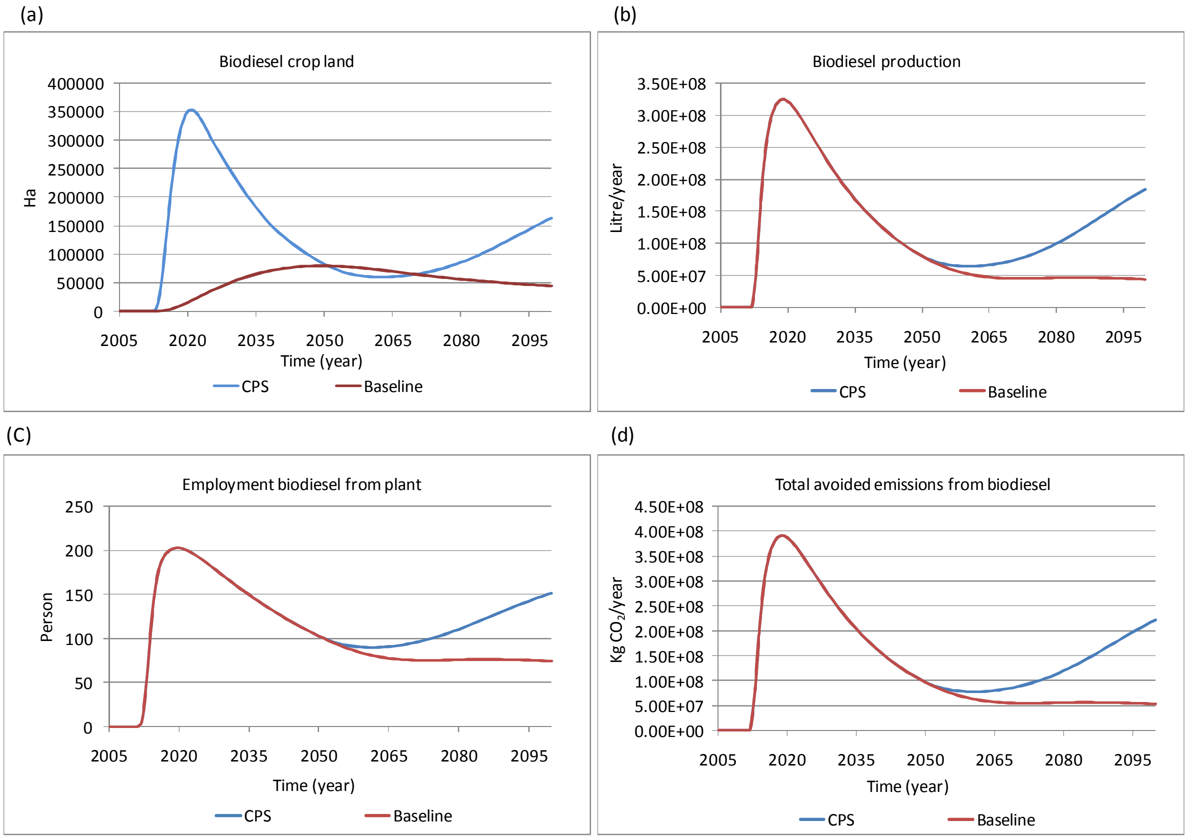

Figure 6.19: Effect of community perception scenario on selected indicators

6.4.5 Support and by-product use scenario (SBPS)

The study also considered a combined scenario of biodiesel support and by-product use. The biodiesel support was set at 1.06 Rand per litre. It is apparent from the results in Figure 6.20 that this even yields higher values of the sustainability indicators than the previous scenarios observed. However, the results of this scenario have only a slight difference with the by-product use scenario discussed previously.

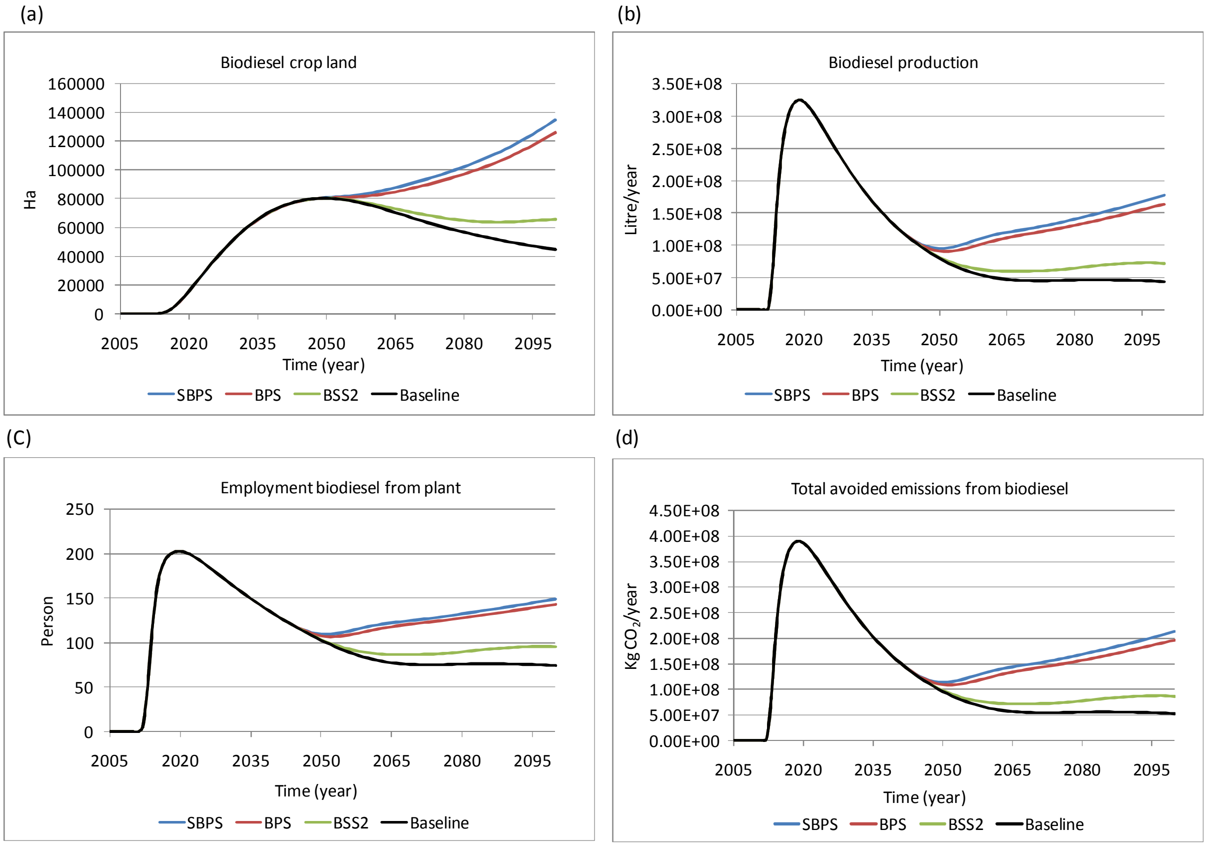

Figure 6.20: Effect of support and by-product use scenario on selected indicators

6.4.6 Perception, support and by-product use scenario (PSBPS)

Another combined scenario included a high initial community perception, biodiesel support and by-product use. In order to model this scenario, the initial perception was set at 0.8, the biodiesel support 1.06 Rand per litre and the by-product switch set to 1. As can be seen in Figure 6.21 this combined effect has a high impact on the selected sustainability indicators relative to all other scenarios. This is primarily due to the combination of the availability of the local feedstock resulting from the willingness to convert fallow land to biodiesel crop land and the improved unit profitability due to support and sales of the biodiesel by-product.

This scenario thus illustrates the need for winning the community acceptance to participate in growing the biodiesel crop.

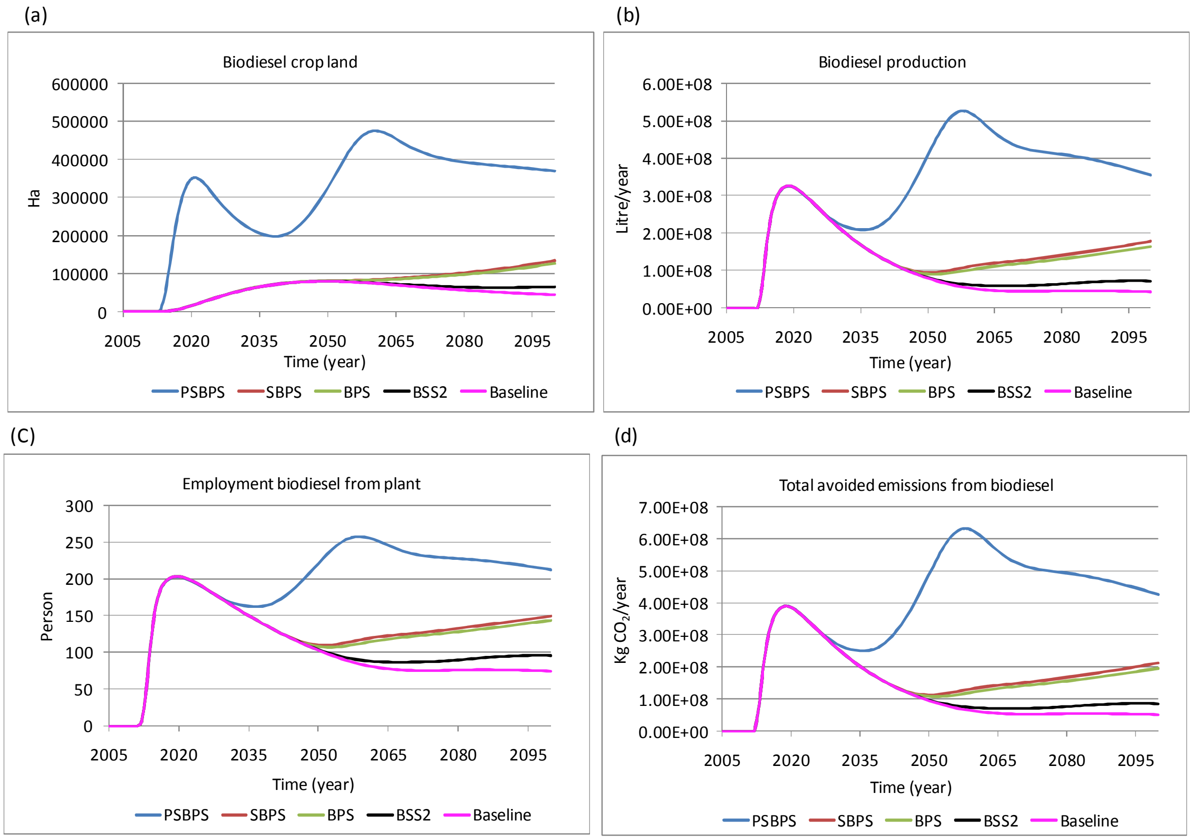

Figure 6.21: Effect of perception, support and by-product use scenario on selected indicators

6.4.7 Scenario analysis discussion

All the scenarios that were discussed in the previous sub-section were presented to the different actors and further discussions around the scenario outcomes were facilitated. While South African biodiesel production value chains do not exist, the results were found to be rational and representative of a potential situation of biodiesel production in South Africa. In addition, based on the *BIOTSA* model results, the consultative approach provided the opportunity of identifying the 'pinch points', or significant issues, for the development of biodiesel value chains in South Africa. This is mapped out in Figure 6.22, following the technology life cycle introduced by Brent and Pretorius (2008) (refer to Figure 1.2).

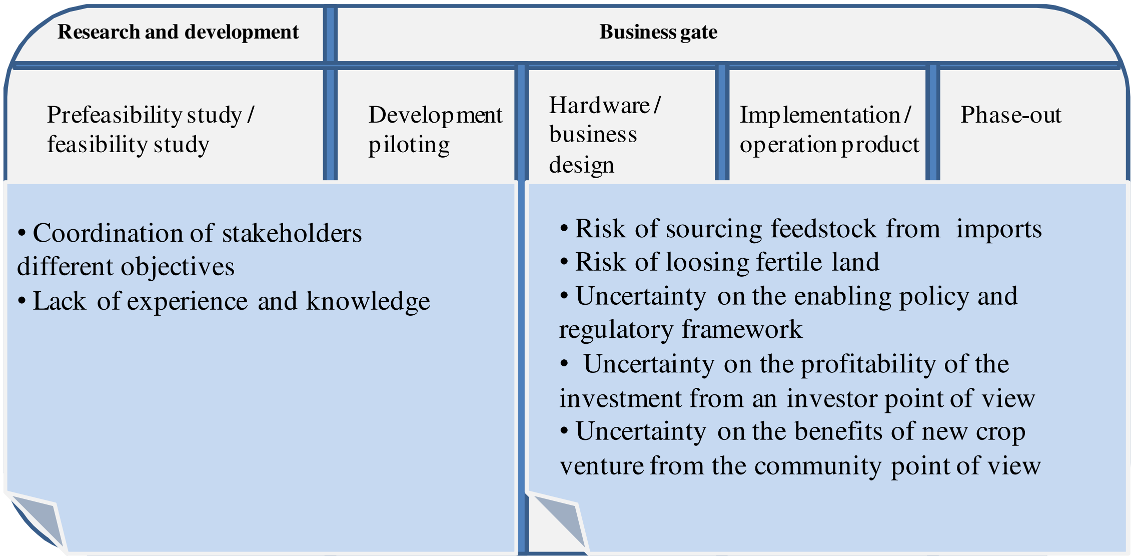

Figure 6.22: Identified pinches along the biodiesel production technology life cycle

One of the main ‘pinch point’ is coordinating the different objectives for the different stakeholders in the biodiesel production development. For instance, for the project developers, one of the main objectives with the biodiesel production is financial viability, while for the community it is the protection of their livelihood. This leaves investors uncertain on whether they can source feedstock locally and on the other hand, the community is uncertain on whether there will be a market for the new crops introduced to them.

Another ‘pinch point’ is on how to improve the community perception in growing crops that were not in their crop mix before. The investors are thus uncertain on the profitability of their investment since not being able to access feedstock locally has a major feedstock cost implication. On the other hand, the community is uncertain about the credibility of the investors and thus find it risky to venture into biodiesel crops farming.

There is also the risk of the community losing their fertile land to biodiesel crop production and this makes the community uncertain on whether this venture would be profitable as opposed to their current farming activities. The uncertainty is intensified by the fact that most of these crops are not grown in the Eastern Cape Province. Thus, the lack of experience and knowledge in the new crops provides a challenge to the communities in the region and hence the developers’ desire to invest. In a similar manner, a lack of experience in large-scale biodiesel production and market leads to a “wait and see” approach from the investors.

Finally, how to ensure biodiesel production development with a limited enabling framework that supports large-scale biodiesel production and an accessible market is also another significant ‘pinch point’. This is because the investors and community are uncertain on the sustainability of the proposed biodiesel production projects.

The potential interventions and planning strategies that could help overcome these ‘pinch points’ is beyond the scope of this study. Hence, further investigations are deemed necessary in order to guide and inform large-scale biodiesel production and market development in South Africa.

6.5 *BIOTSA* MODEL LIMITATION AND CHALLENGES

Computer simulations only provide a simple representation of the reality that is being investigated. Thus, they do not capture all the inherent aspects of the reality therefore resulting in some limitations. The need to provide a specific focus and data unavailability due to non-existence of biodiesel market in South Africa are the main reasons for the limitations of the *BIOTSA* model. Some of the specific limitations of the *BIOTSA* model are:

Biodiesel market**:** The biodiesel production chain consists of crop production, biodiesel production and biodiesel market as illustrated in Figure 6.23.

