MEASURING THE SOCIAL COSTS OF COAL-BASED ELECTRICITY GENERATION IN SOUTH AFRICA

by

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DECLARATION

I declare that this thesis, I hereby submit for the degree of Doctor of Philosophy in Economics at the University of Pretoria is my own work and has not been submitted for a degree at this or any other university.

Signed: …………………………………………

Name: Nonophile Promise Nkambule

DEDICATION

I dedicate this thesis to the Almighty without whom I would have not made it and to Lindiwe Millicent Nkambule, my mother.

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ABSTRACT

Energy technologies interact with the economic, social and environmental systems, and do so not only directly but indirectly as well, through upstream and downstream processes. In addition, the interactions may produce positive and negative repercussions. To make informed decisions on the selection of energy technologies that assist a nation in reaping the socio-economic benefits of power generation technologies with minimal effects on the natural environment, energy technologies need to be understood in the light of the multifaceted system in which they function. But frequently, as disclosed by the literature review conducted in this research, the evaluation of energy technologies lacks clear benchmarks of appropriate assessments, which has resulted in difficulty to compare and to gauge the quality of various assessment practices. The assessment methods and tools tend to be discipline specific with little to no integrations. Parallel with the tools, the technology assessment studies offer piecemeal information that limits deeper understanding of energy technologies and their consequent socio-economic-environmental repercussions.

Improved energy technology assessment requires the use of a holistic and integrative approach that traverses the disciplinary nature of energy technology assessment tools, examines the long-term implications of technologies while at the same time embracing energy technologies' positive-and-negative interactions with the economic, social and environmental systems and in this manner offering economic, social and environmental indicators to assist decision makers in the decision-making process. Accordingly, this study focuses on improving the assessment of energy technologies through the application of a holistic and integrative approach, specifically system dynamics approach along a life-cycle viewpoint. Precisely,

focus is on coal-based electricity generation and in particular, the Kusile coal-fired power station near eMalahleni as a case study.

A COAL-based Power and Social Cost Assessment (COALPSCA) Model was developed for: (i) understanding coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent socio-economic, and environmental impacts over its lifetime and fuel cycle; (ii) aiding coal-based power developers with a useful tool with a clear interface and graphical outputs for detecting the main drivers of private and externality costs and sources of socio-environmental burdens in the system; (iii) aiding energy decision makers with a visual tool for making informed energy-supply decisions that takes into account the financial viability and the socio-environmental consequences of power generation technologies; and for (iv) understanding the impacts of various policy scenarios on the viability of coal-based power generation.

The validation of the COALPSCA Model was also conducted. Five structural validity tests were performed, namely structure verification, boundary adequacy, parameter verification, dimensional consistency and extreme condition tests. Behavioural validity was also conducted which included an analysis of the sensitivity of the model outcomes to key parameters such as the load factor, discount rate, private cost growth rates and damage cost growth rates using univariate and multivariate sensitivity analysis.

Finally, while attempts were made to incorporate most of the important aspects of power generation in a coal-fired power plant, not all intrinsic aspects were incorporated due to lack of data, gaps in knowledge and anticipated model complication. The shortcomings of the model were highlighted and recommendations for future research were made.

Key Words: system dynamics, coal-fired power plant, externality, social cost, private cost, externality cost, coal mine, plant construction, flue gas desulphurisation, economics

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ACRONYMS AND ABBREVIATIONS

AAIC	Anglo American Inyosi Coal
ATSE	Australian Academy of Technological Sciences and Engineering
BDFM	Business Day and Financial Mail
B-BBEE	Broad-Based Black Economic Empowerment
BNEF	Bloomberg New Energy Finance
BP	Beyond Petroleum
c	cents
CCS	Carbon Capture and Storage
CEEPA	Centre for Environmental Economics and Policy in Africa
CF	Capacity Factor
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalence
COALPSCA	COAL-based Power and Social Cost Assessment
CVM	Contingent Valuation Method
EIA	Environmental Impact Assessment
EPRI	Electric Power Research Institute
ESP	ElectroStatic Precipitator
ESPs	ElectroStatic Precipitators
etc.	et cetera
EU	European Union
FBC	Fluidized Bed Combustion
FGD	Flue Gas Desulphurisation
FMA	Financial Model Approach
FOB	Free On Board
FOR	Free On Rail
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWh	Gigawatt hour
IEA GHG	International Energy Agency Greenhouse Gas R&D Programme
IGCC	Integrated Gasification Combined Cycle
IOA	Input-Output Analysis

IPCC	International Panel on Climate Change
IRP	Integrated Resource Plan
IRR	Internal Rate of Return
kcal	kilocalorie
kg	kilogram
kt	kilotons
kWh	kilowatt hour
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCOE	Levelised Cost of Energy
LECOE	Levelised Externality Cost of Energy
LSCOE	Levelised Social Cost of Energy
LEAP	Long-range Energy and Alternatives Planning
MIRR	Modified Internal Rate of Return
MIT	Massachusetts Institute of Technology
MJ	Megajoule
Mt	Mega tons
MW	Megawatt
MWh	Megawatt hour
N_2O	Nitrous Oxide
NERSA	National Energy Regulator of South Africa
NO_2	Nitrogen Dioxide
NO_x	Oxide of Nitrogen
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
O&M	Operation and Maintenance
ORNL & RfF	Oak Ridge National Labouratory and Resources for the Future
PC	Pulverised Combustion
PE	Policy Engineering
PM	Particulate Matter
PPP	Public Private Partnership
R	Rand

ACRONYMS AND ABBREVIATIONS (CONTD.)

RB	Richards Bay
ROM	Run-Of-Mine
SCR	Selective Catalytic Reduction
SD	System Dynamics
sLCOE	simplified Levelised Cost of Energy
SNPV	Social Net Present Value
SO_2	Sulphur Dioxide
USEIA	United States Energy Information Administration
t	ton
T21	Threshold 21
UK	United Kingdom
US	United States
USAID	United States Agency International Development
VOLY	Value of a Life Year
W/	With
W/O	Without
WCA	World Coal Association
WTP	Willingess to Pay
ZAR	South African Rand
$	Dollars
%	Per cent
∂	Discount factor

CHAPTER 1:   INTRODUCTION

1.1   South Africa's economic development & environmental and development planning process

In the initial stages of economic development South Africa relied greatly on its rich mineral resources. Primary capital was mainly accumulated from the mining sector, out of which South Africa supported a strong manufacturing sector (Blignaut & Hassan, 2001). The contribution of mining to Gross Domestic Product (GDP) was about 13.2% in 1970 (South African Reserve Bank cited by Blignaut & Hassan, 2001) and, nowadays, the mining sector still remain the main stimulant behind the development of the country's economy, contributing about 8.8% to GDP. The sectors contribution is about 18% if one factor in the mining sector's indirect and induced effects (Chamber of Mines, 2012). With regards to the range of minerals and quantities produced, South Africa is one of the world's leading mining countries (Statistics South Africa, 2012) and its mineral industry is mainly based on coal, gold and platinum group metals.

Coal is South Africa's main source of energy, providing over 70% of its primary energy and 93% of its electricity (Department of Energy, 2010; World Coal Association (WCA) (2010). Owing to the development of the economy, and the fact that South Africa has not recently invested in augmenting its power generation supply capacity, the maximum production capacity of the existing power stations has been reached (Department of Energy, 2009). The South African government has planned energy projects, to augment its electric power supply reflected in its Integrated Resource Plan (IRP). The IRP investigates how South Africa's electricity demand can be met between 2010 and 2030. The plan include investing in various energy technologies including pulverised combustion plants, Fluidized Bed Combustion (FBC) plants, Integrated Gasification Combined Cycle (IGCC) plants, nuclear plants and renewable energy sources like solar and wind (IRP, 2011). On the other hand, Eskom, a utility owned by the state and that dominate the country's power industry, has begun constructing new two coal-fired power stations in an effort to meet the country's growing demand for electricity, namely the Kusile and Medupi power stations in eMalahleni and Limpopo, respectively (Eskom, 2011; Eskom, 2012a; Eskom. 2013a).

Generally, the environmental and development planning process in the form of an Environmental Impact Assessment (EIA) have been the main driver of project development in South Africa (Hoosen, 2010). EIA is a project-oriented environmental assessment tool for assessing the impacts of planned activities on the environment - the environment is broadly defined to include the economic, social and natural dimensions (Hugo, 2004; Southern African Institute for Environmental Assessment, 2004; Department of Environmental Affairs and Tourism (DEAT), 2008; Department of Environmental Affairs (DEA), 2010). The proper

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assessment of the ecological, economic and social effects of planned development projects is therefore a fundamental process of an EIA, which provides essential information to decision-makers on the potential impacts of planned projects and hence place them in a better position to make informed decisions on whether or not approval should be granted. EIA ensure that activities that are unacceptably damaging to the environment are not authorized and that those that are authorized are carried out in a way that the environmental impacts are minimized or mitigated to acceptable levels (DEAT, 2006a). It is therefore appreciated as a process for minimizing/mitigating the adverse impacts of development on the environment early in the design stages (Ministry of Environment and Tourism, 1997; Hoosen, 2010).

This study focuses on the energy sector and specifically on power generation developments, that is, on developments that are complex, that require multi-billion Rand investments and that are associated with diverse and long-lasting environmental and societal effects at some points in their fuel cycle (World Energy Council, 2004; Georgakellos, 2010). The following sections outline the history of the EIA process in South Africa, discuss EIA effectiveness and weaknesses, and reflect on possible solutions to selected EIA issues. Later on, the project-orientated manner of EIA shifts the direction of this background section to technology assessment owing to its broader scope. Following this route, a discussion of technology assessment concept, various types, functional elements, shortcomings and possible solutions is conducted. This information provides the foundation for framing the research problem and subsequent research objectives.

1.2   EIA regulation and process in South Africa

The EIA process in the country began on non-obligatory grounds in the 1970s. During this time it was undertaken out of free will as a component of Integrated Environmental Management. In September 1997, EIA became mandatory with the declaration of EIA regulations in the form of the Environment Conservation Act (ECA) of 1989 (South Africa, 1989, 1997a,b). The Act provided EIA procedures, which were incorporated into the regulation (Republic of South Africa, 1998). In addition, the 1997 EIA regulations were supplemented by EIA guidelines which charted the application for authorization and the steps of the EIA process (Department of Environmental Affairs and Tourism (DEAT), 1998).

The key steps of the EIA process included: the submission of application for authorization; screening; scoping report writing (which included a plan of study for EIA coupled with extensive public participation); Environmental Impact Report (EIR) preparation which included specialist reports, public involvement and draft environmental management plan; review of environmental impact report by the competent authority; decision making; and monitoring (Wood, 1999). Notable from the early regulation was the requirement for extensive public participation and comprehensive scoping for all projects. About 80% of

the proposed developments were therefore authorized on grounds of an extended scoping report (South Africa, 1997a), also referred to by Sandham, Siphugu and Tshivhandekano (2005) as the mini-EIA or beefed-up scoping report. Furthermore, a large number of development projects were subjected to a full EIA process (Hoosen, 2010). The compounded results of the 1997 EIA process was a lengthy and expensive administrative process (Sandham, van Heerden, Jones, Retief & Morrison-Saunders, 2013) which created bottlenecks in EIA authorization which were perceived to be retardation the country's development (Swanepoel, 2008).

In 2006, new EIA regulations were announced in terms of the National Environmental Management Act (NEMA) and they substituted the Environmental Conservation Act EIA regulations (DEAT, 2006a; South Africa, 2006). The 2006 regulation key changes comprised of the institution of time frames, extending developments that required EIA (e.g. mining), consideration of alternatives to a proposed development, provision for monitoring after authorization and separating the environmental assessment processes into basic and full assessments. The former is suited for developments characterized by minor environmental effects while the latter is undertaken for developments with potentially significant environmental impacts, for example activities characterized by high levels of pollution, land generation and waste generation (DEAT, 2006a; DEAT, 2006b; Kidd & Retief, 2009). Electricity generation and mining activities therefore fall under the full EIA process (Department of Environmental Affairs and Development Planning, 2006).

The assessment process in the new regulation is broadly separated into a basic assessment, scoping procedure and appeal procedure (DEAT, 2006a). Generally the main difference between the assessment process for a basic and full assessment is that a full EIA is subjected to a more detailed scoping assessment than a basic assessment, it requires an EIA and in addition it requires a submission of an application prior to the competent authority (DEAT, 2006a; Republic of South Africa, 2006). For the full assessment, upon submitting the application form and authorization of the scoping report and the EIA proposal, the Environmental Assessment Practitioner (EAP) proceeds with the EIA proposed study. The aim of the EIA is to address concerns raised in the course of scoping, to assess impacts, to determine impacts significance, to frame mitigation actions and to assess in comparative manner alternatives to the proposed activity (DEAT, 2006b; DEAT, 2006c). The new EIA regulation reduced the portion of full EIAs undertaken, quickened the completion of EIAs due to commenting period timeframes and eliminated EIA authorization backlogs (Swanepoel, 2008). With the aim of improving EIA effectiveness and efficiency, in 2010 the third set of EIA regulations became operative (Hildebrandt & Sandhamb, 2014).

1.3 EIA effectiveness and weaknesses

Ever since the initiation of EIA in the United States of America in 1970 and its successive adoption by various governments and environmental agencies around the world, its effectiveness has been a subject of interest to scholars and the EIA practice community (Christensen, Kornov & Nielsen, 2005; Retief & Chabalala, 2009; Heinma & Poder, 2010). The shared response by authorities to perceived poor EIA system performance is to adjust the governing legislation, for example, the appraisals of the Canadian and South African EIA systems (DEAT, 2006a; DEAT, 2008a; Standing Committee on Environment and Sustainable Development, 2011).

EIA effectiveness generally refers to two criteria, namely whether the EIA process achieves its objectives and a procedural criterion which pertains to level of conformity with procedural requirements (Cashmore, Gwilliam, Morgan, Cobb & Bond, 2004; Glasson, Therivel & Chadwick, 2005; Jay, Jones, Slinn & Wood, 2007). It is argued that though research has focused on the procedural side of EIA effectiveness, the evaluation of EIA effectiveness with regards to its goals is a better measure of EIA effectiveness (Cashmore et al. 2004; Jay et al., 2007). Since EIR holds project information in decision-making, it is commonly acknowledged that EIRs of poor quality contribute to EIA ineffectiveness (Wood, 2003; Glasson et al., 2005).

Many researchers have therefore evaluated the quality of EIRs in South Africa (Sandham et al., 2005; Van der Vyver, 2008; Mbhele, 2009; Hildebrandt & Sandhamb, 2014; Sandham, Carroll & Retief, 2010) and internationally (Androulidakis & Karakassis, 2005; Pinho, Maia & Monterrosa, 2007; Heinma & Poder, 2010; Jalava, Pasanen, Saalasti & Kuitunen, 2010) in an effort to gauge the effectiveness of the EIA process.

The literature in developed, developing and transitional economies over the world disclosed that the quality of EIAs and decisions involved had improved over the past half-century with improvement of EIA procedures, enhancement of EIA capacity, increased use of mitigation measures and the occasional non-execution of potentially environmental damaging undertakings that would otherwise would have been permitted (Barker and Wood, 1999; Canelas, Almansa, Merchan & Cifuentes, 2005; Lee, 2000; Jay et al, 2007; Polonen, Hokkanen & Jalava, 2010).

Despite the improvements of EIAs worldwide, the weaknesses usually faced relate to limited capacity of authorities, inadequate public participation, limited scope of impact assessments, poor consideration of project alternatives, impact prediction challenges, inadequate consideration of cumulative impacts and

inadequate follow-up monitoring (Barker and Wood, 1999; Gray and Edwards-Jones, 1999; Jay et al., 2007; Tzoumis, 2007; Kruopiene, Zidonienė & Dvorioniene, 2009; Peterson, 2010).

In South Africa researchers have highlighted more or less similar shortfalls, for instance insufficient public participation (DEAT, 2006a; Hoosen, 2010), lack of political will, for example EIA has been blamed for delaying construction by government officials, lack of skilled government officials to conduct EIR review (Sandham & Pretorius, 2008; Hildebrandt & Sandhamb, 2014), inconsistency in EIR review (DEAT, 2006a; Sandham & Pretorius, 2008), lack of a reference frame for EAP to adhere to (Sandham & Pretorius, 2008), inadequate use of assessment methodologies (Sandham et al., 2010; Sandham & Pretorius, 2008) and poor EIR report quality especially with regards to the provision of information pertaining to impact identification, impact magnitude prediction, impact significance assessment, project alternatives, mitigation measures and monitoring (Sandham et al., 2013). The study by Sandham et al. (2013) is in essence a comparative study of the quality of EIRs conducted under the 2006 and 1997 EIA regulation. 3 of the 7 EIRs under the 1997 EIA system and 8 of the 11 EIRs under the 2006 were planned developments by Eskom (Electricity Supply Commission). The reports were reviewed under four appraisal areas, namely: development description; local environment and baseline conditions; impact identification and evaluation; and, alternatives and mitigation. The more analytical tasks (i.e. impact identification and evaluation, and alternatives and mitigation) which form the basis for decision making performed poorly, along with monitoring.

Analogous analyses of the - South African mining industry EIRs (Sandham, Hoffmann & Retief, 2008), quality of EIRs of various developments in the North West province of South Africa (Sandham & Pretorius, 2008), and quality of EIRs in the context of biological pest control in the Limpopo province (Sandham et al., 2010), also disclosed generally satisfactory grades in descriptive and presentational areas of EIRs while impact identification, prediction and evaluation, and alternatives and mitigation measures remain weaker aspects of EIRs. Such poorer scores in the more analytical components of the EIRs are shared also internationally (Barker & Wood, 1999; Lee, 2000; Polonen et al., 2010; Barker & Jones, 2013).

Since the environment is defined widely in the NEMA (Aucamp, Woodborne, Perold, Bron & Aucamp, 2011; Du Pisani and Sandham, 2006) requiring an estimation of the nature and extent of the effects of the proposed project on the biophysical, economic, social and cultural facets of the environment (DEA, 2010; DEAT, 2008a,b; DEAT, 2006d), some researchers have focused on evaluating the quality of specific dimensions of the environment as opposed to the entire EIR quality discussed above. Focusing on the quality of social impact assessment (SIA) report as a component of EIA, Hildebrandt and Sandhamb (2014)

highlights weak SIA report quality particularly with regards to defining and identifying impacts, impact significance prediction, project alternatives and mitigation measures. The research findings by Hildebrandt and Sandhamb (2014) concur with the findings of Du Pisani and Sandham (2006) in South Africa and with those of Fisher (2011), Burdge (2003) and Glasson and Heaney (1993) who also found SIA or the treatment of socio-economic impact a poor component of EIA in the UK and the US.

Aucamp et al. (2011) and Du Pisani and Sandham (2006) highlighted that the EIA is strongly weighted to the biophysical environment while Kruger and Chapman (2005) noted that many EIRs do not consider socio-economic impacts of planned developments. Hoosen (2014) have noted that though the EIA regulations require an estimation of the nature and extent of the negative and positive effects of the planned project and identified alternatives on the various dimensions of the environment (DEA, 2010; DEAT, 2008a,b; DEAT, 2006d), it does not specify the criteria that needs to be used to estimate the effects.

Perdicoúlis and Glasson (2006) in a review of causal networks (i.e. the diagrammatic illustrations of interactions between elements and the designation of causality to those relations) use in EIA, disclosed that causal networks though they tie well with EIA as they are specially suited for making cause and effect relations explicit (European Commission, 1999a), soliciting where and how impacts arise (Glasson, 2001) and hence suited to fulfill specific principles of EIA conduct, for example transparency, integration and being systematic, their use in modern EIA practice is minimal, simplistic and dwindling. In their random sample of environmental impact statements they found zero count of causal networks use. Among the causal networks discussed in this study are cause-and-effect diagrams, tree diagrams, digraphs, flow diagrams and system dynamics (a discussion of these causal networks is provided in the following section). Perdicoúlis and Glasson (2006) findings concur with those of Wood, Glasson and Beker (2006) who also found the use of similar methods such as decision trees and flow charts in the region of 3% or lower in England and Wales. The scarcity of causal networks in EIA practice might explain the limitation of identifying, predicting, assessing and evaluating impacts in EIA highlighted in the above paragraphs.

On the other hand, Burdge (2003) notes that the economic evaluation of externalities do not feature in the assessment process while Roth and Ambs (2004), Icyk (2006) and Australian Academy of Technological Sciences and Engineering (ATSE), 2009) emphasize the importance of considering externality costs alongside financial costs in decision-making. In addition, since EIA is project-oriented, its narrow focus conceals the true life-cycle impacts associated with a proposed development. For example for a proposed coal-fired power station, a separate independent application will be submitted and additional independent ones will be submitted for other activities upstream or downstream of the power station (e.g. for the coal

mine(s) that will supply that power station, coal transportation and electricity transmission). Not investigating the entire fuel cycle of energy development projects conceals the true impacts and costs associated with energy technologies/sources and may lock a nation in a costly energy path, since power generating projects from any fuel source (e.g. coal, oil, gas, solar and hydropower) are costly activities involving multi-billion Rand investments and are associated with diverse and long-lasting environmental and societal effects at some points in their fuel cycle (World Energy Council, 2004; Georgakellos, 2010). The comprehensive assessment and full cost pricing of energy technologies supports the selection of best source of power from a perspective that accounts for environmental preservation, human health and economic feasibility (Roth & Ambs, 2004).

1.4   Possible suggestions to selected EIA issues

The scarcity of causal networks in EIA practice might explain the limitation of identifying, predicting, assessing and evaluating impacts in EIA highlighted in the previous section. Causal networks are specially good for making cause and effect relations explicit (European Commission, 1999a), soliciting how and from where impacts emanate (Glasson, 2001) and when the causal relationships convey quantitative information (equations) they become capable of numerical simulations, making possible forecasting and hence enhancing decision-making (Perdicoúlis & Glasson, 2006).

In their review of the typology of causal networks use in environmental impact assessment, Perdicoúlis and Glasson (2006) disclosed that causal networks though they are suited to fulfill specific principles of EIA practice like transparency, integration and being systematic, their use in modern EIA practice is simplistic, minimal and dwindling. Specifically the review consisted of: non-graphical expressions of causality in environmental impact assessment namely, (i) text and (ii) matrices; graphical expressions of causality (causal networks) in environmental impact assessment namely, (iii) digraphs/directed-graphs, (iv) cause-and-effect diagrams, (v) flow diagrams and (vi) tree diagrams; and causal networks beyond EIA, that is those in other professional/academic fields that can enhance EIA, for example, system dynamics. In the following paragraphs a brief discussion of the non-graphical expressions of causality in environmental impact assessment, causal networks in EIA and system dynamics is conducted to highlight the superior attributes that system dynamics can offer to enhance EIA practice.

(i) Text - gives considerable liberty when relating project and environmental elements and their interactions. However, text may result in misunderstanding/omissions owing to the complexity of EIA systems (Perdicoúlis & Glasson, 2006). (ii) Matrices – express causality by relating the effects of individual project actions in columns (e.g. construction) to individual environmental parameters in rows (e.g. to

whether or not construction causes noise, the duration of the interaction, probability of occurrence, reversibility, etc.). The shortcomings of impact matrices is that they permit the illustration and study of interactions between only two sets of data so consideration of third set of data (interactions between effects/impacts or indirect impacts) cannot easily be represented in the same matrix (Perdicoúlis & Glasson, 2006). This limitation can be overcome by representing the matrix in a (iii) digraph/directed-graph causal network. Digraphs are conceivably the easiest causal networks with elements represented by nodes and causality between elements represented by unidirectional arrows. The arrows may also incorporate the polarity (+/-) between the elements (Canter, 1996; Perdicoúlis & Glasson, 2006).

On the other hand, though (iv) cause-and-effect diagrams are digraphs their elements are specified in text form in different designs (commonly rectangles). Like in directed-graphs causality between elements is still marked by unidirectional arrows but without demonstrating link polarity. In addition, causal relationships generally convey no quantitative information so the diagrams are less rich in information. In EIA they are used for identifying and predicting impacts (Perdicoúlis & Glasson, 2006; Glasson et al., 2005; Glasson, 2001; European Commission, 1999a). In contrast to cause-and-effect graphs which trace activities and their effects, (v) flow diagrams trace movements of materials/energy. There exists various forms of flow diagrams but some are not causal (Perdicoúlis & Glasson, 2006; Glasson et al., 2005). Last but not least, (vi) tree diagrams resemble trees and may or may not be causal (Perdicoúlis & Glasson, 2006). There are various types of tree diagrams, for instance event trees which are employed towards studying development options concurrently (United Nations Environment Programme, 2002) and decision trees which are used for outlining actions and their effects, impact significance and delineate corresponding decision options (e.g. to draft mitigating measures or not) (Glasson et al., 2005).

System dynamics is a causal mathematical model that represents systems (for example the natural environment, economy, social and energy) and analyses how they behave over time (Sterman, 2000; Forrester, 1961). There are two fundamental types of diagrams in system dynamics namely, causal loop and stock-and-flow diagrams. The former are special digraphs (Sterman, 2000; Ford, 1999) that capture the structure of the system in a qualitative manner. The diagrams indicate cause and effect relations between the system variables, link polarity, feedback loops and delays – all being fundamental attributes of dynamic systems. Causal loop diagrams contain more information than typical digraphs, for example time delays and feedback loops (Perdicoúlis & Glasson, 2006).

Stock and flow diagrams are flow diagrams and they too reflect cause and effect relations (Perdicoúlis & Glasson, 2006) and unlike causal loop diagrams which illustrate the system structure qualitatively, they

capture the quantitative relationships between the variables of the system. The stocks/levels are denoted by rectangles and they show accumulations while the flow variables (i.e. inflow and outflow rates) are denoted by valves and they regulate changes in stocks (Jeong, Kim, Park, Lim, & Lee, 2008). There are two styles of expressing the equations in stock and flow diagrams namely, mathematics and chemistry styles (Perdicoúlis & Glasson, 2006):

Flora populations $= f$(Vegetation clearing)..Mathematics style

Surface mining $\rightarrow$ Vegetation clearing $\rightarrow$ Flora population...Chemistry style

The stock and flow diagrams therefore show in an explicit manner the relations between elements in the system both textually and mathematically. The diagrams are for this reason richer in information than the corresponding causal diagrams and are capable of numerical simulations (Jeong et al., 2008; Perdicoúlis & Glasson, 2006). The stock and flow diagrams permit simulations based on specified scenarios, for example scenarios characterized by project activities, system states and mitigation measures (Perdicoúlis & Glasson, 2006). System dynamics is therefore an experimental approach that can permit learning about development projects through "what if" analysis (Wolstenholme, 2003). It is also a flexible tool (Anand et al., 2005) that can work with numerous bottom-line facets (ecological, economic, social, energy, etc.) through its capability to model a widespread assortment of processes and relationships (Auerhahn, 2008), through decomposing the system into smaller, interacting sub-models that can be analyzed and integrated, keeping the mutual interactions among them. For this reason there is no restriction on what a system dynamics model can be designed to do. It has the capability to model complex problems in terms of flows, stocks, time delays and feedback loops at any level of aggregation, be it at company, industry, country, regional or global level and has capability to handle not only numerous variables but also innumerable units of measure with ease. Lastly, it permits the modeler to control the complexity or boundary of the model and hence the data needs. For instance, a simpler model can be built in the beginning and can be easily extended to address further questions. System dynamics can therefore offer superior attributes to enhance EIA practice.

While the employment of casual networks and specifically system dynamics in EIA practice may rectify the limitation of identifying, predicting, assessing and evaluating impacts, as well as permit transparency, integration and being systematic, the project-orientated manner of EIA, however, limit the scope of impact assessment and hence does not permit a comprehensive assessment of the life-cycle impacts and costs, a limitation that becomes more evident in the context of energy generation development projects due to the importance of fuel-cycle impacts and costs towards informing energy technology selection. For this reason

one could argue that EIA is not broad enough to enable sound energy technology (or power generation projects) assessment to inform policy-making. For this reason an exploration of technology assessment is conducted in the following section since it is broader than EIA. Berg (1994) and Brooks (1994) classify technology assessment into various types that illustrates its broader scope than EIA. The various forms of technology assessment are discussed later in the following section.

1.5   Technology and technology assessment

Technology is the science that deals with the construction and usage of technical artifacts and their interconnection with social, natural and economic environments (Grubler, 1998). Technologies are developed and shaped by social actors, social information (i.e. human skill, reason and techniques) and the economic system (Grubler, 1998). The production and use of technology in turn shapes the social, natural and economic environment (Berkhout & Goudson, 2003; Grubler, 1998). Technology and the social, economic and natural environments are therefore inseparable. The relation between technology and the social, economic and natural environment is, however, a complex one (Grubler, Nakicenovic & Nordhaus 2002). While technology development has the capability of stimulating economic growth (Berkhout & Goudson, 2003), providing societal benefits, improving efficiency of existing activities (i.e. affecting the production function of companies) (Andries, Janssen & Ostrom, 2004; Berkhout & Goudson, 2003), repairing/minimizing/reversing the negative environmental impacts of existing activities (Berkhout & Goudson, 2003), technologies are dependent on the natural environment for raw-materials/resources, their production, use and/or disposal impose negative effects on the natural environment and they depend on the natural environment for waste assimilation (Smith & Stirling, 2008). Technology is therefore fundamental to the well-functioning of economies and societies but needs to be managed to minimize negative impacts, and energy technologies[1] are no exception.

The energy sector has for a long time been driven by technological development (Sagar & Holdren, 2002). Energy technologies and the resultant energy/electricity they generate are essential to meeting basic human needs and for the advancement and development of economies (Ghosh, 2002; Ghader, Azadeh & Zahed, 2006; Vardar & Yumurtaci, 2010; Alter & Syed, 2011). However, aside from the beneficial consequences, energy technologies like all technologies generate undesirable effects in their production, use and/or disposal and in addition, electricity production from any fuel source (e.g. coal, oil, gas, solar and hydropower) also poses undesirable environmental and social effects at some points in its fuel cycle (World

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[1]Energy technologies are devices that produce or transmit or use energy, for instance power plants, boilers, automobiles, etc., and are characterized by various attributes, namely efficiencies, costs, benefits, emissions, etc. (Energy Technology Systems Analysis Program, 2007).

Energy Council, 2004; Georgakellos, 2010). Since energy technologies are not self-governing, their management is essential to enable the realization of the socio-economic benefits with minimal effects on the natural environment.

Technology assessment an imperative discipline in technology management is a strategic designing device for policy making regarding technologies. The concept was developed in the late 1960's at a time when the extensive application of technology began to visibly affect United States inhabitants (Tran, 2007). It was designed to support public policy decision-making by providing an understanding of the likely implications of the extensive expansion of currently in operation technologies or the introduction of new ones (Berloznik & Van Langenhove, 1998). It is therefore a policy study designed to offer decision makers with information regarding the implications of technologies (Coates, 2001; CEFIC, 1997). Its aim is to produce policy alternatives for answers to societal and organizational difficulties which at the practical level apply new technologies or modifies/alters existing technology.

Technology assessment focuses on direct and indirect effects (Coates, 2001; CEFIC, 1997) plus benefits and downsides (CEFIC, 1997). With awareness that technology schemes are rooted within the socio-economic-ecological system, technology assessment uses a theoretic structure that is determined by the three facets of sustainability namely, social, economic and ecological facets (Assefa & Frostell, 2006). The concept of technology assessment was as a result redefined as the evaluation with respect to sustainability of an object fashioned by social actors towards the realization of a goal (Eriksson & Frostell, 2001). Technology assessment enables therefore the assessment of a technology with respect to its supposed defined setting of operation and enables its comprehensive evaluation with reverence to sustainability and in contrast with other solutions yielding similar functions.

The concept is utilized in a number of organizational settings that vary widely in scope and depth (Assefa & Frostell, 2006) including government, industry, academia, research laboratories, power executives (Berloznik & Van Langenhove, 1998; Tran, 2007) and businesses (Berloznik & Van Langenhove, 1998; Tran & Daim, 2008). Through offering information aiding decision making technology assessment can be imperative in influencing improvement in existing technologies, adoption of new technologies, manufacture and purchase decisions and research direction (De Piante, 1997).

Various researchers/institutions distinguish among various forms of technology assessment. For instance, the Institute for Technology Assessment and Systems Analysis classified technology assessment into three types namely problem-induced, project-induced and technology-induced technology assessment (Berg,

1994) while Brooks (1994) distinguishes among five types of technology assessment namely, project, policy, generic, problem and global focused technology assessments. Generic oriented technology assessment examines generic technologies with no orientation to a specific project/place whereas project oriented technology assessment focuses on a concrete project. Problem oriented technology assessment studies an extensive problem area and explores a broad spectrum of technologies and non-technical alternatives towards managing the problem while policy assessment technology assessment is synonymous with problem oriented technology assessment with a greater consideration of technological measures to achieving social goals. Global oriented technology assessment focuses on a cluster of technical, economic, social and political problems affecting the entire globe. Technology assessment is therefore broader than EIA which is project- centered.

Armstrong and Harman (1980) categorized technology assessment into main functional elements namely: technology description and alternative projections – which include a description of the technology, establishing the boundary of the assessment and projection of technology alternatives; impact assessment – which include establishing the impact selection criteria and impact prediction, assessment, comparison and presentation; and policy analysis which involves the implementation of technology/alternatives and relating the assessment of impacts to the address of societies concerns (Durbin & Rapp, 1983; Armstrong and Harman, 1980).

1.6   Technology assessment shortcomings and solutions

Similar to environmental impact assessment which focuses on the impacts of planned development projects, technology assessment centers primarily on the impacts/consequences of a technology before the effects are with ease identifiable (Fleischer, Decker & Fiedeler, 2005). Likewise, policy-making requires an understanding of the potential effects of the institution of technologies before they are extensively applied. Proper assessment of the social, economic and ecological effects of planned developments that employ new technologies is therefore a fundamental process of technology assessment.

The embrace of economic, social and environmental indicators (i.e. sustainability indicators) can therefore be helpful in the evaluation of various developments or developments employing new technologies (Assefa & Frostell, 2006). But frequently, as disclosed by the literature review conducted in this research, the assessment of energy technologies lacks clear benchmarks of appropriate assessments, which has resulted in difficulty to compare and to gauge the quality of various assessment practices. The assessments methods and tools tend to be discipline specific with little to no integrations (Palm & Hansson, 2006). For example, the technology assessment tools are often categorized into financial analysis tools, externalities/impact

analysis tools, systems analysis tools, risk assessment and technical performance assessment (Short, Packey & Holt, 1995). As a result the literature is characterized by energy technology studies that exclusively assess these groupings with little/no integration and with variations in scope and depth. A few selected groupings of technology assessment tools plus examples of related studies are described briefly below:

- Financial analysis tools - financial analysis is essential to corporate decision makers as it entails comparing cash inflows and cash outflows of power generation developments and calculating the corresponding financial return ratios. Financial analysis is therefore an essential constituent of technology assessment but on its own it does not provide an all-inclusive assessment. Financial feasibility may be assessed using different kinds of metrics such as life cycle cost analysis, levelised cost of energy, cost effectiveness analysis, return on investment, net present value and breakeven point analysis (Short et al., 1995). Examples of local studies focusing on the private costs of various energy technologies include those by the Electric Power Research Institute (EPRI) (2010) and Mokheseng (2010);

- Externalities/impact analysis tools - externalities have been given many definitions and names in the literature (Sundquivist, 2000), but the implications of externalities are somewhat the same (Baumol & Oates, 1993). Generally, an externality occurs each time the production/consumption decisions of an agent affects the utility of another in an unintentional manner and when no compensation is made to the affected party by the producer of the undesirable effect. This definition follows the one of Baumol and Oates (1988), Cornes and Sandler (1986), Mishan (1969) and Perman, Ma, McGilvray and Common (1999). In the context of technologies, externalities are the unintended, non-compensated accompanying effects of a technology that are borne by a third party (e.g. society or the environment). Van Horen (1997), Spalding-Fecher and Matibe (2003) and Blignaut, Koch, Riekert, Inglesi-Lotz and Nkambule (2011) offer examples of studies focusing on externalities but with the shortcomings of emphasising the coal combustion phase and a subset of the coal-fuel cycle externalities mainly (e.g. climate change and human health impacts);

- Systems analysis tools - systems thinking analysis is an approach that looks at problems as parts of a whole system. It is centered on the understanding that a system can best be grasped by examining the linkages and interactions between its components and elements. In the viewpoint of technologies, system analysis offers a systems view to technology assessment that enables the assessment of technologies within their domain of operation (Crepea, 1995). There are a number of energy systems analysis models and they may be categorized into bottom-up and top-down energy approaches. Top-

down energy models, also called macroeconomic models, address the energy-economy feedback. The models describe the economic system in detail but they typically describe the energy system in an aggregated manner and as a subdivision of the whole economy. The technical potential of various energy technologies is thus not represented explicitly. Top-down modelers apply general equilibrium models or models that are demand prompted (Hodge et al., 2008). In contrast, bottom-up energy models study the energy system extensively but they do not consider the economic system in detail as in top-down models (Berglund & Soderholm, 2006). As emphasized by Grubler et al. (2002), bottom-up models normally aim at finding the minimum-cost mix of energy technologies serving a specified energy demand. For this reason the models are optimization models that minimize total discounted system cost (or maximize the income of energy systems) conditional on technological and environmental constraints (Kiviluoma & Meibom, 2009). Bottom-up models include the PERSEU, Balmorel, MARKAL and HOMER models.

The top-down and bottom-up energy systems models discussed above, offer piecemeal information that limits deeper understanding of energy technologies and their consequent economic, environmental and societal impacts. This is so, because the top-down models present the energy system as a black-box, by paying no attention to the processes and activities because the matrices used can only analyse a sector as a whole, and as a result differentiation between a range of products or production methods nor technologies is not possible (Weisser, 2007). In addition, environmental focus is on GHGs and the links between plant type/performance and environmental/societal burdens are hidden. The bottom-up models' shortcomings include that they are generally static models, with no feedback loops and time delays. In addition, they optimize for least cost in private terms not in social terms, and environmental focus is on GHGs. Local studies that employed top-down energy models include Pauw (2007) whereas bottom-up energy models have been used by Haw & Hughes (2007) and Winkler, Hughes, Marquard, Haw and Merven (2011).

In the light of the shortcomings of energy technology assessment studies and tools, there have been researchers who have advocated for the use of a holistic and integrated approach, specifically system dynamics approach for the assessment of energy technologies partly due to its capability to permit understanding of energy technologies in the domain of the multifaceted system wherein they are rooted, for example, it permit the study of energy technologies in relation to economic, environmental and social systems (Wolstenholme, 2003). As a special system analysis tool also recognized as a tool for energy technology assessment (Tran & Daim, 2008) system dynamics is special in that it has the supplementary ability to investigate dynamic cause and effect interactions and has the capability to model an extensive diversity of processes and relations in a dynamic manner (Auerhahn, 2008). Among other advantages of

such an approach that makes it suitable for energy technology assessment as stated by Wolstenholme are - its experimental nature that permits learning about the technology in question and its interaction with the sphere of its application through "what if" analysis; its support for collaboration between various stakeholders about the technology; and its support for the examination of the advantages and side effects of an energy technology. System dynamics is, however, not limited to energy analysis owing to its diverse application in various settings, for example in urban planning, economics, medicine, industrial engineering and management (Damle, 2003).

There are a number of system dynamics energy models, for example the Feedback-Rich Energy Economy model, which is a climate-economy model focusing solely on economy-climate interactions (Fiddaman, 1997), the Energy Transition model, which is a general disequilibrium model considering energy-economy interactions (Sterman, 1981) and the IDEAS model, which is a dynamic energy supply and demand policy simulation model of the United States (AES Corporation, 1993) which considers energy in isolation. Most recent applications of coal-related system dynamics models have been developed for the study of various issues, for example comparison of power generation cost (e.g. Jeong et al., 2008), forecasting coal demand, supply and reserves (e.g. Hou et al., 2009), modelling energy supply and demand (e.g. AES Corporation, 1993; Musango, Brent, & Tshangela in press), assessment of coal production environmental pollution loads (e.g. Hou et al., 2009; Yu & Wei, 2012), and GHG mitigation (e.g. Jeong et al., 2008; Saysel & Hekimoglu, 2010).

Often, however, the models provide a partial-view, for example the models were not tailored to specific-coal technologies, are not comprehensive in their assessment of fuel-cycle burdens to help inform energy technology selection (i.e. focus is on a single phase (usually power generation or coal mining) and on a subset of the coal-fuel cycles' undesirable side-effects (usually GHGs)), tend to be still discipline-specific and they tend not to address social cost. Roth and Ambs (2004) for instance, advocates the improvement of assessment practices through the employment of a full cost approach that encompasses not only the traditional costs incurred directly by power utilities (i.e. private costs) but costs incurred in the entire fuel cycle including the conventionally neglected externality cost (social cost = private costs + externality costs) (Roth & Ambs, 2004). According to Roth and Ambs the focus on private costs is unacceptable since it gives limited attention to indirect factors (e.g. environmental and societal burdens and costs) which are taken as exterior to the energy technology. Unless the externalities of electricity generation technologies are identified, quantified and monetized they continue to be unknown, playing no role in the selection of energy technologies (Australian Academy of Technological Sciences and Engineering (ATSE), 2009) and posing hindrance to efficient and sustainable allocation of resources (Icyk, 2006).

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In the light of the problems faced with evaluating energy technologies, the consequent need for formal comprehensive assessment methods to evaluate energy technologies, and the suggestions for improving the assessment of energy technologies as discussed above, this study focuses on improving the assessment of energy technologies through the application of a system dynamics approach along a life-cycle viewpoint, and specifically focuses on the Kusile coal-fired power station near eMalahleni in the Mpumalanga province of South Africa as a case study.

1.7   Problem statement

South Africa has a number of planned development projects, including energy projects with coal-based investments. Generally, the environmental and development planning process, in the form of an EIA have been the main driver of project development in the country (Hoosen, 2010). The analysis of the quality of EIRs, however, disclosed that amongst other issues, the more analytical components of the EIRs which form the basis for decision making are performed poorly for instance with regards to the provision of information pertaining to impact identification and assessment of key impacts (Sandham et al., 2008; Sandham & Pretorius, 2008; Sandham et al. 2013). Concerning the assessment of impacts various researchers have expressed inadequate use of assessment methodologies (Sandham et al., 2010; Sandham & Pretorius, 2008), for instance, causal networks despite their suitability to fulfill specific principles of EIA conduct like transparency, integration and being systematic (Perdicoúlis and Glasson, 2006; Wood et al., 2006). Other concerns pertains to: overemphasis on biophysical environment (Aucamp et al.,2011; Du Pisani & Sandham, 2006); limited consideration of socio-economic impacts of planned developments (Kruger & Chapman, 2005); no consideration of the economic value of externalities (Burdge, 2003) despite the importance of considering externality costs alongside financial costs in decision-making (ATSE, 2009; Icyk, 2006; Roth & Ambs, 2004).

While the employment of causal networks and specifically system dynamics in EIA practice may rectify the limitation of impact identification and the limited scope of impact assessment, as well as permit transparency, integration and being systematic, the narrow project-orientation of EIA, however, limit the scope of impact assessment and hence it hinders a comprehensive assessment of the life-cycle impacts and social costs of developments, a limitation that becomes more evident in the context of energy generation projects due to the importance of fuel-cycle impacts and social costs towards informing energy technology selection. For this reason one could argue that EIA is not broad enough to enable sound energy technology assessment to inform energy policy formulation and therefore an exploration of technology assessment was conducted since it is broader than EIA (Berg, 1994; Brooks, 1994).

The energy technology assessment tools and studies, however, are also not without weaknesses for instance they provide a partial view and partial analysis, respectively, to making informed decisions on the selection of energy technologies. The reason for this being that the assessment tools and methods tend to be discipline specific with little to no integrations, with tools often grouped into financial analysis tools, impact analysis tools, technical performance assessment and so on (Palm & Hansson, 2006), which has consequently resulted in energy technology studies that exclusively assess these groupings with little/no integration and with variations in scope and depth. Other concerns pertain to the none consideration of the economic evaluation of externalities and social costs (Roth & Ambs, 2004) as well as variations in scope and depth in the assessment of externalities (i.e. limited scope of impact assessment) which make comparing various energy development project involving (new) technologies difficult. For instance, the studies differ in terms of the types of externalities they consider, the fuel-cycle stage(s) they investigate, and they do not factor in the long-standing repercussions of the technologies on the environment and social systems.

These shortcomings highlight the lack of recognized technology assessment frameworks to support energy policy formulation in the field of environmental and development planning processes (i.e. in both technology assessment and as well as EIA) and therefore suggests the need for comprehensive assessment to help inform decision-making on energy developments. Wolstenholme (2003) have supported improving energy technology assessment through the use of a holistic and integrated approach, namely system dynamics due to its superior attributes while Roth and Ambs (2004) advocates the improvement of assessment practices through the measurement of not only the traditional costs incurred directly by power utilities but costs incurred in the entire fuel cycle including the conventionally neglected externality costs. This study therefore aspires to promote proper technology assessment at the extensive project level through improving the environmental and development planning processes by means of employing a systems approach, namely system dynamics due to its superior attributes and embedding it within the processes to account for the lifecycle and long-term economic, social and environmental repercussions and social costs of energy development projects. The current study specifically focuses on coal-based electricity generation as a case study.

In the light of this problem, this study advances the environmental and development planning practices (technology assessment/EIA) by contributing in terms of:

- The consideration of the economic value of externalities (Burdge, 2003) and social costs (Roth & Ambs, 2004) owing to the importance of considering externality costs alongside financial costs in decision-making (ATSE, 2009; Icyk, 2006; Roth & Ambs, 2004);

- The use of causal networks, specifically system dynamics to assess the environmental impacts of planned developments (specifically in this study to model the life-cycle impacts and social costs of energy generation projects/developments) due to its suitability to fulfill specific principles of EIA and energy technology practices such as transparency, integration and being systematic (Perdicoúlis and Glasson, 2006; Wood et al., 2006) as well as its ability to offer the numerous positive attributes that are suited for energy technology assessment that were highlighted earlier in this chapter and below, and later in chapter 3; and,

- Permitting a comprehensive assessment of the life-cycle and long-term impacts and social costs of energy generation projects/developments (Roth & Ambs, 2004), due to its importance towards informing energy technology selection.

1.8 Rationale for system dynamics approach and a life-cycle viewpoint

The system dynamics approach was found conducive to the assessment of the environmental impacts and social costs of power-generating technologies, because:

- It permits operation with numerous bottom-line facets through its capability to model an extensive diversity of processes and relations (Auerhahn, 2008), through decomposing the system into smaller, interacting sub-models that can be analyzed and integrated, keeping the mutual interactions among them). For this reason there is no restriction on what a system dynamics model can be designed to do;

- It permits the understanding of energy technologies in the domain of the multifaceted system in which they are rooted (Wolstenholme, 2003);

- It supports for the examination of the advantages and side effects of an energy technology (Wolstenholme, 2003);

- It has capability of modelling complex problems in terms of flows and stocks, feedback loops and time delays (Perdicoúlis & Glasson, 2006) at any level of aggregation, be it at company, industry, country, regional or global level;

- It is a flexible tool (Anand et al., 2005) that can accommodate socio-economic-ecological indicators that can assist decision-makers in the appraisal of energy technologies;

- It is an experimental approach that permits learning about the technology in question and its interaction with the sphere of its application through "what if" analysis (Wolstenholme, 2003), for

example it permit simulations based on specified scenarios, for example scenarios characterized by project activities, system states and mitigation measures (Perdicoúlis & Glasson, 2006);

- It has capability to handle not only numerous variables but also innumerable units of measure with ease (i.e. the measurement metric is not fixed like in general equilibrium models);

- It can be used in data poor problems, for instance, one can conceptualize and formulate a system dynamics model for an anticipated future planned system and, unlike in statistical models, one does not need time series data to drive the model. This is important in this study because the coal-fired power station that is being studied is currently under construction. It is, however, worth mentioning that system dynamics models can be used in conjunction with statistical models or other energy models; and,

- The tool permits the modeler to control the complexity or boundary of the model and hence the data needs. For instance, a simpler model can be built in the beginning and can be easily extended to address further questions.

Other advantages of system dynamics that favoured its use in this study include its offering of quick model design and simulation, in-built error checking capacities, various model outputs comprising diagrams, tables and graphs, extensive sensitivity analysis capabilities, conceptualization of a range of scenarios and effortless experimentation with model structure, parameters, data and outcomes.

On the other hand, a life-cycle viewpoint was deemed important owing to the environmental and social repercussions originating from the various stages of an energy technology's cycle. The approach is therefore opted for because it systematically assesses over the life cycle, all flows (e.g. materials, energy and environmental flows) that go into the investigated system from nature and those that flows out from the system to nature (Ampofo-Anti, 2008; Varun & Ravi, 2009). A life-cycle viewpoint can therefore limit the exclusion of important externalities. Since the approach delineates between the various phases of an energy technology, it is better suited to detecting the transference of impacts between life-cycle stages or between environmental media. It can also serve as a tool for identifying potential socio-economic-ecological improvements (Sherwani, Usmani & Varun, 2010), by this means yielding vital trade-offs information that can be beneficial to decision makers and managers.

1.9   Research objectives

The objectives of the present study are as follows:

- To understand the resource inputs, material requirements and private costs of building, operating and maintaining a coal-fired power station.

- To understand the coal-fuel cycle environmental and societal burdens and costs (coal fuel cycle phases considered: coal mining, coal transportation, plant construction, plant operation, and waste disposal).

- To develop and validate a system dynamics model for understanding coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and fuel cycle.

1.10 Organisation of thesis

The thesis is organized in eight chapters. This first chapter presents the research, research problem, research objectives and organization of the research. Chapter 2 presents the concept of externalities, coal-fuel cycle externalities and a review of the South African power and coal industry. Chapter 3 grounds the research conducted in this study within the economic discipline of study within which it falls and motivates the use of a systems approach by studying the links between system dynamics and the schools of economic thought that underpin this study. Chapter 4 presents a comprehensive survey of the different tools used by various researchers to evaluate power generation technologies and afterwards an analysis of the application of the tools in the power sector with a special focus on coal-based power generation applications. Chapter 5 discusses the strategy of inquiry and the methodological approach that was employed to achieve the study's objectives. Chapter 6 discusses and presents the COAL-based Power and Social Cost Assessment (COALPSCA) Model developed for understanding coal-based power generation and its interactions with resource inputs, material inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts. Chapter 7 presents the COALPSCA Model outcomes, discusses the validation of the model and evaluates the model outcomes under various policy scenarios. Chapter 8 summarises the findings of this study, highlights its limitations and makes recommendations for future research.

CHAPTER 2: EXTERNALITIES AND SOUTH AFRICA'S POWER AND COAL INDUSTRIES

2.1 Introduction

Before proceeding with the presentation of the thesis, it is imperative to provide background information on externalities and social cost, coal-fuel cycle externalities and the South African power and coal industries. This chapter begins by defining the concept of externalities which is followed by a discussion of the environmental and societal impacts linked with the coal-fuel cycle. The South African power industry is discussed in the third section. Special focus is given to Eskom's power stations, electricity sales, coal quality, emissions profile, coal supply and supply contracts. A discussion of the South African coal industry is provided in the fourth section. Focus is on the trends of coal production, consumption and prices. The country's main coal producers and consumers and as well as export coal consumers are also discussed. The fifth section summarises this chapter.

2.1 Externalities defined

Marshall (1890) was the first economist who dwelled on the concept of externalities, followed by his student Pigou (1920). Ever since these early days, economists have paid a great deal of attention to the concept of externalities. However, in the literature there are many definitions of externalities and in addition, externalities have been given many names, including external diseconomies/economies, external effects, adders, third party effects, and neighbourhood effects (Sundquivist, 2000), but nevertheless, the implications of externalities are somewhat the same though a definition that captures all the concept ramifications is regarded by some economists as difficult to provide (Baumol & Oates, 1993).

Generally, an externality occurs each time the production/consumption decisions of an agent affects the utility of another in an unintentional manner and when no compensation is made to the affected party by the producer of the undesirable effect. This definition follows the one of Baumol and Oates (1988), Cornes and Sandler (1986), Mishan (1969) and Perman, Ma, McGilvray and Common (1999). The definition thus states that an externality can occur in the production of a good or consumption of a good and the agents that receive the effect can be a producer, consumer, an individual or society at large, secondly, an externality can be a cost or benefit (Baumol & Oates, 1988), thirdly, the effects of an externality falls on a third party (Cornes & Sandler, 1986), fourthly, it is an unintentional action, so it does not include intentional actions by an agent or else it would be handled within the existing justice system (Mishan, 1969) and lastly,

it involves no compensation, hence it causes inefficiencies and misallocations of resources (Baumol & Oates, 1988)**.**

In order to understand the last point (i.e. that externalities cause inefficiencies and misallocation of resources) it is necessary to discuss externalities in the context of the framework of welfare economic theory. Welfare economics focus on the study of resource allocation and income distribution in an economy in such manner that an efficient state is achieved, a state whereby no individual can be bettered without making others worse-off (Pareto efficiency) (Mishan, 1960; Arrow & Scitovsky, 1969). Welfare economics is therefore concerned with testing the efficiency of economic activities in utilizing society's productive assets. It aims at attaining maximum social welfare.

There are a number of conditions under which social welfare maximisation becomes achievable, for example, the existence of perfect competition, free trade, etc. In the midst of these conditions, the necessary and sufficient condition is the presence of perfect competition. Economic efficiency in allocating resources is attained on the equality of marginal costs and prices. This marginal argument is broadened to incorporate the proposal that marginal social benefit must equate marginal social cost for social welfare maximisation (Ferguson, 1972).

Although the marginal conditions pictured in the establishment of social welfare maximisation are essential to society's welfare improvement, in the real world the conditions are hardly ever met, causing a deviation among social and private benefits and social and private costs. Various causal factors can contribute to the deviation of social and private costs, among which is the existence of externalities (others are, barriers to market entry and trade, poorly defined property rights, etc.). Because of the presence of externalities markets fail to achieve Pareto efficiency (i.e. causing an incident whereby the First Theorem of Welfare Economics fails to apply), hence a divergence between private and social costs.

For illustration purposes consider Firm A that operates in a competitive market. Assume that Firm A produces q quantities of output, at a cost of $c(q)$ (private cost) and sells its product at a market price of p. Firm $A's$ profit maximization problem then becomes: $\pi_A = \max_q pq - c(q)$. π_A is the profit for Firm A. Firm $A's$ equilibrium amount of output (q^*) is yielded by the first order conditions $p = c'(q^*)$ showing that Firm A should produce up to the point where price (p) equals marginal private cost (MPC) (i.e. the point denoted as X in Figure 4.1).

Now assume that the production of q units by Firm A also leads to the production of q units of pollution, i.e. an externality cost of pollution equal to $e(q)$. Hence from society's point of view, the q^* units produced by Firm A are too large, because Firm A only considered private costs in its optimization. Thereby, not taking into account the externality cost of pollution, it imposes on society. The efficient level of production for Firm A in society's view is that which internalises the externality cost. Hence, in order to internalise the externality cost of pollution, Firm A needs to incorporate the externality cost into its profit maximization problem, which then becomes: $\pi_A = \max_{q} pq - c(q) - e(q)$.

The efficient level of output for Firm A in the presence of externalities is yielded by the first order conditions $p = c'(q^e) + e'(q^e)$ showing that Firm A should produce at the point (point Z) where price equals the sum of marginal private cost and marginal externality cost, i.e. marginal social cost (MSC). q^e is the Pareto efficient output (see Figure 4.1). The summation of private and externality costs makes up the social cost of production (social cost = private costs + externality costs) (Pearce & Turner, 1990), which is also called the total economic cost (Kim, 2007).
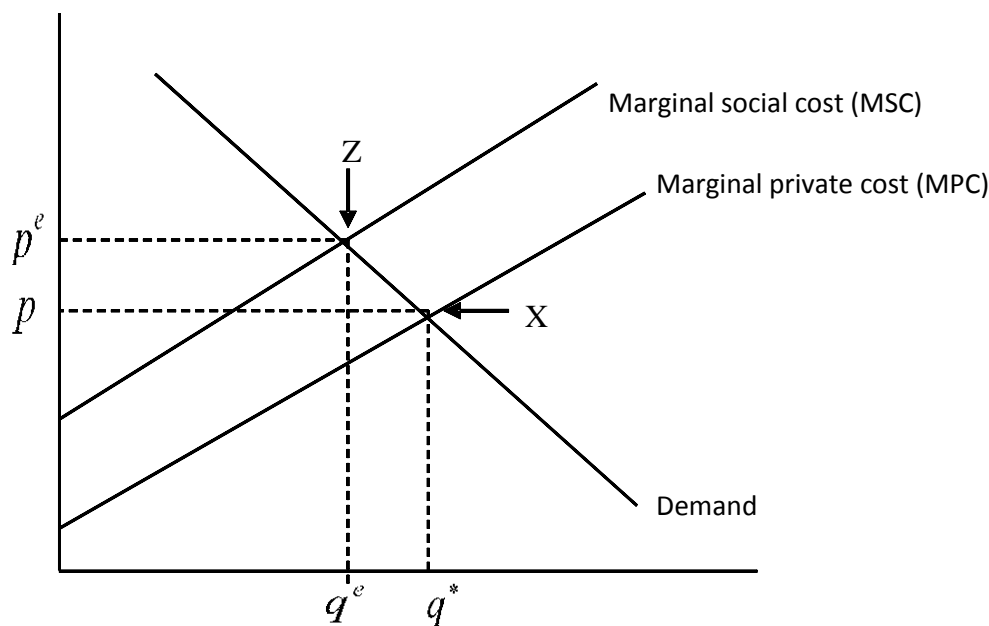
Figure 2.1: Externality costs of production

Source: Own construction

Thus, without internalising the externality cost of pollution produced by Firm A, Firm A only faces MPC and produces an output that is higher in the viewpoint of society $(q^* > q^e)$. Also the price faced when Firm A does not incorporate the externality is lower than when externality costs are incorporated $(p < p^e)$.

This therefore means that using a good without taking into account its social cost, results in resource misallocations because of producers' choice to produce a higher output level than is economically ideal. This higher rate of production translates into more rapid consumption of resources and even more pollution because as long as externality costs are not internalised, the incentive to produce less pollution does not exist, hence more and more pollution is produced since releasing it into the environment is cheap (Tietenberg, 1992).

Though highlighted that externalities need to be internalised, unregulated markets will not internalise externalities themselves, some kind of government intervention is needed. One way, according to Pigouvian teachings, is through taxing the producers of the externality an amount equivalent to the damages caused. Some economists recommend that focus should be on clarifying property rights instead of taxing and yet some favour other methods, such as user fees and tradable emission permit scheme (Energy Information Administration, 1995). To conclude, externalities cause market failure, which in turn leads to non-optimal resource allocation in society's view. So using a good without taking into account its social cost causes misallocation of resources. The externalities linked with the coal-fuel cycle are discussed next.

2.2 The environmental and societal impacts linked with the coal-fuel cycle

Table 2.1 below presents some of the environmental and societal impacts linked with the coal-fuel cycle. The environmental and societal impacts in Table 2.1 are externalities on condition they are negative unintentional consequences of an economic activity that are borne by a third party without or without-full compensation. In the table, the impacts have been broadly categorised into three main classes, namely coal mining and transportation impacts, plant construction impacts and plant operation impacts. Where necessary during the discussion, special reference is made to Kusile's impacts as discussed in the environmental impact assessment report (i.e. NINHAM SHAND, 2007).

Table 2.1: Coal-fuel cycle environmental and societal impacts

Activity	Bio-diversity	Air pollution	GHG	Damage to roads	Accidents	Noise	Water quality
Coal mining & transportation impacts							
Coal mining	✓	✓	✓		✓		✓
Beneficiation	✓						✓
Coal transportation	✓	✓	✓	✓	✓	✓	
Plant construction impacts							
Site preparation	✓	✓	✓	✓	✓	✓	✓
Materials production	✓	✓	✓	✓	✓	✓	✓
Materials transportation		✓	✓		✓	✓	
Construction					✓	✓	
Plant operation impacts							
Material inputs production	✓	✓	✓	✓	✓	✓	✓
Material inputs transportation		✓	✓	✓	✓	✓	
Raw material storage: coal, fuels, etc.	✓						✓
Coal combustion	✓	✓	✓		✓	✓	✓
Flue-gas clean-up: FGD	✓	✓	✓	✓		✓	✓
Ash & FGD waste disposal	✓	✓	✓	✓			✓

Source: Own construction

2.2.1.1 *Coal mining and transportation impacts*

Coal mining is linked with various societal and environmental hazards. It normally impacts the environment in the course of extraction, beneficiation and during coal transportation to a power plant (Mishra, 2009). The main impacts associated with coal mining and transportation include air pollution human health burdens, climate change impacts owing to GHG emissions, injuries and fatalities, water pollution and land-use linked impacts. Air pollution in coal mines stems mostly from emissions of particulate matter, underground fires, coal dust, burning discard dumps (Goldblatt et al., 2002) and methane (CH_4) emissions – a greenhouse gas emitted in the course of coal extraction at a time when coal seams are cut (National Research Council, 2009; Singh, 2008). The main operations producing gases and dust in mines are drilling, blasting, haulage, crushing and transportation. Opencast mines are associated with more air pollution than underground mines, due to that opencast mines create pollution within mining premises and beyond (Singh, 2008).

High incidences of deaths and accidents are linked with coal mining due to falling rocks, CH_4 explosions, material handling and as well as due to coal transporting accidents. Noise pollution is another problem in coal mines which causes problems such as hearing loss and pneumoconiosis (Goldblatt et al., 2002). The quality of water can also be affected by opencast mines by means of leachate from discard dumps, dirty mine water releases or acid mine drainage. Extensive land surfaces may also be disrupted by surface mines. Such mines may also displace people, erode the soil, and impact on local biodiversity through vegetation

cover removal which has the likelihood to negatively impact endangered plant species with subsequent effects on the faunas that use that habitat (NINHAM SHAND, 2007; Singh, 2008). Conversely underground mining may result in surface subsidence (Singh, 2008).

The cleaning of coal using wet cleaning methods may decrease the content of sulphur in coal but it also produces coal slurry which is discarded in slurry dams (Wassung, 2010). The dams are major water contaminant due to their susceptibility to collapse during heavy rains. A number of the coal processing chemicals are also acknowledged to be carcinogenic and to cause lung and heart damages (Epstein et al., 2011).

Coal transportation is also associated with various negative externalities, mainly in the forms of accidents, damage to roadways, air pollution, noise, global warming and congestion (Jorgensen, 2010). Among the classic air pollutants released during the transportation of coal are carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NOx), particulate matter ($PM_{2.5}$), hydrocarbons (HC), sulphur dioxide (SO_2) and lead (Pb). The ailments linked with these air pollutants comprise of lung cancer, bronchitis, lower respiratory illnesses, chronic respiratory disease and eye irritation. The GHGs linked with coal transportation comprise of carbon dioxide (CO_2), nitrous oxide (N_2O) and CH_4. Noise is also linked with coal transportation due to car alarms, road contact and engine noise. Related to accidents are occupational and non-occupational injuries, deaths, material damage and lost productivity (Gaffen et al., 2000). Coal transportation may aslo lead to roadways damage plus congestion (Jorgensen, 2010) while the construction of new roadways may impact on local biodiversity (NINHAM SHAND, 2007).

2.2.1.2   *Plant construction impacts*

Plant construction can be a very destructive operation resulting in a large number of negative externalities. Among the main impacts are biodiversity impacts and increased sediment loads on rivers and streams from the removal of vegetation cover to construct the plant and its ancillary infrastructure (NINHAM SHAND, 2007; US. Department of Energy, 2009). In the case of biodiversity, the removal of vegetation cover can alter the diversity of plants and animals in the study site and/or even impact endangered plant species, with negative impacts on the faunas that use that habitat. In the site in which Kusile is being constructed, there are a range of protected species amongst which are six endangered plant species plus a red data bird species. The overall significance of the impact of the construction phase on terrestrial and aquatic flora and fauna without and with mitigation measures in place has been deemed to be medium (negative) and low (negative), respectively due to the presence of protected species and little natural vegetation cover, owing to extensive agricultural activities in the site (NINHAM SHAND, 2007).

Specifically, though the proposed position of Kusile interconnects with a seasonal watercourse that runs into a river coupled with the occurrence of protected species in wetland communities, the effect of establishing the plant and its related infrastructure on terrestrial flora and fauna was deemed to be low (negative) without mitigation and very low (negative) with mitigation measures implemented (the proposed conveyor belt, pipeline and road placements crossed land largely dominated by agricultural undertakings so the impact was also deemed minimal). Concerning the effects of the power plant and its linked infrastructure on aquatic flora and fauna, the impact assessment results disclosed that the plants infrastructure (consisting of coal stockyard, dams, water and wastewater treatment structures) would directly impact the aquatic environment owing to being right on segments of the wetland and indirectly through loss of wetland services. Though the coal stockyard proposed location could not directly impact any wetlands the seepage from it could impact surrounding aquatic flora and fauna. The proposed layout of the surface infrastructure was deemed to reflect a low (negative) significance impact (NINHAM SHAND, 2007).

On the other hand, the establishment of roads, conveyors, railway line and pipelines were found to affect various wetlands systems with the overall significance of the impact deemed high (negative) owing to its high magnitude, long-term duration and local extent. Due to the proposed location of the above ash dump being in the middle of a high integrity wetland, it would have a direct effect on the aquatic environment coupled with an indirect effect through increased sediment levels owing to dust blown away from it. The ash dump is anticipated to have high (negative) significance impact without mitigation due to its long-term duration and high magnitude, and a very low (negative) significance impact with mitigation measures implemented. Overall the plants and its associated infrastructure layout could effect a low (negative) to very low (negative) impact on the aquatic environment without and with mitigation measures, respectively owing to that the site is generally characterized by low biodiversity, poor and degraded biotic integrity and no endangered aquatic species (NINHAM SHAND, 2007).

Air pollution can also become an issue during the construction phase due to fuel use in heavy machinery, which can, depending on the locality, have a negative effect on the water quality of open water bodies through the deposition of particulates and chemicals in the water (U.S. Department of Energy, 2009). Construction noise can become an issue contingent on the position of the plant, the operations being performed, the construction period and the size of the site (Bohlweki Environmental, 2006; NINHAM SHAND, 2007; Tech Environmental, 2009).

Other negative impacts include: visual effects from construction activities resulting from dust generation, construction equipment, vehicles and presence of workers (Bohlweki Environmental, 2006); negative impacts of construction activities on soils such as soil compaction which decrease aeration, porousness and water holding ability of soils which can increase surface overflow and possibly soil erosion (NINHAM SHAND, 2007); negative impacts linked with the transportation of material inputs necessary for the establishment of the power station - i.e. an activity that requires a number of trips per day leading to an increase in daily traffic volumes on road networks thereby resulting in negative externalities mainly in the forms of air pollution, global climate change, congestion, accidents, damage to roadways and noise (Jorgensen, 2010); and, indirect negative impacts linked with the production of material inputs (such as iron, steel, aluminium, cement, concrete and glass) and manufactured products such as boilers and turbines, which generates a range of negative impacts such as their contribution to global climate change, transportation related impacts and biodiversity impacts (Russell, 2008; InEnergy, 2010).

2.2.1.3   *Plant operation impacts*

The operation of a coal-based plant can also impact the biophysical and social environments in numerous ways (NINHAM SHAND, 2007). The impacts include the emissions of air pollutants such as particulates, SO_2, NO_X, CO_2, N_2O (nitrous oxide) and various trace metals from flue stacks. SO_2 and NO_X contribute to acid deposition, eventually leading to a wide range of environmental impacts, including damage to vegetation, soils, human health, animals and materials (Ma & Jin, 2010). Particulate matter coupled with SO_2, NOx and heavy metals are associated with harmful effect on the health of communities in vicinity to the power station. These air pollutants can also impacts negatively on the quality of water of open water bodies and subsequently aquatic flora and fauna through being deposited in water (U.S. Department of Energy, 2009). CO_2 and N_2O are GHGs released from coal-fired power stations and they contribute to the greenhouse effect as they trap long-wave radiation exiting the surface of the earth, leading to heating-up of the lower atmosphere of the earth, with variations in global/regional climates (Georgakellos, 2010), extended desertification and rising sea levels.

Also associated with the plant operation phase are occupational and non-occupational injuries and fatalities (Department of Minerals and Energy (DME), 2010; Eskom, 2011). Visibility can also be reduced due to particulates/dust generation from materials handling facility, ash-disposal facility and from flue stacks (Ma & Jin, 2010). Visual impairment can also emanate from power station infrastructure such as coal stockyard, ash dump and the power plant. Impact on ambient noise quality can become an issue contingent on the position of the plant, the operations being performed, and the size of the site (Bohlweki Environmental, 2006; NINHAM SHAND, 2007; Tech Environmental, 2009). Above ground ash dumps can

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directly and indirectly impact aquatic environment depending on the location of the ash dump. For example, directly through being sited in a middle of a high integrity wetland or near a river and indirectly through dust carried-away from the dump leading to increased sediment loads in aquatic systems, causing loss of habitat and decreased photosynthesis and physiological stress on organisms (NINHAM SHAND, 2007).

Groundwater can be contaminated through the use of process chemicals, acidic leachate emanating from the coal stockyard, run-off from the coal stockyard, permeation and run-off from dirty water dams, leakage and infiltration of liquid fuel and through runoff and seepage from the ash dumps. At the same time, groundwater levels can also increase owing to artificial renewal from dirty and clean water dams and through runoff from ash dumps and coal stockpiles (NINHAM SHAND, 2007). A range of impacts are aslo associated with electricity usage in the operation phase, for example electricity consumed by the plant itself and electricity used in conveyor belt to transport coal to the plant from the stockpile.

Link with power generation are also a range of indirect impacts connected with the production and transportation of material inputs that are necessary for the operation of the plant, such as limestone for SO_2 abatement in the FGD system which generates a range of upstream impacts such as emissions of GHGs, air pollution, biodiversity impacts, water quality impacts and transport-related impacts such accidents and damage to roadways (Singleton, 2010). On plants fitted with FGD devices, the plant operation phase will also generate a range of impacts linked with the operation of the FGD system. Generally, the impacts are as a result of increased effluent discharge, increased solid waste, increased water use, traffic and transport impacts, visual impacts, increased land-use and increased GHGs especially the principal gas CO_2 owing to a decrease in plant efficiency and also due to FGD chemistry (Singleton, 2010). The wet slurry from the FGD could have negative impacts on the aquatic environment should there be spillage, however, due to waste disposal minimum requirements in the case of Kusile, the significance of the effect is expected to be very low (negative) (NINHAM SHAND, 2007). The South African power industry is discussed next.

2.3   South Africa's power industry

The power industry in South Africa is dominated by Eskom, a utility owned by the state. The utility produces over 90% of the electric power needs of the country (Department of Energy, 2010). It was established in 1923 as the Electricity Supply Commission and by 2002 it was entirely owned by government. The National Energy Regulator of South Africa controls the utility's power prices. In 2011 Eskom burnt 124.7 million tons of coal. In the same period, 237 430 net Gigawatt hours (GWh) of electricity was produced by Eskom of which about 93% was produced from coal-fired power plants (220 219 net GWh) (Eskom, 2011). Total

Eskom electricity sales in 2011 amounted to 224 446 GWh, earning the utility a revenue of R90 375 million. Approximately 6% of the electricity produced was exported to neighbouring countries (Eskom, 2012a).

2.3.1   Eskom's power stations

The existing and future Eskom power stations are presented in Table 2.2. The utility runs 10 base load power stations which are mainly found in the Mpumalanga province. In addition, three power stations have been or are being returned to service in Mpumalanga. All 13 power stations use conventional pulverised-coal technology and are fitted with electrostatic precipitators in order to reduce particulate emissions. On average, the utility's power stations have a generation capacity of 3 400 Megawatt (MW) with a wet re-circulating cooling process and are fitted with precipitators to control dust (Wassung, 2010). Two new power stations are currently under construction, namely Kusile and Medupi power stations in the Witbank and Waterberg coalfields, respectively.

Converse to the conventional pulverised-coal technology used in Eskom's coal plants, the new plants will use supercritical technology (Eberhard, 2011). In a pulverised-coal power plant the coal is first crushed into a smooth-textured powder and then fed into a boiler where the coal is burned to create heat. The heat produces steam which is used to spin turbine(s) to generate electricity. Supercritical plants on the other hand, form part of the pulverised-coal system but use higher pressure and temperatures to boost the efficiency of the plant to about 40% or more (Bohlweki Environmental, 2006). The average thermal efficiencies of Eskom's pulverised-coal power plants were 32.6% in 2011 (Eskom, 2011) and 33.1% in 2010 (Eskom, 2010a). In addition, the new plants will use dry-cooling systems and have capacities above 4 700MW. The Kusile power station will be fitted upfront with a Flue Gas Desulphurisation (FGD) system to remove SO_2 from flue gas while the Medupi power station will initially not be fitted with an FGD system (Njobeni, 2010).

Table 2.2: Eskom's existing and future coal-fired power stations

	Plant name	Province	Capacity	Cooling system	Pollution control technology	Year
Base load	Arnot	Mpumalanga	2100 MW	Wet re-circulating	ESP	1975
	Duvha	Mpumalanga	3600 MW	Wet re-circulating	ESP	1984
	Hendrina	Mpumalanga	2000 MW	Wet re-circulating	ESP	1976
	Kendal	Mpumalanga	4116 MW	Indirect dry	ESP	1993
	Kriel	Mpumalanga	3000MW	Wet re-circulating	ESP	1979
	Lethabo	Free State	3708 MW	Wet re-circulating	ESP	1990
	Majuba	Mpumalanga	4110 MW	Wet re-circulating & dry	ESP	2001
	Matimba	Limpopo	3990 MW	Direct dry	ESP	1994
	Matla	Mpumalanga	3600 MW	Wet re-circulating	ESP	1983
	Tutuka	Mpumalanga	3654 MW	Wet re-circulating	ESP	1990
Return to service	Camden	Mpumalanga	1600 MW	Wet re-circulating	ESP	1973
	Grootvlei	Mpumalanga	1200 MW	Wet re-circulating & dry	ESP	1976
	Komati	Mpumalanga	1000 MW	Wet re-circulating	ESP	1968
New Build	Medupi	Limpopo	4788 MW	Direct dry	ESP	2015
	Kusile	Mpumalanga	4800 MW	Direct dry	ESP, FGD	2017

ESP = ElectroStatic Precipitator for controlling dust; FGD = Flue Gas Desulphurisation for controlling sulphur dioxide

Source: Adapted from Wassung (2010); Eskom (2013a)

2.3.2   Eskom's electricity sales

The state-owned utility distributes electricity to customers in the commercial, industrial, agricultural, mining and residential sectors, and to redistributors (municipalities). Direct electricity sales by Eskom during the 2010/2011 period are presented in Figure 2.2. Most of Eskom's electricity sales are to municipalities (about 41%), industry (about 27%) and the mining sector (about 14%). Electricity sales to commercial and agricultural, foreign, residential and rail sectors are low at 6%, 6%, 5% and 1%, respectively. About 84 000 agricultural customers, 4 million residential customers, 3 000 industrial customers, 49 000 commercial customers and about 1 000 mining customers are served directly by Eskom (Eskom, 2011).
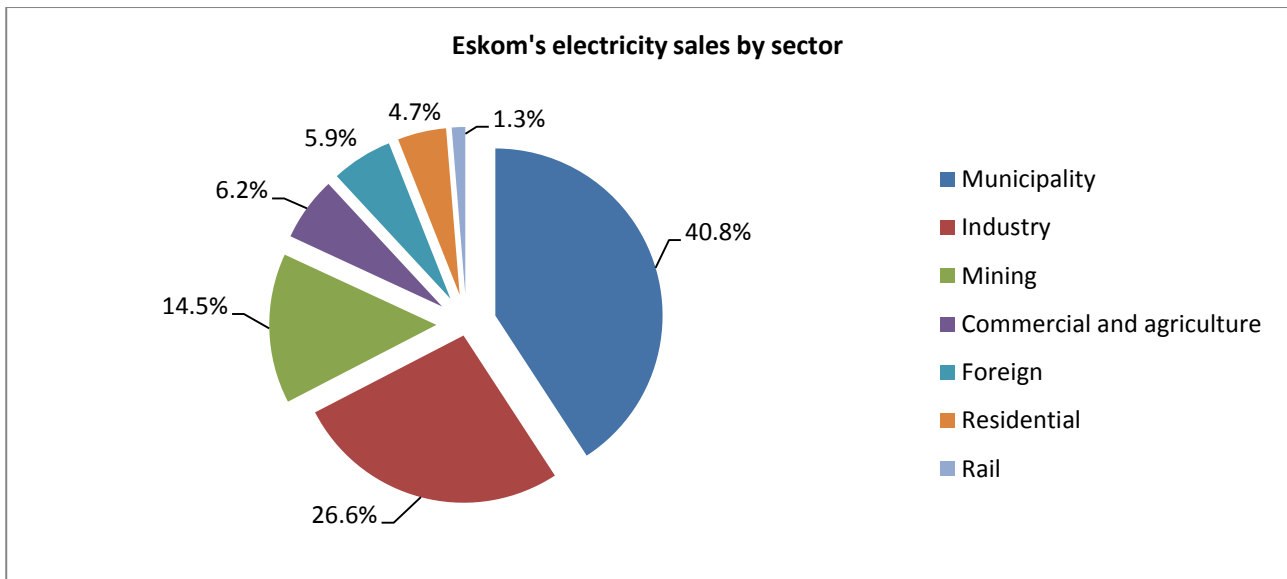
Figure 2.2: Eskom's electricity sales by sector 2010/11

Source: Adapted from Eskom (2011)

2.3.3   Coal quality and emissions profile of Eskom's coal-based plants

The thermal coals used by Eskom in the generation of domestic electrical energy are generally poor coals with a lower calorific value and high ash content. Table 2.3 below shows the quality of coal used and pollutants emitted by Eskom's power plants in the financial years 2006/07 to 2010/11. The table discloses that, in general, Eskom burns coals with an average calorific value of about 19 Megajoules/kilogram (MJ/kg), ash content of about 29% and sulphur content of about 0.80%.