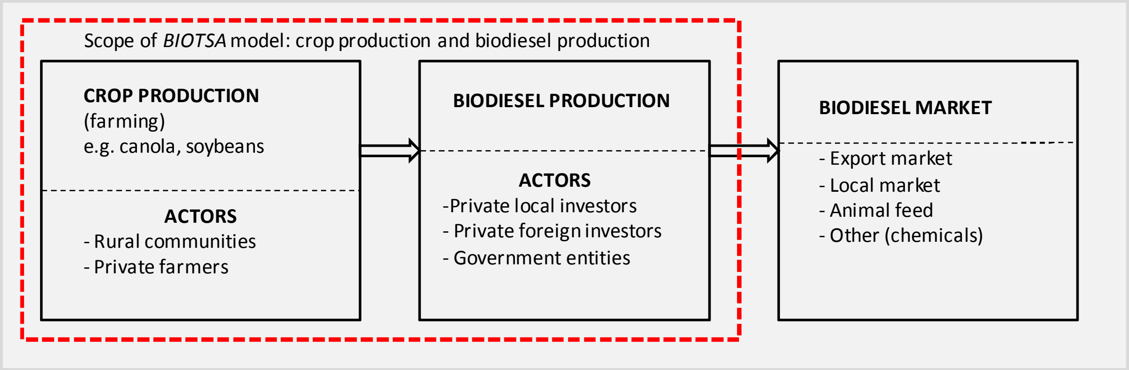

Figure 6.23: Illustration of biodiesel production chain

The biodiesel market can either be export and local consumption. By-products from biodiesel production can be used as animal feed and in oleo-chemical industry. While the *BIOTSA* model considers a project aimed for export market, the boundary is limited to the crop production and biodiesel production chain (see Figure 6.23). The dynamics of the export market was not taken into account although it could influence the selected sustainability indicators such as air emissions. However, the biodiesel production is not mainly dependent on the outside (export) market but on local conditions such as land availability, community perception and local incentives for investments. On the other hand, a project on large-scale biodiesel production for use at the local market in South Africa would have been an interesting one to investigate. The selection of a project for analysis was however based on the most likely or potential large-scale biodiesel production development in South Africa. Due to non-existence of large-scale biodiesel production and market in South Africa, the local market was not considered. This could be attributed to the policy issues and lack of enabling framework to support such a market. It is thus important for future studies to consider the full value chain when there is an enabling framework to support large-scale biodiesel production and market in South Africa.

Implicit farming activities: The *BIOTSA* model assumes that the community can easily alter the fallow land to biofuel crop land as long as they have the acceptance to convert this land. The whole social process such as training of the community on the new farming activity was not considered. This was due to the scope of the study which excluded such analysis.

Feedstock logistics: There are a number of feedstock logistics that are involved in the biodiesel production such as: biomass collection, pre-processing, storage and transportation. Unfortunately, such level of detail was not included in the *BIOTSA* model. This was due to the lack of such information in the South African situation. In addition, given the objectives of the model, this level of detail was deemed unnecessary. However, all these activities that are involved were aggregated to provide the effect of such activities on feedstock cost depending on whether the feedstock would be sourced locally or from importation.

Employment: Biodiesel production development is also claimed to create employment in the farming communities. Unfortunately, the *BIOTSA* model does not consider this type of employment and only employment in the biodiesel plant is considered. This is because the level of information on employment in the whole supply chain is unavailable. In addition, given the land that is planned for biodiesel crop production is in the rural areas, it would be difficult to determine the extent to which this employment would be created and thus this was excluded from the model. However, it is possible and important to include when assessing a medium-scale and small-scale biodiesel production development.

Regardless of the limitations and the challenges discussed, the *BIOTSA* model does provide insights for assessing the impact of biodiesel development on the sustainability indicators and opportunities to improve the value chain, which is summarized in Table 6.15.

Table 6.15: Summary of value chain insights from the *BIOTSA* model

Crop production	**Biodiesel production**
• The need to improve community perception of biodiesel crops benefits, which result from fear and previous bad experiences • Promoting local feedstock production • Focussing on non-food land for biodiesel crop production	• Local job creation at biodiesel plant level • Using by-products as part of income generation outputs • Government support in the biodiesel production • Reducing feedstock costs by sourcing it locally

6.6 CONCLUSION

In this chapter the *BIOTSA* model baseline simulation results and model tests were presented and discussed. These model tests included the validation and verification tests; policy and evaluation tests; and scenario discussion with the key stakeholders. All these provide an insight in the assessment of biodiesel technology development for sustainability in the Eastern Cape Province. Based on the *BIOTSA* model simulation results, the following key findings can be drawn:

- Simulation is not meant for prediction but for providing consistent accounts about the future. Thus, the *BIOTSA* model provides a consistent account of the future biodiesel production development for export purpose in the Eastern Cape Province of South Africa. This understanding could be used to make more robust biodiesel technology development decisions.
- It was determined that the dominant factors affecting the dynamics of the biodiesel production, an economic indicator, is the land availability, biodiesel profit and feedstock availability. These factors influence the investors desired biodiesel plant capacity which in turn determines how much of the biodiesel plant is functional.
- The model shows that high cost of production is the prevalent factor affecting the biodiesel profitability, which is another economic indicator. High costs are attributed

with the feedstock cost. Sourcing feedstock through imports has a much higher cost implication than from local production.

- The baseline simulation analysis of social indicators shows that community perception plays a key role in determining the amount of land converted for biodiesel production crops. With low community perception, biodiesel production development is bound to face a challenge of sourcing local feedstock, which in turn affects the profitability of the investments and hence the biodiesel production development. It is thus important to establish ways of improving the community's perceptions by providing them with clarity of the pros and cons of venturing in the biodiesel crop production. This is however a significant challenge as perception may be resistant to change.
- The environmental indicators baseline analysis ascertained that air emissions, waste production, water use and energy use follow similar dynamics as the biodiesel production, which is the dominant influence of these indicators.
- The validation and verification tests in which the *BIOTSA* model was examined include: structural validity test, behavioural validity test; and expert opinion. The confidence of the *BIOTSA* model was improved by exposing it to these tests. The results from these tests show the *BIOTSA* model capability of generating the "right behaviour for the right reasons".
- The expert opinion on the relevance, reliability, practicability and importance of the *BIOTSA* model indicates a high consensus on the responses for the public agencies. These are mainly the potential users of the *BIOTSA* model. System dynamics, in which the *BIOTSA* model was developed, is however unknown to the public agencies. This calls for creation of awareness to this kind of assessment to the relevant people or users of the model.
- The policy analysis of biodiesel production development indicates that there is no single strategy that is capable of improving the performance of the selected sustainability indicators. Thus, for sustainable biodiesel development, there is need to account for combined strategies such as: support by the government on the biodiesel production; the use of by-products by the developers in revenue generation portfolio; improvement of the local community perception. While large-scale biodiesel production is in its infancy stage in South Africa, the policy results were found to be

rational and representative of a potential situation of biodiesel production development in the Eastern Cape Province.

- The *BIOTSA* model does not capture all the inherent aspects of reality due to either data unavailability and the infancy of the large-scale production and market in South Africa. The need to provide an appropriate simplicity also limited the scope of analysis. Despite the *BIOTSA* model limitations, it does provide insights for assessing the impact of biodiesel development on the sustainability indicators and opportunities to improve the value chain. In addition, opportunities for future research were also identified and are discussed in Chapter 7, which provide the conclusion and recommendations of this study.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

This chapter presents a summary of the key contributions and findings of this study. Limitations of the study are discussed and suggestions for addressing these limitations are highlighted. A summary of how the *BIOTSA* model can be improved is also discussed and attention given to future scenarios on biodiesel production development in South Africa. Although the focus of this study was to demonstrate how *SATSA* framework can improve the technology sustainability assessment using biodiesel production development as a case study, this transdisciplinary study can be considered as a starting point in future understanding of the impacts of biodiesel development in South Africa on selected sustainability indicators.

7.1 CONTRIBUTIONS

This study contributes in the development of a conceptual framework useful for energy technology sustainability assessment, which the author has termed, systems approach to technology sustainability assessment (*SATSA). This is illustrated in Figure 7.1.

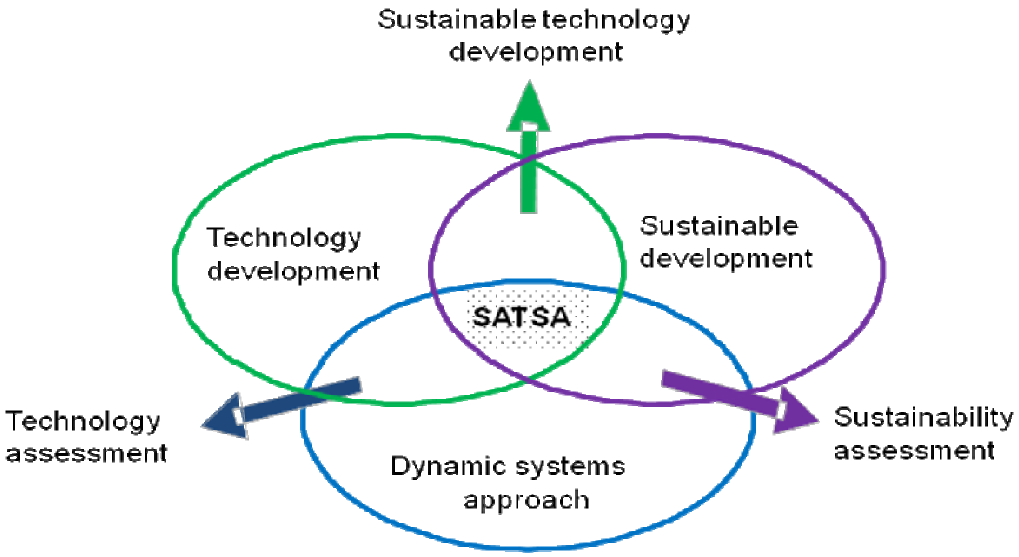

Figure 7.1: Schematic representation of a systems approach to technology sustainability assessment (*SATSA*) framework

Achieving sustainable technology development requires developing approaches or methods that account for the characteristics of the technology development and sustainable development sub-systems. System dynamics is the proposed dynamic systems approach that can guide in providing technology sustainability assessment. *SATSA* lies at the cross-section of technology development, sustainable development, and dynamic systems approach. This implies that a dynamic systems approach can provide the necessary guidance in understanding the system boundaries for long-term technology development within the context of sustainable development criteria or goals.

In addition, this study provided a guiding process or procedure for *SATSA,* using energy technology assessment as an example. The case study of the biodiesel production development in which the *BIOTSA* model was developed makes a unique contribution because system dynamics is relatively uncommon in the South African context. The study has the capacity to contribute to a wide range of renewable energy technology development in South Africa. *SATSA* framework could be adapted to other renewable energy technology assessment.

7.1.1 Research findings discussion

In the literature review the need for improved assessment approaches to investigate energy technology development for sustainability was highlighted. In South Africa particularly, studies reviewed provide a partial analysis which might limit rather than stimulate a deeper understanding of energy technologies that contribute to the sustainability goals. Although a number of studies are familiar with systems thinking, none include the causal relations and feedbacks existing within energy technology development, and how these relations and feedbacks might be addressed through a comprehensive system dynamics approach.

This study investigated the hypothesis that *SATSA* framework making use of system dynamics as the dynamic systems approach could improve the technology sustainability assessment. This is because dynamic systems approach does take into account of the intrinsic properties of technology development and sustainable development. While large-scale biodiesel production in South Africa is non-existent, it was used as a case study to test the hypothesis. Thus, this study introduced the Bioenergy Technology Sustainability Assessment (*BIOTSA*) model that was developed, based on a system dynamics. The *BIOTSA* model was built with a purpose to assess the effect of proposed biodiesel production development in the Eastern Cape on selected sustainability indicators. The *BIOTSA* model was scrutinized with a number of validation and verification tests namely, structural, behavioural and expert opinion (technology assessment practitioners, technology developers and public agencies). Generally, based on these validation tests, the confidence of the *BIOTSA* model was improved and the model is deemed capable of generating the "right behaviour for the right reasons". The expert opinion on the relevance, reliability, practicability and importance of the *BIOTSA* model indicates a high consensus on the responses for the public agencies. These are mainly the potential users of the *BIOTSA* model and they found the model important in improving the current assessment practices in biodiesel production development. This shows the relevance in engaging with stakeholders. They provide insights to modify/refine and validate the model thereby increasing the confidence and usefulness of the model. System dynamics, the basis used in developing the *BIOTSA* model is however, unknown to the technology developers and the public agencies. This calls for awareness creation and knowledge field development to this kind of assessment to the relevant people or potential users of the model.

The *BIOTSA* model does not capture all the inherent aspects of the biodiesel production development and this resulted in some limitation of the model which was: (i) exclusion of biodiesel market; (ii) assumptions on implicit farming activities; (iii) assumptions on feedstock logistics; and (iv) accounting only employment from biodiesel plant. The reason for not incorporating all these aspects was due to the need to provide a specific focus; and data unavailability due to non-existence of large-scale biodiesel production and market in South Africa. While the limitations and the challenges of the *BIOTSA* model were highlighted, the model does provide insights to technology assessment practitioners, technology developers, government agencies and policy-makers in general on the impact of biodiesel development on sustainability indicators. It also provides opportunities for future research which is discussed in Section 7.3.

The baseline simulation and the policy analysis that is based upon the *BIOTSA* model were discussed. These results were evaluated under a number of "what if" scenarios of the potential and or hypothetical policies for the biodiesel production development in the Eastern Cape Province in South Africa. Generally, the results of the *BIOTSA* model indicate its capability to improve technology sustainability assessment and facilitating communication between different actors involved. The fundamental research findings are summarized as follows:

- *SATSA* is a guiding framework in which the *BIOTSA* model was developed. Thus the *BIOTSA* model is a demonstration of how the dynamic systems approach using system dynamics models can make a difference in the energy technology sustainability assessment. A user can interact with the *BIOTSA* model due to its simplicity, clear interface, and ability to represent outputs graphically. In this way, the relevance of the different policy scenarios and their impact on the sustainability indicators can be compared. In addition, unlike the conventional static models, the synergies among different policies can be accounted in the feedback structure of the system dynamics models and allows possible evaluation of the sets of scenarios rather than evaluating one scenario at a time.

- The *BIOTSA* model is also a demonstration of how *SATSA* framework can provide guidance in the analyses of energy technology development which should undergo major transitions and face major sustainability challenges. The *BIOTSA* model provides insights to technology assessment practitioners, technology developers and government agencies on the scale of effect on the sustainability indicators.
- The usefulness of models is based on the data used in their construction and the understanding of the relevant factors and their interactions that needs to be included. While, large-scale biodiesel production and market in South Africa is non-existent, many studies make future predictions other than the case of reporting historical data. Thus, models become useful in exploring changes in expected energy technology development trends.
- In the assessment of the implications of biodiesel development, little or no attention has been given to the adaptive capacity of the local communities, who are immediately affected by these projects. Community perception is key because it affects the feedstock availability and price, which in turn is the critical factor affecting the biodiesel production viability.
- There is need to seek creative solutions in the biodiesel production development in the Eastern Cape Province. In addition, there is need to provide incentives that can stimulate the development of biodiesel production for both community and the investors. On one hand, the community would be reluctant to invest in biodiesel crops unless they have guarantee that there is demand for the biodiesel crops. On the other hand, the biodiesel investors are reluctant to invest if local feedstock supply cannot be assured.
- The current biodiesel support in the South Africa Biofuels Industrial Strategy is not enough to drive the market penetration of large-scale biodiesel production. Policy

targeted on the front end of the whole value chain of the biodiesel production may be required to improve the market penetration. Policies targeted at the front-end of the biodiesel production value chain, for instance, reducing feedstock price and improving availability, would lead to market penetration of this embryonic industry.

- The use of transdisciplinary research highlighted the communication gap between the government policy/decision-makers and technology developers on one hand, and the local communities who are supposed to supply the feedstock on the other hand. There is need to actively engage with the local communities in order to avoid major delays and resistance to participate in growing crops for not only biodiesel production, but also crops for other biofuel production (e.g. bioethanol, biomethanol). While this recommendation is highlighted, the process of changing the local communities' technology and farming practices may take a long time.
- Creating sustainable biodiesel development depends on the complex feedbacks among the economic, social and environmental forces, and includes many actors. No one actor in the biodiesel production development would be able to facilitate this technology development on their own. Using *SATSA* framework in a transdisciplinary approach provides results that are illustrative to stimulate discussion in the policy design process. This was observed in this study where the public agencies realised that system dynamics approach is critical in South Africa and that there is lack of technical capacity to make use of such an analysis. It was also seen an "eye opener" given that the current practice for policy-making utilizes linear and optimization tools. This clearly indicates the benefits of learning of a decision-maker resulting from the use of system dynamics modelling.
- The problem of the practice and implementation of the system dynamics modelling is associated with its strengths. For instance, since system dynamics is not a well-known tool in technology sustainability assessment in South Africa, it was difficult for some actors and decision-makers to grasp the approach.

7.2 THEORETICAL AND PRACTICAL IMPLICATIONS OF THE RESEARCH

This study highlights some key implication for theory development and pragmatic application of system dynamics as the dynamic systems approach of the *SATSA* framework in evaluating ill-defined complex problems. The *SATSA* framework developed in this study provides a general framework for understanding the suitable methodology/approach for use in assessing technology development for sustainability (Chapter 1 and 2). The framework can be extended and tested for other technology development for sustainability other than renewable energy technologies.

The investigation of the intrinsic properties of main elements of *SATSA* framework, that is, technology development, sustainable development and dynamic systems approach (Chapter 2) shows that the system dynamics approach has a potential to improve technology sustainability assessment. This is because system dynamics methodological properties map the intrinsic properties of the three elements. The use of the system dynamics combined with the consultation with key stakeholders enabled the ill-defined hypothesis to be examined, assessed and refined using biodiesel technology development as a case study. While this might be a difficult task, it is however more difficult if the technology assessment practitioners and model developers do not explicitly recognize the transdisciplinary nature of technology assessment for sustainability. This is especially where local communities would be directly or indirectly involved and affected by the technology development

Renewable energy technology assessments in South Africa mainly focus on the economic analysis, mainly the cost-effectiveness, and there is limited account on the social and environmental issues (Chapter 3). The research thus confirmed the lack of technology assessment practices for sustainability in the South African energy sector (Chapter 3) and affirmed the need for such practice. A point worth noting is that complex dynamics appear to be recognised in energy technology development in South Africa. However, many policy interventions ignore this understanding and fail to incorporate the dynamic systems approach to understanding the complex dynamics and provide a usable guide to action in technology development projects. This was also confirmed in the biodiesel technology development case study, where many local communities were uninformed of the proposals to grow crops for biodiesel production in their area.

Finally, system dynamics does have the strength of integrating different information and knowledge from different stakeholders in the technology assessment for sustainability process. It also has the capability of identifying the knowledge gaps and the needs for research. If the technology assessment practitioners and the policy- and decision-makers can see this need and utilize this approach in future technology assessment for sustainability, then this can facilitate communication between the different actors in the energy technology development. Thus all the different levels of actors in energy technology development need to give a consideration to the system dynamics modelling in order to find collaborative solutions of the complex problems of the sustainable transition to renewable energy technologies.

7.3 RECOMMENDATIONS FOR FUTURE WORK

There are opportunities for future research that were identified as a result of this study. First of all, there is opportunity to apply *SATSA* framework on other renewable energy technologies such as electricity generation technologies and the other bioenergy technologies (e.g. bioethanol and biomethanol). Secondly, the case study that was investigated in this study was on biodiesel production development at a provincial level, and excluded the dynamics of the export biodiesel market. There is a potential to customize the *BIOTSA* model and explore large-scale biodiesel production geared for the South African local market and considering the full value chain. In this way, it will provide an investigative model to assess the impacts of biodiesel production development on sustainability indicators in South Africa. This could be possible when there is an enabling framework to support large-scale biodiesel production and market in South Africa.

The community perception sub-model included in the *BIOTSA* model study is an interesting one which needs further qualitative system dynamics analysis. This is because a number of aspects were not included due to its qualitative nature. Future study will require an understanding of the dynamics of the community perceptions on biodiesel benefits. Community perception is an important factor as it will determine the extent to which local production of feedstock for not only biodiesel production but also for other biofuels proposed for development. It is also worth exploring a situation when the biodiesel plant is up and running to investigate the community's perception in growing the crops for biodiesel production. This is because, from the survey visits in areas earmarked for biodiesel crop production, the local communities associated biofuel production development with many other failed projects introduced in their area.

There are current debates in biodiesel production literature concerning the appropriate models that should be introduced in the rural communities in Africa: that is between large-scale and small to medium-scale production (Amigun et al. 2011b)[31]. In order for biodiesel production to fully satisfy the local communities, the biodiesel production for export should be seen as secondary. Small-scale production would mainly target rural development and local market while large-scale production focus only focus on export market and the local community might not benefit as such. Having small-scale production, the impact on the rural communities may be felt more through job creation. Small-scale production might also minimize waste by having a closed-loop production model. There is thus the need to look at the impact of the small-scale biodiesel production in the rural communities which would require a different system dynamics model.

There are three different employment effects that may arise from biodiesel production: direct effect employment; indirect effect employment and induced effect employment. The direct effect employment is created at the feedstock production and biodiesel production sector. Indirect employment is the employment that produces intermediate deliveries to the feedstock or biodiesel production sector. Induced effect employment is the employment that is generated or lost due to the induced effect of feedstock and biodiesel production in other sectors. For instance, jobs lost from the change from food crop production to biodiesel crop production. The *BIOTSA* model only took into account of the direct effect employment at the biodiesel production level. It is important to have a study that investigates these different employment effects in the Eastern Cape Province. In most instances, the induced employment is not accounted for. With such information, this can provide suitable input in the future system dynamics modelling studies.

Finally, a number of “pinch points” or significant issues for biodiesel production development were identified in this study such as: coordination of stakeholders’ different objectives, uncertainty of enabling and regulatory framework, uncertainty on the benefits of new crops to communities and uncertainty of the profitability of biodiesel production investment. The potential interventions and planning strategies that could help overcome

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[31] AMIGUN, B., MUSANGO, J. K. & STAFFORD, W. 2011 Biofuels and sustainability in Africa. *Renewable and Sustainable Energy Reviews* 15:1360-1372

these "pinch points" requires further investigation. This is deemed necessary in order to guide and inform large-scale biodiesel production and market development in South Africa.

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APPENDICES

APPENDIX A: PUBLICATIONS

A1. Peer reviewed Journals

MUSANGO, J.K. & BRENT, A.C. 2011 A conceptual framework for energy technology sustainability assessment. *Energy for Sustainable Development*, 15**,** 84-91.

AMIGUN, B., MUSANGO, J. K. & BRENT, A. C. 2011 Community perspectives on the introduction of biodiesel production in the Eastern Cape province of South Africa: questionnaire survey results. *Energy*, 36**,** 2502-2508.

MUSANGO, J. K. & BRENT, A. C. 2011 Assessing the sustainability of energy technological systems in Southern Africa: A review and way forward. *Technology in Society*, 33**,** 145-155.

MUSANGO, J. K., BRENT, A. C., AMIGUN, B., PRETORIUS, L. & MÜLLER, H. 2011 Technology sustainability assessment of biodiesel development in South Africa: A system dynamics approach. Paper accepted for publication in *Energy*, 16 September 2011.

A2. Conference Proceedings

MUSANGO, J. K., BRENT, A. C., AMIGUN, B., PRETORIUS, L. & MÜLLER, H. 2011 Technology sustainability assessment of biodiesel development in South Africa: A system dynamics approach. Paper presented at the 20th International Conference for Management of Technology, Florida, USA, 10-14 April 2011.

MUSANGO, J. K. & BRENT, A. C. 2010 A framework for energy technology sustainability assessment using system dynamics. Poster paper presented at the PhD Colloquium of the System Dynamics Conference, Seoul, South Korea, 25- 29 July 2010.

MUSANGO, J. K., AMIGUN, B. & BRENT, A. C. 2010 Understanding the implication of investing in biodiesel production in South Africa: A system dynamics approach. Paper presented at the 28th International Conference of System Dynamics Society, Seoul, South Korea, 25-29 July 2010.

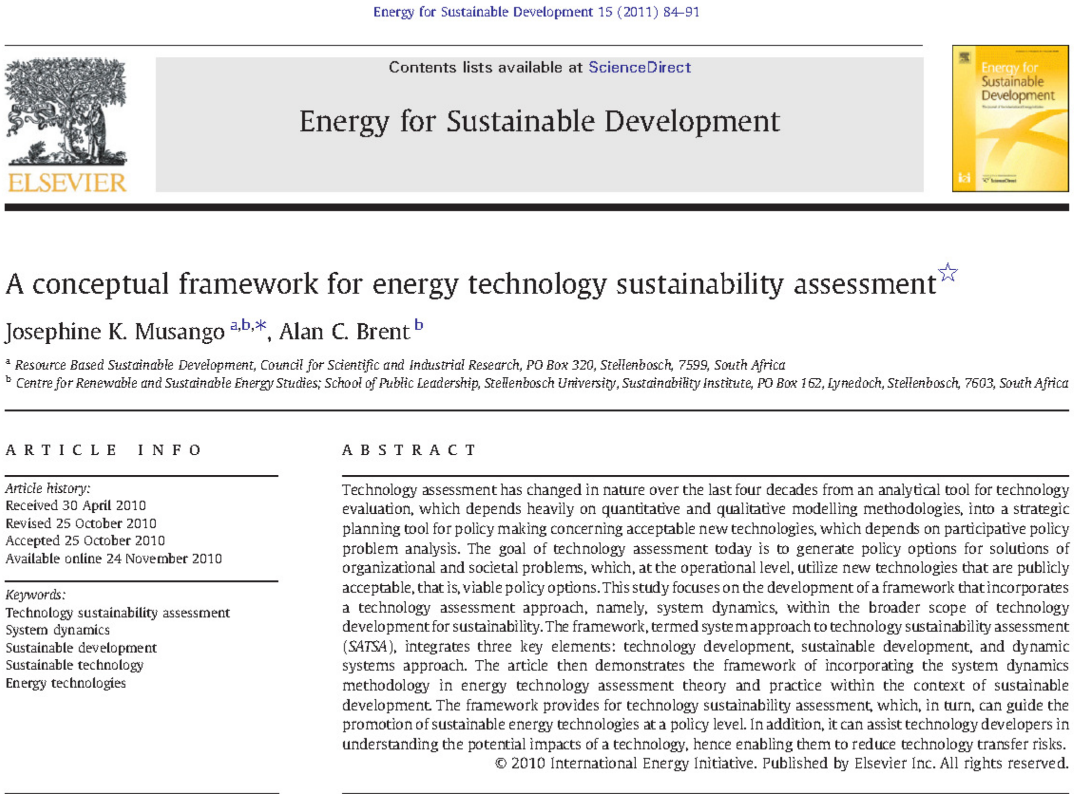
MUSANGO, J. K. & BRENT, A. C. 2010 Assessing the sustainability of energy technological systems in Southern Africa: A review and way forward. Paper presented at the 19th International Conference for Management of Technology, Cairo, Egypt, 8-11 March 2010.

A3. Manuscripts submitted to peer reviewed Journal

MUSANGO, J. K., BRENT, A. C., AMIGUN, B., PRETORIUS, L. & MÜLLER, H. 2011 *SATSA*: A framework for energy technology assessment for sustainability. Manuscript Paper submitted to *Energy Policy*, 31 May 2011 [Manuscript Number **JEPO-D-11-00856**, Under Review].

MUSANGO, J. K., BRENT, A. C., AMIGUN, B., PRETORIUS, L. & MÜLLER, H. 2011 A system dynamics approach to technology sustainability assessment: the case of biodiesel development in South Africa. Paper submitted to *TECHNOVATION*, 27 January 2011 [Manuscript Number **D-11-00053**, Under Review].

A5. Selected abstracts of peer reviewed papers



Energy for Sustainable Development 15 (2011) 84–91

Contents lists available at ScienceDirect

Energy for Sustainable Development

A conceptual framework for energy technology sustainability assessment☆

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ABSTRACT

Technology assessment has changed in nature over the last four decades from an analytical tool for technology evaluation, which depends heavily on quantitative and qualitative modelling methodologies, into a strategic planning tool for policy making concerning acceptable new technologies, which depends on participative policy problem analysis. The goal of technology assessment today is to generate policy options for solutions of organizational and societal problems, which, at the operational level, utilize new technologies that are publicly acceptable, that is, viable policy options. This study focuses on the development of a framework that incorporates a technology assessment approach, namely, system dynamics, within the broader scope of technology development for sustainability. The framework, termed system approach to technology sustainability assessment (*SATSA*), integrates three key elements: technology development, sustainable development, and dynamic systems approach. The article then demonstrates the framework of incorporating the system dynamics methodology in energy technology assessment theory and practice within the context of sustainable development. The framework provides for technology sustainability assessment, which, in turn, can guide the promotion of sustainable energy technologies at a policy level. In addition, it can assist technology developers in understanding the potential impacts of a technology, hence enabling them to reduce technology transfer risks.

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Community perspectives on the introduction of biodiesel production in the Eastern Cape Province of South Africa

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ABSTRACT

This paper presents the outcomes of a questionnaire survey to ascertain the perspectives of local communities on the proposal to construct a large-scale biodiesel production facility in the Eastern Cape Province of South Africa, with feedstock supply to the production facility from the former communal homelands of the Province. A total of 303 questionnaires were administered through interactions with the communities that are expected to be a part of the feedstock production supply chain by visiting households and having in-depth interviews, and through a focus group discussion. Opinions were found to be overwhelmingly against the proposed biodiesel production supply chain. The concerns of local people varied, but the major issues were land availability as this is regarded as their identity; infrastructure development; associated pollution (air and water) posing serious health risk; doubts about the credibility of the developers; food security; and the distortion of the social fabric of the local communities. In general, local people felt that they were excluded from the project development and were asked to accept industrial scale development that will further lead to the impoverishment of the communities. The results also highlighted how large-scale plants may be affected by the local dynamics of perceptions; the willingness to partake in the supply chain was informed by personal, social and institutional factors and beliefs, as well as internal conflicts, due to perceived environmental, social and ecological risks, that were aggravated by miscommunication and the lack of understanding. The paper is deemed useful for policy makers to understand why communities may object to relatively large bioenergy projects, and to assist the developers of such projects to avoid delays and refusal of planning consent that can be associated with adverse local opinions.

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Assessing the sustainability of energy technological systems in Southern Africa: A review and way forward

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Southern Africa

ABSTRACT

The field of technology assessment is not new, but it continues to be relevant today more than ever, especially in the energy sector. Issues related to climate change, energy security and sustainability in general are at the core of all energy policies and strategies. The development of new and more sustainable energy technologies are needed to address these challenges. As part of this, energy technology assessment tools can help decision-makers with the identification of sustainable energy solutions, in order to integrate them in long-term energy policies and strategies. The concept and practice of sustainable development has subsequently manifested in the technology assessment field. This implies the re-classification of technology assessment into ecological, economic and social (and other) goals. In the Southern African context, specifically, there is no formal and coherent approach to energy technology assessment from a sustainability perspective. Governments in the region are finding it challenging to establish national policies concerning energy technology assessment. Indeed, the review reveals the limited use of the term "*technology assessment*" in energy evaluation studies in Southern Africa. Energy sustainability assessments may be reported, but certainly not from the perspectives of the technology management community, and, although a number of studies have discussed the issues of sustainability in technology assessment, none account for technology sustainability assessment from a holistic perspective. The paper argues that it is in this area that further research is needed.