In 2011, coal with an average ash content of 29.03% and an average calorific value of 19.45MJ/kg was burned in Eskom's plants while CO_2, SO_2 and N_2O emissions stood at 230.3 million tons, 1 810 kilotons and 2 906 tons, respectively. Particulates emissions were about 75.8 kilotons (Eskom, 2011). The coal supplied for power generation is mostly from screened run-of-mine (ROM) production while a third is sourced from coal middling from coal washing (run-of-the-mill). The coal quality received by the utility has, however, been worsening in recent years as higher grades are reserved for export market (Eberhard, 2011).

Table 2.3: Coal quality and emissions profile of Eskom's coal-fired power plants

Variable	Units	2006/2007	2007/08	2008/09	2009/2010	2010/11
Average calorific value	MJ/kg	19.06	18.51	19.10	19.22	19.45
Average ash content	%	29.70	29.09	29.70	29.56	29.03
Average sulphur content	%	0.86	0.87	0.83	0.81	0.78
Average thermal efficiency	%	33.9	33.4	33.4	33.1	32.6
Particulates	kt	46.08	50.84	55.64	88.27	75.84
SO_2	kt	1 876	1 950	1 874	1 856	1810
CO_2	Mt	208.9	223.6	221.7	224.7	230.3
N_2O	t	2 730	2 872	2 801	2 825	2 906
NO_x as NO_2	kt	930	984	957	959	977

Source: Adapted from Eskom (2011)

2.3.4 Eskom's coal supply methods and coal supply contracts

All of Eskom's mining is undertaken by private companies and the plants are mainly mine-mouth fed through conveyor belts, though road transportation is also becoming common. For instance, of the 126.23 million tons of coal purchased in 2011, 30.5 million tons were transported by road (Eskom, 2011), signifying that about a quarter of Eskom's coal is supplied through road transportation. The utility is thus exposed to short-term contracts which, in part, are spurred by the fact that the plants run at higher capacities than originally planned and also owing to some collieries failing to meet production expectations for power stations such as Tutuka and Majuba. The increasing reliance of Eskom on short-term contracts has up-surged the utility's average coal price but it is still much lower than international prices (Eberhard, 2011). Coal road supply has, however, impacted road infrastructure to such an extent that Eskom began financing the upkeep of roads. In addition, the increase in the number of road accidents and fatalities has prompted Eskom to invest in public safety awareness initiatives (Eskom, 2011).

Most of the collieries supply coal to Eskom plants through long-term coal contracts. Nine of the power plants are served through long-standing coal contracts. Three of these are fixed-price contracts while six are cost-plus contracts. Coal supply for the fixed-price contract is at a base price which is augmented using an assented formula. For the cost-plus contracts, the power utility and the coal contractor share the capital cost of establishing the mine, with Eskom additionally paying for the operation cost. The coal contractor then receives a net income from Eskom, based on the return on money invested by it. The return on capital invested consists of two components, namely a fixed component that is not based on coal production and a variable component that is based on coal supplied to Eskom. Future coal supply contracts, however, are envisaged to be fixed-price (indexed-priced) contracts since cost-plus arrangements discourage cost minimisation (Eberhard, 2011).

2.4   South Africa's coal industry

2.4.1   Coal production and consumption

Coal has been the backbone of the development of South Africa since 1870, when coal was first used in a Kimberley diamond mine. Since then, coal production rose to approximately 30 million tons in the 1950s and 115 million tons in 1980, following the oil crisis, rising international coal demand and soaring domestic electricity demand (Department of Energy, 2010; Statistics South Africa, 2010). It is estimated that coal production in 2011 stood at about 253 million tons, rendering the country the seventh major producer of coal globally. In the same year the country produced 3.3% of total global coal production (Beyond Petroleum (BP), 2012). If ROM production is considered, instead of saleable coal production, the country produced a total ROM of about 316.2 million tons in 2011, which is a decrease of 0.43% from the tonnes produced in 2010 (Department of Mineral Resources, 2012).

South Africa's saleable coal production and consumption between 2000 and 2011 is presented in Table 2.4 and Figure 2.3. Between 2000 and 2011, South Africa produced a total of about 2 901 million tons of coal. The country's coal production for 2011 (252.8 million tons) decreased by 1.7% from 257.8 million tons in 2010. Compared to approximately 115 million tons of coal produced in 1980, the country's 2011 coal production is roughly 120% higher. Figure 2.3 shows the general steady increase of the country's coal production since 2000.

A closer look at Table 2.4, and more explicitly Figure 2.3, discloses that approximately two thirds of the coal produced in the country is consumed locally while about one third is exported. In 2011, approximately 178 million tons of coal was consumed locally while about 69 million tons were exported. Local coal consumption tonnage in 2011 decreased by 4.7% from 2010, while coal exports in 2011 increased by about 3% from 2010. The domestic consumption of about 178 million tons makes South Africa the fifth major domestic consumer of coal in the globe after China, US (United States), India and Russia (BP, 2012).

Table 2.4: South Africa's historic coal production and consumption (tonx10^6)

Year	Total production	Local consumption	Exports
2000	224.1	154.6	69.9
2001	223.5	152.2	69.2
2002	220.2	157.6	69.2
2003	239.3	168	71.5
2004	242.8	178.3	67.9
2005	245	173.4	71.4
2006	244.8	177	68.7
2007	247.7	182.8	67.7
2008	252.7	197	60.6
2009	250.6	184.7	60.5
2010	257.2	186.4	66.8
2011	252.8	177.7	68.8
Total	**2900.7**	**2089.7**	**812.2**

Source: Adapted from Department of Mineral Resources (2012)
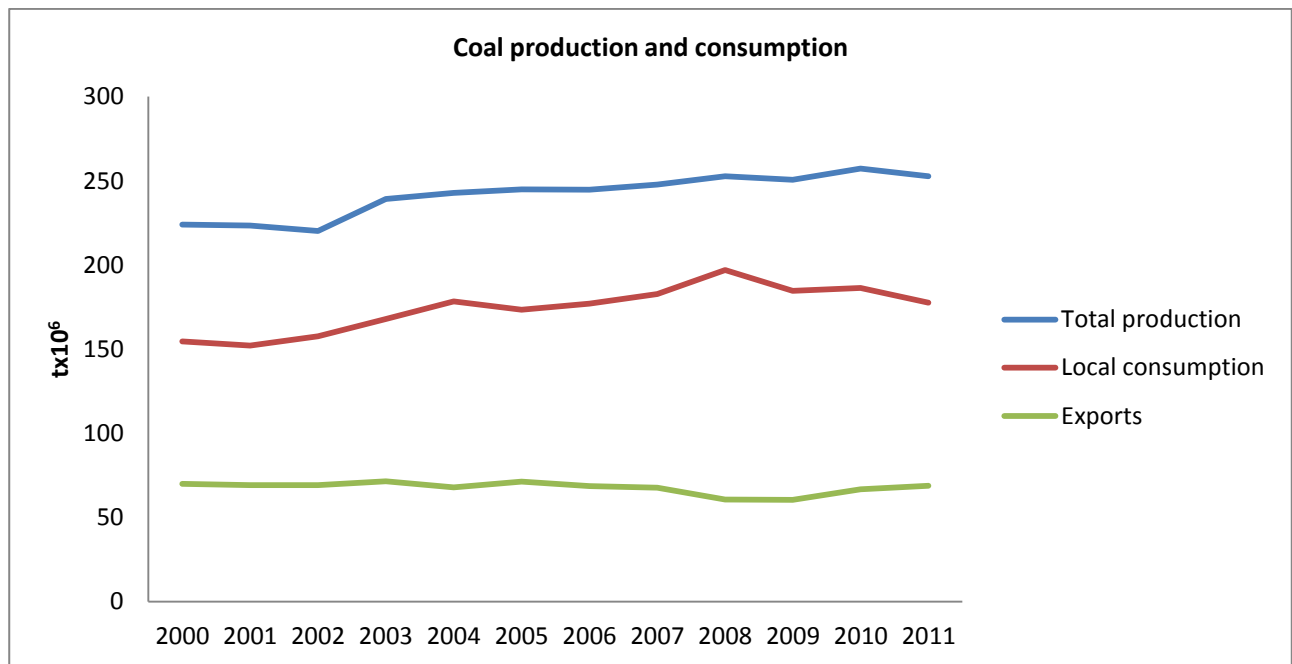
Figure 2.3: SA's historic coal production and consumption (tx10^6)

Source: Adapted from Department of Mineral Resources (2012)

2.4.2   Coal prices

Table 2.5 and Figure 2.4 show the trajectory of local and export sale prices in the past decade. The domestic coal sale price (Free on rail – FOR) increased by 16% from R181 per ton (2010) to R210 per ton (2011), yielding a higher domestic sale revenue of R37.3 billion in 2011 despite the 4.7% decrease in local coal sales between 2010 and 2011. A higher export sale tonnage of approximately 3% between 2010 and 2011, coupled with an export sale price (Free on board – FOB) surge of 31% between 2010 and 2011 (i.e.

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from R561 to R735 per ton), explains the higher export sale revenue of R50.5 billion in 2011. Figure 2.4 further shows the price of exported coal to be very unstable compared to the domestic price of coal.

However, a correction was made to the coal prices for differentials in calorific values. Eskom, for instance, burns coal with a calorific value ranging between 17 and 22MJ/kg (Chamber of Mines, 2011) while export coal, on the other hand, is generally washed and is characterized by high heating values ranging between 24.7 and 26MJ/kg (Eberhard, 2011). The average domestic calorific value was calculated to be 19.5MJ/kg (17–22MJ/kg) while the export calorific value was calculated to be 25.35MJ/kg (24.7–26MJ/kg). This yielded an adjustment factor of 0.769231 (i.e. 19.5MJ/kg ÷ 25.35MJ/kg) which was used to adjust the export coal price. Column C in Table 2.5 shows the adjusted export coal price while Column D shows the price ratio (i.e. adjusted export coal price ÷ domestic coal price). Comparing the domestic coal price (Column A) to the adjusted export coal price (Column C), it becomes evident that the domestic price of coal is lower (by a great margin) than the export coal price with a similar calorific value.

For 2011, for example, the domestic coal price was R210/t while export coal with the same calorific value as domestic coal, would have been sold for R565/t. Domestic miners receive lower returns per ton of coal from serving the domestic market than serving the export market. The price ratio in Column D shows that on average between 2000 and 2011, the price of domestic coal with a calorific value of 19.5MJ/kg was three times lower than that of export coal with a similar calorific value. In 2011, domestic miners supplying the export market received 207% higher returns per ton of coal than domestic miners supplying the domestic market. Coal investors and producers thus have an incentive to supply the export coal market rather than to feed the domestic coal market. Nonetheless, the country's old and inefficient rail infrastructure presents a major hurdle to supplying the export market.

Table 2.5: SA's historic coal price with and without adjustment (R/ton)

Year	Local price – FOR (A)	Export price – FOB (B)	Adjusted export price[1] (C)	Price ratio (D = C/A)
2000	57	160	123	2.2
2001	63	245	188	3.0
2002	75	280	215	2.9
2003	79	189	145	1.8
2004	76	213	164	2.2
2005	86	296	228	2.6
2006	92	316	243	2.6
2007	108	361	278	2.6
2008	153	737	567	3.7
2009	187	512	394	2.1
2010	181	561	432	2.4
2011	210	735	565	2.7
Average	**114**	**384**	**295**	**3**

[1]Export coal price adjusted for differences in calorific values between domestic and export coal

Source: Adapted from Department of Mineral Resources (2012)
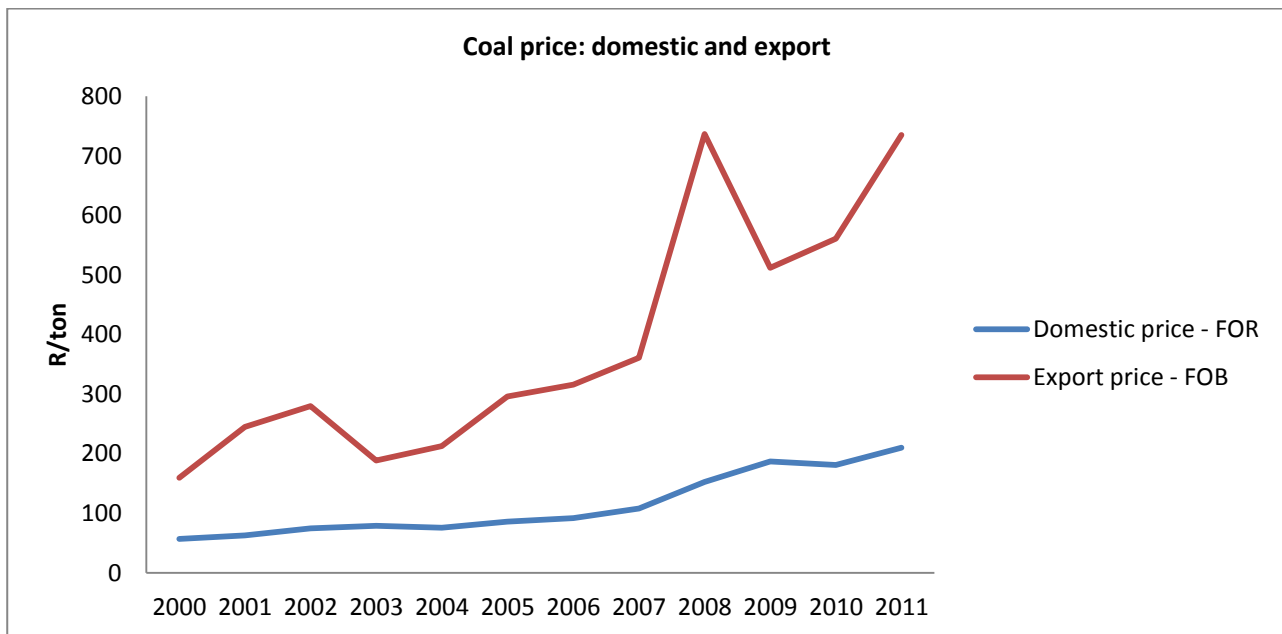
Figure 2.4: Domestic and export coal prices in R/ton (not adjusted)

Source: Adapted from Department of Mineral Resources (2012)

2.4.3   Domestic coal consumers

Domestic coal is used by various users, amongst others, Eskom's use of coal for electricity generation, coal use by Sasol in its coal-to-liquid-fuel plants and the use of coal by small merchants (supplying residential users and small businesses), metallurgical industries and other industries. Of the 177.7 million ton of coal consumed in South Africa in 2011, electricity generation consumed almost two thirds of domestic coal sales

(65.5%), followed by the synthetic fuel sector at 22.6%, industries at 5.2%, metallurgical at 3.1%, merchants and domestic sector at 3%, mining at 0.2% and others at 0.4% (Department of Mineral Resources, 2012). See Figure 2.5 below.
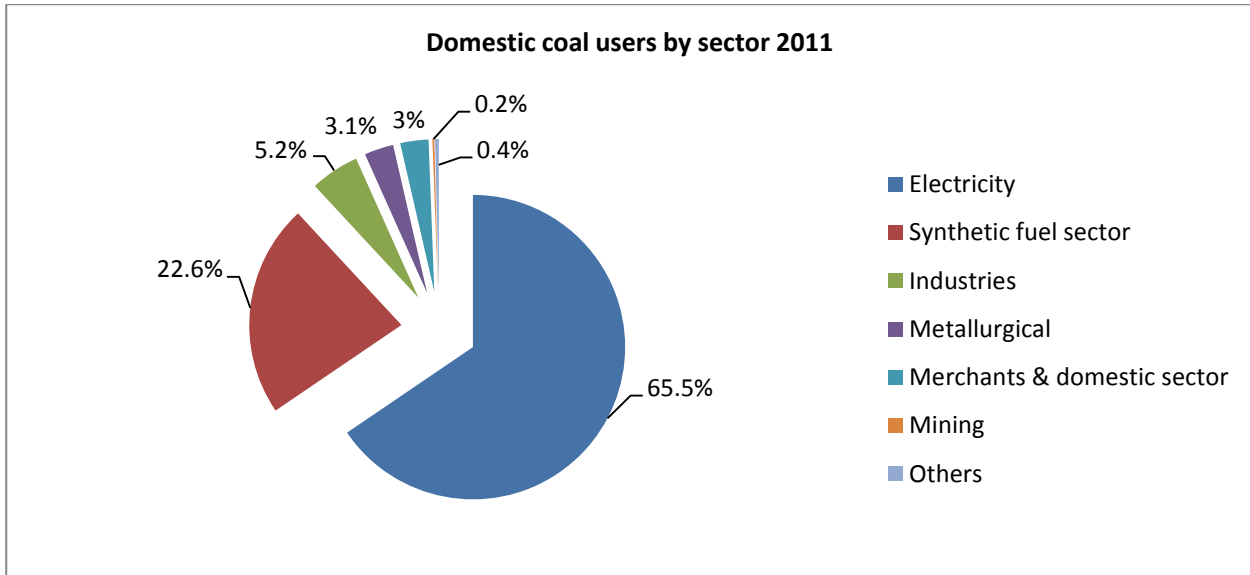
Figure 2.5: SA's domestic coal users by sector 2011

Source: Adapted from Department of Mineral Resources (2012)

2.4.4   Export coal consumers

South Africa exports coal to a number of regions, including Asia, Europe, the Middle East, Latin America, Islands and Africa. Among the Asian countries, the main customers are India and China, while European exports go to countries like Germany, Belgium, Switzerland, France and The Netherlands. The Middle Eastern customers include Israel, United Arab Emirates and Turkey, while in Africa coal is exported to Mozambique and Morocco, among other countries. Island customers include Mauritius and Latin American customers include Brazil, Mexico and Chile (Eberhard, 2011; Department of Mineral Resources, 2012). Figure 2.6 presents the country's export coal sales by region in 2011.

Export coal sales by region 2011
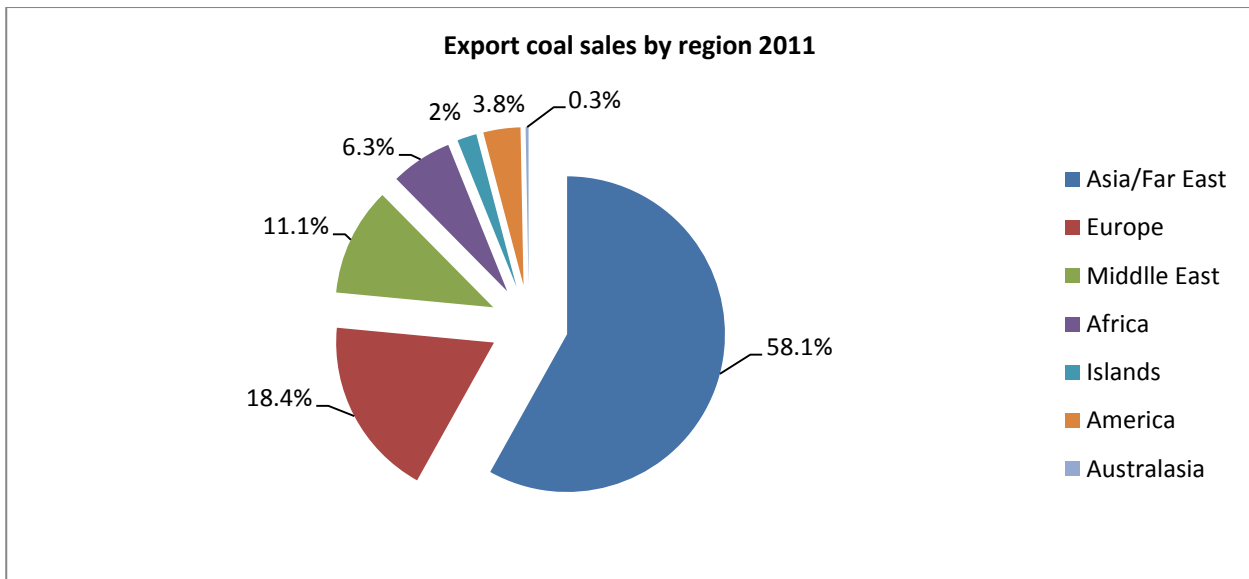
Figure 2.6: South Africa's coal export sales by region 2011

Source: Adapted from Eberhard (2011); Department of Mineral Resources (2012)

Of the 68.8 million tons of coal exported in 2011, the Asian market consumed the most (58.1%), followed by the European market (18.4%), the Middle East (11.1%), Africa (6.3%) and the Islands (2%). The Asian market is South Africa's largest coal importer. India was the leading customer in 2011, importing 25.2% of South Africa's coal, followed by China with 17.8%. The Middle East increased its coal imports in 2011, doubling its 2010 volume. Mozambique became the main importer of South Africa's coal in Africa, importing 5.3% in 2011 (Department of Mineral Resources, 2012). Coal exports to Europe have been decreasing since 2005, from a high of three-quarters of the country's exports in 2005 to below half in 2009. Colombia and Russia are South Africa's competitors in the European markets (Eberhard, 2011).

While there are various export coal products in South Africa, export coal is broadly classified into RB1 and RB2 (RB = Richards Bay) coal specifications. These specifications generally refer to an A grade product with an ash content of 15% and a calorific value of 6 000kcal/kg. RB1 and RB2 differ mainly with regard to their volatile matter. For an RB1 specification, volatile matter has to be a minimum of 22% on an as-received basis, while for RB2, volatile matter has to be a minimum of 25%. In South Africa, higher coal grades are generally reserved for the export market. A higher calorific value and lower ash content constitutes a higher grade of coal (Steyn & Minnitt, 2010). The export coal is washed, an activity that has guaranteed a homogeneous product and has earned South Africa a good reputation in the international coal market (Eberhard, 2011).

While South Africa's coal sales to Europe have been decreasing, the country's coal sales to Asia have been increasing. The country's competitors in the Asian markets are Indonesia and Australia. Although export coal in South Africa is generally characterized by high heating values ranging between 24.7MJ/kg and 26MJ/kg (Eberhard, 2011) with a maximum ash content of no more than 20% (Chamber of Mines, 2011), China imports low grade coal from South Africa. Although China is proposing to impose an import ban of low grade coal in order to curb pollution and favour local coal mines, it has faced fierce protest from power utilities (Business Day and Financial Mail (BDFM) Publishers, 2013a). In 2012, South African coal exports to China surpassed those of India and it is forecasted that South Africa and Australia are likely to surpass Indonesia as the leading primary coal provider to China (Mineweb, 2013).

In South Africa in the past, low grade coal (i.e. coal with a calorific value of 17–22MJ/kg) was used only by Eskom to fuel its power stations. Recently though, low grade coal has become a contested commodity. No longer is it for the exclusive use of Eskom to fuel its power stations, but it is also exported to China and sold at export parity prices (Uninterruptible Power Supplies Direct, 2012). The emergence of export markets for Eskom-grade coal, coupled with other issues such as underinvestment in new capacity in the coal industry, have caused a high level of uncertainty on future domestic coal prices (Creamer Media, 2013). The domestic coal market faces migration of domestic prices to export parity price levels. Although Eskom purchases most of its coal through long-term contracts (cost-plus and fixed-cost contracts) (Eberhard, 2011), which basically means that most of its coal requirements are secured, the amount of coal acquired by Eskom through short-term contracts has been rising over the years due to underperformance of its cost-plus mines (Creamer Media, 2013). In addition, securing long-term coal supplies has been reported as a problem for Eskom (Uninterruptible Power Supplies Direct, 2012).

Coal acquired through short-term contracts was 17% in 2007, and rose to 30% in 2011. Currently, the utility acquires approximately 30 million tons of coal through short-term contracts (Creamer Media, 2013) while burning about 124.7 million tons of coal (Eskom, 2011). It is further forecasted that coal shortages of about 40 million tons per annum will be forthcoming after 2018 (Creamer Media, 2013), an incident that is likely going to cause coal prices to soar tremendously.

2.4.5   South Africa's coal producers

In South Africa only private companies conduct coal mining. The coal is mainly positioned in thick level seams at low depths, making its extraction easier and relatively cheaper. It is, however, for the most part low-quality coal with high ash content (Department of Energy, 2010). Almost half the coal harvested in South Africa is mined from opencast mines while the rest is harvested through underground mining

methods. Of the country's ROM production of about 316.2 million tons in 2011, opencast mining contributed the highest (at 61.9%), followed by board-and-pillar mining (at 33.9%) while long-wall and stopping mining each accounted for 2.1% (Department of Mineral Resources, 2012).

The active coal mines in South Africa are shown in Figure 2.7 and most of them are located in the Mpumalanga province (Statistics South Africa, 2010). The Mpumalanga Central basin – a basin consisting of three coalfields, namely Witbank, Highveld and Ermelo coalfields – accounted for 83.3% of the country's total production in 2011. The Witbank, Highveld and Sasol-Vereeniging coalfields together accounted for 89.4% of total production. The Witbank coalfield produced the highest tonnage (52.3% of total production), followed by the Highveld coalfield (29.5%) and Sasol-Vereeniging coalfield (7.6%) (Department of Mineral Resources, 2012).

The coal mining companies in South Africa can, in general, be categorized into three groups, namely major coal miners, junior coal miners and Broad-Based Black Economic Empowerment (B-BBEE) companies. This, however, is not a precise classification because B-BBEE companies fit into more than one category. The six major producers that produced 80.7% of the country's total production in 2011 are Exxaro Resources, BHP Billiton Coal South Africa, Sasol Mining, Anglo Coal, Xstrata Coal South Africa and Optimum Coal Holdings. Exxaro Resources and Optimum Coal Holdings are B-BBEE companies. The remaining 19.3% was produced by junior coal producers. Junior coal miners and B-BBEE companies jointly accounted for 41% of total coal production. Three major B-BBEE companies, namely Exxaro Resources, Optimum Coal Holdings and Umcebo Mining produced 26% of the country's total production (Department of Mineral Resources, 2012).
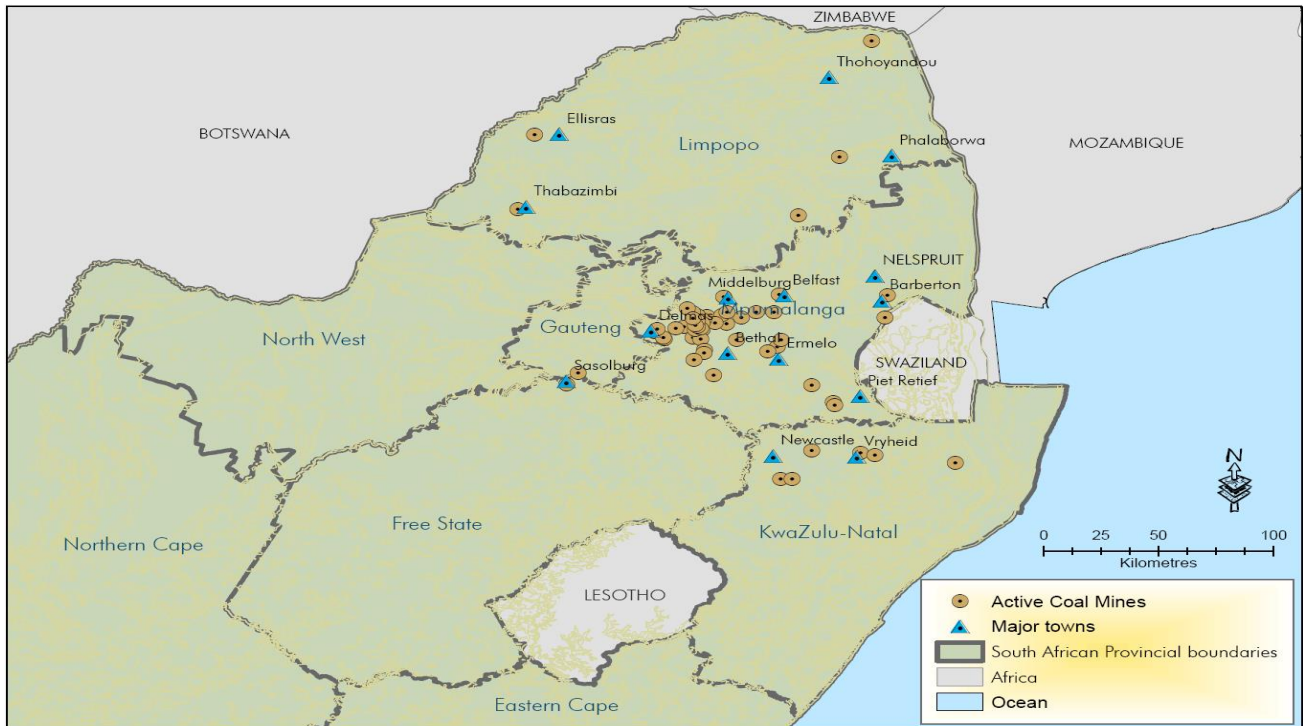
Figure 2.7: South Africa's active coal mines

Source: Statistics South Africa (2010)

2.5   Summary

The concept of externalities, coal-fuel cycle externalities and the South African power and coal industries were reviewed in this chapter. An externality was discussed to occur each time the production/consumption decisions of an agent affects the utility of another in an unintentional manner and when no/full compensation is made to the affected party by the producer of the undesirable effect. Externalities cause market failure, which in turn leads to non-optimal resource allocation in society's view. A number of environmental and societal impacts associated with the coal-fuel cycle were discussed. The impacts were categorised into three main classes, namely coal mining and transportation impacts, plant construction impacts and plant operation impacts. In the discussion of the South African power industry, special focus was given to Eskom's power stations, electricity sales, coal quality, emissions profile, coal supply and coal supply contracts. The discussion of the county's coal industry on the other hand, focused on the trends of coal production, consumption and prices. The country's main coal producers and consumers and as well as export coal consumers were also discussed. The review also highlighted the problems faced by the power and coal industries. The power and coal industries were found to be of major importance to the development of the South African economy.

CHAPTER 3:   ECONOMIC PHILOSOPHY AND SYSTEM DYNAMICS PHILOSOPHY

3.1   Introduction

This chapter seeks to ground the research conducted in this study within the economic discipline of study within which it falls and to motivate the use of a systems approach to model the life-cycle burdens and social costs of coal-based electricity generation by studying the links between system dynamics and the schools of economic thought that underpin this study. In pursuit of these aims, this chapter begins by defining the concept of research paradigms which is followed by a discussion of Guba and Lincoln's social science research paradigm framework for deliberating main matters of research methodology in social science. Section 3.4 reviews the history of economic thought, discussing developments in the economics research field since the 16th century and using Guba and Lincoln's conceptual framework to evaluate the developments. Based on section 3.4, section 3.5 briefly discusses the research paradigms that provide the theoretical basis for this study. Section 3.6 reviews system dynamics origins, main features, and the modelling process and its links with social theories. Based on section 3.6, the section 3.7 and 3.8 try to place the system dynamics practices of the energy literature and that of this current study on Pruyt's extended paradigmatic table. Section 9 summarizes this chapter.

3.2   Research paradigms defined

Generally "paradigms" are beliefs that guide actions (Guba in Creswell, 2008) and have also been termed "worldviews" (Patton, 1990). According to Kuhn (1970), a research paradigm represents the whole collection of beliefs, values, and methods that are mutually embraced by associates of a research community. A research paradigm is therefore a set of beliefs or assumptions that regulate inquiry in a discipline by providing a philosophical and conceptual framework through which organized investigations in that discipline are accomplished (Filstead in Ponterotto, 2005; Schnelker, 2006; Weaver & Olson, 2006).

3.3   Guba and Lincoln's social science research paradigm framework

The literature unveils various research paradigms that could potentially guide a research effort but also various ways in which paradigms have been categorized and labeled (Ponterotto, 2005; Creswell, 2008). One influential typology of research paradigms was that developed by Guba and Lincoln (1994; 2005). These researchers distinguish between four research paradigms, namely positivism, post-positivism (critical realism), critical theory, and constructivism (interpretivism). These research paradigms are presented in Table 3.1 and discussed below, in terms of the philosophical beliefs/assumptions researchers place on

reality (ontology), manner of knowing and construction of knowledge (epistemology), the values underpinning ethics, aesthetics and religion (axiology) and the procedures and techniques the researchers use to investigate what can be known (methodology).

Table 3.1: Research paradigms

Research inquiry	Research paradigms			
	Positivism	**Post-positivism**	**Critical theory**	**Constructivism**
Ontology	Naïve realist - real but apprehendable	Critical realism – reality but only imperfectly and probabilistically apprehendable	Historical realism -virtual reality shaped by social, cultural, political, ethnic, economic and gender values -Formed over time	Relativism - local and specific constructed realities
Epistemology	-Objectivist/dualist -Causal determinism -Finding true	-Modified objectivist/dualist -Causal determinism -Critical community -Findings probably true	-Subjectivist -Value-mediated findings	-Subjectivist -Created findings
Axiology	Propositional knowing about the world is an end in itself, is intrinsically valuable		Propositional, transactional knowing is instrumentally valuable as a means to social emancipation, which as an end in itself, is intrinsically valuable.	
Methodology	-Experimental -Chiefly quantitative -Verification of hypothesis	-Modified experimental -Critical multiplism -May include qualitative -Falsification of hypothesis	Dialogic/dialectical	Hermeneutical/ dialectical

Source: Adapted from Guba and Lincoln (1994)

Traditionally, before 1930, research was modelled after the physical and natural sciences (i.e. hard sciences). During this period scientific investigation and empiricism were the yardstick for research and were represented by positivism. Following the physical and natural sciences, new research fields such as social sciences imitated this successful paradigm but later other paradigms such as post-positivism emerged as researchers started to question the applicability of the positivist approach to human behaviour and society (Plack, 2005).

3.3.1   Positivists and post-positivists

Ontologically, positivists believe in an apprehendable, identifiable and measureable reality, while post-positivists - though they acknowledge an objective reality they believe in one that is only partially/imperfectly apprehendable (Denzin & Lincoln, 1994). In terms of the nature of knowing and construction of knowledge (i.e. epistemology), they both believe in the existence of laws/theories which

control/regulate/direct planet earth, which must be tested/verified and refined to enable humans to understand the world. The knowledge that develops through both these research paradigms is bound by causality. Therefore both paradigms hold causal determinism in that causes determine outcomes/effects/events. The problems studied by positivists and post-positivists thus display the necessity of identifying and evaluating the sources that shape results through cautious examination plus measurement of the objective reality in the actual world. The development of numeric measures of examination is therefore paramount to both research paradigms (Plack, 2005; Creswell, 2008). Positivists use quantitative research to verify truth while post-positivists primarily use quantitative methods but also some qualitative approaches as a method of falsifying *a priori* propositions (Guba & Lincoln, 1994; Crotty, 1998). Axiologically, they both look at propositional knowledge. Positivists argue that investigations must be value and bias-free replicable while post-positivists recognize the existence of human-being interactivity and try hard to minimize such bias (Guba & Lincoln, 1994; Ponterotto & Grieger, 2007).

3.3.2 Constructivists

On the other hand, constructivists ontologically believe in multiple socially constructed realities that can only be imperfectly grasped (i.e. subjective reality). Epistemologically, constructivists create knowledge through interactions and knowledge is accepted through relative consensus. Unlike positivist/post-positivist researchers, constructivist researchers have no interest in forecasting the future or making gross generalizations but within a specific context of human action, the focus is on understanding the subtle and distinctive differences in human behaviour through trying to understand the way in which meanings are fashioned, negotiated and customized (Plack, 2005). The researcher is the primary research tool and is intimately involved with the inquiry (Merriam, 2002). Axiologically, constructivists focus on both clear and linguistic-centered propositional information and implicit plus tacit information (Guba & Lincoln, 1981). Methodologically, constructivists' inquiry differs from that of positivists/post-positivists, in that they commence with an enquiry/concern instead of an *a priori* proposition from theory and the inquiry takes place in the real-world setting (Creswell, 2008). The inquiry is informal, interactive and takes an explanatory and/or descriptive stance. The constructivist researcher uncovers embedded meaning through words and text and therefore employs only qualitative methods (Ponterotto & Grieger, 2007).

3.3.3 Critical theorists

The critical theorist, on the other hand, believes that describing and understanding human behaviour as done by the constructivist researcher is not sufficient. Thus they aim at advancing the welfare of humans, especially marginalized individuals in society through fighting oppression and inquiring the *status quo*. The

critical theorist researcher's goal is therefore to empower members to alter the *status quo* and liberate own-selves from on-going domination (Plack, 2005). The critical theorist researcher is therefore not simply concerned with generating new knowledge but facilitating social change (Kim, 2003). In essence, critical theory is a collection of various paradigms, among which are feminism, cultural studies, neo-Marxism, social theorists, materialism and racialized discourses (Kincheloe & McLaren, 1994; Denzin & Lincoln, 2000). Ontologically, they accept as truth that all that can be known is fundamentally a historical realism formed by a number of factors, including political, social, racial, cultural and economic factors. Epistemologically, as the manner of investigation is wholly value based, the critical inquirer's values are central to the inquiry coupled with those of participants. Knowledge is shaped by the relations between the inquirer and participants (Guba & Lincoln, 1994). Axiologically, this research paradigm is dialectic dialogue that reveals the unrevealed suppositions through which day-to-day happenings are interpreted (Kincheloe & McLaren, 2000). In the following section the history of economic thought is reviewed.

3.4 Economic disciplines and research paradigms

Economics, like other social sciences, is characterised by the existence of diverse schools of thought. The history of economic thought begins with a discussion of two concepts, namely mercantilism and physiocracy, which denotes a system of early economic policy and the development of economic doctrines. This is then followed by a discussion of several concepts, for instance classical, neoclassical, heterodox and environmental economics. At the end of each discussion an attempt is made to classify the economic disciplines according to the research paradigms of Guba and Lincoln discussed earlier.

3.4.1 Mercantilism and Physiocracy

Among the most primitive economic ideas in history is mercantilism. Mercantilism theorists hold that wealth consists in gold and silver (Butler, 2011) and that trade is a zero sum game, with no mutual benefits from trade and that if there was a nation that gains from trade the other nations were losers. At the core of mercantilism is the view that national prosperity can best be attained through maximizing net exports. Mercantilism, in essence, is based on bullionism - an economic theory that considers a country's wealth and success by the quantity of valuable metals (gold or silver) the country owns (Pojer, n.d.). A country with more precious metals than another was therefore considered a rich one (Butler, 2011). This notion had fundamental repercussions for economic policy. A trade surplus had to be maintained by means of export surplus, so a country had to export more than it imports (Magnusson, 2003) and tariffs were used to encourage exports and discourage imports (Rothbath, 2010). Agriculture and manufacturing were promoted in order to increase exports and restrict imports, and sea power was essential to control foreign markets (Pojer, n.d.). Maintenance of a positive trade balance was time and again backed by military might

(Rommelse, 2010). The mercantilism doctrine overshadowed European business activities' course of action in the 16th to late 18th century. During this time mercantilism promoted colonial expansion and was the reason behind persistent European wars (LaHaye, 2008). In spite of its prevalence, however, it only appeared in print in 1763 by Marquis de Mirabeau and was popularised by Adam Smith, a classical economist, who was strongly against its ideas (Magnusson, 2003). Amongst other scholars against mercantilism were John Locke and David Ricardo.

The mercantilism doctrine coexisted with the physiocracy doctrine - the first school that rejected mercantilism. Physiocracy is a new science that saw the wealth of the nation originating from nature, in particular agriculture. It is also called the government of nature. Physiocrats, like mercantilists, studied the economy with the goal of developing economic policies, but unlike mercantilism, physiocracy was led by an intellectual leader, Francois Quesnay. Quesnay was analytical, designed conceptual models that gave the stance of science to the study of economy (Lluch & Argemi, 1994) and supported perfect liberty (Butler, 2011). Quesnay's economic theories included the idea that the source of national wealth was the productive sector, in particular agriculture, and that taxation should be solely imposed on the landowning class (Lluch & Argemi, 1994; Pojer, n.d.). Quesnay developed a tableau economique, which represented the economic system in three networking classes, namely property, productive and sterile classes which represent landowners, agricultural labourers and artisans and merchants, respectively. In the tableau shown is the regeneration of income, a landowner receives rent and spends it on products of artisans and agriculture, who also in turn purchase other products (Phillips, 1995). The tableau portrays the intersectoral flow of money and commodities in an economy (Bilginsoy, 1994). Quesnay's tableau has captivated numerous students of economic doctrines and is regarded as one of the greatest discovery and an initial fruitful attempt to examining a nation's wealth on a macro-economic basis (Marx, 1952; Newman, 1962; Giancarlo, 2011). It marked the beginning of general equilibrium theories and was a basis for welfare analysis (Bilginsoy, 1994).

3.4.1.1 *Criticism of the early political economy schools*

Hume is regarded as a precursor of Adam Smith in that some of his ideas, even those against mercantilism, were reflected in Smith's book "Wealth of Nations" (McGee, 1989), among which is the fallacious goal of continuous positive balance of trade (Ekelund & Hebert, 1975; McGee, 1989) and mercantilists' misconception of money and wealth (McGee, 1989). According to Smith, wealth consists of not only gold and silver but also land, houses and various consumable goods. Silver and gold do not therefore describe the wealth of a country nor is it the sole benefit of foreign trade (Butler, 2011). On the other hand, John Locke pointed out that human labour generated the wealth of the globe and that it is not unchanging as

mercantilists believed. David Ricardo indicated the failure of mercantilists to comprehend the concepts of absolute and comparative advantage and the benefits of trade. Smith was also in opposition to the mercantilist acceptance as truth that trade was a zero-sum game but recognized instead that trade was a positive-sum game, as foreign trade can encourage growth of production capability of a country and increase a country's real worth (Rosenberg, 1960). Using the theory of laissez faire ("leave things alone", a belief than an economy is self-regulating) in analysing the trade problem, Smith explained that an invisible hand would guide trade in a similar manner as done in domestic economic performances, hence he critiqued the mercantilist trade policy of intervention and monopolising trade. Smith considered the wealth ideas and trade theory of mercantilists as nonsensical and untenable (Rosenberg, 1960; Manis, 2005). On the other hand, though Smith did not fully approve of all the ideas of physiocracy, he preferred it over mercantilism because it recognized wealth to consist of not only gold and silver but in a nation's production, and embraced perfect liberty as the finest manner to maximize a nation's wealth. Smith found the main error with physiocracy to be the view of artisans and merchants as a sterile or unproductive class (Butler, 2011).

3.4.1.2   *Appraisal*

As stated earlier, the purpose of describing the mercantilism and physiocracy theories was to offer background on the development of economic doctrines, so no attempt is made to classify the early doctrines into the economic research paradigms of Guba and Lincoln (1994). It is also doubtful that nowadays there is any economist that considers himself/herself mercantalist or physiocrat, however, the theories developed by mercantilists and physiocracts are the foundation of what became modern economics.

3.4.2   Classical economics school

Influenced by mercantilism and physiocracy theories, the classical economic school is often called classical liberalism, as it is based on the liberal doctrine. Beginning with the wealth of nations work in 1776, classical economists supported free market economy. They believed that free markets regulate themselves. Smith, using the concept of the invisible hand, explained how resources would be allocated and how the market would move towards equilibrium without intervention. Classical economists defended that free trade would promote efficient use of resources and boost welfare. Out of the explanations of foreign trade and its mutual benefits came concepts such as specialization and theories of comparative and absolute advantage. Classical economists developed the labour theory of value. A manufactured good's value was believed to be contingent on the costs of creating it, i.e. rent for the landlord, wages for workers and profits for capitalists. The real price of anything was therefore the trouble of getting it. The market price

fluctuations varied according to market forces and altered factor prices (wages and profits). From these came the concepts of perfect market competition and the law of one price (Kucukaksoy, 2011). Later some classical economist began stressing the value of a good to the consumer. Classical economists focused on analysing the causes of economic growth, allocation of surplus output and promoted policies that enhanced the wealth of nations (De Vroey, 1975). Emphasis was therefore on production and what influenced the supply of goods. The goal of classical economists was to assist policy makers to increase the wealth of nations (Meek, 1973). Classical economists introduced numerous ideas that are used in present-day economies, especially in international economics and microeconomics doctrines. Among the classical economists were Adam Smith, William Petty, David Ricardo, John Stuart Mill, and the unorthodox Robert Malthus.

3.4.2.1 *Appraisal*

The problems studied by classical economists reflected the necessity of identifying and evaluating the sources that shape results through cautious examination plus measurement of the objective reality in the actual world. The development of numeric measures of examination was therefore paramount and the knowledge that developed was bound by causality. Classical economists, in analysing social phenomena, stressed the concept of class (i.e. landlords, capitalists and workers) instead of individuals and historical analysis was the tradition. For instance, using historical analysis, they made efforts to explain capitalist mode of production. The ontology, epistemology and methodology of classical economists imply a positivist paradigm.

3.4.3 Neoclassical economics school

Neoclassical economics was first coined by Thorstein Veblen over a century ago while referring to a school of economic thought (Lawson, 2013). The literature, however, discloses diverse interpretations of the term neoclassical economics (Hahn, 1982; Weintraub, 2002), perhaps due to the fact that the school has evolved since its introduction in the 1870s (Dequech, 2007). Broadly, neoclassical economics is characterized by rationality, economic self-interest (Weintraub, 2002), methodological individualism, equilibrium analysis (Hahn, 1984), and mathematical techniques (Brennan & Moehler, 2010; Lawson, 2013). Some scholars, however, note that present-day economics is transitioning from some of the substantive categories, namely economic selfishness, rationality and equilibrium to well-informed self-interest, purposeful behaviour and sustainability (Colander, Holt & Rosser, 2004; Davis, 2005).

Unlike classical economists whose focus was on economic growth and hence assisting policy makers, neoclassical economists focused on efficiency, i.e. optimal allocation of scarce resources among alternative

uses (De Vroey, 1975). Also in contrast to classical economists whose core theoretical structure was centered on capital, the central concept for neoclassical economists is focused on prices – i.e. economic analysis focuses on the determination of equilibrium prices in factor and products markets (Eagly, 1974). Prices in this school are determined by subjective preferences (desires and beliefs) of consumers. Agents are assumed to have rational preferences. While in principle the preferences of agents could be driven by group interests, in practice it is argued there is predominance towards self-interested motives with agents maximizing their own well-being. Economic behaviour is thus conceived as a complex exchange between rational individuals (Brennan & Moehler, 2010) - individuals maximize utility while firms maximize profits (Weintraub, 2002). The analysis of the interplay among rival interests has, however, tended to focus on equilibrium analysis. Mathematical techniques formalize the complex interactions of agents (Brennan & Moehler, 2010).

Neoclassical economics has dominated the twentieth century and introduced a number of theories in connection with economic activity, among which are theory of production, theory of consumption, marginal (productivity and utility) theory, theory of diminishing returns and theories of general equilibrium and Pareto efficiency. The school thus dominates microeconomics. It has, however, been criticized: for reliance on methodological individualism as its unit of analysis; on the assumption of rational choice of individuals and optimization, which has been viewed as overlooking essential aspects of human behaviour (i.e. real people often do not resemble the "economic man", they lack the ability to maximise benefits from their choices (Boldeman, 2007); for normative bias in that instead of explaining actual economies as observed empirically it focuses on utopia (Pareto-optimality and welfare) (Eichner & Kregel, 1975); and on the suitability of its general equilibrium theory in explaining evolving economies (Boldeman, 2007). Some of these criticisms have been merged into latest forms of neoclassical theory as cognizance of economic benchmarks' evolution while most of it has manifested itself in heterodox economics.

3.4.3.1 *Appraisal*

Neoclassical economics acknowledges a reality that is controlled by absolute laws of nature, and views economics as an objective science that is value free. The school of thought focuses on rational explanation of social matters while relying on mathematical techniques. The concept of rationality is an end in itself with no queries raised concerning the source/value of preferences. The ontology, epistemology and methodology of neoclassical economics thus imply a positivist paradigm.

3.4.4   Heterodox economics

Heterodox economics designates various schools of economic thought which oppose the neoclassical approach to understanding socio-economic performance. The reasons behind the rejection of the neoclassical orthodoxy vary among the heterodox schools and there is no single heterodox theory (Gabriel, 2003). The heterodox schools are a growing movement that has been challenging neoclassical economics since the 1870s. Heterodox schools of the time included historical schools and various supporters of mercantilism. After 1945 Keynesian economics became absorbed into the mainstream, forming neoclassical synthesis - partitioned into microeconomics and macroeconomics. The heterodox schools that opposed this synthesis were post-Keynesians, Austrians, Marxist and institutional schools. The mainstream after 1980 became challenged by various research programmes which can also be adapted to heterodox economics, namely evolutionary economics, behavioural economics, experimental economics, complexity economics and neuroeconomics (Davis, 2006). Among the heterodox schools, two influential heterodox schools are discussed further and classified into the research paradigms of Guba and Lincoln namely, Austrian and institutional economics.

3.4.4.1   *Austrian economics and appraisal*

Austrian economics rejected the neoclassical economics approach of explaining market phenomena by way of exact and universal laws. While Austrian school embraces methodological individualism in explaining economic phenomena, it rejects the neoclassical economics' "economic man" and considers a "perceiving man", particularly a "man who grasps the future" (Selgin, 1988). In addition, unlike neoclassical economists the Austrian economists embrace methodological subjectivism, embrace a subjective theory of value and reject empirical modelling, mathematical and statistical methods as they consider individuals too complex (Fritz, 2004) and embrace instead historical description and understanding of social occurrences (Selgin, 1988). Austrian economics also advocates for complete elimination of government control, an extreme case of laissez faire approach (Raico, 1995). Among Austrian economists are Carl Menger, Friedrich von Wiese and Eugen von Bohm-Bawerk. From this discussion the ontology, epistemology and methodology of the Austrian school imply a critical theorist research paradigm.

3.4.4.2   *Institutional economics and appraisal*

Original institutional economics opposes the rational "economic man" model of neoclassical economics, and instead stresses the habitual and routinized personality of human conduct (Veblen, 1919; Stanfield, 1999). The institutions as opposed to individuals are the center of analysis. Institutions are seen as having a cognitive dimension which provides a frame for processing data into meaningful knowledge (Hodgson, 1988). The approach to economics is holistic, systematic plus evolutionary (Wilber & Harrison, 1978) in

pursuit of understanding the dynamics of the socio-economic system (Veblen, 1919; Ayres, 1962). Focus is therefore not on rational, static and equilibrium processes. Theory development is focused on explanation instead of prediction (Arvanitidis, 2006). Among the original institutional economists are Thorstein Veblen and John Commons (Mirowski, 1987). Based on the research paradigms of Guba and Lincoln discussed earlier, the ontology, epistemology and methodology of the original institutional economics suggest a post-positivist research paradigm.

3.4.5 Environmental economics and ecological economics

The importance of nature/environment was noted by classical and neoclassical economists but the comments they made were not reflected in their exposition of theories. The Malthusian scarcity (1798), Ricardian scarcity (1817) and Jevon's coal question (1865) represent such earlier works (Cracker & Rogers, 1971; Common, 1988). It was, however, not until the 1960s and 1970s that the deteriorating quality of the natural environment prompted scholars to apply economic tools to environmental science. The increasing scarcity of none market reflected resources, for example clean air, soil and water became viewed as a consequence of market failure but disagreement arose on how the environmental crisis should be studied, mainly stemming from differences in scientific views. Environmental economics developed and used the theories and methods of neoclassical regime, however, continued environmental deterioration and numerous oppositions to the environmental economics' approach of treating the natural environment within the neoclassical economics framework, led to the formulation of ecological economics (Boyce, 2011).

Environmental economics is the study of economy and environmental association with specific focus on regulation/control with the ultimate goal of sustainable development, while ecological economics is the study of economy and ecosystem interrelationships in the light of biophysical limits with a specific focus on stewardship and has the same goal of ensuring sustainable development (Sahu & Nayak, 1994). Ecological and environmental economics are thus two different sub-disciplines of economics that address environmental issues that now operate as two dissimilar disciplines of economics and environmental science (Sahu & Nayak, 1994). Following in the practice of neoclassical economics, environmental economists assume a reality that is controlled by absolute laws of nature (Tacconi, 1998), and maintain that economics is a positive science that is value-free, that is, they maintained that economics is intended to describe facts devoid of personal value or subjectiveness permitted to affect the facts (Sahu & Nayak, 1994; Tacconi, 1998). Ecological economists on the contrary, recognise a subjective reality, that is, not devoid of personal value (Tacconi, 1998; Boyce, 2011).

The schools' treatment of resources when solving environmental resource-related problems also differed. In the light of a globalized network of resources resulting from globalization, environmental economists employed a model of relative scarcity (prices that reflect scarcity) but in contrast to neoclassical economists, they internalised the dreadful environmental consequences from production and consumption. In contrast, ecological economists used the concept of absolute scarcity, with bounds on the thermodynamics of resources (Sahu & Nayak, 1994), and in line with the biophysical approach to resources, irrespective of the utility they provide, they are deemed to have value (Venkatachalam, 2007).

The schools also differ in terms of the valuation of environmental resources. Environmental economists quantify environmental services using measures such as contingent valuation (willingness to pay and accept cost surveys), travel cost method, hedonic pricing and cost benefit analysis while ecological economists use evaluative methods such as environmental impact assessment, systems analysis and including other more qualitative methods (Batabyal, Kahn & O'Neill, 2003). While ecological economists would make use of such methods too, they would not entirely be responsible for the resource value (Panagopoulos, 2009).

3.4.5.1 *Appraisal*

As elucidated above, economic and ecological economics vary in terms of the underlying philosophy, views on resource scarcity, valuation and methods. The assumption of a reality that is controlled by absolute laws of nature, and the maintenance of that economics is an objective science that is value free, coupled with the use of quantitative methods to value resources and to analyse environmental issues, renders environmental economics a positivist philosophy like neoclassical economics. The appreciation of a subjective reality, and perhaps multiple realities that can only be imperfectly grasped (Tacconi, 1998) renders the ontology of ecological economics to that of a post-positivist and constructivist. The constructivism ontology is useful for explaining matters such as sustainability, in the event that individuals hold different views/explanations of limits (Boyce, 2011). The use of both quantitative and qualitative methods, however, renders ecological economics a post-positivist philosophy.

3.5 Research paradigm(s) underpinning the current study

Among other negative consequences, the environmental degradation as a spin-off of coal-based electric power production is viewed as a consequence of market failure. Among other factors, the presence of externalities causes markets to fail to achieve Pareto efficiency, thereby causing a divergence between private and social costs. Therefore an understanding of the intricate relations between the environment and the power production system is needed to redress market failures in the electric power sector. The review of economic thought discloses that the main concepts in this study, namely production, externalities

and social cost are rooted in neoclassical and environmental economics, particularly, in welfare economic theory, theory of production and Pareto efficiency (more on these in the following Chapter). Neoclassical and environmental economics are therefore the main economic disciplines that provide the theoretical basis for this study. The ontology, epistemology and methodology of both neoclassical and environmental economics fall within the positivist research paradigm of Guba and Lincoln's classification. In the following section, a review is conducted of the origins of system dynamics and its main features, its modelling process, and its links with social theories.

3.6   System dynamics origins, features, modelling process and its links with social theories

3.6.1   Origins of systems theory

Ludwig von Bertalanffy, while conducting a biological study on living organisms, recognized the need to study the living organisms not only in isolation but to consider their relations when studied as a whole. He used the term "organism-as-a-whole" and suggested that this approach be employed in other fields of study too (Von Bertalanffy, 1973). This approach is a systems thinking approach. Systems thinking analysis looks at problems as parts of a whole system. It is premised on the understanding that a system can best be known by examining the linkages and interactions between its elements. Ludwig von Bertalanffy characterizes systems inquest into three key spheres of influence, namely systems technology, systems science and systems philosophy. Systems technology developed from technological and organizational challenges that necessitated integration of skills and knowledge from various domains of study in the second half of the 20th century. Systems technology was, however, constrained by its chiefly instrumental focus and mechanistic world conception (Von Bertalanffy, 1952).

In the early 20th century, while reacting to the growing disintegration and replication of scientific and technological research, Von Bertalanffy proposed the development of a general science of organized complexity (that is general theory of systems or, as commonly known, general systems theory) (Laszlo & Krippner, 1998) as a way of reviving the unity of science (Von Bertalanffy, 1968). General systems theory is whole, integrative and emphasises a structured world and is hence a drastic departure from the mechanistic, linear causality and analytic paradigm of classical science (Von Bertalanffy 1955; Hommand, 2005).

But similar to other pioneering frameworks of thought, general system theory suffered ridicule and abandonment (Laszlo & Krippner, 1998). For Von Bertalanffy the whole and humanistic methodology to knowledge and practice is general systems theory's major contribution (Hommand, 2005). Notwithstanding the criticism general systems theory faced, it profited from analogous developments and prominence of

cybernetics plus information theory, coupled with their extensive application in many fields. In 1954 Kenneth Boulding and his colleagues realized that the systems approach was not restricted to the hard sciences and they applied it to the social sciences (Laszlo & Krippner, 1998). The systems thinking approach was also seen relevant to industrial engineering and management. In a study of management problems in corporate settings, Jay W. Forrester (1958) proposed industrial dynamics (Damle, 2003). Later, various disciplines employed industrial dynamics to address various problems, for example, it was used in urban planning, economics and medicine. Owing to its diverse application in various settings, it became transformed into a more general term called system dynamics (Damle, 2003). By the 1960s, on a trans-disciplinary plane, systems thinking started being acknowledged, as an archetypal attempt at scientific unification and theory construction (Laszlo & Krippner, 1998).

Systems science is therefore an important development that demonstrated the diffusion of Von Bertalanffy thought (i.e. systems approach or system thinking) in all sciences (for example biology, physics, behavioural and social sciences), accentuating interactions between parts and studying any system in association with its environment (Hommand, 2005). Systems theory therefore centres on the arrangements of and associations between parts which link them into a whole (Heylighen & Joslyn, 1992), and as a general frame of inquiry concerned with the study of phenomena and events in a holistic and interactive manner, it is connected to both epistemological and ontological views (Laszlo & Krippner, 1998). Stemming from a systems (science) viewpoint of a relational approach to understanding reality, systems philosophy mirrors a similar reality of worldview, that is, that of organization and interdependence, emphasizing relational patterns between systems parts and the whole (Hommand, 2005). The ontological view thus suggests a nature of reality that consists of systems. The epistemological view suggests a holistic approach highlighting the relationship between systems and their parts/elements (Hjorland & Nicolaisen, 2005).

3.6.2   Origins of system dynamics and its main features

The origins of system dynamics were highlighted briefly while discussing the systems approach above. In this section more background on system dynamics is provided in order to address its philosophical background and its main features. The discussion firstly explains the work of the creator of system dynamics, in order to establish the initial drives, assumptions and aims behind Jay Forrester's development of system dynamics.

What is presently known as system dynamics began in the 1950s when Jay Forrester started searching for links between engineering and management. Equipped with knowledge in feedback control systems, in a faculty seminar in 1956, Forrester criticized economic models on a number of accounts, for example, their

failure to reflect in a satisfactory manner the loop structures that characterize economic systems which consequently led to exclusion of closed loops properties such as accumulations and delays, for not being holistic and integrative - for example they failed to incorporate the flows of money, labour, goods and information in one unified model, for describing systems using linear equations, for not incorporating changing mental attitudes, for overconfidence in regression analysis in defining economic behaviour, and lack of discussions of assumptions underlying economic models (Forrester, 2003).

Forrester visualized new firm-economy models that embrace characteristics such as dynamic structure, incremental changes in variables, information flows, non-linear systems, non-linear differential equations, model complexity, empirical solutions, symbolism (flow diagrams) and correspondence with real counterparts and lastly, models that emphasize structure over coefficient accuracy (Forrester, 1975a). Based on these initial thoughts, Forrester published a paper "Industrial dynamics: a major breakthrough for decision makers" which emphasized that management should embrace unified systems given their profession which necessitates relating the flows of materials, information, capital equipment, money, and labour. The relations among these factors form a foundation for understanding the structure of the system and for anticipating the consequence of decisions and policies (Forrester, 1975b).

Shortly after this paper, Forrester published a book in 1961 entitled "Industrial Dynamics" whereof the major intention was to develop a science for designing effective industrial and economic systems. In the book Forrester explains the industrial dynamics approach for devising effective systems (Damle, 2003). To be included in the model are main factors that will help address the questions to be answered, cause-effect information feedback loops are to be traced and focus must be on closed loop information feedback structures, pictorial representations of the model through flow diagrams are to be conducted and the model variables are to resemble those in the system being represented, formal decision policies are to be formulated, interactions among the system components are to be described via mathematical formalization, the model behaviour can then be generated and its outcomes compared against available knowledge of the real system, model revision is to be conducted until the model resembles actual system in a satisfactory manner, last but not least the model structure and policies are to be redesigned as can be in actual system such that the modifications that produce better or worse behaviour can be established, lastly, the real system can be altered in the manner that improves performance. Forrester also highlighted that model validation/significance rests on the suitability of the model for the purpose it was designed for. The focus therefore is not on predictions but on understanding the structure of the system and our assumptions about it (Forrester, 1961; Damle, 2003).

In these early days, Forrester's focus was on corporate operations, but in a follow-up book "*Principles of Systems"*, he outlined the broader view of systems. He describes a system as an organization of parts that function collectively for a common purpose, highlights the importance of structure in organizing knowledge in any field of study, stressing the notion of mental models and importance of levels and rates as key variables (Forrester, 1971; Forrester, 1975a). The science of designing systems that began in the 1950s as industrial dynamics was rephrased into a broad-spectrum phrase called system dynamics, owing to its diverse application in various settings, for example, in urban planning, economics and medicine (Damle, 2003).

System dynamics, though labelled by many as a method (Sterman, 2000; Lane, 2001), methodology Roberts, 1978), theory (Jackson, 2003) and field of study (Coyle, 2000) has twofold intentions, firstly to understand the behaviour of systems through detecting the factors driving the behaviour of the system. Secondly to observe how the system responds to alterations of the said factors and then to make policy recommendations that improve system performance (Damle, 2003). System dynamics models embrace such characteristics as complexity, information flows, feedback behaviour, dynamic structures, causal loop diagrams and their correspondence with real counterparts, stock and flow diagrams, difference equations, non-linearity, confidence based on model structure, experimental approach and the construction of formal models using computers (Forrester, 1975a; Lane & Oliva 1998; Damle, 2003; Pruyt, 2006).

As a tool that has been characterized as most suited for the framing and understanding of complex problems, it is important to clarify such complex problems (Richardson & Pugh, 1981), which basically refers to problems in feedback rich environments. The complexity stems from the system consisting of various parts that interrelate and generate feedbacks. Feedbacks occur, for example, when a system factor affects another system factor, which in <u>turn</u> affects the first factor, thus forming a loop. The feedbacks can be self-reinforcing (positive) or self-correcting (negative). Self-reinforcing loops amplify change in the system while self-correcting loops oppose change in the system and attempt to bring the system into equilibrium. The feedbacks, together with delays, create dynamics in the system (Damle, 2003).

There are a number of basic modes of system dynamics behaviours, namely exponential growth which occurs because of self-reinforcing feedback (i.e. the rate of growth rises rapidly over time)), exponential decay where overtime the growth of decay rises rapidly, goal-seeking behaviour which occurs because of self-balancing loop (i.e. the structure/corrective-action that attempts to move the state of the system towards a desired state) and oscillation which occurs due to a delay in the self-balancing loop (Damle, 2003; Sterman, 2000). The interactions among the basic behaviours result in derived modes of behavior, among

which are S-shaped growth which occurs because of interactions of a self-reinforcing and a balancing feedback loop, S-shaped growth with overshoot which occurs because of the presence of delays in the balancing loop of the S-shaped growth, and overshoot and collapse which is also displayed by the S-shaped curve when the system's capacity is variable and is diminished and destroyed by the system state. Some other types of system dynamics behaviours include equilibrium behaviour where the system's state remains fairly constant and chaotic behaviour where the system oscillates irregularly (Damle, 2003). The features of system dynamics mentioned in this section will be discussed more elaborately, while presenting the system dynamics modelling process in the following section.

3.6.3   System dynamics modelling process

Various system dynamics modelling arrangements have been suggested by numerous researchers in the literature, for example, Richardson and Anderson (1980), Richardson and Pugh (1981), Roberts, Anderson, Deal, Grant and Shaffer (1983), Ford (1999), Forrester (2000) and Sterman (2000). Some of the suggested modelling steps are presented in Table 3.2. The table suggests that there is substantial consistency in the modelling steps to be followed when constructing system dynamics models.

Table 3.2: System dynamics modelling process

Richardson & Anderson (1980)	Roberts et al. (1983)	Ford (1999)	Sterman (2000)
Problem recognition	Problem definition	Understanding the system	Problem articulation
System conceptualisation	System conceptualization	Dynamic problem	Dynamic hypothesis formulation
Model representation	Model representation	Stock & flow diagrams Causal loop diagram	Simulation model formulation
Model behaviour & evaluation	Model behaviour & evaluation	Reference mode Sensitivity analysis	Testing
Model use	Policy analysis and model use	Policy evaluation	Policy formulation and evaluation

Source: Adapted from Richardson & Anderson (1980), Roberts et al. (1983), Ford (1999), Sterman (2000)

3.6.3.1   *Problem formulation*

Problem formulation is the first and most important step in the model building process. It embraces a number of activities, amongst others, proper description of the problem, identification of key variables that need to be considered, determining the system boundary and establishing the time horizon for the model (Sterman, 2000). A good understanding of the system by the modeller is therefore necessary for proper formulation of the problem.

3.6.3.2 *Dynamic hypothesis formulation*

The dynamic hypothesis formulation stage involves constructing a working theory that explains the problem. This theory explains/describes the dynamic behaviour of the system centered on the feedbacks and causal structure of the system (Sterman, 2000). Causal loop diagrams are part of the dynamic hypothesis formulation step and are an essential feature of system dynamics models that capture the structure of the system in a qualitative manner. They indicate the cause and effect relations amongst the variables in the system and feedback loops of the system. The relationships between the variables are either positive or negative (see Figure 3.1). Positive polarity designates that, all else being equal, an increase (decrease) in the "cause" element will increase (decrease) the "effect" element. So the cause and effect elements travel in a similar direction. Negative polarity indicates that, all else being equal, an increase (decrease) in the "cause" element will decrease (increase) the "effect" element. So the cause and effect elements travel in opposite directions (Sterman, 2000).
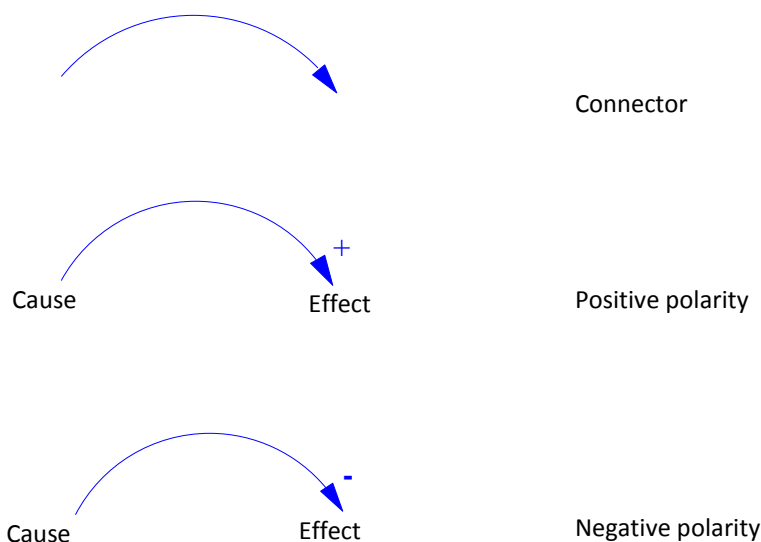
Figure 3.1: Positive and negative causality

Source: Own construction

The interactions between the variables generate feedback loops which determine the dynamics of the system. Feedbacks occur, for example, when one variable in the system affects another variable, which in turn affects the first variable, thereby forming a loop. Feedback loops are either positive or negative (see Figure 3.2) and one having an even number of "-" signs (or only "+" signs) is a positive loop (also called a reinforcing loop), while one having an uneven number of "-" signs is a negative loop (also called a self-balancing loop). Self-reinforcing loops amplify change in the system while self-correcting loops oppose change in the system and attempt to bring the system into equilibrium (Coyle, 1996; Sterman, 2000). The

causal loop diagram, as a tool that illustrates in a qualitative manner the linkages and feedback loops of the system, serves as a quick tool for capturing the hypothesis relating to the basis of dynamics. Model construction tests this hypothesis and it must be adjusted if evidence from the model or from the real system refutes it (Lane, 2000).
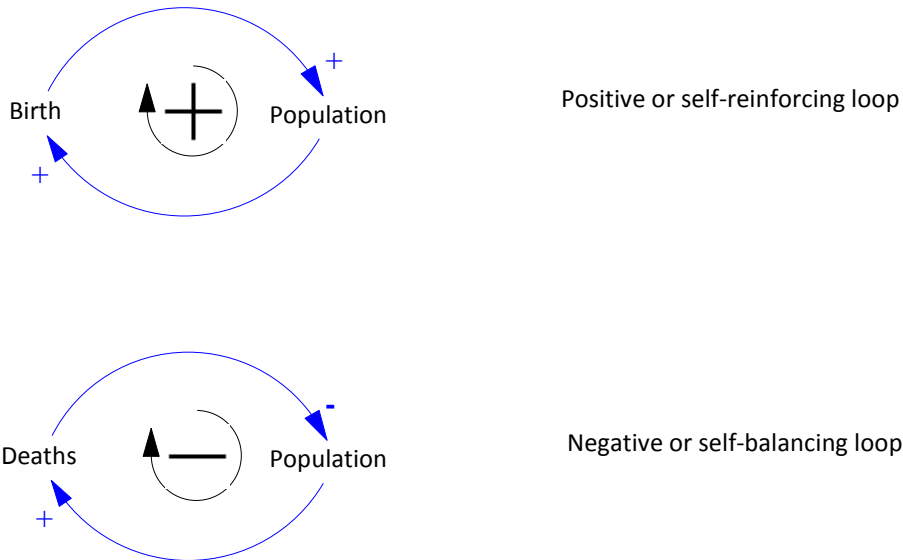
Figure 3.2: Positive and negative feedback loops

Source: Own construction

3.6.3.3   *Model formulation*

Model formulation includes developing maps of causal structure (i.e. constructing stock and flow diagrams) and estimating the parameters of the model (Ford, 1999). Stock and flow diagrams, unlike causal loop diagrams which illustrate the system structure qualitatively, capture the quantitative relationships between the variables of the system by adding stock and flow variables. The stocks or levels denoted by rectangles show accumulations in the complex-whole formed from related parts, while the flow variables (i.e. inflow and outflow rates) denoted by valves, regulate changes in stocks (i.e. by means of filling or draining the stocks), see Figure 3.3. The flow rates are given by various factors, for instance, stock levels or exogenous variables (Jeong et al., 2008) and they can go to other stocks or into infinite sinks and sources, denoted by clouds. Also incorporated into stock and flow diagrams are auxiliary variables. They either represent constants or are calculated from other auxiliary variables or from stocks (Ford, 1999). Shadow variables show variables that relate with other variables in other views of the model.
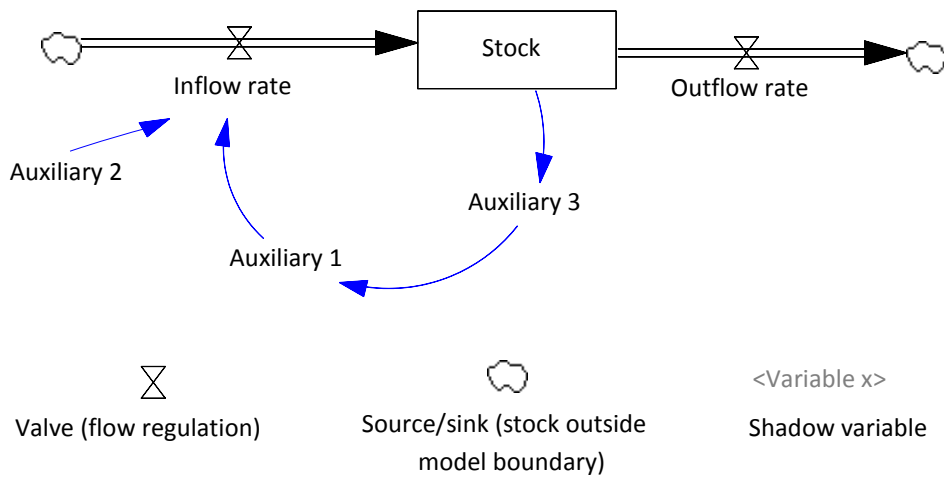
Figure 3.3: Stock and flow diagram

Source: Own construction

Concerning parameter estimation, numerous techniques can be employed to estimate model parameters, such as use of actual data if data is available, conducting surveys if data is unavailable, use of expert input, basing parameter values on modellers' own observation, use of secondary data from literature sources and use of lookup tables which are functions that relate a variable and its causes by sketching a graph of the relationship. The lookup tables can be based on actual data, expert opinion, experiments or artificial data.

3.6.3.4   *Model validation*

A fundamental element of all models, and especially system dynamics, is model validation. It is a continuous series of actions of testing and establishing confidence in the model's usefulness (Forrester & Senge, 1980; Sterman, Richardson & Davidsen, 1988). Building confidence is a gradual process that runs throughout the whole course of model building, beginning with model conceptualisation up until implementation of policy recommendations (Forrester & Senge, 1980; Sterman et al, 1988). Forrester (1961) further emphasises that model validation ought to be judged with reference to a particular purpose, that is, detached from purpose, model validity is worthless. This is considered important for system dynamics models because they are constructed to accomplish a purpose (Holling, 1978; Barlas & Carpenter, 1990).

The purpose of the system dynamics model informs both the conceptual/qualitative-model (i.e. causal loop diagram) and the quantitative/simulation model. During the conceptual modelling phase, focus is on proper problem conceptualisation and on causal relationships identification. If the causal relationships conflict with a known causality or if the problem is misrepresented, then the model outcomes or recommendations would be misleading. In addition, the system dynamics model would be refuted even though the model

behaviour matches observed behaviour. It is for these reasons that in system dynamics, validation of the internal structure of the model is priority, followed by behaviour validity. The accuracy of the behaviour of the model is only meaningful once adequate confidence on model structure was established prior (Barlas, 1989; Barlas, 1994).

Though lack of formal validation tools is regularly the critic of system dynamics methodology (Barlas, 1994), the literature discloses a number of validation tests (Forrester & Senge 1980; Richardson & Pugh, 1981; Sterman, 2000). Structural validity concerns establishing validity with regards to the internal structure of the model. These tests include comparing model structure versus knowledge of the real system or versus general knowledge about the system as evidenced by literature (Barlas, 1994). Five direct structure validation tests were introduced by Forrester and Senge (1980) for system dynamics, namely structure verification, dimensional consistency, boundary adequacy, extreme condition and parameter verification tests. Behaviour validity on the other hand, seeks to establish the extent to which the model's behaviour matches the behaviour of the real system (Barlas, 1996). The focus is on patterns. Among the behaviour validation tools are the behaviour sensitivity test, reference test, modified-behaviour prediction and a face validity test. Finally, based on models being simple representations of actual-world situations, they can never be fully validated (Sterman, 2000) and in addition, no particular test can completely verify a model, but the confidence in a model is improved as the model passes a range of tests (Forrester & Senge, 1980).

3.6.3.5   *Policy design and evaluation*

As highlighted earlier, the intentions of system dynamics are to understand the behaviour of systems by detecting the factors driving the behaviour of the system and observing how the system responds to alterations of the said factors and then making policy recommendations that improve system performance. Policy design and evaluation aimed at alleviating existing problems in the system is therefore central to the development of system dynamics models. Policy scenarios are crafted based on the model outcomes/learning from the model and from anticipations/expectations in the real world (Sterman, 2000). Key model outcomes are then examined and recommendations made that improve the performance of the system (Grant, Pederson & Marin, 1997).

Having discussed the origins of system dynamics, its main features and the modelling process, sufficient background has therefore been provided on system dynamics, the following section discusses the links between system dynamics and social theory by exploring the social theoretic assumptions underpinning system dynamics practice. Specific focus is on the system dynamics paradigms of Pruyt (2006).

3.6.4   Social theoretic assumptions underpinning system dynamics practice

A number of researchers have attempted to position systems sciences within a pragmatic framework for social theories. For instance, Checkland (1981) and Lane (1994) have used the Burrell-Morgan framework of social sciences to position systems sciences and operational research methodologies, while Lane (2001) used the Burrell-Morgan Framework to map system dynamics. On the other hand, Pruyt (2006) considers a different framework founded and extended from the frameworks of Mertens (2002) and Tashakkori and Teddlie (1998), which he uses to discuss various strands of system dynamics practice. To avoid duplication, extensive discussions of these frameworks and attempts at placing system dynamics within a social theory can be found in the said studies. A summary, however, of Pruyt's extended paradigmatic table is provided and discussed in this section, mainly in order to inform the ontological, epistemological and methodological placement of this current study and its links with the schools of economic thought that underpin it (section 3.8), and partly in order to help position the energy literature utilizing system dynamics approach (3.7). Pruyt's extended paradigmatic table consists of six paradigms, namely positivist, post-positivist, critical pluralism, pragmatism, constructivism and transformative-emancipatory-critical (see Table 3.3).

Table 3.3: Pruyt's extended paradigm table

	Positivist	Post-positivist	Critical pluralism	Pragmatism	Transformative-emancipatory-critical	Constructivism
Ontology	(Naive) 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 & qualitative	Quantitative & qualitative	Qualitative, quantitative, 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 & effects
Logic	Deductive	Primarily deductive	Deductive & Inductive	Deductive & inductive	Deductive & inductive	Inductive
Appropriateness of model	Refutable but not refuted	Validated models, results closest to the real world	Do models lead to real insight & understanding	Closest to goal or own value system?	Advancing justice, democracy & oppressed?	Confidence in constructed model
Appropriateness of strategies	Optimal strategy	Probably optimal 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)

Positivist system dynamics & Post-positivist system dynamics: The ontological position of positivist (functionalist or objectivist) system dynamics practices is that the modelled systems resemble real-world systems (i.e. realist) and that of post-positivist is also realist. The epistemological position of positivist

system dynamics practices is that the causal loop and stock and flow diagrams are good objective representations of reality and that the manner to replicate the dynamics of the real-world systems is through quantitative system dynamics simulation (i.e. objective). On the other hand, the epistemological position of post-positivist system dynamics practices is also objective but to a lesser extent contains subjective elements. Axiologically positivist system dynamicists assume value-free investigations which are achieved, among other factors, through modelling the physical flows whereas axiologically post-positivist system dynamicists though they acknowledge that the researcher's theories and values influence knowledge and that modelling and interpretation are value-laden, the employment of the scientific method controls for such influences.