APPENDIX B: QUESTIONNAIRE 1

Technology assessment of renewable energy sustainability in South Africa

October 2010

Participant affiliation: ……………………………………….

Thank you for participating in the system dynamics and energy modelling lecture that was held at Energy Research Centre, University of Cape Town, on 30 September 2010. This is a follow-up request to participate in a short survey for a research study conducted by Josephine K Musango, a PhD candidate at the School of Public Leadership of Stellenbosch University; your inputs will make a significant contribution to the dissertation.

You were selected as a possible participant because the Eastern Cape bioenergy model (*BIOTSA*) was presented to you during the lecture. You are thus kindly requested to provide your opinion on the appropriateness of the developed model to improve renewable energy technology sustainability assessment practices in South Africa. Your response will be voluntary and will be kept strictly confidential. Also, your response will be incorporated with others and thus be used at an aggregated level so that your response can not be singled out.

I thank you for your participation in the survey.

Appropriateness of *BIOTSA* model

1. Please tick YES or NO to each of the following questions

1.1 **Relevance**: Does the Eastern Cape bioenergy model (*BIOTSA*) contribute to a better understanding of sustainable biodiesel development in South Africa?

a) Yes b) No

Please provide reasons for your answer:

1.2 **Reliability**: Is the Eastern Cape bioenergy model (*BIOTSA*) reliable for biodiesel technology assessment?

a) Yes b) No

Please provide reasons for your answer:

1.3 **Practicality**: Is the Eastern Cape bioenergy model (*BIOTSA*) practical for biodiesel technology assessment?

a) Yes b) No

Please provide reasons for your answer:

1.4 **Importance**: Is the Eastern Cape bioenergy model (*BIOTSA*) important for biodiesel technology sustainability assessment in South Africa?

a) Yes b) No

Please provide reasons for your answer:

2. Based on your answers in 1 above, please rate the importance of the different indicators for a model such as *BIOTSA*:

Indicator	**Relevance**	**Reliability**	**Practicality**	**Importance**
BIOTSA Model	a) Low b) Medium c) High d) No Opinion	a) Low b) Medium c) High d) No Opinion	a) Low b) Medium c) High d) No Opinion	a) Low b) Medium c) High d) No Opinion

3. Please provide any other comments that you might have:

APPENDIX C: LETTER & QUESTIONNAIRE 2

Appendix C1: Letter Template

1 November 2010

Dear Sir/Madam (Name of the representative)

I am Josephine K Musango, a PhD candidate at the School of Public Leadership of Stellenbosch University. I am doing research on renewable energy development in South Africa. Currently I am assessing the biodiesel production development in the Eastern Cape Province using an integrated approach.

I am confirming the attendance of the meeting that will be held on XX (Date) at XX (time) am, at XX (name of the institution) office. During the meeting, I will first present to you the integrated assessment for biodiesel development in the Eastern Cape. This will take about 30 minutes. The integrated approach is referred to as Bioenergy Technology Sustainability Assessment (*BIOTSA)*. Thereafter, you will provide your expert suggestions for improving the approach and also suitable scenarios, which will take again another 20 minutes. This will then be followed by a short survey where you will be requested to provide your expert opinion on the appropriateness of *BIOTSA*. This will take no more than 10 minutes of your time. Your response will be voluntary and will be kept strictly confidential. Also, your name and position will not be mentioned in the study and will remain confidential.

Below find the questionnaire for your perusal.

Yours Sincerely

Josephine Kaviti Musango

Appendix C2: Questionnaire 2

Appropriateness of *BIOTSA* model

1. Please tick YES or NO to each of the following questions

1.1 **Relevance**: Does the Eastern Cape bioenergy model (*BIOTSA*) contribute to a better understanding of sustainable biodiesel development in South Africa?

a) Yes b) No

Please provide reasons for your answer:

1.2 **Reliability**: Is the Eastern Cape bioenergy model (*BIOTSA*) reliable for biodiesel development assessment?

a) Yes b) No

Please provide reasons for your answer:

1.3 **Practicality**: Is the Eastern Cape bioenergy model (*BIOTSA*) practical for biodiesel development assessment?

a) Yes b) No

Please provide reasons for your answer:

1.4 **Importance**: Is the Eastern Cape bioenergy model (*BIOTSA*) important for biodiesel development assessment in South Africa?

a) Yes b) No

Please provide reasons for your answer:

2. Based on your answers in 1 above, please rate the importance of the different indicators for a model such as *BIOTSA*:

Indicator	**Relevance**	**Reliability**	**Practicality**	**Importance**
BIOTSA Model	a) Low b) Medium c) High d) No Opinion	a) Low b) Medium c) High d) No Opinion	a) Low b) Medium c) High d) No Opinion	a) Low b) Medium c) High d) Critical e) No Opinion

3. Please provide any other comments that you might have:

APPENDIX D: *BIOTSA* MODEL EQUATIONS

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Appendix D1. Biodiesel production sub-model equations

Accumulated biodiesel production= INTEG (Biodiesel production, 0)
Units: Litre

Average life of biodiesel plant= 20
Units: Year

Biodiesel capacity construction= INTEG (Biodiesel plant construction start-New biodiesel capacity, 0)
Units: Litre

BIODIESEL CAPACITY UTILIZATION= 1
Units: dmnl

Biodiesel crop land= INTEG (Fallow to biodiesel land-Biodiesel crop land to fallow, 0)
Units: ha

Biodiesel discarded capacity= Functional biodiesel capacity/Average life of biodiesel plant
Units: Litre/Year

Biodiesel plant construction start= (Future biodiesel capacity investment)/Capital cost per year
Units: Litre/Year

Biodiesel plant construction time= 3
Units: Year

Biodiesel production= (Functional biodiesel capacity*Days per year*Hours per day)*Effect of trained labour on biodiesel production *BIODIESEL CAPACITY UTILIZATION
Units: Litre/Year

Biodiesel reference= 1.5e+009
Units: Litre

Capital cost per year= Unit capital cost*Hours in a year
Units: rand/Litre

Days per year= 330
Units: day/Year

Desired biodiesel production= DELAY N(Biodiesel production, 1 , Biodiesel production, 1)
Units: Litre/Year

Desired new biodiesel capacity= (((Functional biodiesel capacity/Time to adjust biodiesel capacity) +Biodiesel discarded capacity)*Effect of biodiesel profit on desired capacity*Effect of land availability on desired capacity *Effect of feedstock availability on desired capacity)
Units: Litre/Year

Effect of biodiesel profit on desired capacity= IF THEN ELSE (Time <= 2012, 0, Function for effect of relative profitability (Expected biodiesel profit))
Units: dmnl

Effect of feedstock availability on desired capacity= Function for effect of feedstock availability on desired capacity(Feedstock demand supply ratio)
Units: dmnl

Effect of feedstock supply ratio on cost= Function for effect of feedstock demand supply on cost(Feedstock demand supply ratio)
Units: dmnl

Effect of fertilizer use on canola yield= Function for effect of fertilizer use on yield(FERTILIZER USE SWITCH)
Units: dmnl

Effect of land availability on desired capacity= (Function for effect of land availability on desired production(Land availability ratio))*Perception of biodiesel crops benefits
Units: dmnl

Effect of trained labour on biodiesel production= Functional for effect of trained labour on biodiesel production(Trained labour ratio)
Units: dmnl

Effect of water stress index on canola yield=Function for effect of water stress on canola yield(Water stress index)
Units: dmnl

Expected biodiesel profit= INTEG (Change in expected biodiesel profit, 0)
Units: dmnl

Feedstock demand= Desired biodiesel production*Feedstock use per litre/Kg to ton
Units: ton/Year

Feedstock demand supply ratio= ZIDZ(Feedstock demand, Local feedstock supply)
Units: dmnl

Feedstock needed per litre= Table for learning per billion of biofuel produced(Accumulated biodiesel production /Biodiesel reference)
Units: Kg/Litre

Feedstock use per litre= DELAY N(Feedstock needed per litre, 1 , Initial feedstock needed, 1)
Units: Kg/Litre

FERTILIZER USE SWITCH= 0
Units: dmnl

Function for effect of feedstock availability on desired capacity ([(0.5,0)-(2,3)],(0.5,3),(0.665138,2),(0.788991,1.25),(0.944954,0.8),(1.03976,0.605263),(1.25229,0.3),(1.47401,0.118421),(1.68807,0.0263158),(1.83028,0),(2,0))
Units: dmnl

Function for effect of feedstock demand supply on cost ([(0,0)-(1000,5)],(0,1),(18.3486,1.29386),(70.3364,1.57895),(128.44,1.86404),(200,2.08333),(293.578,2.21491),(400,2.29825),(596.33,2.56579),(700,2.91228),(800,3.24561),(889.908,3.66228),(957.187,4.23246),(1000,5))
Units: dmnl

Function for effect of fertilizer use on yield ([(0,0)-(2,2)],(0,1),(0.25,1.12),(0.5,1.2),(0.75,1.27),(1,1.38),(1.21101,1.32456),(1.5,1.18))
Units: dmnl

Function for effect of land availability on desired production ([(0,-1)-(1.75,2)],(0,1),(0.25,0.5),(0.5,0.3),(0.75,0.15),(1,0.01),(1.25,0),(1.5,0),(1.75,0))
Units: dmnl

Function for effect of relative profitability ([(-1,0)-(1,3)],(-1,0),(-0.75,0),(-0.5,0),0.25,0.25),(0,1.45),(0.25,2.25) ,(0.5,2.65),(0.75,2.85),(1,2.93421))
Units: dimensionless

Functional biodiesel capacity= INTEG (New biodiesel capacity-Biodiesel discarded capacity, 0)
Units: Litre

Functional for effect of trained labour on biodiesel production ([(0,0)-(1.225,1.2)],(0,0),(0.2,0.15),(0.4,0.55),(0.6,0.75),(0.8,0.9),(1,1),(1.22477,0.993421))
Units: dmnl

Future biodiesel capacity investment= (Planned biodiesel investment table(Time)+Desired new biodiesel capacity)* Capital cost per year
Units: rand/Year

Hours per day= 24
Units: 1/day

Initial yield per ha= 1.8
Units: ton/ha/Year

Kg to ton= 1000
Units: Kg/ton

Land availability ratio= Biodiesel crop land/Maximum land availability for biodiesel crop
Units: dmnl

Local feedstock supply= Biodiesel crop land*Yield per ha canola
Units: ton/Year

New biodiesel capacity= Biodiesel capacity construction/Biodiesel plant construction time
Units: Litre/Year

Perception of biodiesel crops benefits= INTEG (Increasing perception-decreasing perception, Initial perception)
Units: dmnl

Planned biodiesel investment table ([(2005,0)-(2050,100000)],(2008,0),(2010,0),(2011,0),(2012,57390),(2013,0),(2014,0),(2015,0),(2016,0),(2018,0),(2020,0),(2022,0),(2024,0),(2025,0),(2026,0))
Units: Litre/Year

Table for learning per billion of biofuel produced ([(0,0)-(6,3)],(0,2),(1,2),(2,1.8),(3,1.75),(4,1.65),(5,1.62),(6,1.6))
Units: Kg/Litre

Time to adjust biodiesel capacity= 2
Units: Year

Trained labour ratio= ZIDZ(Employment biodiesel plant, Desired employment biodiesel plant)
Units: dmnl

Yield per ha canola= Initial yield per ha*Effect of fertilizer use on canola yield*Effect of water stress index on canola yield
Units: ton/ha/Year

****

Appendix D2. Land sub-model equations

Average life of agric land= 100
Units: Year

Average time to mature forests= 10
Units: Year

Biodiesel crop land= INTEG (Fallow to biodiesel land-Biodiesel crop land to fallow,
0)
Units: ha

Biodiesel crop land to fallow= IF THEN ELSE(Desired land for biodiesel crop production-Biodiesel crop land <0, (((Desired land for biodiesel crop production
-Biodiesel crop land)/Time to convert biodiesel crop land to fallow)*Effect of
perception on land conversion *-1),0)
Units: ha/Year

Change in desired forest plantations= (Desired forest plantations-Forest plantations)/Average time to mature forests
Units: ha/Year

Change in the desired crop land= (Desired crop land-Crop land)/Time to convert forest to crop land
Units: ha/Year

Change in the desired settlement land= (Desired settlement land-Settlement land)/Time to convert fallow land
Units: ha/Year

Change in the desired stock land= Stock to fallow+(Desired livestock land-Livestock Land)/Time to convert fallow to stock land
Units: ha/Year

Conservation land= INTEG (Fallow to conservation, Initial conservation land)
Units: ha

Crop land= INTEG (Fallow land to crop+Forest to crop-Crop land to fallow, Initial crop land)
Units: ha

Crop land to fallow= Crop land/Average life of agric land
Units: ha/Year

Desired crop land= Desired crop land per capita*Total population
Units: ha

Desired crop land per capita= 0.48
Units: ha/person

Desired forest plantations= 944830
Units: ha

Desired land for biodiesel crop production= (Feedstock demand/Yield per ha canola)
Units: ha

Desired livestock land= Total population*Land per person
Units: ha

Desired settlement land= Desired settlement land per capita*Total population
Units: ha

Desired settlement land per capita= 0.15
Units: ha/person

Effect of perception on land conversion= Function for effect of perception on land conversion(Perception of biodiesel crops benefits)
Units: dmnl

Fallow land= INTEG (Biodiesel crop land to fallow+Crop land to fallow+Stock to fallow-Fallow land to crop -Fallow land to livestock-Fallow to biodiesel land-Fallow to conservation-Fallow to forest -Fallow to settlement, Initial fallow)
Units: ha

Fallow land to crop= MIN(Change in the desired crop land,(Fallow land)/Time to convert fallow to crop)
Units: ha/Year

Fallow land to livestock= MIN(Change in the desired stock land, Fallow land/Time to convert fallow land)
Units: ha/Year

Fallow to biodiesel land= Max(0,((Desired land for biodiesel crop production-Biodiesel crop land)/Time to convert fallow to biodiesel)*Effect of perception on land conversion)
Units: ha/Year

Fallow to conservation=Fallow land*Fraction of fallow land to conservation
Units: ha/Year

Fallow to forest= MIN(Change in desired forest plantations+Forest to crop,(Fallow land)/Average time to mature forests)
Units: ha/Year

Fallow to settlement= MIN(Change in the desired settlement land,(Fallow land)/Time to convert fallow land)
Units: ha/Year

Feedstock demand= Desired biodiesel production*Feedstock use per litre/Kg to ton
Units: ton/Year

Feedstock import requirement= Max(Feedstock demand-Feedstock locally produced,0)
Units: ton/Year

Feedstock locally produced= Biodiesel crop land*Yield per ha canola
Units: ton/Year

Forest plantations= INTEG (Fallow to forest-Forest to crop, Initial forest plantations)
Units: ha

Forest to crop= MIN(Change in the desired crop land +Crop land to fallow-Fallow land to crop ,Forest plantations/Time to convert forest to crop land)
Units: ha/Year

Fraction of fallow land to conservation= 0
Units: dmnl/Year

Initial conservation land= 169896
Units: ha

Initial crop land= 3.37932e+006
Units: ha

Initial fallow= 675864
Units: ha

Initial forest plantations= 844830
Units: ha

Initial livestock land= 1.08138e+007
Units: ha

Initial settlement land= 1.0138e+006
Units: ha

Land availability ratio= Biodiesel crop land/Maximum land availability for biodiesel crop
Units: dmnl

Land per person= INITIAL(Livestock Land/Total population)
Units: ha/person

Livestock Land= INTEG (Fallow land to livestock-Stock to fallow, Initial livestock land)
Units: ha

Maximum land availability for biodiesel crop= 500000
Units: ha

Relative agriculture land= (Biodiesel crop land+Crop land+Livestock Land)/(Initial crop land+Initial livestock land)
Units: dmnl

Settlement land= INTEG (Fallow to settlement, Initial settlement land)
Units: ha

Stock to fallow= Livestock Land/Time to convert stock land to fallow
Units: ha/Year

Time to convert biodiesel crop land to fallow= 1
Units: Year

Time to convert fallow land= 1
Units: Year

Time to convert fallow to biodiesel= 1
Units: Year

Time to convert fallow to crop= 2
Units: Year

Time to convert fallow to stock land= 1
Units: Year

Time to convert forest to crop land= 10
Units: Year

Time to convert stock land to fallow= 20
Units: Year

Total land= Crop land+Fallow land+Forest plantations+Livestock Land+Settlement land+Conservation land +Biodiesel crop land
Units: ha

Total population= SUM(Population[sex!,age!])
Units: person

Yield per ha canola= Initial yield per ha*Effect of fertilizer use on canola yield*Effect of water stress index on canola yield
Units: ton/ha/Year

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Appendix D3. Biodiesel profitability sub-model equations

Annualized biodiesel capital cost= Annuity factor*Biodiesel capital investment
Units: rand/Year

Annuity factor= (Interest rate*(1+Interest rate)^Average lifespan biodiesel plant)/(((1+Interest rate)^Average lifespan biodiesel plant)- 1)
Units: dmnl

Average labour cost= Average wage*Employment biodiesel plant
Units: rand/Year

Average lifespan biodiesel plant= 20
Units: dmnl

Biodiesel capital investment= Planned investment in biodiesel plant+(Desired new biodiesel capacity*Initial capital cost)
Units: rand/Year

Biodiesel plant water usage= Water usage per litre*Biodiesel production
Units: Litre/Year

biodiesel price= (Oil price/Conversion rate litre to barrel)*Exchange rate
Units: rand/Litre

Biodiesel production= (Functional biodiesel capacity*Days per year*Hours per day)*Effect of trained labour on biodiesel production *BIODIESEL CAPACITY UTILIZATION
Units: Litre/Year

Biodiesel profitability= Total revenues-Operational cost-Annualized biodiesel capital cost
Units: rand/Year

"BY-PRODUCT SWITCH"= 0
Units: dmnl

Change in expected biodiesel profit= (Unit biodiesel profitability-Expected biodiesel profit)/Time to adjust profit
Units: dmnl/Year

Conversion rate litre to barrel= 160
Units: Litre/Barrel

"Cost of water, energy and feedstock"= Energy total cost+Feedstock total cost+Water total cost
Units: rand/Year

Desired new biodiesel capacity= (((Functional biodiesel capacity/Time to adjust biodiesel capacity) +Biodiesel discarded capacity)*Effect of biodiesel profit on desired capacity*Effect of land availability on desired capacity *Effect of feedstock availability on desired capacity)
Units: Litre/Year

Energy price= Energy average price table(Time)
Units: rand/KWh

Energy total cost= Energy price*Energy usage biodiesel production
Units: rand/Year

Energy usage biodiesel production= Energy use per litre*Biodiesel production
Units: KWh/Year

Energy use per litre= 0.04
Units: KWh/Litre

Exchange rate= 8
Units: rand/USD

Expected biodiesel profit= INTEG (Change in expected biodiesel profit, 0)
Units: dmnl

Feedstock cost= INTEG (Changes in feedstock price, 2600)
Units: rand/ton

Feedstock needed per litre= Table for learning per billion of biofuel produced(Accumulated biodiesel production /Biodiesel reference)
Units: Kg/Litre

Feedstock total cost= Feedstock usage*Feedstock cost
Units: rand/Year

Feedstock usage= Biodiesel production*Feedstock use per litre/Kg to ton
Units: ton/Year

Feedstock use per litre= DELAY N(Feedstock needed per litre, 1 , Initial feedstock needed, 1)
Units: Kg/Litre

"Glycerol by-product produced per litre"= 0.075
Units: dmnl

Glycerol produced= Biodiesel production*"Glycerol by-product produced per litre"
Units: Litre/Year

Initial capital cost= INITIAL(Unit capital cost)
Units: rand/Litre

Initial feedstock needed= 2
Units: Kg/Litre

Interest rate= 0.07
Units: dmnl

Kg to ton= 1000
Units: Kg/ton

Learning effect table([(2012,0)-(2050,1)],(2012,1),(2020,0.89),(2050,0.75))
Units: dmnl

Oil price= Oil price table(Time)*Projected relative oil price(Time)
Units: USD/Barrel

Oil price table([(1970,0)-(2100,100)],(1972,3),(1974,12.21),(1978,13.55),(1981,35),(1982,31.55),(1983,29),(1984,27.5),(1985,26.5),(1986,15),(1987,17.5),(1988,14.87),(1989,18.83),(1990,23.18),(1991,20.19),(1992,19.25),(1993,16.74),(1994,15.66),(1995,16.75),(1996,20.46),(1997,18.97),(1998,11.91),(1999,16.55),(2000,27.4),(2001,23),(2002,22.81),(2003,27.69),(2004,37.41),(2005,50.04),(2006,58.3),(2007,64.2),(2008,91.48))
Units: USD/Barrel

Operational cost= Other admin costs+"Cost of water, energy and feedstock"+Average labour cost
Units: rand/Year

Other admin costs= Biodiesel production*Other operational cost
Units: rand/Year

Other operational cost= INTEG (Changes in other operational cost, 0.3)
Units: rand/Litre

Planned investment in biodiesel plant= IF THEN ELSE (Time< 2012,0,3.5e+009)
Units: rand/Year

Price of glycerine= 2
Units: rand/Litre

Projected relative oil price([(2008,0)-(2100,2)],(2008,1),(2009,0.594971),(2010,0.78731),(2011,0.86864),(2012,0.962668),(2013,1.01256),(2014,1.06545),(2015,1.10159),(2016,1.11419),(2017,1.124),(2018,1.13257),(2019,1.14197),(2020,1.13734),(2021,1.14018),(2022,1.1581),(2023,1.14667),(2024,1.15748),(2025,1.17063),(2026,1.1824),(2027,1.20438),(2028,1.22523),(2029,1.23803),(2030,1.26481),(2093.81,1.79825))
Units: dmnl

Revenues from biodiesel= Biodiesel production*(biodiesel price +SUPPORT FOR BIODIESEL PER LITRE)
Units: rand/Year

"Revenues from by-products"= Glycerol produced*Price of glycerine
Units: rand/Year

SUPPORT FOR BIODIESEL PER LITRE= 0
Units: rand/Litre

Time to adjust profit= 1
Units: Year

Total revenues= IF THEN ELSE("BY-PRODUCT SWITCH"=1,Revenues from biodiesel+"Revenues from by-products",Revenues from biodiesel)
Units: rand/Year

Unit biodiesel profitability= IF THEN ELSE(Time>2012, (IF THEN ELSE("BY-PRODUCT SWITCH"=1, (biodiesel price +Price of glycerine-unit total cost of production)/(biodiesel price +Price of glycerine), (biodiesel price-unit total cost of production)/(biodiesel price))), 0)
Units: dmnl

Unit capital cost= INTEG (Changes in capital cost, 6.6)
Units: rand/Litre

Unit operational cost=ZIDZ(Operational cost, Biodiesel production)
Units: rand/Litre

unit total cost of production= (Unit operational cost+Unit capital cost-SUPPORT FOR BIODIESEL PER LITRE)* Learning effect table(Time)
Units: rand/Litre

Water cost= INTEG (Changes in water price, 0.7)
Units: rand/Litre

Water total cost= Biodiesel plant water usage*Water cost
Units: rand/Year

Water usage per litre= 1.2
Units: dmnl

****

Appendix D4. Cost of production sub-model equations

Capital cost growth= 0.001
Units: dmnl/Year

Capital cost per year= Unit capital cost*Hours in a year
Units: rand/Litre

Changes in capital cost= Unit capital cost*Capital cost growth
Units: rand/Litre/Year

Changes in feedstock price= Feedstock cost*Feedstock cost growth*Effect of feedstock supply ratio on cost
Units: rand/ton/Year

Changes in other operational cost= Other operational cost*Other operational cost growth
Units: rand/Litre/Year

Changes in water price= Water cost*water cost growth
Units: rand/Litre/Year

Effect of feedstock supply ratio on cost= Function for effect of feedstock demand supply on cost(Feedstock demand supply ratio)
Units: dmnl

Energy average price table([(2005,0)-(2100,50)],(2005,0.277925),(2006,0.30496),(2007,0.331995),(2008,0.35903),(2009,0.386065),(2010,0.4131),(2011,0.5168),(2012,0.6506),(2013,0.68313),(2014,0.717287),(2015,0.753151),(2016,0.790808),(2017,0.830349),(2018,0.871866),(2019,0.91546),(2020,0.961233),(2021,1.00929),(2022,1.05976),(2023,1.11275),(2024,1.16838),(2025,1.2268),(2026,1.28814),(2027,1.35255),(2028,1.42018),(2029,1.49119),(2030,1.56575),(2031,1.64403),(2032,1.72624),(2033,1.81255),(2034,1.90317),(2035,1.99833),(2036,2.09825),(2037,2.20316),(2038,2.31332),(2039,2.42899),(2040,2.55044),(2041,2.67796),(2042,2.81186),(2043,2.95245),(2044,3.10007),(2045,3.25507),(2046,3.41783),(2047,3.58872),(2048,3.76816),(2049,3.95656),(2050,4.15439),(2051,4.36211),(2052,4.58022),(2053,4.80923),(2054,5.04969),(2055,5.30217),(2056,5.56728),(2057,5.84565),(2058,6.13793),(2059,6.44483),(2060,6.76707),(2061,7.10542),(2062,7.46069),(2063,7.83372),(2064,8.22541),(2065,8.63668),(2066,9.06852),(2067,9.52194),(2068,9.99804),(2069,10.4979),(2070,11.0228),(2071,11.574),(2072,12.1527),(2073,12.7603),(2074,13.3983),(2075,14.0682),(2076,14.7717),(2077,15.5102),(2078,16.2858),(2079,17.1),(2080,17.955),(2081,18.8528),(2082,19.7954),(2083,20.7852),(2084,21.8245),(2085,22.9157),(2086,24.0615),(2087,25.2645),(2088,26.5278),(2089,27.8542),(2090,29.2469),(2091,30.7092),(2092,32.2447),(2093,33.8569),(2094,35.5498),(2095,37.3272),(2096,39.1936),(2097,41.1533),(2098,43.2109),(2099,45.3715),(2100,47.6401))
Units: rand/KWh

Energy price= Energy average price table(Time)
Units: rand/KWh

Feedstock cost= INTEG (Changes in feedstock price, 2600)
Units: rand/ton

Feedstock cost growth= 0.001
Units: dmnl/Year

Hours in a year= 8760
Units: dmnl

Initial capital cost= INITIAL(Unit capital cost)
Units: rand/Litre

Other operational cost= INTEG (Changes in other operational cost, 0.3)
Units: rand/Litre

Other operational cost growth= 0.001
Units: dmnl/Year

Unit capital cost= INTEG (Changes in capital cost, 6.6)
Units: rand/Litre

Water cost= INTEG (Changes in water price, 0.7)
Units: rand/Litre

water cost growth= 0.001
Units: dmnl/Year

****

Appendix D5. Employment from biodiesel plant sub-model equations

Average labour cost= Average wage*Employment biodiesel plant
Units: rand/Year

Average wage= 12000
Units: rand/person/Year

Capacity coefficient= 1
Units: dmnl/Litre

Desired employment biodiesel plant= ((Functional biodiesel capacity * Capacity coefficient)^Employment elasticity)
Units: person

Employment biodiesel plant= INTEG (New trainees, 0)
Units: person

Employment elasticity= 0.5
Units: dmnl

Functional biodiesel capacity= INTEG (New biodiesel capacity-Biodiesel discarded capacity, 0)
Units: Litre

Net recruitment noise= 0
Units: person/Year

New trainees= Workforce in training/Time to complete training
Units: person/Year

Recruiting for training= (Desired employment biodiesel plant-Employment biodiesel plant)/Time to adjust training + Net recruitment noise*RANDOM UNIFORM(-0.5,0.5,0)
Units: person/Year

Time to adjust training= 1
Units: Year

Time to complete training= 0.5
Units: Year

Trained labour ratio= ZIDZ(Employment biodiesel plant, Desired employment biodiesel plant)
Units: dmnl

Workforce in training= INTEG (Recruiting for training-New trainees, 0)
Units: person

****

Appendix D6. Water sub-model equations

Average precipitation= 650
Units: mm/Year

Cross border inflow= 0
Units: Kg/Year

Cubic meters of water per mm of rain per hectare= 10
Units: (m*m*m)/(mm*ha)

Domestic and municipal water demand= Total population*Per capita water demand
Units: Kg/Year

Effect of water stress index on canola yield= Function for effect of water stress on canola yield(Water stress index)
Units: dmnl

Fraction of rain evaporating immediately= 0.25
Units: dmnl

Function for effect of income on pc water demand table([(0,0)-(3,1.5)],(0,0.7),(1,1),(2,1.2),(3,1.25))
Units: dmnl

Function for effect of water stress on canola yield([(0.001,0)-(0.061,1)],(0.001,1),(0.021,0.75),(0.041,0.65),(0.061,0.5))
Units: dmnl

Initial pc water demand= 9125
Units: Kg/Year/person

Kilograms per cubic meter of water = 1000
Units: Kg/(m*m*m)

Per capita water demand= Initial pc water demand*Function for effect of income on pc water demand table (Relative pc real GDP)
Units: Kg/person/Year

Precipitation= Average precipitation*Total land*Cubic meters of water per mm of rain per hectare * Kilograms per cubic meter of water
Units: Kg/Year

Production water demand= Real GDP*Water demand per unit produced
Units: Kg/Year

Real GDP= Relative production*Initial real GDP
Units: rand/Year

Relative pc real GDP= PC real GDP/Initial pc real GDP
Units: dmnl

Renewable water resources available per capita= Total renewable water resources/ Total population
Units: Kg/person/Year

Total land= Crop land+Fallow land+Forest plantations+Livestock Land+Settlement land+Conservation land +Biodiesel crop land
Units: ha

Total population= SUM(Population[sex!,age!])
Units: person

Total renewable water resources= Cross border inflow+Water resources internally produced
Units: Kg/Year

Total water demand= Domestic and municipal water demand+Production water demand
Units: Kg/Year

Water demand per unit produced= 1
Units: Kg/rand

Water resources internally produced= Precipitation*(1-Fraction of rain evaporating immediately)
Units: Kg/Year

Water stress index= Total water demand/Total renewable water resources
Units: dmnl

Average precipitation= 650
Units: mm/Year

Cross border inflow= 0
Units: Kg/Year

Cubic meters of water per mm of rain per hectare= 10
Units: (m*m*m)/(mm*ha)

Domestic and municipal water demand= Total population*Per capita water demand
Units: Kg/Year

Effect of water stress index on canola yield= Function for effect of water stress on canola yield(Water stress index)
Units: dmnl

Fraction of rain evaporating immediately= 0.25
Units: dmnl

Function for effect of income on pc water demand table([(0,0)-(3,1.5)],(0,0.7),(1,1),(2,1.2),(3,1.25))
Units: dmnl

Function for effect of water stress on canola yield([(0.001,0)-(0.061,1)],(0.001,1),(0.021,0.75),(0.041,0.65),(0.061,0.5))
Units: dmnl

Initial pc water demand= 9125
Units: Kg/Year/person

Kilograms per cubic meter of water = 1000
Units: Kg/(m*m*m)

Per capita water demand= Initial pc water demand*Function for effect of income on pc water demand table (Relative pc real GDP)
Units: Kg/person/Year

Precipitation= Average precipitation*Total land*Cubic meters of water per mm of rain per hectare * Kilograms per cubic meter of water
Units: Kg/Year