The practice of system dynamics by positivist assumes that real causes may be pinned down and measurement and interpretation of results is quantitative and objective and if models do not resemble reality they should be refuted which suggests that model validation is done by comparing simulation results to real-world facts. On the other hand, the practice of system dynamics by post-positivist assumes lawful, reasonably stable causal relations which could be probabilistically known and which only change slightly over time. The method of research is primarily quantitative with qualitative models (causal loop diagrams) used with the purpose of developing quantitative models. Model theories are tested, validated or refuted and the logic is principally deductive and the best model is one that mostly resembles the actual-world system. Typical representations of positivist system dynamics practice are neoclassical economics modelling, marginal practices, optimization, forecasting and policy engineering while post-positivist system dynamics practice is to a lesser extent represented in contemporary system dynamics.

Critical pluralist system dynamics: The ontological view of this system dynamics practice is realist in that the actual world exists. The epistemology is, however, subjective in that the actual world is accessible sorely through subjective mental models. The axiology is value-laden in terms of research choice, methodologies, assumptions, etc. The research method is both quantitative and qualitative and modelling is a repetitive series of actions of building, simulation and interpretation and is therefore inductive and deductive. Causality is fundamental to understanding the real world as it generates model behaviour. The models are constructed in cooperation with stakeholders, making them ideographic. The models are centred on generating understanding between the underlying structures and ensuing dynamics and are deemed proper if they are helpful in altering mental models and actual-world structures.

Examples of critical pluralist system dynamics practice include mainstream system dynamics, interactive system dynamics focused on increasing understanding, and broad-system dynamics practice. The specific

ontological and epistemological positions of mainstream system dynamics seem to be indeed (moderately) realist and (moderately) subjective (Pruyt, 2006). Mainstream system dynamicists often start with qualitative system dynamics, then turn to quantitative and then qualitative. The modelling process is therefore qualitative-quantitative-qualitative in that it begins with qualitative information and diagramming (e.g. during problem definition, system conceptualization) then quantitative simulation models are developed and used (i.e. model building/formulation, simulation) but the results of simulations and analyses are interpreted and communicated qualitatively (Pruyt, 2013). Most system dynamics modelling is also highly interactive/participative (a high degree of participation of stakeholders and decision makers is desirable and often necessary) which allows for the: exchange of knowledge and information on existing systems and desired systems; gradual development of understanding, insight, confidence and commitment, and enables the address of factors omitted from the actual models (Forrester 1971; Lane 2000).

Pragmatist system dynamics: The ontological and epistemological positions for this practice in the simulation stage are primarily realist and objective respectively, while often nominalist and subjective in the modelling and explanation stages. The axiology is one of unconcern by value-ladenness of the research choice, theory used, modelling, and interpretation. The methodology is ideographic and the logic is inductive and deductive (i.e. from assumptions and perceptions the model is induced with the simulation results being deduced from simulation). Concerning the issue of causality, pragmatist system dynamicists assume that actual causality in social-economic systems cannot be exactly known as institutions, cultures, and societies evolve, altering existing causality. In addition they assume the model that is closest to reality cannot be known. The focus of pragmatist system dynamicists is not on understanding structural causality that generates observable behavior, but on models that correspond to values or work towards reaching a goal. Measurement is both qualitative and quantitative.

Constructivist system dynamics: The ontological position of this practice is relativist in that in reality systems are nonexistent but only concepts/holons associated with the knower can be described. The epistemological position is subjective in that models describe concepts from a specific viewpoint. The axiology is certainly value bound while a voluntarist human nature is supposed. The methodology is mainly qualitative and it is ideographic. This practice assumes subjective causal interpretations of real world. The models are likely used for learning about other points of view; for gaining insight into potential evolutions; for building shared interpretation; and for finding compromises amongst different views. Examples of this practice include holon dynamics and modelling as radical learning. With regards to **transformative-emancipatory-critical system dynamics:** The ontological position for this system dynamics practice is relativist while the epistemological position is subjective. Its aim is to assist the oppressed and

disadvantaged through using system dynamics tools to promote democracy and Justice. Examples of this practice include the strands of modelling as radical learning to enhance group debates and to deal with power, oppression and beliefs. An attempt at placing the system dynamics practices of the energy-related literature on Pruyt's extended paradigmatic table is attempted in the following section.

3.7   Ontology, epistemology and methodologies of energy-related system dynamics practices

Having reviewed the literature on social theoretic beliefs underlying system dynamics practice and particularly the system dynamics paradigms of Pruyt, an attempt at placing the system dynamics practices of the energy literature on Pruyt's extended paradigmatic table is attempted in this section. While it is not that easy to position the bulk of the energy literature utilizing system dynamics to study an assortment of energy issues wholly on Pruyt's extended paradigmatic table categorised in terms of ontology, epistemology, axiology, methodologies, causality, logic and appropriateness of model and strategy, due to that no detailed information is given in the articles to enable full placement, it is very clear from the model built (reviewed fully in chapter 4) that the ontological/epistemology positions and methodologies of most of the present-day energy literature corresponds with the critical pluralist paradigm and to a lesser extent the post-positivists paradigm.

Examples of these type of modelling in the energy literature are the models of: Pruyt (2007) who built a system dynamics model and used it to investigate the transition of EU-25 electricity generation system, towards a more sustainable energy system characterised by lower CO_2 emissions; Bassi, Shilling and Herren (2007) who constructed a system dynamics model designed to analyse the main energy challenges and choices faced by the United States of America in the wider context of their relation to society, environment and the economy, and with associations with rest of the world; Saysel and Hekimoglu (2010) who developed a dynamic simulation model of the electric power industry in Turkey and used it to study options for CO_2 mitigation; Ford, Vogstad and Hilary (2007) and Vogstad (2005) who modeled green electricity certificates; Jeong et al. (2008) who designed a system dynamics model for power generation costs comparison in a liquefied natural gas combined cycle and coal-based power plants while also taking into account control costs of CO_2 and NO_2; Vogstad, Botterud, Maribu and Jensen (2002) who built a system dynamics model for the Nordic electricity market and used it to investigate the short-term and long-term energy planning trade-offs. The aim was to find efficient policies to aid the transition from fossil-fueled based power supply to renewables; and Musango, Brent, Amigun, Pretorius, & Müller (2012) who used a system dynamics approach to develop a model for assessing the sustainability of bioenergy and used it to assess the effects of the development of a biodiesel industry on a number of sustainability indicators in the Eastern Cape province of South Africa.

Other examples of these system dynamics practices include those that have combined system dynamics models with other methods, for example, Pereira & Saraiva (2010, 2011) who combined system dynamics with generic algorithms, Sanchez, Barquin, Centeno and Lopez-Pea (2008) who combined system dynamics with game theoretical approaches, Tan, Anderson, Dyer and Parker (2010) who combined system dynamics with decision trees, Pasaoglu (2006) who integrated system dynamics with analytical hierarchy processes and Dyner, Ochoa and Franco (2011) who built a system dynamics model linked to an iterative algorithm. System dynamics approach has thus been used widely for modelling various energy issues. The ontological, epistemological and methodological placement of this current study and its links with the economics schools underlying this study are discussed in the following section.

3.8 The ontological, epistemological and methodological placement of this current study and its links with the economics schools underlying this study

The placement of the system dynamics research conducted in this study based on Pruyt's extended paradigmatic table is undertaken. The ontological and epistemological positions for the system dynamics that is taken in this study is realism and (moderately) objective with subjective elements. The view taken is thus that an external real-world exists (or the modeled system resembles a real-world system) and the causal loop and stock-and-flow diagrams are interesting formulations to structure, describe and understand real-world issues such as the social cost assessment issue investigated in this study. Though no primary valuation of externalities is conducted in this study, the manner of knowing and construction of this knowledge (externality costs), can only be grasped mainly through subjective views of the participants, hence the subjective stance. The methodology is mainly quantitative with qualitative models (causal loop diagrams) used for developing quantitative models. The model developed in this current study was also validated in keeping with mainstream system dynamics and due to concerns of value-ladeness. Based on Pruyt's (2006) system dynamics paradigms, the system dynamics investigation conducted in this study can therefore be categorized within the critical pluralist and post-positivist paradigms.

In section 3.5 it was determined that neoclassical and environmental economics provided the theoretical base for this study. The ontology, epistemology and methodology of both neoclassical and environmental economics were discussed to be realist, objective and quantitative, respectively, and hence to fall within the positivist research paradigm of Guba and Lincoln's classification. The proposed modelling approach (system dynamics) thus shares many elements that are consistent with the two economic disciplines that underpin this study, for instance, ontology and epistemology elements and the usage of quantitative techniques. In addition though, the modelling approach proposed in this study offers more features than

the two economic disciplines, such as non-linear structures, dynamic structures, experimental approach (Forrester, 1975a; Robertshaw, Mecca & Rerick, 1978), transdisciplinarity methods, disequilibrium approach and case study approach instead of using abstractions to develop models (Beed & Beed, 2006). Other additional attributes include that it offers a complex unitary approach with the ability to deal with large number of elements and many interactions between elements, a problem-orientated approach, empirical solutions (Forrester, 1975a; Flood & Jackson, 1991) and confidence based on model structure over coefficient accuracy, focus on closed loop information feedback structures and focus not on predictions but on understanding the structure of the system and our assumptions about it (Forrester, 1961).

3.9   Summary

A historical review of the schools of economic thought and system dynamics was provided in this chapter, with the ultimate aims of determining the schools of economic thought that underpin this study and its links with system dynamics. In pursuit of these aims, the history of economic thought was reviewed by discussing developments in the economics research field since the 16th century and through using Guba and Lincoln's social science research paradigm framework to evaluate the developments into distinct social science research paradigms. From this review it became clear that neoclassical and environmental economics provided the theoretical basis for this study. The ontology, epistemology and methodology of both neoclassical and environmental economics were discussed to be realist, objective and quantitative, respectively, and hence to fall within the positivist research paradigm of Guba and Lincoln's classification.

A review of system dynamics origins, main features, modelling process, its links with social theories and its links with the schools of economic thought that underpin this study was then conducted. From this review it became clear that while the proposed modelling approach (system dynamics) shares many elements that are consistent with neoclassical and environmental economics (for instance, through sharing the same ontological position, epistemological position (to a certain extent) and the use of quantitative techniques), the proposed modelling approach also offers more features such as non-linear structures, dynamic structures, experimental approach, transdisciplinarity methods[2], disequilibrium approach, case study approach instead of using abstractions to develop models, problem-orientated approach, empirical solutions, complex unitary approach with the ability to deal with large number of elements and many interactions between elements and confidence based on model structure over coefficient accuracy, focus on closed loop information feedback structures and focus not on predictions but on understanding the structure of the system and our assumptions about it.

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[2] Transdisciplinary methods are none discipline-specific approaches used in transdisciplinary research.

CHAPTER 4: A REVIEW OF POWER GENERATION ASSESSMENT TOOLS AND THEIR APPLICATION

4.1 Introduction

A number of approaches have been used by various researchers to evaluate power generation technologies contingent on the goals plus scopes of the applications. The application of the tools is commonly performed from a financial or environmental viewpoint. In this chapter, an overview of the various tools used by various researchers to estimate the private and/or externality costs of power generation technologies is conducted, followed by a review of the application of the assessment tools in the power sector with a special focus on coal-based power generation applications.

4.2 Power generation technologies assessment tools

The literature discloses various tools and methods that have been used by researchers to evaluate power generation technologies, which can at least be categorised into three broad categories of methods, namely financial analysis methods, impact analysis methods and systems analysis methods (see Table 4.1). The grouping shown is, however, not a precise classification due to that some of the tools fit into more than one category.

Table 4.1: Power generation technology assessment tools and methods

Financial analysis	Impact analysis	Systems analysis

▪ Life cycle cost analysis
▪ Levelised cost of energy
▪ Simple payback period
▪ Discounted payback period
▪ Internal rate of return
▪ Modified internal rate of return
▪ Net present value
	▪ Damage cost approach
	▪ Abatement cost approach
	▪ Benefit transfer technique
	  ○ Simple unit transfer
	  ○ Unit transfer with income adjustment
	  ○ Benefit function transfer
	  ○ Meta-analysis
	
	▪ Life cycle assessment (LCA)
	▪ Hybrid LCA
	  ○ Tiered hybrid LCA
	  ○ Input-output hybrid LCA
	  ○ Integrated hybrid LCA
	
	▪ Environmental impact assessment
	  ○ Ecological impact assessment
	  ○ Health impact assessment
	  ○ Social impact assessment
		▪ System dynamics
		▪ System optimization techniques
		  ○ Linear programming
		  ○ Integer programming
		  ○ Quadratic programming
		  ○ Dynamic programming
		  ○ Nonlinear programming
		  ○ Stochastic programming
		
		▪ Energy systems analysis models
		  ○ PERSUE model
		  ○ Balmorel model
		  ○ EnergyPLAN model
		  ○ MARKAL model
		  ○ HOMER model
		  ○ RETScreen software
		  ○ MESSAGE model
		  ○ POLES model

Source: Adapted from Short et al. (1995), Berglund and Soderholm, 2006; Tran (2007)

4.2.1 Financial analysis methods

Financial analysis is essential to corporate decision makers as it entails comparing revenue (cash inflows) and expenses (cash outflows, e.g. capital/investment cost, maintenance and operation costs) of power generation project alternatives and calculating the corresponding financial return ratios. The financial feasibility of an energy generation project may be assessed using different kinds of metrics such as life cycle cost analysis, levelised cost of energy, cost effectiveness analysis, return on investment, net present value and breakeven point analysis.

Life cycle cost (LCC) analysis is a method for assessing the total costs of constructing/developing, operating/owning and disposing/retiring a product/facility/project. The analysis therefore evaluates costs over a power system's /product's lifetime and is particularly useful for comparing project alternatives that fulfil similar performance requirements but vary in terms of investment/initial and operational costs (Fuller & Petersen, 1996). LCC estimating techniques may generally be categorised into parametric, analogous and detailed models. Cost estimation using a parametric model involves predicting a process's /product's cost by means of regression analysis founded on technical information and historical cost (Dean, 1995; Asiedu & Gu, 2010). Such models correlate technical information and costs with parameters such as design complexity, weight, and performance, which describe the system. They are top-down estimations and are deemed not very accurate, especially for the approximation of product costs that use new technologies (Asiedu & Gu, 2010).

Analogous models on the other hand, estimate cost by analogy/comparison through identification of a comparable product and correcting its cost analogously to the new target product (Shields & Young, 1991). The models' chief shortcoming is that they are highly judgmental (Asiedu & Gu, 2010). Detailed models are bottom-up estimation techniques that estimate direct costs of a product/activity through the use of estimates of material quantities, material prices, labour and labour rates, coupled with an allocation rate for overheads (Shields & Young, 1991; Greves & Schreiber 1993). They are data intensive as they require detailed knowledge of the product and processes but this drawback is counteracted in that bottom-up approaches can achieve the most accurate cost estimates (Asiedu & Gu, 2010). Finally, LCC analyses have been criticised for not considering environmental costs, revenues and returns.

Levelised cost of energy (LCOE) is the cost of electricity per kWh (kilowatt hour) that over the lifespan of the power generating plant fully recovers capital, fuel, operating, financial and decommissioning costs (Davis & Owens, 2003; Denholma & Margolis, 2007; Sovacool, 2008; Paltsev et al., 2011). It is thus the cost per kWh over the lifespan of the investment technology that equals the total life cycle cost when

discounted back to the base year (Short, Packey & Holt, 1995) and is hence quite synonymous with LCC analysis. Like LCC analysis the LCOE can be used to evaluate the cost-effectiveness of various power generation technologies (Park et al., 2011), but is conversely said to provide the fairest/best comparison between energy supply technologies since it takes into account not only the lifetime cost but also the lifetime energy production associated with an energy system (Bandyopadhyay, Groo, Hartley, LeBrun, & Moazed, 2008; Darling, You, Veselka, & Velosa, 2011)

There are multiple calculation methods for the LCOE depending on the level of financial detail. The most common approaches are the simplified LCOE (sLCOE) and the Financial Model Approach (FMA). The sLCOE is the minimum price at which energy must be sold over the life of the energy development to break even, i.e. the LCOE is calculated such that the project's Net Present Value (NPV) is zero (Kornbluth, Greenwood, Jordan, McCaffrey, & Erickson, 2012; Darling et al., 2011). The FMA, on the other hand, captures more complex financial considerations such as revenue requirements, taxes, subsidies and depreciation and calculates the required revenue to achieve a certain internal rate of return (Black and Veatch, 2011). Both methods (i.e. sLCOE and FMA) can be computed in real or nominal terms - that is as real LCOE or nominal LCOE. A nominal LCOE accounts for the effect of inflation over the lifetime of the energy project whereas real LCOE excludes inflation associated with fuel, operation and maintenance costs (Wang, Kurdgelashvili, Byrne, & Barnett, 2011). The choice between real and nominal LCOE is contingent on the purpose of the assessment, with the former mainly preferred by policy makers and the latter by project developers. Despite the form of LCOE selected, the most cost-effective energy technology will not change as long as all energy supply technologies are evaluated using the same method (Short et al., 1995). Finally on the downside, researchers employing LCOE have been criticised for not considering correct plant lifetimes, real load factors of the technologies, the full costs of the plant, for instance decommissioning and environmental costs, and lastly, poor treatment of the uncertainties associated with input parameters (Darling et al., 2011).

The simple payback period, internal rate of return (IRR), discounted payback period, Modified IRR (MIRR) and NPV are other financial indicators that are employed by building economists, cost engineers, operations researchers and others to evaluate (energy) projects. They are commonly computed as secondary/supplementary measures of economic evaluation and are therefore discussed briefly.

The **simple payback period** refers to the number of years that are necessary to recover the development's cost of an investment. This financial indicator provides a quick and simple way of comparing alternative energy projects but it does not consider the time value of money and returns after payback. The

discounted payback period is an upgrade of the simple payback period in that it considers the time value of money but it continues to disregard the returns after payback (Short et al., 1995). The **internal rate of return (IRR)** refers to the discount rate at which the cash inflow of a development equals its cash outflow. That is, a discount rate which makes the NPV of all cash inflows of an investment project zero. This financial indicator can be used to compare investment projects. Generally, the higher the IRR of a project, the more desirable the project. The fallacy with the IRR is that it assumes that the cash flows or interim proceeds from the projects are reinvested at the internal rate of return. In this manner it may overstate profitability (Short et al., 1995). The **modified internal rate of return (MIRR),** also called adjusted IRR, is a form of IRR that assumes that all proceeds from the investment are reinvested at a company's capital cost. The MIRR reflects the profitability of an investment project more accurately. It can be used to evaluate projects having different lifespans or scales since it accounts for varying investment rates. This is an exceptional advantage of the MIRR, especially since project ranking criteria such as IRR and NPV may produce conflicting results under such circumstances due to dissimilar reinvestment assumptions. The **net present value (NPV)** method assumes reinvestment at the discount rate while, as stated earlier, the IRR method assumes reinvestment at the IRR (Short et al., 1995).

In summary, the review of financial measures in this section discloses that different financial measures are suitable for different computations. Generally though, cost-effective energy projects are those with lowest LCOE, LCC, simple payback period and discounted payback period, plus those with high IRR, MIRR and NPV. A combination of these methods is usually used in practice when comparing investments, though different measures may provide dissimilar outcomes.

4.2.2   Impact analysis methods

Explained earlier in the initial chapters of this thesis was that all power generation technologies are accompanied by undesirable side effects at some point in their fuel cycles. They inflict costs on third parties by means of negative influences on human health, climate change, crops, biodiversity, structures, etc. (ATSE, 2009). In this section the various techniques that researchers have used to quantify and value externalities are discussed. The first section discusses how externalities are valued in theory, while the valuation of externalities in practice is covered in the second section. Section three provides an in-depth discussion of the controversies surrounding the placement of monetary values on human life. VSL methodologies are used as an example during this discussion.

4.2.2.1   *Valuation of externalities in theory*

Externalities have a real, direct effect on the utility of consumers because an economic activity that produces an externality (for example, reduce environmental quality), directly causes a change in the utility of individuals. However, externalities are generally not revealed in market transactions and thus not in market prices. So in theory, to achieve a socially optimal level of production in the presence of externalities, externalities need to be valued through monetising individuals' preferences (Sundqvist, 2000). For this reason, the valuation of externalities is theoretically based on welfare economics, which identifies the economic value of a resource as a function of individuals' preferences (i.e. is based on measuring peoples' preferences) (Kim, 2007). The valuation process is anthropocentric and preference revelation involves investigating how much people are willing to pay or accept as reparation for the environmental improvement taking place or not, respectively (Sundqvist, 2000; Kim, 2007). By so doing, economists obtain direct welfare measures associated with specific effects. The compensation principle is therefore the theoretical model of valuing externalities (Kim, 2007).

4.2.2.2   *Valuation of externalities in practice*

In practice, the literature reveals two broad classes of methods employed by scholars to value externalities, namely the damage cost approach and the abatement cost approach. The **abatement cost approach** employs the cost of mitigating or controlling damage as a proxy for the damage caused by an externality. This approach involves analysing existing/proposed regulation with the aim of identifying the marginal cost reduction strategy as required in legislation, which is then taken as an estimate of the value that regulators (and society) implicitly place on specific impacts.

The abatement cost foundation in economic theory is, however, dubious because it depends on the strong belief that regulators make optimal decisions (an assumption that regulators know the damage and abatement costs when designing regulations) (Venema & Barg, 2003; Thopil & Pouris, 2010). However, as the European Commission (1999b) explains, regulators are not aware of these costs and the manner in which they make policy decisions is not reflective of that they set abatement costs to be equivalent to social damages. Secondly, the strong assumption renders the approach irrational since it assumes precisely what it should be trying to evaluate (Office of Technology Assessment, 1994). Thirdly, an additional shortcoming of the abatement cost approach stems from that, say, at a given point in time, regulations were set such that they produce an optimal level of pollution, such a state cannot last for long since society's preferences evolve with time because of changes in information and values (Joskow, 1992). Therefore past preferences may not be reflective of actual effects and their worth to society today. Lastly, according to Joskow (1992), the condition under which abatement cost will bear a resemblance to damage cost is solely when the pollution reduction strategy used in the abatement cost approach as a basis for

externality cost estimation is based on the least cost of controlling emissions. Otherwise, the externality cost estimates will overstate the true damages.

The abatement cost approach is easier to implement as it is not as data intensive as the damage cost approach, but the drawback is that it does not offer an equivalent level of precision (Owen, 2004), as there is no relation to actual damage (Faaij et al., 1998). The abatement cost approach has been employed in various electricity externality studies, for example, the study conducted by Bernow, Biewald and Marron, (1991) and Roth and Ambs (2004). The literature in South Africa on electric sector externality studies, however, does not reflect much use of this approach.

In contrast to the abatement cost approach which estimates the cost of actions/technology that would limit or control the externality, the **damage cost approach** approximates the real externality impacts and allocates a cost to the effects by means of valuation techniques. The approach can be performed in a bottom-up or top-down fashion. The **top-down approach** estimates externality cost of environmental burdens based on national/regional level studies approximating quantities of (prevailing) pollutants and damage caused by pollutants (Sundqvist, 2000). The two main critics of the top-down approach are that it does not allow for the consideration of site specificity of impacts and the various fuel cycle stages. The approach has also been criticised for being derivative due to its dependence on previous estimates (Clarke, 1996). On the positive side, the approach is less data intensive than the bottom-up approach. Various electric sector externality studies have used the top-down approach, for example, the study by Hohmeyer (1988), Hohmeyer (1992), Friedrich and Voss (1993) and Pearce (1995). Most of the studies, however, that employed the top-down approach were conducted in the 80's and 90's. Recent studies made use of the bottom-up approach or used the benefit transfer technique that adjusts monetary estimates from earlier studies and transfers them to new settings.

The bottom-up approach, also identified as the impact pathway approach, traces contaminants and other burdens from their original source, quantifies effects and monetises effects by means of valuation techniques. For example, for pollutants the assessment originates with the determination of emissions loads from a distinct source and the dispersion of these pollutants. This is followed by the determination of marginal damages resulting from emissions using dose-response functions and finally marginal externality costs are obtained as a product of the marginal damages multiplied by their estimated monetary values.

In this approach externalities are therefore quantified in a logical manner. The approach is more in line with economic theory. However, since the approach is location specific, in principle the obtained costs are not

transferable (Kim, 2007). As evidenced by electric sector externalities studies, the bottom-up approach is the most favoured method. On the downside, the bottom-up approach is data intensive in relation to other methods and has been criticised for focusing on impact pathways that are easier to establish, so the approach omits some externality impacts due to lack of data or lack of monetisation ability (Owen, 2004).

Most of the bottom-up studies were carried out in developed economies. Examples include the electric sector externalities studies undertaken by Oak Ridge National Labouratory and Resources for the Future (ORNL & RfF) (1994), Rowe et al. (1995), European Commission (1999b) and European Commission (2005). While most recent studies used the bottom-up approach, some studies in both developing and developed nations made use of the benefit transfer technique. The valuation methods used for monetising externality impacts are discussed next.

Two types of valuation methods can be used to monetise externality impacts, namely the direct valuation method and the indirect valuation method. Linked with these two methods are a number of costing techniques. **The direct valuation method** aims to derive values using direct methods that simulate markets. They are direct in that they are directly designed to elicit willingness to pay or willingness to accept. The stated preference method, also known as the contingent ranking method and the Contingent Valuation Method (CVM), are well-known direct valuation methods. The CVM elicits preferences through asking individuals direct questions through questionnaires (i.e. individuals are asked the amount they are willing to accept or pay for the damage imposed on them (compensation) or for the avoidance of a damage) (Sundqvist, 2002; Icyk, 2006). The stated preference method, on the other hand, is based on questionnaires that are designed to elicit ranking of preferences.

The indirect valuation method, in contrast to the direct valuation method is based on actual behaviour of individuals. The various techniques aim to derive value from market observations. The damage is valued indirectly using a relationship between a marketed good and the externality. Example of indirect valuation methods include change in productivity technique, replacement cost technique, hedonic pricing method and change in income technique. The change in productivity technique is suited for measuring externality impacts that directly affect the production process, for example, those that affect the quantity and quality of output. The observable change in price is then used as a measure of the externality cost. The change in income technique is most suited to measure externality costs that are health related, for example, externalities that cause health effects are measured through individual income changes.

In the replacement cost technique, quantified expenditure necessary to replace a resource/good/service that has been affected by an externality, is used as a measure of the externality cost. The hedonic pricing method is suited to measure externalities that affect characteristics of products, for instance, for measuring noise pollution from wind turbines, house prices in both a quiet and a noisy area can be used to infer persons' willingness to pay to avoid the noise, thereby obtaining an estimate for noise pollution (Icyk, 2006).

As evidenced by the damage cost approach, especially the bottom-up valuation approach, and by the direct and indirect methods of monetising externality impacts above, the study of externalities (identifying, quantifying and monetising externalities) is a time-consuming exercise. In addition, conducting primary valuation assessments in certain contexts, especially in developing countries, might prove difficult as respondents might lack the knowledge of fully understanding what is being valued. Researchers in more recent electric sector externality studies did not necessarily conduct primary valuation studies but rather used the benefit transfer and dose-response techniques discussed below.

The benefit transfer technique does not derive monetary estimates for externalities but rather adjusts and transfers monetary approximations of externalities from earlier studies to new settings. Since extensive work on the valuation of electricity sector impacts (on the environment, on humans, etc.) has been conducted in developed countries (especially in Europe and the US), most recent works have adjusted and transferred the monetary estimates from these studies to present contents. Hence some of the electric sector studies in South Africa and elsewhere have adjusted and used these estimates.

The **Benefit transfer technique,** also called the value transfer technique, is another technique for assessing externality effects of energy technologies, adopted when there are not enough resources and time to perform primary valuation investigations (Navrud, 2004; Navrud & Ready, 2007; New Energy Externalities Developments for Sustainability (NEEDS), 2009). The unit value transfer and function transfer approaches are two key methods to benefit transfer. With the unit value transfer approach, the unit value or damage cost at the study site is taken as a proxy for the new site and is either - (i) taken simply as it is (i.e. **simple unit value transfer**); or (ii) adjusted for income differences between the study site and new sites using GDP per capita and/or adjusted for differences in the costs of living using purchase power parity indices (i.e. **unit transfer with income adjustment**). Though the simple unit value transfer method provides the easiest means of transferring estimates between sites, people between the two sites may be dissimilar in such factors as education, income and other socio-economic characteristics, which might affect the values yielded. The approach therefore ought not to be employed to transfer estimates among nations with

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diverse income levels and costs of living. In such cases the unit transfer with income adjustment works best as it makes adjustments for such differences, though it also does not correct factors such as differences in individual preferences, institutional and cultural conditions and initial environmental quality between countries/states/provinces (NEEDS, 2009).

With the benefit function approach either a benefit function - (i) at the study site is estimated and transported to the new site (i.e. **benefit function transfer**); or (ii) it is approximated from several research sites by means of meta-analysis (i.e. **meta-analysis**). The benefit function can be written as: $WTP_{ij} = b_o + b_1 H_{ij} + b_2 E_j + e$, where WTP_{ij} denotes household $i's$ willingness to pay at the site j, H_{ij} is a set of household i characteristics at site j, E_j denotes the environmental good set of attributes at site j, b_0, b_1 and b_2 are parameters while e is the error term. The bid/WTP-values can be estimated using stated preference or revealed preference methods. The benefit function transfer approach is then implemented by finding a study in the body of written works with estimates for the parameters including the constant. At the new site, the researcher collects data on household and environmental good characteristics and inserts them in the benefit function and then calculates households' WTP. Though transferring the whole benefit function is theoretically more attractive compared to transferring just unit values, for the reason that extensive information is captured by such a transfer, the main drawback of this approach is omission of pertinent variables in the WTP function (NEEDS, 2009).

Meta-analysis on the other hand, combines results from several original valuation studies into one common benefit function. In the regression analysis the outcome of each of the studies is taken as a distinct observation. But in the event of multiple outcomes from one study, various meta-regression specifications are specified. Such equations clarifying differences in unit values may subsequently be used in conjunction with data on H and E (explanatory variables) collected at the new site to construct an adjusted unit value. Meta-analysis thus permits a broader evaluation of the environmental good characteristics, population characteristics and modelling assumptions (NEEDS, 2009).

The **dose-response technique** does not derive individual preferences but uses the links between pollution and impacts and values the final impact at a market shadow price. Intensive research has been conducted in Europe and in North America on dose-response functions that connect human health to the quality of the environment. So researchers elsewhere have modified the dose–response relationships from previous studies for country-specific socio-economic conditions and estimated the health impacts using the opportunity costs of the health effects. Examples of electric sector externality studies utilising this

technique in South Africa include the study conducted by Van Horen (1997) and that conducted by Spalding-Fecher and Matibe (2003).

Life cycle assessment (LCA) is another method for assessing the environmental influences of a product or project (e.g. wind turbine). It assesses such throughout the product/project life cycle (SANS 14040, 2006), that is from the procurement of raw materials, processing, manufacturing, use and finally disposal. This analytic tool systematically defines and measures over the life cycle, all flows (e.g. materials, energy and environmental flows) that go into the investigated system from nature and those that flows out from the system to nature (Ampofo-Anti, 2008; Varun & Ravi, 2009). A LCA study consists of four components, namely the goal and scope (which describes the aim of the assessment, the system and its borders and the functional unit), life-cycle inventory stage (which involves the collection of all the materials, resources and environmental inflows and outflows), life-cycle impact assessment (which conventionally involves classifying the inventory flows into specific impact classes (e.g. global warming) then normalization and weighting of the impacts) and lastly, interpretation of the study results (Tan & Culaba, 2003; Scientific Applications International Corporation, 2006).

As an environmental assessment tool, LCA is favoured because it systematically captures the environmental performance of products over their whole life cycle while embracing all processes, material, energy and environmental flows (Varun & Ravi, 2009). This strength is, however, conditional on the comprehensiveness of the LCA. LCA can also be used as a technique for detecting the transfer of environmental impacts between life-cycle stages or between environmental media, thereby serving as an instrument for detecting possibilities for improvements with the intention of reducing negative impacts on the environment, human health and resource depletion (Sherwani, Usmani & Varun, 2010). This yields vital environmental trade-offs information that can be beneficial to decision makers and managers. On the downside, LCA will not determine the most cost-effective products or processes owing to cost data being missing (Kannan, Leong, Osman & Ho, 2007). Lastly, conducting an LCA may be time consuming and resource demanding, contingent on the comprehensiveness of the LCA (Scientific Applications International Corporation, 2006).

Hybrid LCA refers to any method that combines LCA and input-output analysis (IOA). It is an environmental-economic tool that has been employed by researchers to study environmental and economic issues. Basically IOA is a quantitative method that describes the monetary or physical flows amongst various sectors in the national economy. The economic system's sectoral structure is described by I-O tables while sectoral changes within the system are analysed by I-O models. The tool takes a top-down linear approach to describe industrial structure. It can analyse the entire world economy, national economy, regional area

or even an enterprise. The basic unit of analysis is either a sector, industry or a product group (Leontief, 1986). Economists began applying IOA to environmental issues and problems since the late 1960's, through extending the I-O accounting framework with environmental data.

Three kinds of hybrid LCAs exist namely, input-output hybrid LCA, integrated hybrid LCA and tiered hybrid LCA (Huppes & Suh, 2002). **Tiered hybrid LCA** is a tool that develops and analyses separately the I-O system and process-based system (i.e. LCA). Direct, downstream and lower-order upstream requirements are covered in a thorough process LCA, while IOA is used to examine higher-order requirements (Lenzen, 2001). The tool combines the advantages of site specificity and completeness. **Integrated hybrid LCA** develops independently and merges systematically process-based system and IO-based system (Huppes & Suh, 2002). The two systems become intricately looped. Total production in the I-O system is used to normalise monetary flows whereas the operation time in the process-specific part of life-cycle inventory technology matrix is used to normalise physical product flows (Huppes & Suh, 2002). **Input-output hybrid LCA (IOA-LCA)** starts off from a conventional IOA by disaggregating part of the I-O table in the event of availability of comprehensive sector-based monetary data. Furthermore, substitution of sectoral I-O data with detailed process data or its augmentation with sectoral physical unit data can be conducted. The disaggregation, substitution and augmentation of the direct requirements matrix with process data may result in undesirable flow-on effects (Lenzen, 2001). IOA-LCA has generally been regarded as a quick data collection strategy whose results in comparing products should be interpreted as relative performance indicators rather than absolute indicators (Joshi, 2000).

The hybrid LCA models are linear models whose results represent economic-environmental impacts through industrial sectors' production in line with increased demand. Accordingly, downstream phases such as use and decommissioning phases are not explicitly incorporated in the results (Lenzen, 2001). Moreover, an industry sector embodies an assortment of industry types – this form of aggregation therefore ignores the diversity of industries, products and production methods (Weisser, 2007). Some researchers such as Gronow (2001) find it illogical that price levels affect the estimation of emissions and materials use. The models are incomplete due to considerations of a limited number of environmental effects. Many assumptions also go into crafting the impact vectors (i.e. the values for the environmental impacts and materials consumption) but even so, the I-O data are more unreliable than process LCA data (Treloar & Love, 2000) owing to uncertainty inherent in original data (source data uncertainty), estimation uncertainty of capital flow, allocation uncertainty, imports assumption uncertainty and gate-to-grave truncation error (Lenzen, 2001). Lastly, though the models combine economic and natural systems, the

study of ecological processes interconnections is mostly unsuccessful partly because they are most often too complex to fit into the rigid I-O framework (Fankhauser & McCoy, 1995).

Environmental Impact Assessment (EIA), also termed environmental auditing, environmental impact analysis, environmental appraisal or environmental assessment, is a site-specific environmental management tool for assessing the effects of a planned activity on the environment - social, economic and biophysical dimensions (Ministry of Environment and Tourism, 1997; Hugo, 2004; Southern African Institute for Environmental Assessment, 2004). The holistic definition of EIA thus given encompasses social, health and ecological impact assessments and EIA practitioner teams should therefore encompass expertise from these fields.

The literature presents various EIA models (Weaver, 2003; Hugo, 2004), but common to the models are the main phases in the EIA process. These are project pre-feasibility/screening phase (which is the key planning stage though with minimal information on the design of the proposed development, in this phase a decision is arrived at on whether or not to subject a project to a full EIA, based on evaluating the project mainly against simple checklists for the type of activity), scoping phase (which determines the proposed development's nature of impacts, extent of impacts, their significance and whether they are direct or indirect, or reversible or not – this phase is therefore about identifying significant issues and eliminating insignificant ones), preparation of the draft EIA statement/report, draft EIA statement review/environmental management plan (which assesses the quality of the draft EIA report in terms of data gathered, models used for impact prediction, findings obtained, stakeholders' views on findings and ensures strong commitment to the implementation of the environment management plan), monitoring (which assesses the occurrence of the predicted environmental impacts and checks the effectiveness of mitigation measures), environmental auditing (which audits the performance of the development in line with the final EIA statement) and decommission (which ensures rehabilitation of the environment once operations cease) (Hugo, 2004; Nhamo & Inyang, 2011). The EIA tool thus unveils to decision makers the likely implications of a development project. It is an imperative guide to decision making because it integrates into the planning process of development projects, social and biophysical considerations at the same time that financial and technical factors are considered. It enables the mitigation of adverse environmental effects and enhancement of positive impacts early in the design stages (Ministry of Environment and Tourism, 1997.

In summary, the review of impact analysis tools in this section discloses that various tools are suited for identifying, quantifying and monetising externalities. The advantages and limitations of the reviewed tools

were also discussed. Depending on the aims of the investigations and a number of issues surrounding the research such as availability/unavailability of previous primary valuation studies, various researchers (e.g. environmental economists, environmental practitioners, operation researchers, etc.) have therefore employed various impact analysis tools. The controversies of valuing human life are discussed next.

4.2.2.3 *Controversies of valuing human life*

Among the highest disputed areas of public policy are those concerning dangers to the safety and health of humans. At the heart of these disputes is the valuation of human life. The placement of an economic value on human life is likely to stimulate ethical, philosophical and religious questions. It therefore not unusual for people to object the placement of a monetary value to human life, arbitrating such an exercise to be heartless and belittling the value of existence. Even though some considers a human life priceless or are rather against the expression of the economic value of human life, conflicting demands on limited public funds means it is impossible to save all life, making tradeoffs necessary on programs that saves lives. The refutation to attach explicitly a value on human life simply forces implicit valuations that are reflected in decisions on either to fund or not public projects along with decisions to enforce other regulatory activities (Brannon, 2005; Landefeld & Seskin, 1982). Assigning a value to life is an effort towards making rational decisions about these tradeoffs. Controversy, however, still remains on the correct method for generating approximations for valuing risks to life. Though a standard concept for placing value on human life does not exist, when observing health risk/reward trade-offs made by people, economist frequently consider the value of a statistical life (VSL) (Brannon, 2005). In the following paragraphs VSL methodologies and the criticisms surrounding them are reviewed.

The VSL is the amount of money a person/society is willing to spend to save a human life or rather the value placed on a change in the risk of death. Owing to lack of a formal market for lives, the VSL is only measured through indirect methods, for example through surveys or by means of observing the behavior of humans in risky environments (Brannon, 2005). One manner by which economists estimate the VSL is by observing a person's actual choice, through observing the risks humans are voluntarily willing to take and how much they must be paid for taking them. This is the revealed preferences method (Mankiw, 2012). The implied value of life is inferred from labor-market choices. Much of the revealed preference research uses a wage hedonic approach, which observes the changes in wages as job characteristics changes. Economists estimate the VSL by studying the differences in pay between jobs by controlling for many job characteristics and hence establish the share of the wage compensating for the risk of injury or death. This number (i.e. the risk premium) is then multiplied by the inverse of the risk difference and is said to be the VSL (Leeth & Ruser, 2003; Viscusi, 2003; Viscusi & Aldy, 2003).

Shogren and Stamland (2001) contend that almost all revealed preference assessments are biased upwards. The average VSL is less than the marginal VSL due to that the pay at a specific job is just adequate to lure the marginal employee. Another issue with this method is the appropriate time period that should be used to measure fatality rates. Such is imperative because death rates fluctuate yearly and the choice can affect the VSL. Another problem is that of which form of death rate to use - workers' perceived chances of death or actual death rates. In any case, wage premiums are most probably based on perceived risk than actual risk, so the two can differ. Yet another issue concerns whether it is okay to calculate the VSL by simply multiply the risk premium by the inverse of the risk assumed. Researchers such as Krupnick, Cropper, Alberini, Simon, O'Brien and Goeree, 2002) have found that the risk premium does not necessarily double if the risk doubles (nonlinearity in valuing risk reduction). Lastly, another issue with this approach is the wide variation in VSL estimates by various researchers (Brannon, 2005).

Yet another method used by economists to estimate the value placed by people on their lives is by conducting surveys and asking each person how much money he/she would accept for a marginally higher chance of dying (or how much money each person is willing to pay for mortality risk reduction). In essence each person is asked a series of questions up until the person refuse the money for the higher risk or refuse to pay any amount for risk reduction. This is a contingent valuation method. After the survey the researcher imputes the implied value of a life by each respondent and multiplies it by the inverse of the extra risk taken and averages the valuations (Krupnick et al., 2002). Problems of this approach include the subjectivity of this approach. All questions are imaginary, so why must the respondents responses truly reflect the trade-offs they are willing to make? Another problem is the "protest" vote in which a respondent insists he/she cannot be enticed by any amount of money to accept a higher risk. Should such respondent's value of life (an outlier) be considered in the final average or not or should researchers use a median or truncate the sample? There is no consensus in this issue except that such an outlier should not form part of the estimate. Another critics concerns whether respondents accurately perceive small changes in the probability of death (Murphy, Allen, Stevens, & Weatherhead, 2004; Brannon, 2005), for example a 4 in 10 000 risk from a 6 in 10,000 risk.

The consumer market behavior method is another approach in which the implicit value of life is inferred from product choices, for example purchasing safety improvements like purchasing a car with antilock brakes (this device reduces the occurrence of crashes and death). The implied value of life is then inferred from the cost of this device. Criticisms of this approach include the difficulty of interpreting VSL values from different devices, the issue of whether a distinction is made between safety features from other product

attributes (i.e. the difficulty of determining the extent to which the decision of the buyer was influenced by safety consideration (e.g. purchase decisions might be influenced by proximity of the buyer to a store) and the issue of whether buyers understand the safety improvements inborn in a purchase (Brannon, 2005).

The meta-analysis method is another method. Based on existing studies of the VSL, a meta-analysis seeks to find a representative VSL through attempting to control for exogenous elements that may possibly affect the estimated VSL. Though meta-analyses vary in complexity, a complex one can consider the different risks in various studies and neutralize such differences in the final VSL. A meta-analysis though an upright tool, it is difficult to execute well due to that it can solely be performed on analogous studies using the similar statistical approximation technique. Contingent valuation studies cannot be in a meta-analysis study with revealed preference studies (Mozrek & Taylor, 2002). Another VSL estimation method is the forensic economics method often used by economists when estimating the VSL not for regulatory purposes. The value of a life is placed after death through computing the value today of the future stream of income lost by the household due to death. The contested assumptions of this approach include the issue of the growth rate of income and the deceased retirement age, and whether population averages should be used in such computations? (Brannon, 2005).

Lastly, a common criticism of VSL in regulatory examination is failure to differentiate between saving a life of a young person versus saving a life of a person close to end of life. The value of a statistical life year (VSLY) and the quality adjusted life year (QALY) are variants of VSL that make such modifications. Both approaches make an effort to compute the value of one additional year of a saved life, with the earlier correcting the value for a saved life by means of discounting future life years saved and the later correcting for the amount of life saved plus the quality of life saved. Both approaches differ from the VSL in that VSL is computed from human decisions made either directly in surveys or indirectly in market choices whereas these two approaches require no human behavior observation. The two approaches appear more appealing to policy makers than VSL computations (Brannon, 2005).

4.2.3   Systems analysis methods

Systems thinking analysis is an approach that looks at problems as parts of a whole system. It is centred on the understanding that a system can best be grasped by examining the linkages and interactions between its elements. Any kind of system, for example natural, engineered, human, scientific or conceptual can be studied by systems thinking techniques. System thinking techniques such as system dynamics, systems optimization techniques (e.g. linear, nonlinear and dynamic programming) and energy systems analysis models are discussed in this section.

System dynamics is an approach to understanding how systems behave over time. It is a causal mathematical model (Barlas, 1996) centred on understanding the structure of a system under consideration which results in observable and predictable behaviour (Forrester, 1987). It has gained recognition because of its emphasis on the structure of a system and because of its flexibility (Anand, Vrat & Dahiya, 2005). It combines theory and methods required to study the behaviour of systems. It has a capability to model an extensive diversity of processes and relations in a dynamic fashion (Auerhahn, 2008). Though system dynamics, in an integrated sense, focuses on a system, the system is disintegrated into various interrelating subsystems. It therefore facilitates the understanding of complex systems. It can also capture in an intuitive manner the complex actual-world behaviour of uncertainties which stem from nonlinear feedback constructions, in this manner providing clearer understandings of the sources of the effects of strategic action (Sterman, 2000; Johnson, Taylor & Ford, 2006).

The interactions in a system are fed via interactive feedback loops. The feedback structure of the system that is investigated is what the approach centres on. It is normally represented by means of causal loop diagrams, which provide a qualitative expression of the interactions in the system (Chi, Reiner & Nuttall, 2009), for example, interactions between burning coal for electricity and the related environmental releases, e.g. CO_2. Stock and flow diagrams are then constructed premised on the causal loop diagram and coupled with the addition of equations for all variables in the model (Anand et al., 2005). The stocks control the inertia of the investigated system and can either increase or decrease regularly. The stock in-flows and out-flows regulate the rate of change in stocks. The flow rates are characterised by such factors as the stocks level, exogenous variables and can be taken to represent the output/input of policies (Jeong et al., 2008). Lastly, system dynamics models could be readily constructed and could be used to test various alternative model specifications (Jeong et al., 2008; Chi et al., 2009).

System optimization techniques are methods that are developed to offer "best values" of system design and policy elements - values yielding highest ranks of the performance of systems (Loucks, van Beek, Stedinger, Dijkman & Villars, 2005). The methods therefore select the best element with regard to some criteria (e.g. cost or benefit) from a set of available alternatives. In general, optimization problems in general concern minimizing or maximizing a real function by way of selecting, in a systematic manner, input values from an allowable set and calculating the function's value. Mathematical-programming/optimization/constrained-optimization techniques include, linear, nonlinear, integer, quadratic, dynamic, stochastic and geometric programming. **Linear programming** is a mathematical method that determines the best outcome (e.g. lowest cost or maximum profit) in a mathematical model

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with an objective function that is linear and is subject to linear equality and inequality constraints. It has been applied to solve problems in a number of fields of study, including economics, business and engineering. It has shown worth in modelling various problems in planning, design and scheduling, allocation/assignment. **Quadratic programming,** on the other hand, studies the case where the objective function has quadratic terms, with linear equality and inequality constraints.

Integer programming, also called integer linear programming, centres on linear programmes characterised by all/some of the decision variables taking integer values. A mixed integer programming problem is characterised by some (not all) unknown variables taking integer values. A special case is binary integer programming where variables take values 0 or 1. **Dynamic programming** is a mathematical method for solving complex problems by splitting the problem into smaller sub-problems (optimization strategy). It is therefore appropriate to problems with overlapping sub-problems. The sub-problems are solved independently, their solutions stored and when needed later they are simply looked up and incorporated to reach an overall solution. The approach is useful in the event of repeating sub-problems that grow exponentially as a function of the input size. The word "dynamic" pertains to the time varying aspect of the problems. **Stochastic programming,** on the other hand, models optimization problems where a certain number of the constraints are contingent on variables that are random. The approach therefore deals with problems that involve uncertainty. Most problems in the real world almost always contain some unknown parameters. Stochastic programming has been broadly applied, for instance in investment portfolio optimization overtime and energy optimization (Wallace & Ziemba, 2005). **Nonlinear programming** models the optimization problem where either/both the objective function and constraints are characterised by nonlinear elements.

Energy systems analysis models concern the use of energy systems models for the study of the connections between various elements of energy technologies and the consequences of different decisions on the environment, physical, technical, economic and political systems (Vattenfall Research and Development Magazine, 2011). Energy technologies are devices that produce or transmit or use energy, for instance power plants, boilers, automobiles, etc., and are characterized by various attributes, namely efficiencies, costs, benefits, emissions, etc., (Energy Technology Systems Analysis Program, 2007).

Various energy systems models have been developed and may be categorised into top-down and bottom-up energy methods (Hodge, Aydogan-Cremaschi, Blau, Pekny & Reklaitis, 2008). Top-down energy models, also called macroeconomic models, address the energy-economy feedback. The models describe the economic system in detail but they typically describe in an aggregated manner the energy system and as a

subdivision of the whole economy. The technical potential of various energy technologies is thus not represented explicitly. The outcomes of the model are induced primarily by relative price changes. Top-down modellers apply general equilibrium models or models that are demand prompted (Berglund & Soderholm, 2006; Hodge et al., 2008). Top-down models, however, present the energy system as a black-box, by paying no attention to the processes and activities because the matrices used can only analyse a sector as a whole, and as a result differentiation between a range of products or production methods nor technologies is not possible (Weisser, 2007). Top-down models have been used to study a variety of issues, comprising of the role of energy or specific energy technologies in a national economic system (Papatheodorou, 1990; Galinis & van Leeuwen, 2000), and impact of greenhouse gas reduction policies (Zhang & Baranzini, 2004).

In contrast, bottom-up energy models study the energy system extensively but they do not consider the economic system in detail as in top-down models (Loschel, 2002; Berglund & Soderholm, 2006). As emphasized by Grubler et al. (2002), bottom-up models normally aim at finding the minimum-cost mix of energy technologies serving a specified energy demand. For this reason the models are optimization models that minimize total discounted system cost (or maximise the income of energy systems) conditional on technological and environmental constraints (Berglund & Soderholm, 2006; Jensen & Meibom, 2008; Karlsson & Meibom, 2008; Kiviluoma & Meibom, 2009). Bottom-up models include PERSEU, Balmorel, MARKAL, HOMER and RETScreen software.

PERSEU model is a family of material and energy flow models that apply a multi-periodic linear programming method. It aims at minimising expenditures (e.g. investment, fuel supply, variable and fixed costs) in the context of the whole energy supply system. The energy supply system techno-economic characteristics are reflected by means of applying equations that take into account technical, political and ecological restrictions. Environmental/sustainability issues can also be considered through the extension of the objective function with electricity production externality cost (Fleury, Fichtner & Rentz, 2003). **Balmorel model** is a deterministic linear optimization model which centres on optimizing investments in electricity production, heat production, storage and transmission units while meeting electricity and heat demands in each area and time period. It focuses on a number of countries. Costs minimised in the energy system include new units annualised investment costs, fuel costs, existing and new units operation and maintenance costs plus carbon dioxide quota costs. The model can also be programmed to optimise in other criteria including minimising carbon dioxide emissions (Munster, 2009). A number of countries have applied this model to analyse various technologies and market conditions (Ball, Wietschel & Rentz, 2007; Karlsson & Meibom, 2008).

EnergyPLAN model is an analytical deterministic programming model that has the ability to model different regulation strategies and to integrate fluctuating energy sources (Østergaard, 2009). It optimises energy production while meeting heat and electricity demands in each area and time period. The model minimises marginal production cost and/or fuel consumption and is designed for national analysis. Optimization is carried out manually through iterations. Among the outputs generated by the model are energy production, excess electricity production, electricity import/export, fuel consumption and carbon dioxide emissions (Lund, Duic, Krajacic & Carvalho, 2007; Munster, 2009). A number of energy systems analysis activities have been analysed using this model, including waste-to-energy technologies and renewable energy systems (Lund, 2007; Lund & Mathiesen, 2009; Munster, 2009). **MARKAL** is a linear programming model that is used for energy systems analysis (Loulou, Goldstein & Noble, 2004) that encompasses both energy demand and supply (Fishbone& Abilock, 1981; Mallah & Bansal, 2010). The MARKAL family of models minimizes cost through investment and operating decisions and has been used widely for various purposes, including comparing electricity generation technologies (Naughten, 2003), development of carbon mitigation strategies (Jegarl, Baek, Jang & Ryu, 2009), internalisation of power production externality cost (Rafaj & Kypreos, 2007) and waste management modelling (Cosmi et al. 2000; Salvia, Cosmi, Macchiato & Mangiamele, 2002). The models are intended for national, regional or global analyses.

HOMER model is an optimization model particularly designed for small, remote power systems but also makes provision for grid connection. Various energy technologies costs and the availability of energy resources are considered in this model. It further permits the assessment of economic and technical viability of the various technologies (National Renewable Energy Labouratory, 2008). **RETScreen software** is a decision-support tool designed for evaluating various energy technologies' financial feasibility, energy efficiency, cogeneration projects, benefits from clean energy production, and savings through energy efficiency projects. The model accounts for project costs, financial risk and emission reductions (RESTScreen International, 2012). Other bottom-up energy systems analysis models include **POLES** (Kouvaritakis, Soria & Isoard, 2000) and **MESSAGE** (e.g. Messner, 1997). The bottom-up models' shortcomings include that they are generally static models, with no feedback loops and time delays.

Finally, the review of the systems analysis tools in this section discloses that various models are designed for different purposes (e.g. modelling energy system, and/or economic system, and/or ecological system), different technologies (e.g. renewable energy, non-renewable energy or both), different scales of analyses (e.g. national, regional or global) and different sizes of energy systems.

4.3   A review of power generation studies

In this section electric sector studies are reviewed, with a special focus on those assessing coal-based private and/or externality costs. Sections 4.3.1 to 4.3.3 review international literature assessing power generation private costs, externality costs and studies modelling power generation systems, respectively. Sections 4.3.4 to 4.3.6 review the same for local studies. Several of such studies were conducted in the past three decades in both developing and developed nations. The studies/models differ in terms of the energy-related issues they focus on, scales of analyses (e.g. national or regional), power generation technologies they study, types of externalities they investigate, valuation methods they employ and in terms of the fuel cycle stage(s) they investigate. For these reasons the reviewed studies highlight these issues.

4.3.1   International studies assessing power generation private costs

The literature discloses several international studies that have assessed the private costs of constructing and operating coal-fired power generation technologies, for example Booras and Holt (2004), Davison, (2007), Hoffmann and Szklo (2011) and Cormos (2012). The studies mainly consider three primary air-blown coal generation technologies, namely subcritical, supercritical and ultra-supercritical pulverised coal plants. Subcritical units are the traditional Pulverised Combustion (PC) plants with steam temperatures around 538°C (1,000°F) while supercritical and ultra-supercritical units are newer, higher efficiency cycles with steam temperatures around 565°C (1,050°F) and above (e.g. 593°C (1,100°F)), respectively. Coal based Integrated Gasification Combined Cycle (IGCC) technology is also another type of coal plant that is extensively investigated in the literature, mainly developed to decrease the environmental impact of coal-based plants (Booras & Holt, 2004). Table 4.2 presents a summary of the operating performance and private costs of these coal generation technologies. The cost estimates were adjusted to 2010 US dollars ($) for comparison purposes.

As explained earlier, the LCOE is the cost of electricity per kWh or per MWh (Megawatt hour) over the lifespan of the investment technology (Short et al., 1995). Though quite synonymous with LCC analysis, it is conversely said to provide the fairest/best comparison between energy supply technologies since it takes into account not only the lifetime costs but also the lifetime electricity production of an energy system (Bandyopadhyay et al., 2008; Darling et al., 2011). It is therefore the focus of this review. In addition, due to the somewhat similarities of the two approaches, with the LCOE extending the LCC analysis a step further through factoring energy production and discounting costs, the review focuses on the LCOE. The LCOE consists of three main cost components, namely capital cost, Operation and Maintenance (O&M) costs, and fuel cost, hence the cost breakdown in Table 4.2.

Table 4.2: International studies assessing power generation private costs (2010 values)

Study	Country	Capital cost	O&M cost	Fuel Cost	LCOE	Type of plant
		$/MWh				
Booras & Holt, 2004	US	29.64	8.89	16.60	55.14	Subcritical PC plant, W/O capture, 500MW net, capacity factor 80%, Pittsburgh #8 bituminous coal
		30.95	8.89	15.42	55.26	Supercritical PC plant, W/O capture, 500MW net, Pittsburgh #8 bituminous coal
		33.32	10.91	15.30	59.53	IGCC plant with spare gasifier, W/O capture, 500MW net, Pittsburgh #8 bituminous coal
		30.83	10.20	15.30	56.33	IGCC plant with no spare gasifier, W/O capture, 500MW net, Pittsburgh #8 bituminous coal
DNR & PSCOW, 2007	US	31.38	5.41	19.47	56.26	Supercritical PC plant, W/O capture, 600MW, bituminous coal
		38.95	7.57	17.31	63.83	IGCC plant with assumed spare gasifier, W/O capture, 600MW, bituminous coal
Karmis, 2005	Virginia				73.72	Scrubbed coal, CF 70%, ∂7%, escalation
					74.84	IGCC, W/O capture, escalation
					90.48	IGCC, W/ capture, escalation
BNEF, 2011	Chile				73-155[+1]	Conventional coal plant, Transmission cost
Rubin, Rao & Chen, 2005	US				56.79	Supercritical PC plant, W/O capture
					101.15	Supercritical PC plant, W/ CCS, FGD, SCR, ESP
					59.51	IGCC plant, W/O capture, FGD, SCR, ESP
					85.75	IGCC plant, W/ CCS
IEA GHG, 2004	The Netherlands				50.70	Ultra-supercritical PC plant, W/O capture, FGD, SCR, 758MW net, bituminous coal
					72.06	Ultra-supercritical PC plant, W/ capture, FGD, SCR, 666MW net, bituminous coal
Hoffmann & Szklo, 2011	US	51.29	27.93		79.21	Subcritical PC, W/O capture, FGD, NOx & TSP control, 500MW gross, Illinois#6 bituminous
		69.60	44.86		114.46	IGCC plant with GE gasifier, W/ CCS,596MW gross, Illinois #6 bituminous coal
MIT, 2007	US	28.13	8.11	16.12	52.37	Subcritical PC, W/O capture, 500MW net,Illinois#6bituminous coal
		29.21	8.11	14.39	51.72	Supercritical PC, W/O capture, 500MWnet, Illinois #6 bituminous coal
		29.86	8.11	12.77	50.74	Ultra-supercritical PC, W/O capture, 500MW net, Illinois #6 bituminous coal
		48.90	17.31	22.07	88.28	Subcritical PC, W/ capture, 500MW net, Illinois #6 bituminous coal
		46.96	17.31	18.93	83.20	Supercritical PC, W/ capture, 500MW net,Illinois #6 bituminous coal
		45.87	17.31	16.23	79.41	Ultra-supercritical PC, W/ capture, 500MW net,Illinois #6 bituminous coal
		31.38	9.74	14.39	55.50	IGCC plant, W/O capture, 500MW net
		41.44	11.36	17.74	70.54	IGCC plant, W/ capture, 500MW net, plus CO_2 transport and storage costs
Cormos, 2012	Romania				71.68	IGCC plant, W/O CCS, Shell gasifier, 485.19MW net
					97.03	IGCC plant, W/ CCS, Shell gasifier, 433.18MW net
USEIA, 2012	US	64.9	31.5		96.4[+1.2]	Conventional coal, W/O CCS, CF 85%, transmission cost
		74.1	35.7		109.8[+1.2]	Advanced coal, W/O CCS, CF 85%, transmission cost
		91.8	45.7		137.5[+1.2]	Advanced coal with CSS, CF 85%, add transmission cost
NZEC, 2009	China				43.91	Subcritical PC plant, W/O capture, 295.1MW net, ∂ 10%, capacity factor 85%, bituminous coal
					41.90	Supercritical PC plant, W/O capture, 574.1MW net, ∂ 10%, capacity factor 85%, bituminous coal
					42.08	Ultra-supercritical PC plant, W/O capture, 824MW net, ∂10%, capacity factor 85%, bituminous coal
					71.85	Ultra-supercritical PC plant, W/ capture using MEA solvent, 824MW net, ∂ 10%, capacity factor 85%, bituminous coal
					63.98	IGCC plant, W/ capture using Selexol solvent, 661.7MW net, ∂ 10%, capacity factor 85%, bituminous coal
Davison, 2007	UK	27.92	11.17	22.34	61.43	Ultra-supercritical PC plant, W/O capture, FGD, SCR,758MW net, ∂10%, capacity factor 85%, bituminous coal
		42.45	22.34	23.46	88.24	Ultra-supercritical PC plant, W/ capture using oxy, FGD, SCR, 532MW net, ∂ 10%, capacity factor 85%, bituminous
		39.09	24.57	23.46	87.12	Ultra-supercritical PC plant, W/ capture using Flour, FGD, SCR, 666MW net, ∂10%, capacity factor 85%, bituminous

| | | 32.39 | 12.29 | 21.22 | 65.90 | IGCC Shell plant, W/O capture, 776MW net, ∂ 10%, bituminous coal |
| | | 42.45 | 21.78 | 23.46 | 87.68 | IGCC plant, W/ capture using Selexol solvent, 676MW net, 10%, bituminous coal |

PC – Pulverised Combustion; IGCC – Integrated Gasification Combined Cycle; SCR – Selective Catalytic Reduction; ESP – ElectroStatic Precipitators; W/O – without; W/ – with; CCS – Carbon Capture and Storage; ∂ – discount factor; CF – Capacity Factor.

Table 4.2 discloses that regardless of the coal technology, capital cost is the largest component of the LCOE, followed by the fuel cost and in the lower end are O&M costs. Higher LCOE estimates are also associated with coal technologies that have more pollution control technology, due to their higher capital cost, for instance, plants fitted with FGD, plants with Carbon Capture and Storage (CCS) and plants with only carbon capture. Coal technologies with only carbon capture report lower LCOE than those with CCS in spite of the coal technology in question.

Furthermore disclosed by Table 4.2 is that pulverised combustion using subcritical, supercritical and ultra-supercritical steam cycles without CCS/capture report lower LCOE than similar IGCC plants without CSS/capture, demonstrating that IGCC technology without CCS/capture is a more expensive technology compared to any of the pulverised coal boilers (such is evident in the studies by Booras & Holt, 2004; Karmis, 2005; Rubin et al., 2005; Davison, 2007; Department of Natural Resources & Public Service Commission of Wisconsin (DNR & PSCOW), 2007; Massachusetts Institute of Technology (MIT), 2007). Conversely, IGCC plants with CCS/capture are associated with lower LCOE than pulverised combustion steam cycles with CCS/capture, demonstrating the benefits of avoided CO_2 in IGCC plants over pulverised steam cycles (this is evident in the studies conducted by Rubin et al. (2005), MIT (2007) and NZEC (2009)).

In addition, Table 4.2 further shows no distinct difference between LCOE outcomes of studies that investigate subcritical, supercritical and ultra-supercritical steam cycles. For example, MIT (2007) reports $52.37, $51.72 and $50.74/MWh for subcritical, supercritical and ultra-supercritical units without carbon capture, respectively. MIT (2007) and NZEC (2009) report highest LCOE for subcritical units while Booras & Holt (2004) and the United States Energy Information Administration (USEIA) (2012) report lowest LCOE for subcritical units and high LCOE estimates for supercritical/ultra-supercritical steam cycles.

The higher efficiency units as shown in Table 4.2 are all associated with slightly higher capital cost than the subcritical units. For example, MIT (2007) reports a levelised capital cost of $29.86, $29.21 and $28.13/MWh for ultra-supercritical, supercritical and subcritical units, respectively while Booras & Holt (2004) report $55.26 and $55.14/MWh for supercritical and subcritical units, respectively. The increased efficiency offered by supercritical and ultra-supercritical boilers is one way of reducing GHG emissions per unit of power produced for the reason that less coal is burned in such units. The reduction in pollutants in

such units is not only limited to GHGs but also applies to other pollutants such as SO_2 and NO_X due to less coal being burned. Booras & Holt (2004) estimate that an ultra-supercritical unit with an efficiency of 46-48% would emit about 18-22% less CO_2/MWh of power generated than an equivalent-sized subcritical unit.

A closer look at Table 4.2 also supports the low fuel consumption of the higher efficiency boilers in that higher efficiency boilers are evidently associated with lower fuel cost in the studies by Booras & Holt (2004) and MIT (2007). These units will therefore offer lower emissions and favourable LCOE comparisons over subcritical units in coal-importing countries, that is, in countries where the fuel cost constitutes a higher fraction of the LCOE.

The LCOE of subcritical plants without capture, generally range from a low value of \$44/MWh to a higher value of \$96/MWh. In the upper-end are subcritical plants with more pollution control technology and/or plants that consider electricity transmission costs. The study by Bloomberg New Energy Finance (BNEF) (2011) which reports a high value of \$155/MWh for such plants was considered an outlier and is therefore not included in the given range. The LCOE for higher efficiency plants (i.e. supercritical and ultra-supercritical) without capture, with capture and with CCS range between \$51 - \$110/MWh, \$72 - \$88/MWh and \$101 - \$138/MWh, respectively. IGCC LCOE for plants without capture, with capture and with CCS range between \$56 - \$75/MWh, \$64 - \$90/MWh and \$86 - \$114/MWh. The estimates are sensitive to a number of factors, among which are escalation, discount rate, fuel prices and capacity factor, so most of the studies reviewed here conduct sensitivity analyses. Lastly, while LCOE is a beneficial initial step for approximating the costs of generating electricity, the tool does not consider externality costs associated with the power technologies. Studies that address externality costs of power generation technologies are discussed in the following section.

4.3.2   International studies assessing power generation externality costs

Several international studies have made attempts to quantify the externality costs of coal-based power using various valuation methods. The inflation adjusted damages (2010 values) of the reviewed studies are contained in Table 4.3. The table shows that several of these studies were conducted in Europe and in the US, with estimates varying according to the country in question, fuel cycle stage(s) studied and the range of impacts investigated.

The abatement cost approach was the earliest approach used by researchers to derive damage cost estimates of power generating units from various fuel sources. Some of the early work includes that of Schuman and Cavangh (1982), Chernick and Caverhill (1989) and Bernow et al. (1991). All three studies

focused on air emissions from fossil fuel combustion in the US, so other fuel cycle stages and their associated impacts were not investigated. Table 4.3 shows the estimates from Schuman and Cavangh to be highly variable with estimates from later studies utilising the same approach being relatively stable.

Hohmeyer (1988) was among the early researchers who used the top-down damage cost approach to derive externality estimates for a number of fuel sources including coal. Like other earlier studies, the focus was on air pollution impacts arising from the fuel combustion stage, however, Hohmeyer's own estimates are lower than that of other researchers who used the same approach (i.e. Ottinger, Wooley, Robinsson, Hodas & Babb, 1991; Pearce, Bann & Georgiou, 1992; Faaij et al., 1998) because global warming impacts were not assessed in his study. The bottom-up approach employed in these studies, however, did not allow for site specific type of impacts since it utilizes highly aggregated emissions data to approximate costs of specific pollutants.

With the development of the bottom-up approach, new studies considered site specificity and made attempts to consider the entire coal cycle, for example, European Commission (1999b) and European Commission (2005). Also due to the comprehensiveness of these studies, higher damages were realised than similar studies employing the same approach but focusing on a narrow range of impacts (for example, ORNL & RfF (1994) and European Commission (1995) who report lower damages due to the exclusion of CO_2 damages) and/or a subset of the fuel cycle stages (for example, ORNL & RfF (1994). In addition, like all studies reported in Table 4.3, the bottom-up damage cost estimates vary according to the country in which the assessments were conducted, thus making country specific assessments fundamental.

The benefit transfer technique has also been used by a number of researchers through transferring and adjusting damage cost estimates estimated using the bottom-up approach from other studies to the new contexts, for example Epstein et al. (2011), International Panel on Climate Change (IPCC) (2007a), Sevenster, Croezen, Van Valkengoed, Markowska and Donszelmann (2008) and Bjureby et al. (2008). As expected, the first two studies report damage cost estimates that are within the range of estimates reported by studies employing the bottom-up approach. The latter two studies' damage cost values are, however, not normalised to per kWh and are therefore not reported in Table 4.3.

Lastly, it is important to highlight that few studies (as evidenced by Table 4.3) focused on plant construction and that for those investigating coal mining and transportation the focus was on mainly three impacts, namely climate change impacts, human health burdens due to air pollution, and fatalities due to coal transportation. Finally, though the studies reviewed investigate generation phase externalities, only direct

emissions from combusting coal were quantified and monetised. Thereby a number of operation phase impacts, including indirect impacts linked to the material requirements of operating the plant, were not investigated.

Table 4.3: International studies on power generation externality costs (2010 values)

Study	Country	Method	Externality costs[1] US cents/kWh	Phases & impacts considered
Schuman & Cavangh, 1982	US	Abatement	0.14—99.67	Combustion phase (only CO_2 effects)
Chernick & Caverhill, 1989	US	Abatement	7.69—13.62	Combustion phase (air pollution effects, plus GHGs)
Bernow et al., 1991	US	Abatement	6.61—14.78	Combustion phase (air pollution effects, plus GHGs)
Hohmeyer, 1988	Germany	Top-down	0.15—7.82	Combustion phase (air pollution effects, not GHGs)
Ottinger et al., 1991	US	Top-down	5.80—14.19	Combustion phase (air pollution effects, plus GHGs)
Pearce et al., 1992	UK	Top-down	4.15—22.44	Combustion phase (air pollution effects, plus GHGs)
ORNL & RfF, 1994	US	Bottom-up	0.16—0.71	Mining, transport and combustion phases (air pollution effects, not CO_2)
European Commission, 1995	UK	Bottom-up	1.40	Entire fuel chain - including decommissioning (air pollution effects, not CO_2)
	Germany	Bottom-up	3.42	
European Commission, 1999b	Finland	Bottom-up	0.60—20.59	Entire fuel chain - including decommissioning (air pollution effects, plus GHGs)
	Germany	Bottom-up	2.55—25.53	
	The Netherlands	Bottom-up	1.81—26.40	
Epstein et al., 2011	US	Benefit transfer	9.48(low)	Mining, transport and combustion phases (air pollution effects, plus GHG, coal transportation accidents)
			18.07(best)	
			27.24(high)	
IPCC, 2007a	US	Benefit transfer	7.7	Mining and combustion phases (air pollution effects, plus GHG)

[1]Inflation adjusted values to 2010.

4.3.3   International studies modelling power generation systems

As evidenced by the systems modelling tools in Table 4.1 there are a variety of computer models that have been designed for energy analysis/optimization/planning. As indicated below, the various models are designed for different purposes, for example assessing and comparing energy technologies, cost minimization and reducing greenhouse gases. The models are additionally designed for different technologies (e.g. renewable energy, non-renewable energy or both) and scales of analyses (e.g. national, regional or global).

For instance, the EnergyPLAN model in the literature has mainly been used to simulate renewable-penetrations. It was used by Lund and Mathiesen (2009) and Cosic, Krajacic and Duic (2012) to design 100% renewable energy systems for Denmark and Macedonia, respectively. Liu, Lund and Mathiesen (2011) used it to study the influences and barriers of integrating wind power into China's present energy system while Lund (2006) used it to study the integration of photovoltaics - wind plus wave power - into the electricity supply system of Denmark. The model is designed for national or regional analysis. The MARKAL family of

models on the other hand, are energy/economic/environmental tools that have been used widely for various purposes, including comparing electricity generation technologies (Naughten, 2003), development of carbon mitigation strategies (Jegarl et al., 2009), internalisation of power production externality cost (Rafaj & Kypreos, 2007), analysing the market effects of CO_2 emission markets and the effects on electricity of green certificate market (Unger & Ahlgren, 2005) and waste management modelling (Cosmi et al., 2000; Salvia et al., 2002). The models have been designed for national, regional or global analyses.

The Balmorel model, like the MARKAL tools, has been used to analyse a number of issues, including security of electricity supply (Morthorst, Jensen & Meibom, 2005; Jensen & Meibom, 2008), expansion of electricity transmission (Heggedal, 2006), development of international electricity markets (Ea Energy Analyses, Hagman Energy, COWI. 2008), wind power development (Ea Energy Analyses, 2007; 2008), international green certificates markets and the trade of emissions (Lindboe, Werling, Kofoed-Wiuff & Bregnbaek, 2007). HOMER, a micro-power design tool, has also been used to determine and compare a green (solar and wind) and a diesel-based energy system in Malaysia with respect to net present cost and pollutant gas emission (Ashourian et al., 2013), to simulate a 100% renewable energy system (Lambert, Gilman & Lilienthal, 2006) and to study wind energy potential in Ethiopia (Bekele & Palm, 2009).

The energy systems analysis models thusfar reviewed show diverse application and according to Bassi et al. (2007) although being detailed tools, they do not efficiently simulate the interaction between the energy system and the main factors in the entire economy, environment and society, as does an innovative Threshold 21 (T21) model. T21 is a dynamic simulation framework built to aid extensive, integrated, long-standing, nation-wide planning with severe devotion to causality (Barney, Eberlein & Sharma, 1995). T21 can be built into a system dynamics platform (system dynamics based T21 model) (Bassi et al., 2007). The model has been adapted for developed nations like the US and Italy and developing nations such as Malawi and Mozambique. For example, in Italy it was used by the national environmental agency to study how the Italian government could meet the terms of the Kyoto Protocol GHG commitments without hindering the economy, while in Malawi it was used by the National Economic Council to analyse strategies for reaching Malawi's Vision 2020. In Mozambique it was used by the Ministry of Planning and Development to support the national visioning process, Agenda 2025 and national development planning (Millennium Institute, 2010) while in the US it was used to analyse the main energy challenges and choices faced by the state in the wider context of their relation to society, environment and the economy, and with links to the rest of the world (Bassi et al., 2007).

Other system dynamics energy models that fall into the shortcoming noted by Bassi et al. (2007) include, Energy Transition Model which is a general disequilibrium model considering only energy-economy interactions (Sterman, 1981), Feedback-Rich Energy Economy model which is a climate-economy model focusing solely on economy-climate interactions (Fiddaman, 1997), Petroleum Life Cycle Model (Sterman, Richardson & Davidsen, 1988; Davidsen, Sterman & Richardson, 1990), FOSSIL model (Backus, Green & Masevice, 1979) and IDEAS model (AES Corporation, 1993) which consider energy in isolation. The Petroleum Life Cycle Model depicts the development of the petroleum resource and ancillary industry of the US, beginning in 1870. The IDEAS model is a dynamic energy supply and demand policy simulation model of the US (i.e. an improved version of the FOSSIL model).

Most recent applications of system dynamics modelling to energy-related issues analysis include those that have focused on fossil fuels, for example, Jeong et al. (2008) designed a system dynamics model for power generation costs comparison in a coal-based power plant and a liquefied natural gas combined cycle plant while also taking into account control costs of CO_2 and NO_2. Hoffmann, Hafele and Karl (2013) analysed climate change effects on efficiency and power generation in selected German thermal power plants with once-through and closed-circuit cooling systems through a dynamic simulation model based on a system dynamics methodology. Hou, Xia, Zhang, Lou, Zhang and Xin (2009) developed a system dynamics model to forecast growth trends in coal demand, supply, reserves and pollution under several economic growth scenarios while Fan, Yang and Wei (2007) designed a system dynamics model taking into account coal industry investment, mine construction and reserves and used it to optimise coal investment size.

On the other hand, Robalino-Lopez, Mena-Nieto and Garcia-Ramos (2014) developed a system dynamics model to study the effects of improving the efficiency of fossil energy use and that of reducing fossil energy on CO_2 emissions of Ecuador while Shih and Tseng (2014) focusing on coal-fired power generation as the marginal supplier of electricity, built a system dynamics model to study the social benefits of an energy policy promoting sustainable energy. The model was used to simulate energy saving under energy efficiency improvements and renewable energy promotion. Life-cycle co-reductions of GHGs and classic air pollutants were estimated. Li, Dong, Li, Li, Li, & Wan (2012) designed a system dynamics model for a traditional industrial region in China characterized by high CO_2 emissions (Liaoning Province) and used it to simulate CO_2 emission trends under various scenarios while Feng, Chen and Zhang (2013) modeled energy consumption and CO_2 emission trends for the City of Beijing. Carbon rich fuel (coal) and low carbon fuel such as natural gas were considered. Mao, Dai, Wang, Guo, Cheng, Fang et al. (2013) concentrated on all industries in China and simulated carbon emissions and GDP growth under three scenarios using a system dynamics model. Energy consumption focused on nine energy sources including coal, natural gas and coke.

Qudrat-Ullah and Davidsen (2001) built a dynamic simulation model based on system dynamics to study the dynamics of the electricity system in Pakistan. Focus was on assessing the effects of government policy incentives to private sector investments (coal, oil and gas power plants) on resource import dependency, electricity supply and CO_2 emissions. Dastkhan and Owlia (2014) developed a regional dynamic integrated electricity model to explore the right policies for electricity generation in the Middle East. Among the technologies considered were coal, gas and solar power plants. A number of scenarios and policies were studied. Qudrat-Ullah (2013) developed a system dynamics model to understand electricity supply and demand in Canada. Coal, uranium, crude oil, natural gas, wind and hydro are among the major electricity sources considered.

Other researchers have used system dynamics to model renewable energy technologies or to study the transition towards more sustainable energy systems, for example, Saysel and Hekimoglu (2010) who developed a dynamic simulation model of electric power industry in Turkey (i.e. a model that represents the investment, production, pricing and financing structures of a number of energy technologies including coal) and used it to study options for CO_2 mitigation through fossil fuel based power early retirements and replacements with clean energy resources. Pruyt (2007) used a system dynamics model to study the transition of EU-25 electricity generation system, towards a more sustainable energy system characterised by lower CO_2 emissions while Ford et al. (2007) used system dynamics to simulate price dynamics in a market for tradable green certificates to encourage wind electricity. Vogstad et al. (2002) built a system dynamics model for the Nordic electricity market and used it to investigate the short-term and long-term energy planning trade-offs. The aim was to find efficient policies to aid the transition from fossil-fueled based power supply to renewables. Focusing on the Swiss electricity market, Ochoa and Van Ackere (2009) built a system dynamics model to study the dynamics of capacity expansion and the effects of various policies such as phasing out nuclear and imports and export electricity policies. Among the power plants considered were hydro, nuclear, solar panels and wind turbines.