Production water demand= Real GDP*Water demand per unit produced
Units: Kg/Year

Real GDP= Relative production*Initial real GDP
Units: rand/Year

Relative pc real GDP= PC real GDP/Initial pc real GDP
Units: dmnl

Renewable water resources available per capita= Total renewable water resources/Total population
Units: Kg/person/Year

Total land= Crop land+Fallow land+Forest plantations+Livestock Land+Settlement land+Conservation land+Biodiesel crop land
Units: ha

Total population= SUM(Population[sex!,age!])
Units: person

Total renewable water resources= Cross border inflow+Water resources internally produced
Units: Kg/Year

Total water demand= Domestic and municipal water demand+Production water demand
Units: Kg/Year

Water demand per unit produced= 1
Units: Kg/rand

Water resources internally produced= Precipitation*(1-Fraction of rain evaporating immediately)
Units: Kg/Year

Water stress index= Total water demand/Total renewable water resources
Units: dmnl

****

Appendix D7. Energy sub-model equations

Changes in electricity demand= (((Electricity demand*Relative population^Elasticity of population to demand *Relative real GDP^Elasticity of GDP to demand)-Electricity demand)/Time to adjust electricity demand) +Changes in energy usage
Units: MWh/Year

Changes in energy usage= Energy usage MWh-Previous energy usage
Units: MWh/Year

Convert kWh to MWh= 0.001
Units: MWh/KWh

Elasticity of GDP to demand= 0.002
Units: dmnl

Elasticity of population to demand= 0.001
Units: dmnl

Electricity demand= INTEG (Changes in electricity demand, Initial electricity demand)
Units: MWh

Energy usage biodiesel production= Energy use per litre*Biodiesel production
Units: KWh/Year

Energy usage MWh= Energy usage biodiesel production*Convert kWh to MWh
Units: MWh/Year

Initial electricity demand= 7.136e+006
Units: MWh

Initial total population= INITIAL(Total population)
Units: person

Previous energy usage= DELAY N(Energy usage MWh, 1, Energy usage MWh, 1)
Units: MWh/Year

Relative population= Total population/Initial total population
Units: dmnl

Relative real GDP= Real GDP/Initial real GDP
Units: dmnl

Time to adjust electricity demand=1
Units: Year

Total population= SUM(Population[sex!,age!])
Units: person

****

Appendix D8. Air emissions sub-model equations

Air emissions decomposition= Cumulative net emissions*Emissions decomposition factor
Units: Kg CO2/Year

Air emissions generation= Net emission
Units: Kg CO2/Year

Avoided emission of using biodiesel= 1.2
Units: Kg CO2/Litre

Biodiesel production= (Functional biodiesel capacity*Days per year*Hours per day)*Effect of trained labour on biodiesel production *BIODIESEL CAPACITY UTILIZATION
Units: Litre/Year

Conversion rate litre to barrel= 160
Units: Litre/Barrel

Cumulative net emissions= INTEG (Air emissions generation-Air emissions decomposition, 0)
Units: Kg CO2

Effect of fertilizer use on emissions= Function for effect of fertilizer use on air emissions (FERTILIZER USE SWITCH)
Units: dmnl

Emission per barrel of conventional diesel= 430.7
Units: Kg CO2/Barrel

Emission per litre of conventional diesel= Emission per barrel of conventional diesel/Conversion rate litre to barrel
Units: Kg CO2/Litre

Emissions decomposition factor= 0.001
Units: dmnl/Year

FERTILIZER USE SWITCH= 0
Units: dmnl

Function for effect of fertilizer use on air emissions([(0,0)-(1.5,2)],(0,1),(0.25,1.07018),(0.5,1.07895),(0.75,1.08772),(1,1.09649),(1.25,1.12),(1.5,1.12))
Units: dmnl

Net emission= Total air emission-Total avoided emission from biodiesel
Units: Kg CO2/Year

Net emission per litre= ZIDZ(Net emission, Biodiesel production)
Units: Kg CO2/Litre

Total air emission=Biodiesel production*Emission per litre of conventional diesel*Effect of fertilizer use on emissions
Units: Kg CO2/Year

Total avoided emission from biodiesel= Avoided emission of using biodiesel*Biodiesel production
Units: Kg CO2/Year

****

Appendix D9. Population sub-model equations

AGE specific fertility distribution[childbearing age]= Function for age specific fertility distribution(childbearing age - 2)
Units: dmnl/Year

Average life expectancy= (Life expectancy[female] +Life expectancy[male])/2
Units: Year

Births[female]= SUM(Sexually active female[childbearing age!]*Total fertility rate*AGE specific fertility distribution [childbearing age!]) *Proportion of female babies
Births[male]= SUM(Sexually active female[childbearing age!]*Total fertility rate*AGE specific fertility distribution [childbearing age!]) *(1-Proportion of female babies)
Units: person/Year

Death rate[sex,age]= Death rates table[sex,age] (Life expectancy[sex])
Units: dmnl/Year

Death rates table[female, age 0](
[(0,0)-(100,0.4)],(0,1),(20,0.31),(22.5,0.28),(25,0.26),(27.5,0.25),(30,0.23
),(32.5,0.21),(35,0.2),(37.5,0.19),(40,0.17),(42.5,0.16),(45,0.15),(47.5,0.14
),(50,0.13),(52.5,0.12),(55,0.11),(57.5,0.1),(60,0.09),(62.5,0.09),(65,0.08
),(67.5,0.07),(70,0.06),(72.5,0.05),(75,0.04),(77.5,0.03),(80,0.02))
Death rates table[female, age 1 to 4](
[(0,0)-(100,0.2)],(0,1),(20,0.107747),(22.5,0.096214),(25,0.086166),(27.5
,0.077297),(30,0.069386),(32.5,0.062265),(35,0.055811),(37.5,0.04992),(40,
0.044518),(42.5,0.03942),(45,0.034525),(47.5,0.030069),(50,0.026002),(52.5
,0.022273),(55,0.018843),(57.5,0.015675),(60,0.012736),(62.5,0.009978),(65
,0.007747),(67.5,0.005892),(70,0.004318),(72.5,0.003019),(75,0.001988),(77.5
,0.00121),(80,0.000663))
Death rates table[female, age 5 to 9](
[(0,0)-(100,0.02)],(0,1),(20,0.018731),(22.5,0.016906),(25,0.015271),(27.5
,0.013789),(30,0.01244),(32.5,0.011202),(35,0.01006),(37.5,0.009003),(40,0.00802
),(42.5,0.006989),(45,0.006082),(47.5,0.005257),(50,0.004502),(52.5,0.003809
),(55,0.003168),(57.5,0.002575),(60,0.00202),(62.5,0.001515),(65,0.001183)
,(67.5,0.000876),(70,0.000621),(72.5,0.000418),(75,0.000264),(77.5,0.000152
),(80,7.8e-005))
Death rates table[female, age 10 to 14](
[(0,0)-(100,0.01)],(0,1),(20,0.009836),(22.5,0.00892),(25,0.008096),(27.5
,0.007347),(30,0.006662),(32.5,0.006034),(35,0.005453),(37.5,0.004914),(40
,0.004411),(42.5,0.003941),(45,0.003472),(47.5,0.00304),(50,0.002642),(52.5
,0.002272),(55,0.001927),(57.5,0.001609),(60,0.001309),(62.5,0.001026),(65
,0.000809),(67.5,0.000617),(70,0.000452),(72.5,0.000316),(75,0.000208),(77.5
,0.000128),(80,7e-005))
Death rates table[female, age 15 to 19](
[(0,0)-(100,0.02)],(0,1),(20,0.013531),(22.5,0.012284),(25,0.011165),(27.5
,0.01015),(30,0.009223),(32.5,0.008369),(35,0.007584),(37.5,0.006853),(40,
0.006174),(42.5,0.005598),(45,0.004943),(47.5,0.004339),(50,0.003783),(52.5
,0.003269),(55,0.002794),(57.5,0.002351),(60,0.001937),(62.5,0.001549),(65
,0.001173),(67.5,0.000896),(70,0.000659),(72.5,0.000462),(75,0.000306),(77.5
,0.000186),(80,0.000102))
Death rates table[female, age 20 to 24](
[(0,0)-(100,0.02)],(0,1),(20,0.01693),(22.5,0.015376),(25,0.013979),(27.5
,0.012715),(30,0.011562),(32.5,0.010504),(35,0.009528),(37.5,0.008621),(40

```
          ,0.00778),(42.5,0.00704),(45,0.00625),(47.5,0.005517),(50,0.004839),(52.5,
          0.004207),(55,0.00362),(57.5,0.003071),(60,0.002559),(62.5,0.002075),(65,0.001607
          ),(67.5,0.001247),(70,0.000934),(72.5,0.000669),(75,0.000452),(77.5,0.000286
          ),(80,0.000162))
Death rates table[female, age 25 to 29](
                [(0,0)-(100,0.02)],(0,1),(20,0.01819),(22.5,0.016536),(25,0.015052),(27.5
          ,0.013709),(30,0.012484),(32.5,0.011361),(35,0.010323),(37.5,0.009362),(40
          ,0.008468),(42.5,0.0077),(45,0.006864),(47.5,0.006088),(50,0.005365),(52.5
          ,0.004692),(55,0.004063),(57.5,0.003476),(60,0.002925),(62.5,0.002404),(65
          ,0.001875),(67.5,0.00147),(70,0.001114),(72.5,0.000811),(75,0.000559),(77.5
          ,0.000358),(80,0.00021))
Death rates table[female, age 30 to 34](
                [(0,0)-(100,0.02)],(0,1),(20,0.018977),(22.5,0.017253),(25,0.015708),(27.5
          ,0.01431),(30,0.013033),(32.5,0.011864),(35,0.010784),(37.5,0.009786),(40,
          0.008855),(42.5,0.008013),(45,0.007182),(47.5,0.006403),(50,0.005674),(52.5
          ,0.00499),(55,0.004346),(57.5,0.003738),(60,0.003168),(62.5,0.002626),(65,
          0.002147),(67.5,0.001714),(70,0.001326),(72.5,0.000986),(75,0.000697),(77.5
          ,0.000462),(80,0.00028))
Death rates table[female, age 35 to 39](
                [(0,0)-(100,0.02)],(0,1),(20,0.019955),(22.5,0.018173),(25,0.016574),(27.5
          ,0.015127),(30,0.013806),(32.5,0.012597),(35,0.011481),(37.5,0.010448),(40
          ,0.009486),(42.5,0.008628),(45,0.00778),(47.5,0.006981),(50,0.006227),(52.5
          ,0.005519),(55,0.004847),(57.5,0.004215),(60,0.003616),(62.5,0.003047),(65
          ,0.002527),(67.5,0.002046),(70,0.001611),(72.5,0.001223),(75,0.000886),(77.5
          ,0.000603),(80,0.000378))
Death rates table[female, age 40 to 44](
                [(0,0)-(100,0.04)],(0,1),(20,0.020193),(22.5,0.018461),(25,0.01691),(27.5
          ,0.015505),(30,0.014225),(32.5,0.013048),(35,0.011965),(37.5,0.01096),(40,
          0.010027),(42.5,0.009187),(45,0.008396),(47.5,0.00764),(50,0.006917),(52.5
          ,0.006229),(55,0.005574),(57.5,0.004949),(60,0.004356),(62.5,0.003785),(65
          ,0.003247),(67.5,0.002717),(70,0.002218),(72.5,0.001756),(75,0.001338),(77.5
          ,0.000966),(80,0.000653))
Death rates table[female, age 45 to 49](
                [(0,0)-(100,0.04)],(0,1),(20,0.021268),(22.5,0.019524),(25,0.01796),(27.5
          ,0.016544),(30,0.015252),(32.5,0.014068),(35,0.012976),(37.5,0.011965),(40
          ,0.011022),(42.5,0.010177),(45,0.009401),(47.5,0.008657),(50,0.007937),(52.5
          ,0.007244),(55,0.00658),(57.5,0.005944),(60,0.005333),(62.5,0.004745),(65,
          0.004171),(67.5,0.003582),(70,0.00301),(72.5,0.002464),(75,0.001952),(77.5
          ,0.001478),(80,0.001056))
Death rates table[female, age 50 to 54](
                [(0,0)-(100,0.04)],(0,1),(20,0.027763),(22.5,0.025529),(25,0.023525),(27.5
          ,0.021717),(30,0.020072),(32.5,0.018562),(35,0.017174),(37.5,0.015889),(40
          ,0.014693),(42.5,0.013557),(45,0.012614),(47.5,0.011701),(50,0.010815),(52.5
          ,0.009956),(55,0.009127),(57.5,0.00833),(60,0.007561),(62.5,0.006851),(65,
          0.006135),(67.5,0.005361),(70,0.004602),(72.5,0.003858),(75,0.00314),(77.5
          ,0.002458),(80,0.001829))
Death rates table[female, age 55 to 59](
                [(0,0)-(100,0.04)],(0,1),(20,0.038124),(22.5,0.03506),(25,0.032325),(27.5
          ,0.029863),(30,0.027627),(32.5,0.025582),(35,0.023703),(37.5,0.021968),(40
          ,0.02036),(42.5,0.018867),(45,0.017601),(47.5,0.016369),(50,0.015178),(52.5
```

,0.014022),(55,0.012907),(57.5,0.011831),(60,0.010795),(62.5,0.009813),(65
,0.008829),(67.5,0.007759),(70,0.006703),(72.5,0.005664),(75,0.004653),(77.5
,0.003683),(80,0.002777))
Death rates table[female, age 60 to 64](
[(0,0)-(100,0.08)],(0,1),(20,0.063586),(22.5,0.058245),(25,0.05352),(27.5
,0.049301),(30,0.045498),(32.5,0.042044),(35,0.038887),(37.5,0.035987),(40
,0.033308),(42.5,0.030763),(45,0.028708),(47.5,0.026711),(50,0.024778),(52.5
,0.022906),(55,0.021102),(57.5,0.019361),(60,0.017689),(62.5,0.016171),(65
,0.014587),(67.5,0.012867),(70,0.01116),(72.5,0.009478),(75,0.007832),(77.5
,0.006246),(80,0.004753))
Death rates table[female, age 65 to 69](
[(0,0)-(100,0.1)],(0,1),(20,0.098693),(22.5,0.090243),(25,0.082871),(27.5
,0.076358),(30,0.070546),(32.5,0.065312),(35,0.060565),(37.5,0.056235),(40
,0.05226),(42.5,0.048607),(45,0.045604),(47.5,0.042686),(50,0.039859),(52.5
,0.037122),(55,0.034479),(57.5,0.031933),(60,0.029484),(62.5,0.027191),(65
,0.024787),(67.5,0.022148),(70,0.019498),(72.5,0.016848),(75,0.014214),(77.5
,0.011621),(80,0.009119))
Death rates table[female, age 70 to 74](
[(0,0)-(100,0.2)],(0,1),(20,0.159395),(22.5,0.145124),(25,0.133009),(27.5
,0.12254),(30,0.113358),(32.5,0.105221),(35,0.097937),(37.5,0.091361),(40,
0.08539),(42.5,0.080084),(45,0.075702),(47.5,0.071445),(50,0.067315),(52.5
,0.063316),(55,0.059453),(57.5,0.055731),(60,0.052151),(62.5,0.048695),(65
,0.045019),(67.5,0.040933),(70,0.036768),(72.5,0.032528),(75,0.028216),(77.5
,0.023862),(80,0.019513))
Death rates table[female, age 75 to 79](
[(0,0)-(100,0.4)],(0,1),(20,0.252331),(22.5,0.227439),(25,0.207422),(27.5
,0.190805),(30,0.176687),(32.5,0.164479),(35,0.153767),(37.5,0.144268),(40
,0.135763),(42.5,0.128251),(45,0.122317),(47.5,0.116549),(50,0.110954),(52.5
,0.105536),(55,0.100302),(57.5,0.095255),(60,0.090401),(62.5,0.085765),(65
,0.08059),(67.5,0.074756),(70,0.068712),(72.5,0.062434),(75,0.055897),(77.5
,0.049101),(80,0.042068))
Death rates table[female, age 80 and over](
[(0,0)-(100,0.6)],(0,1),(20,0.410881),(22.5,0.389394),(25,0.370157),(27.5
,0.352756),(30,0.336902),(32.5,0.322367),(35,0.308965),(37.5,0.296544),(40
,0.284989),(42.5,0.274432),(45,0.265855),(47.5,0.257306),(50,0.248818),(52.5
,0.240404),(55,0.232093),(57.5,0.223906),(60,0.215861),(62.5,0.208031),(65
,0.199094),(67.5,0.188776),(70,0.1778),(72.5,0.166073),(75,0.15349),(77.5,
0.139955),(80,0.125409))
Death rates table[male, age 0](
[(0,0)-(100,0.4)],(0,1),(19.92,0.34),(22.299,0.311),(24.661,0.289),(27.007
,0.269),(29.321,0.251),(31.636,0.234),(33.95,0.218),(36.233,0.204),(38.501
,0.19),(40.634,0.178),(42.861,0.167),(45.118,0.156),(47.372,0.145),(49.623
,0.135),(51.869,0.125),(54.108,0.115),(56.341,0.106),(58.58,0.097),(61.252
,0.086),(63.659,0.076),(66.08,0.066),(68.524,0.056),(70.993,0.047),(73.486
,0.037),(76.002,0.028))
Death rates table[male, age 1 to 4](
[(0,0)-(100,0.2)],(0,1),(19.92,0.101096),(22.299,0.090657),(24.661,0.08153
),(27.007,0.073448),(29.321,0.066219),(31.636,0.059702),(33.95,0.053783),(
36.233,0.048373),(38.501,0.043402),(40.634,0.039138),(42.861,0.034408),(45.118
,0.030108),(47.372,0.026188),(49.623,0.0226),(51.869,0.019304),(54.108,0.016268