Additional research in this category include that of Aslani, Helo and Naaranoja (2014) who constructed a system dynamics model to evaluate the role of renewable energy promotion policies on Finland's energy dependency, and Cepeda and Finon (2013) who built a system dynamics model for simulating electricity investment decisions in the case of either market driven or subsidized large-scale wind power development. Qudrat-Ullah (2014) developed a dynamic simulation model based on a system dynamics methodology to investigate the dynamics of electricity generation capacity in Canada. Focus was on identifying a sustainable and balanced electricity generation capacity scenario for the country. Among the energy sources considered were hydro, thermal and nuclear. Focusing on biofuel production Rendon-

Sagardi, Sanchez-Ramirez, Cortes-Robles, Alor-Hernandez and Cedillo-Campos (2014) developed a system dynamics model for assessing the viability in ethanol supply chain for biofuel generation in Mexico. The availability of cropping area, capacity of ethanol and fuel, reduction of CO_2 emissions, as well as five scenarios were evaluated. The feedstocks considered were grain sorghum and sugarcane. Also focusing on biofuels, Barisa, Romagnoli, Blumberga and Blumberga (2014) developed a system dynamics model to gain understanding into the longstanding dynamic behavior of Latvia's biodiesel market. A number of policy instruments in support of biofuel production were explored including state subsidies and increasing taxes on fossil fuels.

Other examples of energy-related system dynamics models include those that have combined system dynamics models with other methods, for example, Yu and Wei (2012) who developed a hybrid model centred on system dynamics and generic algorithm for analysis of coal production and environmental pollution load (specifically three kinds of waste - waste gas, water plus solids) in China. Dyner et al. (2011) built a system dynamics model linked to an iterative algorithm to evaluate the effects of integration of electricity markets on system expansion and security of supply while Pereira and Saraiva (2011) combined system dynamics with generic algorithms to help market agents to develop long-term generation investment plans. System dynamics was used to simulate the evolution of capacity factors, electricity demand and prices while the generic algorithm was utilized towards maximizing the profits of each generation agent (Pereira & Saraiva, 2011). Focusing on wind turbines Tan et al. (2010) combined system dynamics with decision trees to analyze investment alternatives in the face of multiple uncertainities and high managerial flexibility. The combination allowed for the consideration of dynamic complexity (system dynamics) and managerial flexibility (decision tree method).

On the other hand, Sanchez et al. (2008) combined system dynamics with game theoretical methods to study long-term investment dynamics in electricity generation while Pasaoglu (2006) built the model Liberalized Electricity Market Microworld (LEMW) which integrates system dynamics and analytical hierarchy processes. Short-term and long-term dynamics of electricty demand and supply were considered. Also considered were socio-economic and political issues like environmental impact, environmental costs and resource availability. The model permits the evaluation of various business strategies for utilities along with regulatory authorities' programs. Lastly, Vogstad (2005) combined system dynamics and experimental economics to evaluate the effect of emissions trading on the Swedish electricity market. Experiments were used to identify various trading plans for renewable energy certificates.

Systems modelling tools have therefore been developed for several countries and for addressing various energy-related issues, for example, to model fossil fuels and renewable energy, to study the transition towards more sustainable energy systems and furthermore researchers have combined energy-related system dynamics models with other methods such as game theoretical approaches, analytical hierarchy processes, generic algorithms, iterative algorithm and decision trees. However, as evidenced by the review not all facets/features of coal-based power production had been studied by the researchers, for example the models were not tailored to specific coal-based power generation technologies, did not address social cost nor permit deeper (comprehensive) and explicit understanding of coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and fuel cycle. Also evidently environmental focus was on quantifying direct GHG emissions from the coal combustion phase thus numerous combustion phase and upstream environmental impacts can still be incorporated and monetised to advance coal energy analysis.

4.3.4 Local studies assessing power generation private costs

The literature discloses a number of local studies that have studied or rather-modified, private costs of power generation technologies estimated in international studies to the South African context, for example EPRI (2010) and IRP (2011). Mokheseng (2010) estimates the NPV of solar photovoltaics and compares these to coal-based power through adjustments of cost data from the literature. EPRI (2010) provides cost and performance data on a number of power generation technologies, for example fossil fuel based technologies such as pulverised coal, IGCC, Fluidized Bed Combustion (FBC) and renewable resource based technologies such as wind, biomass and solar photovoltaics. The construction and O&M costs of the various power generation technologies were presented as overnight costs, which assumes that the plant is built overnight and for this reason the costs do not include interest and financing costs. Used as a baseline for the cost estimates were recent EPRI studies on US-based plants. Adjustment factors for materials, labour productivity and labour rates were used to convert construction costs for the US to construction costs in South Africa. Assumptions of the fraction of equipment imported and supplied locally were also made. Water consumption and CO_2 emissions were also estimated and reported in the EPRI report. The reported LCOE for various power technologies is shown in Table 4.4.

The outcomes of the EPRI report have been used to facilitate the IRP process of South Africa. The IRP (2011) investigates how South Africa's electricity demand can be met between 2010 and 2030. Various technologies' private costs under various scenarios were reported for a representative pulverised combustion plant, IGCC plant, FBC plant and other fossil–based power plants such as nuclear and

renewable energy sources like wind and solar. Emissions in the form of CO_2, NO_x, SO_2 and particulates were also estimated for the various scenarios. Pulverised coal-based power LCOE from the IRP report are also reported in Table 4.4. Other economic analysis studies in the country address renewable energy sources for example, Pouris (1987) and Du Plessis (2011).

Table 4.4 discloses the LCOE to be highly composed of capital cost, followed by fuel and O&M costs. The fuel costs are generally similar irrespective of the coal technology and plant size, though slightly higher for PC plants than IGCC plants. Plants without FGD show slightly lower LCOE than plants with FGD. The table furthermore shows pulverised units to have lower LCOE than IGCC plants. The limitations of the cost and performance estimates as stated in the EPRI report are that they are conceptualised for the South African context. South Africa's ground-up estimates as stated in the EPRI report were not feasible due to time constraints. Site and company specificity conditions are therefore not reflected by the estimates. Lastly, though the LCOE is a beneficial initial step for approximating the costs of generating electricity, the tool does not consider the externality costs linked with the power technologies. Local studies that address externalities of power generation technologies are discussed in the following section.

Table 4.4: Local studies assessing power generation private costs

Study	Capital cost	O&M cost	Fuel cost	LCOE	Type of plant
	ZAR/MWh				
EPRI, 2010	295	83	144.6	522.6	PC plant, without FGD, 4500MW net, capacity factor 85%
	305.5	84.6	144.6	534.7	PC plant, without FGD, 3000MW net, capacity factor 85%
	321.5	87.2	144.6	553.4	PC plant, without FGD, 1500MW net, capacity factor 85%
	338.8	105.5	146.5	590.8	PC plant, with FGD, 4500MW net, capacity factor 85%
	351.4	107.8	146.5	605.7	PC plant, with FGD, 3000MW net, capacity factor 85%
	373.9	111.9	146.5	632.4	PC plant, with FGD, 1500MW net, capacity factor 85%
	115.3	424	146.4	685.6	Shell IGCC, 3,865MW net
	119.1	439.8	146.4	705.2	Shell IGCC, 2,577 MW net
	125.9	468.1	146.4	740.4	Shell IGCC, 1288MW net
IRP, 2011	212	95	147	464	Pulverised fuel, capacity factor 85%
EPRI, 2010	424	155.2	146.4	685.6	IGCC – six 2x2x1 Shell IGCC
	468.1	125.9	146.4	740.4	IGCC – two 2x2x1 Shell IGCC
	536	95.2	67.3	698.5	Nuclear Areva EPR – 6 units
	629.3	118.1	64.1	811.5	Nuclear AP1000 – 6 units
	666.6	87.3	-	754.3	Wind - 10x2MW farm – wind class 6
	583	74.9	-	657.8	Wind - 100x2MW farm – wind class 6
	1859.8	166	-	2025.8	Soar - Parabolic trough, storage 9hrs, net power 125MW
	1348.7	168		1516.7	Solar - Central receiver, storage 14hrs, net power 125MW

PC – pulverised combustion; IGCC – Integrated Gasification Combined-Cycle Generation; ZAR – South African Rand

4.3.5 Local studies assessing power generation externality costs

Several local studies have made an effort to quantify the externality costs of coal-based power, for example, Dutkiewicz and De Villiers (1993), Van Horen (1997), Van Zyl, Raimondo and Leiman (2002), Spalding-Fecher and Matibe (2003) and Pretorius (2009). The studies by Van Zyl et al. (2002) and Pretorius (2009) focus strictly on the coal mining phase with Pretorius (2009) estimating the water pollution externality cost for Eskom's coal requirements to be R0.38/kWh while Van Zyl et al. (2002) estimate the impact of coal mining on the quality of water in the eMalahleni catchment to be between R8.56 million and R17.13 million (R0.12–R0.23/t). The Van Zyl study further estimates climate change impact of CH_4 emissions emitted during coal mining to range between R180 million and R1.260 billion (R0.98–R6.83/t).

The rest of the studies focus mainly on the operation phase with Dutkiewicz and De Villiers making use of the top-down approach to value externalities while the other local studies used the bottom-up approach or rather transferred damage cost estimates estimated using the bottom-up approach from international studies to the South African context. The inflation adjusted externality costs (2010 values) of the reviewed studies is shown in Table 4.5. The externality cost estimates produced by Dutkiewicz and De Villiers fall in the lower range of the estimates produced by international studies using a similar approach (see Tables 4.3 and 4.5). Those produced by Van Horen are higher than those of Spalding-Fecher and Matibe due to a broader range of impacts being considered. Nonetheless, the estimates from both studies are lower than the damage cost estimates from similar studies conducted abroad (see Tables 4.3 and 4.5), partly because of focusing on a subset of the fuel cycle stages.

Table 4.5: Local studies assessing power generation externality costs (2010 values)

Study	Method	Externality costs[1] US cents/kWh	Phases & impacts considered
Dutkiewicz & de Villiers, 1993	Top-down	0.51	
van Horen, 1997	Benefit transfer	0.76—4.27	Mainly combustion phase (air pollution effects, GHG, water consumption & mining accidents)
Spalding-Fecher & Matibe, 2003	Benefit transfer	0.34—2.24	Combustion phase (air pollution effects, GHG)
Nkambule & Blignaut, 2012	Benefit transfer	4.23—25.66	Coal mining and transportation (air pollution effects, GHGs, mortality, morbidity, water use & pollution, etc.)
Inglesi-Lotz & Blignaut, 2012	Statistical		Combustion phase (water use externality)
Riekert & Koch, 2012	Benefit transfer		Combustion phase (air pollution effects)
Blignaut et al (2012)	Benefit transfer		Combustion phase (CO_2)

[1]Own calculations based on values reported in the studies. Inflation adjusted values (ZAR) and converted to 2010 US dollars ($).

The rest of the studies in Table 4.5 are independent studies, but that were executed in a single project for a specific plant (Kusile), so their externality costs were summed. Nkambule & Blignaut (2012) focused on the externalities of mining coal and transporting it to Kusile. This study is a product of this thesis and it concentrated on climate change effects, air pollution-related health effects, mortality, morbidity, water pollution, water use externality and the loss of ecosystem services. Riekert and Koch (2012), Inglesi-Lotz

and Blignaut (2012), and Blignaut (2012) focused on the coal combustion phase in Kusile, and studied air pollution-related health effects, water consumption externality and climate change effects, respectively. The externality costs of Kusile were approximated to range between 4c/kWh – 26c/kWh, values that are comparable to those produced by similar studies conducted abroad.

The outcomes of these studies are an improvement over the earlier black-box national level studies as they focus on a specific plant and somehow disclose the links between plant type/performance and environmental and societal burdens. Nonetheless, these studies can also be improved upon by making the cause-effect relationships explicit (through a system dynamics model), by widening the breadth and width of the measurable externality costs within the combustion phase (e.g. through assessing public and occupational health impacts (fatalities and mortalities), non-CO_2 GHG impacts, etc.) and through assessing indirect burdens linked with the production and transportation of material requirements for operating Kusile, construction phase burdens, FGD system burdens (as Kusile will be fitted with this technology) and by embracing the long-term repercussions of the coal-fuel chain on the environment and social systems.

4.3.6   Local studies modelling power generation systems

Locally, there are studies that have employed computer models to analyse energy-related issues. For instance, Taviv et al. (2008) used the Long-range Energy and Alternatives Planning (LEAP) energy modelling tool to model energy demand and supply from 2005 to 2030 under alternative assumptions on energy drivers in South Africa. Haw and Hughes (2007) used two energy models, namely the LEAP system to generate South Africa's future energy demand based on GDP and population growth coupled with supply-side options for meeting demand, and the MARKAL model to optimize for least cost. Musango et al. (2009) used a partial T21 model to study energy supply and demand in South Africa, and how energy efficiency measures and nuclear energy production expansion could help meet the country's future energy requirements. Winkler et al. (2011) used the MARKAL model to project GHG emissions under business as usual in South Africa, while Hughes et al. (2007) explored a number of scenarios including final energy demand reduction by 15% lower than the forecasted 2015 levels and the 2013 renewable energy target of 10 000 GWh. Pauw (2007) used the Standard General Equilibrium model to study the probable impact that different climate change mitigation alternatives may possibly have on the South African economy with regards to the wellbeing of households, employment and GDP.

In a different application, Davis, Cohen, Hughes, Durbach & Nyatsanza, (2010) used three models, namely system dynamics modelling, statistical regression analysis and the LEAP model to study the rebound effects of energy efficiency interventions in the residential sector in South Africa and the effectiveness of measures

aimed at reducing the rebound effects. System dynamics was used to model household energy consumption behaviour, regression models were used, among other issues, to test the hypotheses generated by the system dynamics model while the LEAP model was used to assess the rebound effect and its mitigation. Other energy models have been applied to solely address renewable energy issues. For example, Dekker, Nthontho, Chowdhury and Chowdhury (2012) used HOMER software to study the economic viability of introducing photovoltaics/diesel hybrid power systems in each of the six climatic zones of South Africa, while Musango et al. (2012) used a system dynamics approach to develop a model for assessing the sustainability of bioenergy and used it to assess the effects of the development of a biodiesel industry on a number of sustainability indicators in the Eastern Cape province of South Africa.

Based on the T21 framework, South African Green Economy Modelling (SAGEM) was developed to study the transition of South Africa to a green economy. The effects of green economy investments in selected circumstances and sectors including the energy sector were assessed (Department of Environmental Affairs and United Nations Environment Programme, 2013). Though the study include coal-based electricity generation the coal electricity module and coal-related modules (e.g. water demand electricity generation module and air emissions module) are to a great extent black-boxes (e.g. in terms of coal cost, CO_2 emissions and water use) and the study pay no attention to coal technologies and life cycle analysis. In addition, the focus of the study is at a national level and it does not address externality costs and social costs.

The local literature thus discloses that various researchers have employed energy modelling tools to study an assortment of energy issues, among which is modelling South Africa's energy demand and supply (Taviv et al., 2008; Haw & Hughes 2007), modelling bioenergy supply (Musango et al., 2012); projecting the country's GHG emissions under various scenarios (Winkler et al. 2011; Hughes et al. 2007); and studying impacts of various climate change mitigation options on employment, household welfare and GDP (Pauw, 2007). None of the energy models have been employed to study coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and fuel cycle.

4.3.7   Summary

In this chapter, an overview of the various tools employed by various researchers to estimate the private and/or externality costs of power generation technologies was conducted, followed by reviewing the application of the assessment tools in the power sector with special emphasis on coal-based power generation. The review discloses that an assortment of methods and tools have been adopted by

researchers to evaluate power generation technologies contingent on the specific goals and scopes of the applications. The tools were grouped into three broad categories of methods, namely financial analysis methods, impact analysis methods and systems analysis methods. The review of financial measures discloses that different financial measures are suited for different computations. Generally though, cost effective energy projects are those with lowest LCOE, LCC, simple payback period and discounted payback period plus those with high IRR, MIRR and NPV. The review of impact analysis tools discloses that various tools are suited for identifying, quantifying and monetising externalities. Depending on the aims of the investigations and a number of issues surrounding the research (such as time and financial constraints and availability/unavailability of previous primary valuation studies), various researchers employ various impact analysis tools. The review of the systems analysis tools discloses that various systems models are designed for different purposes (e.g. modelling energy system, and/or economic system, and/or ecological system), different technologies (e.g. renewable energy, non-renewable energy or both) and different scales of analyses (e.g. national, regional or global).

Concerning the application of the tools in the power sector, the review discloses that in the past three decades a variety of studies were conducted on electric sector private and externality costs in both developed and developing countries. Earlier externality studies used the abatement cost and bottom-up approaches to derive externality costs estimates while recent studies used the bottom-up approach and/or benefit transfer technique to estimate externality costs of power generation. The studies differ in terms of the types of externalities they focus on, the fuel-cycle stage(s) they investigate, and they do not factor in the long-standing repercussions of the technologies on the environment and social systems. The most investigated externalities internationally and locally are climate change and human health impacts associated with airborne pollution from coal combustion. More attention is still paid to the power generation phase even in more recent studies. These differences in scope affect the outcomes of the studies, make comparing them difficult, and highlight the need for comprehensive externality investigations that widen the range of externalities studied, that consider the various fuel-cycle stages and that embrace the long-term repercussions of the technologies. A systematic investigation of burdens in a life-cycle manner, can limit the exclusion of important externalities in the coal fuel chain, for example, coal mining and processing externalities, coal transportation-related externalities, plant construction-related impacts and can ensure that externality assessments are reflective of how the plant and its associate upstream and downstream processes are operated.

Finally, the literature discloses that systems modelling tools have been developed for several countries and for addressing various energy-related issues (locally the models are mainly used for modelling energy

supply and demand, projecting GHG emissions and studying climate change mitigation options), however, as evidenced by the review not all facets/features of coal-based power production had been studied by the researchers, for example, the models were not tailored to specific coal-based power generation technologies, did not address social cost nor permit deeper (comprehensive) and explicit understanding of coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and fuel cycle.

Specifically, the top-down and bottom-up energy systems models were found to offer piecemeal information that limits deeper understanding of energy technologies and their consequent economic, environmental and societal impacts. This was so because the top-down models presented the energy system as a black-box, by paying no attention to the processes and activities because the matrices used can only analyse a sector as a whole, and as a result differentiation between a range of products or production methods nor technologies was not possible. In addition, environmental focus was on GHGs and the links between plant type/performance and environmental/societal burdens were hidden. The bottom-up models' shortcomings included that they are generally static models, with no feedback loops and time delays. In addition, they optimized for least cost in private terms not in social terms, and environmental focus was on GHGs, especially direct GHG emissions from the coal combustion phase. As a result numerous combustion phase and upstream burdens can still be incorporated and monetised to advance coal energy analysis.

Argued in this study is that a comprehensive assessment of social costs is highly necessary to aid decision-making on least social cost energy options for future energy supply. Advocated for such an assessment is a systems thinking approach namely, system dynamics along a life-cycle viewpoint. The current study thus develops a system dynamics model for understanding coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and fuel cycle.

CHAPTER 5:   RESEARH DESIGN AND METHODS

5.1   Introduction

Research designs are detailed plans and procedures outlining how a research project will be conducted. The designs explain and motivate decisions taken by the researcher regarding the philosophical beliefs that underpins the study (research philosophy/paradigm), the strategy of inquiry for the study (research approach) and the specific methods of data collection, analysis and interpretation (research methods) (Creswell, 2008). This chapter therefore discusses in detail the three main components of the study's research design, namely the research philosophy/paradigm that underpins the study, the strategy of inquiry and the specific research methods that were used to collect and analyse data so as to realize the specific objectives of the study.

5.2   Research paradigm/philosophy

The primary aim of this section is to discuss the research paradigm that underpins this study. In chapter 3 the research conducted in this study was grounded within the economic discipline of study in which it falls and the use of a systems approach to model the life-cycle burdens and social costs of coal-based electricity generation was motivated through studying the links between system dynamics and the schools of economic thought that underpin this study. In pursuit of these aims: the concept of research paradigms was defined; a discussion of Guba and Lincoln's social science research paradigm framework for deliberating main matters of research methodology in social science was conducted; a review of the history of economic thought and the classification of the economic disciplines according to the research paradigms of Guba and Lincoln were conducted; and a review of the literature on social theoretic beliefs underlying system dynamics practice, particularly the system dynamics paradigms of Pruyt was conducted. Based on this information an attempt was made to: determine the schools of economic thought that underpin this study and to classify them according to the research paradigms of Guba and Lincoln; to place the system dynamics practice of this current study on Pruyt's extended paradigmatic table; and to study the links between system dynamics and the schools of economic thought that underpin this study.

The review of economic thought disclosed that the main concepts in this study, namely production, externalities and social cost are rooted in neoclassical and environmental economics, particularly, in welfare economic theory, theory of production and Pareto efficiency. Neoclassical and environmental economics are therefore the main economic disciplines that provide the theoretical basis for this study. The ontology (i.e. the philosophical beliefs/assumptions researchers place on the nature of reality),

epistemology (i.e. the nature of knowing and construction of knowledge) and methodology (i.e. the procedures and techniques the researcher use to investigate what can be known) of both neoclassical and environmental economics were discussed to be realist, objective and quantitative, respectively, and hence to fall within the positivist research paradigm of Guba and Lincoln's classification (i.e. both schools acknowledges a reality that is controlled by absolute laws of nature, views economics as an objective science that is value free and use quantitative methods or mathematical techniques).

The ontological and epistemological positions for the system dynamics that is taken in this study is realism and (moderately) objective with subjective elements. The view taken is thus that an external real-world exists (or the modeled system resembles a real-world system) and the causal loop and stock and flow diagrams are interesting formulations to structure, describe and understand real-world issues such as the life-cycle burdens and social costs assessment issue investigated in this study. Though no primary valuation of externalities is conducted in this study, the manner of knowing and construction of this knowledge (externality costs), can only be grasped mainly through subjective views of the participants, hence the subjective stance. The methodology is mainly quantitative with qualitative models (causal loop diagrams) used for developing quantitative models. The model developed in this current study was also validated in keeping with mainstream system dynamics and due to concerns of value-ladeness. Based on Pruyt's (2006) system dynamics paradigms, the system dynamics investigation conducted in this study can therefore be categorized within the critical pluralist and post-positivist paradigms.

The modelling approach (i.e. system dynamics) thus shares many elements that are consistent with the two economic schools that underpin this study, for instance, through sharing the same ontological position, epistemological position (to a certain extent) and the use of quantitative techniques. In addition though, the proposed modelling approach also offers more features such as non-linear structures, dynamic structures, experimental approach, transdisciplinarity methods, disequilibrium approach, case study approach, problem-orientated approach, empirical solutions, complex unitary approach with the ability to deal with large number of elements and many interactions between elements and confidence based on model structure over coefficient accuracy, focus on closed loop information feedback structures and focus not on predictions but on understanding the structure of the system and our assumptions about it.

5.3   Description of inquiry strategy

An inquiry/research strategy refers to the broad approach that a researcher will employ to address the research problem. In essence, a research strategy provides important links between the research paradigm and data collection and analysis methods. The choice of a specific inquiry strategy will therefore determine

the data collection methods and indirectly affect the decisions concerning suitable data analysis techniques. Research strategies are therefore not in themselves methods for collecting/analysing data (Hiles, 1999).

In the previous section while discussing the research paradigms underpinning this study, it was highlighted in passing that the goal of the study necessitates a quantitative approach, in this section quantitative research together with other core characteristics of the current study are discussed in more detail.

Quantitative research have been seen to be a more scientific and objective form of research (Blaxter, Hughes & Tight, 2006) that is intended to scientifically elucidate phenomenon and issues linked with phenomenon using numerical data. The research approach attempts exact/specific measurement of phenomenon by soliciting answers to such questions as how much, how many, how often, who and when Cooper & Schindler, 2006; Fox & Bayat, 2007). These questions are descriptive as they aim at describing the phenomena under investigation (descriptive research). Looking at the first two objectives of the study, a descriptive quantitative strategy of inquiry is well suited to understanding the resource inputs, material requirements and private costs of building, operating and maintaining a coal-fired power station (objective 1) and to understanding the coal-fuel cycle environmental and societal burdens and costs (objective 2).

Quantitative research may also answer the why and how questions if the aim is to provide explanations for phenomena (i.e., if the aim is to establish cause(s)-effect(s) of phenomena) (Plack, 2005). The proposed study is thus also explanatory in nature in that it seeks to develop and validate a system dynamics model for understanding coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and fuel cycle (objective 3). The current study is therefore classified as using a descriptive and explanatory quantitative strategy of inquiry.

The current study can further be classified as pure research (as opposed to applied research). This is attributable to that the study does not directly focus on solving a specific business/managerial problem (applied research), it is therefore classified as pure research as it is carried out for the sake of advancing human knowledge (Saunders, Lewis & Thornhill, 2009) through understanding coal-based power generation fuel-cycle processes, burdens and social costs. It can also be classified as an empirical study, for the reason that the researcher re-analyzes existing data (Babbie & Mouton, 2001). More information on data collection is given in section 5.4.3.

5.4 Research method

The ultimate purpose of this study is to develop a COAL-based Power and Social Cost Assessment (COALPSCA) Model for understanding coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and fuel cycle. The research methodology chosen to attain this objective is system dynamics. In chapter 3, a number of modelling steps to building system dynamics models were discussed. In this study the system dynamics modelling steps followed when developing the COALPSCA Model were those suggested by Roberts et al. (1983), Ford (1999) and Sterman (2000) but prior to commencing with system dynamics modelling two more modelling steps were incorporated. The methodological framework that was followed in this study is presented in Figure 5.1 and is discussed in the following sub-sections.

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┌────────────────────────────────────────────────────────────┐
│                        Study scope                          │
│   •   Study site                                            │
│   •   Coal-fuel cycle stages                                │
│   •   Societal and environmental burdens/impacts            │
└────────────────────────────────────────────────────────────┘
                              ▼
┌────────────────────────────────────────────────────────────┐
│                   Data colletion process                    │
│   •   Compiling an inventory of materials and resource requirements │
│   •   Compiling an inventory of private costs               │
│   •   Compiling an inventory of environmental and health burdens │
└────────────────────────────────────────────────────────────┘
                              ▼
┌────────────────────────────────────────────────────────────┐
│                 System dynamics modelling                   │
│   •   Problem formulation                                   │
│   •   Dynamic hypothesis formulation                        │
│   •   Model formulation (structure and equations)           │
│   •   Model validation                                      │
│   •   Policy design and evaluation                          │
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Figure 5.1: Procedural framework

5.4.1 Study site: Kusile power station and supporting collieries

In chapter 1 it was highlighted that this study will focus on the energy sector and particularly on coal-based power generation developments. In chapter 2 background information on the South African power industry was provided. Focusing on the dominant power utility (i.e. Eskom) the existing and future Eskom power

stations were presented in Table 2.2. The utility runs 10 base load power stations with three additional power stations which have been or are being returned to service. All 13 power stations use conventional pulverised-coal technology and are fitted with electrostatic precipitators in order to reduce particulate emissions. On average, the utility's power stations was said to have a generation capacity of 3 400 Megawatt (MW) with a wet re-circulating cooling process and are fitted with precipitators to control dust (Wassung, 2010). Two new power stations are, however, currently under construction, namely Kusile and Medupi power stations in the Witbank and Waterberg coalfields, respectively. These two new power stations are considerably larger than the average power station described above (i.e. with capacities above 4 700MW) and will use a variety of new technologies (e.g. combustion technology, cooling system and pollution abatement).

Originally based on these information the plan was to select two plants as representative of South Africa's power plants – an old plant representing old technology and capacity as described above and one of the new power stations in particular Kusile power station as it was reckoned that such a plant better represent the cost structure and societal and environmental impacts of future coal-fired power stations in South Africa. The unwillingness in the end of Eskom to share data on an old existing plant resulted in the study focusing on only Kusile power station as a case study.

The Kusile power station plant is situated in the Mpumalanga province, south of the N4 highway between eMalahleni and Bronkhorstspruit (see Figure 5.2). It is currently under construction and is located on the Hartbeesfontein and Klipfontein farms. The site covers approximately 5 200 hectares and was previously used for maize farming and cattle grazing (NINHAM SHAND, 2007; Eskom, 2010b). The plant will consist of six units, each having 800MW generating capacity, yielding a maximum installed capacity of 4 800MW. The power station is expected to be fully operational in 2018/19 with the first unit coming into operation towards the end of 2014 (Eskom, 2012a). It has a projected lifespan of 50 years (Zitholele Consulting, 2011).

Unlike conventional plants, Kusile will use a variety of new technologies with regards to its combustion technology, cooling system and pollution abatement. As opposed to conventional pulverised-coal technology that is used in all of Eskom's plants, Kusile will use supercritical technology. In a pulverised-coal power plant the coal is firstly fine-crushed into a powder and then fed into a boiler where it is burnt to create heat. The heat produces steam, which is used to spin turbine(s) to generate electricity. Supercritical plants on the other hand, form part of the pulverised-coal system but use higher pressures and temperatures to boost the efficiency of the plant to about 40% or more (Bohlweki Environmental, 2006). Kusile will also be a dry-cooled station (African Development Bank, 2009; Wassung, 2010) that will be fitted

with FGD technology for removal of SO_2 from exhaust flue gases (Eberhard, 2011). Limestone will be used as feedstock in the FGD system (Eskom communication, 2012).
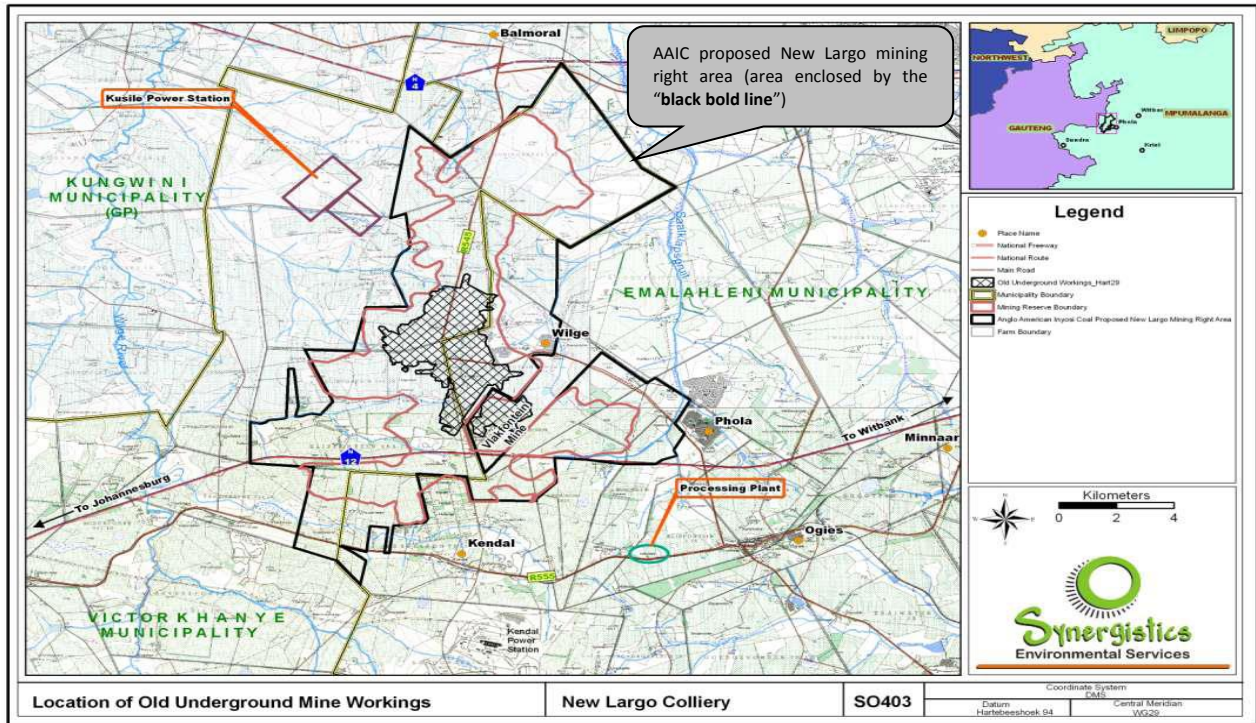
Figure 5.2: Location of Kusile, Phola coal-processing plant and AAIC mining area
Source: Wolmarans and Medallie (2011)

It is estimated that at full capacity, Kusile will require approximately 17 million tons of coal per annum (Synergistics Environmental Services & Zitholele Consulting, 2011). The coal will be sourced from the New Largo coal reserve located east of the Kusile power station and 30km west of eMalahleni. Anglo American Inyosi Coal (AAIC), a subsidiary of Anglo American, through its proposed coal mine (i.e. New Largo colliery), will extract coal from the New Largo coal reserve and supply it to Kusile (see Figure 5.1). The New Largo colliery will be an open-cast coal mine with a minimum raw-coal processing capacity of 12.7 million tons per annum (Wolmarans & Medallie, 2011). While waiting for the completion of the new colliery, Kusile will use coal from the Phola coal-processing plant along with supplementary coal from other collieries, for instance Vlakfontein colliery (Synergistics Environmental Services & Zitholele Consulting, 2011).

The Phola coal-processing plant is located approximately 20km south-east of the Kusile power station (see Figure 5.1) and is owned by Anglo American and BHP Billiton. It has the capacity to beneficiate 16 million tons of coal per annum which is mainly exported. The middlings coal (secondary product) will be supplied

to Kusile via a proposed Phola-Kusile coal conveyor of approximately 21km long, depending on the route chosen and will be designed to transport about 10.4 million tons of coal per annum, over the life of Kusile (Synergistics Environmental Services & Zitholele Consulting, 2010).

5.4.2   Boundary of the study

This study seeks to provide insight into the life-cycle burdens and social costs of investing in a coal-fired power station. The main activities/processes/stages in the coal fuel chain are shown in Figure 5.3. These consist of coal mining, coal processing, coal transportation, plant construction, plant operation, waste disposal and electricity transmission and use. The manufacture and transportation of material inputs for these main activities are also important. The main coal fuel cycle phases considered in this current study are coal mining, coal transportation, manufacture and transportation of main material inputs for constructing the power plant, plant construction, production and transportation of material inputs for operating the plant, power plant operation and waste disposal. The study focused therefore on a broader project scope (life-cyle project wide scope) (see section 5.4.4 under problem formulation for reasons behind the chosen scope). Power transmission and use are, however, not considered in this study as these are generic/standard activities for all sources of electricity.
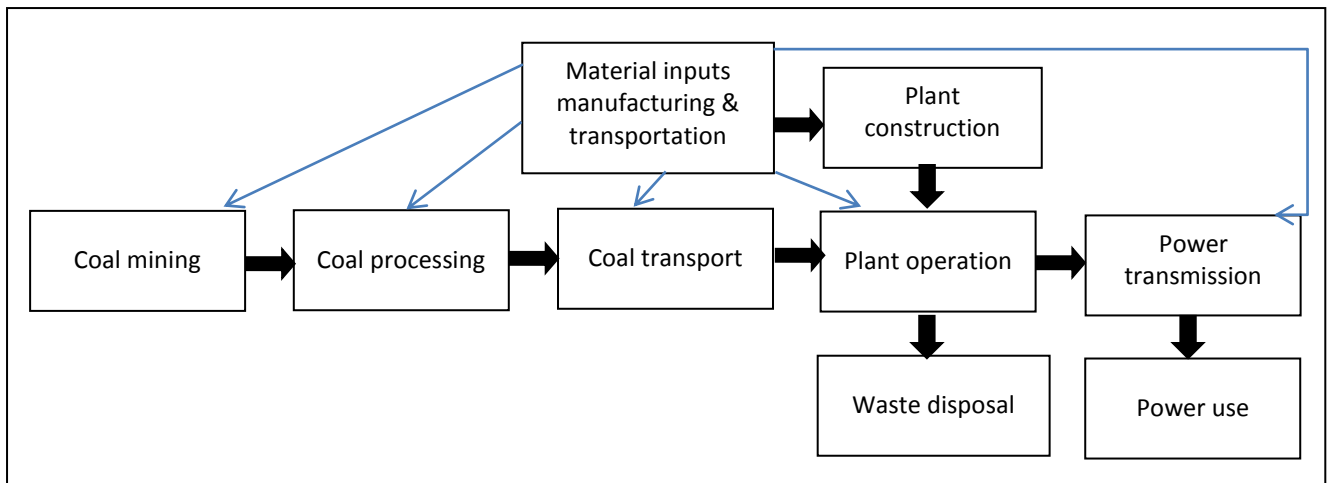
Figure 5.3: Coal-fuel cycle

Source: Own construction

The launching of Kusile power station and its ancillary activities is a source of a number of concerns. For instance, the area that will house Kusile and the mines has already been declared a priority area for air quality management (pollution hotspot) and there are salinity problems in the area (Munnik, Hochmann & Hlabane, 2009). The operation of the coal mines and the power plant will therefore add to the air pollution health crises in the area. Furthermore, the coal mines will increase water pollution, and disrupt large land

surface areas in addition to causing injuries and fatalities (Mishra, 2009). In chapter 2, a detailed discussion was provided of the environmental and societal impacts linked with the coal-fuel cycle as reflected by the literature and Kusile's EIA report (i.e. NINHAM SHAND, 2007). A summary of some of the environmental and societal impacts associated with the coal-fuel cycle were presented in Table 2.1.

Informed by the literature, Kusile's EIA, eMalahleni specific environmental issues, data availability and ease of quantification the externalities considered in this research are: climate change impacts due to GHG emissions, human health impacts due to classic air-pollutants emissions, injuries and fatalities, water consumption, water pollution, and loss of ecosystem services. A detailed block diagram of the life-cyle stages/processes and externalities of interest in this study are shown in Figure 5.4.
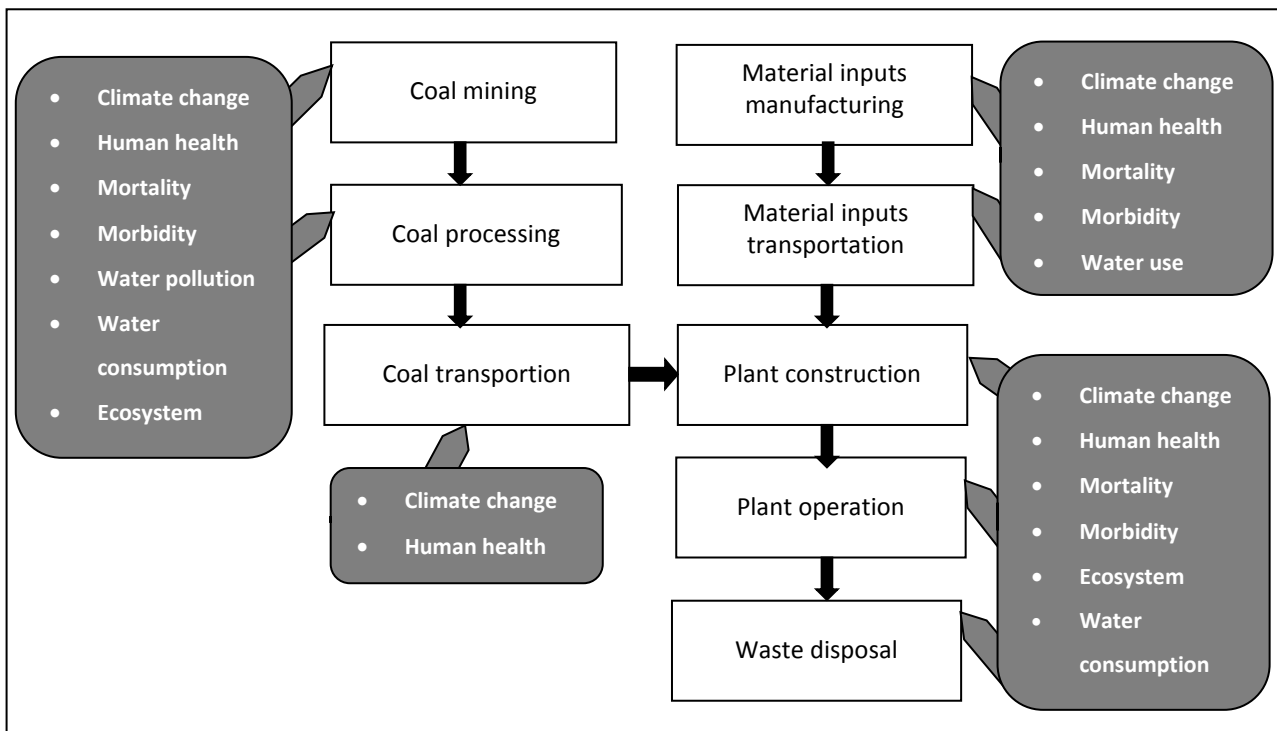
Figure 5.4: Coal-fuel cycle stages and externalities studied

Source: Own construction

As shown by Figure 5.4, the considered externalities vary with the life-cyle stages/processes. For instance concerning transportation, transport-related externalities in a broader sense include such externalities as human health effects due to emissions of classic air pollutants, global warming due to GHG emissions, damage to roadways, noise, accidents and congestion (Jorgensen, 2010). The transport externalities that were instead considered in this current study were those related to fuel use (emissions of classic air pollutants and GHGs), injuries and deaths. Though impact on roadways by coal haulage trucks is a major

issue of concern on Mpumalanga roads and also though a fraction of the coal requirements of Kusile is going to be transported by road, damage to roadways do not form part of the transportation externalities that were considered in this study owing to lack of data.

In order to estimate the damage to roadways linked to Kusile, needed is to know/estimate such cost upfront (say in cents/ton-km) based on the coal haulage by road that is already happening in Mpumalanga since Kusile is not operational. Doing so will require among other things truck load data, truck characteristics, road characteristics and road repair/maintenance cost data, data most of which is unknown and therefore will necessitate an in-depth survey that will take a while to conduct. It is, however, important to mention that for the coal hauling roads in Mpumalanga Eskom has began a road upkeep and repair program. It is reported that Eskom has spent R548 million on the roads in Mpumalanga between 2007 and 2010 plus an extra R100 million on the repairs of potholes (Generation Communication CO 0001 Revision 4, 2011). This of course partly internalizes some of the damage to roadways externality cost.

5.4.3   Data collection process

A wide spectrum of data was collected to address the specific objectives of this study. The data gathering process followed in this study is summarised below while the specific forms of data linked to each activity in the data gathering process are discussed in the following sub-sections.

The data gathering process is as follows:

- Compiling an inventory of the materials and resources used in the construction, operation and maintenance of a coal-fired power station (activity 1);
- Collection of data regarding the Rand costs of building, operating and maintaining a coal-fired power station (i.e. private costs - capital cost, fuel cost, maintenance and operating costs) (activity 2);
- Compiling an inventory of the environmental and societal burdens associated with the generation of electricity from coal. Upstream burdens linked with coal mining, material manufacture, plant construction and waste disposal were also solicited (activity 3); and
- Collection of economic valuation data that will assist in the computation of externality costs for example, monetary values for morbidity and mortality and climate change damage cost (activity 4).

The specific features and sources of the data that were collected are discussed below. During this discussion where appropriate the specific data requirements are linked to the specific objectives of the study.

5.4.3.1   *Compiling an inventory of materials and resources requirements*

The production of electricity from coal requires material and resource inputs from a number of manufacturers and upstream processes. Collection of data on the resources and material requirements necessary to build, operate and maintain Kusile coal-fired power station was therefore necessary in order to partly address objective 1. This entailed conducting an inventory of: (i) materials and resource requirements for constructing the power plant, for example steel, concrete, aluminium, cooling technology and pollution control technologies; (ii) materials and resource requirements for operating the power plant, for example coal requirements, limestone requirements and water use; and (iii) plant operation data that will assist in the building of the power generation sub-model, for example plant capacity (MW), load factor (%), coal composition (e.g. ash, carbon and sulphur), coal energy content (MJ/kg), power plant life span (years) and plant operating hours.

The data requirements for activity one were sourced from secondary and primary sources. The former included Eskom annual reports, information from Eskom website, published studies, media reports and project appraisal reports while primary data was also sought from consultation with Eskom personnel through arranged meetings and by email. Full details of the exact data requirements and corresponding sources of data are reported in chapter 6 while presenting the sub-models.

5.4.3.2   *Compiling an inventory of private costs*

The Rand data on the costs of building, operating and maintaining Kusile power station was collected in order to estimate the private costs of producing coal-based electricity in such a plant (i.e., second activity in the data gathering process). Among other costs these data included coal cost, limestone cost, capital cost and water cost. In the end the data was categorised into capital cost, fuel cost and operating and maintenance costs. Also sourced was data for basing fuel price escalation rates, escalation rates for operation and maintenance costs and interest rate. Data for this activity was sourced from various sources including Eskom communication (2012), Eskom reports, and published studies. Full details of the exact data requirements and corresponding sources of data are reported in chapter 6 while presenting the sub-models.

5.4.3.3   *Compiling an inventory of environmental and societal burdens*

The third activity in the data gathering process concerns the collection of data that concerns the environmental and societal burdens associated with coal mining and transportation, plant construction, plant operation and waste disposal (data associated with objective 2). As discussed in chapter 2, environmental and societal burdens arise at most stages in the coal-to-electricity fuel cycle (materials

manufacturing, mining, transportation, construction, combustion and decommissioning) generating various hazards that affect the health of human and the environment (Epstein et al., 2011). For example, generating electricity from coal is indirectly accountable for air pollution in coal mines, occupational fatalities and injuries in coal mines, air pollution associated with manufacturing material requirements of the power stations and transportation-related pollution too. Hence an inventory of such stage-wise burdens was conducted.

An inventory of information and data to enable the estimation of coal-fuel cyle societal and environmental impacts comprising of climate change impacts due to GHG emissions, human health impacts due to classic air-pollutants emissions, injuries and fatalities, water consumption, water pollution and loss of ecosystem services was solicited from various sources including published studies, EIA reports and Eskom annual reports. The specific data requirements and corresponding sources of data to enable the estimation of coal-fuel cyle burdens are reported in chapter 6 while presenting the sub-models.

5.4.3.4   *Collection of economic valuation data*

The fourth activity in the data gathering process concerned the collection of valuation data that assisted in the computation of externality costs of the studied burdens (objective 2). Briefly discussed therefore in this section are the valuation approaches and the associated sources of data that permitted the valuation of the various burdens studied.

To (i) value morbidity (injuries), two methods can be used, one is based on individual preferences (i.e. willingness to pay and accept compensation studies) and the other is based on opportunity costs namely the cost of illness approach (Guh, Xingbao, Poulos, Qi, Jianwen, von Seidlein et al, 2008; Kochi, Donovan, Champ & Loomis, 2010). Owing to the lack of valuation data in South Africa on individual preference approaches coupled with that for a developing country like South Africa the individual preference approaches are complex and contentious (Van Horen, 1997), estimates based on the cost of illness approach were used. The approach requires the collection of data on actual expenditure on medical treatment, transportation cost and the opportunity cost of not working (i.e., foregone income because of lost time at work). Morbidity value estimates were adapted from a study by Van Horen (1997) who valued injuries using the cost-of-illness approach in South Africa. The values were adjusted to cater for some form of internalisation and inflation. Detailed explanations of these adjustments are provided in chapter 6 when discussing the morbidity and fatalities sub-model.

To (ii) value pre-mature deaths[3] (mortality) two approaches exist, the human capital approach and individual preference approach. In the human capital approach lost life is valued by discounting an individual's future income stream, usually average GDP is used as a substitute for the individual's earnings. The approach is, however, sensitive to the discount rate used. The individual preference approach is the most preferred approach in the literature. A number of studies have valued pre-mature deaths in developed countries but primary research is lacking in many developing countries including South Africa. For this reason, researchers in South Africa such as Van Horen (1997), Turpie, Winkler, Spalding-Flectcher and Midgley (2002) and Turpie, Winkler and Midgley (2004) adopted values from international studies derived through revealed preference and adjusted them for GDP per capita and exchange rates, while Spalding-Fletcher and Matibe (2003) inflated the estimates. The economic value for premature mortality in this study was adapted from the NEEDS (2007) and NewExt (2004) studies. Adjustments were made to the values to reflect the disparity of income levels between the European Union (EU) and South Africa and to cater for inflation and some form of internalisation. Detailed explanations of these adjustments are provided in chapter 6 when discussing the morbidity and fatalities sub-model.

To (iii) estimate damage cost of climate change, generally two approaches can be used, first a bottom-up approach which involves conducting a sectoral analysis which determines the economy-wide impact of climate change and second an approach based on global/national impacts of climate change and its associated damage costs, also called the social damage cost of carbon (Blignaut, 2011). The bottom up approach is, however, plagued by difficulty so a number of researchers approximate the social damage cost of climate change, for example, IPCC (1995), IPCC (2000), Nordhaus, (1993) and Stern (2007), Tol (2005) and Tol (2009). The social damage cost of climate change on national economies is, among other factors, influenced by the choice of the discount rate, countries income levels and the distribution of income amongst and within countries. The aforementioned studies therefore yielded varied estimates.

Locally, a number of studies estimate the climate change damage cost of burning coal for electricity, for example, Blignaut (2012), Blignaut and King (2002), Spalding-Fetcher and Matibe (2003) and Van Horen (1997). Unit damage costs of CO_2 estimated by Blignaut (2012) were used in this current study to estimate the climate change damage costs related to coal mining, coal transportation, plant construction and coal

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[3] There are, however, controversies with this valuation, for example, the ethical problem arising from assigning a fixed monetary value to human life.

combustion. More detailed explanations of the estimates used are provided in chapter 6 when discussing the global pollutants sub-model.

To (iv) value human health impacts of classic air pollutants (i.e. damage cost of classic air pollutants) released during coal mining/transportation/combustion, one can use the impact pathway methodology developed in the ExternE project – which begins with estimating emissions of pollutants, tracking pollutants dispersion in the atmosphere (using dispersion modelling), evaluating the exposure of people, crops and materials to pollutants (quantifying impacts) (AEA Technology Environment, 2005) and then estimating the damage cost of the classic air pollutants by using the individual preference approach, for example, basing the valuations of air pollution mortality on the change of life expectancy (i.e. establishing individual's WTP for gain in life expectancy to estimate the Value of a Life Year (VOLY) lost by air pollution mortality (NewExt, 2004; AEA Technology Environment (2005); NEEDS, 2007; 2008; 2009) or establishing valuations based on accidental death or a small change in the probability of dying (mortality risk) (i.e. an individual's willingness to pay to reduce/avoid the risk of death (Van Horen, 1997). Basing the valuations of air pollution mortality on the change of life expectancy, as opposed to a valuations based on accidental death or a small change in the probability of dying is more advantageous because the approach automatically factor in the constraint that humans die only once regardless of pollution, it offers a unified framework for time series, cohort and intervention studies plus directly yields the life expectancy change as a time integral of the observed mortality rate (Rabl, 2006). In addition, change in life expectancy is further favourable because respondents during surveys show too much difficulty understanding small probability variations while a change in life expectancy is well understood (NewExt, 2003).

Another approach is the benefit transfer technique which too can be based on damage costs calculated based on VOLY or a change in the probability of death. This later approach it involves transferring damage cost of classic air pollutants from previous studies and adjusting the values for income differences between countries. It is normally used if local values of health costs are not available. This approach has been used by the AEA Technology Environment (2005), NEEDS (2007; 2008; 2009) and by Sevenster et al. (2008). All of the damage costs used by these studies were calculated based on VOLY (explained more in chapter 6 when discussing the air pollution sub-model). The procedure adopted by the above studies was followed to approximate the unit damage cost of exposure to classic air pollutants.

To (v) Estimate the economic value of water use in coal mines, during plant construction and during plant operation, needed is to establish the opportunity cost for water to society when engaging in each of these activities. Computing such, if time and resources allow for it, is essential because water is highly

underpriced in South Africa so water users rarely pay the full cost of this resource (Inglesi-Lotz & Blignaut, 2012). This issue is further intensified by the scarcity of water in the country (Turton, 2008). The opportunity cost of water to society when engaging in Kusile coal-fired electricity generation was estimated by Inglesi-Lotz and Blignaut (2012). The opportunity cost values computed in this study were used to base the values used in this current study for plant operation and construction and as well as for coal mining as the coal produced by the proposed coal mine will be 100% dedicated to coal-fired power generation. Some adjustments were, however, made to the estimates by Inglesi-Lotz and Blignaut (2012) and these are explained in chapter 6 when discussing the water consumption sub-model.

To (vi) value water pollution damages by coal mines on other water users, the benefit transfer technique was used. Estimates from a previous local study (i.e. Van Zyl et al., 2002) were used. Van Zyl et al. (2002) estimated the cost imposed on other water users in the eMalahleni catchment due to water pollution emanating from various individual industries. This study and its drawbacks are discussed fully in chapter 6 when discussing the water pollution sub-model. For the power generation phase, Eskom claim to operate under a zero liquid effluent discharge policy, however, as of to date, no formal evaluation of this policy has been conducted and published (Inglesi-Lotz & Blignaut, 2012). For this reason water pollution linked to the power station was not be considered.

To (vii) estimate loss of ecosystem services due to coal mining and plant construction, needed was to establish the opportunity cost of using the land areas occupied by the coal mine and the power station for these uses. Since the mined area and the power station sites are mainly used for maize cultivation and grazing (Eskom, 2010b; Ninham, 2007; Wolmarans & Medallie, 2011) the opportunity cost of these uses is therefore the forgone benefits derived from agricultural production and ecosystem services generated by grasslands (i.e. carbon sequestration potential and carbon storage of the vegetation cover and soils). Estimates of the value of maize and that of ecosystem goods and services generated by grasslands computed in a study by Blignaut et al. (2010) were adapted to this study. Full details of this study and the modifications to the estimates are discussed fully in chapter 6 when discussing the ecosystem services loss sub-model. The following section discusses the main research approach that was chosen to attain the last objective of this study (objective 3).

5.4.4   System dynamics modelling

In assessing the fuel-cyle burdens and social costs of coal-based electricity generation over the lifetime of a coal-based power plant system dynamics modelling was employed. While various modelling steps to building system dynamics models exists as disclosed by the literature in chapter 3, the modelling process

followed in this study was informed by those of Roberts et al. (1983), Ford (1999) and Sterman (2000) and it consisted of problem formulation, dynamic hypothesis formulation, model formulation (structure and equations), model validation and policy design and evaluation. The Vensim software was used to conceptualize, construct, simulate and analyze the COALPSCA Model. Causal loop diagrams, stock and flow diagrams plus simulation modelling are with simplicity and flexibility provided by the Vensim software (Ventana Systems, 2003). In this section a brief description of the system dynamics modelling process is provided with extensive details in the following chapters (chapter 6 and 7).

Problem formulation: Problem formulation is the first and most important step in the model building process. This step embraces a number of activities, among which are defining the problem, identifying key variables, determining the boundary of the system and establishing the time horizon for the model (Sterman, 2000). Informed by the literature review conducted in this study, the research problem addressed in this study was framed and the key variables that needed to be considered were identified. Based on the purpose of the model and the literature review the boundary and time horizon of the model were determined. The study focused on a broader project scope (life-cyle project wide scope) while the time frame was selected such that it was long enough to address the key fuel-cyle burdens and social costs issues of power generation (i.e. a period of 50 years was selected – more explanations in chapter 6).

An inception meeting was also held with a knowledgeable Eskom worker (Unit head) to introduce the then proposed work, to request views about the project, the company's participation and to request the company's willingness to provide data that will foresee the attainment of the research goals. Following this inception meeting and the requests raised to improve the research work, the proposed work was modified to incorporate the need to study the externality costs of one of Eskom's existing plants and to explore the costs and benefits of retrofitting such a plant with new pollution abatement technology as that of Kusile. A follow up meeting and countless data requests, however, did not yield the data on an existing plant, so the study reverted to focusing on Kusile power station. It is also important to mention that the original plan for this research study incorporated a comparative study of the life-cyle burdens and social costs of coal-based power versus that of wind and solar power generation technologies, but time restraints could not permit such investigations.

Dynamic hypothesis formulation: This step involves creating a working theory that explains the system's dynamic behaviour premised on feedbacks and causal structure of the system (Sterman, 2000). Causal loop diagrams (i.e. diagrams that capture the structure of the system in a qualitative manner) were formulated

and they displayed the associations between the main variables in the system and feedback loops. An extensive explanation of this step is provided in chapter 6.

Model formulation: In this step the stock and flow diagrams of the modeled system were constructed and they provided the quantitative relationships between the variables of the system. A number of sub-models were yielded by this step and are presented and discussed in chapter 6.

Model validation: This step involves repeated actions of testing and establishing confidence in the model's usefulness (Forrester & Senge, 1980; Sterman et al., 1988). Validation of the internal structure of the model was conducted first followed by behaviour validity because the accuracy of the model behaviour is only meaningful once adequate confidence on model structure was established prior (Barlas, 1989; Barlas, 1994). Five direct structure validation tests that were introduced by Forrester and Senge (1980) for system dynamics were performed in this study, namely structure verification, dimensional consistency, boundary adequacy, extreme condition and parameter verification tests. Behaviour validity on the other hand, seeks to establish the extent to which the model's behaviour matches the behaviour of the real system (Barlas, 1996). The behaviour sensitivity test was conducted in this study. Detailed explanations of these tests are provided in chapter 7.

Policy design and evaluation aimed at alleviating existing problems in the system is central to the development of system dynamics models. Policy scenarios are crafted based on model results/learning from the model and from anticipations/expectations in the actual world (Sterman, 2000). A number of policy scenarios were defined and evaluated with reference to the baseline scenario. A detailed discussion of the policy design and evaluation step is provided in chapter 7.

5.5   Conclusion

In this chapter explained and motivated were the decisions taken by the researcher regarding the philosophical beliefs that underpins the study, the strategy of inquiry and the methodological approach that was employed to achieve the ultimate objective of constructing and validating a system dynamics model for understanding coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and fuel cycle. Model validation and policy design and evaluation as part of the system dynamics modelling process were also addressed. A more thorough discussion of the modelling process is provided in chapter 6 and 7.

CHAPTER 6:   COAL-BASED POWER AND SOCIAL COST ASSESSMENT (COALPSCA) MODEL

6.1   Introduction

This chapter discusses and presents the COAL-based Power and Social Cost Assessment (COALPSCA) Model developed for understanding coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and fuel cycle. In chapter 3, a number of modelling steps to building system dynamics models were discussed. In this study the modelling steps followed when developing the COALPSCA Model were those suggested by Roberts et al. (1983), Ford (1999) and Sterman (2000). These modelling steps include problem formulation, dynamic hypothesis formulation, model formulation (structure and equations), model validation and policy design and evaluation. The first three modelling steps are discussed in this chapter while the remaining two are discussed in the following chapter. Before the discussion of the modelling steps, the modelling software employed in this research is discussed. This is the followed by a discussion of the problem formulation step, dynamic hypothesis formulation, model boundary and model formulation (structure and equations).

6.2   Software used in the modelling

Vensim software was used to conceptualize, construct, simulate and analyze the COALPSCA Model. The software was specifically developed by Ventana Systems, Inc. for building system dynamics models. Causal loop diagrams, stock and flow diagrams plus simulation modelling are with simplicity and flexibility provided by the Vensim software (Ventana Systems, 2003). There are a number of Vensim software packages, namely Vensim PLE (Personal Learning Edition), PLE Plus, Standard, Professional and DSS in ascending order of increasing functionality. In this study Vensim PLE Plus software was used.

6.3   Problem formulation

Problem formulation is the first and most fundamental step in the model building process. This step embraces a number of activities, among which are defining the problem, identifying key variables and establishing the time horizon for the model (Sterman, 2000). Having a clear purpose of the model is essential to keeping all those participating in the modelling focused on a single problem and keeping the modelling process on course. In addition, models are simple representations of real complex systems, so modellers must refrain from designing a model of the whole system to prevent the model from being as

complex as the system one aims to model. The focus must instead be on a small problem or on models that address a few issues.

The problem addressed in this study can be framed as follows: South Africa has a number of planned development projects, including energy projects with coal-based investments. Generally, the environmental and development planning process, in the form of an EIA have been the main driver of project development in the country (Hoosen, 2010). The analysis of the quality of EIRs, however, disclosed that amongst other issues, the more analytical components of the EIRs which form the basis for decision making are performed poorly for instance with regards to the provision of information pertaining to impact identification and assessment of key impacts (Sandham et al, 2008; Sandham & Pretorius, 2008; Sandham et al. 2013). Concerning the assessment of impacts various researchers have expressed inadequate use of assessment methodologies (Sandham et al., 2010; Sandham & Pretorius, 2008), for instance, causal networks despite their suitability to fulfill specific principles of EIA practice such as transparency, integration and being systematic (Perdicoúlis and Glasson, 2006; Wood et al., 2006). Other concerns pertains to: overemphasis on biophysical environment (Aucamp et al.,2011; Du Pisani & Sandham, 2006); limited consideration of socio-economic impacts of planned developments (Kruger & Chapman, 2005); no consideration of the economic value of externalities (Burdge, 2003) despite the importance of considering externality costs alongside financial costs in decision-making (ATSE, 2009; Icyk, 2006; Roth & Ambs, 2004).

While the employment of causal networks and specifically system dynamics in EIA practice may rectify the limitation of impact identification and the limited scope of impact assessment, as well as permit transparency, integration and being systematic, the narrow project-orientation of EIA, however, limit the scope of impact assessment and hence it hinders a comprehensive assessment of the life-cycle impacts and social costs of developments, a limitation that becomes more evident in the context of energy generation projects due to the importance of fuel-cycle impacts and social costs towards informing energy technology selection. For this reason one could argue that EIA is not broad enough to enable sound energy technology assessment to inform energy policy formulation and therefore an exploration of technology assessment was conducted since it is broader than EIA (Berg, 1994; Brooks, 1994).

The energy technology assessment tools and studies, however, are also not without weaknesses for instance they provide a partial view and partial analysis, respectively, to making informed decisions on the selection of energy technologies. The reason for this being that the assessment tools and methods tend to be discipline specific with little to no integrations, with tools often grouped into financial analysis tools, impact analysis tools, technical performance assessment and so on (Palm & Hansson, 2006), which has

consequently resulted in energy technology studies that exclusively assess these groupings with little/no integration and with variations in scope and depth. Other concerns pertain to the none consideration of the economic evaluation of externalities and social costs (Roth & Ambs, 2004) as well as variations in scope and depth in the assessment of externalities (i.e. limited scope of impact assessment) which make comparing various energy development project involving (new) technologies difficult. For instance, the studies differ in terms of the types of externalities they consider, the fuel-cycle stage(s) they investigate, and they do not factor in the long-standing repercussions of the technologies on the environment and social systems.

These shortcomings highlight the lack of recognized technology assessment frameworks to support energy policy formulation in the field of environmental and development planning processes (i.e. in both technology assessment and as well as EIA) and therefore suggests the need for comprehensive assessment to help inform decision-making on energy developments. Wolstenholme (2003) have supported improving energy technology assessment through the use of a holistic and integrated approach due to its superior attributes while Roth and Ambs (2004) advocates the improvement of assessment practices through the measurement of not only the traditional costs incurred directly by power utilities but costs incurred in the entire fuel cycle including the conventionally neglected externality costs. This study therefore aspires to promote proper technology assessment at the extensive project level through improving the environmental and development planning processes by means of employing a systems approach, namely system dynamics due to its superior attributes and embedding it within the processes to account for the lifecycle and long-term economic, social and environmental repercussions and social costs of energy development projects. The current study specifically focuses on coal-based electricity generation as a case study. The primary aim of this study is therefore to design and validate a system dynamics model for understanding coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and fuel cycle.

The purpose of developing the model is twofold, firstly is to aid energy decision makers with a tool for making informed energy supply decisions that consider not only the financial feasibility of power generation technologies, but also the socio-environmental consequences of the technologies. Secondly, the model is to aid coal-based power developers[4] with a useful tool for detecting the main drivers of the burdens and costs in the system which should yield vital socio-economic-environmental tradeoff information that can be beneficial to them.

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[4] Coal-based power developers refers to the coal-based power plant project developers or companies that run or plan to develop coal-based power plants (e.g. Eskom).

Another important aspect to be considered is establishing the time horizon for the problem at hand, which should be long enough to address the key issues. The Kusile coal-fired power station will run for a period of 50 years, therefore this time frame was considered sufficient to allow for most of the activities involved. While it is true that some of the activities associated with producing power from a coal-fired power plant are likely going to produce lasting effects that exceed the 50 years, for example water pollution from coal mining, a balance needed to be trucked and 50 years was considered a reasonable time frame.

6.4   Dynamic Hypothesis formulation

The dynamic hypothesis formulation step involves constructing a working theory that explains the problem. This theory explains/describes the dynamic behaviour of the system premised on the feedbacks and causal structure of the system (Sterman, 2000). The causal loop diagram is therefore a diagram that illustrates in a qualitative manner the linkages and feedback loops of the system and serves as a quick tool for capturing the hypothesis relating to the basis of dynamics. Model construction tests this hypothesis and it must be adjusted if evidence from the model or from the real system refutes it (Lane, 2000). The causal loop diagram displaying the interactions between the key elements and the feedback loops of the modelled system are shown in Figure 6.1. The interactions associated with coal-based power generation, generation cost and externality costs are qualitatively expressed in the causal loop diagram.

Each arrow in the diagram shows the influence of one variable on another. The relationships between the variables may be either positive or negative. Positive polarity designates that an increase (decrease) in the "cause" variable will increase (decrease) the "effect" variable while negative polarity shows that an increase (decrease) in the "cause" variable will decrease (increase) the "effect" variable (Sterman, 2000). The polarity of the feedback loops is also shown in the causal loop diagram and it can be positive or negative. Self-reinforcing/positive loops (i.e. loops having an even number of "-" signs (or only "+" signs)) amplify change in the system while self-correcting/negative loops (i.e. loops having an uneven number of "-" signs) oppose change in the system and attempt to bring the system into equilibrium (Coyle, 1996; Sterman, 2000).
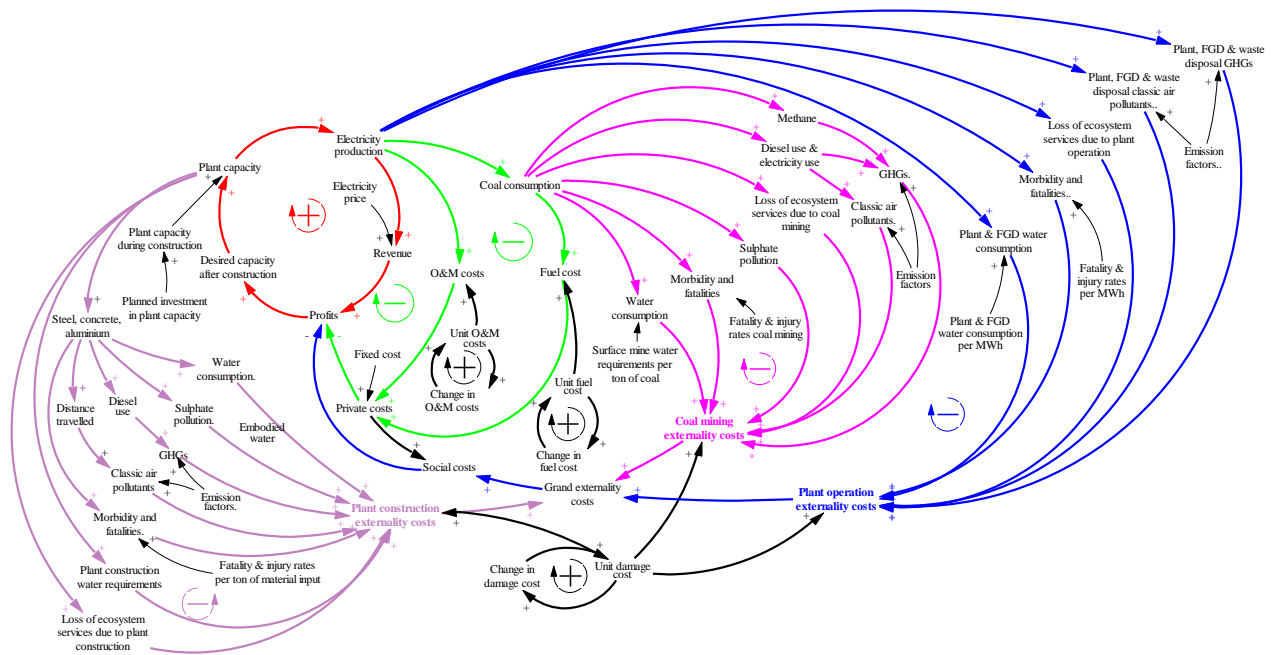
Figure 6.1: Causal loop diagram of the modelled system

There are five main loops (red, green, blue, pink and purple) shown by the diagram. The red reinforcing feedback loop shows plant capacity to be increased by plant capacity during construction period and desired functional capacity after construction period, which are in essence in turn positively influenced by planned investment in plant capacity and profits, respectively. In turn plant capacity stimulates electricity generation. An increase in electricity generation in turn generates revenues and profits which stimulates the desired functional capacity after construction and hence the plant capacity after consideration of plant capacity during the construction phase.

While it is generally true that both the expectations of capacity needs and profitability play an important role in the decision-making process to invest in electricity generation, however, due to the scope/boundary of this model (i.e. a life-cycle project wide scope discussed in chapter 5/7) the effect of the forces of electricity supply and demand on investment decisions was not modelled explicitly as refleted in the above discussion but the investment in plant capacity was based on exogenously planned investment in plant capacity by the developer (i.e. "Planned investment in plant capacity" was taken as a proxy for all factors that affect investment decisions). The final maximum capacity of Kusile at the end of the construction phase is therefore largely a fixed value (e.g. a plant size of 4 800 MW) that is determined by the size of the plant the developer planned to construct in the beginning. The amount that the plant manager wishes to run/operate at a specific point in time after construction (i.e. desired functional capacity after construction) was modeled as a function of expected profitability, coupled with other factors such as plant operating hours and the load factor.

The green balancing loops can be called the "private cost loops" and they basically depict the interactions between electricity production and the private costs of generating electricity. The first green balancing loop shows electricity production to cause a rise in operation and maintenance (O&M) costs which in turn increases the private costs of generating power, which then decreases profits, desired functional capacity after construction, plant capacity and electricity production. The second green balancing loop shows that electricity generation leads to an increase in coal consumption, which increases the fuel cost, which in turn increases the private costs of generating power, which then reduces profits. A decrease in profits reduces the incentive to finance functional capacity after construction, which in turn lowers plant capacity, which consequently reduces electricity production.

The blue, pink and purple collection of loops can be called the "externality cost loops". The purple loops show the interactions between plant capacity construction, plant operation externality costs and profits. Plant capacity (precisely the construction phase component of plant capacity) is shown by the collection of purple balancing loops to increase plant construction water requirements, loss of ecosystem services due to plant construction and a number of burdens (i.e. GHGs, classic air pollutants, sulphate pollution, morbidity and fatalities and water consumption) linked with the main material input requirements for constructing the plant (i.e. steel, concrete and aluminium). These burdens together with the likely damage cost they impose on humans and on the environment, increase the plant construction externality costs which in turn amplify the grand externality costs and social costs, which then reduce profits, desired functional capacity after construction, plant capacity and electricity production.

Electricity production is shown by the collection of blue balancing loops to increase plant, FGD and waste disposal GHG emissions, classic air pollutants, morbidity and fatalities, loss of ecosystem services and water consumption burdens, which in turn coupled with the likely damage cost imposed by these externalities, increase plant operation externality costs which intensify the grand externality costs. The grand externality costs together with the private costs of generating power, in turn raises the social costs, which then reduce profits, desired functional capacity after construction, plant capacity and electricity production.

The pink loops show the interactions between electricity production, coal mining externality costs and profits. Electricity production is shown by the collection of pink balancing loops to increase coal consumption, which in turn increases sulphate pollution, GHG emissions, classic air pollutants, morbidity and fatalities, water consumption and loss of ecosystem services. These externalities coupled with the likely damage cost imposed by them on third parties, in turn augment the coal mining externality costs which in

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turn amplify the grand externality costs and social costs, which then reduce profits, desired functional capacity after construction, plant capacity and electricity production. The other remaining reinforcing loops in the diagram show the dynamics of unit fuel cost, O&M costs and damage cost. The model boundary is discussed next.

6.5   Model boundary

System dynamics focuses on understanding the structure of the system so as to provide insight into the behaviour of the system. Accordingly, system dynamics models should include all the important variables that influence a system's behaviour. The aim of the model or the problem addressed by the model, would determine the variables that are to be treated as endogenous, exogenous or excluded. The COALPSCA Model is a model for understanding the resource requirements, power generation, externalities, private costs and externality costs of a coal-fired power plant in South Africa, namely Kusile power station. The model thus seeks to provide insight into the coal-fuel cycle social cost of investing in a coal-fired power station.

The causal loop diagram presented the interactions between certain important variables of the COALPSCA Model. Table 6.1 summarizes some of the main endogenous, exogenous and excluded variables. The table does not provide the whole list of the variables which are reported fully in section 6.6, where the model equations are discussed. The table indicates that many of the key variables were endogenously generated while some exogenous variables also drove the model. Some variables were excluded due to lack of data (e.g. fatalities and injuries linked to plant construction) and the anticipated complication of including such variables in the model (e.g. ecosystem services lost upstream of the power plant excluding those linked to the coal mine).

Table 6.1: Endogenous, exogenous and excluded variables

Endogenous variables	Exogenous variables
Gross electricity production	Unit water cost
Net electricity production	Unit coal cost
Operational plant capacity	Unit limestone cost
Coal consumption	Other variable O&M costs
Material inputs inventory (coal, steel, water, diesel, etc.)	Other FGD O&M costs
Pollutant loads (CO_2, SO_2, CH_4, N_2O, etc.)	Growth rate of the various private costs
Dry waste	Escalation of damage costs
Levelised cost of energy	Planned plant capacity
Levelised externality cost	**Excluded variables**
Levelised social cost	
Levelised capital cost	Ecosystem services loss upstream of plant & coal mine
NPV before tax and after tax	Plant construction fatalities & injuries
Social NPV before tax and after tax	Plant construction water pollution
Coal-fuel cycle externality cost of water use	Plant operation water pollution
Coal-fuel cycle fatalities and morbidity costs	Electricity demand

6.6   Model formulation: structure and equations

The causal loop diagram presented in section 6.4 displayed the qualitative description of the system, in this section the stock and flow diagrams of the modelled system are constructed and they provide the quantitative relationships between the variables of the system. The stocks/levels are denoted by rectangles and they show accumulations in the system while the flow variables (i.e. inflow and outflow rates) are denoted by valves and they regulate changes in stocks. Stocks are differential equations and are mathematically denoted as follows:

$$Stock(t) = Stock(t_0) + \int_{t_0}^{t} [Inflow(t) - Outflow(t)] dt$$ ………………………………………….……………Integral equation

$$\frac{d(Stock)}{dt} = [Net\ change\ in\ stock] = [Inflow(t) - Outflow(t)] dt$$ …………………………………Differential equation

The integral equation shows that at time t the value of the stock is given by the summation of the stock value at time t_0 and the integral from t_0 to t of the change between inflow and outflow rates. The differential equation shows that at time t the rate at which the stock changes is given by the change between inflow and outflow rates. Also incorporated into stock and flow diagrams are auxiliary variables and shadow variables.

The system dynamics model designed in this study for the assessment of coal-based power and its associated life-cycle private and externality costs is composed of nine sub-models, namely power

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generation, generation cost, water consumption, water pollution, morbidity and fatalities, ecosystem services loss, air pollution, global pollutants and social cost sub-models. The sub-models and associated equations are presented in the following sections, together with a presentation of the parameters used.

6.6.1   Power generation sub-model

The power generation sub-model, models the generation of electricity at Kusile power station. A plant, that is currently under construction and will be fully operational in 2018/19. It will run for a period of 50 years with the first unit becoming operational towards the end of 2014 (Eskom, 2012a). In this study the base year of the model is 2010 so the first unit becomes operational in 2010 and the plant is fully operational in 2015. The model therefore runs for a period of 50 years from 2010 up until 2060. The structure of electricity production in such a plant is represented in Figure 6.2. This sub-model consists of four stock variables, namely plant capacity construction, plant capacity during and after construction as planned, cumulative gross electricity production and cumulative net electricity production.
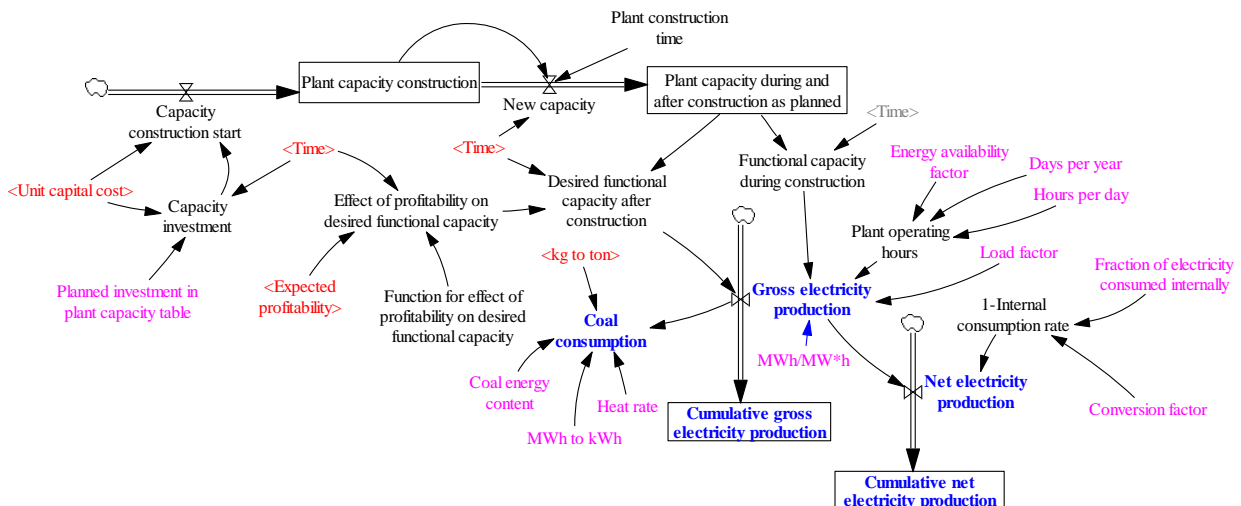
Figure 6.2: Power generation sub-model stock and flow diagram

Plant capacity construction (PCC, MW) is increased by capacity construction start (CC, MW/Year) and reduced by new capacity (NC, MW/Year) upon the completion of construction. Mathematically, the dynamics of plant capacity construction is represented as follows:

$$PCC(t) = PCC(800) + \int [CC - NC] dt \quad \text{...(1)}$$

The first component on the right-hand side represents the initial value of PCC, which is 800 MW. Capacity construction start (CC, MW/Year) is determined by capital investment (CINV, R/Year) divided by the unit capital cost (KC, R/MW). This is represented as:

$$CC = CINV / KC \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(2)$$

The capital investment (CINV, R/Year) is a product of exogenously planned investment in plant capacity (PIPC, MW/Year) and unit capital cost (KC, R/MW). This is denoted as:

$$CINV = PIPC * KC \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(3)$$

The new capacity (NC, MW/Year) on the other hand, is determined by plant capacity construction (PCC, MW) divided by plant construction time (PCt, Year), as follows:

$$NC = PCC / PCt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4)$$

In turn the new capacity (NC, MW/Year) determines plant capacity during and after construction as planned (PCDAC, MW), as follows:

$$PCDAC(t) = PCDAC(800) + \int [NC] dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(5)$$

The first component on the right-hand side represents the initial value of PCDAC, which is 800 MW. Given the plant capacity during and after construction as planned (PCDAC, MW), functional capacity during construction (FCC, MW) and desired functional capacity after construction (DFCA, MW) were computed. Functional capacity during construction was taken as it was from PCDAC over the construction period. It is given by the following equation:

$$FCC(t) = IF\ THEN\ ELSE(Time\ <= 2015,\ PCDAC, 0) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(6)$$

Which states that FCC is to take values of PCDAC if the time is less or equal to 2015 and otherwise values of zero (i.e. if the time is different from the specified one). Regarding desired functional capacity after construction (DFCA, MW), it was modeled as a function of PCDAC (MW) and the effect of profitability on desired functional capacity (EPC, Dmnl), as follows:

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$$DFCA(t) = IF\,THEN\,ELSE(Time \leq 2015, 0, PCDAC*EPC) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(7)$$

Which states that FCA is to take values of zero if the time is less or equal to 2015 and otherwise values that are determined by the product of PCDAC and EPC (i.e. if the time is greater than 2015). The effect of profitability on desired functional capacity (EPC, Dmnl) on the other hand, was modeled as a function of expected profitability. A lookup table was used. Lookups or lookup tables/functions permit the modeller to customize relationships between a variable and its causes. They are useful in the absence of simple arithmetic equations that describe the relationship between input and output variables. In a lookup table the input variable alters the output variable through the lookup function, which is normally a non-linear function (Ventana Systems, 2002). The lookup tables may be informed by experimental data or may be artificially generated. In this study, the lookup function for effect of profitability on desired functional capacity was informed by expected hypothetical behavior.