),(56.341,0.013454),(58.58,0.010822),(61.252,0.007944),(63.659,0.00606),(66.08
,0.00446),(68.524,0.003132),(70.993,0.002074),(73.486,0.00127),(76.002,0.000701
))

Death rates table[male, age 5 to 9](
[(0,0)-(100,0.02)],(0,1),(19.92,0.01657),(22.3,0.015023),(24.66,0.013635)
,(27.01,0.012379),(29.32,0.011231),(31.64,0.010177),(33.95,0.009206),(36.23
,0.008305),(38.5,0.007467),(40.63,0.006619),(42.86,0.005848),(45.12,0.005134
),(47.37,0.004476),(49.62,0.003864),(51.87,0.003296),(54.11,0.002767),(56.34
,0.00227),(58.58,0.001802),(61.25,0.001382),(63.66,0.001058),(66.08,0.000783
),(68.52,0.000553),(70.99,0.000366),(73.49,0.000226),(76,0.000126))

Death rates table[male, age 10 to 14](
[(0,0)-(100,0.008)],(0,1),(19.92,0.007768),(22.3,0.007094),(24.66,0.006486
),(27.01,0.005934),(29.32,0.005429),(31.64,0.004963),(33.95,0.004533),(36.23
,0.004134),(38.5,0.003762),(40.63,0.003411),(42.86,0.003081),(45.12,0.002771
),(47.37,0.002478),(49.62,0.0022),(51.87,0.001937),(54.11,0.00169),(56.34,
0.001454),(58.58,0.001231),(61.25,0.001008),(63.66,0.000819),(66.08,0.000645
),(68.52,0.00049),(70.99,0.000356),(73.49,0.000244),(76,0.000154))

Death rates table[male, age 15 to 19](
[(0,0)-(100,0.02)],(0,1),(19.92,0.011745),(22.3,0.010717),(24.66,0.009792
),(27.01,0.008955),(29.32,0.008187),(31.64,0.007483),(33.95,0.006833),(36.23
,0.006229),(38.5,0.005666),(40.63,0.005183),(42.86,0.004671),(45.12,0.004191
),(47.37,0.003738),(49.62,0.003312),(51.87,0.002911),(54.11,0.002533),(56.34
,0.002175),(58.58,0.001835),(61.25,0.001484),(63.66,0.001197),(66.08,0.000936
),(68.52,0.000705),(70.99,0.000507),(73.49,0.000342),(76,0.000212))

Death rates table[male, age 20 to 24](
[(0,0)-(100,0.02)],(0,1),(19.92,0.017833),(22.3,0.016267),(24.66,0.014861
),(27.01,0.013588),(29.32,0.012429),(31.64,0.011363),(33.95,0.010379),(36.23
,0.00947),(38.5,0.008621),(40.63,0.007904),(42.86,0.007154),(45.12,0.006397
),(47.37,0.00569),(49.62,0.00503),(51.87,0.004413),(54.11,0.003833),(56.34
,0.00329),(58.58,0.002775),(61.25,0.002155),(63.66,0.001702),(66.08,0.001313
),(68.52,0.000974),(70.99,0.000687),(73.49,0.000454),(76,0.000274))

Death rates table[male, age 25 to 29](
[(0,0)-(100,0.02)],(0,1),(19.92,0.017861),(22.3,0.016286),(24.66,0.014872
),(27.01,0.01359),(29.32,0.012423),(31.64,0.011351),(33.95,0.01036),(36.23
,0.009445),(38.5,0.00859),(40.63,0.007869),(42.86,0.007098),(45.12,0.006369
),(47.37,0.005682),(49.62,0.005036),(51.87,0.004429),(54.11,0.003856),(56.34
,0.003316),(58.58,0.002804),(61.25,0.00226),(63.66,0.001823),(66.08,0.001428
),(68.52,0.001076),(70.99,0.000775),(73.49,0.000523),(76,0.000326))

Death rates table[male, age 30 to 34](
[(0,0)-(100,0.02)],(0,1),(19.92,0.017569),(22.3,0.016098),(24.66,0.014776
),(27.01,0.013578),(29.32,0.012486),(31.64,0.011483),(33.95,0.010557),(36.23
,0.009698),(38.5,0.008899),(40.63,0.008222),(42.86,0.007568),(45.12,0.006872
),(47.37,0.006215),(49.62,0.005592),(51.87,0.005002),(54.11,0.004443),(56.34
,0.003915),(58.58,0.003409),(61.25,0.002798),(63.66,0.002297),(66.08,0.001851
),(68.52,0.001442),(70.99,0.001078),(73.49,0.000763),(76,0.000503))

Death rates table[male, age 35 to 39](
[(0,0)-(100,0.02)],(0,1),(19.92,0.019279),(22.3,0.017682),(24.66,0.016247
),(27.01,0.014948),(29.32,0.013764),(31.64,0.012675),(33.95,0.011671),(36.23
,0.010742),(38.5,0.009877),(40.63,0.009146),(42.86,0.00845),(45.12,0.007706
),(47.37,0.006999),(49.62,0.006328),(51.87,0.00569),(54.11,0.005083),(56.34

,0.004508),(58.58,0.003959),(61.25,0.00329),(63.66,0.002741),(66.08,0.002236
),(68.52,0.001766),(70.99,0.001342),(73.49,0.000968),(76,0.000651))
Death rates table[male, age 40 to 44](
[(0,0)-(100,0.04)],(0,1),(19.92,0.022776),(22.3,0.02095),(24.66,0.019312)
,(27.01,0.017831),(29.32,0.01648),(31.64,0.015242),(33.95,0.014098),(36.23
,0.013042),(38.5,0.012057),(40.63,0.011225),(42.86,0.010446),(45.12,0.009623
),(47.37,0.008833),(49.62,0.008075),(51.87,0.007349),(54.11,0.006656),(56.34
,0.005995),(58.58,0.005361),(61.25,0.004582),(63.66,0.00391),(66.08,0.003273
),(68.52,0.002666),(70.99,0.002097),(73.49,0.001577),(76,0.001116))
Death rates table[male, age 45 to 49](
[(0,0)-(100,0.04)],(0,1),(19.92,0.026511),(22.3,0.024484),(24.66,0.022667
),(27.01,0.021024),(29.32,0.019528),(31.64,0.018155),(33.95,0.016891),(36.23
,0.015723),(38.5,0.014634),(40.63,0.013715),(42.86,0.012852),(45.12,0.011973
),(47.37,0.011121),(49.62,0.010298),(51.87,0.009503),(54.11,0.008737),(56.34
,0.008001),(58.58,0.00729),(61.25,0.006434),(63.66,0.005643),(66.08,0.004861
),(68.52,0.004095),(70.99,0.00335),(73.49,0.00264),(76,0.00198))
Death rates table[male, age 50 to 54](
[(0,0)-(100,0.04)],(0,1),(19.92,0.033434),(22.3,0.031013),(24.66,0.028845
),(27.01,0.026888),(29.32,0.025108),(31.64,0.023477),(33.95,0.021977),(36.23
,0.020588),(38.5,0.019299),(40.63,0.018179),(42.86,0.017155),(45.12,0.016154
),(47.37,0.015174),(49.62,0.014219),(51.87,0.013291),(54.11,0.012391),(56.34
,0.01152),(58.58,0.010673),(61.25,0.009678),(63.66,0.008686),(66.08,0.007685
),(68.52,0.006675),(70.99,0.00566),(73.49,0.004655),(76,0.003675))
Death rates table[male, age 55 to 59](
[(0,0)-(100,0.06)],(0,1),(19.92,0.044138),(22.3,0.04106),(24.66,0.038314)
,(27.01,0.035841),(29.32,0.033597),(31.64,0.031544),(33.95,0.02966),(36.23
,0.027918),(38.5,0.026304),(40.63,0.024908),(42.86,0.023655),(45.12,0.022423
),(47.37,0.021217),(49.62,0.020035),(51.87,0.018882),(54.11,0.017758),(56.34
,0.016668),(58.58,0.015606),(61.25,0.014384),(63.66,0.013094),(66.08,0.011774
),(68.52,0.010417),(70.99,0.00903),(73.49,0.007621),(76,0.006211))
Death rates table[male, age 60 to 64](
[(0,0)-(100,0.08)],(0,1),(19.92,0.065496),(22.3,0.060868),(24.66,0.056767
),(27.01,0.053092),(29.32,0.049774),(31.64,0.046754),(33.95,0.04399),(36.23
,0.041446),(38.5,0.039096),(40.63,0.037084),(42.86,0.035279),(45.12,0.033503
),(47.37,0.031763),(49.62,0.03006),(51.87,0.0284),(54.11,0.026783),(56.34,
0.025216),(58.58,0.023688),(61.25,0.0219),(63.66,0.020022),(66.08,0.018091
),(68.52,0.0161),(70.99,0.014056),(73.49,0.011965),(76,0.009852))
Death rates table[male, age 65 to 69](
[(0,0)-(100,0.1)],(0,1),(19.92,0.096446),(22.3,0.089546),(24.66,0.083489)
,(27.01,0.07811),(29.32,0.073284),(31.64,0.068925),(33.95,0.064956),(36.23
,0.061321),(38.5,0.057978),(40.63,0.055173),(42.86,0.052635),(45.12,0.05014
),(47.37,0.047696),(49.62,0.045308),(51.87,0.042977),(54.11,0.040713),(56.34
,0.038515),(58.58,0.036376),(61.25,0.033787),(63.66,0.031099),(66.08,0.028317
),(68.52,0.025433),(70.99,0.022445),(73.49,0.019361),(76,0.016207))
Death rates table[male, age 70 to 74](
[(0,0)-(100,0.2)],(0,1),(19.92,0.149635),(22.3,0.138669),(24.66,0.129223)
,(27.01,0.120967),(29.32,0.113663),(31.64,0.107132),(33.95,0.10125),(36.23
,0.09591),(38.5,0.091032),(40.63,0.086976),(42.86,0.083426),(45.12,0.079866
),(47.37,0.07638),(49.62,0.072976),(51.87,0.069655),(54.11,0.066431),(56.34
,0.063306),(58.58,0.060262),(61.25,0.056487),(63.66,0.052506),(66.08,0.048388

),(68.52,0.044078),(70.99,0.039558),(73.49,0.034824),(76,0.02989))
Death rates table[male, age 75 to 79](
[(0,0)-(100,0.4)],(0,1),(19.92,0.22951),(22.3,0.212135),(24.66,0.197665),
(27.01,0.185337),(29.32,0.174656),(31.64,0.165277),(33.95,0.156946),(36.23
,0.149482),(38.5,0.142737),(40.63,0.137144),(42.86,0.132341),(45.12,0.127625
),(47.37,0.123009),(49.62,0.118498),(51.87,0.114104),(54.11,0.109833),(56.34
,0.105693),(58.58,0.101661),(61.25,0.096657),(63.66,0.091211),(66.08,0.085513
),(68.52,0.079468),(70.99,0.073022),(73.49,0.066131),(76,0.058764))
Death rates table[male, age 80 and over](
[(0,0)-(100,0.4)],(0,1),(19.92,0.387521),(22.3,0.371088),(24.66,0.356328)
,(27.01,0.34296),(29.32,0.330768),(31.64,0.319573),(33.95,0.309246),(36.23
,0.299675),(38.5,0.290759),(40.63,0.28317),(42.86,0.2765),(45.12,0.269829)
,(47.37,0.263169),(49.62,0.256538),(51.87,0.249959),(54.11,0.243444),(56.34
,0.237022),(58.58,0.23066),(61.25,0.222615),(63.66,0.213667),(66.08,0.204084
),(68.52,0.193666),(70.99,0.182251),(73.49,0.16969),(76,0.155821))
Death rates table[sex,newborn](
[(0,0)-(100,10)],(0,0),(100,0))
Units: 1/Year

Deaths[sex,age]= Population[sex,age]*Death rate[sex,age]
Units: person/Year

Desired number of children= Initial desired number of children*Effects of economic conditions on fertility rate
Units: dmnl

Disposable income= Initial disposable income*Relative disposable income table(Time)
Units: rand

Effects of economic conditions on fertility rate= Function of effect of economic conditions on desired number of children table (Relative real GDP)
Units: dmnl

Exchange rate dollar to rand= Official exchange rate(Time)
Units: rand/USD

Function for age specific fertility distribution([(15,0)-
(50,0.1)],(15,0),(20,0.045),(25,0.045),(30,0.04),(35,0.035),(40,0.025),(45,0.01),
(50,0))
Units: dmnl/Year

Function of effect of economic conditions on desired number of children table(
[(0,0)-(10,2)],(0,2),(1,1),(2,0.75),(4,0.5),(8,0.45))
Units: dmnl

Income ppp= DELAY N(PC real GDP/Exchange rate dollar to rand, 1,
Initial income ppp , 1)
Units: USD/person/Year

Initial desired number of children= 2

```
        Units: dmnl

Initial disposable income= 900
        Units: rand

Initial income ppp= 1580
        Units: USD/person/Year

Initial population[male,age]=
        0,
        76416, 77148, 77880, 78612, 79344,
        79280, 80005, 80730, 82805, 84880,
        89630, 91769, 93908, 92900, 91892,
        90765, 89758, 88751, 84959, 81168,
        75838, 72122, 68406, 64814, 61221,
        56666, 53134, 49602, 47567, 45532,
        44358, 42283, 40207, 38020, 35832,
        32447, 30338, 28228, 27772, 27316,
        27703, 27232, 26762, 26455, 26148,
        26250, 25938, 25626, 24804, 23982,
        22830, 22020, 21210, 20483, 19757,
        18674, 17961, 17249, 17155, 17061,
        17518, 17421, 17324, 16920, 16516,
        16228, 15821, 15414, 14550, 13687,
        12643, 11792, 10941, 10022, 9102,
        7740,  6871,  6001,  5663,  5325,
        5665,  5281,  4897,  3918,  2938,
        0,     0,     0,     0,     0,
        0,     0,     0,     0,     0,
        0,     0,     0,     0,     0,
        0
Initial population[female,age]=
                0,
                76008, 76604, 77200, 77796, 78392,
                78077, 78666, 79255, 81386, 83517,
                88483, 90685, 92886, 91877, 90869,
                89578, 88572, 87567, 83983, 80400,
                75257, 71746, 68236, 65032, 61829,
                57537, 54393, 51249, 49957, 48665,
                48768, 47438, 46108, 44198, 42287,
                38961, 37118, 35274, 35107, 34940,
                35769, 35597, 35425, 35245, 35065,
                35510, 35326, 35143, 33921, 32700,
                30731, 29539, 28346, 27443, 26541,
                25374, 24481, 23588, 23348, 23108,
                23248, 23004, 22760, 22516, 22272,
                22683, 22431, 22180, 20862, 19544,
                17650, 16373, 15097, 13892, 12688,
                10847, 9709,  8571,  8315,  8059,
                9193,  8892,  8590,  6872,  5154,
```