Figure 6.3 presents the lookup function for effect of profitability on desired functional capacity. The X-axis denotes expected profitability while the Y-axis represents the effect on desired functional capacity. Expected profitability is a shadow variable in the power generation sub-model so it is elaborated on in the social cost sub-model in section 6.6.9. The input variable (i.e. expected profitability) was normalized in order to make certain that both the input and output variables were independent of the units of measure of other variables in the model (i.e. dimensionless)). As an illustration, the function states that when the price of electricity is equal to the unit cost of production, the expected profit is zero and hence the effect on desired functional capacity is 0.75.
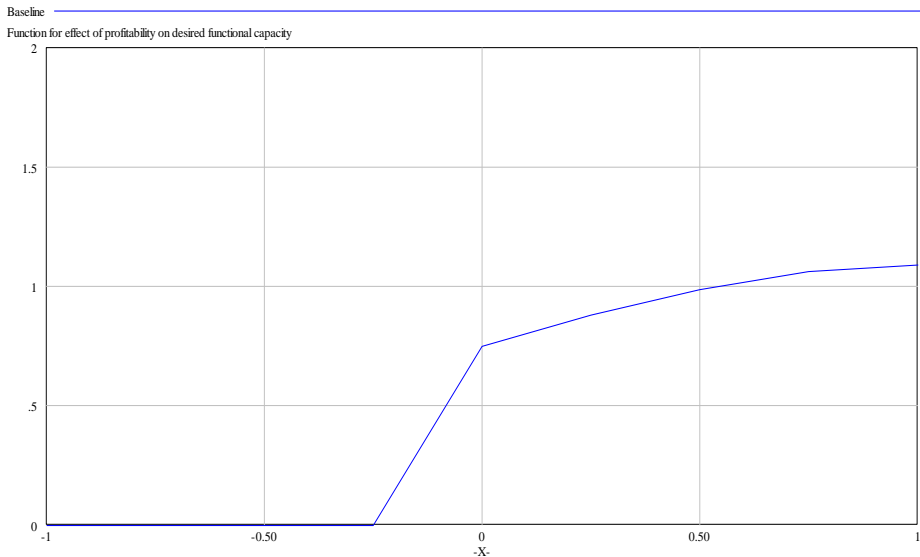
Figure 6.3: Lookup function for effect of profitability on desired functional capacity

Given the functional capacity during construction (FCC, MW), desired functional capacity after construction (DFCA, MW) coupled with plant operating hours (POH, h/Year) and the load factor (LF, Dmnl), gross electricity production (EP, MWh/Year) is estimated as follows:

$$GEP = \left[(FCC * POH) + (DFCA * POH) * LF \right] \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (8)$$

Where, POH (in h/Year) is given by the product of the number of days per year (DPY, Day/Year), hours per day (HPD, h/Day) and energy availability factor (Dmnl). The energy availability factor is the amount of time that the power plant is able to generate energy over some time period, divided by the amount of the time in the period or is simply the percentage of the time that the power plant is able to provide energy to the grid. The plants energy availability factor is mainly a factor of its reliability and the periodic maintain it requires. All else being equal, power plants that are operated less regularly have higher energy availability factors for the reason that they require less maintenance. The load factor on the other hand, refers to the ratio of power produced by a power plant over the theoretical maximum it could produce at full capacity over a time period (e.g. hours, days or weeks or yearly). It is a key variable here as it is important for predicting the amount of power a plant can produce. The load factor is also a key concept for generation cost estimates. The higher the load factor the lower the generation cost per MWh (Lopez, 2006).

Gross electricity production is in turn an inflow to cumulative gross electricity production, which is a third stock of the power generation sub-model. Gross electricity production gives rise to net electricity

production (NEP, MWh/Year), once the fraction of electricity consumed internally by the plant is subtracted (i.e. 1 – Internal consumption rate (Dmnl)). Net electricity production is thus represented as:

$$NEP(t) = GEP * (1 - \text{Internal consumption rate}) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(9)$$

Where 1 - Internal consumption rate is 1 minus the fraction of electricity consumed internally by the plant. Cumulative net electricity production, which is the fourth stock, is therefore an accumulation of net electricity production.

Finally, gross electricity production also determines the amount of coal consumption (CConsump, ton/Year) coupled with data on coal energy content (CEC, MJ/kg) and heat rate (HR, MJ/kWh). Coal consumption is given by:

$$CConsump = \left[((GEP * MWhtoKWh) * HR) / CEC \right] / kgtoton \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(10)$$

The parameters used in the power generation sub-model are presented in Table 6.2. Input variables taken from other sub-models (red variables) are not shown in this table. The complete respective equations of the power generation sub-model are presented in Appendix A.

Table 6.2: Parameters used in the power generation sub-model

Parameter	Units	Baseline value	Data source
Coal energy content	MJ/kg	19.22	Eskom, 2010a.
Days per year	Day/Year	365	Eskom communication, 2012.
Energy availability factor	Dmnl	0.94	Eskom communication, 2012; Eskom, 2012b.
Fraction of electricity consumed internally	Dmnl/Year	0.075	Eskom communication, 2012.
Heat rate	MJ/kWh	9.769	EPRI, 2010.
Hours per day	h/Day	24	Eskom communication, 2012.
Load factor	Dmnl/Year	0.9	NINHAM SHAND. 2007
Planned plant construction table	MW/Year	Time series	Calculated based on Eskom (2012b).

6.6.2   Generation cost sub-model

The generation cost sub-model focuses on the private costs of electricity generation at Kusile power station, specifically the cost per MWh incurred by the electricity producing entity (i.e. Eskom) to produce electricity over the lifespan of the investment technology (i.e. LCOE). Computing the LCOE thus requires both the cost of energy and power generated by an energy generating system to be assessed over the lifetime of the energy generating system (Bandyopadhyay et al., 2008; Zweibel, Mason & Fthenakis, 2008).

The approach, though somehow synonymous with life cycle cost analysis, is said to provide the best comparison between energy technologies because it takes into account not only the lifetime cost but also the lifetime energy production associated with an energy system (Bandyopadhyay et al., 2008; Darling et al., 2011).

Owing to the LCOE's focus on the lifetime of the power generating system when assessing costs and power (Zweibel et al., 2008), the future time series of expenditures and revenues have to be discounted to their present values, by applying a discount rate (Hearps, McConnell, Sandiford & Dargaville, 2011). Accordingly, the LCOE (R/kWh) is the ratio of total lifespan expenses to total anticipated output (i.e. electricity), expressed in present value. Equations (11), (12a), (12b) and (12c) show the general calculation method for the LCOE. Equation (11) shows the equivalence of the present value of the summation of discounted revenues and costs. The calculation begins at $t = 0$ so as to incorporate the initial cost at the start of the first year, or alternatively the initial cost can be placed outside of the summation and then t begins at 1 $(t = 1)$.

$$\sum_{t=0}^{T} \left(E_t * p_{elect} * (1+r)^{-t} \right) = \sum_{t=0}^{T} \left(C_t * (1+r)^{-t} \right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (11)$$

Where: E_t is the energy generated in year t; p_{elect} is the price of electricity; C_t is the cost in time t; $(1+r)^{-t}$ is the discount factor in year t.

The sum total of the present values of the cash flows is zero, hence the NPV of the project is zero (Hearps et al., 2011), meaning an investor breaks-even on the project. One approach therefore to calculating the LCOE is to assume a discount rate and then to solve for the sale price of power that yields a zero NPV for the project. Equations (12a) and (12b) therefore rearrange equation (11) and show the LCOE to be equal to the price of electricity that equates the two discounted cash flows. The equivalence of the LCOE and the electricity price is based on the assumptions of a stable and non-varying discount rate (r) and electricity price over the lifetime of the energy generating system (International Energy Agency, 2010). Equation (12c) shows the LCOE as a ratio of the sum of the present value costs divided by the total amount of electricity adjusted for its economic time value.

The division of each year's physical output by the time preference factor in equations (12a), (12b), and (12c), does not, however, seem to make intuitive sense, for the reason that physical units neither change magnitude over time, nor pay interest. While it is true that a unit of electricity does not pay interest, it

indeed produces a revenue stream that does pay interest, and also a unit of electricity (MWh) generated this year does not have the same economic value as a unit of electricity produced in the following year, because it can be invested into projects that grow our wealth. What is discounted, in essence, is the value of output which is the amount of electricity generated multiplied by its price. It is only after the rearrangement of equation (11) to equations (12a), (12b) and (12c) that it seems as if physical production is being discounted. The necessary discounting of the electricity price in equation (11), leads to the apparent discount of physical output in equation (12a), (12b) and (12c). The substitution of physical production for its price (i.e. economic value) in equation (12a) (from equation (11)) is possible because the nominal and undiscounted price does not change over the lifetime of the energy generating system. The correct time value of the revenue stream is now therefore obtained by adjusting physical production as opposed to price with the correct discount factor. It is in effect, not physical production as such that is discounted but its economic value (International Energy Agency, 2010). Equation 12c has been used by a number of researchers to compute LCOE including Zweibel et al. (2008), IRP (2010), Branker, Pathak and Pearce (2011) and Hernandez-Moro and Martnez-Duart (2013).

$$ p_{elect} = \frac{\sum_{t=0}^{T} \left(C_t * (1+r)^{-t} \right)}{\left(\sum_{t=0}^{T} \left(E_t * (1+r)^{-t} \right) \right)} \quad\text{...(12a)} $$

$$ LCOE = p_{elect} = \frac{\sum_{t=0}^{T} \left(C_t * (1+r)^{-t} \right)}{\left(\sum_{t=0}^{T} \left(E_t * (1+r)^{-t} \right) \right)} \quad\text{...(12b)} $$

$$ LCOE = \frac{\sum_{t=0}^{T} \left(C_t * (1+r)^{-t} \right)}{\left(\sum_{t=0}^{T} \left(E_t * (1+r)^{-t} \right) \right)} \quad\text{..(12c)} $$

Equation 9c's approach to computing the LCOE was used in this study. But before presenting the generation cost sub-model structure, it is import that one address one of the important parameters in the LCOE formula, namely the discount rate. A discount rate is used in the computation of present values of future cash flows. It is fundamental whenever the cash flows accrue at different time frames and especially over long periods. Discounting stems from that a dollar that is received now is worth more than a dollar

that is received in the future. Therefore choosing a discount rate is synonymous with choosing future dollar values or with putting relative values on cash flow estimates occurring in various time periods (Harrison, 2010). A higher discount rate makes future cash flows count for less, so the present value of future cash flows becomes smaller, while by not discounting, one assumes a zero discount rate and basically implies that a dollar received in the future (no matter how distant the future) carries the same value as a dollar received today.

In spite of the importance of discounting there is, however, little consensus over the suitable discount rate to employ for computing present values. The literature recommends various estimates of discount rates in various countries mainly ranging between estimates of 1% to 15%, with developed countries and environmental projects using estimates lying in the lower end, while developing countries generally use higher estimates. Two main schools of thought to discount rate selection have largely influenced the rates used, namely the descriptive and prescriptive approaches. The descriptive approach offers a discount rate that is centered on the opportunity cost of capital invested in the project; it centers on efficiency criterion. On the other hand, the prescriptive approach or normative approach offers a discount rate that is swayed by ethical views about intergenerational equity. It mixes equity and efficiency factors and is encouraged whenever projects have an influence on future generations (Harrison, 2010).

In line with the main schools of thought there are two focal groups of approaches to deriving the discount rate, namely market and non-market rates. The market rates are based on market interest rates and they include the (i) marginal rate of return on private investment, also called investment rate, private sector rate, before-tax rate of return or producer rate, (ii) social marginal rate of time preference, also called consumption rate, after-tax rate of return or consumer rate, (iii) weighted average rate of the investment and consumption rates, and (iv) government borrowing rate or government bond rate which is a risk-free rate (Boardman, Greenberg, Vining & Weimer, 2006).

The social time preference rate (STPR) is an example of a non-market based rate and it accounts for the value that society attaches to current consumption versus future consumption (Boardman et al., 2006; European Commission, 2008). It is generally estimated as $STPR = p + \upsilon g$, where: p denotes the rate at which future consumption is discounted over present consumption by individuals; υ denotes the elasticity of marginal utility of consumption while g denotes the long-run rate of growth of per capita consumption (HM Treasury, 2003). Proponents of STPR, argue against basing the discount rate on market variables due to the market being imperfect, consumers being irrational, and the prevalence of information asymmetry and other distortions (Rozylow, 2013). The STPR is, however, in turn criticized - for difficulty in estimating

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the parameter g, including that there might be a flaw in the estimation of the growth rate because national income might not precisely measure consumption. Another criticism stems from the judgments about intergenerational equality on the parameters υ and g which might be wrong (Boardman et al., 2006). A number of researchers or organizations have suggested using the STPR, including Evans (2005), European Commission (2008) and Rozylow, (2013).

In South Africa, the National Treasury does not stipulate a discount rate for Public Private Partnership (PPP) projects. Various institutions have therefore used various estimates, with some regarding an appropriate discount rate to be the same as the government bond yield (which is considered a risk-free rate) with a maturity matching the PPP project length (Kelman, 2008), the risk-adjusted cost of capital to government and the nominal government bond yield rate over the project term (National Treasury, 2004). The use of the government bond yield has been supported for the main reason that it reflects at any time period, government cost of funds. A discount rate of 8% was recommended by the Department of Environmental Affairs and Tourism (2004) to discount costs and benefits that accrue in the future in cost-benefit studies, with sensitivity analysis carried out at 3% and 10%. On the other hand, the EPRI (2010), in its assessment of power generation technologies in South Africa, used an 8.6% real before tax weighted average cost of capital (after tax was at 7.4%), while sensitivity analysis was carried out at 4% (after tax at 3.2%). The IRP (2011), in its integrated energy plan for electricity in the country, used a real discount rate of 8% which was signed off by the National Treasury as per its use by the National Energy Regulator of South Africa (NERSA) in the utility price application. In line with the above review on power generation technologies, the current study adopts an 8% discount rate in the baseline model and in its response to the uncertainty regarding the appropriate discount rate, sensitivity analysis is conducted at 4%, 6%, 10%, 12% and 15%.

Now, looking at the sub-model, the structure of the generation cost sub-model is represented in Figure 6.4. This sub-model consists of fourteen stock variables, six of which signify the main components of the generation cost, namely cumulative present value (CPV) fuel cost, CPV variable O&M costs, CPV fixed O&M costs, CPV FGD operation cost, CPV net electricity production and cumulative capital cost escalated (capital cost escalated, though included as a stock variable, was not discounted (Branker et al., 2011)). These six main stocks are key inputs into the computation of the LCOE. The other eight stocks in gold text, namely unit capital cost, unit water cost, unit limestone cost, unit coal cost, unit transport cost, other variable O&M costs, fixed O&M costs and other FGD O&M costs, denote the unit cost components behind the key stocks and together with some other variables give rise to the six key stocks.
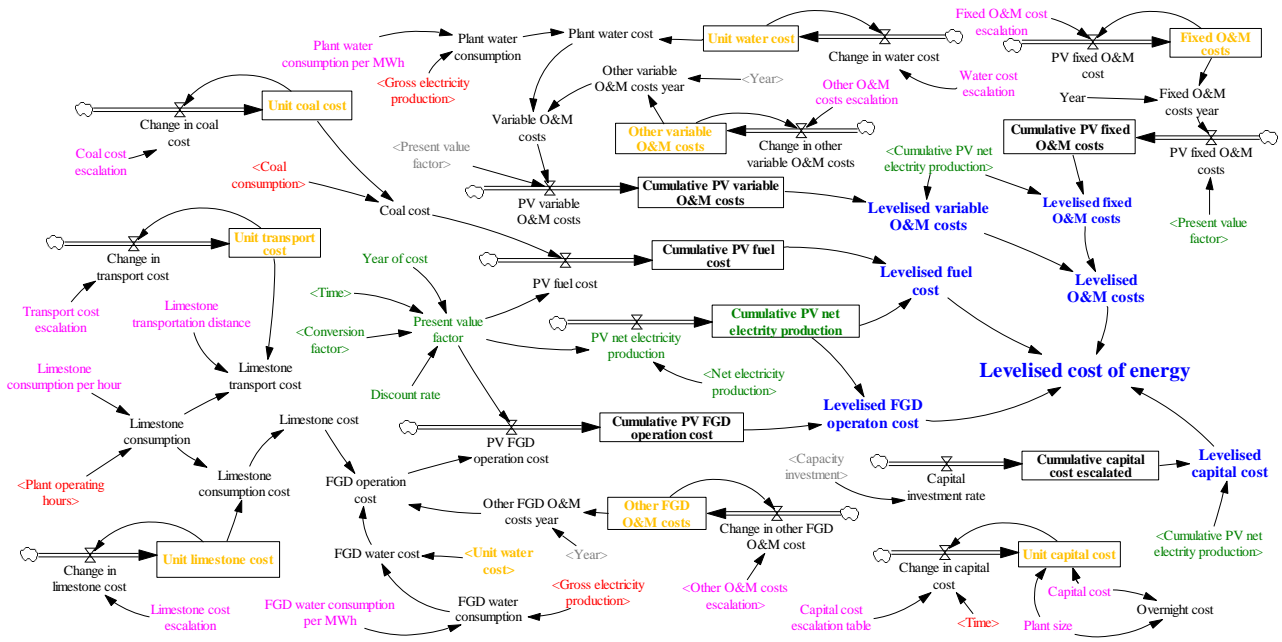
Figure 6.4: Generation cost sub-model stock and flow diagram

The eight subsidiary stocks, namely unit coal cost (UCC, R/ton), unit water cost (UWC, R/m^3), unit transport cost (UTC, R/ton/km), unit limestone cost (ULC, R/ton), other variable O&M costs (OVO & MC,R), fixed O&M costs (FO & MC,R), other FGD O&M costs (OFGDO & MC,R) and unit capital cost (UKC, R/MW), have a relatively similar structure and are influenced by exogenous fractional rate. For example, the unit coal cost (UCC, R/ton) is influenced by the change in coal cost (ΔCC, R/ton/Year), which is in turn determined by coal cost escalation. The equation for unit coal cost is given by:

$$UCC(t) = UCC(210) + \int [\Delta UCC]dt \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(13)$$

In a similar manner, the other subsidiary stocks are estimated as follows:

$$UWC(t) = UWC(0.7) + \int [\Delta UWC]dt \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(14)$$

$$UTC(t) = UTC(1.22) + \int [\Delta UTC]dt \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(15)$$

$$ULC(t) = ULC(335) + \int [\Delta ULC]dt \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(16)$$

$$OVO \& MC(t) = OVO \& MC(7.26e+008) + \int [\Delta OVO \& MC]dt \quad \dots\dots\dots\dots\dots\dots\dots\dots(17)$$

$$FO \& MC(t) = OO \& MC(8.93e+008) + \int [\Delta FO \& MC]dt \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots(18)$$

$$OFGDO \& MC(t) = OFGDO \& MC(1.705e+008) + \int [\Delta FGDO \& MC]dt \quad \dots\dots\dots\dots\dots(19)$$

$$UKC(t) = UKC(Capital\ \cos t / Plantsize) + \int [\Delta UKC]dt \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(20)$$

In turn the unit coal cost (UCC, R/ton) together with the amount of coal consumption (ton/Year), determines the coal cost (CC, R/Year). The coal cost together with the present value factor (PVF, Dmnl), determines the present value fuel cost (PVFC, R/Year), which is an inflow to the cumulative PV fuel cost (CPVFC, R) which is the ninth stock, given by:

$$CPVFC(t) = CPVFC(0) + \int [PVFC] dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(21)$$

The cumulative PV fuel cost (R) coupled with the cumulative PV net electricity production (CPVNEP, MWh) determines the levelised fuel cost (LFC, R/MWh), as follows:

$$LFC = CPVFC / CPVNEP \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(22)$$

The plant water cost (PWC, R/Year) and other variable O&M costs year (OVO & MCY, R/Year) determine the variable O&M costs (VO & MC, R/Year), which together with the present value factor, determine the present value variable O&M costs (PVVO & MC, R/Year) which is an inflow to the cumulative PV variable O&M costs (CPVVO & MC, R) which is the tenth stock, given by:

$$CPVVO \& MC(t) = CPVVO \& MC(0) + \int [PVVO \& MC] dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(23)$$

In turn the cumulative PV variable O&M costs (R) together with the cumulative PV net electricity production (CPVNEP, MWh) determine the levelised variable O&M costs (LVO&MC, R/MWh), as follows:

$$LVO \& MC = CPVO \& MC / CPVNEP \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(24)$$

The fixed O&M costs year (FO&MCY, in R/Year), together with the present value factor, determine the present value fixed O&M costs (PVFO&MC, R/Year) which is an inflow to the cumulative PV fixed O&M costs (CPVFO&MC, R) which is the eleventh stock, given by:

$$CPVFO \& MC(t) = CPVFO \& MC(0) + \int [PVFO \& MC] dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(25)$$

In turn the CPVFO&MC (R) together with the cumulative PV net electricity production (CPVNEP, MWh) determine the levelised fixed O&M costs (LFO&MC, R/MWh), as follows:

$$LFO \& MC = CPVFO \& MC / CPVNEP \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(26)$$

The levelised variable O&M costs and levelised fixed O&M costs represent the direct O&M costs linked to plant operation (excluding the FGD system). These levelised costs are summed to arrive at the levelised O&M costs (LO&MC, R/MWh).

The FGD operation cost (FGDOC, R/Year) which is composed of limestone cost, FGD water cost and other FGD O&M costs year, coupled with the present value factor, determines the present value FGD operation cost (PVFGDOC, R/Year), which is an inflow to the cumulative PV FGD operation cost (CPVFGDOC, R) which is the twelfth stock, given by:

$$CPVFGDOC(t) = CPVFGDOC(0) + \int [PVFGDOC] dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(27)$$

In turn the CPVFGDOC (R), coupled with cumulative PV net electricity production (CPVNEP, MWh), determines the levelised FGD operation cost (LFGDOC, R/MWh), as follows:

$$LFGDOC = CPVFGDOC / CPVNEP \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(28)$$

The thirteenth stock is cumulative PV net electricity production (CPVNEP, MWh) and is determined by the present value net electricity production (PVNEP, MWh/Year) which is a function of net electricity production (MWh/Year) and the present value factor (Dmnl). Cumulative PV net electricity production (CPVNEP, MWh) is given by:

$$CPVNET(t) = CPVNET(1) + \int [PVNEP] dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(29)$$

The last stock (14th) is cumulative capital cost escalated (CKCE, R) and is determined by capital investment rate (KIR, R/Year) which in turn is a function of capital investment. Cumulative capital cost escalated (CKCE, R) is estimated as follows:

$$CKCE(t) = CKCE(0) + \int [KIR] dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(30)$$

Now, concerning the levelised capital cost (LKC, R/MWh), it is determined by cumulative capital cost escalated (KCE, R) and cumulative PV net electricity production (CPVNEP, MWh), as follows:

$$LKC = CKCE / CPVNEP \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(31)$$

Finally, the LCOE (R/MWh) is mathematically represented as a summation of the levelised capital cost (LKC, R/MWh), levelised fuel cost (LFC, R/MWh), levelised O&M cost (LO&MC, R/MWh) and levelised FGD operation cost (LFGDOC, R/MWh), as follows:

$$LCOE = LKC + LFC + O\&MC + LFGDOC \dots\dots\dots(32)$$

The parameters used in the generation cost sub-model are presented in Table 6.3. The complete respective equations of the generation cost sub-model are presented in Appendix A.

Table 6.3: Parameters used in the generation cost sub-model

Parameters	Units	Baseline value	Data source
Capital cost	R	R118.5b	Eskom, 2012a.
Capital cost escalation table	Dmnl/Year	Time series	Assumption.
Coal cost escalation	Dmnl/Year	0.001	Assumption.
FGD water consumption per MWh	m^3/MWh	0.145	NINHAM SHAND, 2007.
Limestone transportation distance	Km	100	Assumption (round trip).
Limestone consumption per hour	ton/h	70	Eskom communication, 2012.
Limestone cost escalation	Dmnl/Year	0.001	Assumption.
Plant O&M costs (both fixed & variable)	%	46 of fuel cost	BDFM Publishers, 2013b.
Plant size	MW	4800	Integrated report, 2011 & 2012.
Transport cost escalation	Dmnl/Year	0.001	Assumption.
Unit capital cost	R/MW	R118.5b ÷ 4800MW	Eskom, 2012a.
Unit coal cost	R/ton	210	Eskom communication, 2012.
Unit limestone cost	R/ton	335	Calculated based on Souza et al (2002).
Unit transport cost	R/ton/km	1.22	Calculated based on Botes (2006).
Unit water cost	R/m3	0.7	Assumption.
Water consumption per MWh	m3/MWh	0.2	Eskom communication, 2012.
Water cost escalation	Dmnl/Year	0.001	Assumption.

6.6.3 Morbidity and fatalities sub-model

The morbidity and fatalities sub-model focuses on human injuries and deaths that arise in the coal-fuel cycle, namely, during coal mining, construction and power generation. Before discussing the sub-model, the address of accidents in externality analysis is discussed first. Since accidents are a complicated topic in externality analysis, care needs to be taken to ensure that what is measured are externality costs. If workers are receiving an occupational risk premium in their wage rate and are voluntarily choosing to bear the risk, there is no externality. So workers are fully compensated for the risk of accidents they are exposed to if such cost is fully internalized through the wage rate. The high frequency of wage-related strikes in the mining/energy sector in South Africa, however, indicates that workers are not happy with their wages and therefore that they are barely receiving an occupational risk premium in their wage rate. In addition, the wage-related strikes coupled with the high level of unemployment rate in the country signify that it is very

unlikely that workers are voluntarily choosing to bear the occupational risk but instead that they are rather forced to bear it as they need to provide for themselves and their families.

On another note, accidents that are suffered by employees involved in the coal-fuel cycle may also be internalized by way of *ex post* compensation to relatives of the victim. In this regard, in the South African case there are two legislations that govern mining health compensation with different benefits, namely the compensation for occupational injuries and diseases act (COIDA) and occupational diseases in mines and works Act (ODIMWA). The ODIMWA is only applicable to lung diseases in the mining industry (i.e. covers permanent incurable conditions) while COIDA applies to all injuries in and beyond the mining industry plus diseases not covered by ODIMWA (i.e. covers incurables and curable conditions). Only a once-off payment is provided by the ODIMWA (i.e. a lump sum payment based on a statutory formula is paid to an individual who becomes disabled) whereas COIDA has a lifetime pension (i.e. the dependents of a worker are entitled to 75% of the worker's salary depending on the level of disability (31% - 100%) in the event that the worker dies due to occupational-related injuries, for instance the widow is paid till the widow dies whereas children benefit until they become self-supporting (United States Agency International Development (USAID), 2008)

On the other hand, medical expenses are only covered for two years by the COIDA whereas ODIMWA prolongs the responsibility over the worker's life. In addition, a number of serious problems have been raised with regards to the acts especially the ODIMWA compared to the COIDA, including poor service delivery (an insignificant proportion of certified disabled miners receive successful compensation), delays in compensation payment, virtually no revisions of compensation figures (not even inflationary alterations). There have also been calls to harmonize the two acts into an integrated compensation system (USAID, 2008). Inadequate and inequitable compensation arrangement therefore characterizes the compensation legislation.

In addition to occupational accidents there are coal-fuel chain accidents that affect the general public. Non-occupational accidents in the fuel chain are mostly involuntarily suffered by the general public though to certain degrees the costs/losses from accidents maybe reduced by individuals through two different protective measures, namely mitigation measures and through buying insurance. Economic theory recommends internalizing the cost of accidents through liability insurance (Kopp & Prud'homme, 2007). Liability insurers pay a combination of annuities and once-off payments related to wage losses and medical costs for injuries and a combination of annuities and once-off payments for fatalities to the family (European Commission, 2005).

In the light of this discussion on occupational and public accidents, it is evident that some degree of internalization is to be expected but the absence of hard data in South Africa with which to approximate and validate the percentage of internalization rendered the researcher to base the internalization risk on the study by the European Commission (2005). In the European Commission externality study, occupational and non-occupational accidents in the fuel cycle were estimated for both Organisation for Economic Co-operation and Development (OECD) countries and non-OECD countries. The internalization estimates used in the study indicated that occupational risk is recognized as largely internalized in industrialized economies while a lower degree of internalization is expected in non-OECD countries. For occupational accident-related mortality, 70% (low), 80% (central) and 100% (high) ranges of internalization were assumed for OECD countries while 0% (low), 50% (central) and 100% (high) were assumed for non-OECD countries. On the other hand, for non-occupational accident-related mortality, 30% (low), 50% (central) and 70% (high) ranges of internalization were assumed for OECD countries while 0% (low), 20% (central) and 50% (high) were assumed for non-OECD countries. The internalization estimates used in the European Commission study further disclose that non-occupational accident-related mortality impacts are recognized as substantially externalized than occupational accident-related mortality. No form of risk internalization was made with regards to injuries in the European Commission study but instead injuries were taken to be 1% to 13% of mortality values (i.e. value(s) of prevented fatality).

In this current study the unit morbidity and mortality values used (i.e. the values of treating injuries suffered by occupational personnel and the general public, and the economic values for premature mortality, respectively) were based on the study by van Horen (1997), and NEEDS (2007) and NewExt (2004) studies, respectively. Van Horen (1997) valued injuries using the cost-of-illness approach. Estimates of medical treatment costs and the opportunity costs of not working were obtained through discussions with public health practitioners. Low, high and central estimates were computed in the Van Horen study and were adjusted for inflation in the current study. It was, however, not possible to gather whether or not any form of internalization of costs for injuries were incorporated in the study as the book providing in-depth explanation to the estimates reported in Van Horen (1997) is out of print. Concerning mortality, the values for mortality were obtained through the adjustment of valuations of changed life expectancy, obtained from the NEEDS (2007) and NewExt (2004) studies. The adjustments were conducted to reflect the disparity of income levels between the European Union (EU) and South Africa (through multiplying the unit cost determined in the EU by the ratio of purchasing power parity gross domestic product (PPP GDP) between the two nations), and to cater for inflation.

In the absence of internalization data in the South African case, morbidity and mortality values in this study were adjusted with an average of 0% (low), 35% (central) and 50% (high) ranges of internalization in line with the average assumed internalization of occupational and non-occupational accident for non-OECD countries reported in the European Commission (2005) study. The internalization estimates used in this current study therefore imply that 50%, 65% and 100% of our low, central and high estimates for mortality and morbidity were assumed to be externalized. Accordingly, the low and central values for mortality and morbidity were both adjusted to reflect 50% and 65% externality while the high estimates were not altered.

Having discussed the above, attention is now reverted to the morbidity and fatalities sub-model. Figure 6.5 represents the structure of this sub-model which consists of two stock variables, namely unit morbidity value and unit mortality value. The unit morbidity value (UMV, R/person) refers to the value of treating injuries suffered by occupational personnel and the general public. As explained earlier, the values for morbidity (low, high and central estimates) were adapted from a study by Van Horen (1997) and were adjusted for inflation and some form of internalization as explained above. The baseline value used in the modelling conducted in this study is the central estimate adjusted for inflation and internalization. The unit value for morbidity is determined by the change in morbidity value (ΔUMV, R/person/Year), which is in turn altered by escalation of damage cost (Dmnl/Year), which is estimated at the growth rate of population. The unit morbidity value (UMV, R/person) is denoted as follows:

$$UMV(t) = UMV(25434) + \int [\Delta UMV] dt \quad \text{...(33)}$$
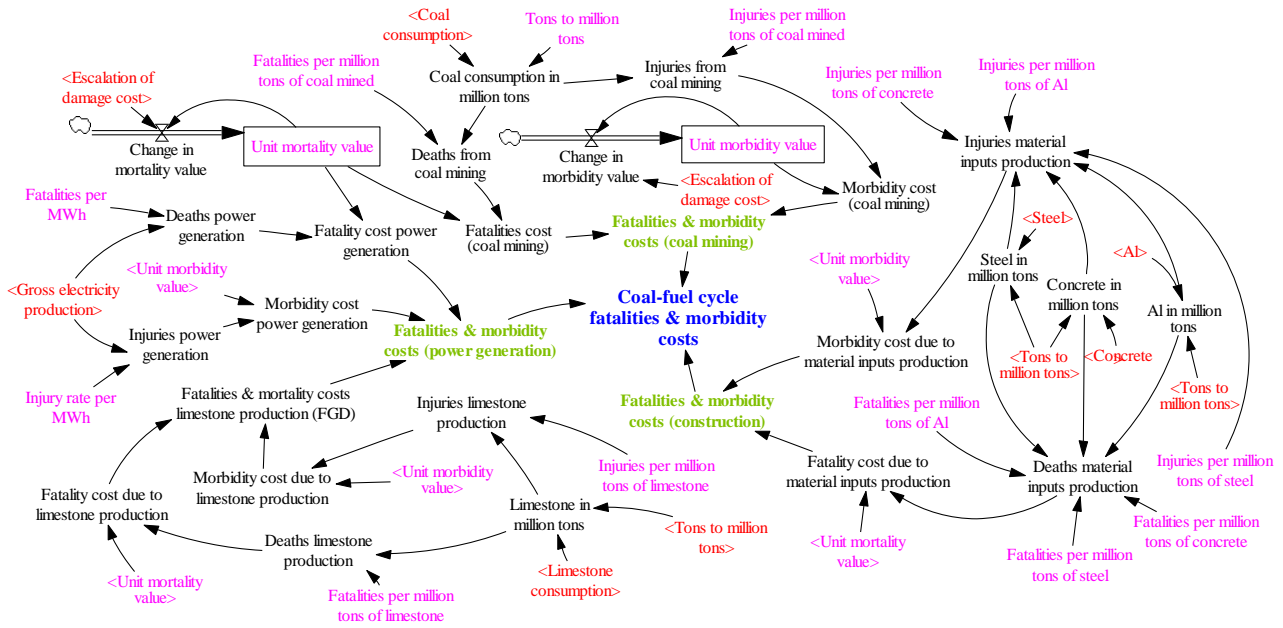
Figure 6.5: Morbidity and fatalities sub-model stock and flow diagram

Similarly, the unit mortality value (UMtV, R/person) refers to the economic value for premature mortality (fatalities or deaths). As explained earlier, the values for mortality were adapted from the NEEDS (2007) and NewExt (2004) studies. In transferring estimates from the EU to the South African context benefit transfer with income adjustment approach was used. The unit transfer with income adjustment approach is usually used when transferring estimates between countries with different income levels and costs of living. This is usually done using purchasing power parity (PPP) and income elasticity (Navrud, 2004; Hainoun *et al*., 2009). The following formula was used in this study to adjust the estimates:

$$UV_{SA} = UV_{Rc} \left(\frac{PPP_{SA}}{PPP_{Rc}} \right)^{\gamma}$$ ……………………………………………………………..............Income adjustment formula

Where, UV_{SA} refers to unitary value in South Africa, UV_{Rc} refers to unitary value in reference country, PPP is the GDP per capita adjusted for purchasing power parity and γ represents the income elasticity. An income elasticity of WTP of < 1 would imply that WTP for the improvement in environmental quality drops with increase in income, that is, as noted by Krupnick et al. (1996) premature mortality risk is an inferior good, meaning an income elasticity of 1 will understate the WTP of lower income countries. In their transfer of mortality values from the United States of America to Central and Eastern Europe Krupnick et al. (1996) used an income elasticity of 0.35 with sensitivity analysis at 1. The income elasticity of WTP was also found by Desaigues et al. (2011) to be less than one in nine countries of the EU25, normally in the range 0.4 - 0.7. While reviewing the literature on the elasticity of WTP Pearce (2003) concluded that the income elasticity

of WTP for environmental change is less than one in most of the studies and that the range 0.3 - 0.7 seem about right. On the other hand, an income elasticity of 1 would imply that WTP for environmental quality varies equivalently with income while an income elasticity that is > 1 would mean environmental quality is a luxury good (McFadden, 1994).

There is therefore disagreement in the literature concerning environmental quality, it is being viewed to be an inferior good by some, a luxury good by some and the elasticity of WTP of 1 is not supported by everyone. In this current study income elasticity's of 1, 0.7 and 0.4 were used, for our low, central and high estimates, respectively. A value of 0.7 was used in the baseline scenario. If the income elasticity is lower in South Africa than assumed in the baseline scenario, the outcome would be an underestimation of the WTP and the externality costs while if it is higher than assumed in this study the WTP values and externality costs would be overestimated. In essence in order to evaluate whether the South African elasticity is underestimated or overestimated, detailed information on the preferences of individuals in South Africa and in the EU would be needed, as would a thorough analysis of the market structures of the various nations. Since individual preferences are not easily measured, it becomes difficult to calculate where the elasticity of South Africa lies in relation to the elasticity in the EU countries. In the absence of data income elasticity's of 1, 0.7 and 0.4 were used.

Overall, the unit mortality values were adjusted to reflect the disparity of income levels between the EU and South Africa and to cater for inflation and some form of internalization. After all the adjustments the central estimate which is used in the baseline model became R245 438/person, with the high estimate at R771 700/person. The unit value for mortality is determined by the change in mortality value (ΔUMtV, R/person/Year), which is in turn altered by escalation of damage cost which is estimated at the growth rate of population. The unit mortality value (UMV, R/person) is given by:

$$UMtV(t) = UMtV(245438) + \int \left[\Delta UMtV \right] dt \quad ....(34)$$

The unit mortality and morbidity values play a central role in the computation of the coal-fuel cycle fatalities and morbidity costs (CCFMC, R/Year). CCFMC is composed of fatalities and morbidity costs streaming from three phases in the coal-fuel cycle, namely fatalities and morbidity costs (coal mining) (FMCM, R/Year), fatalities and morbidity costs (construction) (FMC, R/Year) and fatalities and morbidity costs (power generation) (FMCPG, R/Year) as follows:

$$CCFMC = FMCM + FMC + FMCPG \quad ....(35)$$

The fatalities and morbidity costs (coal mining) (FMCM, R/Year) are determined by fatality cost (coal mining) plus morbidity cost (coal mining). The fatality cost (coal mining) is in turn determined by the deaths from coal mining together with the unit mortality value. The deaths from coal mining in turn are determined by fatalities per million tons of coal mined, coupled with coal consumption in million tons. The morbidity cost (coal mining) on the other hand, is determined by the injuries from coal mining together with unit morbidity value. The injuries from coal mining are a function of the injuries per million tons of coal mined, coupled with coal consumption in million tons. The injuries and fatalities per million tons of coal mined were calculated as averages based on estimates of the deaths, injuries and coal mined in South Africa, reported by the Department of Minerals and Energy (2008; 2010) and WCA (2006-09) for the years 2006 to 2009.

The fatalities and morbidity costs (construction) (FMC, R/Year) are determined as a sum of fatality cost due to material inputs production and morbidity cost due to material inputs production. Three main material inputs, namely aluminium, steel and concrete were considered in this study. The fatality and injury rates per million tons of the main material inputs, coupled with the quantities of the main material inputs, determine the deaths and injuries from the production of the main material inputs, which then together with the unit values for mortality and morbidity, determine the fatality and morbidity costs due to material inputs production. The fatality rate, injury rate and quantities of material inputs were computed as averages based on estimates of deaths, injuries and quantities of material inputs reported by a number of sources including estimates by the Department of Minerals and Energy (2007-2010).

Lastly, fatalities and morbidity costs (power generation) (FMCPG, R) are the sum of four main costs, namely fatality cost from power generation, morbidity cost from power generation and fatalities and morbidity costs from limestone production (FGD). The fatalities and injury rates per MWh coupled with gross electricity production determine the deaths and injuries from power generation, which then together with the unit values for mortality and morbidity determine the fatality and morbidity costs from power generation. The fatalities and injury rates per MWh were computed based on estimates of deaths, injuries and power production in the years 2006 to 2009 (Eskom, 2007; 2009b; 2010a).

The fatalities and morbidity costs from limestone production (FGD) on the other hand, reflect the fatality and morbidity costs that are linked with the FGD process. These costs were, however, only limited to the fatality and morbidity costs linked with the production of limestone (i.e. limestone is used in the flue gas desulphurisation (FGD) system to curb SO_2), so fatality and morbidity costs linked with the direct operation

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of the FGD system were not included, owing to lack of deaths and injuries data in the literature. The fatality and morbidity costs due to limestone production are determined by the deaths and injuries from limestone production coupled with the unit mortality and morbidity values. The deaths and injuries are in turn a function of limestone requirements and the fatality and injury rates. Data to compute the fatality and injury rates was sourced from the Department of Minerals and Energy (2005; 2007). The parameters used in the morbidity and fatalities sub-model are presented in Table 6.4. The complete respective equations of the morbidity and fatalities sub-model are presented in Appendix A.

Table 6.4: Parameters used in the morbidity and fatalities sub-model

Parameters	Units	Baseline value	Data source
Escalation of damage cost	Dmnl/Year	0.011	Statistics South Africa, 2011.
Fatalities per million tons of coal mined	persons/million tons	0.056	Calculated based on DME (2008; 2010) and WCA (2006; 2007; 2008; 2009).
Fatalities per MWh	persons/MWh	0.00000026	Calculated based on Eskom (2007; 2009) and Eskom (2010a).
Fatalities per million tons of Al	Persons/million tons	3.174283457	Calculated based on IndexMundi (2012b) and DME (2007-2010).
Fatalities per million tons of concrete	persons/million tons	0.159	Calculated based on DME (2007 - 2010), Lafarge (2011), IndexMundi (2012a) and Palladian Publications (2013).
Fatalities per million tons of limestone	persons/million tons	0.2906977	Calculated based on DME (2005; 2007) and DMR (2003).
Fatalities per million tons of steel	persons/million tons	2.0158923	Calculated based on DME (2007 - 2010), South African Iron & Steel Institute (2013).
Injuries per million tons of coal mined	persons/million tons	0.823	Calculated based on DME (2008; 2010) and WCA (2006; 2007; 2008; 2009).
Injuries per million tons of Al	persons/million tons	19.91141441	Calculated based on IndexMundi (2012b) and DME (2007-2010).
Injuries per million tons of concrete	persons/million tons	0.995	Calculated based on DME (2007-2010), Lafarge (2011), IndexMundi (2012a), Palladian Publications (2013).
Injuries per million tons of limestone	persons/million tons	1.3372093	Calculated based on DME (2005; 2007) and DMR (2003).
Injuries per million tons of steel	persons/million tons	0.3213741	Calculated based on DME (2007-2010), South African Iron & Steel Institute (2013).
Injuries per MWh	Persons/MWh	0.00000010	Calculated based on Eskom (2007; 2009) and Eskom (2010a).
Unit morbidity value	R/person	25 434	Calculated based on Van Horen (1997).
Unit mortality value	R/person	245 438	Calculated based on NEEDS (2007) and AEA Technology Environment (2005).

6.6.4   Water consumption sub-model

Water is utilized in various activities in the coal-fuel cycle, for example, during the coal mining phase, water is primarily used for dust control, extraction, coal washing and is also lost through evaporation (Wassung, 2010). Water is also used during the building and operation of the plant, operation of the FGD system and in disposing of waste. The water consumption sub-model focuses on estimating the coal-fuel cycle externality cost of water use. Before discussing the sub-model, the study will focus on the importance of

estimating the opportunity cost of water, the water issues in the Olifants river catchment, the opportunity cost of water use in Kusile power station and how and why it was adjusted.

Estimating the opportunity cost of water use is imperative for a number of reasons. Among which are that: water is a scarce resource in South Africa (Turton, 2008) that is not traded in the market; the administered price of water does not reflect the scarcity of water; the price of water seldom reflects the full cost of water delivery (Inglesi-Lotz & Blignaut, 2012), meaning water is under-priced, and lastly, the price of water does not reflect the actual loss of welfare to society attributable to misallocation of water to suboptimal applications, i.e. the administered water prices do not capture society's welfare impact owing to the presence of externalities (Spalding-Fecher & Matibe, 2003).

The Kusile power station, which is the focus of this study, is located in the Olifants River catchment, in particular, upper Olifants together with other power stations, namely Arnot, Kriel, Hendrina, Matla, Kendal, Duvha and Komati (DWA, 2011). The Olifants River is situated in the north-east of South Africa and originates in Gauteng province (Wester, Merrey & De Lange, 2003). Water is a contested resource in the Olifants River catchment which is perceived as one of South Africa's severely stressed catchments in the context of water quantity and quality. Over the years, the water requirements in the catchment have increased extensively owing to rising water demand in various sectors. The water issues in the catchment have led the Department of Water Affairs to undertake a reconciliation strategy for the basin and its users to alleviate existing water deficits and as well as to ensure sustainable supply of water for the future. The conflicting requirements of the various water users, however, present a major challenge in the reconciling process (DWA, 2011).

In the mid portion of the catchment, water is mainly used for irrigation purposes while the Kruger National Park found in the lower end of the catchment, necessitates sufficient river flow for the maintenance of the system's ecological integrity. In the upper portion of the catchment, apart from being used at thermal power plants, water is used mainly for mining and for urban purposes. Most of the thermal power stations in the upper catchment have large water requirements owing to their wet-cooling processes. Owing to the water crisis in the Olifants catchment, all of the previously mentioned power stations are supplied with water either from the upper Komati or the Vaal systems. About 228 million m^3 of water per year are transferred into the Olifants catchment to meet the water requirements of the power stations. The Kusile power station will also receive water from the Vaal system (DWA, 2011).

The opportunity cost of water use to society when engaging in coal-fired electricity generation, was adapted from Inglesi-Lotz and Blignaut (2012). Since the administered prices of water in South Africa do not reflect the actual loss of welfare to society attributable to misallocation of water to suboptimal applications, that is to say the administered water prices do not capture society's welfare impact because externalities are not incorporated into those prices (Spalding-Fecher & Matibe, 2003), Inglesi-Lotz and Blignaut (2012) measured the externality cost of water use through estimating the shadow price of water which served as an indicator of the opportunity cost to society of using water in coal-fired power generation. Shadow prices are commonly relevant in the event that real prices do not represent the actual loss of welfare to society (Moolman et al., 2006).

When estimating the opportunity cost to society of water use in coal-fired electricity generation, the authors firstly estimated the shadow price of water when putting water use into coal-fired power generation. Secondly, they estimated the shadow prices of water when the water was put into various alternative technologies, for example, electricity production from renewable energy technologies like wind and solar. It is important to note that Eskom is a strategic water user and receives its water at about 99.5% level of assurance (Eskom, 2009a). Thus the water that will be used in Kusile will be strictly reserved for the power sector, which is why the authors kept the water within the power sector, by evaluating alternative energy technologies. The opportunity cost of water therefore computed focuses on water earmarked for the power sector.

The shadow prices were computed such that they disclose the net marginal revenue (NMR) of water (i.e. the additional revenue that will be generated by increasing water use by a cubic meter (Moore, 1999)). The higher the NMR of water, the more efficiently water is used. The methodology of determining the true scarcity value of water through estimating its shadow price and thereby comparing shadow prices of water utilising technologies (NMRs), is an approach that has been applied successfully within the agriculture sector (Moore, 1999; Moolman et al., 2006). The marginal revenue function of water determines the unit cost as the opportunity cost.

Thirdly, the opportunity cost of using one technology over another was represented by the difference between the NMRs (i.e. the forgone value of using water on coal-fired power generation rather than in a wind-plant is given by the difference in NMRs between the two water using technologies). The estimated NMR of water for all technologies was in R/m^3 and in order to arrive at the opportunity cost values, a three step process was undertaken: (1) the NMRs of water from the various alternative technologies were subtracted from the NMR of water from the baseline model (i.e. coal-fired power generation); (2) the

differences in NMRs (in R/m^3) were then multiplied with the water volume of the various technologies (m^3) yielding the society wide loss or gain (in R), and then lastly, (3) the opportunity cost (R/kWh) was calculated as the societal loss/gain (R) divided by the net generation output of the baseline model (MWh), times 1000.

Low and high estimates of the opportunity cost of water use in Kusile power station were computed in the Inglesi-Lotz and Blignaut study, i.e. the society-wide loss (opportunity cost) of water use in Kusile coal-fired power station was computed to range between R21 305 million and R42 357million. Dividing these values by the amount of water requirements for Kusile power station (26.166million m^3 (Inglesi-Lotz & Blignaut, 2012)) yields opportunity cost of water per m^3 amounting to a low and high value of R814/m^3 and R 1 619/m^3, respectively. The average of the low and the high estimates is used as the baseline value in this study, but firstly all the opportunity cost values need some adjustment because the power purchased by the water when put into renewables is in essence not real, owing to the fact that the technologies are not yet into such large scales, so renewables will not be able to uptake the water. The following formula was used to adjust the opportunity cost values:

$$\left[1 - \left(\frac{PS_{SW}}{PS_K}\right)\right] * OC_i \quad \dots \dots (36)$$

Where: PS_{SW} is the maximum plant size in MW for solar and wind; PS_K is the maximum plant size in MW of Kusile power station and OC_i is the opportunity cost of water with i denoting either low, baseline or high opportunity cost estimate (i.e. R814/m^3, R1 217/m^3 and R 1 619/m^3, respectively). The IRP (2011), in its policy-adjusted IRP, plans an investment of about 17.8GW in renewables (wind and solar), and on an annual basis mainly an investment of a total of about 800MW in wind-based and solar-based power. This capacity size for wind and solar (i.e. annual value) was therefore used to adjust the opportunity cost values of water in accordance with the above adjustment formula. In accordance with Table 2.3 of the IRP (2011:14) the capacity values reported for the various technologies seems to be load factor adjusted (evidently evidenced by the reported capacity for Kusile i.e. 4 338MW), so also the relevant load factor adjusted capacity generated by COALPSCA for Kusile power station was used.

Having discussed the above, attention is now reverted to the water consumption sub-model. Figure 6.6 presents the structure of the water consumption sub-model. The sub-model has one stock variable, namely the unit opportunity cost of water which plays an essential role in the computation of the coal-fuel cycle opportunity cost of water use. The unit opportunity cost of water use (UOCWU, R/m^3) refers to the forgone benefit to society of water use in the coal-fuel cycle (i.e. the externality cost of water under-pricing). As

explained above, the value for the opportunity cost of water use was adapted from Inglesi-Lotz & Blignaut (2012) who approximated the opportunity cost to society of water use in Kusile power station. The unit opportunity cost of water use (UOCWU, R/m^3) is determined by the change in the opportunity cost of water use (ΔOCW, R/m^3/Year), which is altered by escalation of damage cost (Dmnl/Year), which is estimated at the rate of population growth (Note: the unit damage cost estimates for all the externalities studied in this thesis including that of the opportunity cost of water were escalated at the growth rate of population because the effects of the externalities and hence the externality costs associated with them will be borne by the South African residents as a whole, so the costs will therefore likely grow at the growth rate of the population). The unit opportunity cost of water use is given by:

$$UOCWU(t) = UOCWU(1217) + \int [\Delta OCW] dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(37)$$
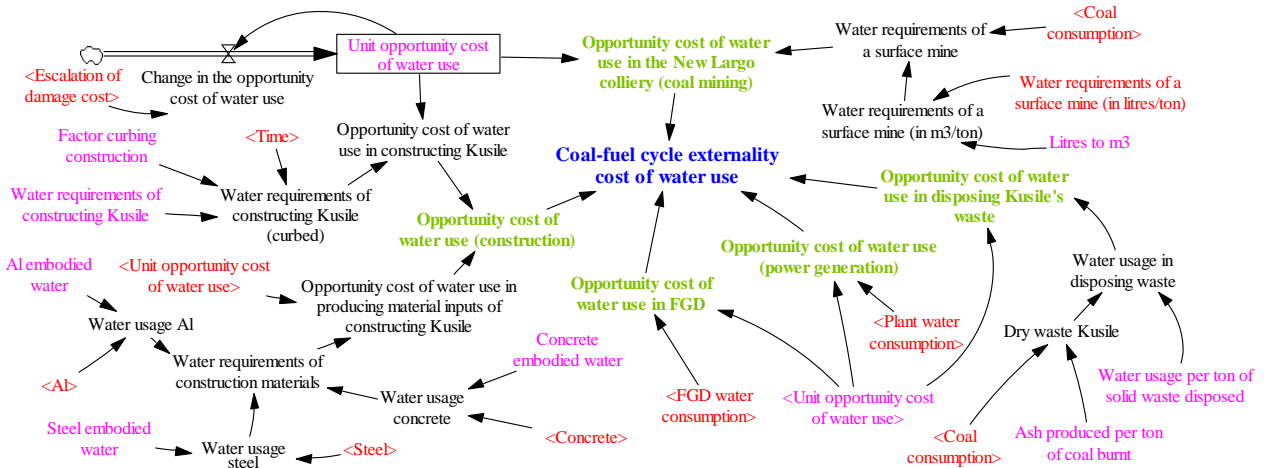
Figure 6.6: Water consumption sub-model stock and flow diagram

The coal-fuel cycle externality cost of water use (CCExtWU, R/Year) is composed of three main costs, namely the opportunity cost of water use in the New Largo colliery (coal mining) (OPWCM, R/Year), the opportunity cost of water use (construction) (OPWC, R/Year) and the opportunity cost of water use (power generation) (OPWPG, R/Year) as follows:

$$CCExtWU = OPWCM + OPWC + OPWPG \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(38)$$

The opportunity cost of water use in the New Largo colliery (coal mining) (OPWCM) is a function of the water requirements of a surface mine and the unit opportunity cost of water use. The opportunity cost of water use (construction) (OPWC) consists of the opportunity cost of water use in constructing Kusile and in

producing material inputs of constructing Kusile. The opportunity cost of water use in producing material inputs of constructing Kusile, is in essence a product of the embodied water in the main material requirements (i.e. aluminium, concrete and steel) and the unit opportunity cost of water use.

Lastly, the opportunity cost of water use (power generation) (OPWPG) is composed of three costs, namely the opportunity cost of water use in the FGD system, the opportunity cost of water use to operate Kusile and the opportunity cost of water use in disposing of Kusile's waste, which are functions of the water requirements for these activities and the unit opportunity cost of water use. For example, the opportunity cost of water use in disposing of Kusile's waste is determined by the unit opportunity cost of water use and the water usage in disposing of waste. The water usage in disposing of waste is a product of the amount of dry waste and the water usage per ton of solid waste disposed. The parameters used in the water consumption sub-model are presented in Table 6.5. The complete respective equations of the water consumption sub-model are presented in Appendix A.

Table 6.5: Parameters used in the water consumption sub-model

Parameters	Units	Baseline value	Data Source
Al embodied water	m3/ton	0.000088	Bardhan, 2012.
Ash produced per ton of coal burnt	Dmnl	0.293	Eskom, 2010a.
Concrete embodied water	m3/ton	26.352	Crawford, 2011.
Escalation of damage cost	Dmnl/Year	0.011	Statistics South Africa, 2011.
Steel embodied water	m3/ton	225	Bardhan, 2012.
Unit opportunity of water	R/m3	1001	Inglesi-Lotz and Blignaut (2012)
Water requirements of a surface mine (in litres/ton)	l/ton	469	Wassung, 2010; Pulles et al (2001).
Water requirements of constructing Kusile	m3	4 123 917	Assumption
Water usage per ton of solid waste disposed	m3/ton	0.076	Spath et al. (1999).

6.6.5   Water pollution sub-model

Water pollution has been characterized as an environmental issue of concern in the eMalahleni area (EO Miners, 2011). It is a costly environmental problem (Naicker et al., 2003; Council for Geoscience, 2010) that imposes costs on various water users. The water pollution sub-model centers on estimating the coal-fuel cycle water pollution damage cost. Figure 6.7 represents the structure of the water pollution sub-model. The sub-model consists of three stocks, namely the unit damage cost of sulphate pollution from coal mining (UDSCM, R/ton), steel production (UDSS, R/ton) and Al & concrete production (UDSAC, R/ton).

The unit damage costs by these industries represent the damages caused by them to other water users in the eMalahleni catchment. The damages were adapted mainly from Van Zyl et al. (2002) who estimated the cost imposed on other water users in the eMalahleni catchment, due to water pollution emanating from

various individual industries. Sulphate was chosen by the researchers as a best available indicator of overall salinity and a major concern in the area. Damages to the industrial and domestic sectors were estimated using preventative expenditures while those to the agricultural sector were estimated using preventative expenditures necessary to maintain yield and lower yields due to pollution. The drawbacks of the Van Zyl study are its focus on sulphate and not on all pollutants, its focus on impacts in the catchment and not downstream, and its lack of addressing natural/environmental uses. Low and high estimates representing the dry and wet seasons, respectively were computed in the Van Zyl study. The averages of the low and the high estimates for coal mining, steel production, and aluminium and cement production were inflated and used as baseline values in this study.
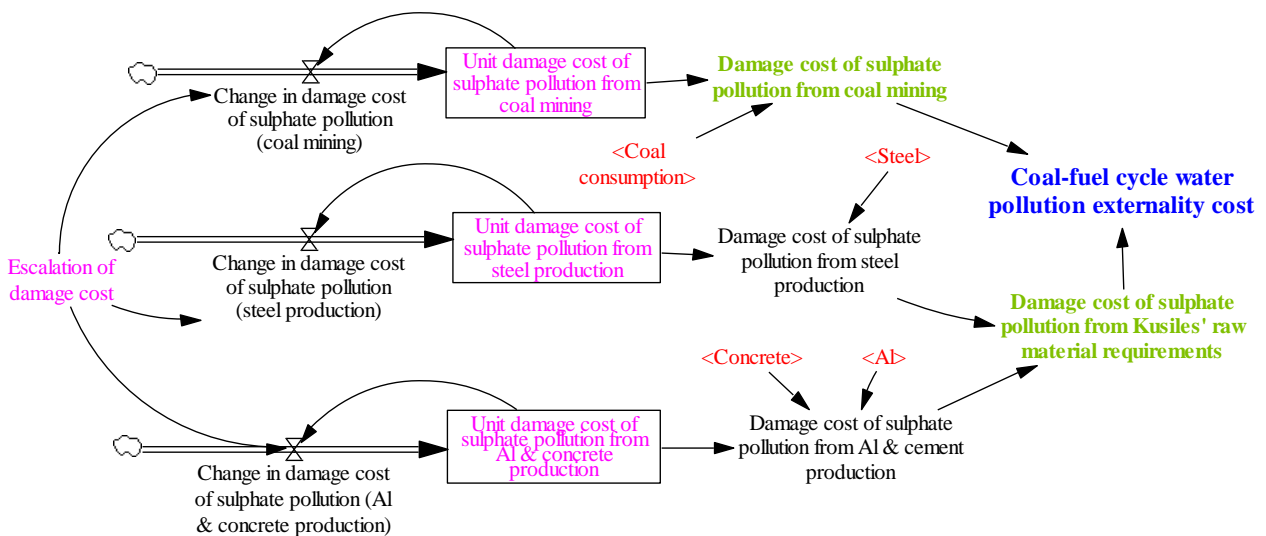
Figure 6.7: Water pollution sub-model stock and flow diagram

The unit damage cost of sulphate pollution from coal mining (UDSCM, R/ton), steel production (UDSS, R/ton) and Al & concrete production (UDSAC, R/ton) is determined by changes in the damage cost of sulphate pollution from coal mining (ΔDSCM, R/ton/Year), steel production (ΔDSS, R/ton) and Al & concrete production (ΔDSAC, R/ton) which are altered by escalation of damage cost, as follows:

$$UDSCM(t) = UDSCM(0.27) + \int [\Delta DSCM] dt \quad\text{...(39)}$$

$$UDSS(t) = UDSS(0.79) + \int [\Delta DSS] dt \quad\text{...(40)}$$

$$UDSAC(t) = UDSAC(0.31) + \int [\Delta DSAC] dt \quad\text{...(41)}$$

The coal-fuel cycle water pollution damage cost (CCWPDC, R/Year) is composed of two main costs, namely the damage cost of sulphate pollution from coal mining (DCSCM, R/Year) and damage cost of sulphate

pollution from Kusile's raw material requirements (DCSMR, R/Year). Water pollution damages from the plant operation phase were not considered in the modelling, since Eskom plans to operate the Kusile plant under a zero liquid effluent discharge policy once it is fully operational (NINHAM SHAND, 2007). In addition, no major effluents are said to arise from limestone mining and processing (BCS-Incorporated, 2002), therefore water pollution emanating from such activities was also not quantified. The coal-fuel cycle water pollution damage cost (CCWPDC) is represented as follows:

$$CCWPDC = DCSCM + DCSMR \dotfill (42)$$

The parameters used in the water pollution sub-model are presented in Table 6.6. The complete equations of the water pollution sub-model are presented in Appendix A.

Table 6.6: Parameters used in the water pollution sub-model

Parameters	Units	Baseline value	Data Source
Escalation of damage cost	Dmnl/Year	0.011	Statistics South Africa, 2011.
Unit damage cost of sulphate pollution from coal mining	R/ton	0.27	Van Zyl et al. (2002)
Unit damage cost of sulphate pollution from steel production	R/ton	0.79	Computed based on EVRAZ (2009) and Van Zyl et al. (2002).
Unit damage cost of sulphate pollution from Al & concrete production	R/ton	0.31	Calculated based on Van Zyl et al. (2002).

6.6.6 Ecosystem services loss sub-model

The ecosystem services loss sub-model is concerned with estimating the coal-fuel cycle cost of lost ecosystem services. The generation of power from Kusile power station will necessitate the construction of a new open-cast mine plus the construction of the power station. The open-cast mine will be located in the New Largo coal reserve, which signifies the extent of the area that could be mined, which covers an area of 6 817 hectares that was mainly used for maize cultivation with an extensive part falling into grasslands (Wolmarans & Medallie, 2011). The Kusile power station, on the other hand, is located in the Hartbeesfontein and Klipfontein farms in eMalahleni, in a site measuring approximately 5 200 hectares, which was previously used for maize farming and cattle grazing (NINHAM SHAND, 2007; Eskom, 2010b). The extraction of the coal resource in the New Largo reserve and the construction of the power plant will therefore lead to loss of both farmlands and grasslands. The opportunity cost of coal mining and plant construction in the said areas is therefore the forgone benefits derived from agricultural production and ecosystem services generated by grasslands. Figure 6.8 presents the structure of the ecosystem services

loss sub-model. The sub-model has two stocks, namely the unit maize price and unit value of ecosystem services generated by grasslands.
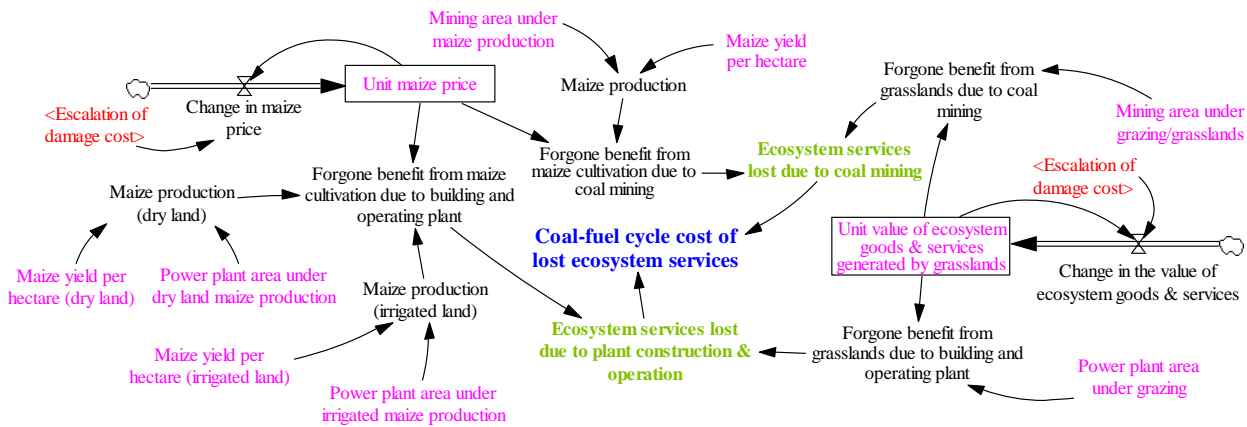
Figure 6.8: Ecosystem services loss sub-model stock and flow diagram

The unit maize price (UMP, R/ton) is an input in the computation of the forgone benefits from maize cultivation. Its initial value was adapted from Blignaut et al. (2010) and is determined by the change in maize price (ΔMP, R/ton/Year), which is altered by escalation of damage cost. The unit maize price is given by:

$$UMP(t) = UMP(1600) + \int [\Delta MP] dt \quad \text{..(43)}$$

The unit value of ecosystem services generated by grasslands (UVEG, R/ha) is an important input in the computation of the forgone benefit from ecosystem services generated by grasslands. Its initial value was adapted from Blignaut et al. (2010). While there are numerous services provided by grasslands, including carbon storage, drought and flood mitigation, sediment reduction, biodiversity maintenance, wildlife habitat provision, aesthetic beauty provision, protection of watersheds, stream and river channels, nutrient cycling and movement, waste detoxification and decomposition, and control of agricultural pests (USDA, 2010), only three of these, namely carbon storage, drought mitigation and sediment reduction, were valued in the study by Blignaut et al. (2010), for a fire-prone grassland ecosystem in the Maloti–Drakensberg mountain range in South Africa. These three ecosystem services were considered immediately viable and marketable, thus the others were excluded to avoid selling services with no immediate market.

In the current study, however, only the carbon storage value could be adapted from Blignaut et al. (2010), not drought mitigation or sediment reduction. The reason for this is that the water values are for a high-rainfall mountain catchment and cannot be equated to highlands low productive grasslands. The carbon

sequestration estimate adapted from the study by Blignaut et al. (2010) is thus considered conservative. The unit value of ecosystem services generated by grasslands (UVEG, R/ha) is determined by the change in the value of ecosystem goods & services (ΔVEG, R/ha/Year), which is in turn altered by escalation of damage cost. The exact equation is given by:

$$UVEG(t) = UVEG(510) + \int [\Delta VEG] dt \quad\text{...(44)}$$

The coal-fuel cycle cost of lost ecosystem services (CCCLES, R/Year) consists of ecosystem services lost due to coal mining (ESLCM, R/Year) and ecosystem services lost due to plant construction & operation (ESLPCO, R/Year) and is represented as follows:

$$CCCLES = ESLCM + ESLPCO \quad\text{...(45)}$$

The ecosystem services lost due to coal mining (ESLCM) are determined by the foregone benefits from maize cultivation and from grasslands due to coal mining while the ecosystem services lost due to plant construction & operation (ESLPCO) are determined by the foregone benefits from maize cultivation and from grasslands due to building and operating the plant. The foregone benefits from maize cultivation and grasslands are a product of the areas under maize production and the unit maize price, and the areas under grasslands and value of ecosystem services lost due to grasslands, respectively. The parameters used in the ecosystem services loss sub-model are presented in Table 6.7. The complete equations of the ecosystem services loss sub-model are presented in Appendix A.

Table 6.7: Parameters used in the ecosystem services loss sub-model

Variables	Units	Baseline value	Data source
Escalation of damage cost	Dmnl/Year	0.011	Statistics South Africa, 2011.
Maize yield per hectare	ton/ha	10	Blignaut et al. (2010).
Maize yield per hectare (dry land)	ton/ha	4.25	Calculated based on NINHAM SHAND (2007).
Maize yield per hectare (irrigated land)	ton/ha	10	NINHAM SHAND, 2007.
Mining area under grazing/grasslands	ha/Year	2045.1	Estimated based on Wolmarans and Madallie (2011).
Mining area under maize production	ha/Year	4771.9	Estimated based on Wolmarans and Madallie (2011).
Power plant area under dry land maize production	ha/Year	1404	Estimated based on NINHAM SHAND (2007) and Eskom (2010b).
Power plant area under grazing	ha/Year	3744	Estimated based on NINHAM SHAND (2007) and Eskom (2010b).
Power plant area under irrigated maize production	ha/Year	52	Estimated based on NINHAM SHAND (2007) and Eskom (2010b).

6.6.7   Air pollution sub-model

Classic air pollutants arise throughout the coal-fuel chain, for instance when coal is mined and transported, during the construction of the plant (e.g. from fuel use on site when ground-works are performed) and during the coal combustion phase. The air pollution sub-model is concerned with estimating the coal-fuel cycle air pollution human health cost. The air pollution sub-model structure is presented in Figure 6.9. The sub-model has seven stocks representing the damage cost of the various classic air pollutants studied, namely SO_2, NO_X, PM, nickel, lead, arsenic and chromium.
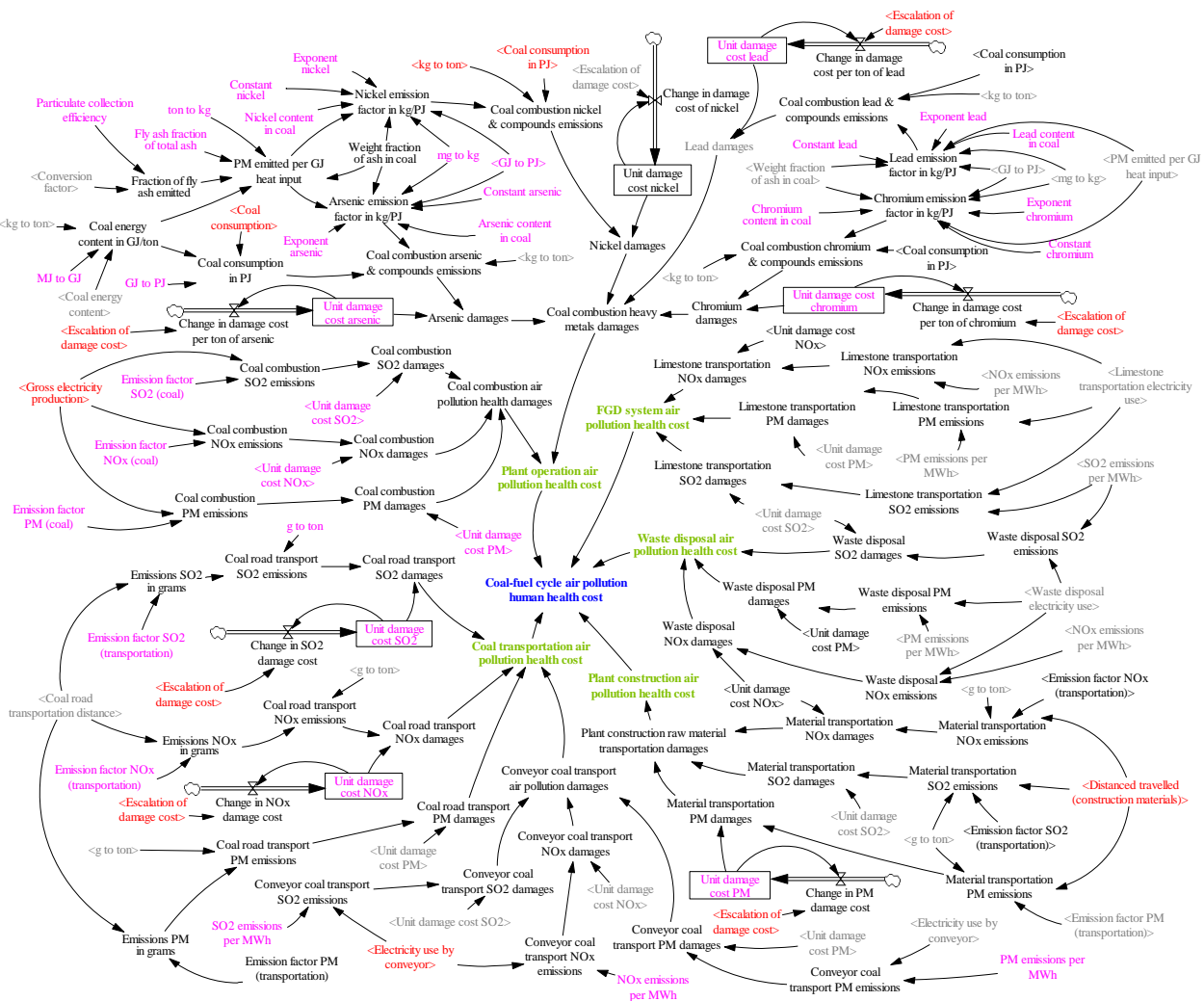
Figure 6.9: Air pollution sub-model stock and flow diagram

The coal-fuel cycle air pollution human health cost (CCAPC, R/Year) is composed of four main costs, namely coal transportation air pollution health cost (CTAC, R/Year), plant construction air pollution health cost (PCAC, R/Year), plant operation air pollution health cost (POAC, R/Year), and waste disposal air pollution health cost (WDAC, R/Year) as follows:

$$CCAPC = CTAC + PCAC + POAC + WDAC \quad\text{...}(46)$$

The coal transportation air pollution health cost (CTAC) reflects the air pollution health costs emanating from the transportation of coal by road and by the conveyor, as planned for Kusile power station. The coal road transportation damages are a function of the transportation distances, emission factors of SO_2, NO_x and PM and the unit damage cost of these gases (a discussion of the unit damage cost of the gases is provided below). Similarly, the conveyor transportation damages are a function of the electricity use in the conveyor, conveyor emission factors of SO_2, NO_x and PM and the unit damage cost of these gases. On the other hand, the plant construction air pollution health cost (PCAC) is determined by plant construction raw material transportation damages, which is in fact a function of the transportation distances of the raw material requirements, emission factors and the unit damage cost of SO_2, NO_x and PM. No data were, however, found on fuel use onsite during the construction of the plant, so damages that could have been realized from such were excluded. The plant construction air pollution health cost becomes zero after the construction period.

The plant operation air pollution health cost (POAC) consists of two main damages, namely coal combustion air pollution health damages and coal combustion heavy metals damages. The coal combustion air pollution health damages are determined by the coal combustion SO_2, NO_x and PM damages, which are in turn a function of power production, emission factors and the unit damage cost of the gases. Concerning the unit damage cost of the classic air pollutants (i.e. SO_2, NO_x and PM) in the coal-fuel chain, these were adapted from NEEDS (2007; 2008; 2009), Sevenster et al. (2008) and from AEA Technology Environment (2005).

AEA Technology Environment followed the impact pathway approach established in the ExternE project when estimating the damage cost of classic air pollutants (e.g. NO_X, SO_2, $PM_{2.5}$) – beginning with estimating emissions of pollutants in various European countries, tracking pollutants dispersion in the atmosphere (using dispersion modelling based on the new EMEP model), evaluating the exposure of people and crops to pollutants and quantifying impacts (using CAFE CBA methodology) and then estimating damages of the classic air pollutants by using estimates of VOLY (Value of a Life Year) from the NewExt (2004) study for mortality impacts. Utilizing data from various sources Sevenster et al. (2008) estimated emissions of pollutants (e.g. SO_2, NO_X, $PM_{2.5}$, etc) for large coal power producing countries and for estimating the damage costs of classic air pollutants, the authors based their estimates on damage costs per ton of emission from the EU-based NEEDS project (ExternE series of projects). In the NEEDS project the damage

costs per ton of a specific local air pollutant were calculated based on value of life year (VOLY$_{EU}$). Sevenster et al. (2008) adjusted the values for purchasing power parity and population for the various countries they investigated. The NEEDS project estimates the VOLY lost by air pollution mortality based on the results of a new contingent valuation survey conducted in European countries. WTP questions for a 6 and 3 months gain in life expectancy were used to estimate the VOLY (NEEDS, 2007; 2008; 2009).

Basing the valuations of air pollution mortality on the change of life expectancy, as opposed to a valuations based on accidental death or a small change in the probability of dying or mortality risk is more advantageous because the approach automatically factor in the constraint that humans die only once irrespective of pollution, it offers a unified framework for time series, cohort and intervention studies plus directly yields the life expectancy change as a time integral of the observed mortality rate (Rabl, 2006). In addition, change in life expectancy is further favourable because respondents during surveys show too much difficulty understanding small probability variations while a change in life expectancy is well understood (NewExt, 2003). In this current study the estimates of the VOLY for the EU (VOLY$_{EU}$) were transferred into this study and adjusted for different levels of income between the EU and South Africa. An adjustment factor was then obtained and was used to adjust the original unit damage costs. Income elasticity's of 1, 0.7 and 0.4 were used in this study, with a value of 0.7 used in the baseline scenario. Overall, the values were adjusted to reflect the disparity of income levels between the EU and South Africa and to cater for inflation and some form of internalization as explained in section 6.5.3 (i.e. Morbidity and fatalities sub-model). The baseline estimates used in this study are found in Table 5.8.

The coal combustion heavy metals damages are determined by arsenic, nickel, lead and chromium damages, which are in turn functions of coal consumption, emission factors and unit damage cost of the said four heavy metals. The emission factors for the four heavy metals were derived using engineering equations for black coal combustion, equations considered more accurate by the National Pollutant Inventory (NPI) (2012) as they consider fuel type and operational settings in the plant. The generic equations used for estimating the heavy metals emission factors are as follows:

$$EF_j = K_j * \left(\frac{C_j}{A} * PM_j \right)^e \ kg/PJ$$

$$PM_j = A * F * ER * \left(\frac{1000}{SE} \right)$$

$$ER = 1 - \left(CE \middle/ 100 \right)$$

Where: EF_j is the emission factor for a specific type of heavy metal denoted as j (kg/PJ); K is a constant of a specific trace metal type; C is the concentration of trace metal in the coal (mg/kg); A is the weight fraction of ash in the coal; e is an exponent specific to a trace metal type; PM is the power plant emission factor for total particulate matter (kg/GJ), F is the flyash fraction of total ash, ER is the fraction of flyash emitted; SE is the specific energy as received (i.e. heating value in GJ/t) and CE is the particulate collection efficiency.

Concerning the unit damage cost of the toxic metals, these were adapted from European Commission (2004) and ExternE-Pol (2005). Specifically, the impact pathway approach or bottom-up damage cost approach was followed to establish the damages of toxic metals, through determining the quantities of metal pollutants emitted by coal-fired power plants in European countries, tracking their dispersion and ultimate deposition in various multimedia, evaluating the human health response to various doses of the pollutants (through dose-response functions), and then valuation of increased morbidity and mortality through surveys assessing individual's preference for avoiding or reducing the risk of death or illness.

Lastly, the waste disposal air pollution health cost (WDAC) is determined by the waste disposal SO_2, NO_x and PM damages, which are in turn functions of electricity use during waste disposal, emission factors and the unit damage cost of the gases. The parameters used in the air pollution sub-model are presented in Table 6.8. The complete equations of the air pollution sub-model are presented in Appendix A.

Table 6.8: Parameters used in the air pollution sub-model

Parameters	Units	Baseline value	Data source
Arsenic content in coal	mg/kg	2.95	Airshed Planning Professionals (2006).
Chromium content in coal	mg/kg	57.02	Airshed Planning Professionals (2006).
Constant arsenic	Dmnl	2.73	NPI (2012).
Constant chromium	Dmnl	2.47	NPI (2012).
Constant lead	Dmnl	2.87	NPI (2012).
Constant nickel	Dmnl	2.84	NPI (2012).
Emission factor NO_x (coal)	ton/MWh	2.4	Calculated based on Riekert and Koch (2011).
Emission factor NO_x (transportation)	g/km	13.04	Stone and Bennett (n.d.).
Emission factor PM (coal)	ton/MWh	0.22	Calculated based on Riekert and Koch (2011).
Emission factor PM (transportation)	g/km	0.68	Stone and Bennett (n.d.).
Emission factor SO_2 (coal)	ton/MWh	10.02	Calculated based on Riekert and Koch (2011).
Emission factor SO_2 (transportation)	g/km	1.66	Stone and Bennett (n.d.).
Escalation of damage cost	Dmnl/Year	0.011	Statistics South Africa, 2011.
Exponent arsenic	Dmnl	0.85	NPI (2012).
Exponent chromium	Dmnl	0.58	NPI (2012).
Exponent lead	Dmnl	0.8	NPI (2012).
Exponent nickel	Dmnl	0.48	NPI (2012).
Flyash fraction of total ash	Dmnl	0.2	Airshed Planning Professionals (2006).
Lead content in coal	mg/kg	20.38	Airshed Planning Professionals (2006).
Nickel content in coal	mg/kg	25.69	Airshed Planning Professionals (2006).
NO_x emissions per MWh	ton/MWh	0.00389	Calculated based on Eskom (2010a).
Particulate collection efficiency	Dmnl	99.8	NINHAM SHAND (2007).
PM emissions per MWh	ton/MWh	0.000358	Calculated based on Eskom (2010a).
SO_2 emissions per MWh	ton/MWh	0.00753	Calculated based on Eskom (2010a).
Unit damage cost arsenic	R/ton	339976	ExternE-Pol (2005) and European Commission (2004).
Unit damage cost chromium	R/ton	133866	ExternE-Pol (2005) and European Commission (2004).
Unit damage cost lead	R/ton	6799530	ExternE-Pol (2005) and European Commission (2004).
Unit damage cost nickel	R/ton	16149	ExternE-Pol (2005) and European Commission (2004).
Unit damage cost NO_x	R/ton	41 952	Calculated based on NEEDS (2007; 2008; 2009), Sevenster et al. (2008) and from AEA Technology Environment (2005).
Unit damage cost PM	R/ton	227 175	
Unit damage cost SO_2	R/ton	51 619	

6.6.8   Global pollutants sub-model

Scientists concur that greenhouse gases such as CO_2, N_2O, CH_4, tropospheric ozone (O_3) and water vapour are the principal gases responsible for global warming (Gaffen et al., 2000). Greenhouse gases arise throughout the coal-fuel chain, for example CH_4 is the principal GHG associated with coal mining, released when coal seams are cut (National Research Council, 2009; Singh, 2008), CO_2 is the key GHG linked with the transport sector with CH_4 emitted in small quantities (Gaffen et al., 2000) and CO_2, CH_4 and N_2O are released when coal is combusted. The global pollutants sub-model is concerned with estimating the coal-fuel cycle global warming damage cost. The sub-model focuses mainly on three GHGs, namely CH_4, CO_2, and N_2O linked with coal mining and transportation, plant construction, plant operation and waste disposal. All the studied GHGs and their damages were expressed in their CO_2 equivalence (CO_2e). The structure of this

sub-model is presented in Figure 6.10 and it contains two stocks, namely the unit damage cost of CO_2 and the unit train emission damage cost.

The coal-fuel cycle global warming damage cost (CCGWC, R/Year) is composed of four main costs, namely coal mining & transportation global warming damages (CMTGWD,R/Year), plant construction global warming damages (PCGWD, R/Year), plant operation global warming damages (POGWD, R/Year) and waste disposal global warming damages (WDGWD, R), as follows:

$$CCGWC = CMTGWD + PCGWD + POGWD + WSGWD$$ ....(47)

The coal mining & transportation global warming damages (CMTGWD) are determined by three main damages, namely coal mining CO_2e damages emanating from CH_4 emissions during mining, conveyor coal transport damages which are composed of CO_2e damages of N_2O, CH_4 and CO_2 emanating from electricity use in the conveyor, and coal road transport global warming damages, which are essentially composed of coal road transport CO_2e damages of N_2O, CH_4 and CO_2. These latter damages are in turn determined by the pollutant loads, unit damage cost of CO_2 and global warming potentials of the gases. The pollutant loads of the three gases are a function of various variables, including the quantity of coal transported by road, truck capacity, transportation distance and truck fuel consumption.

Concerning the unit damage cost of CO_2 (i.e. unit value of CO_2), the values that were used in this study were based on a study by Blignaut (2012) which developed a range of unit values centred on published (peer reviews) studies while studying the social damage cost linked with climate change in a South African coal-fired power plant (i.e. Kusile). The following range of values were developed in the Blignaut study, R5.83/tCO_2 (low), R104.93/tCO_2 (market), R109.80/tCO_2 (median), R177.79/tCO_2 (high), R600.42/tCO_2 (very high), and R819.91/tCO_2 (Stern 2007; 2008). The average market rate was computed after considering carbon prices within the EU ETS programme, prices in the voluntary carbon market and CER prices. The median, market and high unit value estimate were arguably selected as the most likely range in the Blignaut study and were therefore used in this study. The baseline estimate in this current study is therefore R109.80/tCO_2.

The plant construction global warming damages (PCGWD) are determined by two damages, namely firstly construction material CO_2e damages, which is in essence determined by the quantities of the main material inputs (steel, concrete and aluminium), their embodied GHGs, the global warming potentials of the GHGs and the unit damage cost of CO_2. The capacity construction rate influences the quantities of the main

material inputs used during the construction period. Secondly, material transportation CO_2e damages which in real meaning is determined by a number of variables, including fuel consumption, emission factors, unit damage cost of CO_2 and global warming potential of the GHGs.

On the other hand, the plant operation global warming damages (POGWD) are determined by three damages, namely firstly coal combustion damages, which are determined in essence by a number of variables including electricity production, emission factors of N_2O and CO_2, the global warming potentials of GHGs, and the unit damage cost of CO_2. Secondly, limestone transportation damages which are determined by limestone consumption, limestone transportation distance and the unit train emission damage cost. Thirdly, limestone use damages which are essentially a function of limestone consumption, limestone use CO_2 emission factor and the unit damage cost of CO_2. Lastly, the waste disposal global warming damages (WDGWD) are a function of various variables, including the amount of dry waste, transportation distance, electricity use by the conveyor, global warming potentials of the GHGs and the unit damage cost of CO_2.

Figure 6.10: Global pollutants sub-model stock and flow diagram

The parameters used in the global pollutants sub-model are presented in Table 6.9. The complete equations of the climate change sub-model are presented in Appendix A.

Table 6.9: Parameters used in the global pollutants sub-model

Parameters	Units	Baseline value	Data source
Al C_2F_6 embodiment	kg/ton	0.04	IPCC (2007b).
Al CF_4 embodiment	kg/ton	0.8	IPCC (2007b).
Al CO_2 embodiment	kg/ton	5301	Bosch & Kuenen (2009).
AL per MW	ton/MW	0.419	Spath et al (1999).
C emission factor for diesel	ton C/TJ	20.2	IPCC (1996).
Carbon %	Dmnl	0.425	Pinheiro et al (1997).
Carbon oxidation factor	Dmnl	0.99	Blignaut et al (2005).
CH4 emission m^3/ton	m3/ton	0.014	Cook (2005) and Lloyd and Cook (2005).
Coal road transportation distance	Km	2.21484e+007	Calculated based on Synergistics Environmental Services and Zitholele Consulting (2011) and Coaltech (2009).
Concrete CO_2e embodiment	kg/ton	119.72	InEnergy (2010).
Concrete per MW	ton/MW	158.758	Spath et al (1999).
Construction material use schedule	Dmnl/Year	Fraction	Timeseries
Conveyor electricity use per ton-km	MWh/ton/km	0.0002	ContiTech AG (2013).
Conveyor length	Km	42	Calculated based on Synergistics Environmental Services and Zitholele Consulting (2011).
Density of bituminous coal	kg/m3	732	Cook (2005).
Diesel oxidation factor	Dmnl	0.99	IPCC (1996).
Distance travelled Kusile waste	Km	30	Zitholele Consulting (2011).
Energy density of diesel	MJ/l	38.46	Downs et al (1998) and Lammers (2009).
Escalation of damage cost	Dmnl/Year	0.011	Statistics South Africa, 2011.
Fraction of coal transported by road	Dmnl	0.27	Calculated based on Synergistics Environmental Services and Zitholele Consulting (2011) and Coaltech (2009).
Global warming potential C_2F_6	Dmnl	12200	IPCC (2007c).
Global warming potential CF_4	Dmnl	7390	IPCC (2007c).
Global warming potential CH_4	Dmnl	23	IPCC (2001).
Global warming potential N_2O	Dmnl	310	IPCC (2001).
Gravimetric factor converting C to CO_2	Dmnl	3.667	Blignaut et al (2005).
Limestone use CO_2 emission factor	kg/ton	439.71	IPCC (2007a).
N2O emissions per MWh	ton/MWh	0.0000115	Calculated based on Eskom (2010a).
Steel CH_4 embodiment	kg/ton	0.003	IPCC, 1996.
Steel CO_2 embodiment	kg/ton	2710	Bosch & Kuenen (2009)
Steel N_2O embodiment	kg/ton	0.040	IPCC, 1996
Steel per MW	ton/MW	50.721	Spath et al (1999).
Truck fuel consumption in l/km	l/km	0.35	Odeh and Cockerill (2008).
Unit damage cost CO_2	R/ton	109.89	Blignaut (2012).
Unit train emissions damage cost	R/ton/km	0.018	Jorgensen (2010).

6.6.9   Social cost sub-model

The social cost sub-model is concerned with estimating nine economic indicators in addition to the LCOE discussed in the generation cost sub-model, namely levelised externality cost of energy (LECOE), levelised social cost of energy (LSCOE), cumulative PV revenue, cumulative PV cost, NPV before tax, NPV after tax,

cumulative PV externality cost, social NPV before tax, and social NPV after tax. Expected profitability is also discussed in this sub-model as explained in section 6.6.1. The structure of the social cost sub-model is presented in Figure 6.11, mainly characterised by the nine economic indicators.
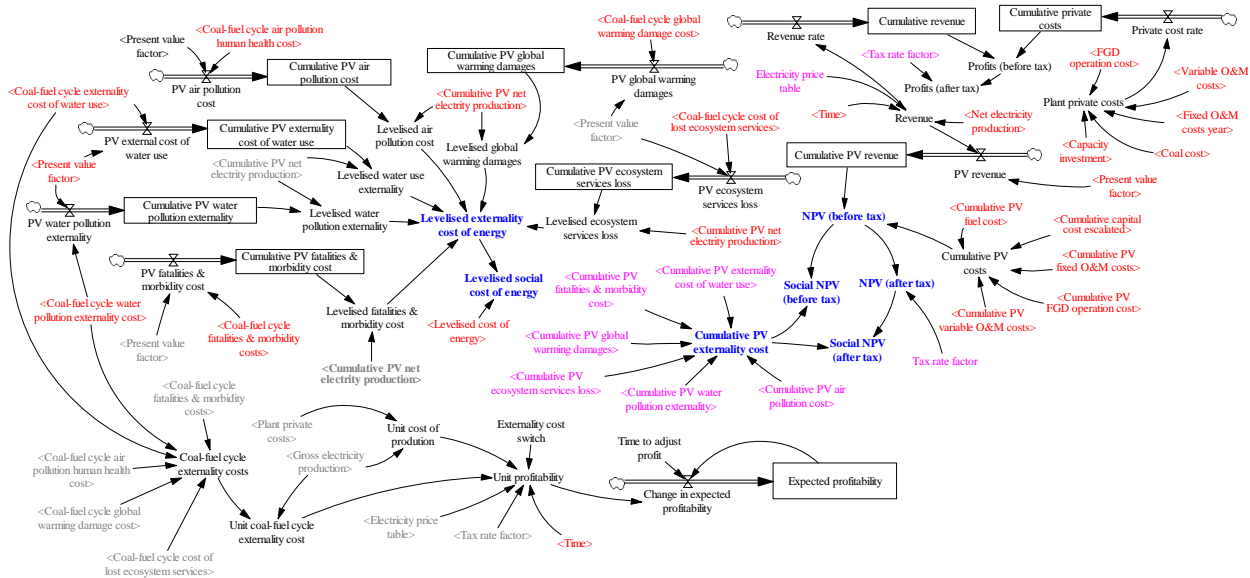
Figure 6.11: Social cost sub-model stock and flow diagram

The levelised externality cost of energy (LECOE) and the levelised social cost of energy (LSCOE) are computed in a similar manner as done for the LCOE. The levelised externality cost of energy is composed of six stocks which reflect the six externalities studied in the coal-fuel cycle. The coal-fuel cycle externality cost of water use together with the present value factor determines the PV externality cost of water use (PVExWU, R/Year), which is an inflow to the cumulative PV externality cost of water use (CPVExWU, R) which is the first stock given by:

$$CPVExWU(t) = CPVExWU(0) + \int [PVExWU]dt \text{ ....(48)}$$

The cumulative PV externality cost of water use, coupled with cumulative PV net electricity production (PVNEP, MWh), determines the levelised water use externality (LWUEx, R/MWh), as follows:

$$LWUEx = CPVExWU \ / \ CPVNEP \text{ ....(49)}$$

On the other hand, the coal-fuel cycle water pollution externality, together with the present value factor, determines the PV water pollution externality (PVWPEx, R/Year), which is an inflow to the cumulative PV water pollution externality (CPVWPEx, R) which is the second stock, given by:

$$CPVWPEx(t) = CPVWPEx(0) + \int[PVWPEx]dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(50)$$

The cumulative PV water pollution externality, coupled with cumulative PV net electricity production (CPVNEP, MWh), determines the levelised water pollution externality (LWPEx, R/MWh), as follows:

$$LWPEx = CPVWPEx / CPVNEP \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(51)$$

In turn, the coal-fuel cycle fatalities & morbidity costs, together with the present value factor, determine the PV fatalities & morbidity costs (PVFMC, R/Year), which is an inflow to the cumulative PV fatalities & morbidity costs (CPVFMC, R) which is the third stock, given by:

$$CPVFMC(t) = CPVFMC(0) + \int[PVFMC]dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(52)$$

The cumulative PV fatalities & morbidity cost, coupled with cumulative PV net electricity production (CPVNEP, MWh), determines the levelised fatalities & morbidity cost (LFMC, R/MWh), as follows:

$$LFMC = CPVFMC / CPVNEP \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(53)$$

The coal-fuel cycle cost of lost ecosystem services, together with the present value factor, determines the PV ecosystem services loss (PVESSL, R/Year), which is an inflow to the cumulative PV ecosystem services loss (CPVESSL, R) which is the fourth stock, given by:

$$CPVESSL(t) = CPVESSL(0) + \int[PVESSL]dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(54)$$

The cumulative PV ecosystem services loss, coupled with cumulative PV net electricity production (CPVNEP, MWh), determines the levelised ecosystem services loss (LESSL, R/MWh), as follows:

$$LESSL = CPVESSL / CPVNEP \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(55)$$

In turn, the coal-fuel cycle air pollution human health cost, together with the present value factor, determines the PV air pollution cost (PVAPC, R/Year), which is an inflow to the cumulative PV air pollution cost (CPVAPC, R) which is the fifth stock, given by:

$$CPVAPC(t) = CPVAPC(0) + \int[PVAPC]dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(56)$$

The cumulative PV air pollution cost, coupled with cumulative PV net electricity production (CPVNEP, MWh), determines the levelised air pollution cost (LAPC, R/MWh), as follows:

$$LAPC = CPVAPC / CPVNEP \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(57)$$

Finally, the coal-fuel cycle global warming damage cost, together with the present value factor, determine the PV global warming damages (PVGWD, R/Year), which is an inflow to the cumulative PV global warming damages (CPVGWD, R) which is the sixth stock, given by:

$$CPVGWD(t) = CPVGWD(0) + \int[PVGWDC]dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(58)$$

The cumulative PV global warming damages, coupled with cumulative PV net electricity production (CPVNEP, MWh), determine the levelised global warming damages (LGWD, R/MWh), as follows:

$$LGWD = CPVGWD / CPVNEP \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(59)$$

The six levelised externalities discussed above (i.e. levelised water use externality, water pollution externality, fatalities and morbidity costs, ecosystem services loss, air pollution cost and global warming damages) are summed to yield the levelised externality cost of energy (LECOE, R/MWh), which is the first economic indicator, represented as follows:

$$LECOE = LWUEx + LWPEx + LFMC + LESSL + LAPC + LGWD \dots\dots\dots\dots\dots\dots\dots\dots\dots(60)$$

The levelised social cost of energy (LSCOE, R/MWh), which is the second economic indicator, is specified by the levelised externality cost of energy (LECOE, R/MWh) and the earlier computed LCOE (R/MWh), as follows:

$$LSCOE = LCOE - LECOE \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(61)$$

The third economic indicator is the cumulative PV revenue (CPVR, R). The revenue and the present value factor determines the PV revenue (PVR, R/Year), which is an inflow to the CPVR. The revenue is the function of the energy price and net electricity production. The energy price was entered as a table,

depicting the time series of the wholesale energy price, computed based on a number of sources including Lana (2010), Eskom (2012c), Eskom (2013b), NERSA (2013) and BDFM Publishers (2013c). The cumulative present value revenue (CPVR, R) is given by:

$$CPVR(t) = CPVR(0) + \int [PVR] dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(62)$$

The fourth economic indicator is the cumulative PV cost (CPVC, R), which is a summation of the cumulative private costs of generating coal in Kusile, namely cumulative capital cost escalated (CKCE), cumulative PV fuel cost (CPVFC), cumulative PV variable O&M costs (CPVVO&MC), cumulative PV fixed O&M costs (CPVFO&MC) and cumulative PV FGD operation cost (CPVFGDOC), as follows:

$$CPVC = CKCE + CPVFC + CPVVO\&MC + CPVFO\&MC + CPVFGDOC \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(63)$$

The fifth and sixth economic indicators concern the net present value, which is an economic measure for examining cash outflows (costs) and cash inflows (revenues) of investing in the Kusile project. Before and after tax NPVs were computed. The NPV before tax (NPV$_{bt}$, R) is given by the difference between the cumulative PV revenue (CPVR, R) and cumulative PV cost (CPVC, R) whereas the NPV after tax (NPV$_{at}$, R) corrects the NPV before tax with a tax rate factor (TaxR, Dmnl) which is based on NERSA (2013). The NPVs before tax and after tax are given by the following equations, respectively:

$$NPV_{bt} = CPVR - CPVC \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(64)$$

$$NPV_{at} = NPV_{bt} * TaxR \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(65)$$

The seventh economic indicator is the cumulative PV externality cost (CPVExC, R), which is a summation of the cumulative PV externality costs computed earlier, namely cumulative PV externality cost of water use (CPVExWU), cumulative PV water pollution externality (CPVWPEx), cumulative PV fatalities & morbidity costs (CPVFMC), cumulative PV ecosystem services loss (CPVESSL), cumulative PV air pollution cost (CPVAPC) and cumulative PV global warming damages (CPVGWD). The cumulative present value externality cost is represented as follows:

$$CPVExC = CPVExWU + CPVWPEx + CPVFMC + CPVESSL + CPVAPC + CPVGWD \dots\dots\dots\dots\dots\dots\dots\dots(66)$$

The eighth and ninth economic indicators concern the social NPV, which is an indicator that examines the private and externality costs and benefits of the Kusile project. Before tax and after tax social NPVs were computed. The social NPV before tax (SNPV$_{bt}$, R) is yielded by the difference between the NPV before tax (NPV$_{bt}$, R) and the cumulative PV externality cost (CPVExC, R) whereas the social NPV after tax (SNPV$_{at}$, R) is yielded by the difference between the NPV after tax (NPV$_{af}$, R) and the cumulative PV externality cost (CPVExC, R). The before tax and after tax social NPVs are given by the following equations, respectively:

$$SNPV_{bt} = NPV_{bt} - PVExC \quad \text{...(67)}$$

$$SNPV_{at} = NPV_{at} - PVExC \quad \text{...(68)}$$

Lastly, one more stock presented in the social cost sub-model is expected profitability (EP, Dmnl) which basically represents the balance between the electricity price and the unit cost of production. Expected profitability (EP, Dmnl) is driven by the change in expected profitability (CEP, Year) and is represented as follows:

$$\text{EP}(t) = \text{EP}(0) + \int [CEP] dt \quad \text{...(69)}$$

The change in expected profitability is represented by the following equation:

$$CEP = (UP - EP)/Tap \quad \text{...(70)}$$

Where, UP is the unit profitability (Dmnl) and Tap is the time to adjust profitability (Year). The unit profitability (UP, Dmnl) in turn is determined by the electricity price (EP, R/MWh) and the unit cost of production (UCP, R/MWh) and is represented as follows:

$$UP = (EP - UCP)/EP \quad \text{...(71)}$$

The unit cost of production (UCP, R/MWh) represents such costs such as fuel cost (i.e. coal cost), variable O&M costs, fixed O&M costs and FGD operation cost. The effect of externality costs on the profitability of the plant was not accounted for in the initial analysis but instead a switch was used that tested for its incorporation. A value of 1 is taken by the switch if externality costs are included in the computation of the unit profitability, otherwise zero if not.

The complete respective equations and the rest of the equations of the social cost sub-model are contained in Appendix A.

6.7   Summary

In this chapter, the modelling process followed in developing the COALPSCA Model was discussed. The first and essential step in the model building process is problem formulation which saw the framing of the problem addressed in this study, the purpose of the model and a discussion of the time horizon for the model. The main concern of this research was stated as to understand the design and performance of a coal-fired power plant and its interconnections with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and fuel cycle. The purpose of developing the model was stated as twofold, firstly to aid energy decision makers with a tool for making informed energy supply decisions that consider not only the financial feasibility of power generation technologies, but in addition the socio-environmental consequence of the technologies. Secondly, the model is to aid coal-based power developers with a useful tool for detecting the main drivers of the burdens and costs in the system which should yield vital socio-economic-environmental tradeoff information that can be beneficial to them. A period of 50 years was considered a reasonable time frame to address the key issues in this study.

The next important step involved the formulation of the dynamic hypothesis which saw the construction of a working theory that explains the problem. The behaviour of the power generation system with its upstream processes and to a certain extent its downstream processes was qualitatively expressed in the causal loop diagram based on the causal structure and feedbacks of the system. The model boundary was then discussed. Lastly, the stock and flow structures of the modeled system were constructed and they provided the quantitative relationships between the variables of the system by adding stock and flow variables. The COALPSCA Model was separated into nine sub-models, namely power generation, generation cost, water consumption, water pollution, morbidity and fatalities, ecosystem services loss, air pollution, global pollutants and social cost sub-models. In the next section the outcomes of the COALPSCA Model are presented together with validation tests and policy design and evaluation.

CHAPTER 7: RESULTS

7.1 Introduction

In the previous section, a life-cycle power generation and social cost assessment model for coal-based power (COALPSCA) was constructed based on the system dynamics approach. The results of COALPSCA are reported in this section. The model results are by no means to be viewed as predictions, but rather as likely evolutions of coal-based power generation from which, understanding might be derived to making informed decisions. Presented firstly are the baseline results, followed by the validation and verification of COALPSCA, which include an analysis and discussion of the sensitivity of the model outcomes to key parameters such as the load factor, discount rate, cost growth rates of all private costs in the model (e.g. coal, limestone, water, O&M and capital costs), cost growth rates of all damage cost estimates and the sensitivity of the model outcomes to lower and higher range estimates. This is then followed by an evaluation of the model outcomes under various policy scenarios that could be faced by coal-based power utilities, namely carbon taxation and the sale of coal domestically at export parity prices. A summary of the results is then presented lastly.

7.2 Baseline results

The COALPSCA Model aims to demonstrate the assessment of the social cost of coal-based power generation in the Kusile power station. An analysis of the outcomes of the model, on selected economic and environmental indicators under various scenarios, was conducted. The focus in this section is on the baseline scenario. The baseline scenario represents power production in the Kusile power station over a period of 50 years as planned by Eskom. The key input parameters used in the baseline scenario are contained in Table 7.1. As anticipated by Eskom, the baseline scenario assumes a 90% load factor while an energy content of 19.22MJ/kg is used, as per the typical coal consumed by the entity (Eskom, 2010a). The scenario further assumes a 0.1% growth rate of all private costs (e.g. limestone, O&M, water and coal costs) while the studied externalities' damage costs were escalated at the growth rate of population, i.e. 1.1%.. The damage costs were escalated at the growth rate of population growth because the effects of the externalities and hence the externality costs associated with them will be borne by the South African residents as a whole, so the costs will therefore likely grow at the growth rate of the population. Average values of low and high estimates were used as starting values to value the studied externalities and based on Eskom communication (2012) a unit cost of coal of R210 per ton was used in the baseline model. A discount rate of 8% was used in the baseline scenario as discussed earlier in section.

Table 7.1: Baseline scenario input parameters

Parameter	Units	Baseline value
Load factor	Dmnl (%)	0.9 (90%)
Coal energy content	MJ/kg	19.22
Private cost growth rates (i.e. coal, limestone, water, O&M & capital cost)	Dmnl/Year (%)	0.1 (0.1%)
Escalation of damage cost	Dmnl/Year (%)	1.1%
Externality damages	Various units	Average estimates
Discount rate	Dmnl	0.08 (8%)
Unit coal cost	R/ton	210

The economic and environmental/societal indicators used for the analysis of the COALPSCA Model outcomes are contained in Table 7.2. In general, ten economic indicators representing the performance of the plant, the cost incurred by plant developers and the community at large were considered. In addition, six environmental indicators reflecting the six coal-fuel cycle externalities quantified and monetized in this study were also considered.

Table 7.2: Economic and socio-environmental indicators

Economic indicator	Environmental/societal indicator
- Electricity production - Generation cost (capital, fuel & O&M) - Levelised cost of energy (LCOE) - Levelised externality cost of energy (LECOE) - Levelised social cost of energy (LSCOE) - Cumulative PV revenue - Cumulative PV cost - NPV - Cumulative PV externality cost - Social NPV	- Water use - Water pollution - Fatalities & morbidity - Ecosystem services loss - Air emissions - GHG emissions

7.2.1 Electricity generation

There are various factors that influence the amount of electricity generation, including plant capacity, load factor, operating hours, idle capacity, profits and plant's own electricity consumption. An increase in plant capacity, load factor, operating hours and profits positively affect power generation while an increase in idle capacity and plant's own electricity consumption negatively affects generation. The plant was modelled to produce 90% of the total amount of electricity it could theoretically produce over its lifetime (i.e. load factor of 90%). For this reason, 10% of the plant capacity was held idle. 7.5% of the electricity produced by the plant was modelled to be consumed internally by Kusile according to Eskom communication (2012). Plant operating hours were estimated at about 8234 hours annually after correcting for energy availability factor of about 90% (based on Eskom communication, 2012). The energy availability factor as explained

earlier is mainly a factor of its reliability and the periodic maintain it requires (i.e. it corrects for the fact that the power plant does not run continuously over its lifetime but needs to be shut down for service at times).

The baseline scenario electricity production outcomes are presented in Table 7.3. The model estimates an annual net electricity production of 32.8 million MWh (gross 35.5 million MWh) once Kusile is fully operational. Eskom on the other hand, using a 90% load factor and an energy availability factor of 84%, estimates Kusile's annual net electricity production at about 32.7 million MWh (Eskom, 2010c). The COALPSCA Model estimate is therefore analogous to the estimate by Eskom with about 0.3% variation. Total net electricity production over Kusile's lifetime is estimated by COALPSCA at about 1.6 billion MWh (gross 1.7 MWh). About 18 million tons of coal is estimated by COALPSCA to be consumed annually once Kusile is fully operational. An estimate that is comparable with NINHAM SHAND (2007) estimates of 21.1 million tons for a 5400MW plant or 18.8 million tons if one corrects the estimate to Kusile's actual size, yielding about 4% variation (Table 6.7). In addition, Synergistics Environmental Services and Zitholele Consulting (2011), as well as Wolmarans and Medallie (2011), estimate annual coal requirements of about 17 million tons for Kusile, estimates yielding about 5.6% variation to the estimate by the COALPSCA Model (Table 7.4).

Table 7.3: Baseline scenario electricity production (gross and net)

Output variable	Units	Model outcomes	Eskom projection	% variation
Net electricity production	Million MWh/Year	32.8	32.7	0.3
Gross electricity production	Million MWh/Year	35.5		
Cumulative net electricity production	Billion MWh	1.6		
Cumulative gross electricity production	Billion MWh	1.7		

Table 7.4: Coal consumption (Million tons)

Classic air pollutant	Model outcomes	NINHAM SHAND (corrected)	% variation	Wolmarans & Medallie[a]	% variation
Coal consumption (annual)	18	18.8	4.3	17	5.6
Coal consumption (lifetime)	870.3				

[a] Aslo Synergistics Environmental Services and Zitholele Consulting (2011)

7.2.2   Private costs

The economic indicators linked to the private costs of generating electricity include - (i) the generation cost which consists of capital, fuel, FGD, fixed and variable O&M costs; (ii) the LCOE which is categorized into capital, fuel, FGD, fixed and variable O&M costs; and (iii) the NPV which consists of cumulative PV revenues

and costs. The private costs of producing coal-based electricity are presented in Table 7.5. The overall escalated lifetime generation cost of power in Kusile is estimated by the COALPSCA Model to be about 410.5 billion Rands. The main generating cost components determining the generation cost are fuel and capital costs, which individually constitute about 46% and 29%, respectively. Fixed and variable O&M costs make up about 11% and 9% of the generation cost, respectively, while FGD operation cost contributes the least at about 5%.

Table 7.5: Baseline scenario private costs over Kusile's lifetime

Output variable	Units	Model outcomes	Calc. Eskom (2011)	EPRI (2010)
Capital cost	R billion	118.8 (28.9%)[a]		
Fuel cost	R billion	187.7 (45.7%)[a]		
Fixed O&M costs	R billion	46.7 (11.4%)[a]		
Variable O&M costs	R billion	38.2 (9.3%)[a]		
FGD operation cost	R billion	19.2 (4.7%)[a]		
Total generation cost	**R billion**	**410.5**		
Levelised capital cost	R/MWh	362.2		338.8
Levelised fuel cost	R/MWh	117		146.5
Levelised fixed O&M costs	R/MWh	33.7		105.5
Levelised variable O&M costs	R/MWh	27.5		
Levelised FGD operation cost	R/MWh	13.8		
LCOE	**R/MWh**	**554.2**	540.2[b] - 584.6[c]	590.8
Cumulative PV cost	R billion	181.8		
Cumulative PV revenue	R billion	274		
NPV (before tax)	**R billion**	**92.2**		
NPV (after tax)	**R billion**	**66.4**		

[a] Proportions (%) of electricity generation cost; [b] Calculated based on Eskom's reported benchmarked value to the same base year and exchange rate as that of EPRI (2010) (i.e. USD73/MWh); [c] Calculated based on Eskom's reported non-benchmarked value (i.e. USD73/MWh).

For the LCOE computations, the time series of expenses were discounted to present values (2010 base year) by the use of a discount rate. A discount rate of 8% was used for the baseline scenario. So the LCOE (R/KWh) is the ratio of total lifetime expenses to total expected output (i.e. electricity), expressed in present value. The LCOE for generating electricity in Kusile is estimated at R554.2/MWh. Levelised capital and fuel costs are about R362.2/MWh and R117/MWh, respectively, while levelised fixed and variable O&M costs are estimated at about R33.7/MWh and R27.5/MWh, respectively. Constituting the least to the lifetime LCOE is the levelised FGD operation cost of about R13.8/MWh (see Table 7.5). Figure 7.1 below shows the LCOE simulation outputs as estimated by the COALPSCA Model. The LCOE computations conducted in this study are in nominal (i.e. current) Rands, meaning the effects of inflation are taken into account when looking at future costs, however, it must be noted that for the baseline scenario escalation was assumed to be 0.1% (a value that is less than the current inflation rate in South Africa).
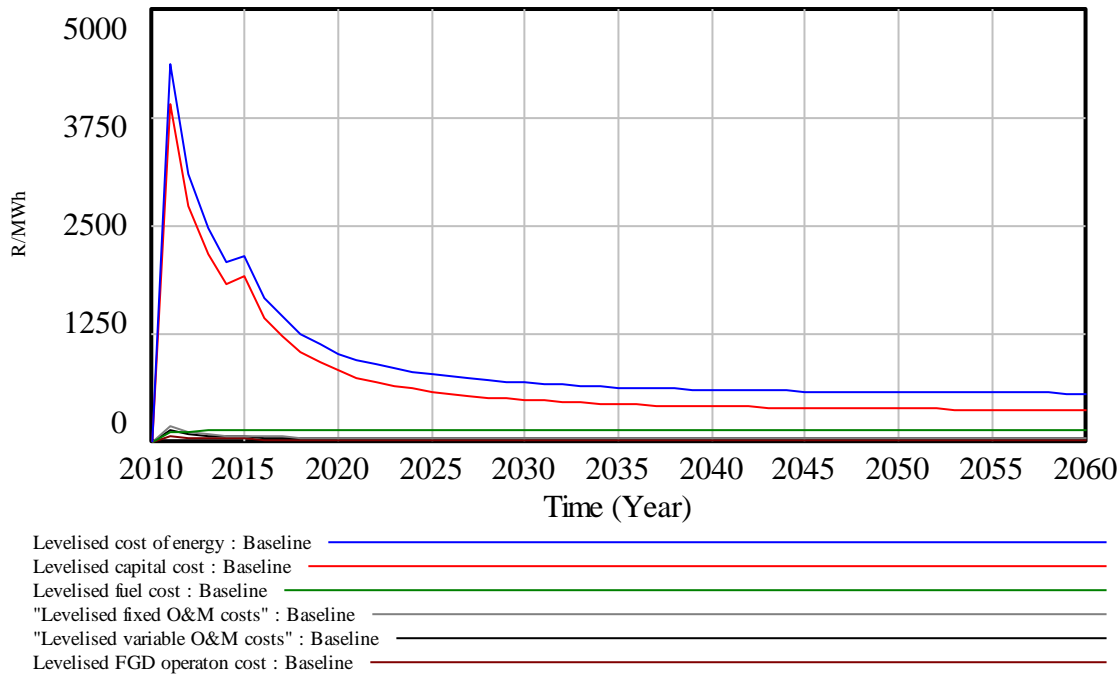
LCOE outputs

Figure 7.1: LCOE outputs

While it is quite problematic to compare the LCOE from various studies due to the various assumptions used, for example technology, plant size, plant design, load factor, base year, exchange rate, discount rates, etc., the LCOE computed in this study was compared to that computed by EPRI (2010) and Eskom (2011). EPRI (2010) computed a LCOE for a pulverised coal plant of 4 856MW (gross) with FGD, using a load factor of 85%. The cost estimates computed by EPRI (2010) were based on most recent EPRI studies (US), which were adjusted for the South African case. Constant dollar estimates were computed by the EPRI and the base year was also 2010 as in this study. In spite of the plant performance and financial assumption differences between this study and that conducted by EPRI, the overall lifetime LCOE from both studies is not diversely different. EPRI computed an overall lifetime LCOE of R590.8/MWh while in this study COALPSCA estimated a LCOE of R554.2/MWh.

On the other hand, even though Eskom computed the LCOE for Kusile, the entity does not disclose the financial parameters used, neither the breakdown of the LCOE nor the exact method of assessment. In its Annual Report for 2011, Eskom benchmarked Kusile's LCOE to the same base year and exchange rate as that of EPRI (2010) and reported a value of USD79/MWh, which translates to R584.6/MWh if the exchange rate used by EPRI is adopted (7.4ZAR (South African Rand)/US dollar). In the same Annual Report, Eskom reports the LCOE for Kusile to be USD73/MWh (not benchmarked) (Eskom, 2011), which translates to R540.2/MWh at an exchange rate of 7.4ZAR/US dollar as used by EPRI. The LCOE of R554.2/MWh

computed by COALPSCA in the current study is therefore more comparable to the estimate by Eskom of R540.2/MWh, though not diversely different from the estimate by EPRI (2010) of R590.8/MWh. In 2012 Eskom reported that it had altered the levelised cost model and that the computations made earlier would change once the Board had approved them (Eskom, 2012c).

On another note, net present value analysis - an economic measure for examining cash outflows (costs) and cash inflows (revenues) collectively - was also conducted. The NPV simulation output is presented in Figure 7.2 and is accompanied by the NPV output in Table 7.5. Before tax and after tax NPVs were computed. A tax rate of 28% (NERSA, 2013) was used for the after tax computations. The COALPSCA Model (Figure 7.2) indicates a fast declining negative NPV (after tax) from year 2010 up until year 2015, which is mainly as a result of the incurred capital cost coupled with low revenues owing to low plant capacity. From year 2015 up until year 2024, the plant is at full capacity but it is unable to generate enough revenue to cover the private costs, hence the negative NPV. From year 2025 onwards the NPV becomes incrementally positive.

The cumulative PV revenue (Table 7.5) is estimated at about 274 billion Rands, while the cumulative PV cost comprising capital, FGD and O&M costs is estimated at about 181.8 billion Rands. The NPV (before tax) of generating coal in Kusile is therefore estimated at about 92.2 billion Rands (NPV after tax is about 66.4 billion Rands). The positive NPV shows that the investment is economical. Had the NPV been negative it would have indicated that the returns are worth less than the cash outflows and therefore not a good investment. A zero NPV would have made the investor indifferent as to whether to make the investment. It must, however, be noted that the LCOE and the NPV as reported above, exclude the environmental and societal costs linked with generating electricity in Kusile. The life-cycle externality costs of producing electricity in Kusile are presented in the following section.
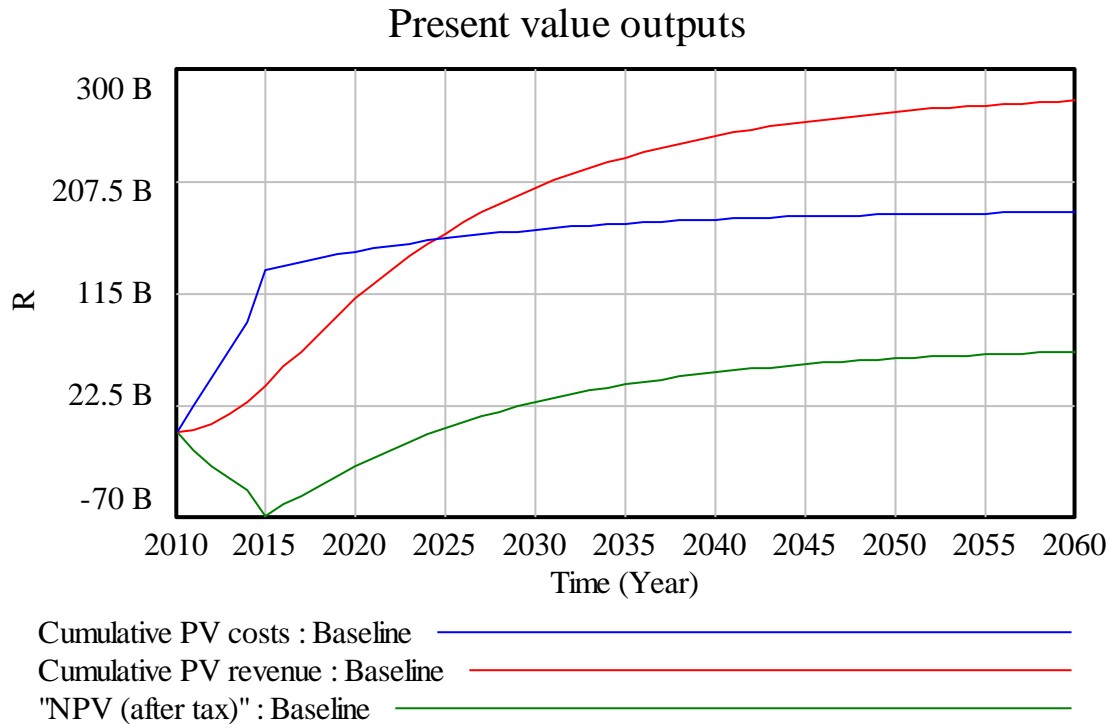
Present value outputs

Legend	
Cumulative PV costs : Baseline	——
Cumulative PV revenue : Baseline	——
"NPV (after tax)" : Baseline	——

Figure 7.2: Present value costs and revenues

7.2.3   Externalities inventory

The externalities quantified and monetized in the COALPSCA Model consist of water use, water pollution, fatalities and morbidity, ecosystem services loss, air pollution (i.e. classic air pollutants) and GHG emissions. The externalities were assessed in the entire coal-fuel cycle, excluding the transmission and use phases. The coal mining phase, plant construction phase with its associated upstream phases, transportation phase, plant operation phase, and the waste disposal phase were therefore investigated. Water use in the coal-fuel cycle over the lifetime of Kusile is presented in Table 7.6.

The water use indicator represents water consumption in the various coal-fuel cycle phases. The COALPSCA Model estimates water consumption of about 1.1 billion m^3 over the life-cycle and lifetime of Kusile. About 37% of the water is consumed during the coal mining phase (an estimate that incorporates coal washing), while plant operation consumes about 31% of the lifetime water use by Kusile (Table 4.3). The FGD system also consumes significant quantities of water which constitutes about 22% of Kusile's lifetime water use. The FGD system is estimated to consume an annual amount of 5.1 million m^3 of water once Kusile reaches full capacity. The estimate is comparable with NINHAM SHAND's (2007) estimates of 5.5 million m^3 for a 5400MW plant or 4.9 million m^3 if one corrects the estimate to Kusile's actual size, yielding about 3.9% variation. On the other hand, plant construction and waste disposal use less water of about 9% and 2%,

respectively. The model further estimates that once Kusile reaches full capacity, annual water consumption over its fuel cycle will amount to about 21 million m^3.

Table 7.6: Coal-fuel cycle water use (Million m^3) over Kusile's lifetime

Coal-fuel cycle phase	Model output
Mining	408.2 (36.6%)
Plant operation	342.5 (30.7%)
FGD system	248.3 (22.3%)
Plant construction & materials inputs	95.5 (8.6%)
Waste disposal	19.4 (1.7%)
Total (life-cycle & lifetime)	**1 114**

The fatalities and morbidity indicators represent the injuries and deaths that arise in the coal-fuel cycle. For the baseline scenario, central estimates of fatality and injury rates from various sources linked with the various coal-fuel cycle phases were applied (see Table 6.4 in the methods section). Table 7.7 presents the fatalities and morbidity output. The model estimates that approximately 503 deaths are likely to be suffered by the general public and by occupational personnel over the whole life-cycle and lifetime of Kusile. The plant operation phase contributes about 90% to the lifetime fatalities, while coal mining contributes about 10%. No estimates of fatalities on the construction phase could be obtained from Eskom or from the literature. Construction phase materials inputs fatalities were insignificant at less than 0.1%.

Concerning injuries, the model estimates that approximately 928 persons are likely to be injured over the lifetime of Kusile. The coal mining phase contributes about 77% to the lifetime injuries, while the plant operation phase contributes about 23% (this figure includes injuries associated with limestone procurement). The construction phase material procurement contributes the least at less than 0.1% (this figure excludes estimates of injuries linked with the construction of the plant due to lack of data). Based on the model output, the coal mining phase is more prone to injuries than deaths, whereas the plant operation phase is more prone to deaths than injuries.

Table 7.7: Coal-fuel cycle fatalities and morbidity over Kusile's lifetime

Coal-fuel cycle phase	Fatalities & morbidity (Units - Persons)	
	Deaths	**Injuries**
Coal mining	49 (9.7%)	716 (77.2%)
Materials inputs	<1 (<0.1%)	1 (<0.1%)
Plant operation & limestone production	454 (90.3%)	211 (22.7%)
Total (life-cycle & lifetime)	**503**	**928**

Concerning land use, the model focuses on the land area associated with the coal mine and the power plant. Both areas were used for grazing and crop production, so the mining of coal for Kusile and the generation of power in Kusile changes the current land uses and the associated benefits derived from their use. Since the focus of the study is on a specific plant of a particular size, the year on year land area associated with the power plant and the coal mine is fairly constant. Table 7.8 presents the land uses. The coal mine occupies an area of 6 817 hectares which was mainly allocated to maize production. 70% of the land (4 771.9 hectares) was allocated to maize production, with the remaining 30% (2 045.1 hectares) being under grazing/grasslands (Wolmarans & Madallie, 2011). The power plant occupies an area of 1 456 hectares of which about 96% and 4% were allocated to maize production and grazing/grasslands, respectively (NINHAM SHAND (2007); Eskom (2010b).

Table 7.8: Coal-fuel cycle land use (Hectares)

Coal-fuel cycle phase	Crop production			Total
	Irrigated land	Grasslands	Grazing	
Coal mining	4771.9		2045.1	6817
Plant operation	1404	52		1456

Another class of environmental indicators concerns air pollution loads, namely classic air pollutants and GHGs. Three main classic air pollutants were considered, namely emissions of SO_2, NO_x and PM originating from coal transportation, plant construction, plant operation, FGD system and waste disposal. In the baseline scenario, mainly central estimates of emission factors from a number of sources were applied (see Table 7.8 in the methods section). Air pollution loads in the coal-fuel cycle over the lifetime of Kusile are presented in Table 7.9. Concerning coal transportation, the emissions estimated by the COALPSCA Model reflect coal transportation to Kusile in the early years by road, and then once the conveyor has been established, transportation mainly by the conveyor, with the remainder transported by road (Synergistics Environmental Services and Zitholele Consulting, 2011). The model estimates coal transportation emissions of SO_2, NO_x and PM of about 42 000 tons, 35 000 tons and 2 700 tons, respectively over the lifetime of Kusile.

Table 7.9: Coal-fuel cycle classic air pollutant loads over Kusile's lifetime

Coal-fuel cycle phase	Units	Classic air pollutants					
		SO_2	%	NO_x	%	PM	%
Coal transportation	Tons	42 061	2.5	35 490	0.9	2 679	0.7
Construction material transportation	Tons	5	<0.01	42	<0.01	2	<0.01
Plant operation	Million tons	1.6	96.5	3.9	98.9	0.4	99.1
FGD system (limestone transport)	Tons	5 313	0.3	2 744	0.1	253	0.1
Waste disposal	Tons	11 521	0.7	5 952	0.2	548	0.1
Total (life-cycle & lifetime)	**Million tons**	**1.7**		**3.9**		**0.4**	

Coal combustion phase emissions of SO_2, NO_x and PM are estimated at about 1.6, 3.9 and 0.4 million tons, respectively over the lifetime of Kusile. The SO_2 emissions were adjusted to reflect installation of the FGD system. The coal combustion phase as shown in Table 7.9 is the highest emitter of the studied classic air pollutants in the coal-fuel chain. This phase contributes over 95% of Kusile's lifetime SO_2, NO_x and PM emissions. The model further estimates the annual emissions of SO_2, NO_x and PM from coal combustion in the order of 33.8, 81.1 and 7.9 thousand tons, respectively once Kusile reaches full capacity (Table 7.10). NINHAM SHAND (2007) in an EIA for a 5400MW plant, i.e. a plant that is slightly higher than the actual size of Kusile which is 4800MW, estimates annual tonnages of SO_2, NO_x and PM of about 36.4 (if one corrects for 90% SO_2 removal efficiency), 87.4 and 7.9 thousand tons, respectively (Table 6.10). Riekert and Koch (2012) corrected the estimates reported in NINHAM SHAND (2007) for Kusile's actual size (i.e. 4800MW) and reports SO_2, NO_x and PM of about 32.3 (if one corrects for 90% SO_2 removal efficiency), 77.7 and 7.8 thousand tons, respectively (Table 7.10). The COALPSCA Model estimates are thus more comparable to the estimates by Riekert and Koch (2012) with less than 4% variation.

In addition, four trace metal emissions from the coal combustion phase, namely arsenic, chromium, lead and nickel were estimated. Though the year-on-year trace metals emissions are about a ton, with the exception of arsenic which is quite low, they are more lethal than most of the other classic air pollutants. Chromium, nickel, lead and arsenic were estimated at about 46 tons, 35 tons, 24 tons and 4 tons, respectively over the lifetime of Kusile.

Table 7.10: Annual emissions of classic air pollutants - coal combustion (Thousand t)

Classic air pollutant	Model outcomes	NINHAM SHAND (2007)	% variation	Riekert & Koch (2012)	% variation
SO_2	33.8	36.4	7.1	32.3	4.4
NO_x	81.1	87.4	7.2	77.7	4.1
PM	7.9	7.9	0	7.8	1.3

Concerning the FGD system, the emissions estimated by the model reflect emissions associated with the transportation of limestone to Kusile through electric railway. The model estimates limestone transportation emissions of SO_2, NO_x and PM of about 5 300t, 2 700t and 253t, respectively over the lifetime of Kusile. On another note, the disposal of waste, mainly flyash, which will be transported to the disposal site through a conveyor, emits SO_2, NO_x and $PM_{2.5}$ of about 11 500t, 6 000t and 500t, respectively (Table 6.9). Waste disposal emits less classic air pollutants mainly because of the efficiency of the conveyor, which is estimated to consume about 31 786 MWh/Year once Kusile is fully operational. The transportation of construction materials releases insignificant quantities of the studied classic air pollutants. In addition,

no data were available on the direct emission from the construction of the plant, so the construction phase air pollution estimates are underestimated.

The main GHGs investigated in the coal-fuel chain are CO_2, CH_4, and N_2O. The various GHGs' global warming potentials were used to convert the GHGs into their CO_2 equivalence. Five main coal-fuel chain phases were investigated, namely coal mining and transportation, plant construction, plant operation, FGD system and waste disposal. The coal-fuel cycle GHG pollutant loads over the lifetime of Kusile are presented in Table 7.11. The model estimates emissions of about 1 583 million tons of CO_2e over the coal-fuel cycle and lifetime of Kusile. About 85% of the GHGs emanate from the combustion phase while coal mining and transportation contribute about 13%. Plant construction, FGD operation and waste disposal each generate GHGs of about or less than 1%. The coal combustion phase is thus the main source of GHGs in the coal-fuel chain. Annual emissions of CO_2 and CO_2e from coal combustion, once Kusile reaches full capacity, are estimated by COALPSCA at 27.9 and 28 million tons, respectively (Table 7.12). These estimates are comparable with NINHAM SHAND's (2007) estimates of 29.9 and 36.8 million tons for a 5400MW plant or 26.6 and 32.7 million tons if one corrects the estimates to Kusile's actual size (Table 7.12). In the following sub-section the quantified externalities are monetized.

Table 7.11: Coal-fuel cycle greenhouse gas pollutant loads over Kusile's lifetime

Coal-fuel cycle phase	GHGs - mainly CO_2, CH_4 & N_2O	%
	CO_2e (Million t)	
Coal mining & transportation	210.5	13.3
Construction material & transportation	8.9	0.6
Plant operation	1 348.9	85.2
FGD system	13.5	0.9
Waste disposal	1.2	0.1
Total (life-cycle & lifetime)	**1 582.9**	

Table 7.12: Annual emissions of greenhouse gases - coal combustion (Million t)

Classic air pollutant	Model outcomes	NINHAM SHAND (2007)	% variation	NINHAM SHAND (corrected)	% variation
CO_2	27.9	29.9	6.7	26.6	4.7
CO_2e	28	36.8	23.9	32.7	14.4

7.2.4   Externality costs

The externalities quantified in the previous section, are monetized in this sub-section. The damage cost estimates or economic values of the studied externalities are discussed while presenting the results. For the baseline scenario, all damage costs were escalated at the rate of population growth which is 1.1% (Statistics South Africa, 2011). The coal-fuel cycle externality cost over the lifetime of Kusile is presented in Table 7.13.

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Concerning water, the water price is a fundamental indicator of the availability and cost of supplying water (Van der Zaag & Savenjie, 2006), nonetheless, in South Africa though water is a resource in critical supply, the administered water price does not signal the state of water scarcity or reflect the opportunity cost of the resource. The opportunity cost of water use in Kusile was estimated by Inglesi-Lotz & Blignaut (2012). The estimates from this study formed the basis of opportunity cost analysis in the coal-fuel chain. The baseline scenario society-wide opportunity cost of water use in the coal-fuel chain is estimated at about 1 474 billion Rands over the lifetime of Kusile. About 31% of the cost stems from the operation of the plant while its ancillary water using activities, namely FGD system and waste disposal account for about 23% and 2%, respectively. Coal mining and washing account for approximately 37% of the coal-fuel cycle lifetime cost while plant construction accounts for about 7%.

Table 7.13: Coal-fuel cycle externality cost (Billion Rands) over Kusile's lifetime

Coal-fuel cycle phase	Water use	Water pollution	Fatalities & morbidity	Ecosystem loss	Classic air pollutant	GHGs	Grand % per phase	c/kWh
Coal mining/transport	551.4 (37.4%)	0.3 (99.9%)	0.0 (20.5%)	5.3 (86.3%)	5.7 (1.3%)	31.2 (13.3%)	**27.3%**	**37**
Plant construction	98.0 (6.6%)	0.0 (0.1%)	0.0 (<0.1%)	0.8 (13.7%)	0.0 (<0.1%)	1.0 (0.4%)	**4.6%**	**6**
Plant operation	462.6 (31.4%)	X	0.2 (79.4%)		450.6 (98.3%)	200 (85.3%)	**51.2%**	**70**
FGD system	335.4 (22.8%)	X	X		0.6 (0.1%)	2 (0.8%)	**15.6%**	**21**
Waste disposal	26.2 (1.8%)	X	X		1.3 (0.3%)	0.2 (0.1%)	**1.3%**	**2**
Total cost per externality	**1473.5**	**0.3**	**0.2**	**6.1**	**458.2**	**234.4**		**136**
Grand cost	**2 172.7**							
Grand % per externality	**67.8%**	**<0.1%**	**<0.1%**	**0.3%**	**21.1%**	**10.8%**		

Turning to water pollution, the water pollution externality was monetised only for the coal mine and for Kusile's raw material requirements for building the coal plant. The water pollution associated with the direct construction and operation of Kusile was excluded, owing to Eskom's stated zero effluent discharge policy (NINHAM SHAND, 2007)). Regarding the water pollution damage cost, adapted to this study were direct damage costs of sulphate pollution from various industries on other water users in the eMalahleni area, estimated by Van Zyl et al. (2002). The shortcomings of the Van Zyl et al. (2002) study include its focus on sulphate and not all pollutants, its focus on impacts in the catchment and not downstream and lack of address of natural/environmental uses. Owing to the Van Zyl study's shortcomings, the estimates computed in the current study are considered conservative. The COALPSCA Model estimates the water pollution externality at about 0.3 billion Rands and is more or less wholly associated with the mining of coal (99.9%).

Concerning the economic value for morbidity, cost estimates estimated using the cost-of-illness approach by Van Horen (1997), through discussions with public health practitioners in South Africa were transferred to this study by adjusting the values for inflation and some form of internalization. The economic values for mortality were based on valuation of changed life expectancy, obtained from the NEEDS (2007) and NewExt (2004) studies. The values were adjusted to reflect the disparity of income levels between the EU and South Africa and to cater for inflation and some form of internalization. For the baseline scenario, central cost estimates for morbidity and mortality were used. The COALPSCA Model estimates monetary estimates for morbidity and mortality of about 0.2 billion Rands over the life-cycle and lifetime of Kusile. About 79% of this cost is attributable to the plant operation phase while approximately a one-fifth is attributable to the coal mine.

Pertaining to land use, the extraction of the coal resource and the establishment and operation of the coal plant will lead to loss of farmlands and grasslands. The opportunity cost of these activities is therefore the forgone benefits derived from agricultural production and ecosystem services generated by grasslands. The market price of maize and the maize yield per hectare for dry and irrigated land were used to compute the foregone benefit from maize production, while the value of ecosystem goods and services generated by grasslands was adapted from a study undertaken by Blignaut et al. (2010) for the Maloti–Drakensberg mountain range of South Africa. The model estimates an ecosystem services loss of about 6 billion Rands over the life-cycle and lifetime of Kusile. About 86% of the lifetime loss is linked with the surface coal mine while the remainder is attributable to the power plant and its ancillary activities. Since the power plant and associated structures occupy a few hectares, most of the power station related ecosystem services loss is associated with waste disposal.

On another note, the health cost of air pollution in the coal fuel chain was estimated based on damage costs per ton of a specific local air pollutant adapted from NEEDS (2007; 2008; 2009), Sevenster et al. (2008) and from AEA Technology Environment (2005). The original estimates are based on value of a life year (VOLY) lost due to air pollution, estimated using change of life expectancy. Basing the valuations of air pollution mortality on the change of life expectancy, as opposed to a valuations based on accidental death or a small change in the probability of dying is more appealing because the approach automatically factor in the constraint that humans die only once irrespective of pollution, it offers a unified framework for time series, cohort and intervention studies plus directly yields the life expectancy change as a time integral of the observed mortality rate (Rabl, 2006). In addition, change in life expectancy is further favourable because respondents during surveys show too much difficulty understanding small probability variations while a change in life expectancy is well understood (NewExt, 2003). The estimates were adjusted to reflect

the disparity of income levels between the EU and South Africa and to cater for inflation and some form of internalization. For the baseline scenario central cost estimates of the three main classic air pollutants studied were used. The model estimates the health cost of air pollution at about 458 billion Rands over the life-cycle and lifetime of Kusile. The coal combustion phase makes up most of the air pollution health cost at 98%, followed by the coal mining phase at about 1%. Waste disposal, FGD system and plant construction make up the least of the lifetime air pollution cost of about 0.3%, 0.1% and less than 0.1%, respectively.

Turning to global warming, the global warming damage cost associated with GHG releases in the coal fuel chain was quantified through the application of a range of CO_2 damage cost estimates, ranging between R5.86/tCO_2 – R820.56/tCO_2, adapted from a study by Blignaut (2012). Blignaut (2012) highlights that the arguable most probable range of the global warming damage cost is given by the market, median and high damage rates (i.e. damage cost ranging between R104.98/tCO_2 – R177.94/tCO_2). These are the damage costs used in this study. For base case analysis, the market estimate was used (i.e. R109.89/tCO_2). The GHGs were adjusted to reflect their global warming potential alongside that of carbon dioxide. The National Treasury in South Africa also plans to impose a tax on emitters of greenhouse gases of R120/ton of carbon dioxide equivalence (CO_2e) above the tax-free threshold (BDFM Publishers, 2013d). The National Treasury's proposed tax therefore falls within the range used in this study and its impacts are specially discussed later in chapter 7 together with other carbon tax scenarios. The model estimates a CO_2e global warming damage cost of about 234 billion Rands over the coal-fuel cycle and lifetime of Kusile. The coal combustion phase generates the majority of this cost (85%), followed by the coal mining phase at about 13%. GHG damages from the transportation and use of limestone in the FGD system are about 0.8% while even lower estimates are associated with plant construction and waste disposal.

The total coal-fuel cycle externality cost over the lifetime of Kusile is estimated at about 2 173 billion Rands (Table 7.13). Most of the externality cost stems from three groups of externalities, namely the water use externality, air pollution health cost and the global warming damage cost which accounts for about 68%, 21% and 11%, respectively. Table 6.13 further discloses the grand distribution of the total externality cost per coal-fuel cycle phase over the lifetime of Kusile. The plant combustion phase, FGD system and waste disposal house about 51%, 16% and 1.3% of the total coal-fuel cycle externality cost, respectively. The operation phase with its ancillary activities (i.e. FGD system and waste disposal), accordingly accounts for about two thirds of the externality cost. A significant amount of the total coal-fuel cycle externality cost also stems from the mining and transportation of coal, which accounts for almost a third (27%) of the cost. The plant construction phase houses about 5% of the lifetime cost. Three main coal-fuel cycle phases thus contribute the most to the total externality cost over the lifetime of Kusile, namely plant operation, FGD

system operation and the mining and transportation of coal. Collectively the three phases make up about 94% of the lifetime externality cost.

Based on Kusile's lifetime electricity production of about 1.6 billion MWh, the base case construction phase externality cost is about 6c/kWh (see Table 7:13). There are, however, no studies locally to compare this estimate with and the two international studies (European Commission, 1995; 1999b) that study the construction phase do not report explicitly the externality cost linked with this phase. The externality cost of mining and transporting coal to Kusile is about 37c/kWh while that of the power plant (including waste disposal but excluding FGD system) is 72c/kWh. The FGD system externality cost is about 21c/kWh while the FGD system and the power plant combined produce an externality cost of 93c/kWh, which is about 100% of the electricity price that will prevail at the end of the simulation (93c/kWh). The base case coal-fuel cycle externality cost thus amounts to 136c/kWh (see Table 7:13) (when converted to US cents/kWh it is about 19c/kWh) and falls in the middle range of the international externality cost studies reported in Table 4.3, while clearly above most of the local studies (in Table 4.5) because of the inclusion of more externalities and coal-fuel cycle phases. The combined externality cost estimate of Nkambule & Blignaut (2012), Riekert and Koch (2012), Inglesi-Lotz and Blignaut (2012), and Blignaut (2012) reported in Table 4.5 (i.e. 4.23 – 25.66 in US cents/kWh or in South African Rands 31c/kWh – 188c/kWh), shows a rather higher externality cost compared to the base case estimate computed in the current study, irrespective of that more externalities and fuel-cycle stages are being included in this study because the four collective studies' estimates are low to high estimates whereas the COALPSCA Model value is a baseline value.

A further look at Table 7.13 discloses the plant operation phase externality cost to be connected with water use, air pollution and GHG emissions, while the coal mining and transportation externality cost is mainly associated with water usage, air pollution, GHG emissions and loss of ecosystem services due to the disruptive nature of a surface mine on land. On the other hand, the FGD system externality cost mainly stems from water use.

Interestingly, the installation of the FGD system increases water use while curbing SO_2 emissions. So in order to explore this interesting trade-off between water use externality and human health cost savings, simulated was the lifetime air pollution health cost and opportunity cost of water use with and without the installation of the FGD system. Since the FGD system is linked with the coal combustion phase in that the air pollution health cost savings are revealed in the coal combustion phase, the air pollution health cost and the water use externality cost were quantified for the coal combustion phase jointly with the FGD system and waste disposal phases. Table 7.14 reports the outcomes of this application.

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Without the installation of the FGD system, the air pollution health cost and water use externality cost are estimated at about 1 472 and 489 billion Rands, respectively. Fitting the power plant with an FGD system reduces the air pollution health cost to about 453 billion Rands while increasing the water use externality cost to about 824 billion Rands. These outcomes disclose that the installation of the FGD system introduces an extra water use externality cost of about 335 billion Rands while creating air pollution health cost savings of about 1 019 billion Rands. For this reason, the installation of the FGD system is a sensible effort (on the grounds of externality cost versus externality cost savings) since its air pollution health cost savings outweigh the water use externality cost it introduces (positive net change of about 684 billion Rands). Water is, however, a scarce resource in South Africa and human health is without doubt valuable, so the country and its people need to decide what it is willing to forego in order to gain the other. Give-up water in exchange for clean air and hence gain better human health or vice versa. On the other hand, in order for one to reach a final conclusion about the economic viability of the FGD system, the private and externality costs associated with the FGD system need to be fully paid off by the savings.

Table 7.14: FGD system or not, costs and savings (Billion Rands) over Kusile's lifetime

Externality cost	With FGD system	No FGD system	FGD system installation extra externality cost or savings
Water use externality cost	824.2[A]	488.8[B]	B - A = -335.4 (cost)
Air pollution health cost	452.5[C]	1471.7[D]	D - C = 1019.2 (savings)
Net change			**Savings + cost = 683.8**

7.2.5 Social cost

In the previous sections the private costs and the externality costs of energy were reported. In this section both costs are examined jointly since the true cost of energy is composed of not only the price of electricity that is reflected on electric bills (i.e. private costs) but also the less obvious negative impacts of electricity generation on third parties, for example, on the environment and on society. A more holistic accounting of the full cost of energy thus embraces both the private costs and the externality costs and is known as the social cost of energy (Greenstone & Looney, 2012).

A number of economic indicators were computed and reported in the previous sections, including the LCOE, the NPV and externality costs. In this section, three additional economic indicators are computed, namely the levelised externality cost of energy (LECOE), the levelised social cost of energy (LSCOE) and the social net present value (SNPV). The LECOE and the LSCOE were estimated in a similar manner as done for the LCOE – thus they are measured in R/MWh. The LECOE and LSCOE outcomes are reported in Table 7.15. The levelised externality cost of energy is estimated by the model at about R1 370.8/MWh. The LECOE,

when added to the LCOE (computed earlier amounting to R554.2/MWh), yields a levelised social cost of energy (LSCOE) of about R1 925/MWh. The LCOE thus reflects about 29% of the true cost of coal while the externality cost makes up approximately 71% of the social cost of energy. A little over two thirds of the true cost of electricity therefore does not reflect on the balance sheet of the utility and is borne by society.

Comparing the LECOE estimated in this study of R1 370.8/MWh, to the four collective studies' (i.e. Nkambule & Blignaut (2012), Riekert and Koch (2012), Inglesi-Lotz and Blignaut (2012), and Blignaut (2012)) externality cost for Kusile conducted for the year 2010, of between R310/MWh – R1 880/MWh (2010 values), the collective studies' estimates are comparable but slightly higher compared to the base case value computed by COALPSCA as they are low to higher range estimates. Another reasons that could slightly elevate the four collective studies' externality costs above those computed in this study could be the downward adjustment of the opportunity cost of water in the current study (attributed to the fact that renewable technologies are not yet on large enough scales enabling them to uptake/utilize the water or to generate electricity analogous to Kusile), and the air pollution health costs and fatalities and morbidity costs internalization that was accounted for in this study.

Table 7.15: Levelised externality and social cost of energy (R/MWh) over Kusile's lifetime

Present value output	Model output
Levelised externality cost of energy (LECOE)	1 370.8
Levelised social cost of energy (LSCOE)	1 925.0

The social net present value (SNPV) on the other hand, is synonymous with social benefit-cost analysis in that it aims to compare the benefits and costs of a project/action by taking into consideration both the private and externality costs and benefits. The SNPV approach discounts these costs over the lifetime of the investment to arrive at a present value measure. By definition, the SNPV ought to also incorporate positive externalities. In this study the SNPV reflects the present value of investing in Kusile (i.e. private benefits/returns less private costs) less the present value of the externality costs.

The selected present value output is presented in Table 7.16, accompanied by the present value simulation output in Figure 7.3. The NPV before tax of generating coal in Kusile was earlier reported as 92.2 billion Rands (NPV after tax is about 66.4 billion Rands), this, coupled with the cumulative PV externality cost of 449.5 billion Rands yields a SNPV (before tax) of -357.3 billion Rands (SNPV after tax is about -383.2 billion Rands). Figure 7.3 shows a negative SNPV after tax (alike for before tax) throughout the lifetime of Kusile, highlighting that year on year Kusile will be unable to generate enough revenue to cover the negative

externalities it imposes on third parties. The earlier computed positive NPV shows that the investment is economical and passes a private cost benefit analysis, but when the externality effects of the investment on third parties are incorporated, the project is no longer acceptable as it does not generate positive net social benefits, but significant externalities that impose a large externality cost.

Table 7.16: Selected present value output (Billion Rands)

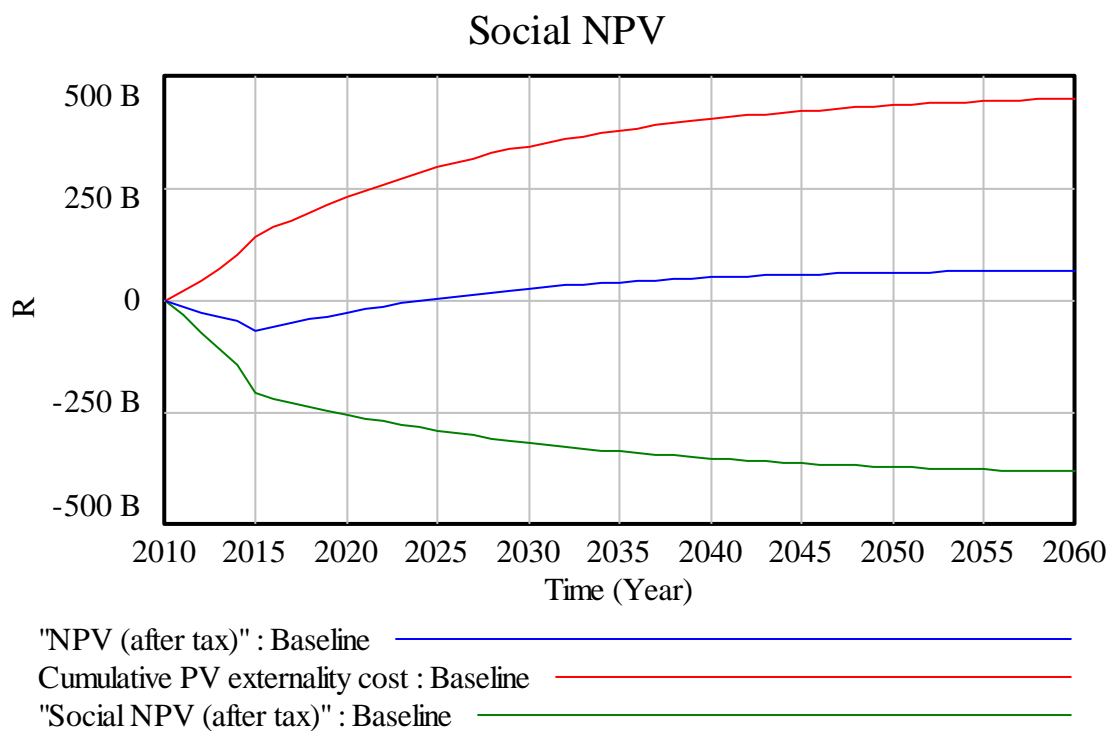| Present value output	Model outcomes
NPV (before tax)	92.2
NPV (after tax)	66.7
Cumulative PV externality cost	449.5
SNPV (before tax)	-357.3
SNPV (after tax)	-383.2

Figure 7.3: Social NPV

In the previous sections the private costs and the externality costs of energy were reported. In this section both costs are examined jointly since. A more holistic accounting of the full cost of energy thus embraces both the private costs and the externality costs and is known as the social cost of energy (Greenstone & Looney, 2012).

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7.3   Model validation

Model validation involves repeated actions of testing and establishing confidence in the model (Forester & Senge, 1980; Sterman et al., 1988). This process runs through the entire process of model building, beginning with model conceptualization up until implementation of policy recommendations (Forester & Senge, 1980; Sterman et al., 1988). Based on models being simple representations of actual-world situations, they can, however, never be fully validated (Sterman, 2000) and in addition, no particular test can completely verify a model but the confidence in a model is improved as the model passes a range of tests (Forrester & Senge, 1980). Forrester (1961) furthermore emphasizes that model validation ought to be judged with reference to a particular purpose, that is, detached from purpose, model validity is worthless. This is considered important for system dynamics models because they are built to fulfill a purpose (Holling, 1978; Barlas & Carpenter, 1990).

In system dynamics, the internal structure of the model needs to be validated first, followed by validation of model behaviour. The accuracy of model behaviour is only meaningful once adequate confidence on model structure has been established beforehand (Barlas, 1989; Barlas, 1994). This sensible order of model validation is not difficult to comprehend, since the usefulness of a system dynamics model lies in its capability to relate patterns of behaviour of a system to the structures that underlie the system (Qudrat-Ullah, 2012). That is, system dynamics models are causal models, which seek to understand how the internal structure of a system helps to create visible patterns of behaviour of a system. Hence structural validity comes first, followed by behaviour validity which seeks to establish how well the model generated behaviour mirrors the behaviour of a real system. Model validation thus seeks to establish – whether the model is acceptable, given its purpose (Goodall, 1972; Forrester and Senge, 1980; Zebda, 2002); and to establish the degree of confidence to place in the model based on inferences of an actual system (Curry, Deuermeyer & Feldman, 1989; Barlas, 1994; Sterman, 2000). Though lack of formal validation tools is regularly the critique of system dynamics methodology (Barlas, 1994), the literature discloses a number of validation tests which are described below. An explanation is also given of how they were used in this study.

7.3.1   Structural validity

Structural validity concerns establishing validity with regards to the internal structure of the model. These tests involve comparing model structure versus knowledge of the real system or versus general knowledge of the system as evidenced by literature (Barlas, 1994). Five direct structure validation tests were introduced by Forrester and Senge (1980) for system dynamics, namely boundary accuracy, structure

verification, dimensional consistency, parameter verification, and extreme condition tests and were conducted in this study. The model boundary was discussed in section 6.5, so it is not reported here.

7.3.1.1 *Structure verification test*

This test concerns comparing model structure versus the actual system structure/knowledge in the literature. It assesses the consistency of model structure with the descriptive knowledge of the real system actuality modelled (Forrester & Senge, 1980). For structural verification three approaches were used. Firstly, when developing the causal relationships in the model, Eskom- and Kusile-specific data were used, that is, available knowledge of the (currently under construction) system. The conceptual model of the modelled system was presented by the causal loop diagram in the methods section. It was shown that investment in electricity generation increases plant capacity, which boots power generation, which then generates revenues and profits for utility owners. At the same time an increase in power generation triggers an increase in resource input use, for example coal which increases the fuel cost, which together with other material/resource requirements, increases the private costs of generating power. On another note, the increase in power generation directly and indirectly (e.g. through upstream services) produces negative externalities, for example GHG emissions, classic air pollutants, injuries, fatalities, water pollution, loss of ecosystem services and water consumption externality. These burdens, coupled with the likely damages they impose on humans and on the environment, signify the externality costs which, together with the private costs of generating power (capital, fuel and O&M costs), intensifies the social cost, which then negatively affects the revenues and profits earned by utility owners. The causal relationships of the COALPSCA Model were founded on available knowledge of the real system, and for that reason they served as a form of empirical structure validation (Zebda, 2002).

Secondly, all the stock variables by definition should either be positive or zero, but not negative. So as the stocks approaches zero so should the outflows from the stocks. This test was conducted for the stocks and flows in the COALPSCA Model. Thirdly, the validity of each of the model equations against available knowledge was conducted by directly comparing each of the model equations with the (currently under construction) real system (empirical) and with generalized knowledge of the system existing in the literature (theoretical). As an example of how model equations were evaluated see, Table 7.17. In the light of these tests, the COALPSCA Model was found to be a reasonable, simplified match of the real-world system.

Table 7.17: Examples of structure test

Model equation	Available knowledge on real system
$CConsump = \left[((GEP * MWhtoKWh) * HR) / CEC\right] / kgtoton$	Coal consumption (CConsump) is the amount of coal consumed by the plant and is a function of the coal energy content (CEC), heat rate of the plant (HR) and gross electricity production (GEP).
$GEP = \left[(FCC * POH) + (DFCA * POH) * LF\right]$	For a system that is evaluated at the farm gate, gross electricity production is the quantity of power produced by the plant and is not net of the amount of power internally consumed by the plant. Gross electricity production is a function of the plant operating hours (a variable in the developed model that was adjusted for the time the plant will be shut down for maintenance, i.e. energy availability factor), load factor and the plant functional capacity [in the developed model, functional capacity was separated into functional capacity during construction (FCC) and desired functional capacity after construction (DFCA)].

7.3.1.2 *Dimensional consistency test*

The dimensional consistency test intends to establish the unit's uniformity of all model equations. That is, for each model equation, the measurement units of all the variables in it must be dimensionally consistent without including scaling parameters that in the real world have no meaning (Forrester & Senge, 1980; Sterman, 2000). So the measurement units enable the checking of dimensional consistency of model equations. Accordingly, the dimension of input variables of the COALPSCA Model equations was examined. In addition, the menu item Model>Units Check was used to check the COALPSCA Model equations in totality.