0, 0, 0, 0, 0,
0, 0, 0, 0, 0,
0, 0, 0, 0, 0,
0
Units: person

Initial population growth= 0.0125
Units: dmnl/Year

Life expectancy[male]= Life expectancy[female]-MFLE DIFFERENCE
Life expectancy[female]= Normal life expectancy+MFLE DIFFERENCE/2
Units: Year

Local condition adjustment factor= -3.17
Units: Year

MFLE DIFFERENCE=4.4
Units: Year

Net Migration[sex,age over 0]= Population[sex,age over 0]*Net migration rate
Units: person/Year

Net migration rate= 0
Units: dmnl/Year

Normal life expectancy= Normal life expectancy table (Income ppp)+Local condition adjustment factor
Units: Year

Normal life expectancy table([(80,0)-(20000,100)],(100,30),(400,45),(846,59),(1306,68.51),(2000,73),(3021,74.5),(5000,76),(9788,78),(20000,80))
Units: Year

Official exchange rate([(2001,0)-(2008,12)],(2001,8.60918),(2002.06,10.54),(2003,7.56475),(2004,6.45969),(2005,6.35933),(2006,6.77155),(2007,7.04536),(2008,8))
Units: rand/USD

PC real GDP= Real GDP/Total population
Units: rand/person/Year

Population[sex,newborn]= INTEG (Births[sex],
Initial population[sex,newborn])
Population[sex,age over 0]= INTEG (- Deaths[sex,age over 0] + Net Migration[sex,age over 0],Initial population[sex,age over 0])
Units: person

Population cohort shift[sex]= SHIFT IF TRUE(Population[sex, newborn], MODULO(Time,1)<TIME STEP/2, age 100, 1,0)

Units: person

Population growth rate= TREND(Total population,Time to measure pop growth,Initial population growth)
Units: dmnl/Year

Proportion of female babies= 0.525
Units: dmnl

Proportion using conscious control= 0.35
Units: dmnl

Relative disposable income= Relative disposable income table(Time)
Units: dmnl

Relative disposable income table([(2005,0)-(2050,2)],(2005,1),(2015,1.25),(2030,1.5),(2050,1.95))
Units: dmnl

Relative real GDP= Real GDP/Initial real GDP
Units: dmnl

Sexually active female[childbearing age]= Population[female,childbearing age]
Units: person

TIME STEP = 0.0625
Units: Year [0,?]

Time to measure pop growth=1
Units: Year

Total births= SUM(Births[sex!])
Units: person/Year

Total deaths= SUM(Deaths[sex!,age!])
Units: person/Year

Total fertility rate= Desired number of children*Proportion using conscious control +Unconsciously desired fertility * (1-Proportion using conscious control)
Units: dmnl

Total population= SUM(Population[sex!,age!])
Units: person

Total sexually active female= SUM(Sexually active female[childbearing age!])
Units: person

Unconsciously desired fertility= 3
Units: dmnl

****

Appendix D10. GDP sub-model equations

Average depreciation time= 20
Units: Year

Average life expectancy= (Life expectancy[female] +Life expectancy[male])/2
Units: Year

Capital= INTEG (Gross capital formation-Depreciation, Initial capital)
Units: rand

Capital share= 0.4
Units: dmnl

Depreciation= Capital/Average depreciation time
Units: rand/Year

Effect of life expectancy on tfp= Relative life expectancy^Elasticity of tfp to life expectancy
Units: dmnl

Elasticity of tfp to life expectancy= 0.08
Units: dmnl

Fraction not eligible for work= 0.2
Units: dmnl

Future biodiesel capacity investment= (Planned biodiesel investment table(Time)+Biodiesel supply line adjustment)*Capital cost per year
Units: rand/Year

Future biodiesel investment= Future biodiesel capacity investment
Units: rand/Year

GDP growth= SA GDP growth rate(Time)*SA GDP
Units: rand/Year

GDPdeflator([(2005,0)-(2050,2)],(2005,0.722004),(2006,0.67274),(2007,0.617246),(2008,0.556849),(2050,0.307018))
Units: dmnl

Gross capital formation= Total investment EC+Future biodiesel investment
Units: rand/Year

Initial capital= 1.08e+011
Units: rand

Initial labour force= INITIAL(Total labour force)
Units: person

Initial life expectancy= INITIAL(Average life expectancy)
Units: Year

Initial pc real GDP= INITIAL(PC real GDP)
Units: rand/person/Year

Initial real GDP= 4.85e+010
Units: rand/Year

Initial real GDP growth rate= 0.04
Units: dmnl/Year

Labour share= 0.6
Units: dmnl

Nominal gdp= Real GDP/GDPdeflator(Time)
Units: rand/Year

PC real GDP= Real GDP/Total population
Units: rand/person/Year

Population[sex,newborn]= INTEG (Births[sex],
Initial population[sex,newborn])
Population[sex,age over 0]= INTEG (Deaths[sex,age over 0] + Net Migration[sex,age over 0],Initial population[sex,age over 0])
Units: person

Proportion of investment in EC relative to SA= 0.06
Units: dmnl

Proportion of SA investment to GDP([(2005,0)-(2050,0.25)],(2005,0.1682),(2006,0.1858),(2007,0.2054),(2008,0.2218),(2050,0.25))
Units: dmnl

Real GDP= Relative production*Initial real GDP
Units: rand/Year

Real GDP growth rate= TREND(Real GDP,Time to measure GDP growth,Initial real GDP growth rate)
Units: dmnl/Year

Relative agriculture land=(Biodiesel crop land+Crop land+Livestock Land)/(Initial crop land+Initial livestock land)
Units: dmnl

Relative capital=Capital/Initial capital

Units: dmnl

Relative labour force=Total labour force/Initial labour force
Units: dmnl

Relative life expectancy= Average life expectancy/Initial life expectancy
Units: dmnl

Relative pc real GDP=PC real GDP/Initial pc real GDP
Units: dmnl

Relative production= Relative capital^Capital share*Relative labour force^Labour share*Relative agriculture land^(1-Capital share-Labour share) *Total factor productivity
Units: dmnl

Relative real GDP=Real GDP/Initial real GDP
Units: dmnl

SA GDP= INTEG (GDP growth,
1.13354e+012)
Units: rand

SA GDP growth rate(
[(2005,0)-(2050,0.06)],(2005,0.0432119),(2006,0.0436734),(2007,0.0435452),
(2008,0.0437844),(2009,0.0403202),(2010,0.0384596),(2011,0.035394),(2012,0.0315043
),(2013,0.029121),(2014,0.0278417),(2015,0.0260644),(2016,0.0228918),(2017,
0.022392),(2018,0.021578),(2019,0.0207438),(2020,0.0199879),(2021,0.0192773
),(2022,0.0185941),(2023,0.0178417),(2024,0.0171613),(2025,0.0165558),(2026
,0.0170135),(2027,0.0168133),(2028,0.0163238),(2029,0.015736),(2030,0.0150853
),(2031,0.014481),(2032,0.0138524),(2033,0.0133628),(2034,0.0127652),(2035,
0.0121268),(2036,0.0113177),(2037,0.0104594),(2038,0.00943253),(2039,0.00852035
),(2040,0.00765957),(2041,0.00694473),(2042,0.00629321),(2043,0.0058359),(2044
,0.00529943),(2045,0.00474541),(2046,0.00404085),(2047,0.00329255),(2048,0.00225055
),(2049,0.00136647),(2050,0.00054292))
Units: dmnl/Year

Time to adjust investment=1
Units: Year

Time to measure GDP growth=1
Units: Year

Total factor productivity=Effect of life expectancy on tfp
Units: dmnl

Total investment EC= (Proportion of investment in EC relative to SA*Total investment South Africa)/Time to adjust investment
Units: rand/Year

Total investment South Africa=Proportion of SA investment to GDP(Time)*SA GDP
Units: rand

Total labour force=SUM(Population[sex!,working age!])*(1-Fraction not eligible for work)
Units: person

Total population=SUM(Population[sex!,age!])
Units: person

****

Appendix D11. Community perception sub-model equations

Decreasing perception=(Fear*Perceived complexity*Perception of biodiesel crops benefits)/Time to change perception
Units: dmnl/Year

Effect of land availability on perception=Function effect of land availability on perception(Land availability ratio)
Units: dmnl

Effect of perception on land conversion= Function for effect of perception on land conversion(Perception of biodiesel crops benefits)
Units: dmnl

Fear= Function for effect of previous experience on fear(Previous experience)
Units: dmnl

Function effect of land availability on perception([(0,-0.6)-(1,0.25)],(0,0.2),(0.0428135,0.153474),(0.08,0.127237),(0.12844,0.102386),(0.201835,0.0777544),(0.3,0.055),(0.357798,0.0342105),(0.449541,0.00526316),(0.535168,-0.0322368),(0.64526,-0.115351),(0.782875,-0.249),(0.896024,-0.394956),(1,-0.5))
Units: dmnl

Function for effect of perception on land conversion([(0,0)-(2,1.5)],(0,0),(0.1,0),(0.25,0.05),(0.3,0.1),(0.4,0.2),(0.5,0.45),(0.75,0.85),(1,1),(2,1))
Units: dmnl

Function for effect of previous experience on fear([(0,0)-(1,1)],(0,0.995),(0.1,0.905),(0.2,0.795),(0.3,0.705),(0.4,0.595),(0.5,0.495),(0.6,0.395),(0.7,0.305),(0.8,0.205),(0.9,0.195),(1,0.19))
Units: dmnl

Function for effect of previous experience on perceived complexity([(0,0)-(1,1)],(0,0.995),(0.0795107,0.881579),(0.17737,0.754386),(0.272171,0.622807),

(0.333333,0.530702),(0.397554,0.434211),(0.504587,0.285088),(0.614679,0.179825),(0.761468,0.0877193),(0.874618,0.0482456),(1,0.001))
Units: dmnl

Increasing perception= ((Perception of biodiesel crops benefits*Effect of land availability on perception)/Time to change perception) *Previous experience
Units: dmnl/Year

Initial perception= 0.1
Units: dmnl

Land availability ratio= Biodiesel crop land/Maximum land availability for biodiesel crop
Units: dmnl

Perceived complexity= Function for effect of previous experience on perceived complexity(Previous experience)
Units: dmnl

Perception of biodiesel crops benefits= INTEG (Increasing perception-decreasing perception, Initial perception)
Units: dmnl

Previous experience= 1
Units: dmnl

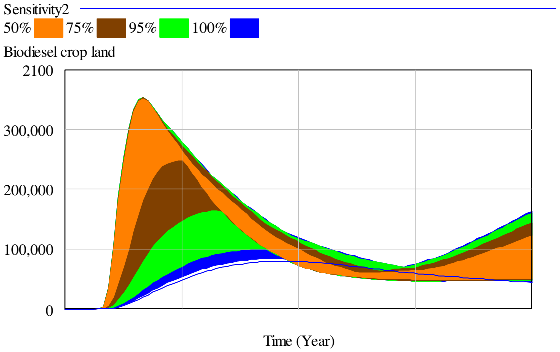
Time to change perception= 10
Units: Year

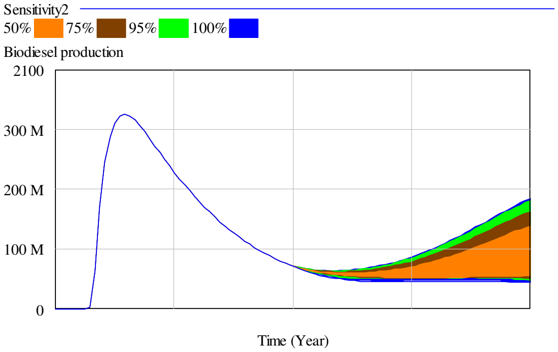
****

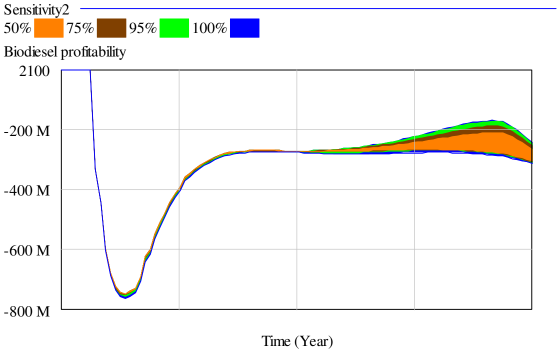
APPENDIX E: ADDITIONAL SENSITIVITY RESULTS

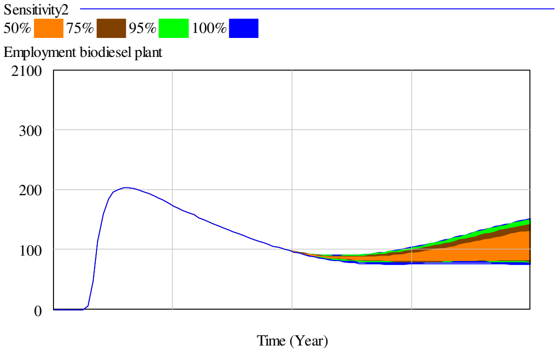
Appendix E1: Sensitivity of selected indicators to initial community perception

Parameter	Unit	Value	Range
Initial perception	Dimensionless	0.1	[0.1, 0.8]



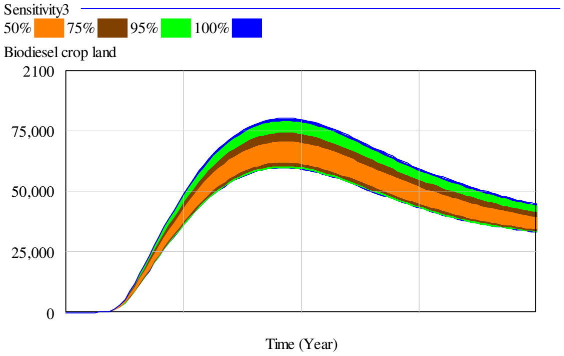


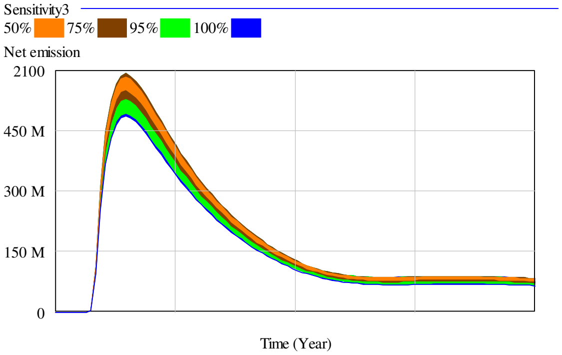




Appendix E2: Sensitivity of selected indicators to fertilizer use

Parameter	Unit	Value	Range
Fertilizer use switch	Dimensionless	0	[0, 1.5]





Appendix E3: Sensitivity of selected indicators to biodiesel support

Parameter	Unit	Value	Range
Support for biodiesel per litre	Rand/litre	0	[0, 8]