7.3.1.3 *Parameter verification test*

The parameter verification test concerns the conceptual and numerical evaluation of constant parameters of the model against knowledge of the actual system. It assesses the consistency of the model parameters against the system's descriptive and numerical knowledge (Forrester & Senge, 1980). The values allocated to COALPSCA Model parameters were obtained from existing knowledge of the system, coupled with available numerical data on Kusile and its associated processes. As an illustration, Table 7.18 presents the main input parameters, baseline values and data sources used in the power generation sub-model (a comprehensive list of parameters used in the COALPSCA Model are presented in table form in the methods section, after the discussion of each sub-model).

Table 7.18: Selected parameters, values and data sources - power generation

Variable	Units	Baseline value	Data source
Coal energy content	MJ/kg	19.22	Eskom, 2010a.
Days per year	Day/Year	365	Eskom communication, 2012.
Fraction of electricity consumed internally	Dmnl/Year	0.075	Eskom communication, 2012.
Heat rate	MJ/kWh	9.769	EPRI, 2010.
Hours per day	h/Day	24	Eskom communication, 2012.
Load factor	Dmnl/Year	0.9	NINHAM SHAND. 2007
Planned investment in plant capacity table	MW/Year	Time series	Calculated based on Eskom (2012b).

7.3.1.4   *Extreme condition test*

This test concerns assigning extreme values to certain parameters and evaluating the plausibleness of the model reproduced behaviour versus knowledge/anticipation of what may take place in comparable conditions in real life. For the model to pass this test, it must demonstrate logical behaviour under extreme conditions (Forrester & Senge, 1980). Two extreme condition tests are presented in this section.

In extreme condition test 1, the planned investment in plant capacity table was set to zero, which in reality means no capital investment into electricity production, therefore no capacity construction and consequently no electricity production and no GHGs being emitted by the power plant (e.g. CO_2). The COALPSCA Model outcomes for this condition are presented in Figure 7.4 and are in agreement with this extreme condition.
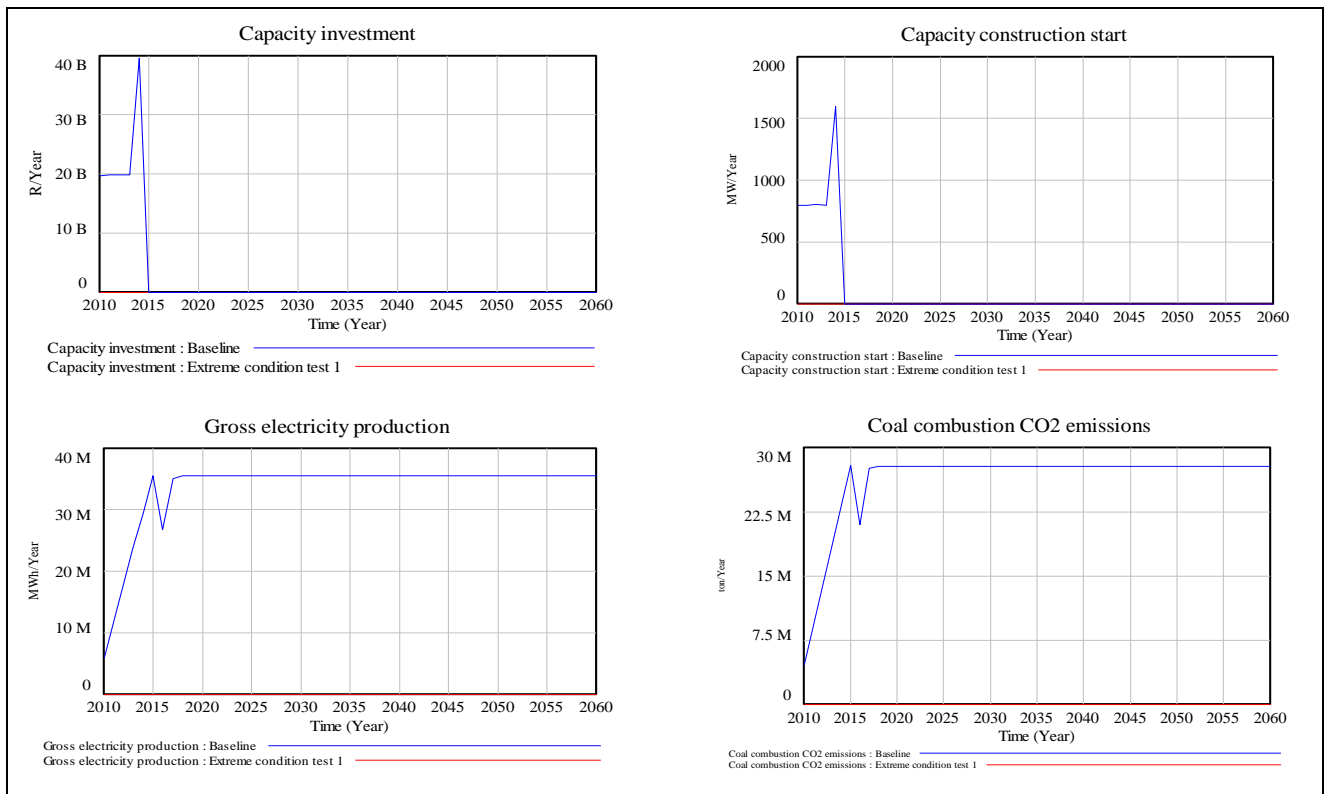
Figure 7.4: COALPSCA Model behaviour under extreme condition test 1

In extreme condition test 2, the unit cost of coal was grown to R1 100/ton from the baseline value of R210/ton. In reality, with such escalation in the price of coal, the fuel cost (or coal cost) will soar high, increasing the private costs of power generation by a great margin, because the fuel cost is a major cost component of the generation cost, making up over 46% of the utility's generation cost in the base case (see Table 7.5). The higher private cost would negatively affect the profitability of coal-based power and the utility's ability to repay its debt. The simulation results in Figure 7.5 accurately depict this extreme condition.
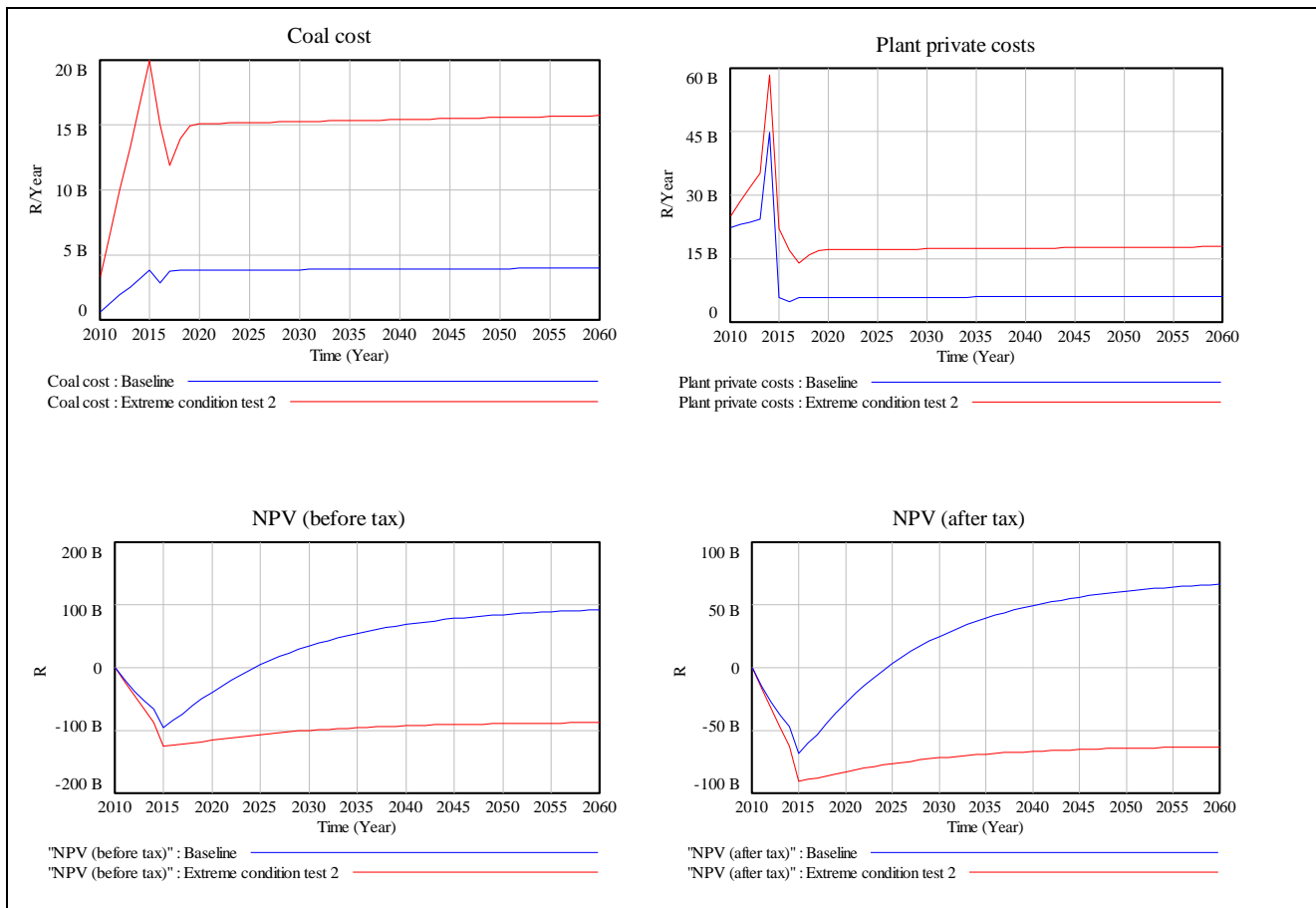
Figure 7.5: COALPSCA Model behaviour under extreme condition test 2

The COALPSCA Model behaviour under extreme conditions mimics the anticipated behaviour of the actual system under comparable extreme conditions. The model therefore passes the extreme condition test and model validity is improved. Behaviour validity is discussed in the following section.

7.3.2   Behaviour validity

Behaviour validity seeks to establish how well the model produced behaviour matches the behaviour of the real system (Barlas, 1996.) The focus is on patterns. Among the behaviour validation tools are the behaviour sensitivity test, reference test, modified-behaviour prediction test and a face validity test.

7.3.2.1   *Face validity test, reference test and modified-behaviour prediction test*

A face validity test can be used when simulation models are applied to operational problems. In this test, experts evaluate the closeness of the model and its outcomes to the real system (Zebda, 2002). A face validity test, could not, however, be undertaken because Kusile power station is still under construction, and therefore not yet in operation. On another note though, one can argue that it had been evaluated since the thesis and the articles produced from it were evaluated by experts when sent to external

examiners or journals. In a reference test, the model is simulated a few years back and the model outcomes are compared to historical data. However, given that Kusile is still under construction and that Eskom was not willing to share data relevant to this research on existing plants, the reference test could not be performed. A modified-behaviour prediction test is only possible if data on the modified patterns of the real system can be sourced - in which case the model then passes the test on condition it can mimic the modified behaviour (Forrester & Senge, 1980). Data absence/inaccessibility, as explained earlier, prevented execution of these tests.

7.3.2.2   *Behaviour sensitivity test/sensitivity analysis*

The behaviour sensitivity test seeks to uncover the parameters the model is responsive to and questions whether the real system would also display higher responsiveness to the said parameters (Barlas, 1994). This test is synonymous with sensitivity analysis. The aim of sensitivity analysis therefore is to study the effects of variations in model assumptions on model results (Saltelli et al., 2000). The assumptions may be about parameter values or feedback loops and they portray uncertain information that cannot be gathered from real life observations. System dynamics model parameters are subject to uncertainty, so sensitivity analysis is a noteworthy task for the reliability of simulation results (Hekimoğlu & Barlus, 2010).

The frequently used system dynamics approaches to deal with uncertainty include univariate sensitivity analysis and multivariate sensitivity analysis (Pruyt, 2007). Two types of sensitivity analysis were conducted in this study, namely univariate and multivariate sensitivity analysis. Univariate (one-way/one-at-a-time) sensitivity analysis was conducted through varying the value of one parameter at a time while holding all other parameters constant at their base case value. This form of sensitivity analysis can highlight the most influential parameters in the model outputs but it is insufficient for a complete investigation of the model in nonlinear and complex models due to that nonlinear relationships among model components may produce unanticipated output change when simultaneous changes in more than one parameter values occur (Sterman, 2000). For this reason univariate sensitivity analysis is often followed by multivariate sensitivity analysis, which assesses the effects of simultaneous change of several variables on model outputs (Monte Carlo simulation).

Monte Carlo simulation also known as multivariate sensitivity simulation examines the future likelihood of output variables of importance through running a large amount of simulations by repeatedly drawing samples from probability distributions of uncertain variables. Given the uncertain parameters, confidence bounds are utilised for demonstrating model outputs. Like with any long-term analysis there is uncertainty about the costs and the technical factors in a coal-fired power plant. The sensitivity analysis in this study

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focused on the load factor, discount rate, cost growth rates of all private costs in the model (e.g. coal, limestone, water, O&M and capital costs), cost growth rates of all damage cost estimates and the sensitivity of the model outcomes to lower and higher range estimates. Uncertainties concerning such variables are a reality for energy markets (International Energy Agency, 2010) so all these parameters are important input variables that can affect among other factors the production of coal-based power, total generating cost of power, LCOE, LECOE and the financial viability of coal based power. To assess the impact of these parameters on selected model outcomes, minimum and maximum values were assigned to each of them along with a random distribution over which to vary them. Table 7.19 shows the range of values assigned to each of the uncertain parameters with the exception of lower and higher range damage costs estimates which are shown in Figure 7.20. The number of simulations was set at 400 and the random uniform distribution was used.

Table 7.19: Minimum and maximum parameter values versus baseline values

Parameter	Units	Baseline value	Minimum – Maximum
Discount rate	Dimensionless (%)	0.08 (8%)	0.04 – 0.12 (4% to 12%)
Private cost growth rates (i.e., coal, O&M & capital cost, etc.)	Dimensionless/Year (%)	0.001 (0.1%)	-0.05 – 0.05 (-5% to 5%)
Load factor	Dimensionless (%)	0.9 (90%)	0.85 – 0.95 (85% to 95%)
Damage cost growth rates	Dimensionless/Year (%)	0.011 (1.1%)	-0.0055 – 0.0165

Concerning the lower and higher range damage costs estimates which are shown in Table 7.20, apart from univariate and multivariate sensitivity analysis I also conducted manual sensitivity testing (i.e. through changing the value of a constant one at a time and simulating) because it delivers more insightful findings that are key to this study. The outcomes of this exercise are reported last after univariate and multivariate sensitivity analysis.

Table 7.20: Lower and higher range damage cost estimates versus baseline values

Variable	Units	Lower	Base case	Higher
Unit morbidity value	R/person	9 130	25 434	59 998
Unit mortality value	R/person	69 285	245 438	771 700
Unit opportunity of water use	R/m3	669	1 001	1 331
Steel embodied water	m3/ton	200	225	250
Water requirements of a surface mine (in litres/ton)	l/ton	431	469	581
Unit damage cost of sulphate pollution from coal mining	R/ton	0.19	0.27	0.34
Unit damage cost of sulphate pollution from steel production	R/ton	0.58	0.79	0.99
Unit damage cost of sulphate pollution from Al & concrete production	R/ton	0.14	0.31	0.48
Maize yield per hectare (dry land)	ton/ha	3.5	4.25	5
Unit damage cost SO_2	R/ton	29 025	51 619	86 778
Unit damage cost NO_x	R/ton	26 735	41 952	64 689
Unit damage cost PM	R/ton	116 739	227 175	402 332
Unit damage cost CO_2	R/ton	104.98	109.89	177.94

The univariate sensitivity analysis outcomes for variations in discount rate, load factor, private cost growth rates, damage cost growth rates, and lower and higher damage costs estimates are presented in Figure 7.6, 7.7 7.8, 7.9 and 7.10, respectively in form of confidence bounds for selected output variables while the multivariate sensitivity analysis outcomes are reported in Figure 7.11. In all the figures the base case run is shown by the solid (blue) line (i.e., run name sensitivity).

Focusing on Figure 7.6 which shows the sensitivity of the LCOE and NPV after tax to variations in discount rate, the base case run indicates a fast declining negative NPV after tax from year 2010 up until year 2015, which is mainly as a result of the incurred capital cost coupled with low revenues owing to low plant capacity. From year 2015 up until year 2024, the plant is at full capacity but it is unable to generate enough revenue to cover the private cost, hence the negative NPV. From year 2025 onwards the NPV becomes incrementally positive and by the end of the simulation (year 2060) it is estimated at 66.4 billion Rands. Given the uncertainties in the discount rate, the 100% confidence bounds suggest that the NPV after tax could range from R5 billion to R217 billion by the end of the simulation while the LCOE could range from R378/MWh to R775/MWh by the end of the simulation (the base case run for the LCOE by the end of the simulation is estimated at about R554/MWh). Figure 7.6 therefore reveals a wide band of uncertainty on the simulated LCOE and NPV after tax but coal-based power could still be a viable enterprise.
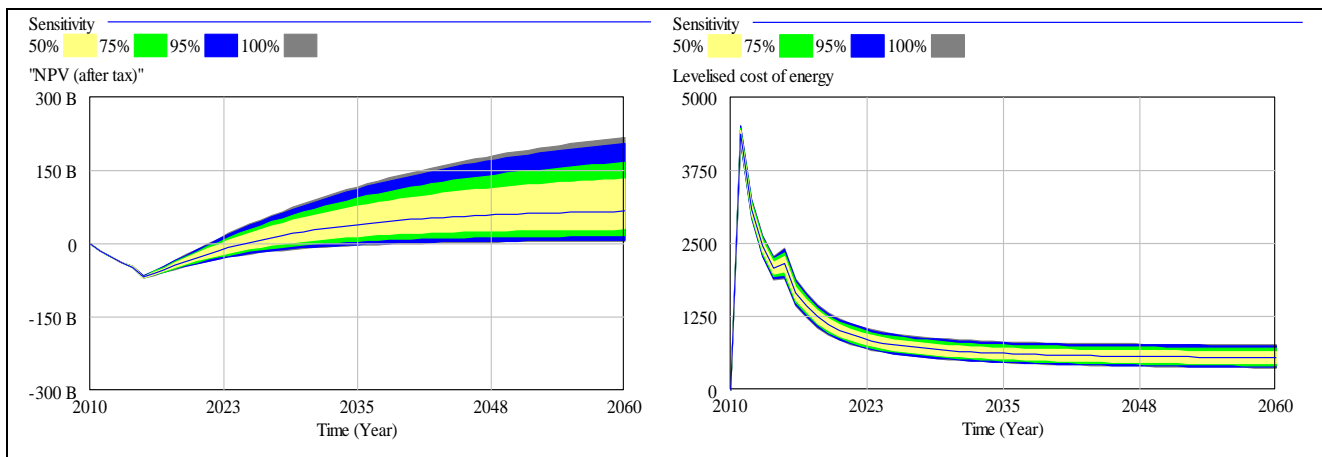

Figure 7.6: Confidence bounds for discount rate (range: 0.04 to 0.12) on selected model outcomes

Turning our attention to Figures 7.7 which shows the sensitivity of model outcomes to variations in private cost growth rates, the confidence bounds of the NPV after tax and the LCOE show the same general patterns as in Figure 7.6. The 100% confidence bounds unveil that the total generation cost (i.e., cumulative private costs), LCOE and the NPV after tax could range between R217 billion – R980 billion (base run cumulative private costs are estimated at R410 billion), R464/MWh - R808/MWh and between R4 billion –

R90 billion, respectively by the end of the simulation. The selected model outcomes are therefore sensitive to variations in cost growth rates but their bands of uncertainty are narrow than those effected by variations in discount rates. Also the project is still economically viable.
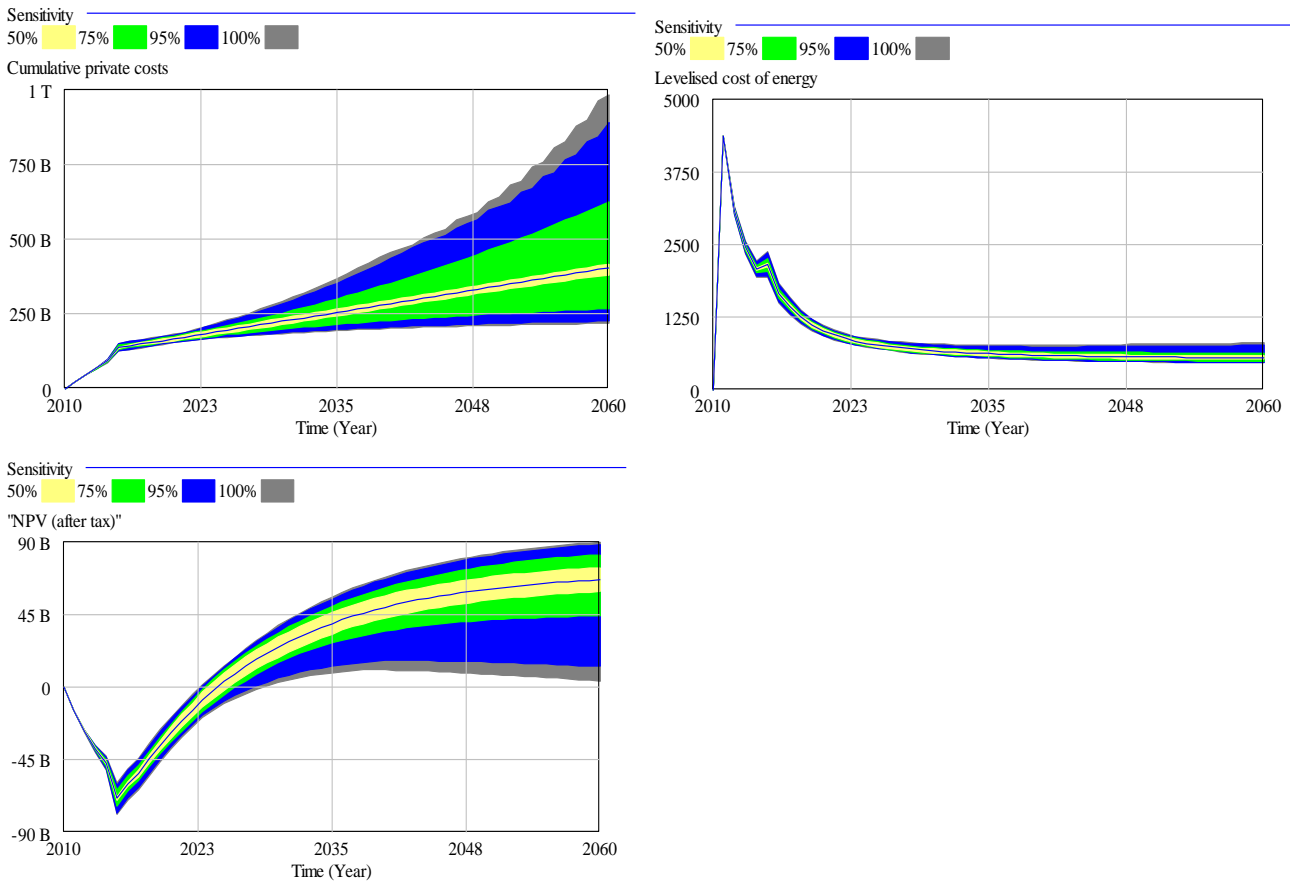

Figure 7.7: Confidence bounds for private cost growth rates (range: -0.05 to 0.05) on selected model outcomes

On the other hand, the plant load factor which is the ratio of power produced by a power plant over the theoretical maximum it could produce at full capacity over a time period is a key variable to the economics of power generation as it is useful for predicting the amount of electric power production per unit of generating capacity that would earn revenues to cover the generation cost of a power plant. There is generally an inverse relationship between the load factor and the plant-costs/ LCOE, because the higher the load factor, the lower the generation cost per MWh due to that the higher the load factor the more electricity is produced and the more the private costs of the plants are distributed across the electricity, basically making power production cheaper. The response of the plant private costs and LCOE to variations in load factor is shown in Figure 7.8. Figure 7.8 displays even more narrow bands of uncertainty on the simulated private costs and LCOE than those in Figure 7.6 and 7.7. This could be partly attributable to that Kusile is planned to be a base load power station (Eskom, 201c; Eskom communication, 2013), so it is likely

going to be operated at higher load factors. The univariate sensitivity analysis outcomes highlight the important drivers of the generation cost of coal-based power to be the discount rate, cost growth rates and the load factor in descending order.
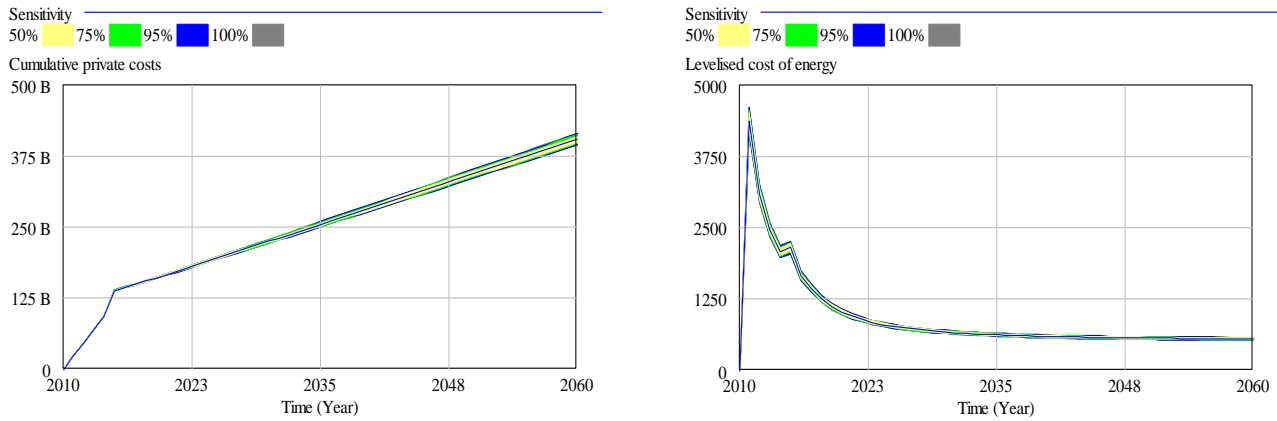

Figure 7.8: Confidence bounds for load factor (range: 0.85 to 0.95) on selected model outcomes

Now turning to the externality related uncertainties, given the uncertainties in the damage cost growth rates of +/- 50% of the base case growth rate (i.e. base case 0.011%), the 100% confidence bounds suggest that the coal-fuel cycle externality costs, levelised externality cost of energy and social NPV after-tax could range between R24 billion –R72billion (base run at R55 billion), R1 131/MWh to R1 470/MWh (base run at R1 370/MWh) and –R303 billion to –R416 billion to (base run at -R383.2 billion), respectively by the end of the simulation (Table 7.9) while sensitivity of coal-fuel cyle externality costs, levelised externality cost of energy and social NPV after-tax could range between R42 billion – R68 billion, R1 046/MWh to R1 693/MWh and –R276 billion to –R490 billion in the case of low and high damage costs estimates by the end of the simulation (Table 7.10). The selected model outcomes are therefore sensitive to variations in damage cost growth rates but their bands of uncertainty are narrow than those to variations in low and high damage costs estimates.
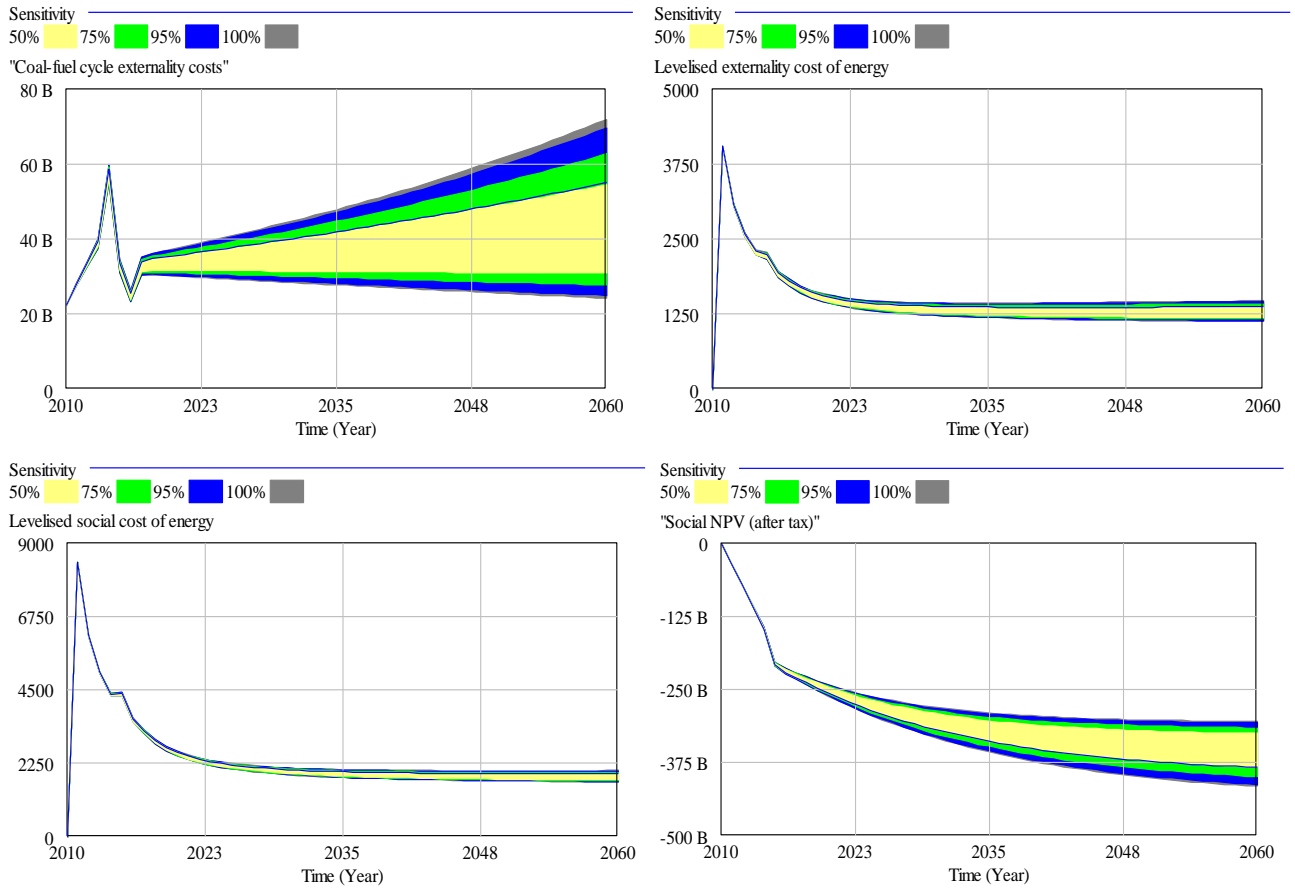
Figure 7.9: Confidence bounds for damage cost growth rates (range: -0.0055 to 0.0165) on selected model outcomes
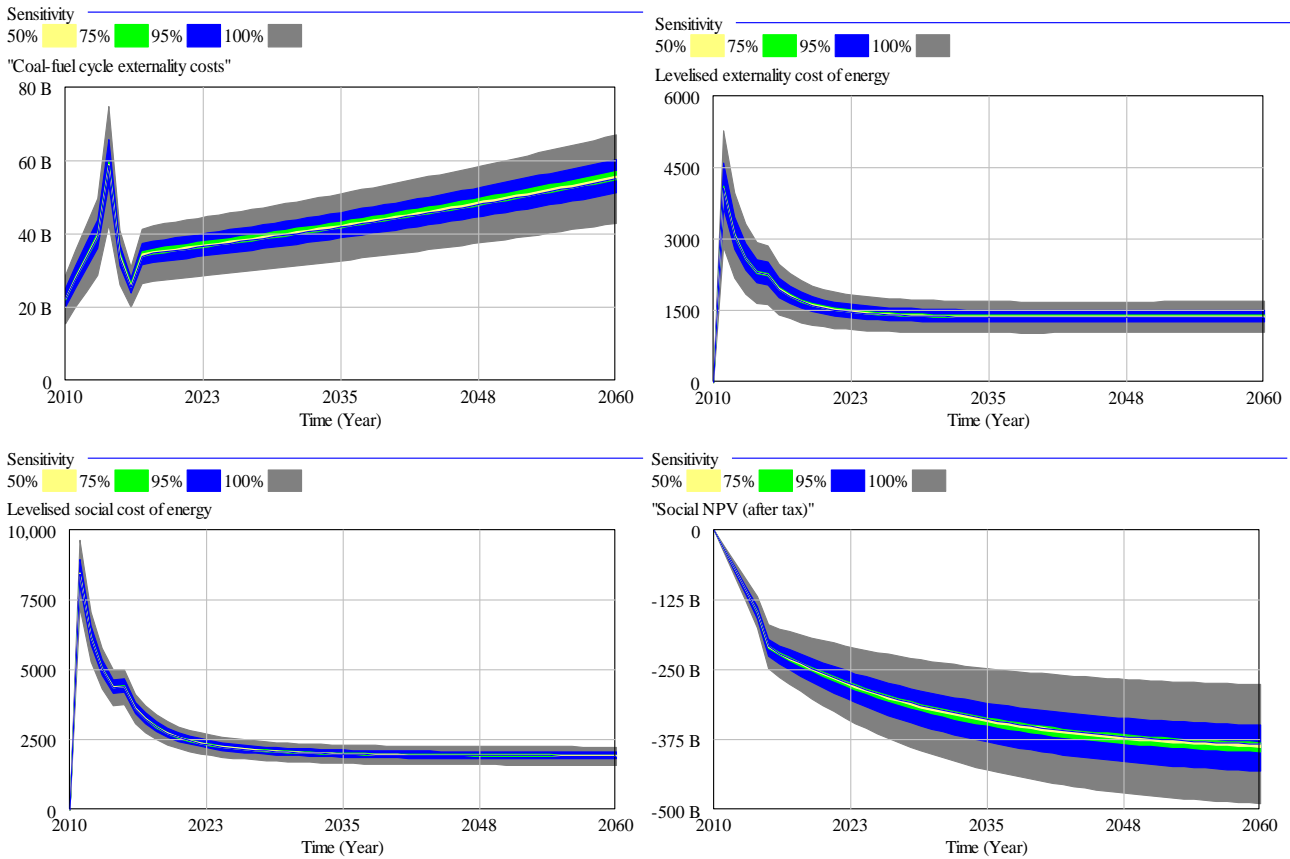
Figure 7.10: Confidence bounds for low and high damage costs estimates (range: Table 7.20) on selected model outcomes

The effects of the simultaneous change in discount rate, load factor, private cost growth rates, damage cost growth rates and lower and higher damage costs estimates, on selected model variables are presented in Figure 7.10 in form of confidence bounds. For instance the 100% confidence bounds suggest that the total private costs ranges between R200 billion - R1 trillion while the LCOE and NPV after tax range from R261 billion – R1 088 billion and between -R207 billion to -R907billion, respectively by the end of the simulation. So though the confidence bounds show the same general patterns as in the univariate analyses, Figure 7.11 shows slightly wider bands of uncertainty on all simulated outputs than any of the univariate sensitivity analysis. The combined uncertainty in all the uncertain parameters translates into a more uncertainty in selected model results by the end of the simulation.
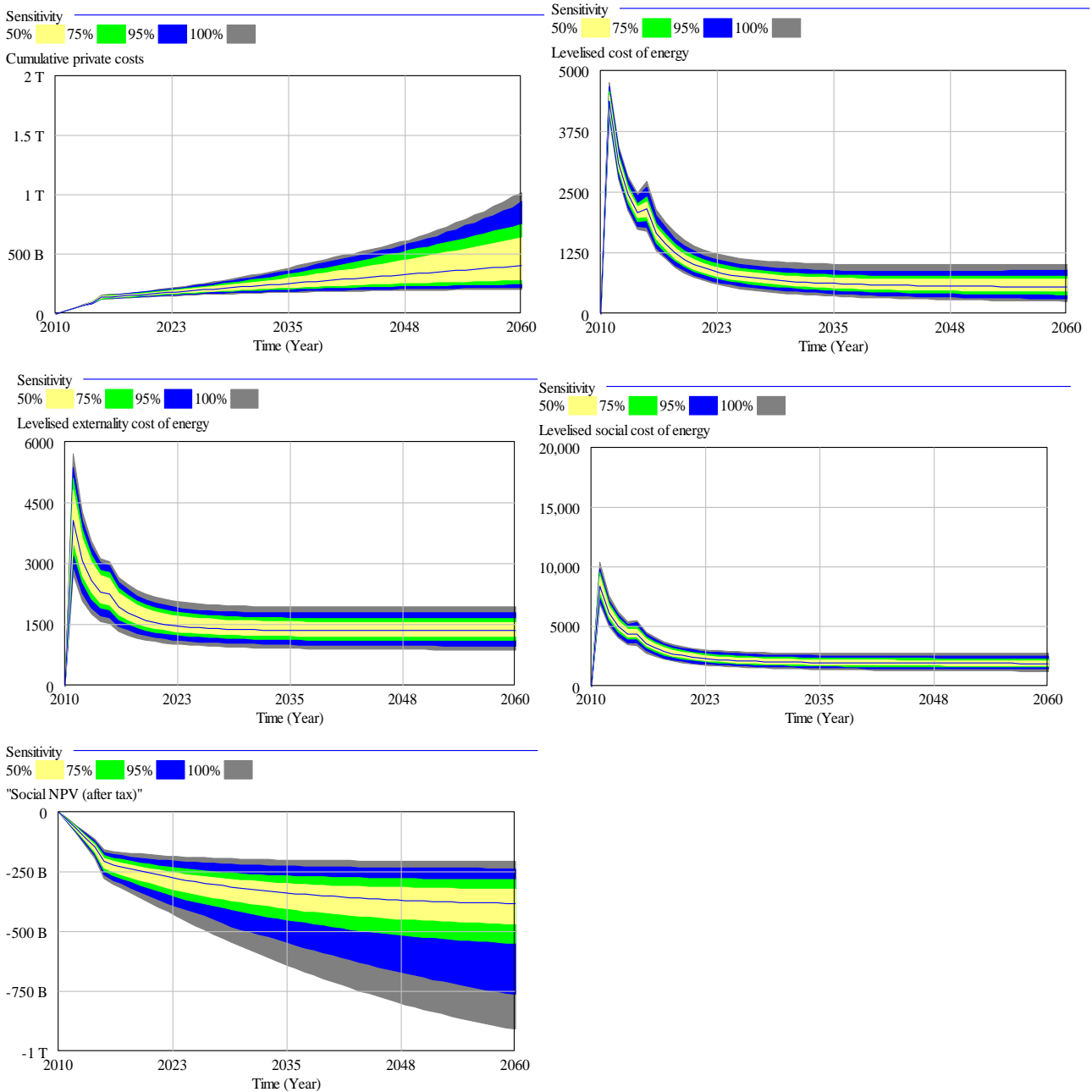
Figure 7.11: Confidence bounds for of all uncertain parameters on selected model outcomes (multivariate)

Now turning to the manual sensitivity testing of lower and higher range damage costs estimates which was discussed earlier, the sensitivity analysis outcomes of this exercise are reported in Table 7.21 and later in Table 7.22. The tables report the findings over the lifetime of Kusile. Table 7.21 shows the total coal-fuel cycle externality cost over the lifetime of Kusile to range from a low value of about R1 450 billion to a high value of R3 279 billion (base case at R2 173 billion). The base case estimate is therefore approximately 33% higher and 34% lower than the lower and higher estimates, respectively.

The lower range damage cost scenario is expected to lower the social cost of power generation and consequently improve the attractiveness of coal-based power by lowering the externality cost and hence improving the social NPV of the project. The levelised externality cost of energy (LECOE) is estimated by the model to range from a low value of R908/MWh to a high value of R2 052/MWh (baseline R1 371/MWh). Comparing the LECOE to the four collective studies' (i.e. Nkambule & Blignaut (2012), Riekert and Koch (2012), Inglesi-Lotz and Blignaut (2012), and Blignaut (2012)) externality cost for Kusile conducted for the year 2010, of between R310/MWh – R1 880/MWh, this study's estimates are comparable but higher due to the inclusion of more externalities and fuel-cycle phases.

The lower range scenario lowers the base case levelised social cost of energy from R1 925/MWh to R1 462/MWh while the higher estimate increases it to R2 606/MWh. The LCOE was earlier estimated as R554.2/MWh, so with the use of the lower and higher range scenarios the LCOE was found to reflect about 38% or 21%, respectively of the true cost of coal, while the externality cost makes up the remainder. About two-thirds to three-quarters of the true cost of electricity therefore do not reflect on the balance sheet of the utility and are borne by society. With the use of the lower range scenario, the social NPV (after tax) improves from its base case value of –383 billion to –R231 billion but is still negative and therefore coal-based power is still unattractive in social terms. The higher range scenario further worsens the social NPV (after tax) of coal-based power to –R606 billion. So with the use of lower or higher damage cost estimates, Kusile will still be unable to generate enough revenue to cover the negative externalities it imposes on third parties.

Table 7.21: Lower and higher range lifetime externality costs versus baseline over the lifetime of Kusile

Externality	Units	Lower	Base case	Higher
Total coal-fuel cycle externality cost	R billion	1 449.8	2 172.7	3 279.0
Externality cost as % of base case	%	33%	0%	34%
Levelised externality cost of energy	R/MWh	908.0	1 370.8	2 051.6
Levelised social cost of energy	R/MWh	1 462.2	1 925.0	2 605.8
Social NPV (after tax)	R billion	-231.4	-383.2	-606.4

Regarding the externality costs per phase obtained over the life-time of Kusile shown in Table 7.22, the overall life-time externality cost of mining and transporting coal to Kusile ranges between R377 and R974 billion (base case R594 billion). Water consumption makes up over 90% of the coal mining and transportation externality cost, followed by global warming damage cost and then ecosystem service loss. Based on Kusile's lifetime coal consumption of about 0.870 billion tons as estimated by COALPSCA, the externality cost linked with the mining and transportation of coal translates into between R434 – R1120/t

(base case R683/t). A value that is noticeably higher than that of the earlier South African studies discussed in section 4.3.5, because of the inclusion of more externalities and a higher price of carbon. Based on, Kusile's lifetime electricity production of about 1.6 billion MWh, the externality cost of mining and transporting coal to Kusile ranges between 24c/kWh - 61c/kWh (base case 37c/kWh). Based on the electricity tariff that will prevail at the end of the simulation (i.e. 93c/kWh), the externality cost will be between 26% - 66% of the electricity price (base case 40%).

Concerning the power plant, the externality cost considers the externalities from the direct combustion of coal plus those from waste disposal. The FGD process will be reported on separately hereafter. The lifetime externality cost from the operation of the power plant ranges between R784 and R1 715 billion. Water consumption makes up about 40% of the externality cost, followed by air pollution human health cost and global warming damages. Based on lifetime power generation, the power plant externality cost translates to between 49c/kWh - 107c/kWh (base case 72c/kWh) which represents between 53% - 115% (base case 77%) of the electricity tariff that will prevail at the end of the simulation. The externality cost in c/kWh (ZAR), when converted to US cents/kWh, ranges between 7c/kWh - 15c/kWh (base case 10/KWh) and falls within a fair range with both the international and local studies reported on Tables 4.3 and 4.5, respectively.

Table 7.22: Lower and higher range life-time externality costs per phase versus baseline

Externality	Coal mining & transportation			Plant operation & waste disposal			FGD system operation			Construction Not annual but over entire construction phase		
	Low	Base	High	Low	Base	High	Low	Base	High	Low	Base	High
	Billion Rands											
Water use	338.6	551.4	908.2	326.7	488.8	649.9	224.1	335.4	445.9	61.3	98.0	138.6
Water pollution	0.2	0.3	0.4							0.0	0.0	0.0
Fatalities & morbidity	0.0	0.0	0.1	0.05	0.2	0.5				0.0	0.0	0.0
Ecosystem loss	5.3	5.3	5.3	0.72	0.8	0.9					0.0	
Classic air pollutants	3.3	5.7	9.5	265.2	451.9	739.1	0.3	0.6	1.0	0.0		0.0
GHGs	29.8	31.2	50.5	191.3	200.2	324.2	1.9	2	3.2	1.0	1.0	1.6
Total	**377.3**	**593.9**	**974.0**	**783.9**	**1141.9**	**1,714.7**	**226.4**	**338**	**450.1**	**62.3**	**99**	**140.2**
c/kWh	**24**	**37**	**61**	**49**	**72**	**107**	**14**	**21**	**28**	**4**	**6**	**9**

The operation of the FGD system on the other hand, produces a lifetime externality cost that ranges between R226 – R450 billion (base case R338 billion). Owing to data unavailability, only water- and air-pollution related externalities were considered. Water consumption dominates the externality cost more so

than in the power plant (about 99%), followed by global warming damages and air pollution human health costs. The FGD system externality cost ranges between 14c/kWh - 28c/kWh (base case 21c/kWh) which represents between 15% - 30% (base case 23%) of the electricity tariff that will prevail at full capacity. The FGD system and the power plant combined produce an externality cost that ranges between 63c/kWh – 135c/kWh (base case 93c/kWh). Fitting Kusile with an FGD system will therefore generate approximately a third of the externality cost of the power station. The entire power station (i.e. coal combustion, FGD operation and waste disposal) represents between 68% - 145% (base case 100%) of the electricity tariff at full capacity.

Lastly, with regards to the plant construction phase, COALPSCA estimates the externality cost of constructing Kusile to range between R62 - R140 billion (base case 99 billion). Water consumption dominates the externality cost (over 98%), followed by global warming damage cost while the other externality costs are very low. The construction phase externality cost translates to between 4c/kWh - 9c/kWh (base case 6c/kWh). There are, however, no studies locally to compare these estimates with and the two international studies (European Commission, 1995; 1999b) that did study the construction phase, do not report explicitly the externality cost linked with this phase.

Summarizing the fuel-cycle externality costs reported above, the coal-fuel cycle externality cost ranges between 91c/kWh – 205c/kWh with the base case at 136c/kWh (when converted to US cents/kWh it ranges between 12c/kWh - 28c/kWh with the base case at 19c/kWh). The plant combustion phase with waste disposal comprised most of the externality cost (49c/kWh - 107c/kWh), followed by coal mining and transportation (24c/kWh - 61c/kWh), then the FGD system (14c/kWh - 28c/kWh), and lastly the construction phase (4c/kWh - 9c/kWh). The externality cost generated by the model falls within the range of the international studies reported on Table 4.3 and the local studies in in Table 4.5, but is slightly higher than those that study the entire coal-fuel chain owing to the inclusion of more externalities and coal-fuel cycle phases.

7.4   Policy analysis

In this section an evaluation is conducted of the COALPSCA Model outcomes under two potential policies that could be faced by coal-based power utilities. The first policy is linked to Eskom's concern that domestic coal prices will soar to export levels, and is named the export parity coal pricing (EPP) policy. The second policy concerns a form of internalizing the externality cost of coal-based power generation through carbon taxation, and is named the carbon tax policy. Both policies are discussed further below. Sixteen scenarios were formulated to evaluate the implementation effects of the two policies. Table 7.23 presents a

summary of these scenarios while the following sections provide a discussion of the policies, scenarios and model outcomes.

Table 7.23: Policy scenarios

Scenarios		Export parity coal pricing (R/ton)	Carbon tax (R/ton of CO_2e)
Name	Abbreviation		
Baseline	Base	Baseline – 210	0
Export parity coal pricing	EPPP600	600	0
	EPPP700	700	0
	EPPP800	800	0
Carbon tax at 10%	CT100	Baseline	100 - growth rate 10%
	CT120	Baseline	120 - growth rate 10%
	CT150	Baseline	150 - growth rate 10%
	CT200	Baseline	200 - growth rate 10%
Carbon tax at 5%	CT100	Baseline	100 - growth rate 5%
	CT120	Baseline	120 - growth rate 5%
	CT150	Baseline	150 - growth rate 5%
	CT200	Baseline	200 - growth rate 5%
Carbon tax at 0.1%	CT100	Baseline	100 - growth rate 0.1%
	CT120	Baseline	120 - growth rate 0.1%
	CT150	Baseline	150 - growth rate 0.1%
	CT200	Baseline	200 - growth rate 0.1%

7.4.1 Export parity coal pricing scenarios

The sale of coal domestically at export parity prices is a looming danger facing the South African industry and especially the energy sector as the main user of coal. The looming price threat can be explained by various factors, including the emergence of viable export markets competing for Eskom's low-grade coal and under-investment in the coal mining industry which might result in coal shortage and therefore a rise in coal price, i.e. coal shortage is forecasted to commence after 2018 (Creamer Media, 2013). It is therefore imperative to explore the probable implications of various coal price regimes on the cost of generating coal-based power.

In general, Eskom secures most of its coal through long-term (mostly cost-plus) contracts, as discussed in section 2.3.4. Furthermore, personal communication with Joubert reaffirmed that Eskom sourced the bulk of its coal through long-term coal supply agreements and that the amount of this coal is roughly less than or equal to 80% of each power station's annual coal usage and coal usage over its expected lifetime. This percentage might, however, vary dependent on the power station's expected position in the fleet 'merit order' which is mainly centred on the variable cost of a power plant. In this regard, in the process of adjusting the number of plants to service instantaneous electricity demand, a lower-fuel-cost plant will be dispatched earlier than a high-fuel-cost plant. Since long-term coal supply agreements imply a very high risk to the supplier, most of the agreements follow the cost-plus return on investment approach with some cost

efficiency incentives. The coal prices paid for through long-term supply agreements may or not be higher than market prices for analogous coal grades (Eskom communication, 2013).

While coal volume flexibility is useful to all power stations, it needs to be less for low-fuel-cost plants. Based on the discussion above, the short-term, more flexible contracts might provide 20% of the annual coal requirement, to augment the long-term, annual-volume contracts (i.e. 80%) and might be subject to export competition. For the purchaser, a balance needs to be struck between flexibility and cost, because flexibility implies more risk for the supplier and often a higher price for the purchaser. Kusile, as a base-load power station, will be contracted on long-term, cost-plus return on investment agreements and, depending on national electricity demand growth being higher/lower than currently envisaged, it could imply variances, necessitating some flexibility with the shorter-term, flexible contracts being exposed to export opportunities (Eskom communication, 2013).

In the light of the above discussion, 25% of the annual coal usage in Kusile was exposed to export competition as a worst-case scenario. The export parity coal pricing policy reflects three coal pricing regimes, namely R600/ton (Creamer media, 2013), R700/ton and R800/ton, which were introduced from year 2022 in the model. The export parity price outcomes are represented in Figure 7.12.

The export price regimes are expected to increase the fuel cost, total generation cost and therefore also the LCOE. This is so because these variables are positively related to the LCOE. The Figure shows that increasing the price of coal has an immediate and fairly noticeable effect on fuel costs, which will amplify the cost of generating power and possibly power tariffs. The levelised fuel cost increases from the baseline value of R117/MWh to R142/MWh, R149/MWh and R155/MWh in the case of the EPPP600, EPPP700 and EPP800 scenarios, respectively. The figure continues to show the positive effect of the coal price regimes on the LCOE which increases by +/-7%. Given that the EPPP600, EPPP700 and EPPP800 scenarios, show domestic coal price increases of about 65%, 70% and 73%, respectively, whilst they effect +/-7% sensitivity to the LCOE, the LCOE is thus not that response to the fuel prices, which could be mainly explained by that only 25% of the coal requirements of Kusile were exposed to export competition. The LCOE arranges between R580/MWh - 593/MWh for the EPPP scenarios

The NPV (after tax) simulation output in Figure 7.12 displays that the export price regimes diminish the attractiveness of coal-based power as shown by the declining NPV as the unit cost of coal rises. For example, the rise in fuel prices decreases the baseline NPV (after tax) from R66.4 billion to between R57.3 – R60.4 billion. In summary, should coal prices rise to export parity price levels the total generation cost of

coal-based power would increase but not by a great margin, given the 25% exposure to export competition. Under this exposure Kusile will still be a viable enterprise if one chooses to disregard the externality costs associated with such an investment.
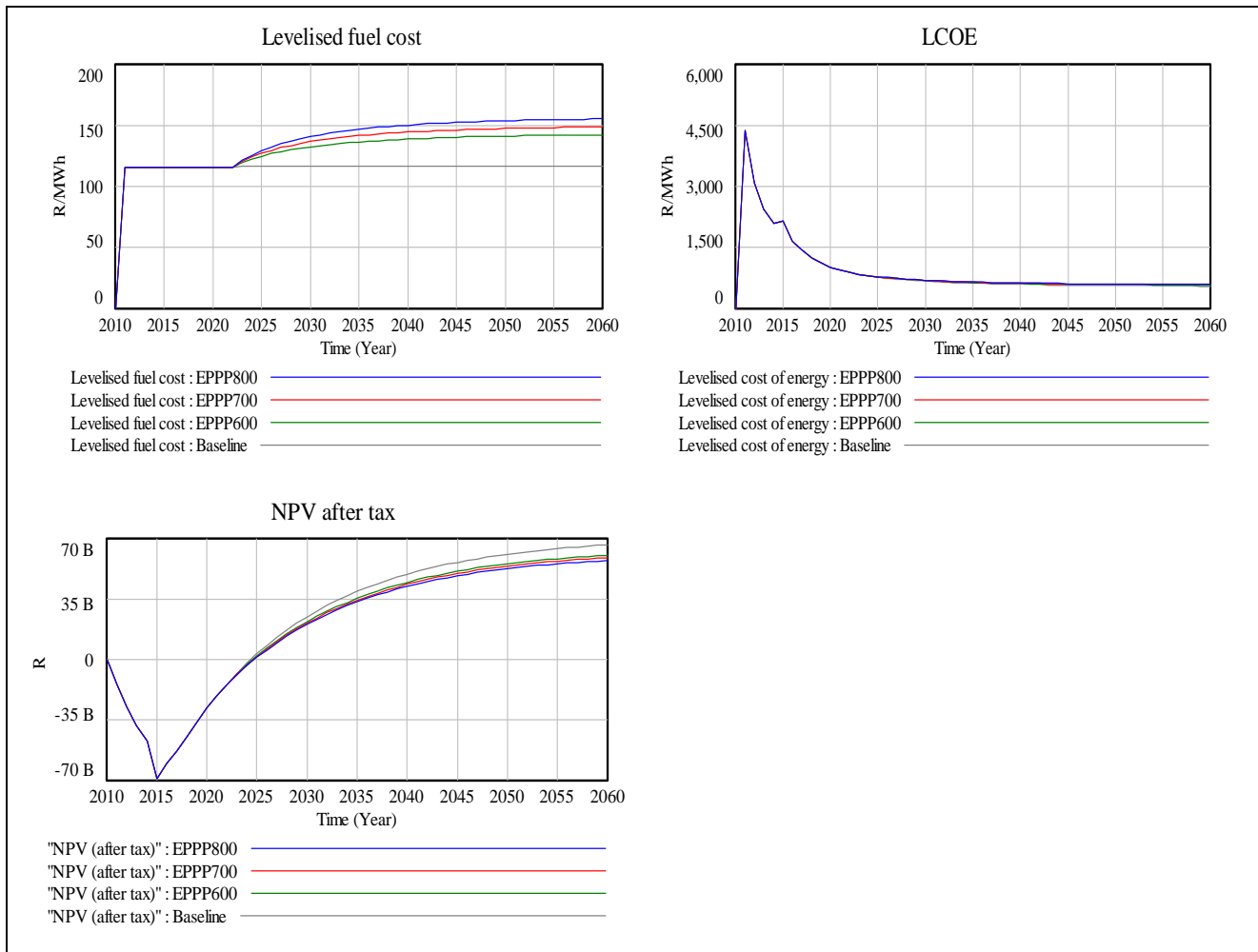

Figure 7.12: Export parity price outcomes

7.4.2   Carbon tax scenarios

With discussions being underway on the imposition of carbon taxes to producers of greenhouse gases, it is a looming threat facing the South African industry, and especially the energy sector as the main producer of GHGs. For its energy needs, South Africa is largely dependent on coal - a source of energy known for its high emissions of GHGs, especially CO_2. As a form of mitigating the risk of climate change, National Treasury has opted to impose a carbon tax on emitters of GHGs. Companies would not pay for the entire emissions they cause, but a tax-free exemption threshold and offset to a maximum of 90% is proposed, to minimize negative impact on local firms' competitiveness and also to lighten the burden of higher energy prices on households (National Treasury, 2013).

The carbon tax proposal was revised recently, with the new proposal raising the threshold beyond which the tax is payable, and suggesting subsidies to invest in low-carbon technologies, among other issues. The proposed tax by National Treasury is R120/ton of CO_2 equivalence beyond the tax-free threshold (National Treasury, 2013) which is normally 60% for all companies (BDFM Publishers, 2013d). Eskom will pay for only 40% of its CO_2e emissions, that is, a tax-free exemption threshold of 60% (National Treasury, 2013), resulting in an effective tax rate of R48/ton of CO_2e. Eskom could invest in offset investments of its own, and such investments could be subtracted from its tax liability to a maximum of 10%. This results in a minimum tax liability of R36/ton of CO_2e. Also, in acknowledgment of the complexity of quantifying, reporting on, and policing the emissions of a gas that is odourless and colourless, the tax is going to be imposed as a fossil-fuel input tax, based on carbon contents of fossil-fuels like coal, natural gas and crude oil (Urban Earth, 2012; Urban Africa, 2013). For the purposes of this study, the tax would therefore have been a fuel input tax based on coal consumption, but since GHG emissions were estimated in the current study, the tax was imposed on CO_2e emissions.

In contrast to the proposed tax by National Treasury, Robbie Louw, the director of Promethium, and Harmke Immink concur that, based on South Africa's GHG emissions, R100/ton is more sensible (Esterhuizen, 2013). The tax proposed by Treasury is also not well received by business enterprises, who foresee the tax rate raising the cost of doing business in the country. Treasury plans effecting the proposed carbon tax beginning 2015 (BDFM Publishers, 2013d) and increasing it annually by 10% within the first phase, which is from 2015 to 2019 (Esterhuizen, 2013; National Treasury, 2013). Following this phase, the tax will be revised to a new tax rate and to lower tax-free thresholds which will be effective from 2020 (National Treasury, 2013). It is therefore important to explore the likely implications of various carbon tax regimes on the cost of generating power from coal. Four carbon tax regimes, R100/ton of CO_2e, R120/ton of CO_2e, R150/ton of CO_2e, and R200/ton of CO_2e, were introduced in the COALPSCA Model. The carbon tax scenarios at 10%, 5% and 0.1% shown in Table 7.23, escalate these four tax regimes at an annual rate of 10%, 5% and 0.1% over the entire lifetime of Kusile, respectively. In addition, in all the scenarios, Kusile was assumed to be charged for only 30% of its combustion phase emissions.

The carbon tax regimes are expected to increase the cost of generating power in a coal-based plant, by imposing a new operational cost, namely carbon tax cost. The carbon tax also generates revenue for the government that can be put to a number of uses, such as support of cleaner sources of electricity. The model unveiled that the proposed tax rate of R120/ton of CO_2e, generates revenue over the lifetime of Kusile that ranges between R47 billion at 0.1% growth rate, R1 283 billion at 10% growth rate (R216 billion at 5% growth rate). Given that the government plans to lower tax-free thresholds beginning 2020 (National

Treasury, 2013), and perhaps revise the tax rate upwards, these revenue streams as estimated by the model, are lower-end estimates for the growth rates in question. Overall for all carbon tax regimes (low to high) at growth rates of 10%, 5% and 0.1%, the model estimates revenues ranging between R1 069 – R2 138 billion, R180 – R361 billion, R39 – R79 billion, respectively.

The power plant externality costs of the entire GHG emissions (100%) at the low, median and high damage cost of carbon listed in Table 7.20 (i.e. based on Blignaut, 2012) were computed (growth rate 0.1%) and based on the resultant GHG emissions externality costs, carbon tax scenarios (listed in Table 7.23) were explored that recouped the various costs. The 100% GHG emissions externality costs at the unit damage cost of CO_2 of R104.98/ton, R109.89/ton and R177.94/ton amounts to R142 billion, R148 billion, R240 billion, respectively. Previously, it was stated that all four carbon tax regimes at growth rates of 10%, 5% and 0.1%, yielded government revenues ranging between R1069 – R2138 billion, R180 – R361 billion, R39 – R79 billion, respectively, so evidently none of the four carbon tax regimes at the growth rate of 0.1% recovers any of the 100% GHG emissions externality costs while the carbon tax regimes at the growth rate of 10% will overly recoup the 100% GHG emissions externality costs. The revenues generated by CT100, CT120, CT150 and CT200 at 5% growth rate are R180 billion, R216 billion, R270 billion and R361 billion, respectively. So the CT100 scenario at 5% growth rate more than recoups the low and median 100% GHG emissions externality costs computed using the unit damage cost of CO_2 of R104.98/ton and R109.89/ton, respectively while the CT150 scenario at 5% growth rate more than recoups the high 100% GHG emissions externality cost computed using the unit damage cost of CO_2 of R177.94/ton. These findings therefore suggest that regardless of the carbon tax regimes the growth rate of the carbon tax regimes need to be carefully selected since it greatly alters the resultant payable GHG externality cost or government revenues, which negatively affect the financial viability of coal-based power plants. Based on these findings growing any of the carbon tax regimes at 10% nullify the fact that coal-power plants pay for only 30% of their GHG emissions, this is so because such a higher growth rate tend to more than recoup the 100% GHG emissions externality costs (depending on the unit damage cost of CO_2 effected). Regarding the unit carbon tax regimes and carbon tax growth rates combined, the findings suggest that the carbon tax should preferably be lower than R150/ton of CO_2 and be grown at a growth rate lower than 5%, or else coal-based power plants pay way above 100% of their GHG emissions.

The carbon tax regimes in Table 7.23 impose a new operational cost (i.e. carbon tax cost) which is expected to increase the cost of generating power in a coal-based plant, which should amplify the LCOE. The simulation output of the new operational cost (i.e. carbon tax cost) at various tax regimes and growth rates is shown in Figure 7.13. The figure depicts the increasing effect of the levelised carbon tax per tax regime,

from the low growth rate of 0.1% to the higher growth rate of 10%. Increasing the tax regimes at 10% is shown to have the greatest impact on the generation cost of coal-based power, with levelised carbon tax estimates ranging between R179/MWh – R358/MWh.
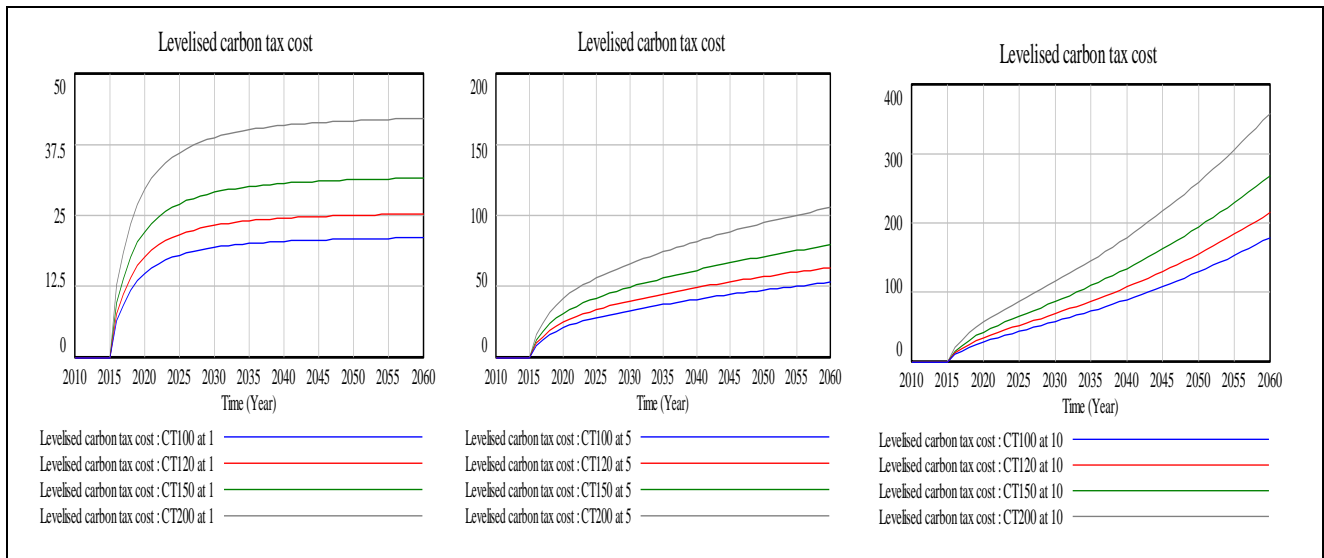

Figure 7.13: Carbon tax cost at various tax regimes and growth rates

Figure 7.14 shows the LCOE for all the carbon tax scenarios, the carbon tax inclusive LCOE estimates range between R575/MWh – R913/MWh, effecting sensitivity on the LCOE of about +/-39%, +/-16% and +/-7% when grown at 10%, 5% and 0.1% growth rates, respectively. With LCOE for renewable technologies such as wind plants and solar based-power, estimated at about R658/MWh – R1052/MWh depending on wind classes and R1517/MWh – R2026/MWh depending on technology type and storage hours, respectively, wind energy will quickly become cost-competitive with coal based power, if any of the four tax regimes are escalated at either 5% or 10%.
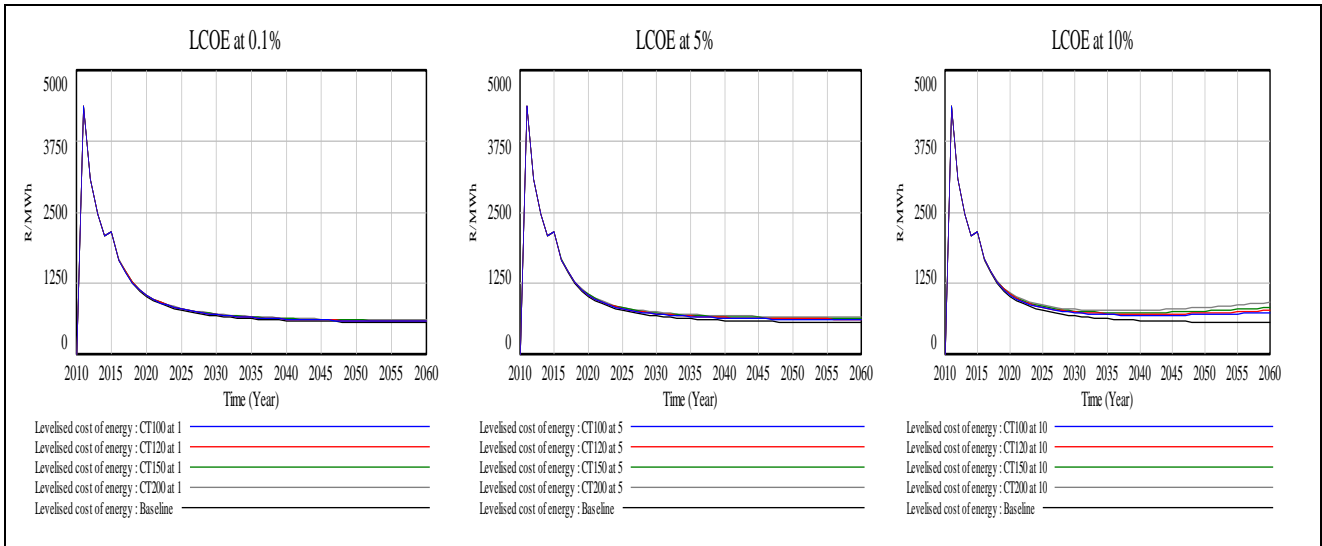
Figure 7.14: Carbon tax effects on LCOE

Figure 7.15 depicts the NPV (after tax) simulation output at various tax regimes and growth rates. The figure shows the weakening financial viability of coal-based power as shown by the declining NPV as the carbon tax rates and growth rates are increased. The tax regimes at the 10% growth rate show the largest change of the baseline value (R66.4 billion) which decreases to between R24.1 billion (at CT100) and -R18.3 billion (at CT200). The CT200 tax regime at 10% growth rate is the only scenario that yields a negative NPV, so for the most part, if coal-based power utilities should be charged the studied regimes at 5% or 0.1% and only for about one third of the GHGs they emitted, coal-based power production would still be a viable enterprise, with NPV ranging between R42 – R54 billion or R56 – R61 billion, respectively. The financial viability of coal-based power would, however, be profoundly worsened by any of the studied tax regimes when perpetually grown at 10% over the lifetime of the plant.
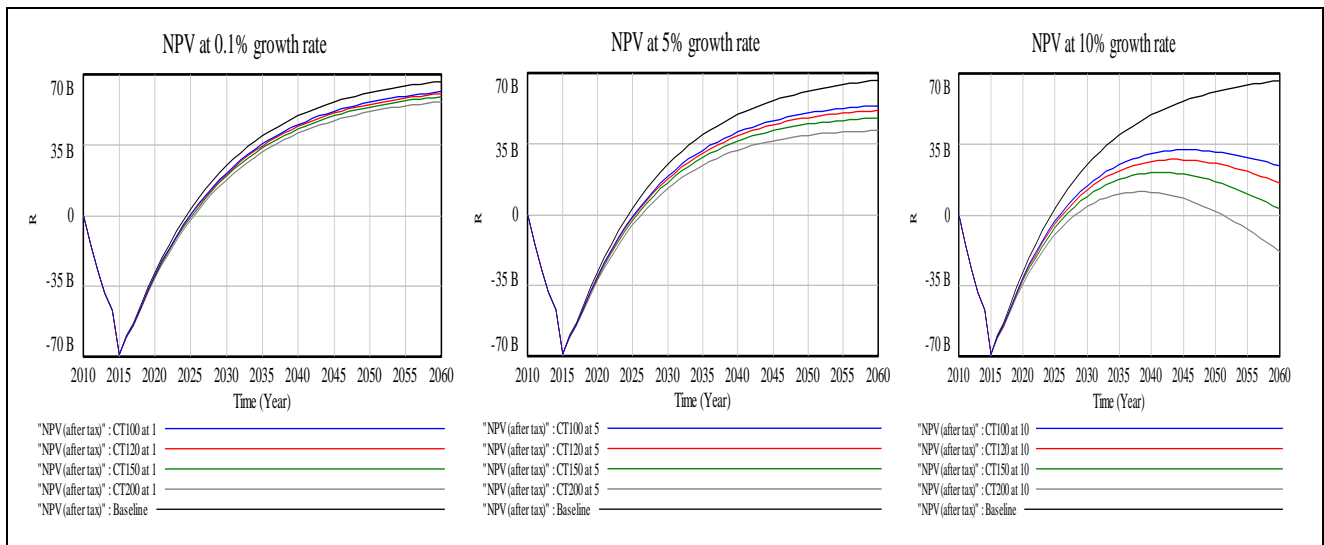
Figure 7.15: NPV at various tax regimes and growth rates

7.5   Summary

In this chapter the COALPSCA Model baseline outcomes were analyzed based on sixteen economic and environmental/societal indicators. Ten of these indicators were economic indicators representing the performance of the plant and the cost incurred by plant developers and the community at large. The remaining six indicators were environmental indicators reflecting the six main categories of externalities quantified and monetized in this study. This analysis was followed by model validation tests and lastly, policy analysis. The key findings of the study are summarized below.

Baseline results: Based on model settings, the main factors influencing the behaviour of electricity generation are – (i) investment in plant capacity; (ii) load factor; (iii) plant operating hours, and (iii) profits. The model showed that the behaviour of the resource inputs into power generation (e.g. coal consumption) and plant construction (e.g. steel) follows the same dynamics as that of power generation and construction schedule, respectively. The environmental indicators analysis also established that most of the indicators studied in the coal-fuel chain, (e.g. air emissions (classic air pollutants, trace metals and GHGs), water use, fatalities, morbidity and waste production), with the exception of the construction phase, mainly follow similar dynamics as that of power generation, while those from the construction phase mainly follow the construction schedule behaviour.

Concerning the costs of generating power (private costs), the model showed that the main determinants of generation cost and the LCOE are fuel and capital costs. These costs are therefore the main factors determining the viability of coal-based power. The model estimates a base case lifetime generation cost of Kusile of about 411 billion Rands, with the LCOE at about R554/MWh. NPV analysis was also performed and

it was positive, indicating that investing in Kusile is economical in private terms, but after attaching economic values to the studied environmental indicators (externalities), the model estimated a negative social NPV throughout the lifetime of Kusile.

The model estimated the base case coal-fuel cycle externality cost over the lifetime of Kusile to be about 2 173 billion Rands. The base case externality cost per kWh sent out is therefore about 136c/kWh - specifically 72c/kWh is attributable to the power plant and waste disposal phases, 37c/kWh stems from the coal mining and transportation phase, while the FGD system and plant construction contribute 21c/kWh and 6c/kWh, respectively. Most of the externality cost stems from three types of externalities, namely water use (68%), air pollution health cost (21%) and global warming damage cost (11%), and from three coal-fuel cycle phases, namely plant operation (51%), coal mining and transportation (27%) and FGD system operation (16%). Collectively the three phases make up about 94% of the lifetime externality cost.

Finally, since the installation of the FGD system increases water use while curbing SO_2 emissions, this interesting trade-off between water use and SO_2 emissions was explored by studying the air pollution health cost and opportunity cost of water use with and without the installation of the FGD system. The installation of the FGD system was found to be a sensible effort (on the grounds of externality cost versus externality cost savings) since its air pollution health cost savings outweigh the water use externality cost it introduces. Water is, however, a scarce resource in South Africa and human health is without doubt valuable, so the country and its people need to decide what it is willing to forego in order to gain the other. Give-up water in exchange for clean air and hence gain better human health or vice versa. On the other hand, in order for one to reach a final conclusion about the economic viability of the FGD system, the private and externality costs associated with the FGD system need to be fully paid off by the savings.

Model validation: Five structural validity tests were performed in this study, namely structure verification, dimensional consistency, boundary adequacy, extreme condition and parameter verification tests. In the light of these tests the COALPSCA Model was found to be a reasonable simplified match of the real-world system. Behaviour validity tests were also conducted. Like with any long-term analysis there is uncertainty about the costs and the technical factors in a coal-fired power plant. To learn how uncertainty in parameter estimates translates into uncertainty in simulated model outputs, sensitivity analysis was conducted first by using univariate sensitivity analysis followed by multivariate sensitivity analysis. Sensitivity analysis in this study focused on the load factor, discount rate, cost growth rates of all private costs in the model (e.g. coal, limestone, water, O&M and capital costs), cost growth rates of all damage cost estimates and the sensitivity of the model outcomes to lower and higher range estimates. Uncertainties concerning such

variables are a reality for energy markets so all these parameters are important input variables that can affect among other factors the production of coal-based power, total generating cost of power, LCOE, LECOE and the financial viability of coal based power.

Given the individual uncertainties in discount rate, load factor and private cost growth rates, univariate sensitivity analysis highlight the important drivers of the generation cost of coal-based power to be the discount rate, cost growth rates and the load factor in descending order. While given the individual uncertainties in damage cost growth rates, and lower and higher damage costs estimates, univariate sensitivity analysis highlight narrow bands of uncertainty to variations in damage cost growth rates than those to variations in low and high damage costs estimates. The effects of the simultaneous change in discount rate, load factor, private cost growth rates, damage cost growth rates and lower and higher damage costs estimates disclosed that though the confidence bounds of the multivariate analysis show the same general patterns as in the univariate analyses, the multivariate analysis outcomes show slightly wider bands of uncertainty on all simulated outputs than any of the univariate sensitivity analysis. The combined uncertainty in all the uncertain parameters translates into a more uncertainty in selected model results by the end of the simulation.

Policy analysis: The COALPSCA Model outcomes were evaluated under two potential policy scenarios that could be faced by coal-based power utilities, namely carbon taxation and the pricing of domestic coal at export parity price levels. Fifteen scenarios characterized by the two policies at various price regimes and growth rates, were defined and evaluated with reference to the baseline scenario. Due to the amount of coal exposed to export competition (25%), the total generation cost and consequently the LCOE were found to be fairly responsive to the export coal price regimes (+/-7%). Under this exposure, coal-based power production would still be a viable enterprise if one chose to disregard the externality costs associated with such an investment.

Conversely, the total generation cost of coal-based power was found to be moderately to severely impacted by the carbon tax regimes, depending on the rate at which they were grown. The four tax regimes were found to effect +/-39%, +/-16% and +/-7% sensitivity on the LCOE when grown at 10%, 5% and 0.1% growth rates, respectively, with carbon tax inclusive LCOE estimates ranging between R575/MWh - R913/MWh. Coal-based power production would still be a viable enterprise if power utilities were charged the studied tax regimes at 5% or 0.1%, and only for one third of the GHGs they emitted. The financial viability of coal-based power would, however, be profoundly worsened by any of the studied tax regimes when perpetually grown at 10% over the lifetime of the plant.

On another note, the power plant externality costs of the entire GHG emissions (100%) were also computed using the unit damage costs of CO_2 listed in Table 7.20 (i.e. based on Blignaut, 2012) grown at 0.1% and based on the resultant GHG emissions externality costs, carbon tax scenarios (listed in Table 7.23) were explored that recouped the various costs. The findings: (i) suggested that regardless of the carbon tax regimes the growth rate of the carbon tax regimes need to be carefully selected since it greatly alters the resultant payable GHG externality cost or government revenues, which negatively affect the financial viability of coal-based power plants; (ii) disclosed that growing any of the carbon tax regimes at 10% nullify the fact that coal-power plants pay for only 30% of their GHG emissions; and (iii) further suggested that the carbon tax should at most be preferably lower than R150/ton of CO_2 and be grown at a growth rate lower than 5%, or else coal-based power plants pay way above 100% of their GHG emissions.

Lastly, not all basic aspects of reality are considered by the model, partly owing to the lack of data and anticipated model complication of including certain parameters (e.g. ecosystem services lost upstream of the power plant, excluding those linked with the coal mine). Regardless of the limitations, the model does indeed provide a reasonable, simplified demonstration of the use of system dynamics for the assessment of electricity generation, fuel-cycle externalities and social cost associated with a coal-based power plant.

CHAPTER 8: CONCLUSION, LIMITATIONS AND RECOMMENDATIONS

8.1 The research conducted in this study and main findings

The primary concern of this study was to understand coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and fuel cycle, through the application of a system dynamics approach along a life-cycle viewpoint. A model that assesses power generation and the social cost of generating power in the coal-fuel chain named COALPSCA was therefore developed. The purpose of developing the model was twofold - firstly, to aid energy decision makers with a tool for making informed energy supply decisions that consider the financial viability of power generation technologies, but also the socio-environmental consequence of the technologies. Secondly, to aid coal-based power developers with a useful tool for detecting the main drivers of the burdens and costs in the system which should yield vital socio-economic-environmental tradeoff information that can be beneficial to them.

Early in this thesis a historical review was conducted of the schools of economic thought and system dynamics, with the ultimate aims of determining the schools of economic thought that underpins this study and its links with system dynamics. The review of economic thought disclosed that the main concepts in this study, namely production, externalities and social cost are rooted in neoclassical and environmental economics, particularly, in welfare economic theory, theory of production and Pareto efficiency. Neoclassical and environmental economics were therefore the main economic disciplines that provided the theoretical base for this study. The ontology, epistemology and methodology of both neoclassical and environmental economics were discussed to be realist, objective and quantitative, respectively, and hence to fall within the positivist research paradigm of Guba and Lincoln's classification. The proposed modelling approach (system dynamics) was found to share many elements that are consistent with the two economic disciplines that underpin this study, for instance, ontology and epistemology elements and the use of quantitative techniques, but in addition, to offer more features such as a complex unitary approach with the ability to deal with large number of elements and many interactions between elements, experimental approach and empirical solutions, case study approach instead of using abstractions to develop models, problem-orientated approach, transdisciplinarity methods, confidence based on model structure over coefficient accuracy, emphasis on understanding system's structure and our assumptions about it as opposed to focusing on predictions, non-linear structures, dynamic structures, disequilibrium approach and focus on closed loop information feedback structures.

A review of power generation assessment tools and their application was conducted. The review disclosed that an assortment of methods and tools have been adopted by researchers to evaluate power generation technologies contingent on the specific aims and scopes of the applications. The tools were grouped into three broad categories of methods, namely financial, impact, and systems analysis methods. The review of financial measures disclosed that different financial measures are suited for different computations, but generally cost-effective energy projects are those with lowest LCOE, LCC, simple payback period and discounted payback period plus those with high IRR, MIRR and NPV. The review of impact analysis tools discloses that various tools are suited for identifying, quantifying and monetizing externalities. Depending on the aims of the investigations and a number of issues surrounding the research (such as time and financial constraints and availability/unavailability of previous primary valuation studies) various researchers employed various impact analysis tools. On the other hand, the review of the systems analysis tools unveiled that various systems models are designed for different purposes (e.g. modelling energy system, and/or economic system, and/or ecological system), different technologies (e.g. renewable energy, non-renewable energy or both), different scales of analyses (e.g. national, regional or global) and different sizes of energy systems.

Concerning the application of the tools in the power sector, the review disclosed that in the past three decades many studies have been undertaken on electric sector costs in both developed and developing nations. Earlier externality studies used the abatement cost and bottom-up approaches to derive externality costs estimates while recent studies used the bottom-up approach and benefit transfer technique to estimate externality cost of power generation. The studies differ in terms of the types of externalities they consider, the fuel-cycle stage(s) they investigate and they do not factor in the long-standing repercussions of the technologies on the environment and social systems. The most investigated externalities internationally and locally are climate change and human health impacts associated with airborne pollution from coal combustion. Both locally and internationally more attention is still paid to the power generation phase. These differences in scope affected the outcomes of the studies, made comparing them difficult, and highlighted the need for comprehensive externality investigations that widen the range of externalities studied, that consider the various fuel-cycle stages and that embrace the long-term repercussions of the technologies on the environmental and social systems.

The literature on systems analysis models disclosed that various models have been developed for addressing various energy-related issues (for instance, locally the models are mainly used for modelling energy supply and demand, projecting GHG emissions and studying climate change mitigation options), however, as evidenced by the review not all facets/features of power generation had been studied by the

researchers, for example, the models were not tailored to specific coal-based power generation technologies, did not address social cost, nor permit deeper understanding of coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and life-cycle. Also environmental focus was evidently on quantifying direct GHG emissions from the coal combustion phase, thus numerous combustion phase and upstream burdens could still be incorporated and monetized to advance coal energy analysis. Finally, no study was found that used a system dynamics approach to assess power generation and the social cost of coal-based power generation over its lifetime and fuel cycle.

The modelling steps suggested by Roberts et al. (1983), Ford (1999), and Sterman (2000), namely problem formulation, dynamic hypothesis, model formulation (structure and equations), model validation and policy design and evaluation, were followed in developing and validating the COALPSCA Model. The model was used for:

- Understanding coal-based power generation and its interactions with resource inputs, private costs, externalities, externality costs and hence its consequent economic, social and environmental impacts over its lifetime and life-cycle;
- Aiding energy decision makers with a visual tool for making informed energy supply decisions that consider the financial viability and the socio-environmental consequences of power generation technologies;
- Aiding coal-based power developers with a useful tool with a clear interface and graphical outputs for detecting the main drivers of costs and sources of socio-environmental burdens in the system which should yield vital socio-economic-environmental tradeoff information;
- Understanding the impacts of various policy scenarios on the viability of coal-based power generation; and,
- Validating the model since no historical data existed on Kusile power station.

The main findings of this research are as follows:

- Pertaining to the private costs – the baseline scenario disclosed that investing in Kusile was economical and that fuel and capital costs were the main cost components determining the financial viability of coal-based power. The baseline model estimated the lifetime generation cost of power in Kusile at about 411 billion Rands, while the LCOE was estimated at about R554/kWh.
- The externalities inventory analysis unveiled the plant operation phase as the highest water using phase in the coal-fuel chain, with the combustion phase and FGD system using about 31% and 22%,

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respectively of the coal-fuel cycle water requirements. Water use in the coal mining phase was also found to be high (37%), making the coal-fuel cycle a large yet hidden water user. Another important outcome from the inventory output is that the coal mining phase was found to be more prone to injuries than deaths whereas the plant operation phase was found to be more prone to deaths than injuries. Human safety is therefore a serious problem in these two phases. Concerning air pollution loads, CO_2e emissions were estimated at about 1 583 million tons over the coal-fuel cycle and lifetime of Kusile, with low SO_2 emissions due to the installation of the FGD system. Over 85% of the air pollutants emanated from the combustion phase.

- Concerning the externalities - the model estimated the total coal-fuel cycle externality cost over the lifetime of Kusile to range between R1 450 billion – R3 379 billion (baseline R2 173 billion) or between 91c/kWh – 205c/kWh sent out (baseline 136c/kWh). Specifically, 49c/kWh - 107c/kWh (baseline 72c/kWh) is attributable to the power plant and waste disposal phases, 24c/kWh - 61c/kWh (baseline 37c/kWh) is linked with coal mining and transportation while the FGD system and plant construction contribute 14c/kWh - 28c/kWh (baseline 21c/kWh) and 4c/kWh - 9c/kWh (baseline 6c/kWh), respectively. Most of the externality cost stems from three types of externalities, namely water use, air pollution health cost and global warming damages, in descending order, and from three coal-fuel cycle phases, namely plant operation, coal mining and transportation and FGD system, in descending order. The externality cost generated by the model when converted to US cents/kWh it ranges between 12c/kWh - 28c/kWh with the base case at 19c/kWh, so it falls within the range of the international studies reported on Table 4.3 and the local studies in in Table 4.5, but is slightly higher than those that study the entire coal-fuel chain owing to the inclusion of more externalities and coal-fuel cycle phases.

- The social cost analysis unveiled that about two-thirds to three-quarters of the true cost of coal-based electricity is not reflected in the balance sheet of the utility but is borne by society. Accounting for the life-cycle burdens of coal-derived electricity thus conservatively doubles to triples the price of electricity, making renewable energy sources like wind and solar attractive.

- With regard to policy evaluation (i.e. carbon tax policy and the pricing of domestic coal at export parity price levels) – owing to the amount of coal exposed to export competition (25%), the total generation cost and consequently the LCOE was found to be fairly responsive to the export coal price regimes (+/-7%). Coal-based power production was still found to be a viable enterprise under the export parity price regimes. Conversely, the total generation cost of coal-based power was found to be moderately to severely impacted by the carbon tax regimes (+/-39%), depending on the rate at which they were grown (10%, 5% or 0.1%). Enforcing any of the studied carbon tax regimes at 5% or 0.1% to only about one third of the GHGs emissions, would still make coal-based

power generation a viable enterprise, while tax escalation at 10% would profoundly worsen the financial viability of coal-based power, quickly making renewable energy (especially wind energy) cost-competitive with coal-based power. In the event that both policies are faced simultaneously by power utilities, coal-based power will become even more costly further encouraging market penetration of cleaner sources of energy. Carbon taxation as a policy instrument to mitigate climate change will therefore bring great market penetration of clean technologies in the near future if carefully planned and implemented.

On another note, the power plant externality costs of the entire GHG emissions (100%) were also computed using the unit damage costs of CO_2 listed in Table 7.20 (i.e. based on Blignaut, 2012) grown at 0.1% and based on the resultant GHG emissions externality costs, carbon tax scenarios (listed in Table 7.23) were explored that recouped the various costs. The findings: (i) suggested that regardless of the carbon tax regimes the growth rate of the carbon tax regimes need to be carefully selected since it greatly alters the resultant payable GHG externality cost or government revenues, which negatively affect the financial viability of coal-based power plants; (ii) disclosed that growing any of the carbon tax regimes at 10% nullify the fact that coal-power plants pay for only 30% of their GHG emissions; and (iii) further suggested that the carbon tax should at most be preferably lower than R150/ton of CO_2 and be grown at a growth rate lower than 5%, or else coal-based power plants pay way above 100% of their GHG emissions.

8.2   COALPSCA Model limitations

The COALPSCA Model, while it attempted to incorporate most of the important aspects of power generation in a coal-fired power plant and its links with economic, social and environmental issues, it does not capture all the intrinsic aspects. The limitations of the model include:

- The exclusions of important burdens due to lack of data, such as fatalities and injuries linked with plant construction, water pollution linked with the power plant and FGD system, noise pollution and damages to roads;
- The exclusion of some burdens due to the anticipated and unnecessary complications they could pose, such as ecosystem services lost upstream of the power plant though not including those linked with the coal mine (e.g. ecosystem services lost due to resource requirements for building and operating the plant);

- The exclusion of the influence of electricity demand on plant investment (i.e. investment in plant capacity was exogenously modelled), due to the limited scope of the model, i.e. model focused on a single plant;

- Inflating damage cost values to the base year of this study (2010) using the consumer price index, which likely underestimated the costs, for instance, the inflation of medical costs likely exceeds that of the normal basket; and lastly,

- While a concerted effort was made to solicit and use South African based data in computing most of the externality costs, for placing value on air pollution related human health effects, used were damage cost estimates from international studies which were adjusted for income differences, inflation and currency exchange to the South African context. Moreover, there are limitations of adjusting and transferring externality costs from secondary data, such as carrying forward errors from previous studies (i.e. judgment and potential bias). Conducting primary research on the externalities studied in this study was mostly, however, impossible due to that the power plant and the coal mine are under construction. This was mitigated by using mainly published literature and focusing on a range of externality cost estimates, instead of point estimates.

8.3   What could be done to improve the COALPSCA Model and energy research

In spite of these limitations, the model does indeed provide a reasonable, simplified demonstration of the employment of a system dynamics approach to the assessment of electricity generation, resource/material inputs, externalities and the social cost associated with a coal-based power plant over its lifetime and fuel cycle, in a transparent manner. In addition, it provides - (i) coal-based power developers with a useful tool for detecting the main drivers of burdens and costs in the system, which should yield vital socio-economic-ecological tradeoff information; and (ii) energy decision makers with a tool for making informed energy supply decisions that consider not only the financial feasibility of power-generation technologies, but also the socio-environmental consequences of the technologies.

What could have been more interesting to inform the energy supply debate, would have been to conduct similar social cost assessments for renewable energy technologies, for instance, wind and solar, as initially planned in the conception days of this research and comparing them to the outcomes of this study. However, time and financial restraints did not allow for such to be conducted in this research. The development of similar social cost assessment models for alternative energy sources, both renewables and non-renewables, is therefore recommended, because all power generation alternatives are associated with varying socio-economic-environmental effects and private costs. In this regard, social cost assessment may help with capacity expansion decisions because of its ability to evaluate the trade-offs of electricity

generation alternatives. It will moreover limit the politicization of capacity expansion plans, by encouraging energy planners to be transparent about their assumptions, which will likely stimulate public debate among various stakeholder groups and possibly shape future capacity expansion decisions based on a broader consensus.

Future research on externalities of energy technologies can also be improved by practically verifying the growth rate of the damage cost of various externality burdens through conducting surveys which solicit the various damage costs over some period of time. Another issue that can be explored in future works, is conducting primary research in the South African context of air pollution impacts on human health. Such an in-depth research could be a lengthy process, owing to the necessity of understanding the dispersion of pollutants, their ultimate deposition and the responsiveness of humans to various doses of pollution. In addition, placing a value on human-health-impairment/loss-of-a-human-life might prove difficult as respondents could lack the knowledge of fully understanding what is being valued.

The COALPSCA Model was built for a single Eskom power plant, namely Kusile power station, and it therefore excluded all of Eskom's coal-based power plants or coal-fired power plants in South Africa. There is thus the possibility of customizing the COALPSCA Model for the entire country through considering the specificity of other coal plants, thereby enabling the assessment of the social cost of coal-based power production in South Africa. Customizing the model to incorporate all of the country's power plants will also – (i) enable the exploration of the private and externality costs of retrofitting Eskom's/the-country's coal-fired power plants with FGD systems; and (ii) how doing so will affect coal-based power's attractiveness and, most importantly, (iii) implications of the retrofits on water consumption. In addition, customizing the model will also facilitate an evaluation of the factual country-level implications of coal-based power utilities' exposure to carbon taxation and export parity coal price levels.

8.4   Way forward for the South African government

The harshest way forward for the South African government in its address of the serious impacts of coal-based electricity generation, would be to reform the pricing system for coal-based electricity in the country such that all the externality costs are properly reflected in the price. Doing so, will however, result in serious socio-economic consequences, so the government needs to be strategic in its externality internalization approach in order to minimize the socio-economic impacts, say by focusing its attention on the main burdens in the coal-fuel chain such as water use, air pollution human health effects and climate change effects due to GHG emissions, as revealed by the COAPSCA model.

Since the analysis conducted in this work unveils that most of the externality cost in the coal-fuel chain is linked with water use (over 65%), lowering the water consumption of existing and new power plants and coal mines, necessitates policy changes at both the local and national levels, which will force these dominant water users to reduce their water consumption to minimal levels, using existing and affordable technology. Existing power plants in the country, for instance, mostly uses wet-recirculating cooling system, so existing plants can be required to upgrade to dry cooling systems over some sensible time period. By doing so, the price of power will rise to mirror the costs of retrofits, which will make less water demanding power generation sources more competitive. Alternatively, the South African government may directly internalize the externality cost of water use for all water users in the country through pricing water well. This will necessitate estimating the opportunity cost of water use for a number of industries/water-users, which in the most part has been done for a number of dominant water users, so what the government need to do is to take these studies serious, and do what is necessary to channel water use to efficient uses.

Concerning air pollution human health effects, which is the second largest externality in the coal-fuel chain (over 21%) and which is mainly associated with the power plant – the government can take action by requiring retrofits of all existing plants with FGD device over some reasonable period of time, and as well as requiring new plants to be fitted with this device. The ideal device should preferably be dry FGD in order to minimize water consumption. Such retrofits will not only safeguard human health but will assist in reinstating the balance between clean and dirty power generation sources, and will encourage eventual transformation of the existing fleet of dirty power stations to extensively more sustainable power technologies.

With regards to the third largest externality cost in the coal fuel chain, namely climate change effects due to GHG emissions (over 11%) – the South African government has taken action and intends to internalize the externality cost of carbon emissions on producers of GHGs beginning 2015, through a carbon tax of R120/ton of CO_2e emissions. As explained in the policy evaluation section, companies will not pay for the entire GHGs they emit, so the effectiveness of this tax in internalizing the externality cost of carbon emissions will depend on how low the tax-free thresholds are and the rate at which the tax will be grown. The analysis conducted in this study disclosed that enforcing any of the studied carbon tax regimes at 5% or 0.1% to only about one third of the GHGs emissions, would still make coal-based power generation a viable enterprise, while tax escalation at 10% would profoundly worsen the financial viability of coal-based power, and encourage market penetration of cleaner sources of energy. At the 10% tax growth rate, renewable energy (especially wind energy) quickly becomes cost-competitive with coal-based power. Carbon taxation

as a policy instrument to mitigate climate change will therefore bring great market penetration of clean technologies in the near future if carefully planned and implemented.

Lastly, though accounting for the life-cycle burdens of coal-based electricity generation was found to double to triple the price of electricity, making non-fossil fuel sources such as wind energy attractive, all electricity generation technologies are accompanied by undesirable side-effects at some point in their fuel cycles, so comparative analyses of life-cycle social costs of all power generation sources in South Africa are necessary to offer guidance to future energy policy development.

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APPENDICES

Appendix A: COALPSCA Model equations

A1: Power generation sub-model equations

1-Internal consumption rate=Conversion factor-Fraction of electricity consumed internally
Units: Dmnl

Capacity construction start=Capacity investment/Unit capital cost
Units: MW/Year

Capacity investment=(Planned investment in plant capacity table(Time))*Unit capital cost
Units: R/Year

Coal consumption=(((Gross electricity production*MWh to kWh)*Heat rate)/Coal energy content)/kg to ton
Units: ton/Year

Coal energy content=19.22
Units: MJ/kg

Conversion factor=1
Units: Dmnl

Cumulative gross electricity production=INTEG (Gross electricity production, 0)
Units: MWh

Cumulative net electricity production=INTEG (Net electricity production, 0)
Units: MWh

Days per year=365
Units: Day/Year

Desired functional capacity after construction=IF THEN ELSE(Time<=2015,0,Plant capacity during and after construction as planned*Effect of profitability on desired functional capacity)
Units: MW

Effect of profitability on desired functional capacity=IF THEN ELSE(Time<=2015,0,Function for effect of profitability on desired functional capacity(Expected profitability))
Units: Dmnl

Energy availability factor=0.94
Units: Dmnl

Expected profitability= INTEG (Change in expected profitability, 0)
Units: Dmnl

FINAL TIME=2060
Units: Year

Fraction of electricity consumed internally=0.075
Units: Dmnl

Function for effect of profitability on desired functional capacity ([(-30,0)-(1,1.6)],(-30,0),(-0.75,0),(-0.5,0),(-0.25,0),(0,0.75),(0.25,0.878),(0.5,0.987),(0.75,1.061),(1,1.091))
Units: Dmnl

Functional capacity during construction=IF THEN ELSE(Time<=2015,Plant capacity during and after construction as planned, 0)
Units: MW

Gross electricity production=(((Functional capacity during construction*Plant operating hours)+(Desired functional capacity after construction*Plant operating hours))*Load factor)*MWh/MW*h
Units: MWh/Year

Heat rate=9.769
Units: MJ/kWh

Hours per day=24
Units: h/Day

INITIAL TIME=2010
       Units: Year

kg to ton=1000
Units: kg/ton

Load factor=0.9
Units: Dmnl

MWh to kWh=1000
Units: kWh/MWh

MWh/MW*h=1
Units: MWh/(MW*h)

Net electricity production=Gross electricity production*1-Internal consumption rate
Units: MWh/Year

New capacity=IF THEN ELSE(Time<=2014,Plant capacity construction/Plant construction time, 0)
Units: MW/Year

Planned investment in plant capacity table ([(2010,0)-(2060,2000)],(2010,800),(2011,800),(2012,800),(2013,800),(2014,1600),(2015,0),(2016,0),(2017,0),(2018,0),(2019,0),(2020,0),(2021,0),(2022,0),(2023,0),(2024,0),(2025,0),(2026,0),(2027,0),(2028,0),(2029,0),(2030,0),(2031,0),(2032,0),(2033,0),(2034,0),(2035,0),(2036,0),(2037,0),(2038,0),(2039,0),(2040,0),(2041,0),(2042,0),(2043,0),(2044,0),(2045,0),(2046,0),(2047,0),(2048,0),(2049,0),(2050,0),(2051,0),(2052,0),(2053,0),(2054,0),(2055,0),(2056,0),(2057,0),(2058,0),(2059,0),(2060,0))
Units: MW/Year

Plant capacity construction= INTEG (Capacity construction start-New capacity, 800)
Units: MW

Plant capacity during and after construction as planned= INTEG (New capacity, 800)
Units: MW

Plant construction time=1
Units: Year

Plant operating hours=Days per year*Hours per day*Energy availability factor
Units: h/Year

Unit capital cost= INTEG (Change in capital cost, Capital cost/Plant size)
Units: R/MW

A2: Generation cost sub-model equations

Capacity investment=(Planned investment in plant capacity table(Time))*Unit capital cost
Units: R/Year

Capital cost=1.185e+011
Units: R

Capital cost escalation table ([(2010,0)-(2060,0.002)],(2010,0.001),(2011,0.001),(2012,0.001),(2013,0.001),(2014,0.001),(2015,0),(2016,0),(2017,0),(2018,0),(2019,0),(2020,0),(2021,0),(2022,0),(2023,0),(2024,0),(2025,0),(2026,0),(2027,0),(2028,0),(2029,0),(2030,0),(2031,0),(2032,0),(2033,0),(2034,0),(2035,0),(2036,0),(2037,0),(2038,0),(2039,0),(2040,0),(2041,0),(2042,0),(2043,0),(2044,0),(2045,0),(2046,0),(2047,0),(2048,0),(2049,0),(2050,0),(2051,0),(2052,0),(2053,0),(2054,0),(2055,0),(2056,0),(2057,0),(2058,0),(2059,0),(2060,0))
Units: Dmnl/Year

Capital investment rate=Capacity investment
Units: R/Year

Change in capital cost=(Capital cost escalation table(Time))*Unit capital cost
Units: R/MW/Year

Change in coal cost=Unit coal cost*Coal cost escalation
Units: (R/ton/Year)

Change in limestone cost=Unit limestone cost*Limestone cost escalation
Units: (R/ton/Year)

Change in other FGD O&M cost=Other FGD O&M costs*Other O&M costs escalation
Units: R/Year

Change in other variable O&M costs=Other variable O&M costs*Other O&M costs escalation
Units: (R/Year)

Change in transport cost=Unit transport cost*Transport cost escalation

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Units: (R/ton/km/Year)

Change in water cost=Unit water cost*Water cost escalation
Units: (R/m3/Year)

Coal consumption=(((Gross electricity production*MWh to kWh)*Heat rate)/Coal energy content)/kg to ton
Units: ton/Year

Coal cost=Coal consumption*Unit coal cost
Units: R/Year

Coal cost escalation=0.001
Units: Dmnl/Year

Conversion factor=1
Units: Dmnl

Cumulative capital cost escalated=INTEG (capital investment rate, 0)
Units: R

Cumulative PV FGD operation cost=INTEG (PV FGD operation cost, 0)
Units: R

Cumulative PV fixed O&M costs=INTEG (PV fixed O&M costs, 0)
Units: R

Cumulative PV fuel cost=INTEG (PV fuel cost, 0)
Units: R

Cumulative PV net electrity production=INTEG (PV net electricity production, 1)
Units: MWh

Cumulative PV variable O&M costs=INTEG (PV variable O&M costs, 0)
Units: R

Discount rate=0.08
Units: Dmnl

FGD operation cost=FGD water cost+Limestone cost+Other FGD O&M costs year
Units: R/Year

FGD water consumption=FGD water consumption per MWh*Gross electricity production
Units: m3/Year

FGD water consumption per MWh=0.145
Units: m3/MWh

FGD water cost=FGD water consumption*Unit water cost
Units: R/Year

FINAL TIME=2060

Units: Year

Fixed O&M cost escalation=0.001
Units: Dmnl/Year

Fixed O&M costs year=Fixed O&M costs/Year
Units: R/Year

Fixed O&M costs=INTEG (PV fixed O&M cost, 8.93e+008)
Units: R

Gross electricity production=(((Functional capacity during construction*Plant operating hours)+(Desired functional capacity after construction*Plant operating hours))*Load factor)*MWh/MW*h
Units: MWh/Year

INITIAL TIME=2010
Units: Year

Levelised capital cost=Cumulative capital cost escalated/Cumulative PV net electrity production
Units: R/MWh

Levelised cost of energy=Levelised fuel cost+Levelised O&M costs+Levelised FGD operaton cost+Levelised capital cost
Units: R/MWh

Levelised FGD operaton cost=Cumulative PV FGD operation cost/Cumulative PV net electrity production
Units: R/MWh

Levelised fixed O&M costs=Cumulative PV fixed O&M costs/Cumulative PV net electrity production
Units: R/MWh

Levelised fuel cost=Cumulative PV fuel cost/Cumulative PV net electrity production
Units: R/MWh

Levelised O&M costs=Levelised variable O&M costs+Levelised fixed O&M costs
Units: R/MWh

Levelised variable O&M costs=Cumulative PV variable O&M costs/Cumulative PV net electrity production
Units: R/MWh

Limestone consumption=Limestone consumption per hour*Plant operating hours
Units: ton/Year

Limestone consumption cost=Limestone consumption*Unit limestone cost
Units: R/Year

Limestone consumption per hour=70
Units: ton/h

Limestone cost=Limestone consumption cost
Units: R/Year

Limestone cost escalation=0.001
Units: Dmnl/Year

Limestone transport cost=Unit transport cost*Limestone transportation distance*Limestone consumption
Units: R/Year

Limestone transportation distance=120
Units: km

Net electricity production=Gross electricity production*1-Internal consumption rate
Units: MWh/Year

Other FGD O&M costs year=Other FGD O&M costs/Year
Units: R/Year

Other FGD O&M cost= INTEG (Change in other FGD O&M cost, 1.705e+008)
Units: R

Other O&M costs escalation=0.001
Units: Dmnl/Year

Other variable O&M costs year=Other variable O&M costs/Year
Units: R/Year

Other variable O&M costs= INTEG (Change in other variable O&M costs, 7.26e+008)
Units: R

Overnight cost=Capital cost/Plant size
Units: R/MW

Planned investment in plant capacity table ([(2010,0)-(2060,2000)],(2010,800),(2011,800),(2012,800),(2013,800),(2014,1600),(2015,0),(2016,0),(2017,0),(2018,0),(2019,0),(2020,0),(2021,0),(2022,0),(2023,0),(2024,0),(2025,0),(2026,0),(2027,0),(2028,0),(2029,0),(2030,0),(2031,0),(2032,0),(2033,0),(2034,0),(2035,0),(2036,0),(2037,0),(2038,0),(2039,0),(2040,0),(2041,0),(2042,0),(2043,0),(2044,0),(2045,0),(2046,0),(2047,0),(2048,0),(2049,0),(2050,0),(2051,0),(2052,0),(2053,0),(2054,0),(2055,0),(2056,0),(2057,0),(2058,0),(2059,0),(2060,0))
Units: MW/Year

Plant operating hours=Days per year*Hours per day*Energy availability factor
Units: h/Year

Plant size=4800
Units: MW

Plant water consumption=Plant water consumption per MWh*Gross electricity production
Units: m3/Year

Plant water consumption per MWh=0.2
Units: m3/MWh

Plant water cost=Plant water consumption*Unit water cost
Units: R/Year

Present value factor=((Conversion factor+Discount rate)^Year of cost(Time))
Units: Dmnl

PV FGD operation cost=FGD operation cost/Present value factor
Units: R/Year

PV fixed O&M cost=Fixed O&M costs*Fixed O&M cost escalation
Units: R/Year

PV fixed O&M costs=Fixed O&M costs year/Present value factor
Units: R/Year

PV fuel cost=Coal cost/Present value factor
Units: R/Year

PV net electricity production=Net electricity production/Present value factor
Units: MWh/Year

PV variable O&M costs=Variable O&M costs/Present value factor
Units: R/Year

Transport cost escalation=0.001
Units: Dmnl/Year

Unit capital cost=INTEG (Change in capital cost, Capital cost/Plant size)
Units: R/MW

Unit coal cost=INTEG (Change in coal cost, 210)
Units: R/ton

Unit limestone cost=INTEG (Change in limestone cost, 335)
Units: R/ton

Unit transport cost=INTEG (Change in transport cost, 1.22)
Units: R/ton/km

Unit water cost=INTEG (Change in water cost, 0.7)
Units: R/m3

Variable O&M costs=Plant water cost+Other variable O&M costs year
Units: R/Year

Water cost escalation=0.001
Units: Dmnl/Year

Year=1
Units: Year

Year of cost ([(2010,0)-(2060,60)],(2010,1),(2011,2),(2012,3),(2013,4),(2014,5),(2015,6),(2016,7),(2017,8),(2018,9),(2019,10),(2020,11),(2021,12),(2022,13),(2023,14),(2024,15),(2025,16),(2026,17),(2027,18),(2028,19),(2029,20),(2030,21),(2031,22),(2032,23),(2033,24),(2034,25),(2035,26),(2036,27),(2037,28),(2038,29),(2039,30),(2040,31),(2041,32),(2042,33),(2043,34),(2044,35),(2045,36),(2046,37),(2047,38),(2048,39),(2049,40),(2050,41),(2051,42),(2052,43),(2053,44),(2054,45),(2055,46),(2056,47),(2057,48),(2058,49),(2059,50),(2060,51))
Units: Dmnl

A3: Morbidity and fatalities sub-model equations

Al=Al per MW*Capacity construction start
Units: ton/Year

Al in million tons=Al/Tons to million tons
Units: million tons/Year

Change in morbidity value=Unit morbidity value*Escalation of damage cost
Units: R/person/Year

Change in mortality value=Unit mortality value*Escalation of damage cost
Units: R/person/Year

Coal consumption=(((Gross electricity production*MWh to kWh)*Heat rate)/Coal energy content)/kg to ton
Units: ton/Year

Coal consumption in million tons=Coal consumption/Tons to million tons
Units: million tons/Year

Coal-fuel cycle fatalities & morbidity costs=Fatalities & morbidity costs (coal mining)+Fatalities & morbidity costs (construction)+Fatalities & morbidity costs (power generation)
Units: R/Year

Concrete=Concrete per MW*Capacity construction start
Units: ton/Year

Concrete in million tons=Concrete/Tons to million tons
Units: million tons/Year

Deaths from coal mining=Fatalities per million tons of coal mined*Coal consumption in million tons
Units: person/Year

Deaths limestone production=Fatalities per million tons of limestone*Limestone in million tons
Units: person/Year

Deaths material inputs production=(Fatalities per million tons of Al*Al in million tons)+(Fatalities per million tons of concrete*Concrete in million tons)+(Fatalities per million tons of steel*Steel in million tons)
Units: person/Year

Deaths power generation=Fatalities per MWh*Gross electricity production
Units: person/Year

Escalation of damage cost=0.011
Units: Dmnl/Year

Fatalities & morbidity costs (coal mining)=Fatalities cost (coal mining)+Morbidity cost (coal mining)
Units: R/Year

Fatalities & morbidity costs (construction)=Fatality cost due to material inputs production+Morbidity cost due to material inputs production
Units: R/Year

Fatalities & morbidity costs (power generation)=Fatalities & mortality costs limestone production (FGD)+Fatality cost power generation+Morbidity cost power generation
Units: R/Year

Fatalities & mortality costs limestone production (FGD)=Fatality cost due to limestone production+Morbidity cost due to limestone production
Units: R/Year

Fatalities cost (coal mining)=Deaths from coal mining*Unit mortality value
Units: R/Year

Fatalities per million tons of Al= 3.17428
Units: persons/million tons

Fatalities per million tons of coal mined=0.056
Units: person/million tons

Fatalities per million tons of concrete=0.159
Units: person/million tons

Fatalities per million tons of limestone= 0.290698
Units: person/million tons

Fatalities per million tons of steel=0.321374
Units: person/million tons

Fatalities per MWh=2.6e-007
Units: person/MWh

Fatality cost due to limestone production=Deaths limestone production*Unit mortality value
Units: R/Year

Fatality cost due to material inputs production= Deaths material inputs production*Unit mortality value
Units: R/Year

Fatality cost power generation=Deaths power generation*Unit mortality value
Units: R/Year

FINAL TIME=2060
Units: Year

Gross electricity production=(((Functional capacity during construction*Plant operating hours)+(Desired functional capacity after construction*Plant operating hours))*Load factor)*"MWh/MW*h"
Units: MWh/Year

INITIAL TIME=2010
Units: Year

Injuries from coal mining=Injuries per million tons of coal mined*Coal consumption in million tons
Units: person/Year

Injuries limestone production=Injuries per million tons of limestone*Limestone in million tons
Units: person/Year

Injuries material inputs production=(Injuries per million tons of Al*Al in million tons)+(Injuries per million tons of concrete*Concrete in million tons)+(Injuries per million tons of steel*Steel in million tons)
Units: person/Year

Injuries per million tons of Al=19.9114
Units: person/million tons

Injuries per million tons of coal mined= 0.823
Units: person/million tons

Injuries per million tons of concrete=0.995
Units: person/million tons

Injuries per million tons of limestone=1.33721
Units: person/million tons

Injuries per million tons of steel=2.01589
Units: person/million tons

Injuries power generation=Injury rate per MWh*Gross electricity production
Units: person/Year

Injury rate per MWh=1e-007
Units: person/MWh

Limestone consumption=Limestone consumption per hour*Plant operating hours
Units: ton/Year

Limestone in million tons=Limestone consumption/Tons to million tons
Units: million tons/Year

Morbidity cost (coal mining)=Injuries from coal mining*Unit morbidity value
Units: R/Year

Morbidity cost due to limestone production=Injuries limestone production*Unit morbidity value
Units: R/Year

Morbidity cost due to material inputs production=Injuries material inputs production*Unit morbidity value
Units: R/Year

Morbidity cost power generation=Injuries power generation*Unit morbidity value
Units: R/Year

Steel=Steel per MW*Capacity construction start
Units: ton/Year

Steel in million tons=Steel/Tons to million tons
Units: million tons/Year

Tons to million tons=1e+006
Units: ton/million tons

Unit morbidity value=INTEG (Change in morbidity value, 25434)
Units: R/person

Unit mortality value= INTEG (Change in mortality value, 245438)
Units: R/person

A4: Water consumption sub-model equations

Al=Al per MW*Capacity construction start
Units: ton/Year

Al embodied water=8.8e-005
Units: m3/ton

Ash produced per ton of coal burnt=0.293
Units: ton/ton

Change in the opportunity cost of water use=Unit opportunity cost of water use*Escalation of damage cost
Units: R/m3/Year

Coal consumption=(((Gross electricity production*MWh to kWh)*Heat rate)/Coal energy content)/kg to ton
Units: ton/Year

Coal-fuel cycle externality cost of water use=Opportunity cost of water use (construction)+Opportunity cost of water use (power generation)+Opportunity cost of water use in disposing Kusile's waste+Opportunity cost of water use in FGD+Opportunity cost of water use in the New Largo colliery (coal mining)
Units: R/Year

Concrete=Concrete per MW*Capacity construction start
Units: ton/Year

Concrete embodied water=26.352
Units: m3/ton

Dry waste Kusile=Ash produced per ton of coal burnt*Coal consumption
Units: ton/Year

Escalation of damage cost=0.011
Units: Dmnl/Year

Factor curbing construction ([(2010,0)-(2060,1)],(2010,1),(2011,1),(2012,1),(2013,1),(2014,1),(2015,0),(2016,0),(2017,0),(2018,0),(2019,0),(2020,0),(2021,0),(2022,0),(2023,0),(2024,0),(2025,0),(2026,0),(2027,0),(2028,0),(2029,0),(2030,0),(2031,0),(2032,0),(2033,0),(2034,0),(2035,0),(2036,0),(2037,0),(2038,0),(2039,0),(2040,0),(2041,0),(2042,0),(2043,0),(2044,0),(2045,0),(2046,0),(2047,0),(2048,0),(2049,0),(2050,0),(2051,0),(2052,0),(2053,0),(2054,0),(2055,0),(2056,0),(2057,0),(2058,0),(2059,0),(2060,0))
Units: Dmnl

FGD water consumption=FGD water consumption per MWh*Gross electricity production
Units: m3/Year

FINAL TIME=2060
Units: Year

INITIAL TIME=2010
Units: Year

Litres to m3=1000
Units: l/m3

Opportunity cost of water use (construction)=Opportunity cost of water use in producing material inputs of constructing Kusile+Opportunity cost of water use in constructing Kusile
Units: R/Year

Opportunity cost of water use (power generation)=Unit opportunity cost of water use*Plant water consumption
Units: R/Year

Opportunity cost of water use in constructing Kusile=Unit opportunity cost of water use*Water requirements of constructing Kusile (curbed)
Units: R/Year

Opportunity cost of water use in disposing Kusile's waste=Unit opportunity cost of water use*Water usage in disposing waste
Units: R/Year

Opportunity cost of water use in FGD=Unit opportunity cost of water use*FGD water consumption
Units: R/Year

Opportunity cost of water use in producing material inputs of constructing Kusile=Unit opportunity cost of water use*Water requirements of construction materials
Units: R/Year

Opportunity cost of water use in the New Largo colliery (coal mining)=Unit opportunity cost of water use*Water requirements of a surface mine
Units: R/Year

Plant water consumption=Plant water consumption per MWh*Gross electricity production
Units: m3/Year

Steel=Steel per MW*Capacity construction start
Units: ton/Year

Steel embodied water=225
Units: m3/ton

Unit opportunity cost of water use=INTEG (Change in the opportunity cost of water use, 1001)
Units: R/m3

Water requirements of a surface mine=Water requirements of a surface mine (in m3/ton)*Coal consumption
Units: m3/Year

Water requirements of a surface mine (in litres/ton)=469
Units: l/ton

Water requirements of a surface mine (in m3/ton)=Water requirements of a surface mine (in litres/ton)/Litres to m3
Units: m3/ton

Water requirements of constructing Kusile=4.12392e+006
Units: m3/Year

Water requirements of constructing Kusile (curbed)=(Water requirements of constructing Kusile*Factor curbing construction(Time))
Units: m3/Year

Water requirements of construction materials=Water usage Al+Water usage concrete+Water usage steel
Units: m3/Year

Water usage Al=Al embodied water*Al
Units: m3/Year

Water usage concrete=Concrete embodied water*Concrete
Units: m3/Year

Water usage in disposing waste=Water usage per ton of solid waste disposed*Dry waste Kusile
Units: m3/Year

Water usage per ton of solid waste disposed=0.076
Units: m3/ton

Water usage steel=Steel embodied water*Steel
Units: m3/Year

A5: Water pollution sub-model equations

Al=Al per MW*Capacity construction start

Units: ton/Year

Change in damage cost of sulphate pollution (Al & concrete production) =Unit damage cost of sulphate pollution from Al & concrete production*Escalation of damage cost
Units: R/ton/Year

Change in damage cost of sulphate pollution (coal mining)=Unit damage cost of sulphate pollution from coal mining*Escalation of damage cost
Units: R/ton/Year

Change in damage cost of sulphate pollution (steel production)= Unit damage cost of sulphate pollution from steel production*Escalation of damage cost
Units: R/ton/Year

Coal consumption=(((Gross electricity production*MWh to kWh)*Heat rate)/Coal energy content)/kg to ton
Units: ton/Year

Coal-fuel cycle water pollution externality cost=Damage cost of sulphate pollution from coal mining+Damage cost of sulphate pollution from Kusiles' raw material requirements
Units: R/Year

Concrete=Concrete per MW*Capacity construction start
Units: ton/Year

Damage cost of sulphate pollution from Al & cement production=(Unit damage cost of sulphate pollution from Al & concrete production*Al)+(Unit damage cost of sulphate pollution from Al & concrete production*Concrete)
Units: R/Year

Damage cost of sulphate pollution from coal mining=Unit damage cost of sulphate pollution from coal mining*Coal consumption
Units: R/Year

Damage cost of sulphate pollution from Kusiles' raw material requirements=Damage cost of sulphate pollution from Al & cement production+Damage cost of sulphate pollution from steel production
Units: R/Year

Damage cost of sulphate pollution from steel production=Unit damage cost of sulphate pollution from steel production*Steel
Units: R/Year

Escalation of damage cost=0.011
Units: Dmnl/Year

FINAL TIME=2060
Units: Year

INITIAL TIME=2010
Units: Year

Steel=Steel per MW*Capacity construction start

Units: ton/Year

Unit damage cost of sulphate pollution from Al & concrete production=INTEG (Change in damage cost of sulphate pollution (Al & concrete production), 0.31)
Units: R/ton

Unit damage cost of sulphate pollution from coal mining=INTEG (Change in damage cost of sulphate pollution (coal mining), 0.27)
Units: R/ton

Unit damage cost of sulphate pollution from steel production=INTEG (Change in damage cost of sulphate pollution (steel production), 0.79)
Units: R/ton

A6: Ecosystem services loss sub-model equations

Change in maize price=Unit maize price*Escalation of damage cost
Units: R/ton/Year

Change in the value of ecosystem goods & services=Unit value of ecosystem goods & services generated by grasslands*Escalation of damage cost
Units: R/ha/Year

Coal-fuel cycle cost of lost ecosystem services=Ecosystem services lost due to coal mining+"Ecosystem services lost due to plant construction & operation"
Units: R/Year

Ecosystem services lost due to coal mining=Forgone benefit from grasslands due to coal mining+Forgone benefit from maize cultivation due to coal mining
Units: R/Year

Ecosystem services lost due to plant construction & operation=Forgone benefit from grasslands due to building and operating plant+Forgone benefit from maize cultivation due to building and operating plant
Units: R/Year

Escalation of damage cost=0.011
Units: Dmnl/Year

FINAL TIME=2060
Units: Year

Forgone benefit from grasslands due to building and operating plant=Power plant area under grazing*Unit value of ecosystem goods & services generated by grasslands
Units: R/Year

Forgone benefit from grasslands due to coal mining=Mining area under grazing/grasslands*Unit value of ecosystem goods & services generated by grasslands
Units: R/Year

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Forgone benefit from maize cultivation due to building and operating plant=(Maize production (dry land)*Unit maize price)+(Maize production (irrigated land)*Unit maize price)
Units: R/Year

Forgone benefit from maize cultivation due to coal mining=Maize production*Unit maize price
Units: R/Year

INITIAL TIME=2010
Units: Year

Maize production=Mining area under maize production*Maize yield per hectare
Units: ton/Year

Maize production (dry land)=Power plant area under dry land maize production*Maize yield per hectare (dry land)
Units: ton/Year

Maize production (irrigated land)=Power plant area under irrigated maize production*Maize yield per hectare (irrigated land)
Units: ton/Year

Maize yield per hectare=10
Units: ton/ha

Maize yield per hectare (dry land)=4.25
Units: ton/ha

Maize yield per hectare (irrigated land)=10
Units: ton/ha

Mining area under grazing/grasslands=2045.1
Units: ha/Year

Mining area under maize production=4771.9
Units: ha/Year

Power plant area under dry land maize production=1404
Units: ha/Year

Power plant area under grazing=3744
Units: ha/Year

Power plant area under irrigated maize production=52
Units: ha/Year

Unit maize price=INTEG (Change in maize price, 1600)
Units: R/ton

Unit value of ecosystem goods & services generated by grasslands=INTEG (Change in the value of ecosystem goods & services, 510)
Units: R/ha

A7: Air pollution sub-model equations

Arsenic content in coal=2.95
Units: mg/kg

Arsenic damages=Coal combustion arsenic & compounds emissions*Unit damage cost arsenic
Units: R/Year

Arsenic emission factor in kg/PJ=Constant arsenic*(((Arsenic content in coal/Weight fraction of ash in coal)*PM emitted per GJ heat input)*GJ to PJ/mg to kg)^(Exponent arsenic)
Units: kg/PJ

Change in damage cost of nickel=Unit damage cost nickel*Escalation of damage cost
Units: R/ton/Year

Change in damage cost per ton of arsenic=Unit damage cost arsenic*Escalation of damage cost
Units: R/ton/Year

Change in damage cost per ton of chromium=Unit damage cost chromium*Escalation of damage cost
Units: R/ton/Year

Change in damage cost per ton of lead=Unit damage cost lead*Escalation of damage cost
Units: R/ton/Year

Change in NOx damage cost=Unit damage cost NOx*Escalation of damage cost
Units: R/ton/Year

Change in PM damage cost=Unit damage cost PM*Escalation of damage cost
Units: R/ton/Year

Change in SO2 damage cost=Unit damage cost SO2*Escalation of damage cost
Units: R/ton/Year

Chromium content in coal=57.02
Units: mg/kg

Chromium damages=Coal combustion chromium & compounds emissions*Unit damage cost chromium
Units: R/Year

Chromium emission factor in kg/PJ=Constant chromium*(((Chromium content in coal/Weight fraction of ash in coal)*PM emitted per GJ heat input)*GJ to PJ/mg to kg)^(Exponent chromium)
Units: kg/PJ

Coal combustion air pollution health damages=Coal combustion NOx damages+Coal combustion PM damages+Coal combustion SO2 damages
Units: R/Year

Coal combustion arsenic & compounds emissions=(Arsenic emission factor in kg/PJ*Coal consumption in PJ)/kg to ton
Units: ton/Year

Coal combustion chromium & compounds emissions=(Chromium emission factor in kg/PJ*Coal consumption in PJ)/kg to ton
Units: ton/Year

Coal combustion heavy metals damages=Arsenic damages+Chromium damages+Lead damages+Nickel damages
Units: R/Year

Coal combustion lead & compounds emissions= (Lead emission factor in kg/PJ*Coal consumption in PJ)/kg to ton
Units: ton/Year

Coal combustion nickel & compounds emissions=(Nickel emission factor in kg/PJ*Coal consumption in PJ)/kg to ton
Units: ton/Year

Coal combustion NOx damages=Coal combustion NOx emissions*Unit damage cost NOx
Units: R/Year

Coal combustion NOx emissions=Gross electricity production*Emission factor NOx (coal)
Units: ton/Year

Coal combustion PM damages=Coal combustion PM emissions*Unit damage cost PM
Units: R/Year

Coal combustion PM emissions=Gross electricity production*"Emission factor PM (coal)"
Units: ton/Year

Coal combustion SO2 damages=Coal combustion SO2 emissions*Unit damage cost SO2
Units: R/Year

Coal combustion SO2 emissions=Gross electricity production*Emission factor SO2 (coal)
Units: ton/Year

Coal consumption=(((Gross electricity production*MWh to kWh)*Heat rate)/Coal energy content)/kg to ton
Units: ton/Year

Coal consumption in PJ=(Coal energy content in GJ/ton*Coal consumption)/GJ to PJ
Units: PJ/Year

Coal energy content=19.22
Units: MJ/kg

Coal energy content in GJ/ton=Coal energy content*(kg to ton/MJ to GJ)
Units: GJ/ton

Coal road transport NOx damages=Coal road transport NOx emissions*Unit damage cost NOx
Units: R/Year

Coal road transport NOx emissions=Emissions NOx in grams/g to ton

Units: ton/Year

Coal road transport PM damages=Coal road transport PM emissions*Unit damage cost PM
Units: R/Year

Coal road transport PM emissions=Emissions PM in grams/g to ton
Units: ton/Year

Coal road transport SO2 damages=Coal road transport SO2 emissions*Unit damage cost SO2
Units: R/Year

Coal road transport SO2 emissions=Emissions SO2 in grams/g to ton
Units: ton/Year

Coal road transportation distance=2.21484e+007
Units: km/Year

Coal transportation air pollution health cost=Coal road transport NOx damages+Coal road transport PM damages+Coal road transport SO2 damages+Conveyor coal transport air pollution damages
Units: R/Year

Coal-fuel cycle air pollution human health cost= Coal transportation air pollution health cost+FGD system air pollution health cost +Plant construction air pollution health cost+Plant operation air pollution health cost+Waste disposal air pollution health cost
Units: R/Year

Constant arsenic=2.73
Units: Dmnl

Constant chromium=2.47
Units: Dmnl

Constant lead=2.87
Units: Dmnl

Constant nickel=2.84
Units: Dmnl

Conversion factor=1
Units: Dmnl

Conveyor coal transport air pollution damages=Conveyor coal transport NOx damages+Conveyor coal transport PM damages+Conveyor coal transport SO2 damages
Units: R/Year

Conveyor coal transport NOx damages= Conveyor coal transport NOx emissions*Unit damage cost NOx
Units: R/Year

Conveyor coal transport NOx emissions=NOx emissions per MWh*Electricity use by conveyor
Units: ton/Year

Conveyor coal transport PM damages=Conveyor coal transport PM emissions*Unit damage cost PM
Units: R/Year

Conveyor coal transport PM emissions=PM emissions per MWh*Electricity use by conveyor
Units: ton/Year

Conveyor coal transport SO2 damages=Conveyor coal transport SO2 emissions*Unit damage cost SO2
Units: R/Year

Conveyor coal transport SO2 emissions=SO2 emissions per MWh*Electricity use by conveyor
Units: ton/Year

Distanced travelled (construction materials)=Number of road trips*Transportation distance (round trip)
Units: km/Year

Electricity use by conveyor=Conveyor electricity use per ton-km*Conveyor transported coal*Conveyor length
Units: MWh/Year

Emission factor NOx (coal)=0.00228
Units: ton/MWh

Emission factor NOx (transportation)=13.04
Units: g/km

Emission factor PM (coal)=0.000221
Units: ton/MWh

Emission factor PM (transportation)=0.68
Units: g/km

Emission factor SO2 (coal)=0.00095
Units: ton/MWh

Emission factor SO2 (transportation)=1.66
Units: g/km

Emissions NOx in grams=Coal road transportation distance*Emission factor NOx (transportation)
Units: g/Year

Emissions PM in grams=Coal road transportation distance*Emission factor PM (transportation)
Units: g/Year

Emissions SO2 in grams=Coal road transportation distance*"Emission factor SO2 (transportation)"
Units: g/Year

Escalation of damage cost=0.011
Units: Dmnl/Year

Exponent arsenic=0.85
Units: Dmnl

Exponent chromium=0.58
Units: Dmnl

Exponent lead= 0.8
Units: Dmnl

Exponent nickel=0.48
Units: Dmnl

FGD system air pollution health cost=Limestone transportation NOx damages+Limestone transportation PM damages+Limestone transportation SO2 damages
Units: R/Year

FINAL TIME=2060
Units: Year

Fly ash fraction of total ash=0.2
Units: Dmnl

Fraction of fly ash emitted=(Conversion factor-(Particulate collection efficiency/100))
Units: Dmnl

g to ton=1e+006
Units: g/ton

GJ to PJ=1e+006
Units: GJ/PJ

Gross electricity production=(((Functional capacity during construction*Plant operating hours)+(Desired functional capacity after construction*Plant operating hours))*Load factor)*"MWh/MW*h"
Units: MWh/Year

INITIAL TIME=2010
Units: Year

kg to ton=1000
Units: kg/ton

Lead content in coal=20.38
Units: mg/kg

Lead damages=Coal combustion lead & compounds emissions*Unit damage cost lead
Units: R/Year

Lead emission factor in kg/PJ=Constant lead*(((Lead content in coal/Weight fraction of ash in coal)*PM emitted per GJ heat input)*GJ to PJ/mg to kg)^(Exponent lead)
Units: kg/PJ

Limestone transportation electricity use=Conveyor electricity use per ton-km*Limestone consumption*Limestone transportation distance

Units: MWh/Year

Limestone transportation NOx damages=Limestone transportation NOx emissions*Unit damage cost NOx
Units: R/Year

Limestone transportation NOx emissions=NOx emissions per MWh*Limestone transportation electricity use
Units: ton/Year

Limestone transportation PM damages=Limestone transportation PM emissions*Unit damage cost PM
Units: R/Year

Limestone transportation PM emissions=PM emissions per MWh*Limestone transportation electricity use
Units: ton/Year

Limestone transportation SO2 damages=Limestone transportation SO2 emissions*Unit damage cost SO2
Units: R/Year

Limestone transportation SO2 emissions=SO2 emissions per MWh*Limestone transportation electricity use
Units: ton/Year

Material transportation NOx damages=Material transportation NOx emissions*Unit damage cost NOx
Units: R/Year

Material transportation NOx emissions=(Distanced travelled (construction materials)*Emission factor NOx (transportation))/g to ton
Units: ton/Year

Material transportation PM damages=Material transportation PM emissions*Unit damage cost PM
Units: R/Year

Material transportation PM emissions=(Distanced travelled (construction materials)*Emission factor PM (transportation))/g to ton
Units: ton/Year

Material transportation SO2 damages=Material transportation SO2 emissions*Unit damage cost SO2
Units: R/Year

Material transportation SO2 emissions=(Distanced travelled (construction materials)*Emission factor SO2 (transportation))/g to ton
Units: ton/Year

mg to kg=1e+006
Units: mg/kg

MJ to GJ=1000
Units: MJ/GJ

Nickel content in coal=25.69
Units: mg/kg

Nickel damages=Coal combustion nickel & compounds emissions*unit damage cost nickel

Units: R/Year

Nickel emission factor in kg/PJ=Constant nickel*(((Nickel content in coal/Weight fraction of ash in coal*PM emitted per GJ heat input)*GJ to PJ/mg to kg)^(Exponent nickel)
Units: kg/PJ

NOx emissions per MWh=0.00389
Units: ton/MWh

Particulate collection efficiency=99.8
Units: Dmnl

Plant construction air pollution health cost=Plant construction raw material transportation damages
Units: R/Year

Plant construction raw material transportation damages=Material transportation NOx damages+Material transportation PM damages+Material transportation SO2 damages
Units: R/Year

Plant operation air pollution health cost=Coal combustion air pollution health damages+Coal combustion heavy metals damages
Units: R/Year

PM emissions per MWh=0.000358
Units: ton/MWh

PM emitted per GJ heat input=Weight fraction of ash in coal*Fly ash fraction of total ash*Fraction of fly ash emitted*ton to kg/"Coal energy content in GJ/ton"
Units: kg/GJ

SO2 emissions per MWh=0.00753
Units: ton/MWh

 ton to kg=1000
Units: kg/ton

Unit damage cost arsenic=INTEG (Change in damage cost per ton of arsenic, 339976)
Units: R/ton

Unit damage cost chromium=INTEG (Change in damage cost per ton of chromium, 133866)
Units: R/ton

Unit damage cost lead=INTEG (Change in damage cost per ton of lead, 6.79953e+006)
Units: R/ton

Unit damage cost nickel=INTEG (Change in damage cost of nickel, 16149)
Units: R/ton

Unit damage cost NOx=INTEG (Change in NOx damage cost, 41952)
Units: R/ton

Unit damage cost PM=INTEG (Change in PM damage cost, 227175)
Units: R/ton

Unit damage cost SO2=INTEG (Change in SO2 damage cost, 51619)
Units: R/ton

Waste disposal air pollution health cost=Waste disposal NOx damages+Waste disposal PM damages+Waste disposal SO2 damages
Units: R/Year

Waste disposal electricity use=Conveyor electricity use per ton-km*Dry waste Kusile*Distance travelled Kusile waste
Units: MWh/Year

Waste disposal NOx damages=Waste disposal NOx emissions*Unit damage cost NOx
Units: R/Year

Waste disposal NOx emissions=NOx emissions per MWh*Waste disposal electricity use
Units: ton/Year

Waste disposal PM damages=Waste disposal PM emissions*Unit damage cost PM
Units: R/Year

Waste disposal PM emissions=PM emissions per MWh*Waste disposal electricity use
Units: ton/Year

Waste disposal SO2 damages=Waste disposal SO2 emissions*Unit damage cost SO2
Units: R/Year

Waste disposal SO2 emissions=SO2 emissions per MWh*Waste disposal electricity use
Units: ton/Year

Weight fraction of ash in coal=29.6
Units: Dmnl

A8: Global pollutants sub-model equations

Al=Al per MW*Capacity construction start
Units: ton/Year

Al C2F6 embodiment=0.04
Units: kg/ton

Al CF4 embodiment=0.8
Units: kg/ton

Al CO2 embodiment=5301
Units: kg/ton

Al per MW=0.419
Units: ton/MW

Al production CO2e emissions=((CO2 Al production)+(C2F4 Al production*Global warming potential C2F6)+(CF4 Al production*Global warming potential CF4))/kg to ton
Units: ton/Year

C emission factor for diesel=20.2
Units: ton/TJ

C2F4 Al production=Al*Al C2F6 embodiment
Units: kg/Year

Capacity construction start=Capacity investment/Unit capital cost
Units: MW/Year

Carbon %=0.425
Units: Dmnl

Carbon oxidation factor=0.99
Units: Dmnl

CF4 Al production=Al*Al CF4 embodiment
Units: kg/Year

CH4 emission factor for heavy duty diesel vehicles=1.97917e-008
Units: ton/l

CH4 emission m3/ton=0.014
Units: m3/ton

CH4 emission per ton of coal=CH4 emission m3/ton*Density of bituminous coal
Units: kg/ton

CH4 steel production=Steel*Steel CH4 embodiment
Units: kg/Year

Change in CO2 damage cost=Unit damage cost CO2*Escalation of damage cost
Units: R/ton/Year

CO2 Al production=Al*Al CO2 embodiment
Units: kg/Year

CO2 emission factor=(1/Coal energy content in kJ/ton)*Carbon %*Gravimetric factor converting C to CO2*Carbon oxidation factor
Units: ton/kJ

CO2 emission per MWh=IF THEN ELSE(Gross electricity production<1e-006,0,Coal combustion CO2 emissions/Gross electricity production)
Units: ton/MWh

CO2 steel production=Steel*Steel CO2 embodiment
Units: kg/Year

Coal combustion CO2 damages=Coal combustion CO2 emissions*Unit damage cost CO2
Units: R/Year

Coal combustion CO2 emissions=CO2 emission factor*Coal consumption in kJ
Units: ton/Year

Coal combustion CO2e damages (N2O)=Coal combustion CO2e emissions (N2O)*Unit damage cost CO2
Units: R/Year

Coal combustion CO2e emissions (N2O)=N2O emissions per MWh*Gross electricity production*Global warming potential N2O
Units: ton/Year

Coal consumption=(((Gross electricity production*MWh to kWh)*Heat rate)/Coal energy content)/kg to ton
Units: ton/Year

Coal consumption in kJ=Coal energy content in kJ/ton*Coal consumption
Units: kJ/Year

Coal energy content=19.22
Units: MJ/kg

Coal energy content in kJ/ton=Coal energy content*(kg to ton/MJ to kJ)
Units: kJ/ton

Coal mining & transportation global warming damages= Coal mining CO2e damages+Coal road transport global warming damages+Conveyor coal transport damages
Units: R/Year

Coal mining CO2e damages=Unit damage cost CO2*Coal mining CO2e emissions (CH4)
Units: R/Year

Coal mining CO2e emissions (CH4)=((CH4 emission per ton of coal*Coal consumption)/kg to ton)*Global warming potential CH4
Units: ton/Year

Coal road transpoirt CO2e damages=Unit damage cost CO2*Coal road transport CO2e emissions (CH4)
Units: R/Year

Coal road transport CO2 damages=Coal road transport CO2 emissions*Unit damage cost CO2
Units: R/Year

Coal road transport CO2 emissions=Diesel consumption in TJ*C emission factor for diesel*Diesel oxidation factor*Gravimetric factor converting C to CO2
Units: ton/Year

Coal road transport CO2e damages=Unit damage cost CO2*Coal road transport CO2e emissions (N2O)
Units: R/Year

Coal road transport CO2e emissions (CH4)=(CH4 emission factor for heavy duty diesel vehicles*Diesel consumption in litres (coal transport))*Global warming potential CH4
Units: ton/Year

Coal road transport CO2e emissions (N2O)=(N2O emission factor for heavy duty diesel vehicle*Diesel consumption in litres (coal transport))*Global warming potential N2O
Units: ton/Year

Coal road transport global warming damages=Coal road transport CO2 damages+Coal road transport CO2e damages+Coal road transpoirt CO2e damages
Units: R/Year

Coal road transportation distance=2.21484e+007
Units: km/Year

Coal-fuel cycle global warming damage cost=Coal mining & transportation global warming damages"+FGD system global warming damages+Plant construction global warming damages+Plant operation global warming damages+Waste disposal global warming damages
Units: R/Year

Concrete=Concrete per MW*Capacity construction start
Units: ton/Year

Concrete CO2e embodiment=119.72
Units: kg/ton

Concrete per MW=158.758
Units: ton/MW

Concrete production CO2e emissions=(Concrete*Concrete CO2e embodiment)/kg to ton
Units: ton/Year

Construction materials CO2e damages=(Unit damage cost CO2*Steel production CO2e emissions)+(Unit damage cost CO2*Al production CO2e emissions)+(Unit damage cost CO2*Concrete production CO2e emissions)
Units: R/Year

Conversion factor=1
Units: Dmnl

Conveyor coal transport CO2 damages=Unit damage cost CO2*Conveyor coal transport CO2 emissions
Units: R/Year

Conveyor coal transport CO2 emissions=CO2 emission per MWh*Electricity use by conveyor
Units: ton/Year

Conveyor coal transport CO2e damages=Unit damage cost CO2*Conveyor coal transport CO2e emissions (N2O)
Units: R/Year

Conveyor coal transport CO2e emissions (N2O)=N2O emissions per MWh*Electricity use by conveyor*Global warming potential N2O
Units: ton/Year

Conveyor coal transport damages=Conveyor coal transport CO2 damages+Conveyor coal transport CO2e damages
Units: R/Year

Conveyor electricity use per ton-km=0.0002
Units: MWh/ton/km

Conveyor length=42
Units: km

Conveyor transported coal=(Conversion factor-Fraction of coal transported by road)*Coal consumption
Units: ton/Year

Density of bituminous coal=732
Units: kg/m3

Diesel consumption (TJ)=(Diesel consumption in litres (construction)*Energy density of diesel)/MJ to TJ
Units: TJ/Year

Diesel consumption in litres (coal transport)=Coal road transportation distance*Truck fuel consumption in l/km
Units: l/Year

Diesel consumption in litres (construction)=Distanced travelled (construction materials)*Truck fuel consumption in l/km
Units: l/Year

Diesel consumption in TJ=(Diesel consumption in litres (coal transport)*Energy density of diesel)/MJ to TJ
Units: TJ/Year

Diesel oxidation factor= 0.99
Units: Dmnl

Distance travelled Kusile waste=30
Units: km

Distanced travelled (construction materials)=Number of road trips*Transportation distance (round trip)
Units: km/Year

Dry waste Kusile=Ash produced per ton of coal burnt*Coal consumption
Units: ton/Year

Electricity use by conveyor=Conveyor electricity use per ton-km*Conveyor transported coal*Conveyor length
Units: MWh/Year

Energy density of diesel=38.46

Units: MJ/l

Escalation of damage cost=0.011
Units: Dmnl/Year

FGD system global warming damages=Limestone transportation CO2 damages+Limestone transportation CO2e damages (N2O)+Limestone use damages (FGD)
Units: R/Year

FINAL TIME=2060
Units: Year

Fraction of coal transported by road=0.27
Units: Dmnl

Global warming potential C2F6=12200
Units: Dmnl

Global warming potential CF4=7390
Units: Dmnl

Global warming potential CH4=23
Units: Dmnl

Global warming potential N2O=310
Units: Dmnl

Gravimetric factor converting C to CO2=3.667
Units: Dmnl

Gross electricity production=(((Functional capacity during construction*Plant operating hours)+(Desired functional capacity after construction*Plant operating hours))*Load factor)*MWh/MW*h
Units: MWh/Year

INITIAL TIME=2010
Units: Year

kg to ton=1000
Units: kg/ton

Limestone consumption=Limestone consumption per hour*Plant operating hours
Units: ton/Year

Limestone transportation CO2 damages=Unit damage cost CO2*Limestone transportation CO2 emissions
Units: R/Year

Limestone transportation CO2 emissions=CO2 emission per MWh*Limestone transportation electricity use
Units: ton/Year

Limestone transportation CO2e damages (N2O)=Unit damage cost CO2*"Limestone transportation CO2e emissions (N2O)

Units: R/Year

Limestone transportation CO2e emissions (N2O)=N2O emissions per MWh*Limestone transportation electricity use*Global warming potential N2O
Units: ton/Year

Limestone transportation distance=120
Units: km

Limestone transportation electricity use=Conveyor electricity use per ton-km*Limestone consumption*Limestone transportation distance
Units: MWh/Year

Limestone use CO2 damages=Limestone use CO2 emissions*Unit damage cost CO2
Units: R/Year

Limestone use CO2 emission factor=439.71
Units: kg/ton

Limestone use CO2 emissions=(Limestone use CO2 emission factor*Limestone consumption)/kg to ton
Units: ton/Year

Limestone use damages (FGD)=Limestone use CO2 damages
Units: R/Year

Main material inputs=Al+Concrete+Steel
Units: ton/Year

Material transportation CO2e damages=(Unit damage cost CO2*Materials transportation CO2 emissions)+(Unit damage cost CO2*Materials transportation CO2e emissions (CH4))+(Unit damage cost CO2*Materials transportation CO2e emissions (N2O))
Units: R/Year

Materials transportation CO2 emissions=C emission factor for diesel*"Diesel consumption (TJ)"*Diesel oxidation factor*Gravimetric factor converting C to CO2
Units: ton/Year

Materials transportation CO2e emissions (CH4)=(CH4 emission factor for heavy duty diesel vehicles*"Diesel consumption in litres (construction))*Global warming potential CH4
Units: ton/Year

Materials transportation CO2e emissions (N2O)=(N2O emission factor for heavy duty diesel vehicle*Diesel consumption in litres (construction))*Global warming potential N2O
Units: ton/Year

MJ to kJ=1000
Units: MJ/kJ

MJ to TJ=1e+006
Units: MJ/TJ

N2O emission factor for heavy duty diesel vehicle=9.16667e-009
Units: ton/l

N2O emissions per MWh=1.15e-005
Units: ton/MWh

N2O steel production=Steel*Steel N2O embodiment
Units: kg/Year

Number of road trips=Main material inputs/Truck capacity
Units: Dmnl/Year

Plant construction global warming damages=Construction materials CO2e damages+Material transportation CO2e damages
Units: R/Year

Plant operation global warming damages=Coal combustion CO2 damages+Coal combustion CO2e damages (N2O)
Units: R/Year

Steel=Steel per MW*Capacity construction start
Units: ton/Year

Steel CH4 embodiment=100
Units: kg/ton

Steel CO2 embodiment=2710
Units: kg/ton

Steel N2O embodiment=100
Units: kg/ton

Steel per MW=50.721
Units: ton/MW

Steel production CO2e emissions=((CO2 steel production)+(CH4 steel production*Global warming potential CH4)+(N2O steel production*Global warming potential N2O))/kg to ton
Units: ton/Year

Transportation distance (round trip)=100
Units: km

Truck capacity=31
Units: ton

Truck fuel consumption in l/km=0.35
Units: l/km

Unit damage cost CO2=INTEG (Change in CO2 damage cost, 109.89)
Units: R/ton

Waste disposal CO2 damages=Unit damage cost CO2*Waste disposal CO2 emissions
Units: R/Year

Waste disposal CO2 emissions=CO2 emission per MWh*Waste disposal electricity use
Units: ton/Year

Waste disposal CO2e damages (N2O)=Unit damage cost CO2*Waste disposal CO2e emissions (N2O)
Units: R/Year

Waste disposal CO2e emissions (N2O)=N2O emissions per MWh*Waste disposal electricity use*Global warming potential N2O
Units: ton/Year

Waste disposal electricity use=Conveyor electricity use per ton-km*Dry waste Kusile*Distance travelled Kusile waste
Units: MWh/Year

Waste disposal global warming damages=Waste disposal CO2 damages+Waste disposal CO2e damages (N2O)
Units: R/Year

A9: Social cost sub-model equations

Capacity investment=(Planned investment in plant capacity table(Time))*Unit capital cost
Units: R/Year

Change in expected profitability=(Unit profitability-Expected profitability)/Time to adjust profit
Units: Dmnl/Year

Coal cost=Coal consumption*Unit coal cost
Units: R/Year

Coal-fuel cycle air pollution human health cost= Coal transportation air pollution health cost+FGD system air pollution health cost+Plant construction air pollution health cost+Plant operation air pollution health cost+Waste disposal air pollution health cost
Units: R/Year

Coal-fuel cycle cost of lost ecosystem services=Ecosystem services lost due to coal mining+Ecosystem services lost due to plant construction & operation
Units: R/Year

Coal-fuel cycle externality cost of water use=Opportunity cost of water use (construction)+Opportunity cost of water use (power generation)+Opportunity cost of water use in disposing Kusile's waste+Opportunity cost of water use in FGD+Opportunity cost of water use in the New Largo colliery (coal mining)
Units: R/Year

Coal-fuel cycle externality costs=Coal-fuel cycle air pollution human health cost+Coal-fuel cycle cost of lost ecosystem services+Coal-fuel cycle externality cost of water use"+"Coal-fuel cycle fatalities & morbidity costs+Coal-fuel cycle global warming damage cost+Coal-fuel cycle water pollution externality cost
Units: R/Year

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Coal-fuel cycle fatalities & morbidity costs=Fatalities & morbidity costs (coal mining)+Fatalities & morbidity costs (construction)+Fatalities & morbidity costs (power generation)
Units: R/Year

Coal-fuel cycle global warming damage cost=Coal mining & transportation global warming damages+FGD system global warming damages+Plant construction global warming damages+Plant operation global warming damages+Waste disposal global warming damages
Units: R/Year

Coal-fuel cycle water pollution externality cost=Damage cost of sulphate pollution from coal mining+Damage cost of sulphate pollution from Kusiles' raw material requirements
Units: R/Year

Cumulative capital cost escalated=INTEG (capital investment rate, 0)
Units: R

Cumulative private costs=INTEG (Private cost rate, 0)
Units: R

Cumulative PV air pollution cost=INTEG (PV air pollution cost, 0)
Units: R

Cumulative PV costs=Cumulative capital cost escalated+Cumulative PV fuel cost+Cumulative PV fixed O&M costs+Cumulative PV variable O&M costs+Cumulative PV FGD operation cost
Units: R

Cumulative PV ecosystem services loss=INTEG (PV ecosystem services loss, 0)
Units: R

Cumulative PV externality cost=Cumulative PV air pollution cost+Cumulative PV ecosystem services loss+Cumulative PV externality cost of water use+Cumulative PV fatalities & morbidity cost+Cumulative PV global warming damages+Cumulative PV water pollution externality
Units: R

Cumulative PV externality cost of water use=INTEG (PV external cost of water use, 0)
Units: R

Cumulative PV fatalities & morbidity cost=INTEG (PV fatalities & morbidity cost, 0)
Units: R

Cumulative PV FGD operation cost=INTEG (PV FGD operation cost, 0)
Units: R

Cumulative PV fixed O&M costs=INTEG (PV fixed O&M costs, 0)
Units: R

Cumulative PV fuel cost=INTEG (PV fuel cost, 0)
Units: R

Cumulative PV global warming damages=INTEG (PV global warming damages, 0)
Units: R

Cumulative PV net electrity production=INTEG (PV net electricity production, 1)
Units: MWh

Cumulative PV revenue=INTEG (PV revenue, 0)
    Units: R

Cumulative PV variable O&M costs=INTEG (PV variable O&M costs, 0)
Units: R

Cumulative PV water pollution externality=INTEG (PV water pollution externality, 0)
Units: R

Cumulative revenue=INTEG (Revenue rate, 0)
Units: R

Electricity price table ([(2010,0)-(2061,1500)],(2010,413.1),(2011,516.8),(2012,599.49),(2013,655.1),(2014,707.51),(2015,764.11),(2016,825.24),(2017,891.26),(2018,892.15),(2019,893.04),(2020,893.93),(2021,894.83),(2022,895.72),(2023,896.62),(2024,897.51),(2025,898.41),(2026,899.31),(2027,900.21),(2028,901.11),(2029,902.01),(2030,902.91),(2031,903.82),(2032,904.72),(2033,905.62),(2034,906.53),(2035,907.44),(2036,908.34),(2037,909.25),(2038,910.16),(2039,911.07),(2040,911.98),(2041,912.89),(2042,913.81),(2043,914.72),(2044,915.64),(2045,916.55),(2046,917.47),(2047,918.39),(2048,919.3),(2049,920.22),(2050,921.14),(2051,922.06),(2052,922.99),(2053,923.91),(2054,924.83),(2055,925.76),(2056,926.68),(2057,927.61),(2058,928.54),(2059,929.47),(2060,930.4))
Units: R/MWh

Expected profitability=INTEG (Change in expected profitability, 0)
Units: Dmnl

Externality cost switch= 0
    Units: Dmnl

FGD operation cost=FGD water cost+Limestone cost+Other FGD O&M costs year
    Units: R/Year

FINAL TIME=2060
Units: Year

Fixed O&M costs year=Fixed O&M costs/Year
Units: R/Year

Gross electricity production=(((Functional capacity during construction*Plant operating hours)+(Desired functional capacity after construction*Plant operating hours))*Load factor)*MWh/MW*h
Units: MWh/Year

INITIAL TIME=2010
Units: Year

Levelised air pollution cost=Cumulative PV air pollution cost/Cumulative PV net electrity production
Units: R/MWh

Levelised cost of energy=Levelised fuel cost+Levelised O&M costs+Levelised FGD operaton cost+Levelised capital cost
Units: R/MWh

Levelised ecosystem services loss=Cumulative PV ecosystem services loss/Cumulative PV net electrity production
Units: R/MWh

Levelised externality cost of energy=Levelised air pollution cost+Levelised ecosystem services loss+Levelised fatalities & morbidity cost+Levelised global warming damages+Levelised water pollution externality+Levelised water use externality
Units: R/MWh

Levelised fatalities & morbidity cost=Cumulative PV fatalities & morbidity cost/Cumulative PV net electrity production
Units: R/MWh

Levelised global warming damages=Cumulative PV global warming damages/Cumulative PV net electrity production
Units: R/MWh

Levelised social cost of energy=Levelised cost of energy+Levelised externality cost of energy
Units: R/MWh

Levelised water pollution externality=Cumulative PV water pollution externality/Cumulative PV net electrity production
Units: R/MWh

Levelised water use externality=Cumulative PV externality cost of water use/Cumulative PV net electrity production
Units: R/MWh

Net electricity production=Gross electricity production*1-Internal consumption rate
Units: MWh/Year

NPV (after tax)=NPV (before tax)*Tax rate factor
Units: R

NPV (before tax)=Cumulative PV revenue-Cumulative PV costs
Units: R

Planned investment in plant capacity table ([[(2010,0)-(2060,2000)]],(2010,800),(2011,800),(2012,800),(2013,800),(2014,1600),(2015,0),(2016,0),(2017,0),(2018,0), (2019,0),(2020,0),(2021,0),(2022,0),(2023,0),(2024,0),(2025,0),(2026,0),(2027,0),(2028,0),(2029,0),(2030,0), (2031,0),(2032,0),(2033,0),(2034,0),(2035,0),(2036,0),(2037,0),(2038,0),(2039,0),(2040,0),(2041,0),(2042,0), (2043,0),(2044,0),(2045,0),(2046,0),(2047,0),(2048,0),(2049,0),(2050,0),(2051,0),(2052,0),(2053,0),(2054,0), (2055,0),(2056,0),(2057,0),(2058,0),(2059,0),(2060,0))
Units: MW/Year

Plant private costs=Capacity investment+Coal cost+FGD operation cost+Fixed O&M costs year+Variable O&M costs

Units: R/Year

Present value factor=((Conversion factor+Discount rate)^Year of cost(Time))
Units: Dmnl

Private cost rate=Plant private costs
Units: R/Year

Profits (after tax)=Profits (before tax)*Tax rate factor
Units: R

Profits (before tax)=Cumulative revenue-Cumulative private costs
Units: R

PV air pollution cost=Coal-fuel cycle air pollution human health cost/Present value factor
Units: R/Year

PV ecosystem services loss=Coal-fuel cycle cost of lost ecosystem services/Present value factor
Units: R/Year

PV external cost of water use=Coal-fuel cycle externality cost of water use/Present value factor
Units: R/Year

PV fatalities & morbidity cost=Coal-fuel cycle fatalities & morbidity costs/Present value factor
Units: R/Year

PV global warming damages=Coal-fuel cycle global warming damage cost/Present value factor
Units: R/Year

PV revenue=Revenue/Present value factor
Units: R/Year

PV water pollution externality=Coal-fuel cycle water pollution externality cost/Present value factor
Units: R/Year

Revenue=Electricity price table(Time)*Net electricity production
Units: R/Year

Revenue rate=Revenue
Units: R/Year

Social NPV (after tax)=NPV (after tax)-Cumulative PV externality cost
Units: R

Social NPV (before tax)=NPV (before tax)-Cumulative PV externality cost
Units: R

Tax rate factor=0.72
Units: Dmnl

Time to adjust profit=1

Units: Year

Unit coal-fuel cycle externality cost=IF THEN ELSE(Gross electricity production<1e-006,0,Coal-fuel cycle externality costs/Gross electricity production)
Units: R/MWh

Unit cost of prodution=IF THEN ELSE(Gross electricity production<=1e-006,0,Plant private costs/Gross electricity production)
Units: R/MWh

Unit profitability=IF THEN ELSE(Time>2015,(IF THEN ELSE(Externality cost switch=1,(((Electricity price table (Time)*Tax rate factor)-(Unit cost of prodution+Unit coal-fuel cycle externality cost))/Electricity price table(Time)), (((Electricity price table(Time)*Tax rate factor)-Unit cost of prodution)/Electricity price table(Time)))),0)
Units: Dmnl

Variable O&M costs=Plant water cost+Other variable O&M costs year
Units: R/Year

Year of cost ([(2010,0)-(2060,60)],(2010,1),(2011,2),(2012,3),(2013,4),(2014,5),(2015,6),(2016,7),(2017,8),(2018,9),(2019,10),(2020,11),(2021,12),(2022,13),(2023,14),(2024,15),(2025,16),(2026,17),(2027,18),(2028,19),(2029,20),(2030,21),(2031,22),(2032,23),(2033,24),(2034,25),(2035,26),(2036,27),(2037,28),(2038,29),(2039,30),(2040,31),(2041,32),(2042,33),(2043,34),(2044,35),(2045,36),(2046,37),(2047,38),(2048,39),(2049,40),(2050,41),(2051,42),(2052,43),(2053,44),(2054,45),(2055,46),(2056,47),(2057,48),(2058,49),(2059,50),(2060,51))
Units: Dmnl